POTENTIAL AND CHALLENGES OF MANAGED AQUIFER RECHARGE IN AN OVER EXPLOITED AQUIFER OF DHAKA CITY

M.Sc. Engineering Thesis

by

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DEPARTMENT OF WATER RESOURCES ENGINEERING

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

DHAKA-1000, BANGLADESH

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Submitted to

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Candidate's Decleration

It is hereby declared that this thesis work or any part of it has not been submitted elsewhere for the award of any other degree or diploma.

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Certification of Thesis

The thesis titled **"POTENTIAL AND CHALLENGES OF MANAGED AQUIFER RECHARGE IN AN OVER EXPLOITED AQUIFER OF DHAKA CITY"**, submitted by Mollika Pervin , Roll No: 040816006 (P), Session April 2008, to the department of Water Resources Engineering, Bangladesh University of Engineering and Technology, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of Master of Science in Water Resources Engineering and approved as to its style and content. Examination held on March 24, 2015.

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ABSTRACT

The present study analyzed the role of Managed aquifer recharge (MAR) on the improvement of water supply condition in Dhaka, the capital of Bangladesh. Dhaka is one of the most challenging megacities with regards to its sustainable water resources management, in particular drinking water supply. Population growth would create additional drinking water demand in the near future (year 2025). The population of Dhaka City is presently about 14 million and according to present trends in population growth, that number will most likely increase to 22 million by the year 2025. According to previous studies, due to over-exploitation of the regional aquifer system the current groundwater resources trend is non-sustainable. It results in very fast decrease in groundwater levels of about 2 to 3 m/y. New water resources management strategies are needed to confirm drinking water supply and sustainable groundwater development (i.e., halt of groundwater decline). MAR would help to restore groundwater resources in Dhaka city by using, for example, collected rainwater. This thesis briefly explores the potential, viability, and challenges with respect to the implementation of Managed Aquifer Recharge (MAR) as a contribution to sustainable water resources development in Dhaka City.

Rainwater harvesting together with water capturing from the open spaces can meet up to 20%-30% of the present water supply demand in Dhaka City. Though the pheripheral rivers are polluted, nearby big rivers (such as Meghna) can be a source of water during the monsoon. The estimated volume of storage for the upper Dupitila aquifer is about 1120 Mm^3. Hydraulic conductivities of the Dhaka City aquifer would allow for the dispersion of recharged water with low costs of recovery, making MAR viable. Lithologs and 3D block diagrams reveal that the top most clay layer ranges between 8 and 52 m in most places. Considering the top impermeable layer thickness (TIL) and land cover classification, four primary MAR techniques have been suggested: (1) infiltration basin (TIL thickness: 0-10 m), (2) cascade type recharge trench/pit (TIL thickness: 10-32 m), (3) Aquifer storage, transfer and recovery, ASTR (32-52 m), and (4) use of natural wetlands to recharge the water collected from open spaces. The regional groundwater flow direction, from North-West and North-East towards Dhaka City, may allow the use

of the aquifer as a treatment facility and transport medium for groundwater development, if spreading basins are installed in the greater Dhaka City area.

Preliminary hydrogeochemical investigations reveal that in some places groundwater is already polluted by industrial waste. Therefore, a comprehensive geochemical model is required to identify potential geochemical processes related to the infiltration or injection of storm water. Nevertheless, the preliminary evaluation of the potential of MAR implementation in this region, which is based on available conventional and non-conventional water resources, aquifer characteristics, and applicability of MAR technologies as well as water treatment requirements, shows that MAR is viable and can play a key role in sustaining water resource development amidst increasing pressures on the current water resources of Dhaka City, Bangladesh.

Chapter 1

INTRODUCTION

1.1 Background

Bangladesh is a developing country in South Asia, with an area of 147,570 km^2. It has a population of 150 million (according to BBS, 2011). Bangladesh has a comparatively low natural resource base but high density of population. Due to huge population pressure the natural resources of this country is under stress; some are over exploited or used suboptimal. The climate of Bangladesh is characterized by high temperatures, excessive humidity and fairly marked seasonal variations of precipitation. The mean annual rainfall varies widely within the country according to the geographical locations, ranging from 1,200 mm in the extreme west to 5,800 mm in the east and northeast.

Bangladesh is considered as the largest delta in the world, formed by the Ganges, the Brahmaputra and the Meghna river system, characterized by flat terrain interlaced with the intricate system of rivers and tidal channels. Besides these main big rivers, there are about 700 rivers, canals and streams in Bangladesh. The topography of the country is comparatively flat (Figure 1.1).

Flood, cyclones, storm surges are considered regular natural events in Bangladesh (Shaji et al., 2014). Arsenic in groundwater is also considered as one of the main threat to safe drinking water supply to most of the upzilas (small administrative district in Bangladesh) (Ali et al., 2003). Recently, serious problems of environmental degradation are resulting from unplanned urbanization in Bangladesh. The present pattern of urbanisation is leading to various problems like land use alterations; degradation of community ambient environment; less control on industrial waste emissions and environmental pollution due to inadequate management of human and domestic wastes (Hossain 2008).

Groundwater resource development in Bangladesh is being increased with the rising demand for potable water due to population explosion. Providing safe drinking water is a burning issue in over populated urban area like Dhaka, as the urban environments are in many cases hostile to groundwater. There is conflict between rapid urban development and the sustainability of groundwater resources in a number of mega-cities throughout the developing world (Morris et al. 1997). Large-scale abstractions always bring changes in the natural system of the aquifer and also in the environment (Chawala, 1994; Eisen & Anderson, 1980).

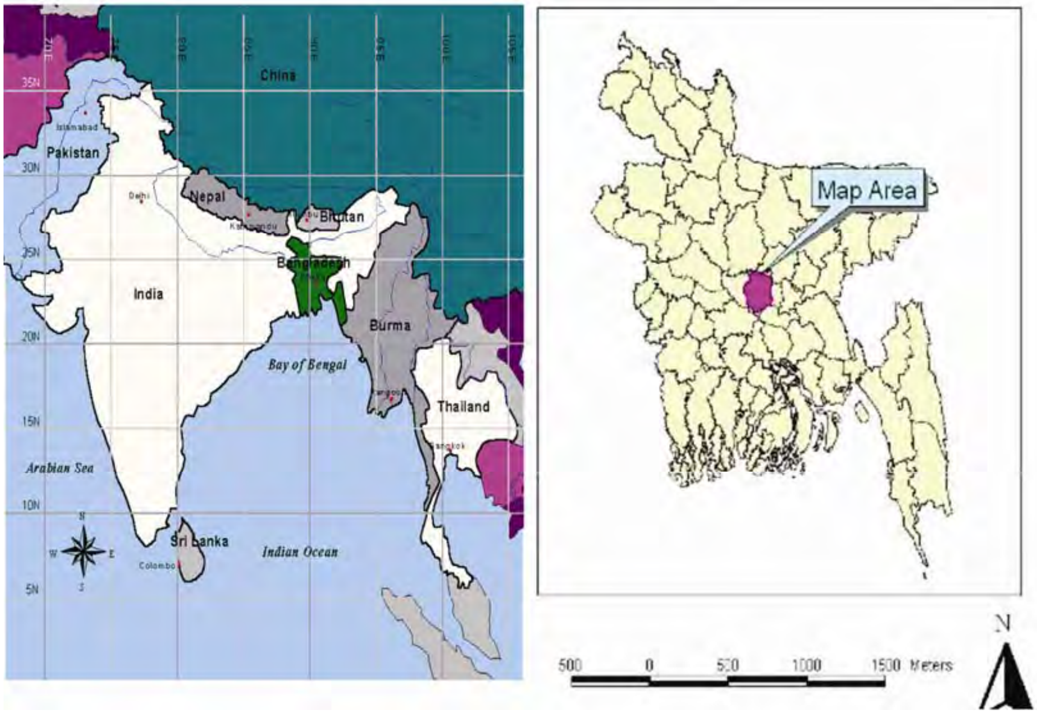


Figure 1.1: General map of the study area

In a populous city like Dhaka (the 10th largest city of the world according to City Mayor Statistics, 2008) exponential growth rates, in terms of number of wells and estimated accumulated pumping volumes, give an impression of an explosion rather than a steady and controlled evolution. Rapid population growth and so rapid urbanization during the last three decades has taken place, which creates extra pressure on the land. The size of Dhaka City has grown from 9.38 sq. km in 1600 to 590 sq. km in 1997 (Sultana 2009). According to Sultana (2009), human settlement in Dhaka city started from seventh century but the natural geomorphological setting began to be modified probably from the twelfth century. The expansion of the city became very extensive after 1975 and extended to abandoned channel and depression (Dewan and Yamaguchi, 2009). Undulating Madhupur Clay surfaces in the north and east where being leveled and filling activities became an essential factor of urbanization. Now the city is expanding in every direction, having a centre in the downtown areas. With the development of the city, wide roads and other paved areas replaced the unpaved areas, natural depressions, and agricultural land. In many cases, natural drainage canals and open water bodies were filled up for development works.

A significant siltation in the khals and rivers in and around Dhaka City has taken place due to expansion of the Dhaka Metropolitan area over the last few decades for flood control embankment and sluice gate across the rivers and canals. At the initial phase of urban development of Dhaka, water is mostly abstracted by Shallow Tube wells. With the expansion of urban areas and increase in, groundwater abstraction increases and lead to a number of negative environmental impacts. Urbanization (construction of roads, buildings, pavements airport runways and construction of dam, embankments) hinder the natural drainage system and reduce natural recharge. More over present land development practices in the swampy areas is also reducing the natural recharge. Hence, the drinking water supply is becoming a challenge for the City (see chapter 4 for detail description of water resources in Dhaka city).

1.2 Scope of the study

Dhaka City is facing challenges with the problem of shortage in water supply (DWASA 2006). Historically, Dhaka City faces immense problems related to flooding, water logging and drainage congestions during Monsoon (Haque and Alam 2003). Presently, 75% of water of Dhaka City is supplied by Dhaka Water and Sanitation Authority (DWASA). 83% of the drinking water originates from groundwater (GW) sources via 518 deep tube-wells (DTW) and 17% is supplied by three major surface water treatment plants such as Saidabad surface water treatment plant, Dhaka Water works and Narayangonj Water works (DWASA, 2012). The population of Dhaka City is about 9 million (BBS, 2011), water supplies by DWASA cover 8.6 million people (Haque ,2007) and according to growth trends, the population may reach 22 million by the year 2025 (ADB, 2007), which would create a drinking water demand of an additional 80% in the near future. To meet the requirements either surface water or groundwater sources need to be explored.

The upper aquifer of the city is almost empty and thus to secure drinking water supply for the people DWASA has installed high capacity water wells to tap the lower aquifer (Haque, 2006). In most of the region, groundwater extraction exceeds recharge to the upper aquifers. Average groundwater depletion is about 2-3 m/year (Haque, 2006; Akhter et al., 2009 and Rahman 2011), making calls for the alleviation of upper aquifer exploitation and the exploration of more suitable and sustainable water resources well-founded.

There are a number of rivers are flowing around Dhaka city (Figure 1.2). The peripheral rivers are the nearest dependable surface water (SW) source. However, continued pollution makes the nearby SW is no longer considered as suitable water supply source (Subramanian, 2004, Kamal et al., 1999). Especially, the river along the Tongi Canal, the Balu River, the Turag River, the Buriganga River, Shitalakkhya River and the Dhaleshwari River are highly polluted by industrial waste and effluent, as reported by Rahman and Hossain, (2008). The authors concluded that though river water is currently not suitable for drinking water supply, it could be used for drinking water supply after proper treatment during the monsoon season, though the quantity and quality is not defined yet.

DWASA is feeling an urgent need to relieve the pressure on groundwater dependent drinking water supply. In order to reduce pressure on the currently used groundwater sources and to include other groundwater resources of the area, integrated water resources management (IWRM) is needed for water conservation in Dhaka City. Worldwide, IWRM has shown that an integrated management of surface and groundwater resources can be more efficient by means of managed aquifer recharge (MAR) (Rusteberg et al., 2010). MAR in conjunction with IWRM would help to restore groundwater resources in Dhaka city by using, for example, collected urban monsoon runoff, excess surface water from rivers, and treated effluents from wastewater treatment plants. The use of this water type has been successfully implemented and demonstrated in different parts of the world such as in the USA; Australia, Israel, U.K etc. Depending on the aquifer type and water availability several MAR techniques (such as Infiltration basin, recharge well, river bank filtration etc.) are in practice now.

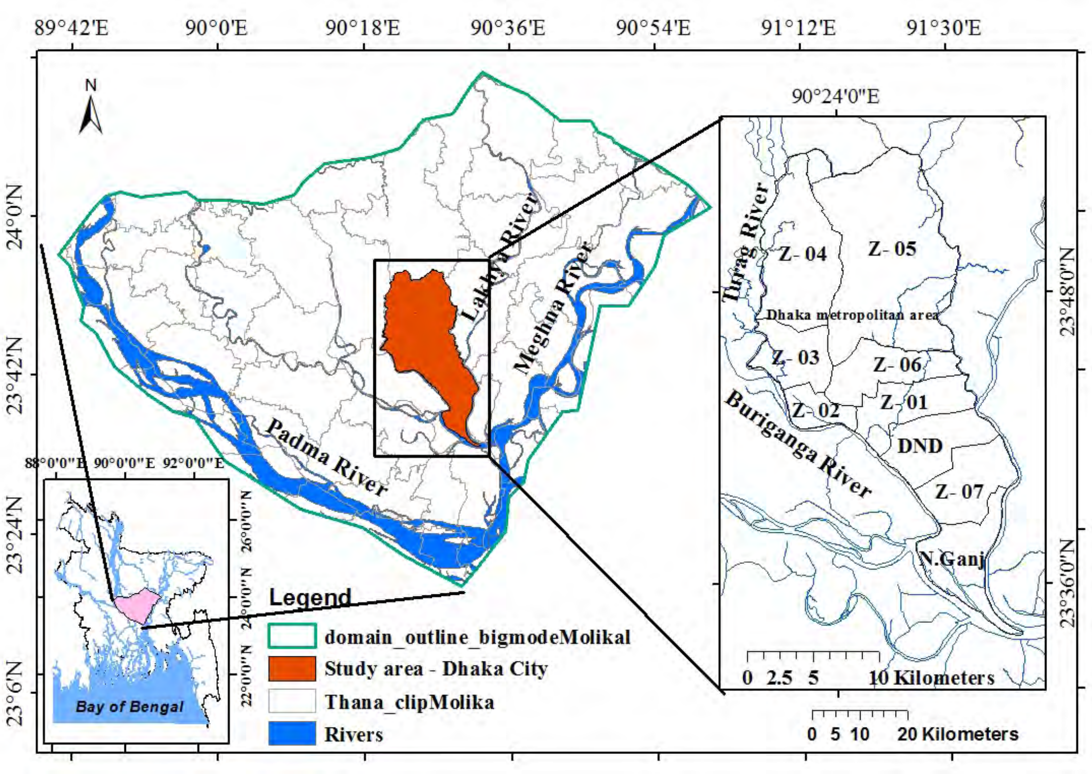


Figure 1.2: Study Area- Dhaka city

MAR is considered as a part of IWRM and so the implementation of MAR is not straight forward. The successful implementation of a MAR project in any location depends on a number of factors such as the hydrogeological situation, the infrastructure, and regulatory mechanisms (Maliva and Missimer, 2010). Hence, before any MAR project implementation a pre-feasibility study should be undertaken. The scope of this study is to evaluate the hydrogeological situation in Dhaka City in the context of a planned MAR implementation. The study provides a preliminary hydrological feasibility assessment to determine if MAR can be successfully implemented and operated with optimum recovery efficiency.

1.3 Objective of the study

The overall objective of the study is to explore the potentiality, viability, and challenges of a MAR project implementation and its contributions to a sustainable groundwater resources development and to a strengthened water supply for Dhaka City.

The specific objectives of the study are:

1. Identification of the need of Managed Aquifer Recharge (MAR) by analyzing the existing water resources problem to strengthen water supply and groundwater development in the upper aquifer of the city.
2. Identification of potential alternative water sources (such as rainwater) and their availability for MAR implementation
3. Selection of proper combination of MAR location and technology, and identification of the challenges for MAR implementation in the study area

The possible outcomes of the study are:

1. Detailed viability assessment of MAR implementation in Dhaka City
2. Water availability for MAR projects in Dhaka city
3. Appropriate MAR technology for the study area including detailed technical description
4. Future challenges and their potential solutions for MAR implementation in the study area

1.4 Structure of the thesis

Chapter 1 presents the specific objectives of the study and portrays the outline of the whole report.

Chapter 2 offers the relevant scientific background, current practice and experiences of MAR, and the overall planning and management of MAR.

Chapter 3 shows the overall methodology of the research.

Chapter 4 explains the water resources system of Dhaka city and indicates the requirement of MAR in the city

Chapter 5 presents the results on the hydrological, hydrogeological and groundwater quality analysis. A comprehensive discussion is also made on the potential and challenges of MAR in Dhaka city.

Chapter 6 presents the conclusions and recommendations for further study.

Chapter 2

LITERATURE REVIEW

2.1 General

With an aim to set research methodologies, an intensive literature review has been performed and briefly explained in this chapter. This chapter basically explain the basic of managed aquifer recharge, its history in the world and basic requirements to implement an MAR project. This chapter also reports about the current practice of MAR and in the world together with the regional (e.g. south Asian) studies. A brief analysis of the Mar related studies also summarised here to find the research gap for further studies.

2.2 Managed Aquifer Recharge (MAR)

Managed aquifer recharge is the purposeful recharge of an aquifer under controlled conditions to store the water for later abstraction or to achieve environmental benefits. Water can be added to the aquifer by infiltration (via structures such as ponds, basins, galleries and trenches) or injection via wells. There are many potential sources of recharge water including storm water runoff (excess or redirected), treated wastewater, water from watercourses or aquifers, and imported water

MAR projects have the potential to increase water availability by generating water supplies from sources that may otherwise be wasted. It can provide environmental, social and economic benefits. Benefits include improved maintenance of wetlands, opportunity for seasonal storage of water (in times of surplus to meet need in times of demand), prevention of salt-water intrusion, increased water availability for irrigation use and augmentation of drinking water supplies (known as groundwater replenishment). Managed aquifer recharge also has the potential to improve water quality through natural processes. It may assist in the removal of nutrients such as phosphates and organics, the degradation of chemicals (such as disinfection by-products) and pathogen die-off.

Managed aquifer recharge will not be feasible everywhere, due to hydrogeological, environmental or cost constraints. In some cases where stormwater or treated wastewater is considered for irrigation or other non-drinking purposes, direct use of the water could be preferable to managed aquifer recharge. There is potential for managed aquifer recharge to play an important role in the sustainable management of Dhaka City's water resources, however there are a number of environmental, health and social issues associated with the process that need to be addressed.

2.3 History of Managed Aquifer Recharge

A brief overview on the history of MAR, briefly presented below, is based on Todd (1959), Signore et al., (1970), Maliva and Missimer (2010) and several other articles on MAR that have been cited herein.

The history of MAR in the U.S is very old (Todd, 1954). Todd, (1959) indicated that MAR was being widely investigated and successfully implemented by the middle of the 20th century for different purposes. In Iowa, artificial recharge of groundwater by means of flooding basin has been successful in operation to build groundwater yield since 1910 (Maffitt, 1943). Brashears (1946) reported that in Long Island, New York, more than 200 recharge wells were operated in summer 1944 to return the pumped water that had been withdrawn. The first successful test of an Aquifer Storage and Recovery (ASR) system with mixing of fresh water with brackish water appears to have been performed at Camp Peary (Cederstrom, 1947). In the United States, the first long term ASR well field was implemented in Wildwood, New Jersey in 1968 and the function of the wells was to prevent salinity intrusion and assist to meet peak season water demand (Lacombe, 1997; Pyne, 2004). According to Zielbauer (1966), the first successfully operated ASR project to protect sea water intrusion was constructed along Santa Monica Bay.

In the USA, there has been a noticeable increase in the number of ASR schemes during the past 20 years. According to AWWA, 2002, a survey in 2001 indicated that there were 30 operational schemes and 10 further pilot studies being conducted. Later Pyne, (2005) reported that the number of ASR systems had increased to 72 by March 2005. In February 2009, 542 ASR wells and 661 AR wells were operating or capable of operation in the United States (EPA, 2009b).

In Europe, MAR schemes have been in operation for over one hundred years (Water & Forestry, 2007). In Germany the Düsseldorf water works started river bank infiltration (RBF) in the Rhine river in 1870 (Schubbert, 2002; Shandu et al., 2011). According to Schmidt et al., (2003) 50 plants are now operating based on groundwater artificial recharge and 300 water works uses RBF. The pioneer infiltration basin for groundwater (GW) recharge was constructed in Sweden by Richert in 1898 (Jansa, 1951). A 250-meter distance between the infiltration basin and the recovery wells was recommended by the author to get perfect purification of surface water by infiltration. The East London Waterworks Company conducted artificial recharge experimentation in the Chalk and Basal sands aquifer of the London Basin, England in 1890, but detailed information was not recorded (Satchell and Wilkinson, 1973). The first practical attention for MAR was given by Metropolitan Water Board in 1950's by demonstrating an experimental of recharge with four injection well in La Valley Chalk aquifer (Boniface 1959, Satchell and Wilkinson, 1973). In Finland, the first successful MAR project started in Vaasa in 1929. The operation of MAR project in wide scale started in 1960s. In 2002, 25 water works use groundwater artificial recharge technology (Katko et al., 2004). In 1950s, large scale MAR projects were initiated in Netherlands (Water and Foresty 2009). Nowadays 16% of Germany's drinking water supply is produced by RBF (Schmidt et al, 2003). Moreover, MAR provides 50% of drinking water supply in Slovak Republic, 45% in Hungary (Shankar et al., 2009; Grischek et al., 2005), 22% In the Netherlands, >20% in Sweden (Water and Forestry, 2009), 13-15% in Finland (Katko et al., 2004).

Aquifer Storage and Recovery (ASR) using storm water was carried out at Mount Gambier, in close proximity to Blue Lake in South Australia in 1880s (DWLBC, 2010) and have been proven to strengthen city's water supply (Dillon et al., 2009a). The largest MAR project operations in Australia established in the mid 1960s on the Burdekin Delta, Queenslans (Charlesworth et al., 2002) and now the capacity of the project is 45 GL/year, using infiltration basin (Dillon et al., 2009a). Use of urban storm runoff was initiated in 1992 at Andrews Farm South Australia in lime stone aquifer (Gerges et al., 2002). According to Dillon et al. (2009b), recharge of stormwater via infiltration gallery was established at Kensington, New Southwales in 2007. The use of reclaimed water in

Australia via several MAR techniques (e.g., ASR, SAT etc.) have been started since 1999 (Toze et al., 2002; Dillon et al., 2009b). A number of MAR projects are now being in operation in Australia in several provinces using several techniques for different end use such as, drinking water supply, agricultural use, salinity intrusion prevention etc. CSIRO (http://www.csiro.au/) and the South Australian Department of Water resources have been working closely to develop ASR with urban storm water and reclaimed water (IAH-MAR, 2003) for more than a decade in different parts of Australia. The present capacity of MAR in Australia is 60 Mm^3/yr and potential is 300 Mm^3/yr (Dillon, 2009b). A detail information on the history of managed aquifer recharge in Australia can be found in Dillon et al. (2009a and 2009b).

China has a long history in managed aquifer recharge. According to Wang et al., (2010), people in Huantai county of Shandong excavated subsurface channel-wells along the Wuhe River during the Qing Dynasty, and used surface water for artificial groundwater recharge. Since the 1960's, cooling water and tap water were used to recharge groundwater in order to develop the groundwater level and to supply new "cool resource" and “heat resource” in Shanghai (Wang et al., 2010).

Harpaz (1971) (cited in Maliva and Missimer, 2010) reported that Israel had an earlier successful ASR project implementation than the USA, which began in 1955. In Dan region, Israel recharge of effluents to groundwater started in 1970s, albeit the water supply company of Israel decided on SAT in 1955 (Aharoni and Cikurel, 2011). Nowadays, Menashe, a plant located in Israel's northern part of the coastal aquifer is the largest MAR project with average recharge capacity of 11.7 Mm^3 per year (Mekorot, 2011).

The practice of groundwater artificial recharge in the Middle-East is not new. Parsons tried the first MAR project by using surface runoff in Kuwait in 1964 and later, in 1970, injection of desalinated water in the aquifer was tested. In Qatar, the implementation of MAR in large scale was done in 1992-93. The MAR experience in the United Arab Emirates is new. The MAR initiatives have been started in 1998 and still a number of pilot projects are on progress. (Dawoud, 2008).

In Namibia, the experience of MAR, using sand dams, is up to 50 years (Wipplinger, 1953, cited in, 2007). In Atlantis, located 50 km north of Cape Town, South Africa MAR is in operation for over 20 years to augment local groundwater supplies. The water sources are urban storm water runoff and high quality treated domestic wastewater (Murray and Tredoux, 2004). It is one of the largest MAR scheme in South Africa. Other MAR schemes that in operation are: Polokwane, Karkams, Calvinia (South Africa) and Omdel, Walvis Bay, Windhoek (Namibia). Windhoek is the largest MAR scheme in Namibia, where the objective of MAR is to store water in the aquifer with view to supply water during drought time (Murray et al., 2000).

From the above information it is clear that MAR is a useful technique to strengthen water resources supply. Since 1990, a remarkable progress has been made to understand the underground processes and water quality changes during the infiltration or injection of recharged water. Nowadays the concern is more to the inclusion of MAR into the Integrated Water Resources Management (IWRM) concept. The following sections in the chapter will give a brief overview on the different technical, management and planning issues of MAR.

2.4 Managed Aquifer Recharge (MAR) projects- Basic considerations

The four very basic requirements for MAR implementation are:

i. Water Source: Availability of non-committed and non conventional water surplus for recharge
ii. MAR Location (hydrogeology): Suitable and adequate place is quite important for implementation of the project. Physical success of MAR recharge project depends greatly on the local surface and subsurface conditions
iii. MAR Technology or Methodology: Methodologies should be appropriate to meet the defined objectives and local hydrogeological settings
iv. Recovery of Water: In order to use the recharged water efficiently, a recovery plan is quite essential.

These four above mentioned requirements are briefly explained below-

2.4.1 Water source

Required amount of water should be available for recharge. The main water sources for MAR are: Surface water, Storm-water runoff, treated effluent, potable water, and imported water (after UNESCO-IHP, 2005). A brief explanation of these water types from the MAR point of view are stated below:

(a) Surface water

The availability and abundance of surface water depends on the geographic location and climatic variability. Depending on the climatic condition, surface water can be a significant source of water for MAR. Under humid conditions, moderate variability in river discharge can be expected but perennial rivers are dominant. Under arid or semi-arid conditions, ephemeral rivers prevail. Water from perennial rivers can be diverted to nearby recharge facilities or canalized to more distant facilities. Induced bank filtration directly from rivers is an option commonly employed (UNESCO-IHP, 2005). If river water is directly used for recharge, the silt carried by the water can result in clogging. On the other hand, lake water, if not polluted by anthropogenic sources is good for recharge without pre-treatment (Huisman and Olsthoorn, 1983). In general, water coming from polluted river or lake should go through proper pre-treatment processes prior to recharge. Even, it is always recommended to perform a basic pre-treatment though the surface water is not polluted.

(b) Storm-water runoff

Storm water runoff can defined as the water that can be generated from a land surface after a rainy event. Storm-water runoff contributes a significant volume of water for recharge in urban areas, especially. The amount of runoff is highly dependent on the daily and seasonal variation of rainfall intensity. Retention basins, grassed areas, porous pavement and wetlands are useful to trap the runoff for artificial recharge (Murray et al., 1998). In rural areas, intense rainfall can generate surface runoff from agricultural fields as well as uncultivated open spaces. It is recommended to use the runoff for the infiltration through a sand or soil layer to reduce some of the dissolved constituents (UNESCO-IHP, 2005). Storm–water is usually highly variable in its quality, especially in the urban areas. The contamination of the storm-water runoff depends on the path it follows and the contamination of the path. The highest contamination load can be observed in the “first flush,” which should be diverted to the treatment facilities to improve quality. The best quality runoff water in urban areas is from rooftops and increasingly initiatives (e.g. government buildings in India) are being made to direct this water immediately to groundwater recharge through infiltration galleries, wells, and boreholes. When this runoff is recharged directly into the subsurface by means of injection wells, the beneficial effects of infiltration through an unsaturated zone are lost and the risk of contamination of the aquifer increases and may need to be compensated by other forms of pre-treatment before injection, such as slow sand filtration (UNESCO-IHP, 2005).

(c) Treated effluent (Reclaimed water)

Overtime, the volume of waster is increasing. The increase in volume of wastewater is not only due to the increase in population but also due to increase in wastewater collection network. Wastewater after proper treatment can be a significant source for MAR, as the supply of treated effluent is uniform over the time and more predictable. The main concern for the recharge of treated wastewater is the quality (Murray and Tredoux, 1998). Reclaimed water quality is primarily determined by the quality of the source water, the presence and nature of industries discharging wastes to the sewers and the pre-treatment processes applied. The compounds of concern depend on the wastewater source, i.e. industrial or domestic wastewater. Wastewater as a source offers a significant potential for all non-potable uses, such as unrestricted irrigation. However, with proper pre- and post-treatment or dilution with native groundwater, potable use also can be a viable option (Bouwer, 1996).

The main constraints on the utilization of treated effluent are the gaining of public acceptance, as well as the related cost for pipelines, pumping stations, etc. to convey the water from the wastewater treatment plant to the specific MAR site. Using spreading basins has the advantages of improving the quality of the wastewater through Soil Aquifer Treatment (SAT) and dilution with natural groundwater (Bouwer, 2002). Use of the reclaimed wastewater for irrigation of fodder crops is more easily accepted than irrigating crops for direct human consumption and use for potable supply. Higher levels of treatment, monitoring, and security of operation are needed regularly as the use of reclaimed wastewater approaches direct reuse (UNESCO-IHP, 2005).

(d) Potable water

In Aquifer Storage and Recovery (ASR) schemes, potable water is a major source of recharge water. Improved-quality treated water is injected through wells, usually into confined aquifers. This water displaces the native water, and has indicated to be a cost-effective and environmentally sustainable method for resolving a wide variety of problems, such as seasonal groundwater shortages (Pyne, 1995). The schemes are usually constructed near water treatment plants, the source of the recharge water, to save cost and to utilize surplus treatment capacity.

In arid areas, such as the Gulf region of the Middle East, where water scarcity prevails, potable water from desalination plants is used to fill the water deficit. To ensure water availability during emergencies, for example, when desalination plants are out of order, large freshwater storage capacities are required. Field trials have been undertaken to evaluate the feasibility of introducing desalinated water into aquifers to build up this freshwater reservoir (Mukhopadhyay and Al-Sulaimi, 1998).

2.4.2 MAR location

MAR location is considered as the important part of the planning procedure and the success of a MAR scheme principally depends on the proper choice of location. In addition to the surface condition, the selection of MAR location mainly depends on the local hydrogeological conditions. According to UNESCO-IHP (2005), the main factors to consider for hydrogeological conditions are: Physical and hydraulic boundaries of the aquifer and degree of confinement, hydrogeological properties of the aquifer and overlying formations, hydraulic gradient in the aquifer, depth to aquifer/piezometric surface, groundwater quality, aquifer mineralogy and sediment chemistry. Besides these factors, distance from the source, power supply and access to the location also need to be considered. UNESCO-IHP (2005) reported on the four general groups of hydrogeological environments, namely alluvium, fractured rock, consolidated sandstone aquifers, and carbonate aquifers. A brief description of the aquifers is given below (after UNESCO-IHP, 2005):

(a) Alluvium aquifer

The sediments of alluvium aquifers are predominantly sand and gravel, sometimes overlain by a silt layer. Major deposits were usually left behind by former river systems. The hydraulic conductivity of the aquifer is variable (USGS 2009a). The aquifer consists of fluvial, marine, and lacustrine deposits ranging in thickness from a few meters to kilometres (UNESCO-IHP, 2005). The groundwater table is usually unconfined and the groundwater travels short to medium distances, thus less dispersion of recharge water occurs.

(b) Fractured rock aquifer

This type of aquifer usually consists of fractured bedrock comprising igneous, metamorphic or volcanic rocks. The porosity of this aquifer type is small and pores are not well connected (USGS 2009b). Despite having low storativity and transmissivity, the aquifer may be the only source of groundwater in some regions so careful management is required (Murray and Tedoux, 2002). Fractured rocks may often have limited recovery efficiency due to their heterogeneous characteristics (Wendelborn et al., 2005). Success in exploiting groundwater, as well as recharging aquifers, depends on locating these weathered or fractured zones where they are saturated. Abstraction from wells in the hard rock aquifer can drain the overlying alluvium/weathered zone seasonally. (UNESCO-IHP, 2005) The appropriate recharge method will depend on which aquifer is targeted for recharge. If the unconsolidated alluvium is targeted, then infiltration basins or trenches may be most effective; however, if the deeper, hard rock aquifer is targeted then borehole injection may be the only option. Specific capacity of wells is 100% in fractured rock aquifers, whereas specific capacities are half for pumping in alluvium aquifers (Bouwer, 1994; UNESCO-IHP, 2005).

(c) Consolidated sandstone aquifer

Secondary openings in consolidated sandstone aquifer, such as fractures, joints, and bedding planes can store and transport a huge volume of water despite the low to moderate hydraulic conductivity (USGS, 2009c). If the permeability of the aquifer is comparatively high, then recharged water is likely to be dissipated quickly and may be lost to base flow in rivers (Gale, 2001). A good understanding of the hydraulics of the aquifer is therefore needed to ensure that the outcomes of MAR are useful (UNESCO-IHE, 2005).

(d) Carbonate aquifer

Most carbonate rock aquifers originated as sedimentary deposits in marine environments (USGS, 2009d). Carbonate aquifer types vary in permeability; such as limestone karst aquifers, which have higher permeability than that of non-karstic limestone carbonate aquifers (Worthington, 2009). The response of karstic aquifers is the most extreme in terms of dissipation of recharged water and the presence of fast pathways for contaminants (Ford and Williams, 2007). Karstic aquifers can provide utilizable storage where groundwater flow is constrained, for example in a confined aquifer (UNESCO-IHE, 2005). The geochemical reactions that might occur between the recharge water and the native groundwater depend on the saturation index of calcite and dolomite of both waters and pH in addition to the presence of some trace minerals (Maliva and Missimer, 2010)

2.4.3 MAR technology

A number of techniques or schemes exist to enhance recharge of groundwater and they are as varied as the ingenuity of those involved in MAR plant construction and operation or the many types of local hydrogeological conditions. These schemes are designed with the primary objective of enhancing recharge (intentional recharge) but aquifers can also be recharged unintentionally (incidental recharge) whilst undertaking other activities, such as irrigation. Intentional methods are aimed at enhancing groundwater supplies but may also achieve other purposes, such as flood mitigation, reduced soil erosion, or change of land use (UNESCO-IHP, 2005). In this section, the intentional recharge is considered. According to UNESCO-IHP, (2005) and CGWB, (2000), the recharge methodologies are grouped into six broad categories, which are:

(a) Direct surface techniques (spreading basin)

    i. Infiltration ponds or basins
    ii. Soil Aquifer Treatment (SAT)
    iii. Controlled flooding
    iv. Percolation tanks

(b) In-channel modifications

    i. Sand storage dams
    ii. Percolation ponds behind check dams, gabions, etc.
    iii. Subsurface dams
    iv. Leaky dams and recharge releases

(c) Direct subsurface techniques (well, shaft, and borehole recharge)

    i. Open recharge wells, pits, and shafts
    ii. Aquifer Storage and Recovery (ASR)

(d) Indirect recharge (induced recharge)

    i. Induced bank infiltration
    ii. Inter-dune filtration

(e) Rainwater harvesting (RWH)

    i. Roof top rainwater harvesting
    ii. Rainwater recharge from open spaces (e.g., field bunds)

The following sections briefly describe the most commonly practiced techniques of MAR that are quite relevant for the study:

a) Direct surface techniques (spreading basin)

Direct subsurface techniques are the most common and economic way of implementing

MAR. Particularly, in cases where the upper aquifer is the target aquifer and it is unconfined, spreading basin is used for MAR (UNESCO-IHP, 2005):. The infiltrated water percolates through the aquifer media beneath the surface. In situations where there is a reliable source of good-quality input water, and spreading infiltration can be operated throughout the year, then hydraulic loadings of typically 30 m/yr can be achieved for fine texture soils like sandy loams, 100 m/yr for loamy soils, 300 m/yr for medium clean sands, and 500 m/yr for coarse clean sands (Bouwer, 2002a). Evaporation rates from open water surfaces range from about 0.4 m/yr for cool wet climates to 2.4 m/yr for warm dry climates comprise are relatively minor component of the water balance. Percolation of water through the soil column involves several processes in the vadose zone. At the basin–soil interface, the combined effect of sedimentation, filtration, aeration, and microbial growth lead to the formation of a biologically active zone that may be impermeable (Bouwer, 1997). Due to the formation of this filter skin, the infiltration rate may become reduced with time. Therefore, regular monitoring of the clogging, infiltration rate and open water evaporation is essential for the spreading basin.

a(i) Infiltration ponds or basins

According to UNESCO-IHP, (2005) an infiltration basin is either excavated in the ground, or it comprises an area of land surrounded by a bank, which retains the water to be recharged (e.g. storm-water runoff) until it has infiltrated through the basin bed. If the aquifer material is fine, rapid clogging will occur. In this case, covering the bottom and sides with a layer of medium sand or geotextile (Bouwer, 2002) approximately 0.5 m thick can delay the clogging process and extend the recharge periods in the facility (Huisman and Olsthoorn, 1983). The infiltration rate and the basin area determine the volume of recharge achievable. In order to maintain the proper functioning of the basin/pond bed, drying and scraping of the basin bottom should be done rotationally. The depth of the basin should be shallow enough to dry the pond rapidly. Water levels in the basin should be maintained in that way that the growth of vegetations or algal accumulation is prevented.

a(ii) Soil aquifer treatment

Implementation of Soil Aquifer Treatment (SAT) is now a common practice for MAR and will be increasingly important (Drewes, 2009). Figure 2.1 shows a typical lay out of SAT setup in an unconfined aquifer where observation well and recovery well are shown also. Practical research undertaken over the last few decades has investigated hydraulic, operational and bio-geochemical processes involved in wastewater recharge and recovery through SAT. SAT is an economical and aesthetic wastewater reuse approach. Since the soil and the aquifer can act as natural filters, SAT systems can remove suspended solids, biodegradable materials, bacteria, viruses, and other microorganisms (Bouwer, 1997).

Figure 2.1: Schematic view of soil Aquifer Treatment (after UNESCO-IHP, 2005)

During SAT, secondary or tertiary treated wastewater infiltrates into the subsurface from an infiltration basin, which continues to percolate through the unsaturated zone and then finally mixes with native groundwater. Wastewater reuse process has several advantages including storage to minimize supply/demand variability, quality improvements due to passage through the soil and aquifer, favorable economics, and better public acceptance of water reuse (Bouwer, 2002b). The secondary effluent can be recovered for irrigation reuse. For portable reuse, the recharged water should be treated with reverse osmosis or carbon filtration prior to SAT.

a(iii) Controlled flooding

Control flooding is cost-effective where a huge volume of surface water is available and the spreading basin is quite flat. Highest infiltration rates are observed on areas with undisturbed vegetation and soil cover (Todd, 1959). In order to control the flooding process at all times, banks or ditches should surround the entire basin. High sediment loads that are present in the surface water will deposit on the surface and reduce recharge rates and remedial measures may have to be undertaken to maintain desired rates of infiltration (UNESCO-IHP, 2005). Agricultural land used for flooding recharge can be benefited from the sediment load, but this needs to be balanced against the reduced recharge rates (Esfandiari-Baiat and Rahbar, 2004).

a(iv) Percolation tank

Percolation tanks are used in India for MAR both in alluvial as well as in hard rock formations (CGWB, 2000). The storage capacity of percolation tanks are designed such that the water percolates to the aquifer to avoid open water evaporation loss. Percolation tanks are normally constructed on second to third order streams since the catchment and the submergence areas are smaller and thus are constructed on uncultivable land (UNESCO-IHP, 2005). Percolation tanks can be located on highly fractured and weathered rock for speedy recharge. In this case, the design of the recovery well is quite important. In the case of alluvium, bouldary formations are ideal for locating percolation tanks (CGWB, 2000). The aquifer to be recharged should have sufficient thickness of permeable vadose zone to accommodate recharge and water quality improvement. The sand in the vadose zone is considered to act as filter media.

b) In-channel modifications

In channel modification is a technique where the rivers, streams or canal are modified to store water and to enhance the vertical recharge. The modifications are done by using dam, primarily.

b(i) Sand storage dams

Sand dams are best constructed in undulating terrain under arid climatic conditions, where runoff is often experienced as flash floods. The dams are typically constructed in sandy, ephemeral riverbeds in distinct basins. A dam wall is constructed on the bedrock, across the width of the riverbed to slow down flash floods event. This allows coarser material and sediments to settle out and accumulate behind the dam wall (UNESCO-IHP, 2005). The dam wall can be raised after each successive flood event, the height of the wall thereby determining the flood flow and the amount of material accumulating. However, sufficient overflow should be allowed for finer material to get carried away

(Murray and Tredoux, 1998). With time, successive floods build up an artificial aquifer, which allows water to infiltrate rather than migrating downstream. Water stored is available for abstraction, however, sand storage dams can also be constructed over permeable bedrock and thus replenish the underlying aquifer.

b(ii) Percolation tanks behind check-dams

An economical way of artificially recharging water can be achieved by the construction of check-dams across a stream or river bed. To avoid annual erosion or destruction of these structures a concrete spillway is often constructed and to contain and channel surface runoff, bunds are also built. Related field bunds restrain the water flow to the stream and thus help this water to infiltrate into the ground as well as reducing soil erosion (UNESCO-IHP, 2005). As the water is only bounded in these structures for short periods, the land can be cultivated immediately afterwards in order to utilize the soil moisture. This can result in an additional agricultural production. Plowing the land also maintains the infiltration capacity, in readiness for the next period of input. In Kenya and many parts of India, surface weirs, and in Taiwan, inflatable dams, have been used to prolong the presence of water and increase the wetted area of alluvium in ephemeral streams.

b(iii) Subsurface dams

Subsurface (underground) dams may be used to detain water in alluvial aquifers. In ephemeral streams where basement heights constrict flow, a trench is constructed across the streambed keyed into the basement rocks and backfilled with low permeability material to constrain groundwater flow. The groundwater is recovered from wells or boreholes.

b(iv) Leaky dams and recharge releases

Where flow is very “flashy” and contains large amounts of suspended solids, constructing dams on these ephemeral streams can retard the water (Figure 2.2a). The water is then released through pipes to the downstream reaches of the river where groundwater recharge can occur (Kahlown and Abdullah, 2004). A particular difference on this idea is the building of leaky dams from rock-filled gabions with pipes running through the dam. These structures hold on high-energy flash-floods, increases settlement of suspended sediment and release of the silt free water through leakage to infiltrate in the downstream riverbed (UNESCO-IHP, 2005). A good example of this practice is the OMDEL dam scheme in Namibia (Zeelie, 2002).

Figure 2.2: Schematic view of (a) leaky dams and recharge release, and (b) sub surface dams (modified after UNESCO-IHP, 2005)

c) Direct subsurface techniques (well, shaft, and borehole recharge)

Basically, these techniques are widely practiced around the world where the aquifer is situated very deep from the surface (Figure 2.2b). Conventional injection techniques are primarily used.

c(i) Open wells and shafts

This method is principally applied where the soil has low infiltration capacity. In general, production wells that have run dry due to falling groundwater tables resulting from over-exploitation are increasingly being used for this purpose. Well-clogging might be a potential problem for this technique. In loosely consolidated material, recharge pits and trenches are used in cases where silty material overlies the aquifer, which occurs at shallow depth (5-15m) (Bouwer, 1996). Recharge structures are constructed in that way that it just reaches to the aquifer (Murray and Tredoux, 1998). Trenches can be backfilled with coarse sand or fine gravel or with geotextile and recharge water is applied to the surface of the backfill. The recharge facilities should be covered to protect against dust, sunlight animals and people. In general, the cost effectiveness of these techniques should be examined carefully.

c(ii) Aquifer Storage and Recovery (ASR)

Aquifer Storage and Recovery (ASR) is a well known and very often used MAR technique where land is scarce for flooding and where a comparatively impermeable layer overlies the target aquifer (Figure 2.3a). High quality water is injected by recharge wells and recovered after certain periods of time. Water can also be injected into a borehole and recovered by another borehole some distance away. This technique is referred as Aquifer Storage Transfer and Recovery (ASTR) (Figure 2.3b). This technique allows the water to travel a certain distance for the improvement of the water quality. Well-clogging is one the often cited problems facing ASR systems. Carbonate aquifers exhibit the least clogging due to gradual dissolution of calcite by slightly acidic injectants and if periodic back flushing is maintained. The injectants applied in an ASR system should pass through proper pre-treatment before any injection (UNESCO-IHP, 2005).

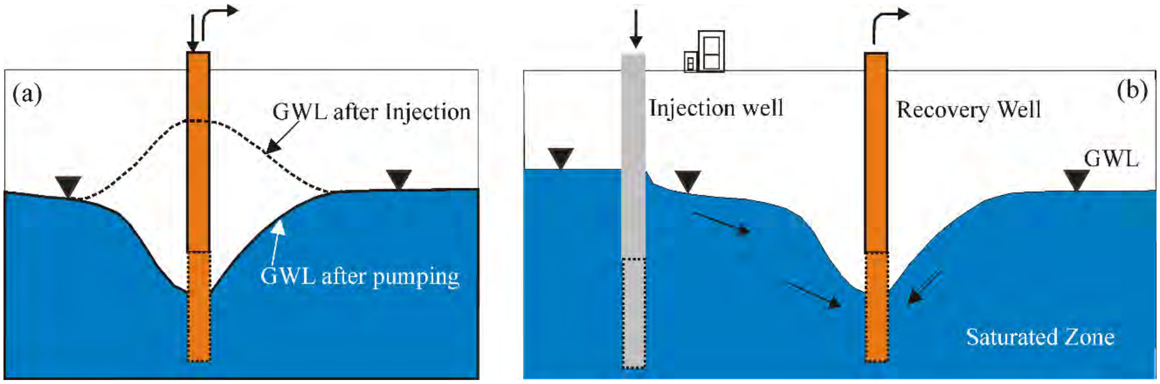


Figure 2.3: Schematic view of (a) ASR and (b) ASTR (modified after UNESCO-IHP, 2005)

d) Indirect Recharge

Indirect recharge is the technique where technology are used to increase the recharge. This is somehow different than the natural recharge procedure.

d (i)Induced bank infiltration

Riverbed infiltration schemes generally consist of a line of boreholes at a short distance from and parallel to the bank of a river or stream (Figure 2.4a). Pumping of the boreholes lowers the water table adjacent to the river or lake, inducing river water to enter the aquifer system. To assure satisfactory purification of the surface water in the ground via natural processes, the design should ensure a travel time exceeding one month or even two months (Huisman and Olsthoorn, 1983). The factors controlling the success of induced infiltration schemes are: a reliable source of surface water with acceptable quality, good permeability of the river or lake-bed deposits, and the compatibility of the geological formation adjacent to the surface water body (O'Hare et al., 1982). Provided that the permeability of the stream or lake-bed and aquifer are high and the aquifer is sufficiently thick, large amounts of groundwater may be withdrawn from a well or a gallery without causing much adverse effects on the groundwater table further inland (Huisman and Olsthoorn, 1983). Clogging is an important factor to consider. For example, in Dresden, Germany, sever clogging of the riverbed occurred in the 1980s primarily due to high loads of organics from pulp and paper factories in the upstream (Grischek et al., 2010)

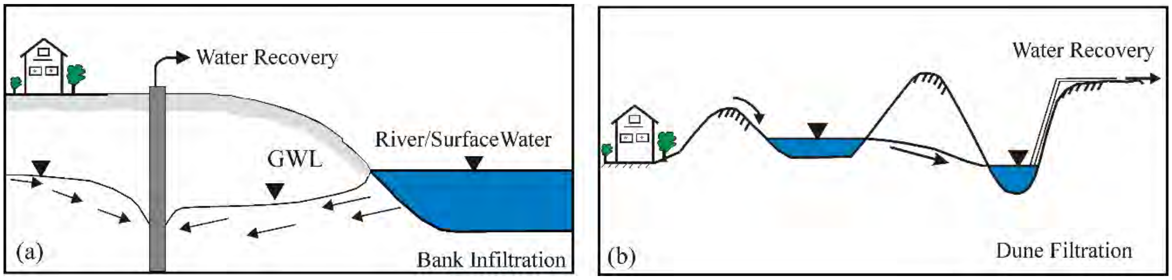


Figure 2.4: Schematic view of (a) Bank infiltration, and (b) Dune filtration (modified after UNESCO-IHP, 2005

d(ii) Inter-dune filtration

This method is used in coastal zones, where the valleys between coastal sand dunes are flooded with recharge water to infiltrate into the underlying aquifer and induce storage (Figure 2.4b). The resulting groundwater mound can play an important role in preventing salinity intrusion as well as providing a source of water further inland. This technique has been used for centuries and is highly developed along the coast of the Netherlands where rivers are the source of water for the recharge (UNESCO-IHP, 2005). In other schemes, storm and treated urban wastewater are the sources of water. A prime objective of these types of schemes is to improve the source water quality. Much research has been undertaken to understand and optimize the management recharge facility and possible clogging (UNESCO-IHP, 2005).

e) Rainwater harvesting (RWH)

Rainwater harvesting is a very ancient technique to conserve water from rain. In many villages of Bangladesh it is practiced for long time. As the rainwater is quite pollution free, it is more popular than any technique.

e(i) Roof top rainwater harvesting

Roof top rainwater harvesting can conserve rainwater for either potable use or for recharge of groundwater (Figure 2.5a). This approach requires connecting the outlet pipe from a guttered roof top to divert rainwater to either existing wells or other recharge structures or to storage tanks. In order to avoid contaminating the rainwater, drainpipes, roof surfaces, and storage tanks should be constructed of chemically inert materials such as plastic, aluminum, galvanized iron, or fiber glass (UNEP, 1997). Where the water is used for direct consumption, the initial water from a rainstorm is often flushed out in order to get rid of the accumulated dirt from the collection area and gutters. Advantages of collecting and storing rainwater in urban areas include an increase of water supply as well as a decrease in the amount of storm-water run-off and consequent flooding, drainage congestion, or water logging.

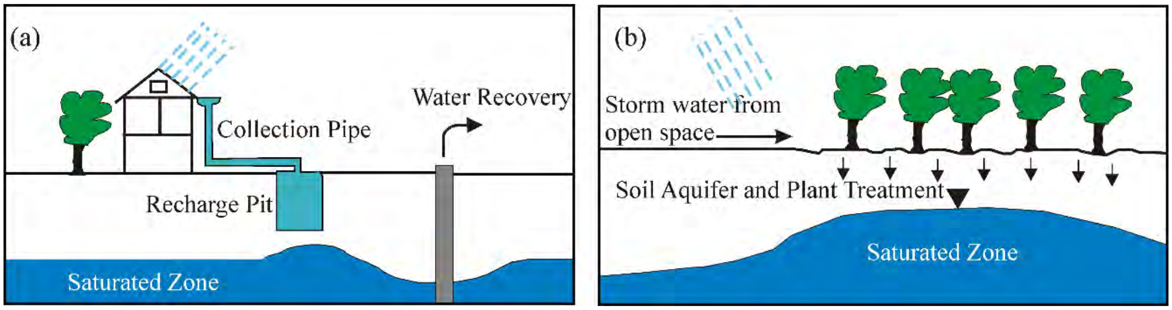


Figure 2.5: Schematic view of (a) Rooftop rainwater harvesting, and (b) Rainwater collection from open spaces and SAT using a wetland. (Modified after UNESCO-IHP, 2005)

e(ii) Rainwater recharge from open spaces (e.g., field bunds)

Rainwater harvesting methods using open spaces involve micro-watershed management methods that allow rainwater collection, infiltration, and percolation into the subsurface ((Figure 2.5b). The runoff has to be minimized and the collection of water has to be optimized by providing an adequate number of recharge pits and trenches. In large parks or botanical gardens, storage of rainwater in small ponds/lakes is also possible since the storage surface can be integrated with the landscape of the particular places (KSCST, 2010). Again, rainwater that falls on the paved surfaces can be diverted to the nearby pit and can be infiltrated. Recharge trenches or pits are commonly used to enhance the recharge to the aquifer. The advantage of wetlands can be achieved in this technology.

2.4.4 Recovery of MAR water

Recovery of MAR water is a very important issue and should be considered from the beginning of a MAR project. A number of projects did several estimation techniques in order to find the maximum recovery of recharged water. This techniques are primarily depends on the aquifer type, water quality, the conductivity of the aquifer, slope of the aquifer etc. In general, design of recovery wells depends on the local hydrogeological conditions and also the point of demand site.

The use of recovered water is an important issue to design the pre-treatment facilities. The primary use of recovered water can be: (a) Potable use (c) Non-potable use (d) Irrigation, (d) Industrial use. Potable use of water is for drinking purposes. Use of recovered water for drinking purposes are too common in the world as the quality of the water should be very high and also this option is not too much socially accepted. Non-potable use of water consist main washing purposes at household. This one is accepted by the people to some extent but especial piping system need to be designed in the building or houses to provide the facility. Most common use of recovered water is agricultural use. Most of the MAR projects aimed at using the recovered water for irrigation and this option is quite acceptable by the people as well. Industrial use can be restricted to the purposes where the quality of water is not necessarily should be high such as washing purposes

2.5 Planning and Operation of Managed Aquifer Recharge (MAR)

2.5.1 Planning of Managed Aquifer Recharge Project

Maliva and Missimer, 2010 stated, "*It is not an overstatement that the single most important process for the successful implementation of an ASR project is planning*". Nowadays the planning and management of MAR projects are being discussed at different levels of research, by individuals, or combined study. Proper planning of MAR project increases the success by reducing the unnecessary investment, confirming the storage, and eliminating unexpected surprises. Various issues involved in MAR project planning have been discussed in a number of publications, including Brown (2005), Pyne (2005), Dillion and Molloy (2006), Dillion et al., (2007), and NRC, (2008).

For brackish-water storage zone ASR systems, Brown (2005) developed a 12-step "ASR Planning Decision Framework." The main focus of the framework is desktop investigation, evaluation of project alternatives, feasibility checking, and pilot plant experimentation. NRC (2008) suggested the following five-step processes: Phase I: Feasibility evaluation; Phase II: Field investigation and experimentation using pilot plants; Phase III: Project design; Phase IV: ASR system construction; Phase V: Project review and adaptive management. These steps are mostly common to any MAR project implementation. A most important process that wasn't mentioned explicitly in the steps is the project approval from the regulatory institution. The plan, design and cost of the MAR scheme largely depend on regulatory requirements. However, in short, the project planning should study the available source of water in the area, presence of storage, proper location and corresponding MAR techniques, important regulatory issues and economics. If the situation is favorable for a MAR project, than an evaluation of project alternatives is required. The evaluation can be made by assessing the environmental, health, social and economic impacts of the alternative projects. Mathematical modeling, economic models, questionnaire survey and field campaign are common procedure for assessing the above-mentioned impacts.

2.5.2 Operation of MAR project

Operation of MAR projects is also considered as one of the main issues for MAR planning, which has not received too much attention. Dillon, (2009) summarizes some operational issues that are mentioned in the Australian guidelines for wastewater recycling, which are: (1) Clogging (2) Recovery efficiency (3) Interactions with other groundwater users/stakeholders (4) Salinity intrusion (5) Operations designed to protect groundwater dependent ecosystems (GDEs) (6) management of recharge facilities. These issues are general for most MAR projects. The data acquisition system and monitoring network are considered the most important tool for better operation. Good operation of MAR facilities results is risk minimization.

2.6 Review of studies related to MAR in Dhaka City

Several researchers studied the feasibility of rainwater harvesting in Dhaka city. But the combination of MAR and RWHS system has not been studied in details.

Rahman (2001) performed a model study to demonstrate the applicability of Rooftop RWHS in Dhaka City. The study showed that underground storage might be helpful to store and supply to the non-drinking demand points. The study estimated that the 100% degree of security might not be economically beneficial considering high investment cost. The author suggested an extensive economical modeling to evaluate the economic feasibility.

Sultana (2007) developed a tool to design RWHS for multistoried building. The tool also estimates the cost related to the implementation. The study provides some guidelines for economic RWHS that can be implemented not only in Dhaka but also any other location.

Rahman et al. (2011) estimated that maximum 0.38 m^3 of water deficit occurs during April and 0.25 m^3 excess water is available in October. The authors reported that 33% water demand can be met through individual RWHS and 10% of water demand can be met by community based RWHS.

A study by Islam et al., 2010 concludes that the slum dwellers living in Dhaka City are willing to accept RWHS as an alternatives source of safe drinking water. The dwellers are interested to pay extra money for the system but require some financial support from the government to install the system. Later another study from Islam et al. (2011)

assessed the most critical parameters for RWHS implementation. The authors estimated that cost of the RWHS system is most sensitive parameter followed by roof area and the water demand, respectively.

Quasem and Islam (2004) demonstrated the applicability of MAR combined with RWHS in Dhaka city. The study can be considered as one of the earliest study on this issue. The authors proposed to install pipeline that will distribute the water collected from rooftops to the injection well network. The distribution pipe network was designed parallel to the road network.

Sultana (2009) performed an analysis regarding the suitable site for managed aquifer recharge. A simple GIS overlay method was used to identify potential location. Thickness of clay layers, natural water bodies were considered to select the site. The classified locations are categorized for several MAR technologies. Some of the technologies are really optimistic choice due to the topography, surface water quality and availability of land. The study discussed about the possibility of storm water harvesting but no analysis is given about the use of surface water and wastewater, which are very primary issue of MAR.

Rahman et al. (2010) reported about a hydrogeological investigation towards MAR project implementation in Dhaka city considering the upper DupiTila Aquifer as the storage. The study analysed the characteristics of the upper Dupitila Aquifer and reported that the aquifer has the potentiality to store rainwater. The study put emphasis on groundwater modeling study in order to understand the potential changes of water quality after injection of rainwater.

Shahidullah and Ahmed (2010) preformed a very preliminary analysis to check the potentiality of MAR in the city. From the secondary data, the authors confirmed the feasibility of MAR using rainwater to combate water supply problems. The study estimates that MAR can deliver additional 27335.62 $*10^6$ Liter water to the groundwater system.

Mutaza et al., (2011) mentioned that RWHS would be a greener approach to combat water supply condition in Bangladesh. Rooftop rainwater harvesting system implementation would increase the entire construction cost of a building by 0.5%. Additionally, RWHS combined with MAR will recharge 108 million M^3 per year which is equal to 31% of the deficit Dhaka faces every year, but the study did not show the detail estimation.

A pilot study by IWM (2011) tested the feasibility of MAR combined with RWHS in two places (Lalmatia and Segunbagicha) at Dhaka but experiment was done at Segunbagicha WASA compound. The study suggested that ca. 1.89 m groundwater level recovery could be assumed if MAR project is implemented. As in Segunbagicha area for out flowing recharge water through injection well by gravity, minimum 560 kpa hydrostatic pressure is to be maintained inside injection well, while target aquifer layer has 57m depth to groundwater level. The pilot test data confirms that the dense pumping well network did not allow the water to stay at the place for a long time. So, no long-term impact of injection was observed.

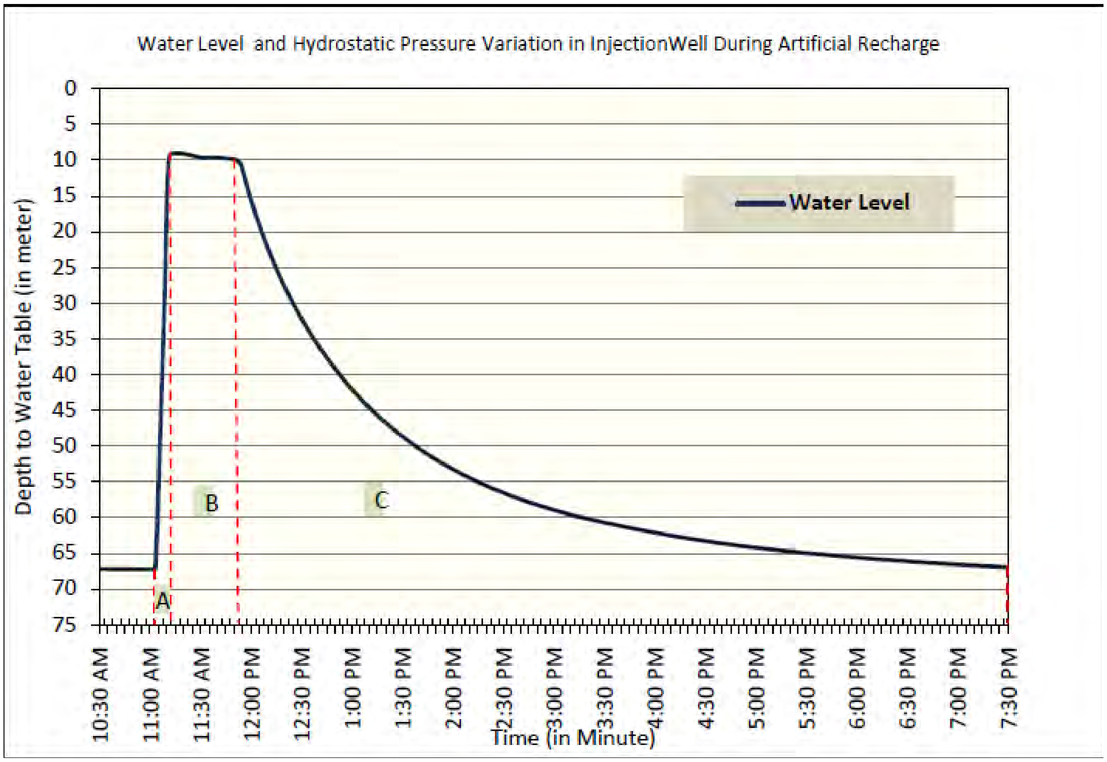


Figure 2.6: Depth to water table with time during MAR experiment at Segunbagicha (Reference: IWM, 2011)

2.7 Experience of MAR around the world

Although MAR is practiced throughout the world, much of the information is sourced in USA, Europe, Australia, Israel, and India. Information regarding MAR implementation in South Africa and Latin America is scant and the description of MAR projects is not well documented in most of the cases.

In the United States, most of the current Aquifer Storage and Recovery (ASR) schemes involve potable water (AWWA, 2002). In the USA, a number of MAR schemes are using the alluvium aquifer. In most cases, the confined aquifers are being used for water storage. A substantial number of projects (according Brown 2005) are implemented to protect salinity intrusion at the coastal region.

The majority of successful MAR schemes within Australia operate in deep, confined, tertiary limestone (calcarenite) aquifers, whereas limited success has occurred in sandy aquifers (DWLBC, 2002). Of the bedrock types, the predominant rock type is sedimentary. The storm run-off is considered as one of the main water source for MAR.

The Dan Region (Israel) project, the largest artificial recharge project in Israel, uses the treated effluent from Tel Aviv and reuses the stored water for unrestricted irrigation. This project has a long history and has been using wastewater for soil aquifer treatment (SAT).

In Europe, Germany, Belgium, Hungary, France, Finland are practicing MAR. Bank infiltration is well practiced in Germany (Balke and Zhu, 2008) along the Rhine, Main, Elbe and Ruhr rivers. Approximately 15% of Germany’s drinking water is produced through MAR (Water & Forestry, 2007). In Germany, 54% of the MAR applications are mostly for drinking water supply (Water & Forestry, 2007). In China, most MAR projects are aimed at the enhancement of groundwater resources (Han, 2003).

Among the South Asian countries, India has a long history of MAR (Bhattacharya, 2010). Rainwater harvesting is considered the oldest form of conservation of rainwater both on ground and under-ground and this was practiced in the arid and semi-arid

Table 2.1: Major MAR technologies and their implementation (MAR methodology is taken after UNESCO-IHP 2005)

MAR technology	General methodologies for MAR	Example of MAR implementation (including implemented, experimental, and planned projects)
Rainwater harvesting	Desiltation of village ponds	Harayana (Rainwaterharvesting, 2011), West Bengal (Banerjee, 2012)
	Field bunds, irrigation fields	Cholistan (Kahlon 2006), Balochistan (Pakistan) (UNESCO 2012)
	Roof-top rainwater harvesting	Delhi (Sharma 2007), Bangladesh (Rashid 2001), Srilanka (Ariyananda 2004)
Spreading methods	Infiltration ponds and basins; soil aquifer treatment; controlled flooding; irrigation field recharge	Gujrat, Tamid Nadu (India) (Bhattachary, 2010; CGWB 2000) Ahmedabad (India) (CGWB, 2000)
In-channel modifications	Percolation ponds behind check dams Gabions, nala bunds Sand storage dams Subsurface dams and dykes	Assam, Maharastra West Bengal, Gujarat, Tamid Nadu (India) [Bhattacharya, 2010; CGWB , 2000]
	Leaky dams and recharge release	Balochistan, Pothwar (Pakistan) [UNESCO 2012]
Well, shaft and borehole recharge	Open wells and shafts	Gujrat (India) (Bhattacharya, 2010)
	Aquifer storage and recovery Aquifer storage, treatment, and recovery	Kathmandu valley (Nepal) (Dixit and Upadhya, 2005). Bangladesh (Acacia Water, 2012)
Induced bank infiltration	Bank infiltration and Inter/dune infiltration	Haridwar (India) (Dash et al., 2010) Chapainawabgonj (Bangladesh) (Tuinhof and Kemper 2010)

regions of India in the sixth century (Sakthivadivel, 2008). The history of MAR implementation in India can be broadly classified into four phases. The first phase is until 1960 when traditional water harvesting methods were used; the second phase is the period between 1960 and 1990 - the time of large scale groundwater use; the third phase is the period between 1990 and 2008 - the time of water scarcity; the fourth phase is the modern time (Sakthivadivel, 2008). In the states of Maharstra, Gujrat, Kerala and Tamil Nadu several techniques of MAR are now being practiced (Bhattacharya, 2010). The government of India has prepared a master plan to implement MAR in different states of India (CGWB, 2000). In some places of Pakistan MAR is now commonly practiced.

2.8 Summary

From the above sections related to the background of MAR and its related experiences, it is clear that MAR can be used as a strategy to combat water scarcity at different parts of the world. Therefore, it can be considered also as a potential solution against the water resources problem at Dhaka City. Implementation of MAR project is not straight forward and hence a number of surface and sub-surface characteristics should be considered. In order to check the feasibility study a number of studies have been done for Dhaka city (section 2.6). The already performed studies did not considered the complete hydrological components, such as water sources, aquifer condition, and suitable MAR technologies. Some of these issues are partly considered. So, an integrated study is still missing to implement MAR in the city. As MAR is not a new concept and it has been already successfully installed in the region (South Asia), there is a huge potential also to successfully run MAR projects in Dhaka.

Chapter 3

THEORY AND METHODOLOGY

3.1 General

This chapter explains the overall concept of MAR feasibility analysis for Dhaka city. The basic theory of groundwater, aquifer and recharge techniques are briefly explained. Finally, the methods that were applied for different data analysis have explained elaborately.

3.2 Concept of the Study

The overall concept of the study is to perform an integrated analysis considering hydrology, hydrogeology and groundwater quality issues to find a potential solution to implement MAR in the city. The following key Water Resources System (WRS) components should be studied in detail at the beginning of the pre-feasibility study (Step-1): (1) Hydrology, (2) Hydrogeology, and (3) Groundwater quality. An intensive investigation is required within these three research fields based on the extensive acquisition of information concerning each field. Relevant research and regulatory institutions should be contacted at this stage to facilitate the gathering of information from any previous studies that may already have been done. The information obtained should help quantify and describe surface water sources (quantity and quality), precipitation (e.g., amounts, trends), wastewater production and treatment, aquifer stratigraphy and lithology, groundwater flow and transport properties, groundwater quality information, aquifer mineralogy, etc. The gathering of information and their analysis is very important and lengthy, and should be regarded as being Step-2 in the pre-feasibility analysis process. The results obtained from Step-2 are subsequently viewed in context to MAR components and requirements, such as the available water sources for recharge and the possible locations and MAR technologies which may be implemented (Step-3).

Step-3 is a process in itself by which relevant information which has already been obtained is viewed in light of the MAR planning. Based on Steps 2 and 3, the potential of MAR and the challenges facing MAR implementation in a region may be assessed (Step-4). Step-4, ‘The Potential and Challenges for MAR,’ results in the exact identification of the information gaps present and the identification of the appropriate research required. Afterwards, the MAR pre-feasibility study continues and recommendations are formulated (Step-6). These detailed recommendations should finally be integrated within the guidelines of IWRM and within the realm of the primary WRS components again until the all goals have been met.

3.3 Theory

3.3.1 Groundwater

Groundwater is considered as one of the most important water resources in the world. Ca. 29% of the available fresh water is the groundwater. The groundwater resource is one of the key factors in making the country self-sufficient in food production. Groundwater-irrigated agriculture plays an important role in poverty alleviation and has greatly increased food production. Until now, availability of groundwater has not been a constraint to agricultural development. But this resource is increasingly facing various problems including quality hazards in many areas where the exposure to pollution from agriculture, urbanized areas and industrial sites as well as arsenic contamination in shallower groundwater aquifers makes the water unfit for human consumption and in some cases even for irrigation purposes. High rates of pumping for irrigation and other uses from the shallow aquifers in coastal areas may result in widespread saltwater intrusion, downward leakage of arsenic concentrations and the general degradation of water resources (Zahid, 2006).

It is important to know the aurface runoff in order to estimate the required design parameter for water harvesting. The following formula (Kuichling 1889) can be used to estimate peak discharge and surface run off:

$$Q_p = C_f \times C \times I \times A \tag{3.1}$$

Where, $Q_p$is the maximum rate of run-off (m^3/s), C is the runoff coefficient representing a ratio of runoff to rainfall, I is the intensity (mm/h) of rainfall having a duration equal to the time of concentration (t_c), A is the drainage area (km^2), C_f is a unit conversion factor (1.008 for English units: ft/s, in/h and acres; and 0.278 for SI units: of m^3/s, mm/h, and km^2). The formula assumes that the rainfall intensity for any given duration is uniform over the entire catchment.

3.3.2 Aquifer

An aquifer is a body composed of sand, rock through which water can easily move. Aquifers must be both permeable and porous and include such rock types as sandstone, conglomerate, fractured limestone and unconsolidated sand and gravel. In Bangladesh, most aquifers are composed of medium to fine sand. Aquifers can be two types which are: unconfined and confined. Unconfined aquifers are those into which water seeps from the ground surface directly above the aquifer (Bear, 1978). Confined aquifers are those in which an impermeable clay layer exists that prevents water from seeping into the aquifer from the ground surface located directly above. Instead, water seeps into confined aquifers from farther away where the impermeable layer doesn't exist. But in some cases the overlying impermeable layer can transmit some waters due to it material properties. Those aquifers are called leaky aquifer or semi-permeable aquifer.

3.3.3 Recharge

Basically, groundwater resource comprises of two parts – dynamic resource in the variably saturated zone that reflects seasonal recharge and discharge of aquifers and static resource below this zone, which remains perennially saturated (Das, 2006). Recharge means the replenishment of groundwater storage that is depleted by withdrawal of groundwater with the extraction wells, loss by evaporation and drainage by natural processes. The sources of groundwater replenishment are deep percolation of rain, deep percolation from irrigated lands, seepage from the water bodies and horizontal

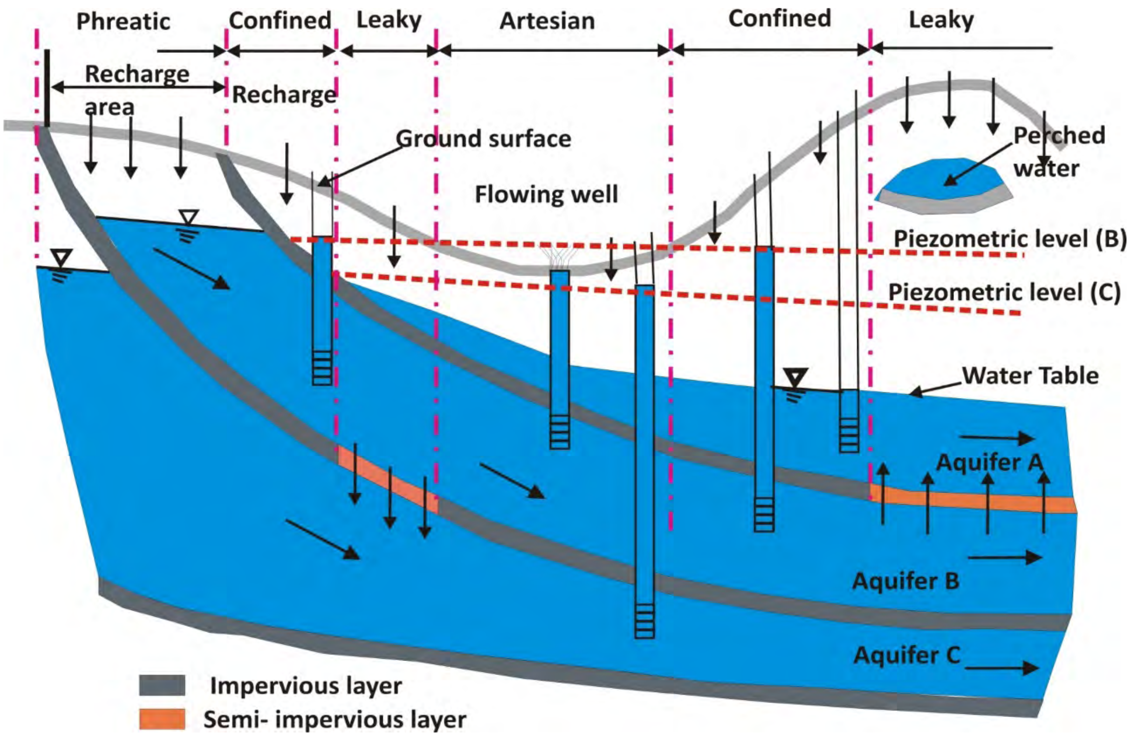


Figure 3.1: Schematic diagram of basic aquifer types (Source: Bear, 1978)

flow of groundwater etc. Recharge to groundwater depends on different physical, climatic and hydraulic properties related to soil and aquifer.

A number of recharge estimation techniques has been proposed and used by several researchers. Figure 3.2 shows a classification of the recharge methods (based on Scanlon et al. 2002, CGWB 2009 and Rahman et al. 2013). The classification are based on (i) surface water information, (ii) unsaturated zone information, (iii) saturated zone information. Water balance method, numerical modelling, isotope approaches are common for all three types of recharge estimation class. It is clear from the figure that unsaturated zone information is of great importance to estimate groundwater recharge. As groundwater flow process through the unsaturated zone is not simple, a number of methods evolved for this zone. However, it is also clear that no numerical modelling approach has been proposed to estimate groundwater recharge data based on surface water information. The different methods also shows the span of data requirement to perform analysis. In this chapter, no detail descript ion of these methods will be provided. For detail description please see the Scanlon et al., (2002).

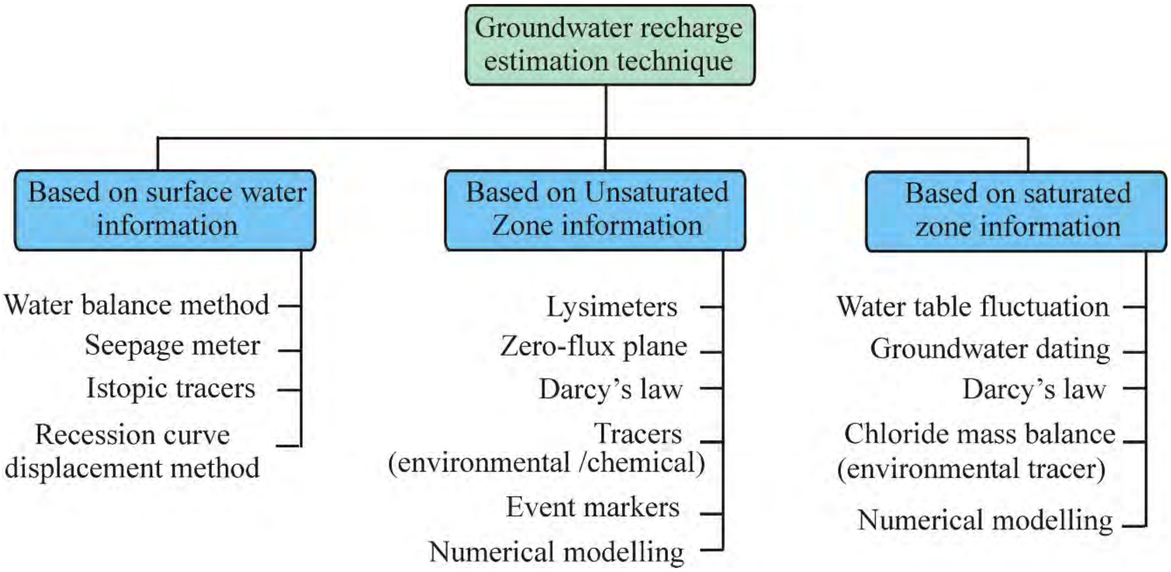


Figure 3.2: Classification of recharge estimation technique based on surface water and groundwater system (Source: Rahman et al., 2013)

3.4 Methodology of the Study

Based on the methodology depicted in Figure 3.2, a pre-feasibility study for determining the viability of MAR implementation in an overexploited urban aquifer in Dhaka, Bangladesh was undertaken. The most concentration was focused on identifying the potential and challenges of MAR in the region. The recommendations for this project are being presented based on the technical information. No details on regulatory and operational issues were investigated.

Three components of hydrological cycle were considered: Hydrology, Hydrogeology and groundwater quality to analyse MAR opportunity in Dhaka city. Basically, data related to water demand and supply, surface water characteristics, sub surface characteristics were analysed from the point of view of MAR and its requirement such as water to recharge, aquifer to store and technique to recharge. A comprehensive analysis were done to find the potential of MAR and also related challenges that can make the groundwater more polluted were carefully determined. These MAR capabilities were checked against water resources system of the city.

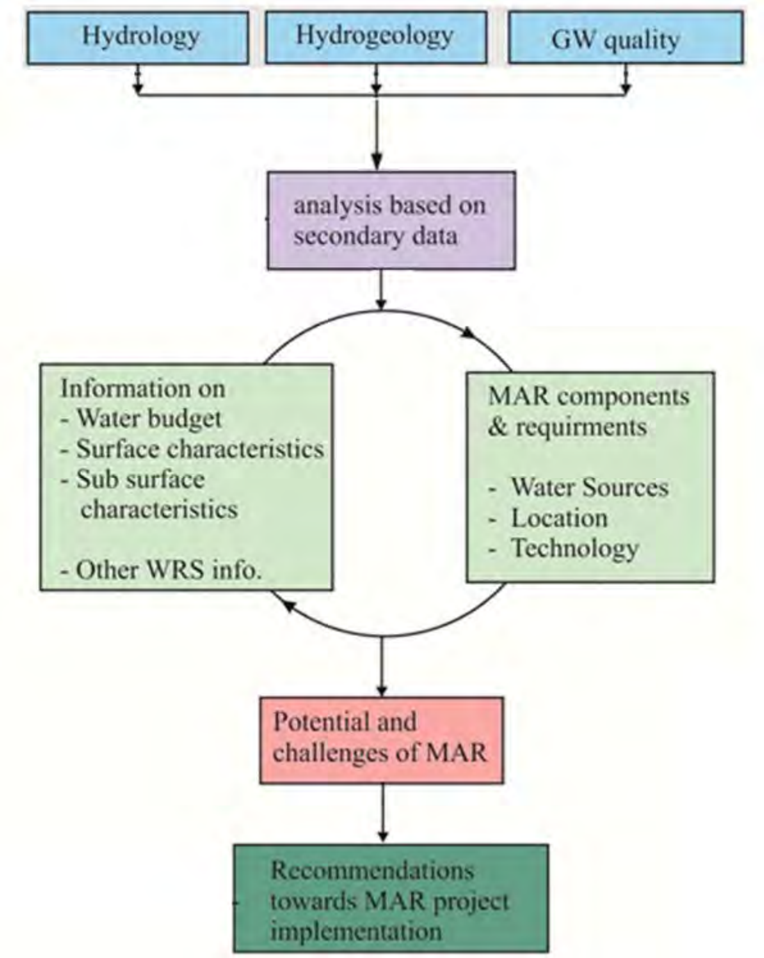


Figure 3.3: Methodology of the study

For the implementation of above-mentioned methodology in the Dhaka City and to collect the required hydrological and hydrogeological, a number of institutions will be contracted. The institutions are: Bangladesh Water Development Board (BWDB), Bangladesh Meteorological Department (BMD), Department of Environment (DoE), Bangladesh University of Engineering and Technology (BUET), Institute of Water Modelling (IWM) and Dhaka University. A brief description of the methods that are used to for (i) Hydrology, (ii) Hydrogeology, and (iii) groundwater quality are explained in section 3.5, 3.6 and 3.7, respectively.

3.5 Hydrological Analysis

In hydrological data analysis, data relevant to water sources are only considered. Rainfall, evaporation, temperature, humidity, surface water discharge, river networks, waste water quality and quantity were collected from different secondary water sources.

3.5.1 Data Collection and Processing

Hydrological data such as rainfall, river discharge, water supply information, were collected from secondary sources. Several organizations and institutions such as Bangladesh Meteorological Department (BMD), DWASA, Institute of Water Modelling (IWM), Bangladesh Water Development Board (BWDB), Department of Water resources Engineering of BUET, were communicated to collect the relevant data. All collected data, from secondary sources, were checked for quality and consistency. Standard methods (such as double mass curve) were used for filling the missing data, if required.

Estimation of maximum storage required to store rainwater

This study used two methods to estimate the storage capacity required to store maximum water. He methods are (a) Mass curve method, (b) Area consumed (Ac) - Volume consumed (Vc) method. A brief explanation of these two methods are given below:

Mass curve method (Nissen-Petersen and Gould, 2000):

This method considered the principal of monthly water balance method. Starting with a assume volume of water already in the tanks, the volume collected at each month is added to the previous balance and the demand is subtracted. The initial volume of water in the tanks would be provided by hauling or capturing water prior to withdrawing water from the system. The mass curve calculation was done suing the historical rainfall data (year 1954 to year 2013). From the monthly balance estimation the maximum water storage was determined. The estimation technique can be expressed by the following equations:

$$S_k=\Sigma((AP_i-D_iN_i)) \tag{3.2}$$

$$S=MAX(S_k) \tag{3.3}$$

Where,

A= Catchment area (m^2)

D = target water demand (litres/capita/day) or (litres/family/day)

k = the final month of recording storage

N = number of days in the given month

P = rainfall over given time period (mm)

S_k = storage requirement after month k (litres)

S = maximum storage requirement (litres)

(a) Ac –Vc method (IWACO BV, 1981) :

The volume of the storage tank was also determined using the Area consumed (Ac) – Volume consumed (Vc) relation method. Required volume was calculated using monthly water demand. In this method, a relationship between critical catchment area (m^2) and minimum storage volume provided (m^3) was determined based on a series of N (54) year actual monthly rainfall data and a selected frequency of periods with limited supply.

3.6 Hydrogeological analysis

Hydrogeological data such as groundwater level, lithology, pumping test data, aquifer thickness information were collected from secondary sources. Several organizations and institutions such as DWASA, Institute of Water Modelling (IWM), Bangladesh Water Development Board (BWDB), Department of Water resources Engineering of BUET, and Geology Department of Dhaka University were communicated to collect the relevant data. All collected data, from secondary sources, were checked for quality and consistency. Standard methods (such as double mass curve) were used for filling the missing data, if required.

3.6.1 Groundwater table contour map

Groundwater levels data for the Dupitila aquifer were collected from 15 monitoring stations of BWDB existing in and around the city. ArcGIS geostatistical toolbox was used for spatial analysis of these water level data. Kriging interpolation method was used. The quality of GWL data in the city is not of high standard because of manual observation, lack of concentration in data bookkeeping and the density of production wells. Again, it is likely that the interpolation might not represent the actual water level as the density of pumping wells are different at different places and the pumping rate is also different. However, manual and visual checking was taken intensively to avoid any unrealistic interpolation.

3.6.2 Cross section preparation

More than 300 well log data in the Dhaka city and its surrounding region were collected, characteristics of the sediments recorded for each well log, such as lithology, colour and grain-size distribution within the depth were analysed in this study. Geodin 6.0, RockWork 2004 and Arc GIS used to the lithologs and examine the hydrogeological settings of the different aquifer of the study area. This information confirms that the local geology is representative of the regional geological unit. Hydrogeological parameter of this area are governed by the lithostratigraphy.

ArcGIS was used to prepare and visualise spatial maps.

MAR site selection map

MAR site suitability map was prepared using the thickness of the top impermeable layer at different places of the city. The thicknesses were taken from the lithology available and interpolated for the entire city using ArcGIS spatial analysis tool. On top of that, open area, low lying area (collected from Sharmin 2009) etc., were overlaid in the software. Based on the thickness of the impermeable layer thickness, three MAR techniques were suggested.

3.7 Groundwater quality

Groundwater quality data was collected basically from secondary sources. DWASA collected several groundwater samples in 2006 and published in a report (DWASA, 2006). These data were collected and analysed according to the need of this thesis. Piper diagram using a software called “AquiSolve” were prepared to understand the aquifer water type. ArcGIS were used to prepare the spatial analysis map. Excel was used to compare different set of data.

3.8 Driver - Pressure - State - Impact –Response (DPSIR) analysis

The DPSIR concept has been developed to evaluate interactions between the society and the environment based on the assumption of a causal connection between them (STRIVER, 2008; Kristensen, 2004). The strategies that were developed by the European Commission for the implementation of the Water Framework Directive (WFD) have identified the DPSIR framework as a convenient approach to identify stress factors and their effects on the environment (OECD, 1993; OECD, 2003). Once the driving forces have been listed, the resulting stress factors (pressures in the DPSIR framework) can be defined and consequences for the water resources system can be assessed.

Table 3.1: DPSIR definition (modified after Quevauviller, 2010)

Term	Definition
Driver	An anthropogenic activity that may have an environmental effect (e.g. agriculture, industry)
Pressure	The direct effect of the driver (for example, an effect that causes a change in flow or a change in the land use pattern)
State	The condition of the water body, human health or social structure resulting from both natural and anthropogenic factors (i.e. physical, chemical and economical characteristics)
Impact	The environmental effect of the pressure (e.g. ecosystem modified, increase health risk)
Response	The measures taken to improve the state of the water body (e.g. demand management, use of non-conventional water, developing best practice guidance for agriculture)

Driving forces (Drivers), in the form of social, ecological, economic or environmental development put forth Pressure on the environment and, as a consequence, the State of the environment changes. This leads to Impacts that may reduce a societal Response that feeds back to the Driving forces, Pressures, State or Impacts (EEA, 1999; STRIVER, 2008).

3.9 Summary

In general, the overall concept of this study is to perform a prefeasibility analysis based on secondary data, A huge number of data and information have been collected from several government and academic organisations. The collected data were formatted, consistency was checked and analysed using different state-of-the art methodology (such as ArcGIS, Surfer 8 software etc.).

Chapter 4

STUDY AREA AND WATER RESOURCES SYSTEM ANALYSIS

4.1 General

The study is focused on the Dhaka Metropolitan City, DND (Dhaka-Narayanganj-Demra) area, Narayanganj (N.Ganj) municipality. The area is located between $23^{0}35'$ to $23^{0}54'$ north latitude and $90^{0}20'$ to $90^{0}33'$ east latitude, and covers 370 km^2 in total. It is surrounded by the Tongi Canal to the north, the Turag-Buriganga River system to the west, the Balu River to the east, and the Sitalakya River to the south. In this study, a number of thanas (small administrative areas) in the vicinity of Dhaka City are also included in order to investigate the regional water resources that may assist in solving local water supply problems and a MAR implementation (Figure 4.1).

Maintenance Operations Development Services (MODS) zone of Dhaka City

Since 1963, DWASA is responsible for the supply of drinking water as well as the collection and disposal of domestic sewage and storm water from Dhaka City and Narayanganj (Haq, 2006). For operational purposes, the entire service area of DWASA had been divided into seven zones, six of them within the Dhaka Municipality and one zone representing Narayanganj. Recently, DWASA subdivided Zone 5 into three further zones, namely Zone - 5, Zone – 8, and Zone – 9. Also, Zone - 4 has been subdivided into Zone - 4 and Zone – 10 for management purposes. In this study the old subdivisions (7 zones) were maintained for the analysis purposes, because most of the information is based on the old management zones.

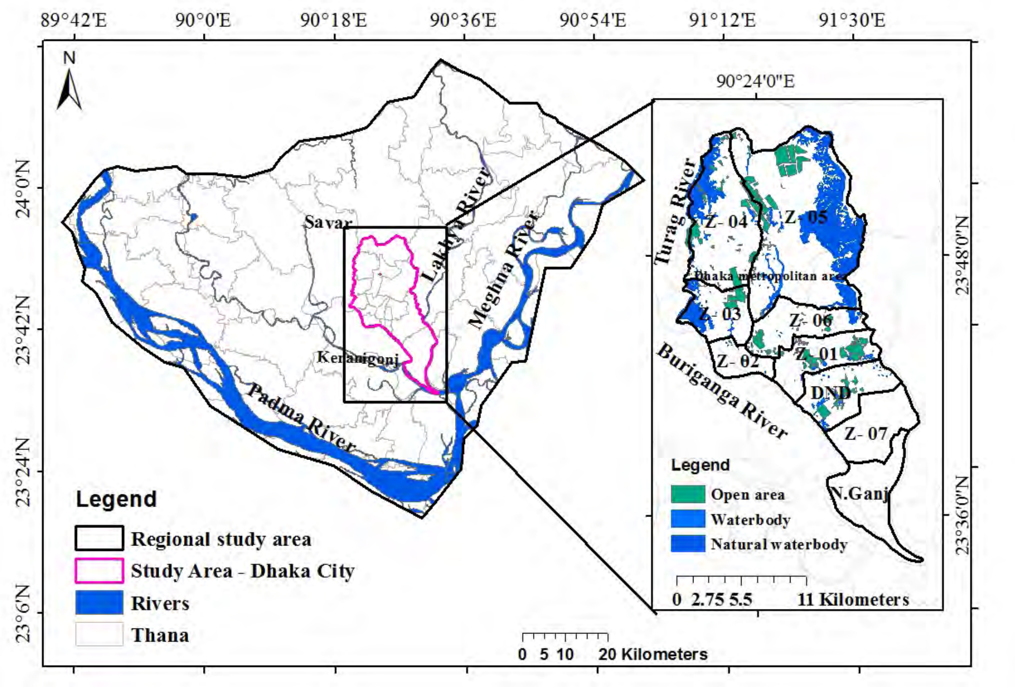


Figure 4.1: Study area showing local boundaries and DWASA management zones

4.2 Climate

The Dhaka City area experiences the Indian Ocean monsoon climate with four meteorological seasons: pre-monsoon (March to May), monsoon (June to September), post-monsoon (October to November) and dry (December to February). Long-term annual rainfall is in the range of 1700 to 2200 mm. About 80% of rainfall occurs from June to September (JICA, 1991). Mean monthly rainfall during this period is between 319 and 403 mm. During the last 52 years the precipitation increase 381 mm. In pre monsoon season the total rainfall pattern is fluctuating in Dhaka City. In 1953, the total rainfall was 364 mm. which was 877 mm in 1988 (the flooding year in Bangladesh). In 1998, the total rainfall had increased but not such level of 1988. After that, the amount of rainfall is decreasing. However, in post monsoon season the amount of rainfall of Dhaka City is decreased. In this season the rainfall amount exist between ranges between 10 0mm and 400 mm (Table 4.1). The monthly average evaporation ranges 80 and 130 mm (Table 4.2). Evaporation is related to the temperature and the bright sunshine. In 1953-1963, the average bright sunshine was 7.3 hours which becomes 6.2 hours in 1997-2004.It indicates that, the bright sunshine is decreasing.

Table 4.1: Monthly Rainfall (in mm) of Dhaka City

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Avg	7.73	22.1	57.4	137.3	297.7	394.8	403.4	329	319	185	34.6	10.5
max	68	95	195	318	707	856	694	552	839	568	172	106
min	0	0	0	17	69	89	136	59	91	29	0	0

(Source: JICA, 1991; BMD, 2013)

Table 4.2: Monthly Evaporation (in mm) of Dhaka City

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Avg	104	79	81	77	78	83	87	130	118	106	75	105

(Source: JICA, 1991; BMD, 2013)

Historical data analysis conclude that, in general, monthly average temperatures range between 250C and 310C. Maximum and minimum temperatures are 40 °C and 6 °C, respectively.In 1953-1963, the average annual maximum temperature was 30.4 ºC, which becomes 30.6 ºC in 1997-2005. But in 1986-1996, the average annual temperature was 31 ºC. It is the evidence of temperature increase but slowly. Nevertheless, the highest maximum temperature of Dhaka City was in pre monsoon season in 1990-2000 and the lowest maximum temperature was in winter season in 1990-2000. In 1953-1963, the average minimum temperature was 20.82 ºC, which becomes 21.76 ºC in 1997-2005. It proves that, the minimum temperature is increasing. Moreover, the highest minimum temperature of Dhaka City was in monsoon season (1995) and the lowest minimum temperature was in winter season (1955). In pre monsoon and post monsoon season, the minimum temperature exists between 20 ºC -24 ºC.

Table 4.3: Monthly Temperature (in ^{0}C) of Dhaka City

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Avg	18.6	21.5	26.1	28.7	28.9	28.7	28.7	28.7	28.7	27.4	23.6	19.8
Highest	34.2	36.6	40.6	42.3	40.6	38.4	35.2	35.9	35.3	38.8	33.3	31.2
Lowest	5.6	4.5	10.4	15.6	18.4	20.4	21.7	21	22	10.4	10.6	6.7

(Source: JICA, 1991)

The monthly average humidity a ranges between 63% and 87%. From this data we can easily understand that the relative humidity is increased 2 percent over the 50 years. From the analysis of historical data it can be said that the relative humidity at different is year is varying. These variation might occurred due to the pollution level of the city. And, it might be the ultimate result of unplanned urbanization and development.

Table 4.4: Monthly Humidity (in %) of Dhaka City

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Avg	70.7	66	63	71	79	86	87	86	86	81	75	74

(Source: JICA, 1991)

4.3 Geomorphology and Natural Drainage system of Dhaka region

There are about 40 natural khals in the study area such as Boaliakhal, Gobindapurkhal, Nalikhal and Uzanpurkhal. The khals drain to boundaryrivers: the Tongi Khal and the Balu river (Figure 4.2). An area of 32.24 Km2 is drained to the Balu while 8.45 Km2 to the TongiKhal (Source: DWASA, 2006). The Boaliakhal with a drainage area of 22.11 Km2 is the major drainage system. The storm runoff is accumulated in the low-lying areas, flows through khals and ultimately is discharged to the river. The lowlands and wetlands perform important drainage function by storing stormwater and keep the relatively higher lands free from rainfall flood.

Dhaka city is surrounded by rivers (Figure 4.2) that receive water from the Brahmaputra (Jamuna). The water level in the boundary river remains high during monsoon and flood water enters the area through the khal system. During flood season, almost entire area look like a lake with settlement areas as islands connected by roads. The khals are not distinguishable during this period. They become visible during dry season. Water level in the boundary river is a controlling factor in storm drainage in Dhaka city. Among the peripheral rivers Turag is the longest river with 71 km reach (catchment area 1201 Km^2, Table 4.5, BWDB 2005). The next longest river is the Buriganga with 45 Km length and 235 Km^2).

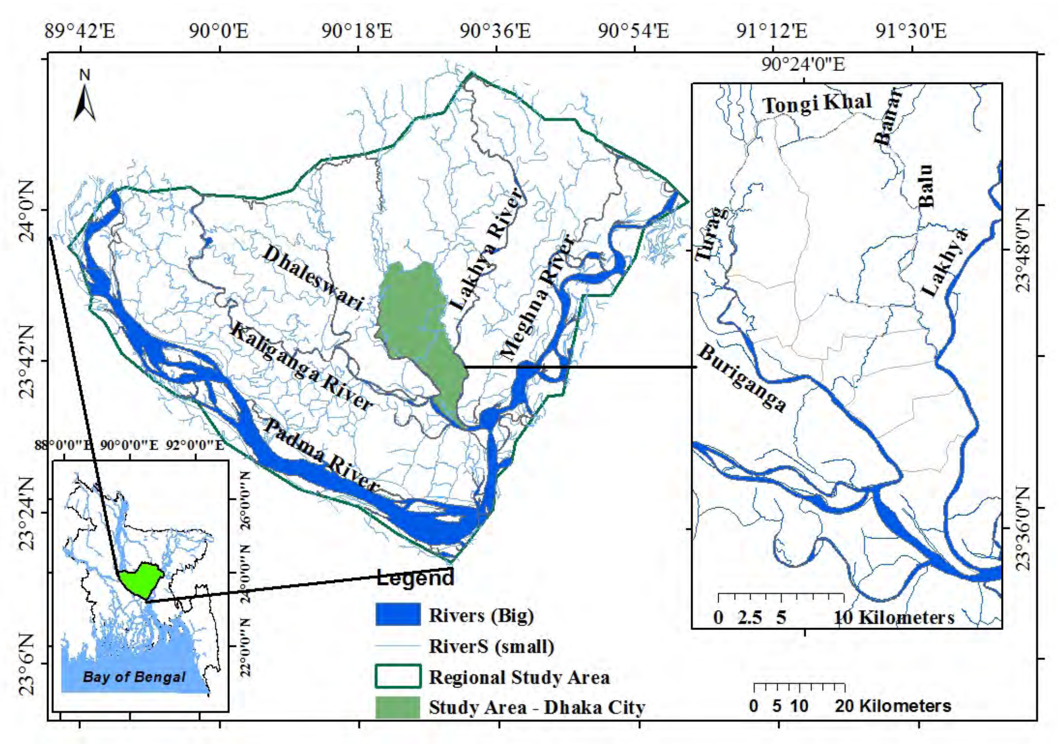


Figure 4.2: Study area showing the river networks around Dhaka City

Among the major rivers Turag comes from the north and joins the Buriganga River (Tidal River) near Mirpur, Balu comes from north-east and joins Lakhya River near Demra, and Tongi Khal takes water from Turag River and discharges it into Balu River. The rivers commonly show Dendritic Pattern and only the western part of river system shows Trellis Pattern. Most are these streams and canals are seasonal, ill drained and fed by the Monsoon water. There are more than 40 drainage channels (khals) including main and branch channels in the city.

Table 4.5: Major characteristics of the major peripheral rivers in Dhaka city during dry season.

Name of the River	**Length (km)**	**Avg. Depth (m)**	**Catchment area (m^2)**
Buriganga	45	14.00	253
Turag	71	13.5	1021
Balu	45	9.63	722
Tongi Khal	17	9.15	45

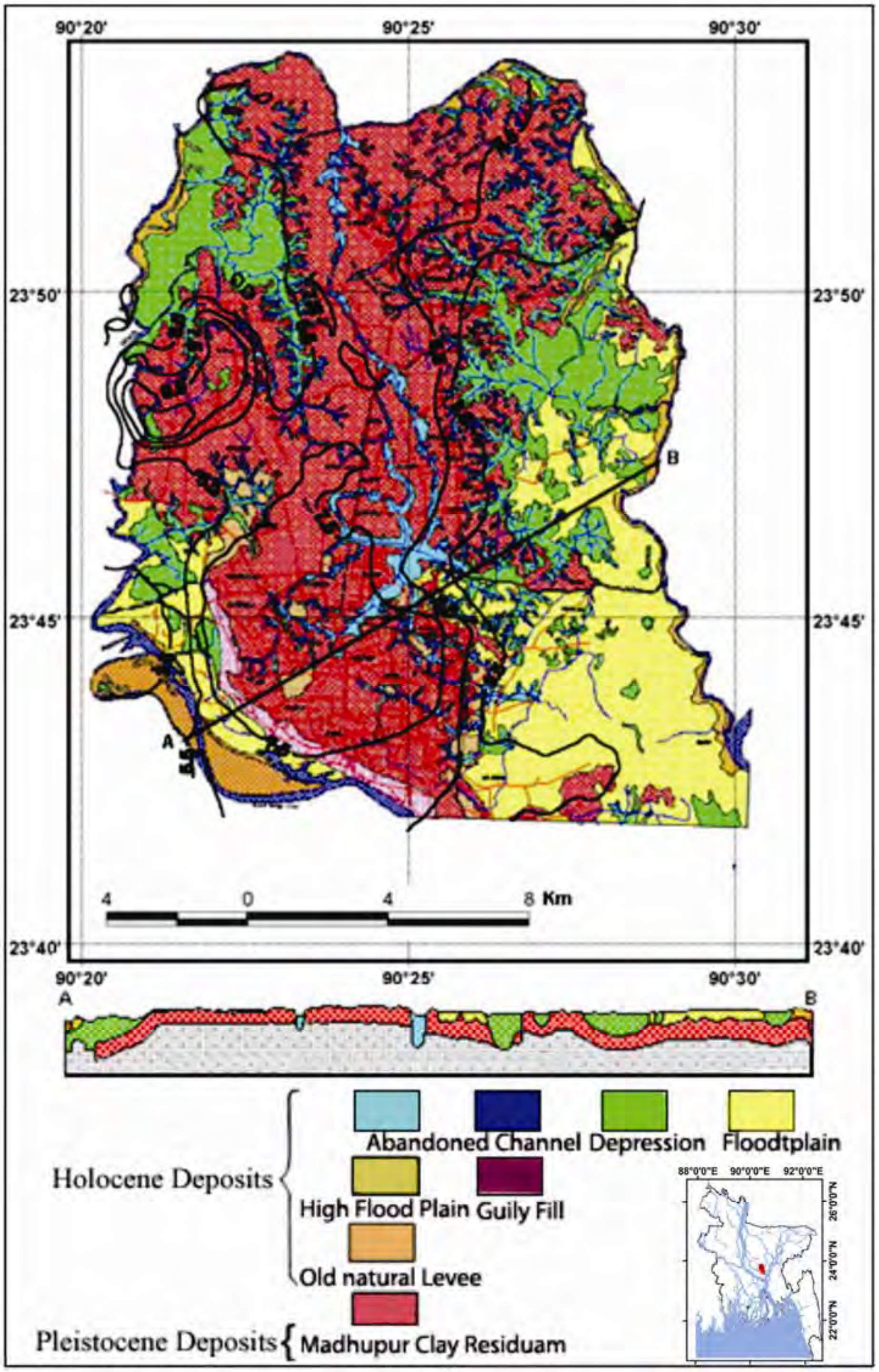


Figure 4.3: Geomorphological map of Dhaka city (Source: Hoque, 2007)

The surface geology of the metropolis follows the geomorphic expression of the area. At the land surface, Pleistocene alluvium occupies the dissected uplands, and alluvium of recent river-borne deposits covers the low lying flood plains (Figure 4.3). The area is well linked with the surrounding big rivers by the interconnecting streams, streamlets, retention lakes ponds and canals.

4.4 Geology and Hydrogeology

The geological and hydrogeological condition of an area should be understand well to implement any groundwater related project. The extent and capacity of any geological formation determines the project design parameters (such as no. of wells, volume of recharge water, place of recovery wells). So, in this study the regional of Bangladesh and Dhaka regional were studied quite intensively.

4.4.1 Geology of Bangladesh

Bangladesh is a part of Bengal basin which is about 200 km wide in the northeast and broadens to about 500 km in the vicinity of the Bay of Bengal and bounded by the Himalayan ranges and the Shillong massif to the north, the Indian shield to the west and the Arakan Chin massif to the east. The area is underlain by poorly consolidated or unconsolidated sediments of Tertiary and Quaternary ages. (Aggarwal et al., 2000). Tectonic deformation of pre-tertiary consolidated sediments and deltaic sedimentation are the major factors which determined the geological structure of Bangladesh. Sedimentary deposits of Bangladesh mainly consist of those laid down by the Ganges, Brahmaputra and Meghna (GBM) river systems (Aggarwal et al., 2000). Quaternary sediments cover approximately 82% of the country and rocks from Paleocene to the Pleistocene are exposed in 18% of the area in the hilly region (Hussain and Abdullah, 2001). Bangladesh contains thick sediment (up to 20 km in the southern part) sequences of Permian to Holocene. The sediment thickness is shallowest in northern Bangladesh (114 m). Major part of the sediment is deposited by the Ganges-Brahmaputra-Meghna river systems during Miocene to Holocene time (Aggarwal et al., 2000). However, during the Pleistocene and Holocene time large volume of sediments were laid down in the Ganges-Brahmaputra-Meghna (GBM) delta complex by the mighty rivers that built up the delta and aquifer systems. The input of the sediments and their distribution was largely controlled by tectonic activities (rising Himalayas) and the climatic changes in the region. (Hussain and Abdullah, 2001).

Biswas (1992) states that the high volume of sediment discharge from Himalaya is the primary reason for the huge sediment discharge in Bay of Bengal. The geologically different catchments of the Ganges and Brahmaputra rivers influence the character of sediments deposited within the Bengal basin. Sediments from the Ganges are composed of highly weathered sedimentary and volcanic rocks, and therefore, have heavy clay load. Sediments from the Brahmaputra are predominantly un-weathered and relativity coarser. (Aggarwal et al., 2000). The Pleistocene alluvial terraces, originally deposited as floodplains of the Ganges and Brahmaputra rivers, are highly oxidized, weathered and more compact, compared to recent floodplain sediments. These deposits are composed primarily of silt and sand, and in the lower delta they are principally silt, clay and peat. The Holocene sediments, overlying the Dupitila Formation of the Pleistocene age, comprise varying degrees of alternate layers of unconsolidated sand, silt and clay. These sediments are mostly floodplain, back swamps and near-shore tidal deposits (Hussain and Abdullah, 2001). A detailed Bengal basin stratigraphy, sedimentation history and age of different layers can be sought in the Hussain and Abdullah's (2001)report.

4.2.1 Geology of Dhaka Region

Among the major tectonic elements Dhaka belongs to Bengal Fore Deep. Geologically, the Dhaka city is situated in the Pleistocene uplifted block (Madhupur Tract) within the passive margin surrounded by subsiding floodplains (Miah and Bazlee, 1968) bounded on the west by a series of NW-SE trending en-echelon faults including the Dhamrai, Maijail and Kaliakoir. The area is characterized by numbers of faults terminating and delineating different blocks. They are NW-SE trending Padma fault, Kartoya-Banar fault, Tista-Old Brahmaputra fault, N-S trending Dubri-Jamuna-Madhupur fault (Khandoker, 1987) controlling the tectonics of Dhaka and its environs. The geo-tectonics and its structural arrangement in the area control the geology-stratigraphy and hydrogeology of the area (Figure 4.4).

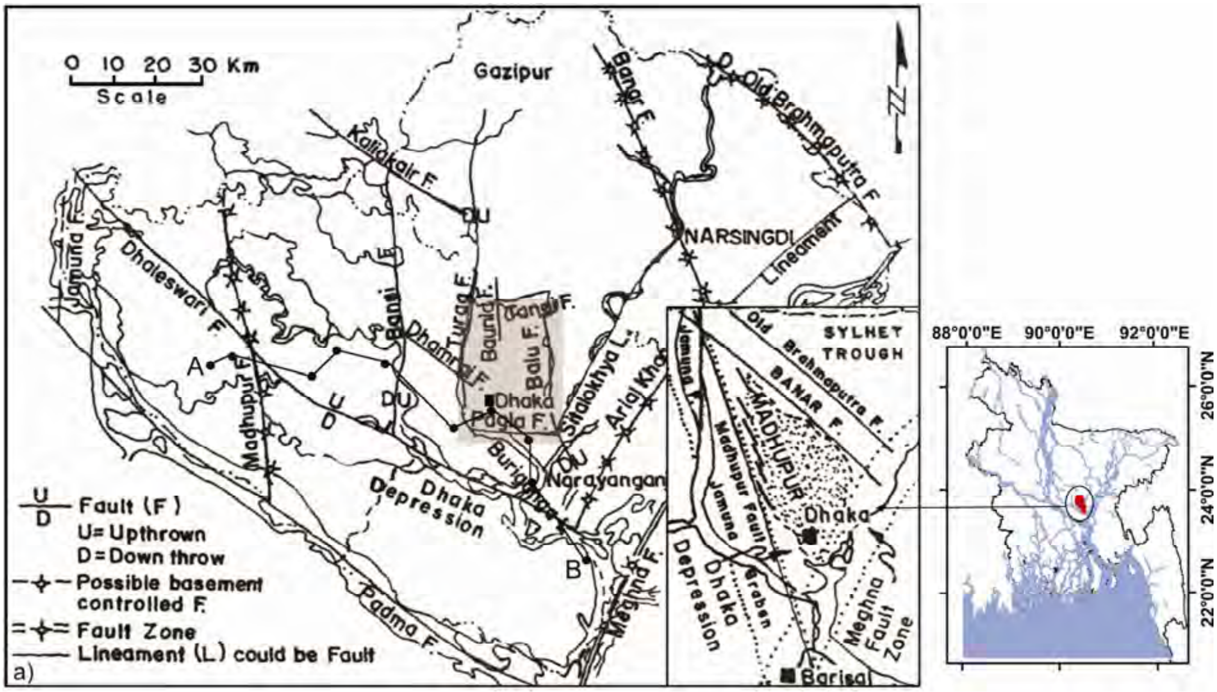


Figure 4.4: Tectonic map of Dhaka region (source: EPC/ MMP 1991; Khandoker, 1987 and Hoque, 2007)

The Madhupur Tract itself is a remnant block of Plio-Pleistocene sediments comprising the DupiTila and Madhupur Formations, isolated following widespread incision of the land surface during the late Quaternary, and its boundaries are in part fault controlled (Monsur 1990; Hasan 1999). The Madhupur Clay formation is unconformably overlain by Alluvium formation and underlain by DupiTila formation. The geology of the study area is characterized by Quaternary alluvial sequences, which commonly show good aquifer properties. The study area consists of the southern half of the Madhupur tract, which is surrounded by the flood plains of Jamuna, Ganges, and Meghna Rivers (DWASA, 2006). Marsch clay, alluvial clay and silt, alluvial silt and Madhupur clay is main aquifer materials (Figure 4.5). Basically Modhupur clay constitute the top layer of the central part of the aquifer. The south part contains mainly Alluvial silt. Marsch clay is situated mainly in the west and east part of the city. The study area is characterized by a 400-500 m thick unconsolidated sequence of fluvio-deltaic sediments, which is overlain by the Modhupur and/or flood plain clay materials (5 m to 25 m thick, Table 4.6) (Hoque, 2004; Hoque et al., 2007). The subsurface lithologies reveal that the aquifer and aquitard layers don’t have similar gradients as the surface topography, and the aquifers are separated by an aquitard/aquiclude. The subsurface geology (within 300 m of depth) of Dhaka city can be generally subdivided into seven layers (DWASA, 2006). The upper aquifer is directly connected to the surrounding rivers. The aquifers of Dhaka City generally possess large transmissivities and storage coefficients and the hydraulic conductivity values of the aquifers are moderate (DWASA, 2006). Table 4.6 shows a brief description of the Dhaka city regional stratigraphy.

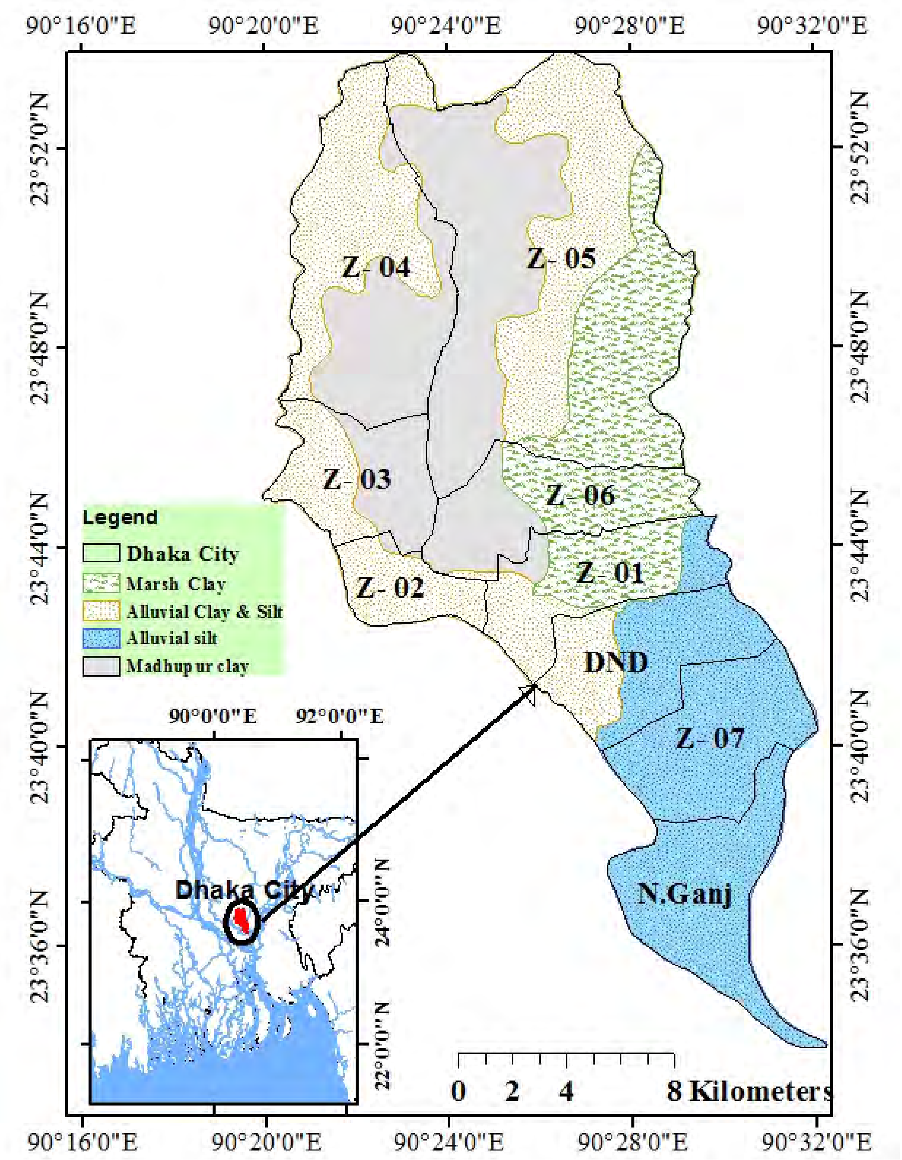


Figure 4.5: Geological map of Dhaka and its surrounding area (source: USGS, 2001)

Table 4.6: Stratigraphy and hydrogeological characteristics of Dhaka City

Stratigraphic	Stratigraphic	Lithology	Thickness	Function in

age	name		(m)	aquifer system
The Flood Plain Area				
Holocene	Flood plain	Alluvial silt, sand and clay	6–15	Aquitard –1
Late Pleistocene to Holocene	Dhamrai Formation	Alluvial sand	100–200	Upper Dupitila Aquifer - 1
Pre-Pleistocene	Not named	Unknown	–	
The Madhupur Tract Area				
Recent	Lowland alluvium Swamp	levee, and riverbed sediments	0–5	Top soil/Aquitard 1
Holocene	Bashabo Formation	(Sand discontinuous)	3–25	Upper Dupitila Aquifer-1
Pleistocene	Madhupur Clay Formation	Silty clay member, Fluvio-deltaic sand	6–25	Aquitard –2
Plio–Pleistocene	DupiTila Formation	DupiTila clay stones Fluvio–deltaic sands	100–180	Upper Dupitila Aquifer- 2
Miocene	Girujan Clay	Bluish clay	50–100	Aquitard -3

(Source: Morris et al.2003)

4.5 Water resources problem in Dhaka city – Brief analysis

Historically, Dhaka City has had immense problems related to flooding, waterlogging and drainage congestions during Monsoon (Alam and Rabbani, 2007). Drinking water supply, over exploitation of groundwater, surface water pollution are big concern nowadays. The following section briefly explains some key water resources problems of Dhaka city that are relevant to this present study.

4.5.1 Water Supply Deficit

The population data, demand and supply data taken from DWASA 2012, Hoque 2007 and ADB 2007.Figure 4.2 shows the water budget situation (Demand-supply) of Dhaka from 1963 to 2025. From 1970s DWASA have been facing problem to supply adequate water to the city dwellers. In course of time, the water supply deficit is going higher (Figure 4.6). In 2010, DWASA supplied 2006 MLPD against the demand of 2485 MLPD leading to a water supply deficit of 479 MLPD. In 2025, the water supply deficit will be 2413 MLPD, if no development measures have been taken.

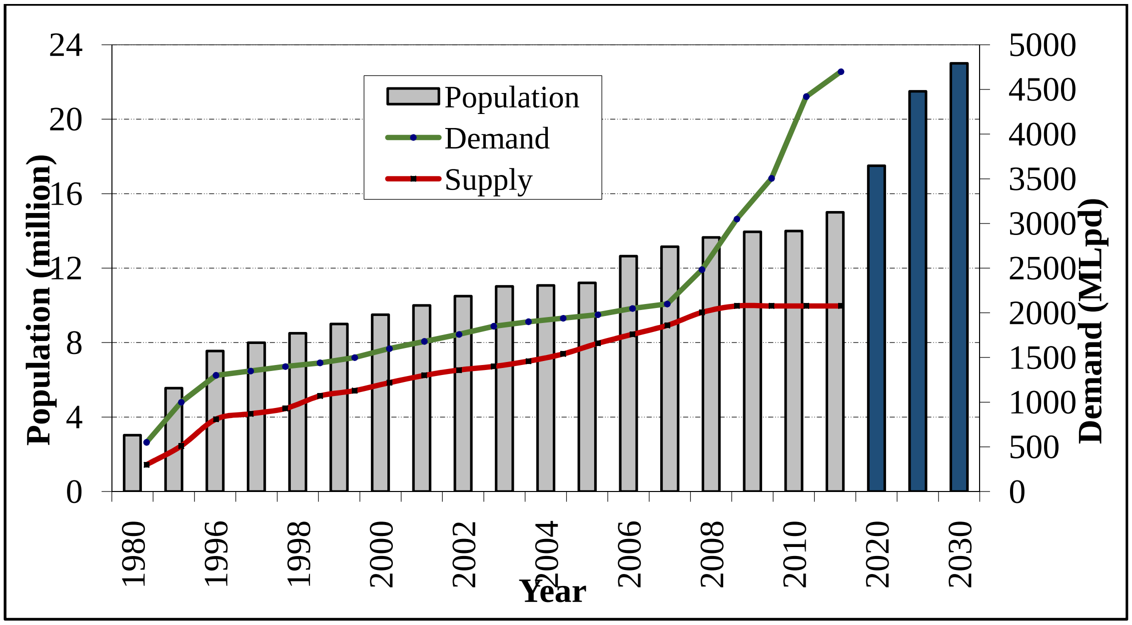


Figure 4.6: Water budget situation of Dhaka City from year 1980 to year 2025. Deep color population area indicates future condition (Source: BBS,2011)

4.5.2 Groundwater level decline- long term data analysis

The first groundwater (GW) development in Dhaka City was initiated by the Department of Public Health Engineering in 1949. In the 1960s, groundwater was the principal water supply source. By the year 1966, groundwater covered almost 75% of the total drinking water supply (Ahmed et al., 1999) and in 2010, groundwater abstraction increased ca. 70 times compared to the GW extraction in 1966. According to the record of DWASA, in 1970s only 49 DTWs were functioning whereas the current number is 612. Groundwater level mining situation is directly related to the number of DTWs installation. Figure 4.7 shows the position and number of DTWs that are installed in different decades from 1970. DWASA installed almost 50% of today’s DTWs in 1990s. In 1970 to 1980, most of the wells are installed close to the rivers, gradually installation of the wells spread to the centre of the city. Besides these DTWs, a number of private production wells are operating to withdraw groundwater from the upper Dupitila aquifer. The positions of the

DTW are extremely important in order to selelct the position of MAR well. If the pumping wells are close the MAR well, the water that are recharged via injection well will be withdrawn by the existing pumping wells and minimum resident time of 180 days might not be maintained. Hence, the planning of the recovery well would be also problematic.

Table 4.7 shows that in 30 years, groundwater extraction in Dhaka City has been increased by ca. 140% and population is increased by 366%. In order to meet the extra demand, still DWASA is looking for alternative water resources.

Table 4.7: Total extraction of groundwater in Dhaka City from 1983.

Year	**Extracted volume (Mm^3)**
1983	137
1988	152
1993	237.5
1998	306
2003	416.5
2008	539
2013	327

Figure 4.7 shows historical development of groundwater extraction in six zones of Dhaka city. It is clear from the figure that in 2000s, groundwater extraction increased a lot in all zones. Besides installing a number of DTWs, DWASA also rehabilitated a number of old DTWs in 2000s. So, groundwater extraction rate was much higher in this decade.

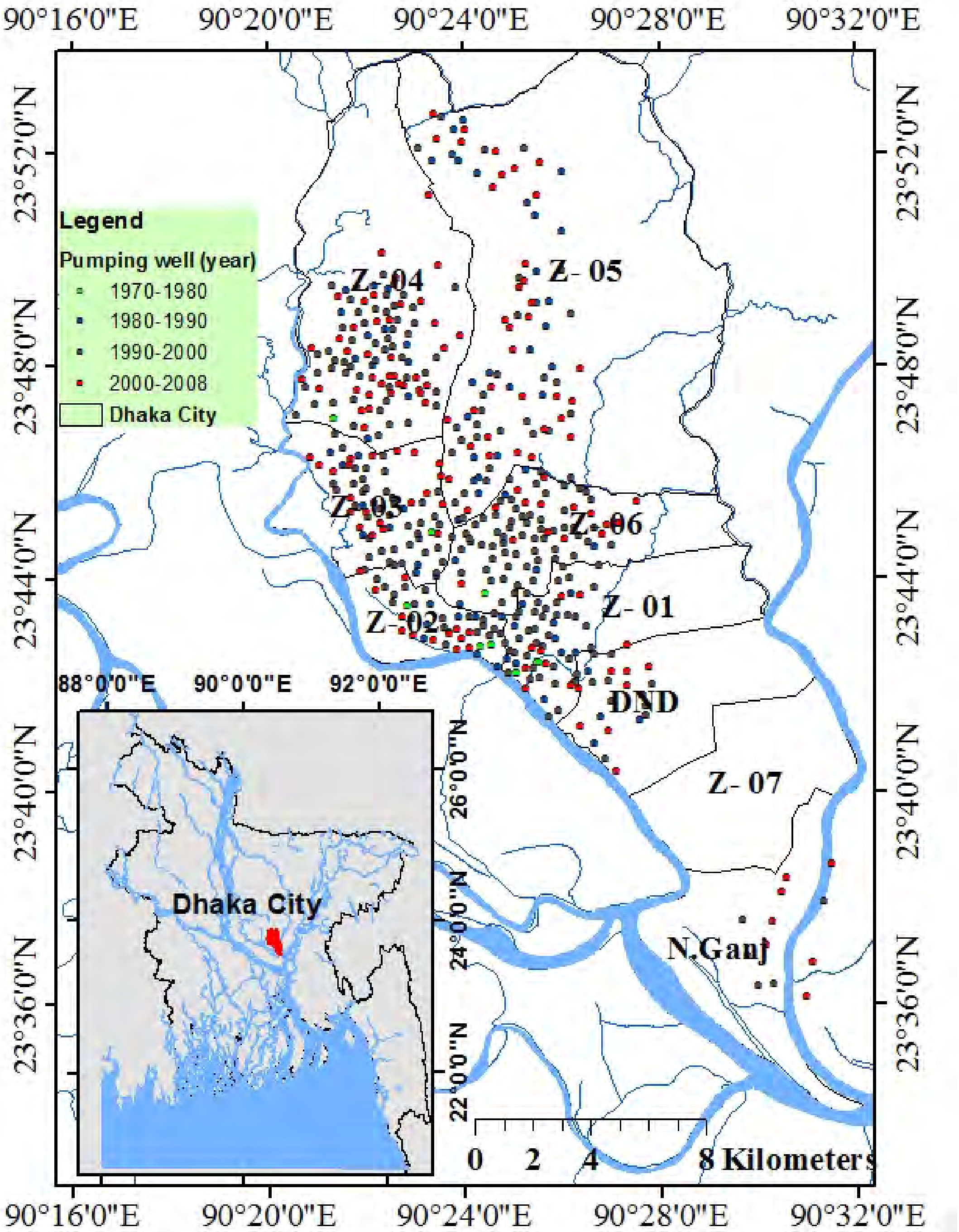
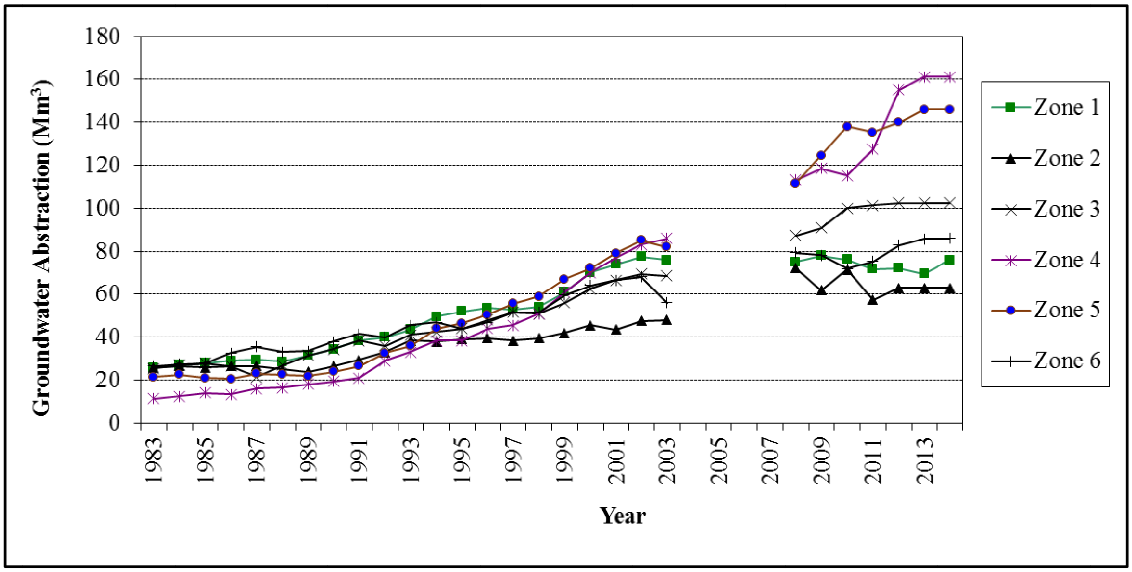


Figure 4.7: Position of DWASA pumping wells in different decades

Figure 4.8 shows the historical development of GW extraction from the aquifer in different MOD zone of DWASA. Data was taken from Hoque 2007 and DWASA website. No data from year 2004 to 2007.

It is clear from the figure that after 1990, the extraction volume increased rapidly and these information closely match with the increased number of DTW installation during year. 1990-2000. However it seems that Zone 4 and Zone 5 extract the maximum amount of water which is due to the bigger administrative area under these MOD zones. However, the data of year 2011 to 2013 reveals that the increasing trend of GW extraction becomes plateu in all MOD zones except in Zone 1. However, data more years are required to confirm these.

Figure 4.8: Groundwater extraction from the Dupitila Aquifer.



Data not available

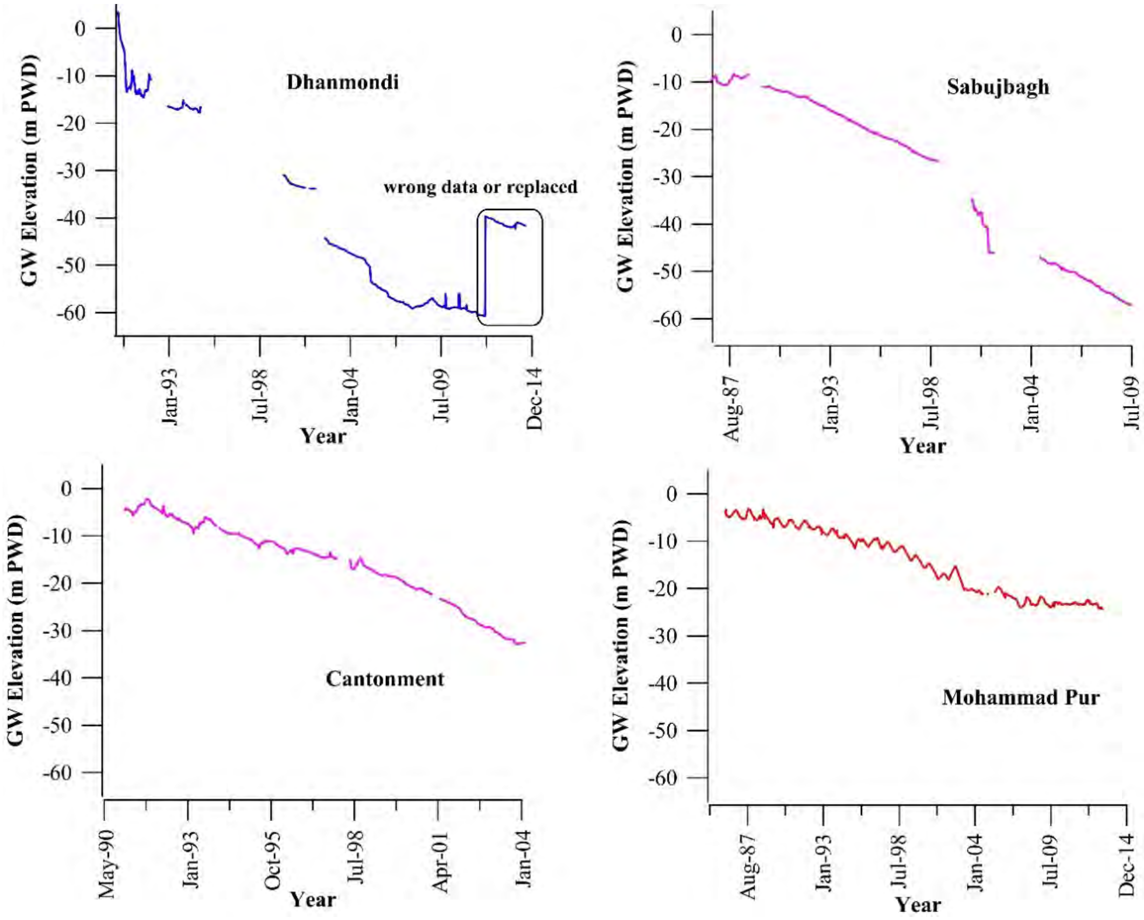


Figure 4.9: Groundwater level elevation with time in four different places in Dhaka for different years

From Figure 4.9, it is clear that the decline of groundwater level in Dhaka city aquifers are alarming. Though it has been mentioned by several researchers that the GWL declines 2-3 m/year (Hoque, 2006; DWASA, 2006), but it seems that the rate has been increased during last 15 years.

4.5.3 Groundwater flow and Recharge

For understanding the behavior of MAR water and to plan recovery system, it is important to know the groundwater flow directions at the aquifer and essentially the natural recharge of the area. According to historical data and several research reports, groundwater flow has significantly changed since urban development began. Before urban development, recharge to the Dupitila aquifer was controlled by topography and vertical leakage through the Madhupur clay (Ahmed et al. 1999). Historically, groundwater flow was controlled by boundary faults of the Madhupur Tract and discharge to the flood plain aquifer (Ahmed et al. 1999; Burgess et al. 2011). Regional groundwater flow was directed towards the south and southeast of the city (DWASA 2006). Intensive groundwater mining from the upper Dupitila aquifer has significantly influenced the groundwater flow direction. Monitoring of the spatial and temporal distribution of groundwater levels (GWL) in Dhaka City shows a significant decrease in GWL in the central and western regions since 1980. By the end of the 1990s, the GWL depression had spread widely in the central part of the city, where a drop in GWL of -10 m to -15 m was observed (Rahman et al. 2011). In 2008, the GWL showed a wide cone especially in Zone 4 and movement of the GWL depression to the southwestern part of the city. The spatial GWL distribution indicates lateral groundwater flow from nearby zones to the central part of the city (Rahman et al. 2011). Steep piezometric gradients near the Buriganga River (in Zone 3, Zone 2 and partly Zone 1) suggest that the river acts as a hydraulic barrier for the aquifer system that inhibits groundwater mining further to the west and southwest of the city. In the eastern part of the city, groundwater extraction is comparatively low and groundwater levels vary between -12 m and -29 m PWD (minimum GWL in the center of the city was approximately -60 m). The recharge rate in this part of the city is likely controlled by vertical percolation of water from low-lying areas and wetlands that are mostly flooded by the Balu River. The biggest part of this area remains under water for over half of the year (Chowdhury et al. 1998). The 2- and 100-year river flood levels for this area are 6.25 and 7.99 m PWD, respectively (JICA 1992). The exact recharge mechanism at this area is yet to be explored.

The current amount of natural recharge is yet unknown and difficult to quantify (Burgess et al. 2011). Increased urbanization has reduced water retention areas and natural drainage paths, resulting in increased surface runoff due to reduced natural recharge (Bari and Hasan 2001; Tawhid 2004). Burgess et al. (2011) estimated that recharge through the Madhupur Clay has decreased by 20% from 1966 to 1997. Besides natural recharge, leakage from the water supply network and from the storm drainage system contributes to vertical recharge. This however, poses another problem of aquifer contamination. Hoque (2004) estimated that in Dhaka City 25-30% of recharge is due to leakage from the sewage system.

4.5.4 Present status of groundwater quality

Very few studies have been conducted to assess the temporal and spatial variation of groundwater quality in Dhaka City. Only at two monitoring wells (Motijheel and Mohammadpur), BWDB has performed long-term groundwater quality monitoring, but unfortunately the data quality is not reliable due to poor ionic balance (Ahmed et al., 1999). However, the monitoring data show that there is long-term deterioration in groundwater quality in the upper Dupitila aquifer. At the Motijheel monitoring well, chloride concentration increased from 2 mg/l in 1974 to 44 mg/l in 1988 (Ahmed et al., 1999), total dissolved solids (TDS) increased from 83 mg/l in 1973 to 160 mg/l in 1997, and nitrate increased from 0 mg/l in 1973 to 2.6 mg/l in 1997. This information indicates a general trend of contamination in the upper Dupitila aquifer. The greatest contamination of groundwater in Dhaka city is likely related to the industrial zones (at Hazaribagh, and Tejgaon) (Hassan, 1997, Saha and Ali, 2001; Zahid et al., 2006). Hassan et al. (1999) identified chloroform, perchloroethylene, p-xylene and benzene in groundwater at Tejgaon. At Hazaribagh, shallow groundwater is polluted by chromium and lead, which are used in the tannery industries at the area (Saha and Ali, 2001; Zahid et al., 2006, Shams et al., 2009).

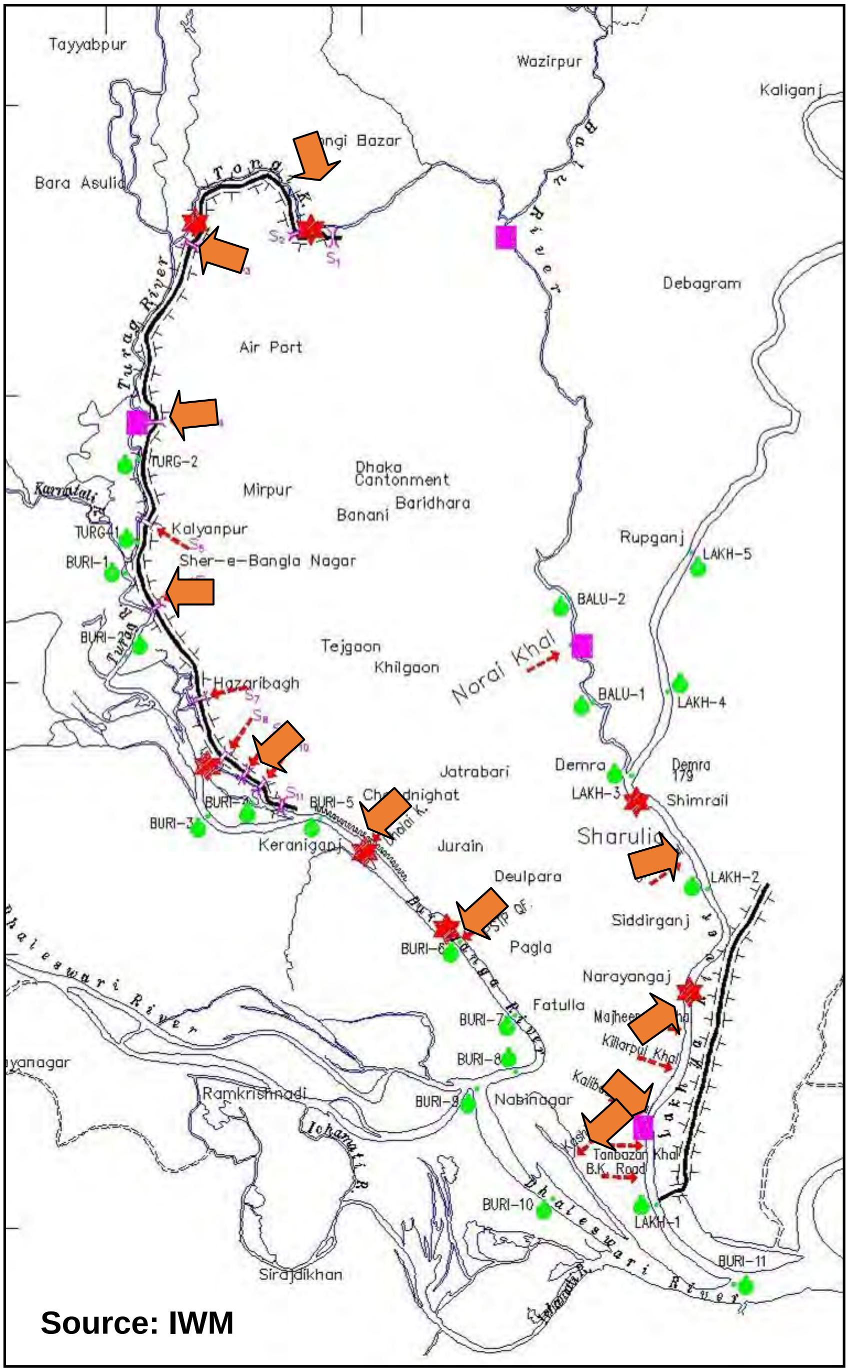
The rivers are connected to the main aquifer. Therefore, the polluted rivers possess a great threat to the aquifer pollution. Presence of considerably high quantity of Cl^-, $SO4^{-2}$, NO_3^- and EC values in the wells near the Buriganga river suggest migration of pollution from the surface water to the groundwater, stated by several researchers (e.g., Ahmed et al., 1995, Hasan et al., 1999; DWASA, 2006) and this has been later proved by mathematical modeling and isotopic analysis by Burgess et al., 2011. Very few data is available about the possible groundwater contamination from landfill sites. Pollution of shallow aquifer in a Matuail landfill site, near to Jatrabari, has been reported by Ahmed et al., (1998).

A number of fuel stations may contribute to the Non-aqueous Phase Liquid (NAPL) contamination of Dhaka City groundwater, as many of them are not properly constructed and become old. The fuels may leak from the holding tank due to improper construction and therefore, may act as a pollutant source of NAPL in the aquifer. There are more other sources of NAPL contamination in Dhaka city such as vehicle repairing workshop, chemical industries etc. (M. Shamsudduha, Holiday, November 11, 2004).

4.5.4 Present status of surface water quality

The river along the Tongi Canal, the Balu River, the Turag River, the Buriganga River, and the Dhaleshwari River (see Figure 4.9) are highly polluted by industrial waste and effluent, as reported by many researchers (e.g., Rahman and Hossain, 2007; Ahmad et al., 2010, Kamal et al., 1999). The Turag - Buriganga river system receives wastewater from Dhaka City through some canals (locally called as “Khal”) via sluice gates. Pagla waste water treatment plant discharge effluent to the Buriganga River. Additionally this river receives huge waste from a number of small industries located along the river bank (Moniruzzaman et al., 2009), and from tannery industries located at Hazaribagh (Shams et al., 2009). Similarl,yBalu-Lakhya River system is also polluted with organic and human wastes. The Balu River receives municipal waste through different khals and industrial waste from Tejgaon industrial zone. The Lakhya River receives untreated discharge of many textile and dyeing industries that are located along the bank of the river.

Analysis of available data from Department of Environment (DoE) shows that along the river reaches, the 5-day Biological Oxygen Demand (BOD_5) is extremely high. Rahman and Hossain (2007) reported Phosphate exceeds the limiting value along the entire reach of the river systems. Moniruzzaman et al., (2009) stated that water of Buriganga River has nitrate pollution. Ahmad et al., (2010) reported about Chromium (Cr) and Lead (Pb) pollution in the Buriganga River. The authors also reported high concentration of Pb in the Buriganga river sediment. Mottableb et al., 1999 detected higher hydrocarbons (C_{12}-C_{24}) in the Buriganga river water. In the rivers, the pollution level varies seasonally with higher pollution in dry season (November – March) (Moniruzzaman et al., 2009).



Source: IWM

Figure 4.10: Surface water pollution loadings from Dhaka city

4.6 Driver- Pressure-Sate-Impact- Response (DPSIR) Analysis

Considering the earlier mentioned problems of water supply and future demands, many studies have suggested the exploration of alternative resources for water supply to meet the current and future water demand of Dhaka City. The main driving forces on water and the environment in Dhaka City and potential responses were identified, using the DPSIR approach. Figure 4.11 states the main driving forces (D), pressures (P), states (S) impacts (I), and responses (R) at Dhaka City. Population increase is the main driving force to put pressure on the water resources. Human development such as industrial, agricultural and tourism immense stress on the water resources system. In general the climate is the common driving force for water resources development in any region in the world. Change in land use, climatic change, soil hazards, contamination generation etc. are the main pressure of the water resources system. These conditions change the state of groundwater, surface water, ecology, health, wastewater treatment etc. The possible impact of the change of these status is on SW and groundwater quantity and quality, loss of wetland etc. An example of causal chain would be: Due to increase in population, GW extraction is increased and it changes the status of GW. Due change is GW status, GW quantity decreased and hence the environmental degradation happens.

The figure demonstrates that the water resources development of Dhaka City is non-sustainable. Four major responses have been identified to mitigate water scarcity and to improve water supply. The implementation of MAR should consider the development of non-conventional water resources and apply state-of-the-art management and optimization techniques. An integrated response concept is required, based on IWRM.

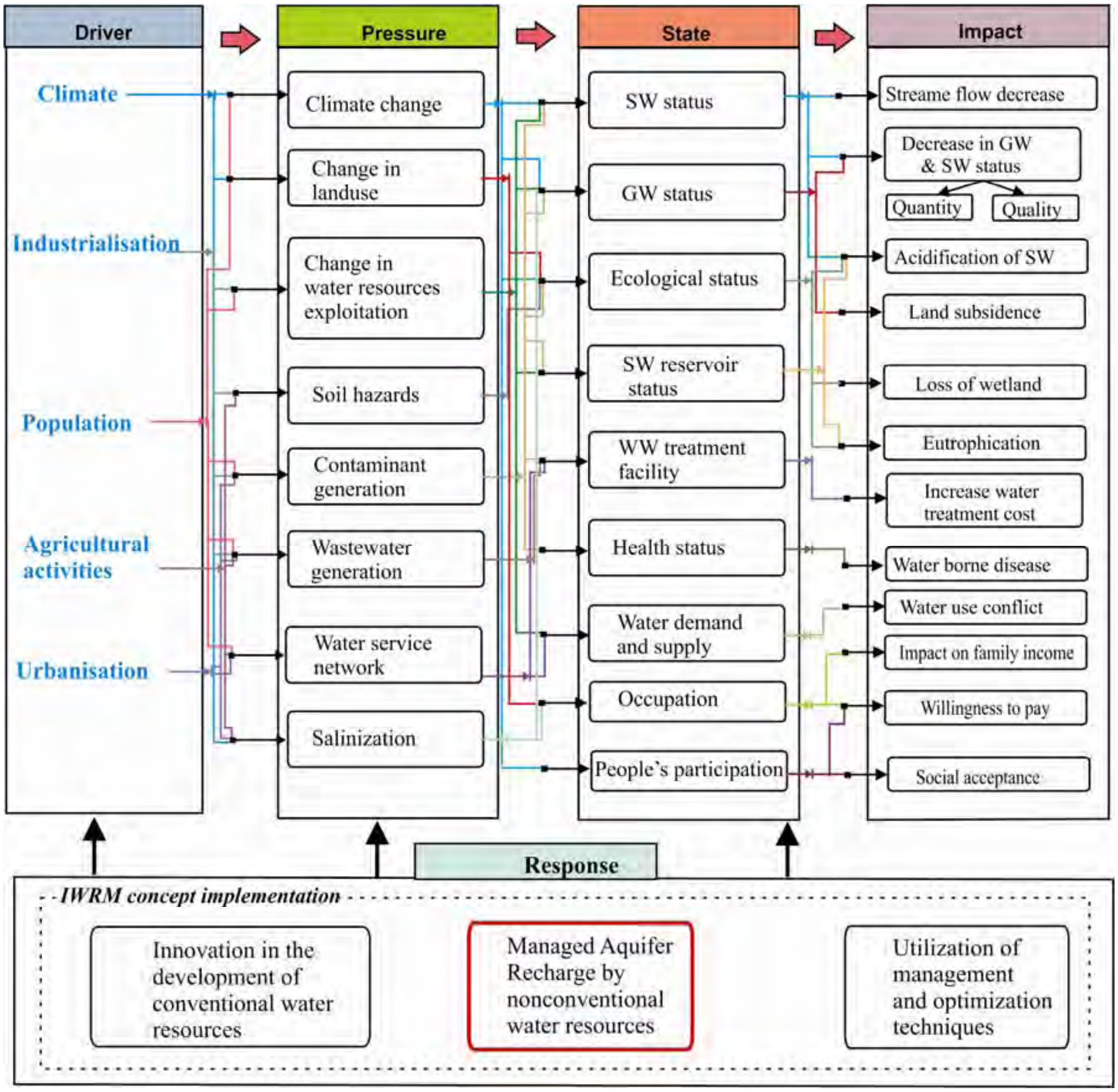


Figure 4.11: DPSIR analysis showing the causal chain of water resources problem in Dhaka city

The following main restrictions complicate the use of the available surface water sources for strengthening the water supply at Dhaka City: a) conventional treatment methods may not remediate polluted water bodies in an efficient and economical way, b) high investments are required to provide the infrastructure, c) personnel must be trained and be qualified to handle tasks in IWRM, d) and a long-term implementation process is needed. As the use of surface water for large-scale water supply is not feasible for the immediate future, MAR is the best alternative for the enhancement of water supply and groundwater resources development in Dhaka City.

4.7 Summary

The water budget situation of the city clearly indicates that Dhaka city should look for sources of water to combat the water scarcity. The water supply will deficit further in near future. In general, the results indicate that the trend of GWL lowering during the last 30 years in the city is substantial and a clarification of the picture of the most GW critical zones within the upper Dupitila aquifer is obtained. Urban dynamics, such as lateral spread of the urban area, may directly correlate to the GWL level mining phenomena over the past three decades. The spatial GWL distribution indicates lateral flow of groundwater from the nearby zones to the central part of the city that may trigger transport of pollutants from surrounding rivers, which are connected directly with the upper Dupitila aquifer, to the centre of the City. The peripheral rivers are already polluted. Hence, conventional water sources are not adequate here.

DPSIR analysis reveals that MAR could be a potential response to solve the water resources problem at the city. MAR techniques have been used in many parts of the world, such as the USA, Australia, Israel, and Germany. The water to be recharged can be clean water (storm water, imported water) as well as treated effluent. Main recharge methods are infiltration basins, bank filtration, sink-pits, canals, and injection wells, but the actual implementation of schemes varies widely from country to country (UNESCO-IHP, 2005). Specific technology depends on the type of water or effluent, on the soils and sub-surface profiles, on underground hydraulic characteristics, on the availability of land for such projects, and on the proximity of contamination sources and risk of seawater intrusion in coastal aquifers among many other factors. MAR has been widely practiced in South Asia, e.g. in India. The typical goals of using MAR in this region are: (i) to maintain and strengthen natural groundwater as an economic resource, (ii) to create short-term or long-term groundwater storage, (iii) to prevent groundwater mining, (iv) to provide treatment and storage for treated wastewater for reuse, and (v) to decrease losses due to evaporation.

Chapter 5

RESULTS AND DISCUSSIONS

5.1 General

Based on the water resources system analysis and available hydrological information, an extensive analysis to identify potential and challenges for MAR implementation in Dhaka City were performed. Based on the hydrological data, water sources (Surface water, groundwater and wastewater) for MAR implementation were performed. Based on groundwater level, lithology the aquifers of the city were identified. Finally these chapter presents the potential and challenges of MAR implementation in the city.

5.2 Water Sources Analysis - Surface Water (SW)

Surface water is considered as the main source of water to recharge due to its availability and quantity. The quality of surface water varies from place to place. In this section the results of surface water analysis are given.

5.2.1 Surface Water Quantity

The Dhaleswari-Kaliganga, Bangshi-Turag-Buriganga and Balu-Lakhya are the main river systems in and around Dhaka City. Padma and Meghna are the two major rivers close to Dhaka City. The Kaliganga river originates from the Dhaleswari and again meets with the Dhaleswari after travelling around 71 Km. These rivers contain a significant amount of water, which could be used in MAR. Figure 5.1 shows the stations where the analysis were undertaken (information source: DWASA, 2006). Table 5.1 (data source: DWASA 2006) shows the 80% and 50 % dependable flow of major rivers near Dhaka such as Buriganga, Lakhya, Kaliganga and two major big rivers of Bangladesh. The analysis reveals that at these locations the rivers has high discharge, such as the discharge of Lakhya at Narayangonj is 89.31 m^3/s. Discharge of Kaliganga river at Taraghat is comparatively low (13.4 m^3/s). The flow of Kaliganga increases to 30000-4000 m^3/s during monsoon, though it reduces significantly during dry season.

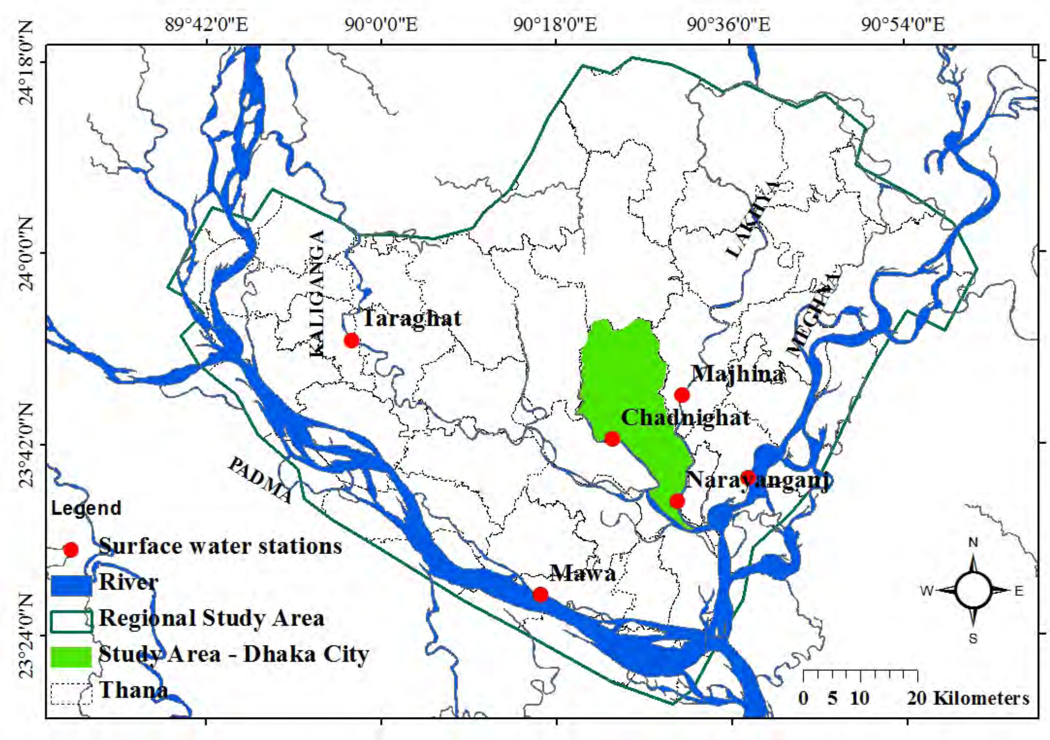


Figure 5.1: Locations of surface water resources in the rivers near Dhaka City.

Table 5.1: Water availability at different rivers around Dhaka city

River and location	80% dependable flow (m^3/s)	50% dependable flow (m^3/s)
Buriganga at Chandnighat	58.66	110.17
Lakhya at Narayanganj	89.31	151.58
Lakhya at Majhina	61.4	112.86
Kaliganga at Taraghat	13.4	13.9
Padma at Mawa	6025	-
Meghna at BaidderBazzar	187	-

Volume of tidal discharge and navigation depth at four locations are given in Table 5.2 (Data source: DWASA, 2006). Average tidal volume during dry season of Buriganga at Chadnighat is 8.08 MCM (Million-Cubic Meter). The draft at this station is 9.46 m at the lowest water level of 0.603 m (PWD). According to BIWTA specifications, the Buriganga is classified as class I for navigability (BITWA, 1988) with required Least

Available Depth (LAD) of 3.66 m -3.96 m. This means that sufficient draft is available even during the lowest tidal condition. Average tidal volume during dry season of Lakhya at Narayangonj and Majhina are 10.71 MCM and 6.36 MCM, respectively. The draft at these stations are 4.17 m and 5.9 m (900 million litre per day withdrawal scenario at Majhina) at the lowest water level of 0.52 m (PWD) and 0.805 m (PWD), respectively. According to BIWTA specifications, the Lakhya is classified as class III for navigability (BITWA, 1988) with required LAD of 1.52-1.83 m. This means that sufficient draft is available even during the lowest tidal condition.It is estimated that the change in water depth at Majhina on Lakhya River is only around 0.2 m after withdrawal of 10 m^3/s (DWASA, 2006).

Table 5.2: Tidal discharge and Navigation depth at different rivers around Dhaka city

River and location	Tidal discharge (MCM/cycle)	Navigation depth (m)
Buriganga at Chandnighat	8.08	9.46
Lakhya at Narayanganj	10.71	4.17
Lakhya at Majhina	6.36	5.9
Kaliganga at Taraghat	Non-todal	1.55

Taraghat is a non-tidal river. Estimated maximum discharge of Kaliganga is 3500 m^3/sand during dry season it becomes almost dry. Minimum water level for the Kaliganga is 1.556 m (PWD). According to BIWTA specifications, the Kaliganga is classified as class VI for navigability (BITWA, 1988) with required LAD of 1.52 m and minimum available draft is 2.78 m that is more than the required. It is estimated that the change in water depth at Majhina on Lakhya River (Figure 5.1) is only around 0.2 m after withdrawal of 10 m^3/s (DWASA, 2006).

Mathematical modelling studies by DWASA (2006) concluded that withdrawal of water from rivers for water supply purposes is possible, while keeping the local ecology intact, considering 40 % flow for ecological flow-demand in the stream.

5.2.2 Surface Water Quality

The main obstacle, however, is the quality of water from these rivers. Increasing pollution from domestic and industrial sources deteriorates water quality of these peripheral river systems (Hadiuzzaman, 2005). Since 1997, recorded coliform concentrations in the Buriganga River varied between 3,000 and 910,000 per 100 ml., in the Balu River between 8,500 and 203,000 per 100 ml, and in the Turag River between 29,000 and 80,000 per 100 ml, which is much higher compared to the Lakhya River (between 600 and 5,000 per 100 ml) (WSP, 1998; DWASA, 2004, Hadiuzzaman, 2005).

Table 5.3 shows some major water quality parameters measured by DWASA (2006) at the four location where water quantity also measured. The bold numbers indicate that this parameter exceeds the Bangladesh water quality standard value. It is clear that Biological oxygen demand (BOD) at 5 day, Chemical Oxygen Demand (COD) and Total suspended solid (TSS) are main three water quality parameters that exceeds the standard value. The other parameters are below.

High level of heavy metals have been reported by Rahman et al. (2013). Table 5.4 shows concentrations of five heavy metals: Cadmium (Ca), Chromium (Cr), Lead (Pb), Nickel(Cr), and Zinc (Zn) in five peripheral rivers of the city. With respect to drinking water standard, Shitalkhya River and Turag possess better water quality than that of other rivers. Buriganga is the worst among all the rivers in terms of water quality. Cr and Zn concentrations at all rivers are lower than that of the drinking quality standard. However, except Buriganga, all other rivers are not still polluted with heavy metals.

Table 5.3: Major water quality parameters of three important peripheral rivers

Parameter	Unit	BD drinking quality standard	Buriganga at Chadnighat	Lakhya at Narayangong	Lakhya at Majhina	Kaliganga at Taraghat
Temp	0C	20-30	29.2	28.2	30.9	29.2

pH		6.5-8.5	7.42	7.48	7.58	7.64
DO	mg/l	6	0.0	2.3	3.10	3.5
BOD	mg/l	0.2	**50.0**	**4.6**	**15.0**	**3.0**
COD	mg/l	4.0	**73.1**	**7.9**	**25.5**	**5.1**
Chloride	mg/l	150-600	92.0	24.0	-	20.0
Nitrate (NO3-N)	mg/l	10	1.0	1.7	2.7	0.30
Ammonia (NH3-N)	mg/l	0.5	0.31	0.0	0.01	0.02
TDS	mg/l	1000	623	180	315	365
TSS	mg/l	10	38	12	17	5
Sulphate	mg/l	400	29.7	23.4	-	3.8
Phosphate	mg/l	6	5.25	0.85	1.20	1.65

Source: DWASA (2006)

The Balu-Lakhya River and the Kaliganga River offer better water quality in comparison to the other rivers (Rahman and Hossain, 2008), making these more suitable for MAR. It should be considered that, during the monsoon, the river water quality improves considerably due to a dilution effect caused by surface run-off. To evaluate the actual feasibility of using surface water for MAR, detailed studies on water treatment, suitable pre-treatment technologies, and cost-benefit relationships are required.

Table 5.4: Concentration (in mg/l) of heavy metals (Pb, Cd) in peripheral rivers in 2012.

Parameter	Bangladesh drinking quality standard	Buriganga	Balu	Turag	Tongikhal	Shitalakhya

Cd	0.005	0.018	0.11	0.003	0.015	0.003
Cr	0.05	0.042	0.02	0.006	0.024	0.005
Pb	0.05	0.11	0.02	0.008	0.041	0.005
Ni	0.1	0.14	0.009	0.008	0.01	0.005
Zn	5.0	0.95	0.86	1.055	1.21	0.106

(Source: Rahman et al., 2011)

5.3 Water Sources Analysis- Rainwater

Dhaka City has an average rainfall of 2078 mm (BMD, 2013) considering historical rainfall data (Figure 5.2). Rainwater is an important source of water for MAR used elsewhere and offers advantages with respect to water quality for MAR use in Dhaka City (UNESCO-IHP, 2005). Rainwater is naturally soft (unlike well water), contains almost no dissolved minerals or salts, is virtually fee of chemical compounds, and thus requires fewer costs for treatment (Rahman and Yusuf, 2000; Rahman et al., 2003; Appelo and Postma, 2005, Islam et al., 2010).

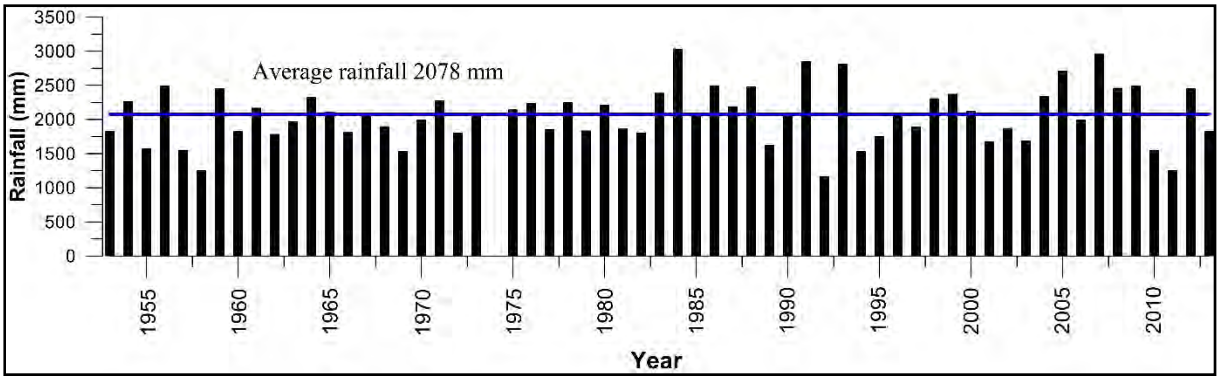


Figure 5.2: Historical (year 1953 to year 2013) time series rainfall data

Average monthly rainfall distribution (Figure 5.3), estimated from the historical data, shows that Monthly average rainfall highest in July (403 mm) and followed by June (395 mm) and August (330 mm). In general, the main rainy season in the city is from May to September. Rainwater harvesting is thus quite useful during this time of the year.

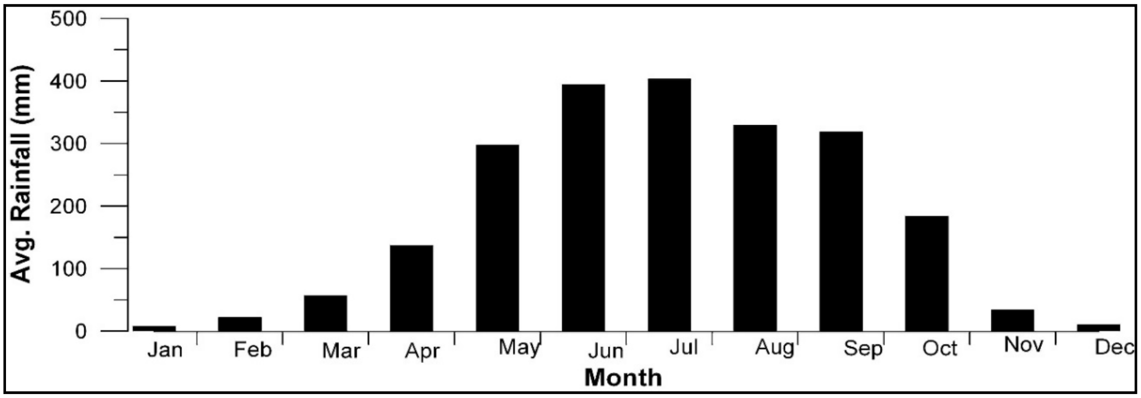


Figure 5.3: Average monthly rainfall pattern in Dhaka City

There are two potential approaches to implement MAR using rainwater in Dhaka City. The approaches are: (a) Collection of Storm water run-off, (b) Roof top Rainwater harvesting combined with MAR

5.3.1 Storm Water run-off

The open spaces such as park, playground, gardens and fellow lands can be used as catchments for collection of rainwater as runoff. According to Sultana (2009), Dhaka city has 24.39 km^2 open spaces and they can be utilised after proper management plan.

The following formula (Kuichling, 1889) can be used to estimate peak discharge and surface run off:

$$Q_p = C_f \times C \times I \times A \tag{5.1}$$

Where, $Q_p$is the maximum rate of run-off (m^3/s), C is the runoff coefficient representing a ratio of runoff to rainfall, I is the intensity (mm/h) of rainfall having a duration equal to the time of concentration (t_c), A is the drainage area (km^2), C_f is a unit conversion factor (1.008 for English units: ft/s, in/h and acres; and 0.278 for SI units: of m^3/s, mm/h, and km^2). The formula assumes that the rainfall intensity for any given duration is uniform over the entire catchment. The values of C and I were considered as 0.2 and 3.25, respectively (Bari and Hasan, 2001). Open spaces (unpaved area) available for rainwater collection in the city have an extent of 24.39 km^2 (data obtained from Sultana 2009). Using the equation 1(condition 1), estimated peak discharge from open spaces in Dhaka City is 4.4 m^3/s (Table 5.5). For urban area, C value is higher (0.5 to 0.6, 0.55 has been taken), so the peak discharge is even higher. The estimated value for condition 2 is 12.10 m^3/s. But, one should not consider the value as the volume for RWH system. This peak discharge is considered for the design of MAR facility so that the system can operate with maximum discharge capacity or can be designed in a way that the peak discharge does not cause over flooding of retention basin, if some are installed. However, Table 5.6 gives the volume of water that can be collected from total open spaces and from some individual open spaces.

Table 5.5: Peak discharge estimation for MAR facility design

	C_f	**C**	**I**	**A**	**Qp**
Condition-1	0.278	0.2	3.25	24.39	4.4
Condition-2	0.278	0.55	3.25	24.39	12,1

Table 5.6: Volume of water that can be collected from open spaces

Open Space	**Coefficient (C)**	**Average rainfall**	**Area**	**Volume**
		m	**Km^2**	**Mm^3**
Ramna Park	0.2	2.078	0.27	0.11
OsmaniUddan	0.2	2.078	0.13	0.05
ChnadrimaUddan	0.2	2.078	0.28	0.12
Botanical garden and zoo	0.2	2.078	1.63	0.68
Shisu Park &SohrawardiUddan	0.2	2.078	0.59	0.24
Lalbagh Fort	0.2	2.078	0.05	0.02
Mirpur Stadium	0.2	2.078	0.04	0.02
Dhaka Stadium	0.2	2.078	0.03	0.01

Old Airport	0.2	2.078	1.79	0.74
Air Port	0.2	2.078	1.19	0.50
Bhasani Stadium BangaBhaban	0.2 0.2	2.078 2.078	0.02 0.16	0.01 0.07
Total Open spaces including the above mentioned	**0.2**	**2.078**	**24.74**	**10.28**

(Source: Sharmin, 2009)

Considering only the open spaces, only 28 ML/d (million litres per day) (considering 75% efficiency in runoff collection) would be available in a year for MAR. This way, 1 % of the total daily demand estimated for the year 2015 (the total water demand is 2800 ML/d, according to ADB, 2007) could be recharged and stored in the aquifer of Dhaka City.

Considering unpaved area (including roofs) is about 65% of Dhaka city (GOOD, 2011) as shown in Table 5.8, it is possible to harvest 299 Mm^3 in a year indicating,.i.e. 820Mlpd which is about 29% of today's demand (the total water demand is 2800 ML/d, according to ADB, 2007).

Table 5.7: Volume of water that can be harvested from the paved area.

	Coefficient (C)	**Average rainfall(I)**	**Area(A)**	**Volume**
		m	**Km^2**	**Mm^3**
Paved	0.6	2.078	240	299

5.3.2 Roof top rainwater harvesting combined with MAR

Secondly, MAR of rainwater can also be implemented with conventional rooftop rainwater harvesting systems. Rooftop rainwater harvesting is a common practice of water conservation nowadays in different parts of the world, including Bangladesh (Rahman and Yusuf, 2000). Generally, in urban areas, the rainwater is captured from roof catchments and stored in a small reservoir. After filling the reservoir, excess rainwater is to be drained out. The excess water can be stored in the subsurface. Table 5.6 and Table 5.7 show two different estimations of monthly rainwater volume, which can be harvested in Dhaka City, based on two different approaches, using total DWASA water supply connections and the total number of concrete houses available for rainwater collection.

Considering the total number of water supply connections in Dhaka City (Table 5.8), and if 75% of the average rainfall is harvested(according to UNEP, 1998), the total annual volume would be 125 Mm^3 (125,000 million L yr^{-1}) of water. Excess water can be stored especially from May to September. Maximum water can be harvested in June and July (ca. 30 Mm^3). Average water harvest volume is ca. 14 Mm^3 and November to March the harvested volume is below the average. These months need supply from the harvested water done in other months.

Table 5.8: Rainwater harvesting using the roofs of the DWASA water supply connections

City area	Month	Avg. rainfall	Total rainfall	Total DWASA water supply connection **	Each roof area*	Total roof area	Monthly total runoff volume
Km^2		mm	$M\ m^3$		m^2	Km^2	$M\ m^3$
370	January	7.73	2.9	327136	232.34	76.0	0.59
370	February	22.1	8.2	327136	232.34	76.0	1.68
370	March	57.4	21.2	327136	232.34	76.0	4.36
370	April	137.35	50.8	327136	232.34	76.0	10.44
370	May	297.7	110.1	327136	232.34	76.0	22.63
370	June	394.8	146.1	327136	232.34	76.0	30.01
370	July	403.4	149.3	327136	232.34	76.0	30.66
370	August	329.6	122.0	327136	232.34	76.0	25.05

370	September	318.9	118.0	327136	232.34	76.0	24.24
370	October	184.8	68.4	327136	232.34	76.0	14.05
370	November	34.6	12.8	327136	232.34	76.0	2.63
370	December	10.5	3.9	327136	232.34	76.0	0.80
	Total						167.13

*Source: DWASA.2001; ** DWASA, 2014

Table 5.9: Rainwater harvesting using the roofs of available houses

City area	Month	Avg. rainfall	Total rainfall	No of Household **	Each roof area*	Total roof area	Monthly total runoff volume
Km^2		mm	M m^3		m^2	Km^2	M m^3
370	January	7.73	2.9	678300	110	74.6	0.58
370	February	22.1	8.2	678300	110	74.6	1.65
370	March	57.4	21.2	678300	110	74.6	4.28
370	April	137.35	50.8	678300	110	74.6	10.25
370	May	297.7	110.1	678300	110	74.6	22.21
370	June	394.8	146.1	678300	110	74.6	29.46
370	July	403.4	149.3	678300	110	74.6	30.10
370	August	329.6	122.0	678300	110	74.6	24.59
370	September	318.9	118.0	678300	110	74.6	23.79
370	October	184.8	68.4	678300	110	74.6	13.79
370	November	34.6	12.8	678300	110	74.6	2.58

370	December	10.5	3.9	678300	110	74.6	0.78
	Total						164.06

*Source: BBS, 2006

Another estimation (Table 5.9), considering the total number of concrete houses available for rainwater collection, shows that the amount of harvested rainwater is 164 Mm^3 and if the collection efficiency is 75%, than annually 123 Mm^3 water will be available for use. Table 5.10 indicates that excess water can be stored especially from May to September. Maximum water can be harvested in June and July (ca. 30 Mm^3). Average water harvest volume is ca. 13.66 Mm^3 and November to April the harvested volume is below the average. These months need supply from the harvested water done in other months.

Both estimations together suggest that ca. 450 MLpd (0.45Mm^3 per day) can be stored for further usage, which is 23% of today's total daily demand. DWASA (2006) estimated that the groundwater-mining rate of the upper Dupitila aquifer is 96.55 Mm^3yr^{-1}. If the amount of harvested water is used for MAR, groundwater mining could be negated in the aquifer. It can be suggested that 50 % of the harvested water could be supplied instantaneously after primary treatment to the users, and the rest can be used for groundwater augmentation. In that way, some portion of the daily demand can be met immediately in addition to creating a groundwater level rise. If 47.5 Mm^3 (50% of the harvested water) can be recharged, the groundwater level will increase by about 1.5 m yr^{-1} (considering an average specific yield of $S_y = 0.1$ and a city area of 302.58 km^2), considering the existing trend of water level decline.

Figure 5.4 shows the amount of harvested water under different sizes of service area (roof area). From the figure, it can be stated that 90% of the service area (225 km^2) should be taken under RWH system to meet the water supply deficit in 2015. To meet for further future demand, e.g., in 2020, RWHS using roofs might not fulfill the deficit, which will be more challenging for the water company and the municipality.

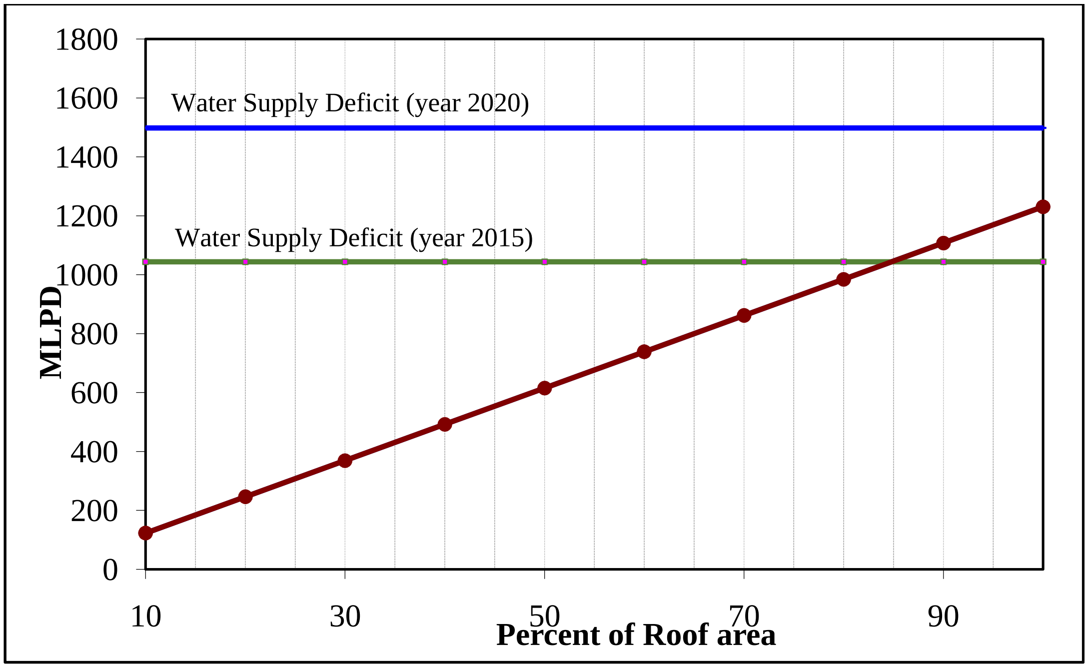


Figure 5.4: Activation of roof area for rainwater harvest in considers 100% of build-up area is service area for RWH.

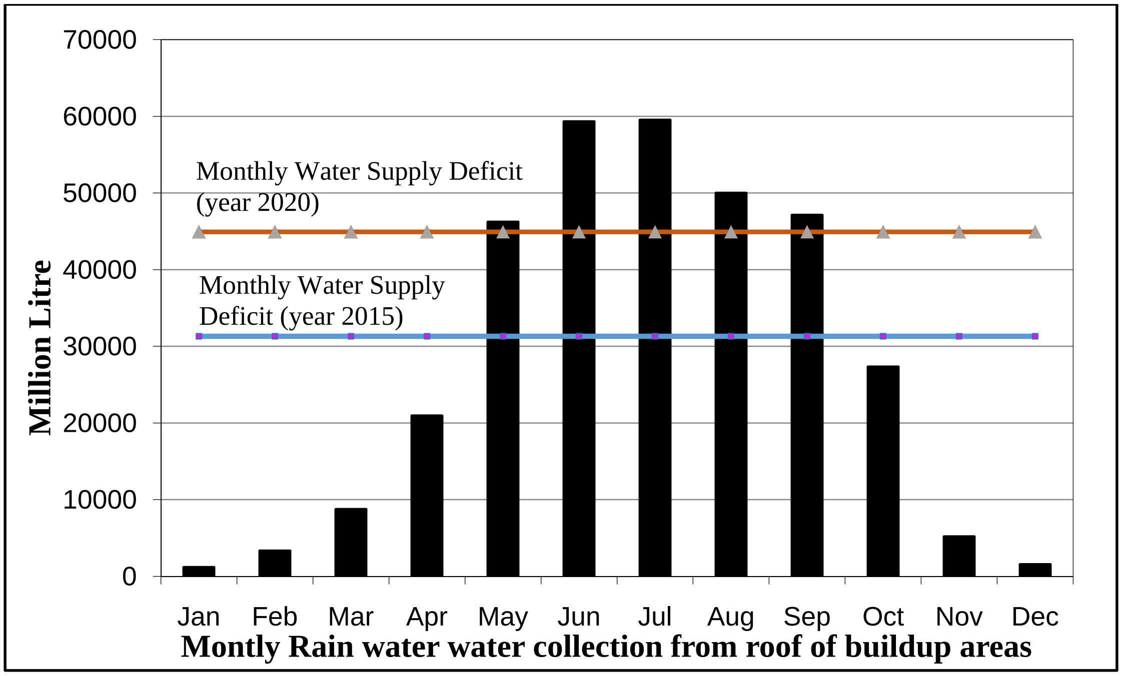


Figure 5.5: Monthly water deficit and yearly available rainfall distribution show the opportunity of rainwater storage in water scarce months.

From Figure 5.5, it is clear that during May to October excess rainwater is available, if they can be properly saved, they can be used during dry season (November to December).

Table 5.10: Rainwater Quality (sampled in September 2012)

Sample no.	**Temp**	**pH**	**EC**	**DO**	**F$^-$**	**Cl$^-$**	**SO$_4^{2-}$**	**NO$_3^-$**	**Na$^+$**	**NH$_4^+$**	**K$^+$**	**Mg^{2+}**	**Ca^{2+}**
	^{0}C		µs/cm	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Sample 1	27.3	6.5	92	4.31	n.a.	0.73	1.35	n.a.	0.41	n.a.	0.41	0.25	3.2
Sample 2	26.8	5.03	67	4.62	<0,05	0.95	5.20	3.42	0.36	2.46	0.36	0.24	2.5
BD Std	30	7	n.a.	6	1	150	400	10	200	0.2	12	35	75

n.a. = not available at the water sample

Table 5.10 shows rainwater quality of the two collected samples at Dhaka City. One sample was taken at Jatrabari (sample 1) and the other one at Juraine (sample 2), near Buriganga River. No major contamination has been observed in the rainwater which is good for further use, i.e., less pre-treatment is required. Sultana (2009) examined rainwater quality and also reported that the water is good for harvesting, especially for MAR. The author reported that (pH within the range of6.4 to 7.2, EC 89 to118µs/cm and DO 4.8 to 7.9 mg/l).

5.4 Water Sources Analysis - Wastewater

Nowadays, a number of countries are using treated effluent for reuse through artificial groundwater recharge techniques (e.g., Dan region of Shafdan, Israel). In arid and semi-arid region where surface runoff is negligible, wastewaters from different sectors are being considered for reuse via MAR (Missimer et al. 2014). In addition to water supply improvement, wastewater reuse improves the environmental situation by protecting groundwater and surface water from contamination.

In Dhaka City, treated wastewater can be a suitable source of water as the volume of wastewater is high. DWASA manages three types of wastewater: storm water, as well as domestic and industrial wastewater. The domestic and industrial wastewaters are collected by a sewer system and are discharged into the rivers except for the treatment facility at Pagla, Narayanganj. Presently the only one WWTP with a capacity of 0.12

million m^3/d is in function, treating approximately 30% of the total wastewater production (Amin et al., 1998). This WWTP consists of primary sedimentation tank and facilitative Lagoon to treat sewage water and discharges the treated water into the River Buriganga and contributes to the pollution of the river water. Greywater, generated from wash basins, sinks, baths, showers or wash machines, is a major fraction of domestic wastewater (ca. 75%) (Eriksson et al. 2012). The grey water produced in multi-storied buildings, community residence and single house hold can contribute a huge volume to recycle and reuse via MAR. The average water consumption in Dhaka city is about 250 lpcd (litres per capita per day) and out of it around 188 lpcd can be reused after proper treatment. Kitchen water are high in suspended solids, fats, oil and grease indicating high organic carbon at the water. So, kitchen water need more treatment before reuse than other grey water. The rest of the grey water also required proper, but not extensive pre-treatment before reuse. The treatment of these waters is comparatively cheaper than centralised wastewater and can reduce huge pressure of the combined sewer system of Dhaka City. According to a survey reported by DoE and LGED (2010), it is clear that organic pollutant is predominant in wastewater of the city. Total BOD loading in the industrial wastewater is much higher than that in domestic wastewater.

Table 5.11 shows water quality of grey water in Dhaka City. Abedin and Rakib (2013) collected grey water of five categories: cloth washing, dish washing, floor washing, handwashing and bathing from Dhaka city. Kitchen water was found to be the most polluted, exceeding the standard water quality limit (BD std) of Bangladesh.Kitchen wastes are rich in suspended solids, fats, oils, and grease, and their generally high organic content encourages the growth of bacteria. In all type of water COD, color, BOD_5, TSS and FC exceeds the limit indicating careful pretreatment before any reuse.

Table 5.11: Water quality of domestic grey water in Dhaka City

Parameter	Unit	BD std	Floor Wash	Cloth Wash	Kitchen Wash	Bath Wash	Basin Water
pH		6.5-8.5	6.71	7.4	5.8	6.28	6.5
Color	Pt-Co	15	262	311	517	477	407
Turbidity	NTU	10	340	396	320	89	82

COD	mg/l	4	889	1254	1847	690	972
BOD_5	mg/l	0.2	379	74	587	367	334
TDS	mg/l	1000	630	1120	651	445	118
TSS	mg/l	10	673	1203	1858	79	58
FC	CFU/100 ml	0	42500	1400	22600	733	433

(Source: Abedin and Rakib, 2013)

The treatment process in the Pagla WWTP is basically a low cost treatment option consisting of a grit chamber, primary sedimentation tank, facultative lagoon, chlorination chamber, and sludge lagoon (Amin et al., 1998, Figure 5.6). The treated wastewater is released to the river Buriganga (Haq, 2006). According to Amin et al. (1998), the final effluent of the WWTP exceeds the allowable limits of environmental quality standards for discharge into surface water bodies. In order to use treated wastewater for MAR, further treatment of the effluent is required before recharge. In this case the costs of treatment also play an important role. A number of small and large industries are located in Dhaka City. A review of the monitoring results performed by the Development Planning & Management (DPM) (DPM, 2006) shows that only 12% of the industries comply with the Environmental Quality Standard (EQS) of 5-day Biochemical Oxygen Demand (BOD_5) of 50 mg/l in the effluent. In addition, total concentrations of dissolved solids and total suspended solids are elevated. Consequently, the poorly treated wastewater from the industry will make the implementation of wastewater reuse complicated and costly in Dhaka City.

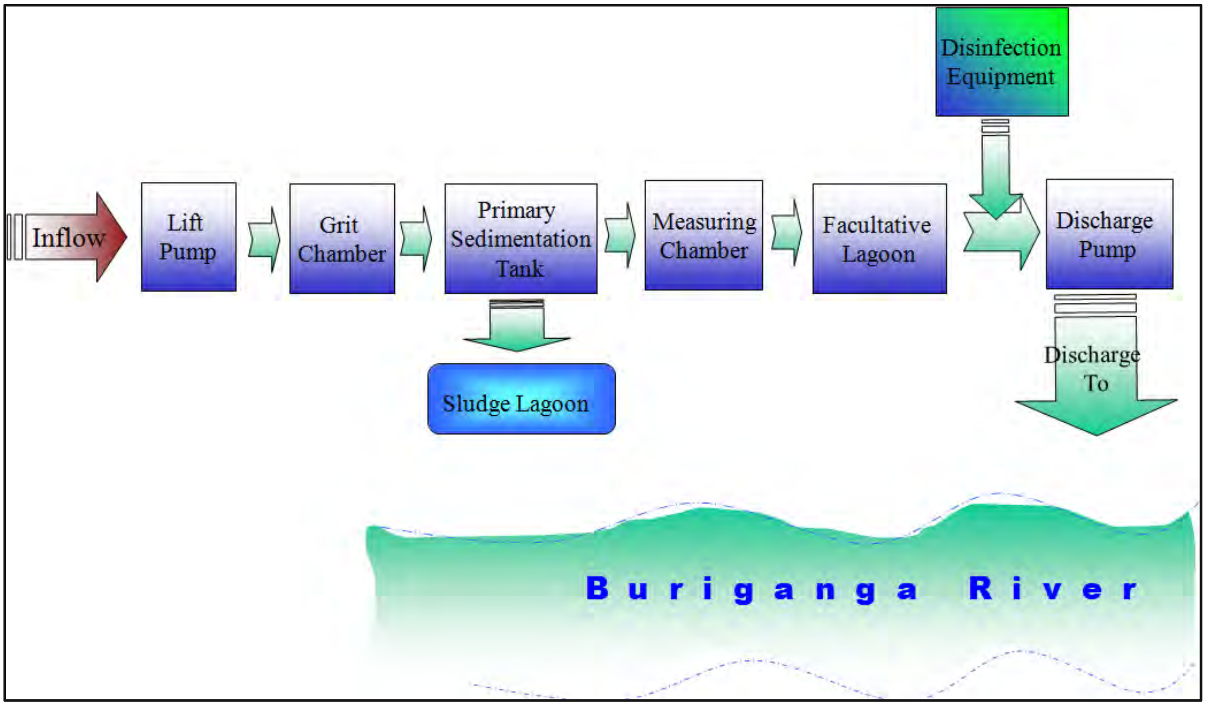


Figure 5.6: Steps of waste water treament process in Pagla treatment plant

5.5 Hydrogeological Analysis

To implement MAR projects, the availability of aquifer storage and existence of suitable sites for the related MAR structures are two principal requirements. Several criteria should be considered in order to identify the most suitable places for MAR implementation, and therefore hydrogeological analysis is quite important. After a careful pre-feasibility analysis, the relation of the local and regional hydro(geo)logy with the MAR concept can be established. The detailed hydrogeological analysis of Dhaka City and its surrounding area is given in the following sections.

5.5.1 Chronology of Events- Groundwater Depletion

In order to understand the trend of GWL mining in Dhaka City, the spatial distribution of groundwater levels were generated for every 2 years between year 1980 and 2005. GWL surfaces of the years 1980, 1990, 2000, and 2012 are shown in Figure 5.7 to Figure 5.10. The spatial distribution of groundwater level data shows that in the year 1980, the overall GWL of Dhaka City was relatively high. In about 90% of the places in Dhaka city, the GWL was in the range between -2 m and +7 m relative to the PWD (Public Works

Datum). In almost the entire area of Zone 03 and some parts of Zone 04, 05 and 06, the GWL was comparatively lower, ranging between -9 m and -3 m below PWD (Figure 5.7). In general, by December 1980, the GWL of the central and western part of the city is relatively lower compared to other parts of the city. At the end of 1990 (Figure 5.8), the GWL depression spread widely, centering the central part of the city (ranges between -10 m to -15 m). The GWL status at the end of year 2000 (Figure 5.9) shows that the trend of GWL lowering continued in Zone 05, 06 and some parts of Zone 03 and 04. The cone of depression is seen at the central part of the city, as of the year 1990. The 2012 GWL surface (Figure 5.10) indicates a wider cone of depression especially in Zone 04 and the sharp GWL depression is moved to the southwestern part from the central part of the city.

Figure 5.11 to Figure 5.13 shows the GWL mining situation in Dhaka City during three time periods, such as between the years 1980 and 1990 (Figure 5.11), between the years 1990 and 2000 (Figure 5.12), and between the years 2000 and 2012 (Figure 5.13). From Figure 5.11, it is clear that during the years 1980 to 1990, the average GWL drop is 12 m. This is due to the construction of DWASA production wells. During the period of 1980 to1990, 34 production wells had been constructed in the city. About 85% of the wells were concentrated in the central part of the city and therefore the enormous abstraction caused GWL lowering below the central part of the city. During the years 1990 to 2000, another 193 production wells were constructed in the City. This amount is 6 times higher compared to the period between 1980 and 1990. The need of fresh water for a growing population had triggered in increase in new production wells in the city at that time. The effect of high abstraction during this time period is shown in Figure 5.12. This figure shows that the GWL mining area, in other words, the ‘critical area’, was moved to Zone 05 and 06 during the years 1990 to 2000. The GWL decreasing part of the aquifer moved to the north part of the city. During these 10 years, average GWL level drop in Zone 06 and 05 was 31 m which is about 2.5 times greater than that of during the period of 1980-1990. Figure 4.10c shows that only by 12 years from 2000 to 2012, groundwater level had declined about 46 m below the PWD in zone 04.

Figure 5.7: Spatial distribution of groundwater level at the end of year 1980

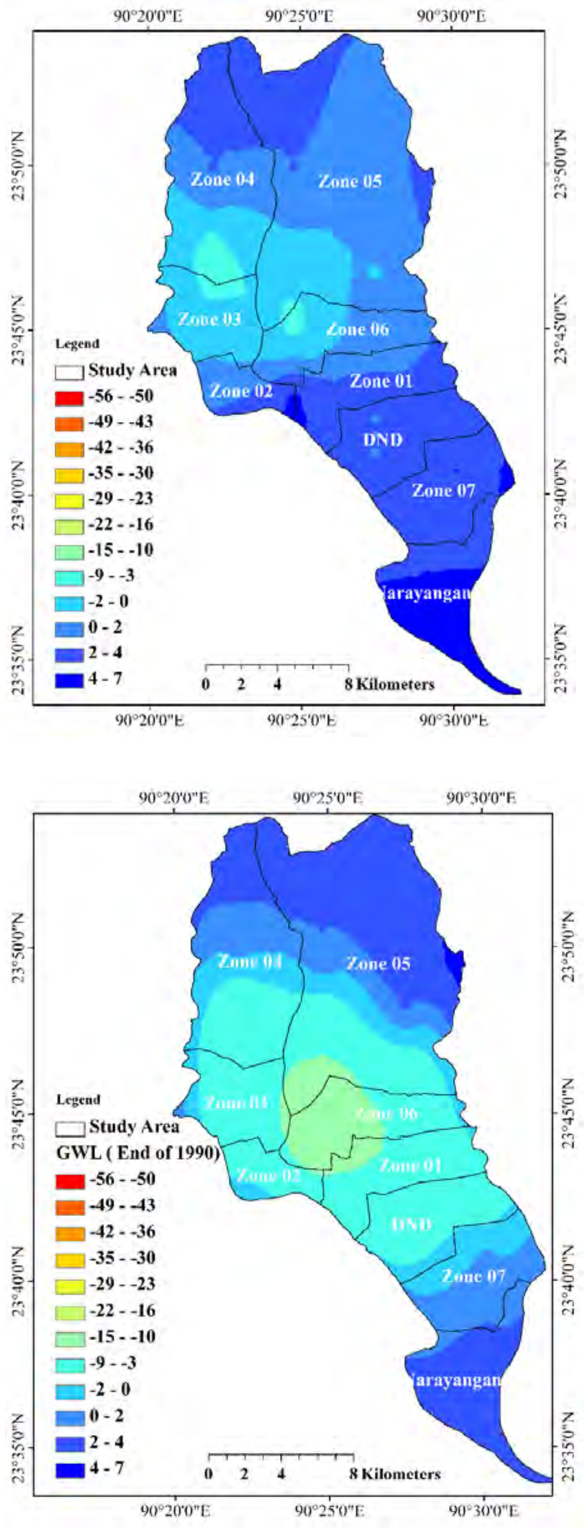


Figure 5.8: Spatial distribution of groundwater level at the end of year 1990

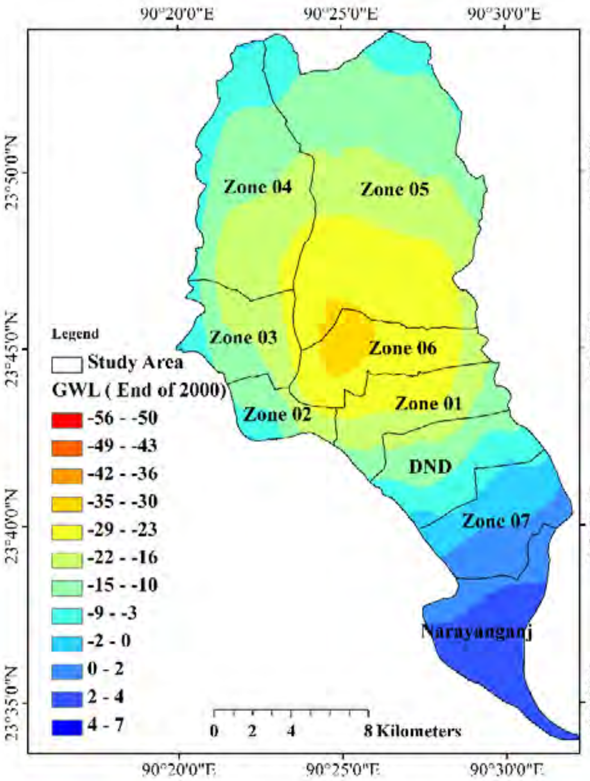


Figure 5.9: Spatial distribution of groundwater level at the end of year 2000

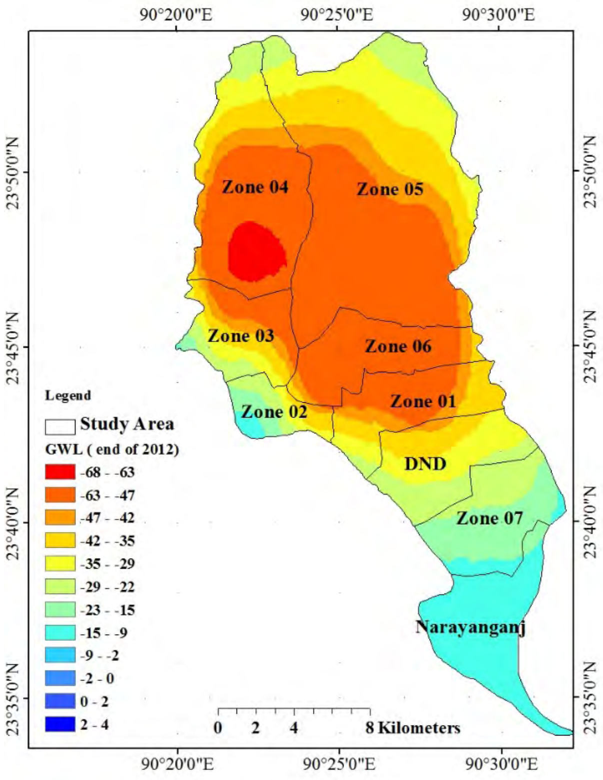


Figure5.10: Spatial distribution of groundwater level at the end of year 2012

The rate of groundwater level decline is 4.0 m per year over this time span at this zone, which shows that the rate of GWL mining is increasing at an alarming rate.This results also in agreement with the extending number of DTWs during this time at this zone. In general, the results indicate that the trend of GWL lowering during the last 30 years in the city is substantial and a clarification of the picture of the most GW critical zones within the upper Dupitila aquifer is obtained. The results clearly show the effect of pumping on the aquifer, which is GWL lowering. Urban dynamics, such as lateral spread of the urban area, may directly correlate to the GWL level mining phenomena over the past three decades.

This is to note that number of available groundwater observation data is very less in compared to the extent of the area and there are no data available at the eastern part and south-eastern part (Narayangonj) of the city. The values indicated in the spatial maps (Figure 5.7 to Figure 5.13) are generated by interpolation (kriging method) using some data outside of the city. Hence, real data of these area may change the GWL situation of these part.

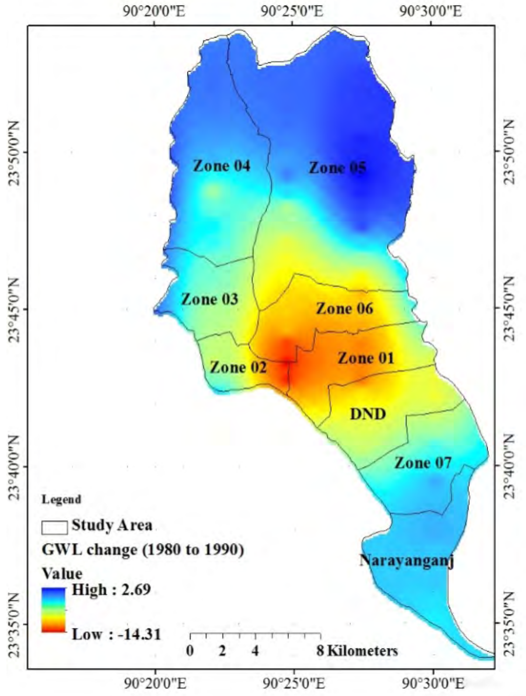


Figure 5.11:Groundwater level drop (a) from year 1980 to 1990

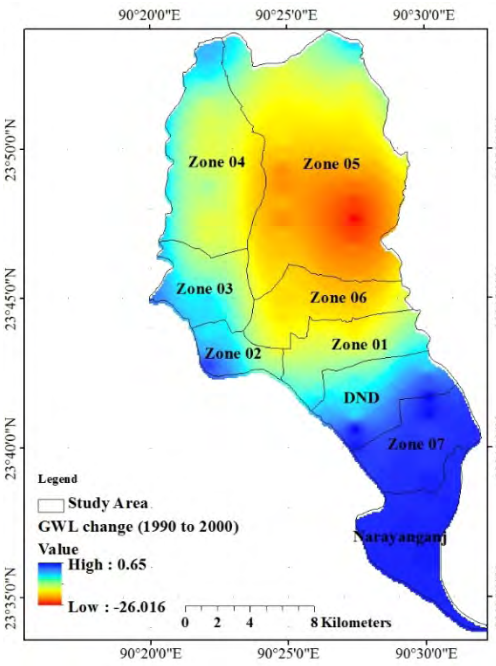


Figure 5.12:Groundwater level drop (a) from year 1990 to 2000

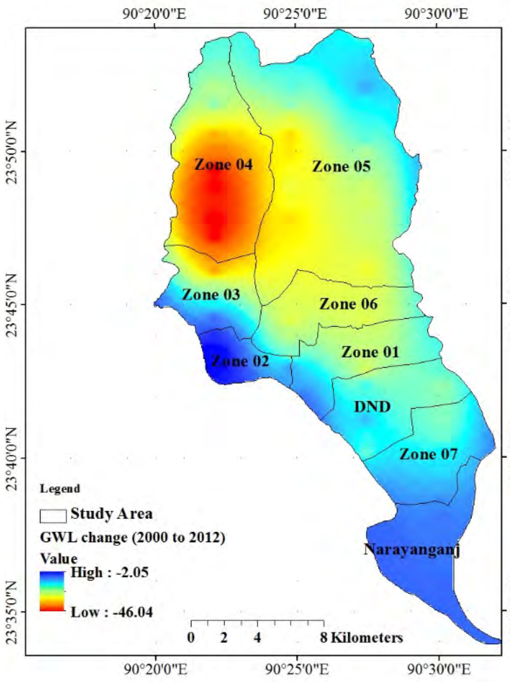


Figure 5.13: Groundwater level drop year 2000 to 2012

5.5.2 Hydrogeological condition

The geology of the study area is characterized by Quaternary alluvial sequences, which commonly show favorable aquifer properties. The study area spans the southern half of the Madhupur tract, which is surrounded by the flood plains of Jamuna, Ganges and Meghna Rivers (DWASA, 2006). The general stratigraphy and hydrogeological characteristic of Dhaka City is given in Chapter 4.

This study performs lithology analysis. Based on the lithology information aquifer layering were done. Based on the layer information 3-D block diagram prepared. Four cross sections are also prepared using lithological information (Figure 5.14).

The study area is characterized by a 400-500 m thick unconsolidated sequence of fluvio-deltaic sediments, which is overlain by the Modhupur and/or flood plain clay materials (5 m to 25 m thick) (Hoque, 2004; Hoque et al., 2007). Geological cross-sections were drawn and analysed to determine the lateral and vertical extent of the subsurface layers, particularly of the aquifers in the study area. The subsurface lithologies reveal that aquifer and aquitard layers don’t have similar gradients as the surface topography, and the aquifers are separated by an aquitard/aquiclude.

From the analysis of several lithologies and cross-sections (DWASA 2006), the subsurface geology (within 300 m of depth) of Dhaka city can be generally subdivided into nine units except top soil (Figure 5.15). The first clay layer is called “Aquitard -1”. Then second layer “Upper Dupitila Aquifer-1” that is primarily consists of fine and medium sand. “Aquitard- 2” flows the second layer containing clay and silty clay. The fourth layer is “Upper Dupitila Aquifer-2” which comprises of fine sand, medium sand and coarse sand. “Aquitard -3”, comprises of clay, separate upper Dupitila aquifer and lower Dupitila aquifer. . “Aquitard -4”, thickest aquitard makes the lower aquifer into two aquifer parts. Both lower Dupitila aquifer primarily consist of medium to coarse sand. Finally, at the lowest depth, “Aquitard- 5” exists.

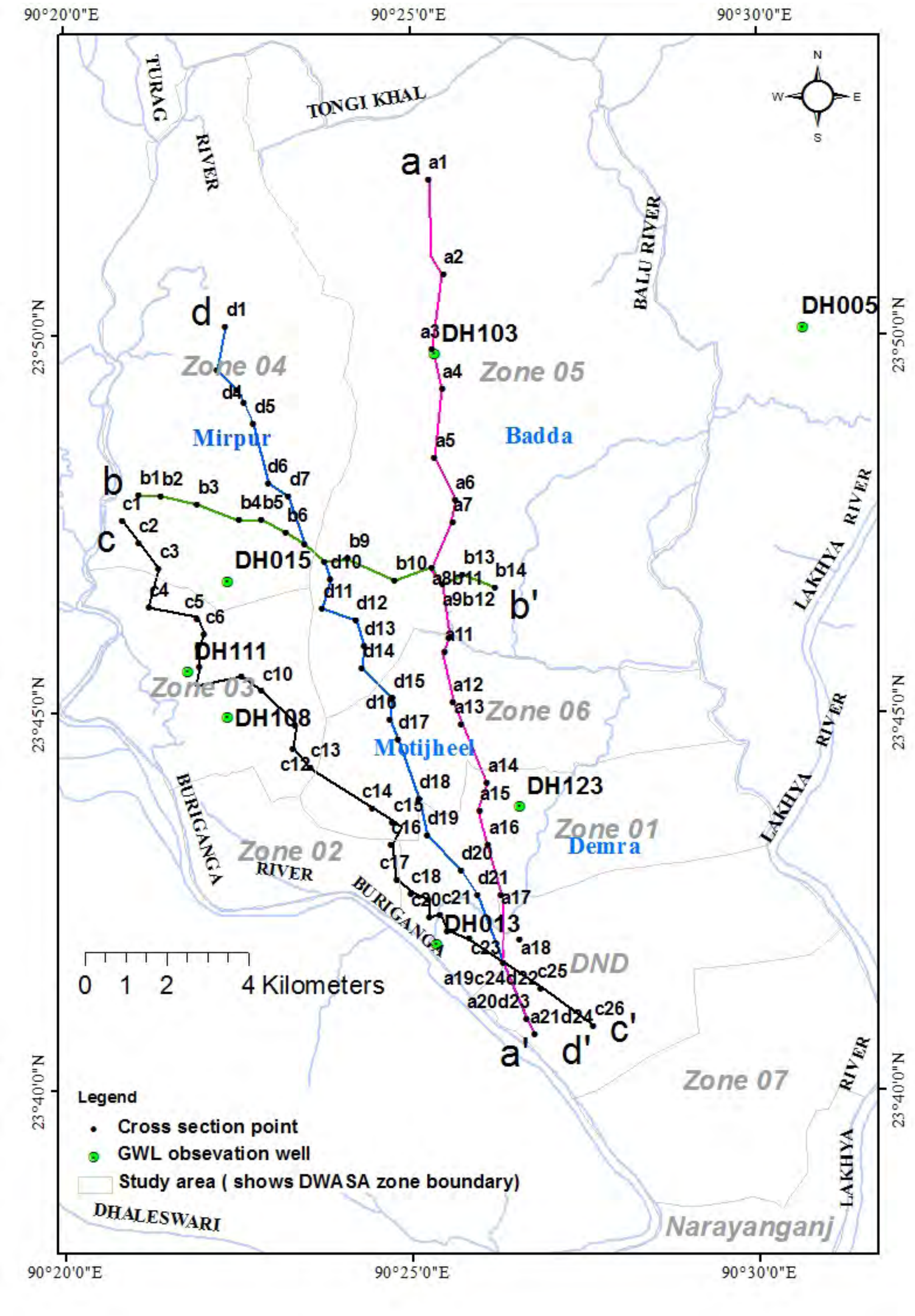


Figure 5.14: Map showing cross section and position of groundwater level

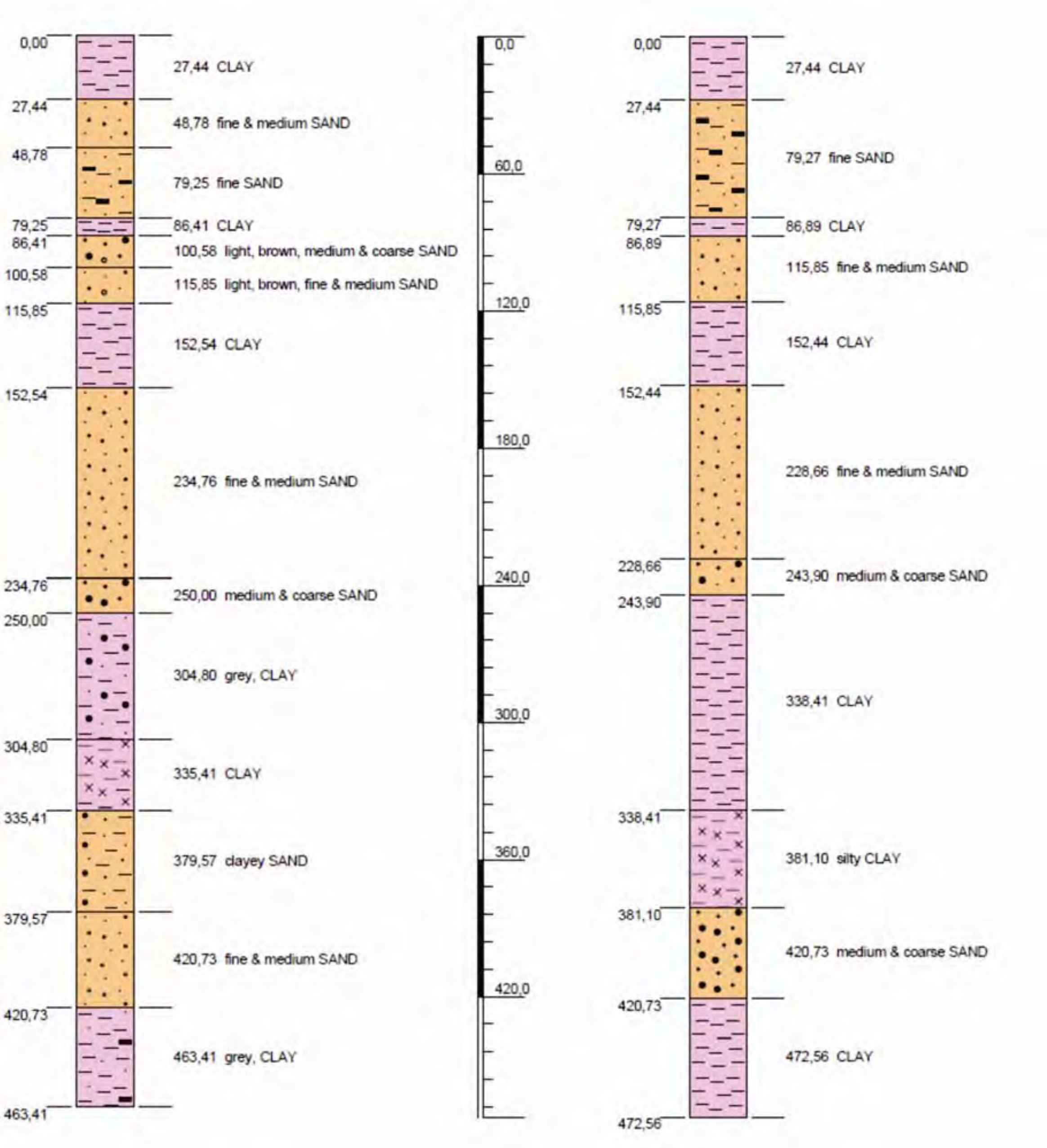


Table 5.15: Description of two typical deep lithology at Gulshan (left) and Lalbagh (right).

Table 5.12 gives an overview of the thickness of the nine layers identified. Lithologs (Figure 5.15, Table 5.11) and 3D block diagrams (Figure 5.16 and Figure 5.17) reveal that the top most clay layer, just below the topsoil, ranges between 8 and 52 m in most places. It seems that Zone 3 has the lowest average thickness of the upper aquitard, whereas Zone 6 possesses the maximum thickness. Below the top aquitard, the upper

Dupitila aquifer-1 is composed of medium-grained sand with admixture of occasional coarse and fine-grained sand. Below this aquifer a low permeable silty-clay layer (aquitard-2) exists. The upper Dupitila aquifer-2 seems to be the thickest aquifer. It is mainly composed of medium to coarse-grained sand with occasional presence of gravel.

Table 5.12: Zone-wise average thickness of different hydrogeological layers in Dhaka

Hydrogeological layer	Layer average thickness (meter)						
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	N.ganj
Aquitard - 1	20.43	16.55	13.23	17.39	20.63	26.37	20.60
Upper Dupitila Aquifer -1	33.89	47.51	48.71	40.73	39.09	35.30	24.70
Aquitard - 2	13.03	6.41	13.19	9.36	9.14	10.15	35.13
Upper Dupitila Aquifer -2	89.27	77.15	53.92	56.45	83.09	85.86	10.99
Aquitard - 3	11.43	21.64	29.08	24.64	14.20	24.83	43.67
Lower Dupitila Aquifer -1	38.54	33.53		56.48	18.29	32.01	46.20
Aquitard - 4	24.01	15.2		12.59		15.55	13.22
Lower Dupitila Aquifer -2	100.61			83.52		57.92	83.82
Aquitard -5	11.21			6.53		12.20	10.25

Aquifer-3 is mainly composed of silty clay. The third aquifer (lower Dupitila aquifer-1) is composed of medium to coarse-grained sand, making it an excellent aquifer with a high hydraulic conductivity and a high storage coefficient. The lower Dupitila aquifer-2 is separated from the above aquifer by an aquitard (aquitard-4), which has an average thickness of 16 m.

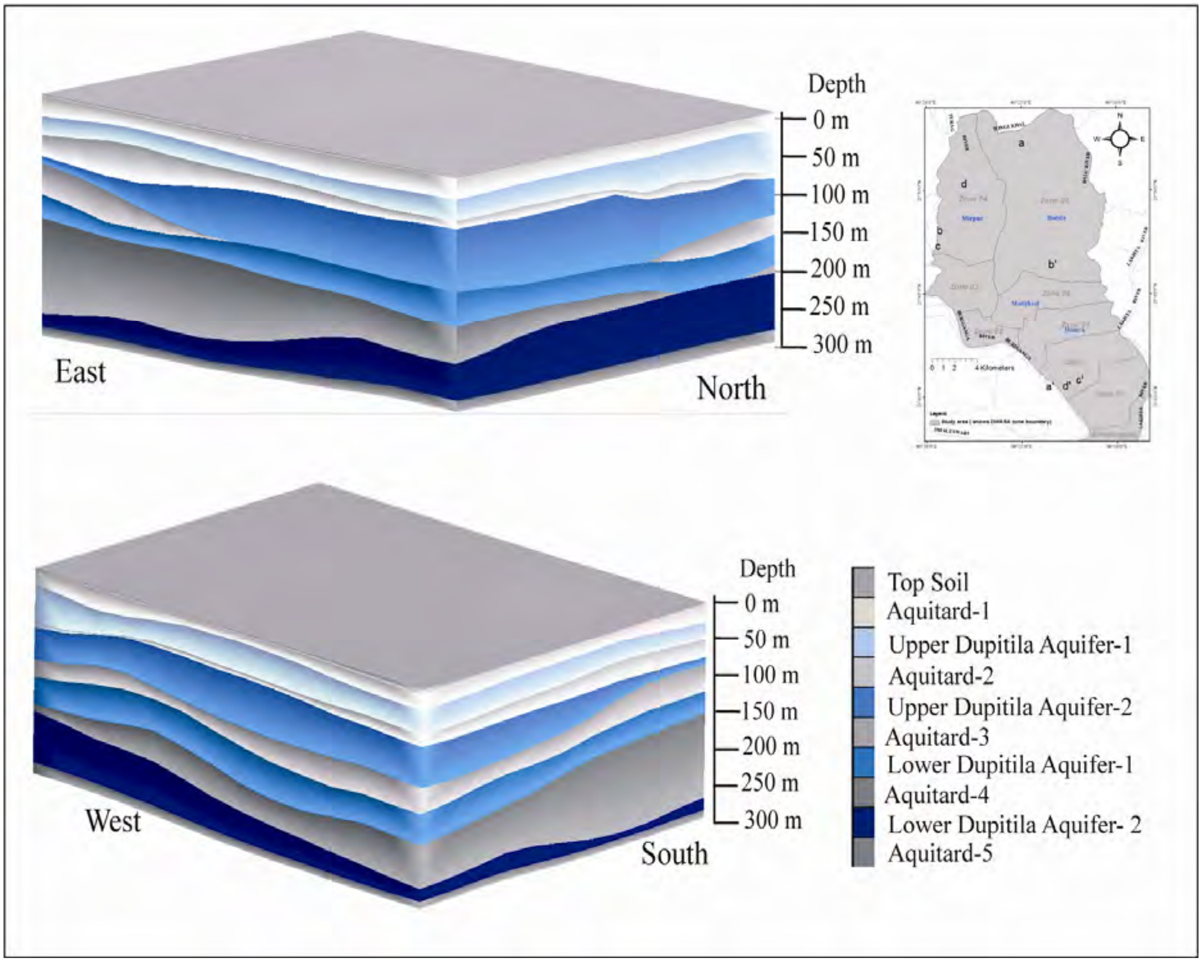


Figure 5.16: 3-D view of the existing hydrogeological layers of Dhaka City.

As the depths are generally obtained from bore logs, they are limited to around 150 m to 175 m, and the characteristics of the aquitard-4 and lower aquifer-2 couldn’t be established vertically and laterally. However, from the available information it can be concluded that the South - East (SE) part of the city area is characterized by a thick deep aquitard (aquitard-4). Like Dhaka City, the aquifer system around Dhaka City possesses the same geological characteristics with less complexity (detailed description and figure are not included here).

The material properties of the four aquitard (e.g. silty-clay with low permeability) control the hydraulic continuity between the aquifers. In some places the continuity is interrupted due to the presence of plastic clays. The rivers are in contact with the upper Dupitilaaquifer-1. Figure 5.16 shows that aquitard-2 is not continuous, and thus merges into the upper Dupitila aquifer-2 in some places and the lower Dupitila aquifer-1, e.g. in the North - East part of Dhaka City.

Four hydrogeological cross sections (locations are shown in Figure 5.13) are drawn in this study and Figure 5.17 presents the cross sections. One cross section a-a' is drawn from North to South, cross section b-b' is drawn in East to West direction.Another cross section (c-c') is drawn from West to South-East of the city. The cross section d-d' is drawn from Noth to South-East direction. Some more cross sections are drawn also and these four representative cross sections are shown only. Only few bore logs cover upto 300 m depth, so the deep lithology are not clearly presented here and for our purpose it is not required. However, the cross sections show that the upper Dupitila aquifer is not homogenous and consist layering of medium and fine sand. The first two layers are continuous and hence, injecting surface waters in the upper aquifer may mix with the water level in the second layer. However, it seems that the deep aquifer is mostly separated from the upper aquifers indicating to mixing with the recharges water. No fault in the subsurface have been identified.

According to records and long-term aquifer test results from Bangladesh Water Development Board (BWDB), the hydraulic conductivities (K) of the upper Dupitila aquifers range between $6.22\text{x}10^{-5}$ m/s and $1.98\text{x}10^{-4}$ m/s, and specific yields vary between 0.06 and 0.20. The hydraulic conductivities of the aquifers around Dhaka City range between $8.83\text{x}10^{-5}$ m/s and $9.32\text{x}10^{-4}$ m/s, with an average value of $4.73\text{x}10^{-4}$ m/s, and the specific yields vary between 0.10 and 0.25. The aquifers of Dhaka City generally possess large transmissivity and storage coefficients (DWASA, 2006). The estimated volume of storage for the upper Dupitila aquifer-1 is about 1120 Mm^3, without considering the consolidation due to urbanization, and for the upper Dupitila aquifer-2 it is 2616 Mm^3. As the water from the upper Dupitila aquifer-1 is almost exploited (Hoque et al., 2007, DWASA, 2006), the entire storage capacity is available for MAR.

From the limited groundwater level monitoring data, it can be said that the GWL level is deep (ca. 68 m) in the central part of the city such as in Mirpur and Motijheel. In these places, the upper Dupitila Aquifer is almost dewatered. Near the Buriganga River and northeastern part of the city the depth to groundwater level is with about 35 meters indicating that the upper Dupitila Aquifer-1 is still not completely dewatered. The groundwater level just outside of the city is within suction limit (7 m), which indicates that the river acts as a hydraulic barrier.

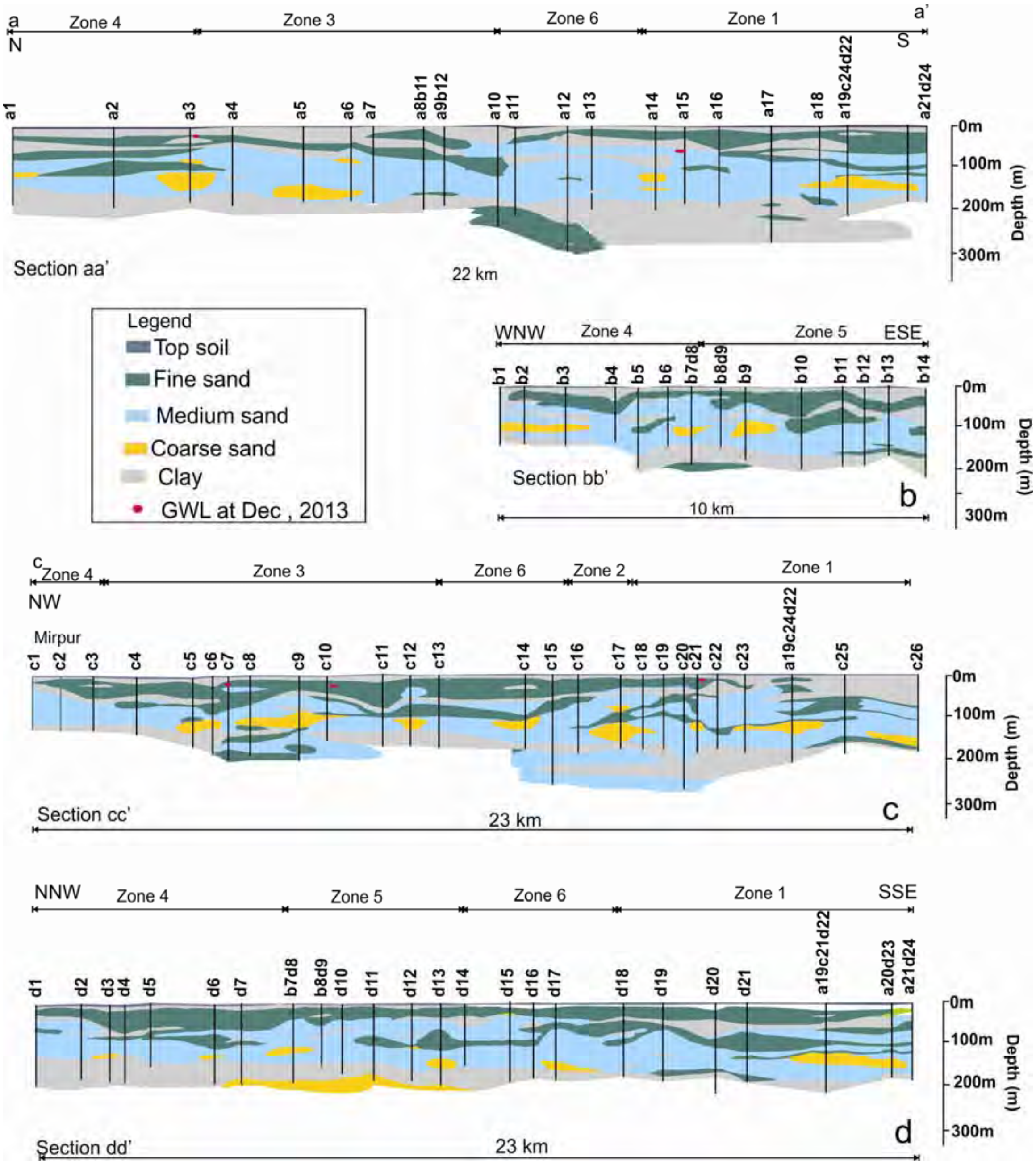


Figure 5.17: Lithological section sections of (a) a-a', (b) b-b', (c) c-c', (d) d-d'

5.6 Groundwater Quality

While MAR offers the benefit of storing water in the aquifer, hydrogeochemical processes that might pose risks to the success of an operational scheme must be considered (Dillon et al., 1999). Hence, it is quite important to understand the existing hydrogeochemical status of groundwater and the aquifer conditions before injection of oxygenated water.

In order to get spatial and vertical distributions of electrical conductivity (EC) in the aquifer, DWASA carried out a survey in 2006 at 228 production wells operated by DWASA. Figure 5.18 shows the vertical and spatial distribution of EC in the upper Dupitila aquifer. EC values range between 200 µS/cm and 1100 µS/cm (depth between 60 m and 200 m). About 80% of the production wells surveyed in Dhaka City and Narayanganj have EC values less than 500 µS/cm. EC values > 1000 µS/cm were found at shallow groundwater depths (i.e., in hand tube wells containing filters at < 30 m depth) of the upper Dupitila aquifer. Some groundwater samples near the central and western part of the city and near the Buriganga River show elevated EC values ranging between 500 µS/cm and 1000 µS/cm. Intrusion of contamination near the Buriganga River is consistent with the hypothesis of induced recharge from the river (Ahmed et al., 1999; Hoque and Bala, 2004). Elevated EC values are generally observed near the most polluted river and surface water bodies, e.g. Buriganga, Balu River etc., and industrial areas such as Tejgaon, Hazaribagh, Pallabi, and Narayanganj. In general, the variation of EC values in the upper Dupitila aquifer may indicate anthropogenic contamination by waste disposal, leakage from surface water bodies, leakage from the sewage network etc. Below 200 m, EC values range between 200 µS/cm and 500 µS/cm in the lower Dupitila aquifer.

Samples collected show average temperature and pH values of 28°C and 6.6, respectively. Dissolved oxygen (DO) data (DO values range between 0.95 and 4.89 mg/L with an average of 2.52 mg/L) reveal that the upper Dupitila aquifer is relatively more oxidized than lower Dupilita aquifer (DO values range between 0 and 0.7 mg/L, Haque, 2006).

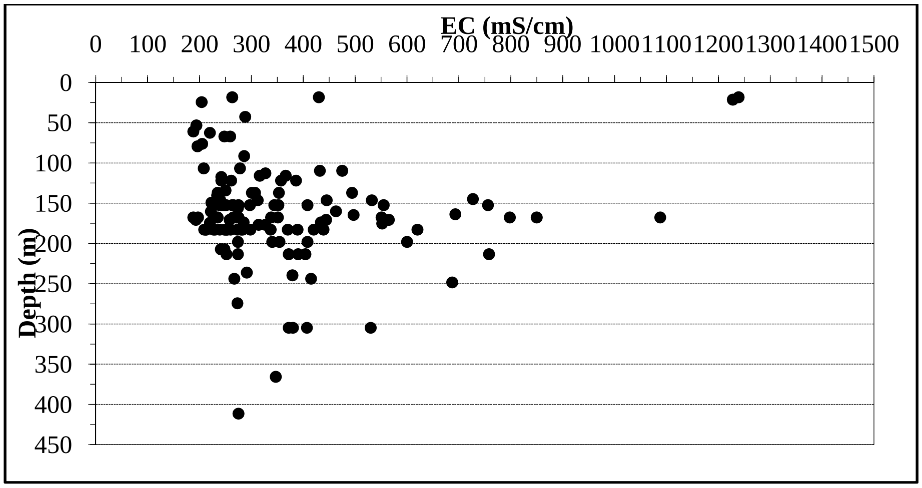


Figure 5.18: Variation of EC with depth in groundwater of Dhaka and Narayanganj.

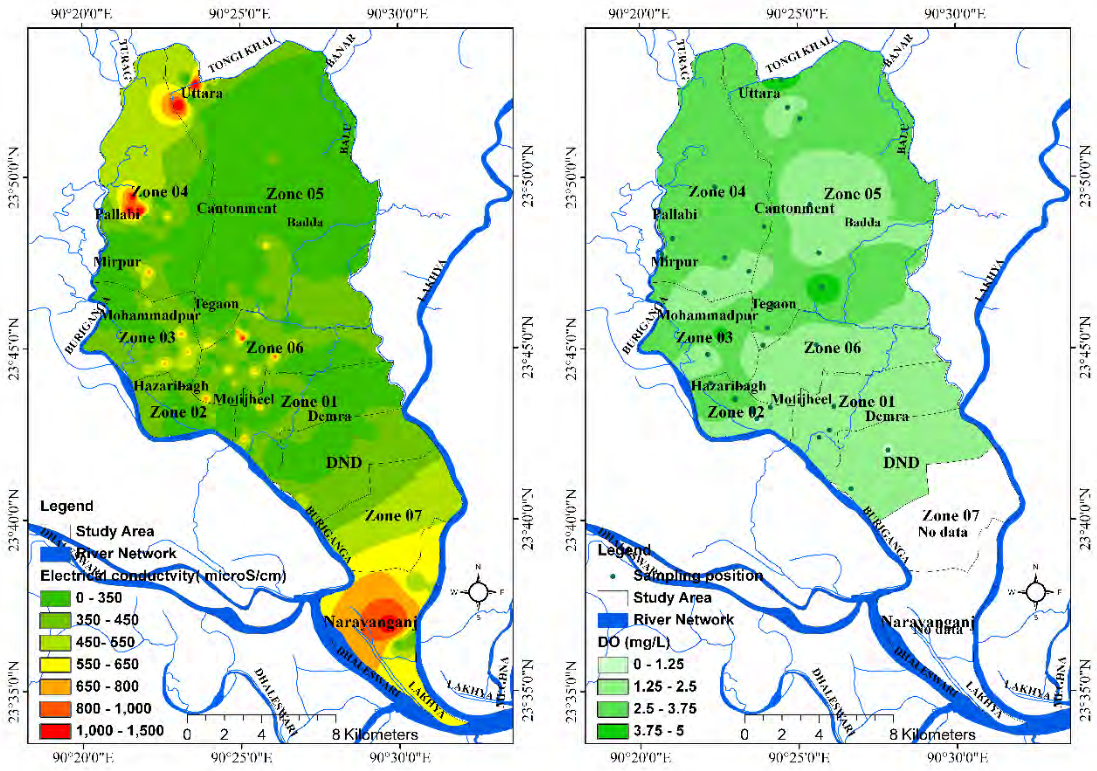


Figure 5.19: Distribution of electrical conductivity and dissolved oxygen in the Dhaka City and Narayanganj groundwater.

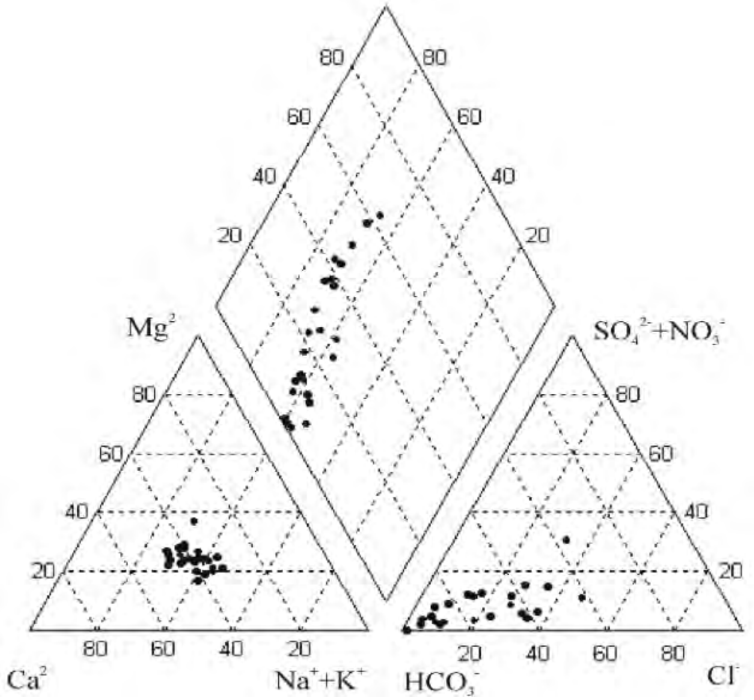


Figure 5.20: Characterization of the groundwater in diagrams after Piper (1944)

Spatial distribution of DO is shown in Figure 5.19 (right). Data of major ions depict that there is some variations in the concentrations in the upper aquifer at the sampled locations. Results of chemical analyses reveal that the primary ions in groundwater include co-equal amounts of the cations calcium (Ca^{+2}), and magnesium (Mg^{+2}), and a predominance of the bicarbonate (HCO$_3^-$) anion. Figure 5.20 shows a piper dram combining eight major anions and cations of the groundwater samples, as in most groundwater these ions make up 95 to 100% of the ions in solution. The lower right trilinear diagram contains anion (Cl$^-$, SO$_4^{-2}$, N0$_3^-$, HC0$_3^-$, information and the lower left trilinear contains cation (Na$^+$, K$^+$, Ca^{+2}, Mg^{+2}) information. The upper trilinear contains combine information. The aquifer of Dhaka City contains predominantly Ca-Mg-HCO$_3$ type groundwater (Figure 5.20).

Most of the trace elements are below WHO standard values (WHO, 2006) and Bangladesh standards (GoB, 1997), except for iron (Fe) and manganese (Mn) (Figure 5.21). In some places (e.g. Basaboo, Shampur), however, the concentrations of these trace metals exceed the WHO limits and Bangladesh standards. Iron and manganese concentrations are two critical parameters for the selection of groundwater well sites for rainwater injection. Total iron concentrations range between 0.02 mg/l and 1.2 mg/l, and total manganese concentrations range between 0.002 mg/l and 0.48 mg/l, respectively.

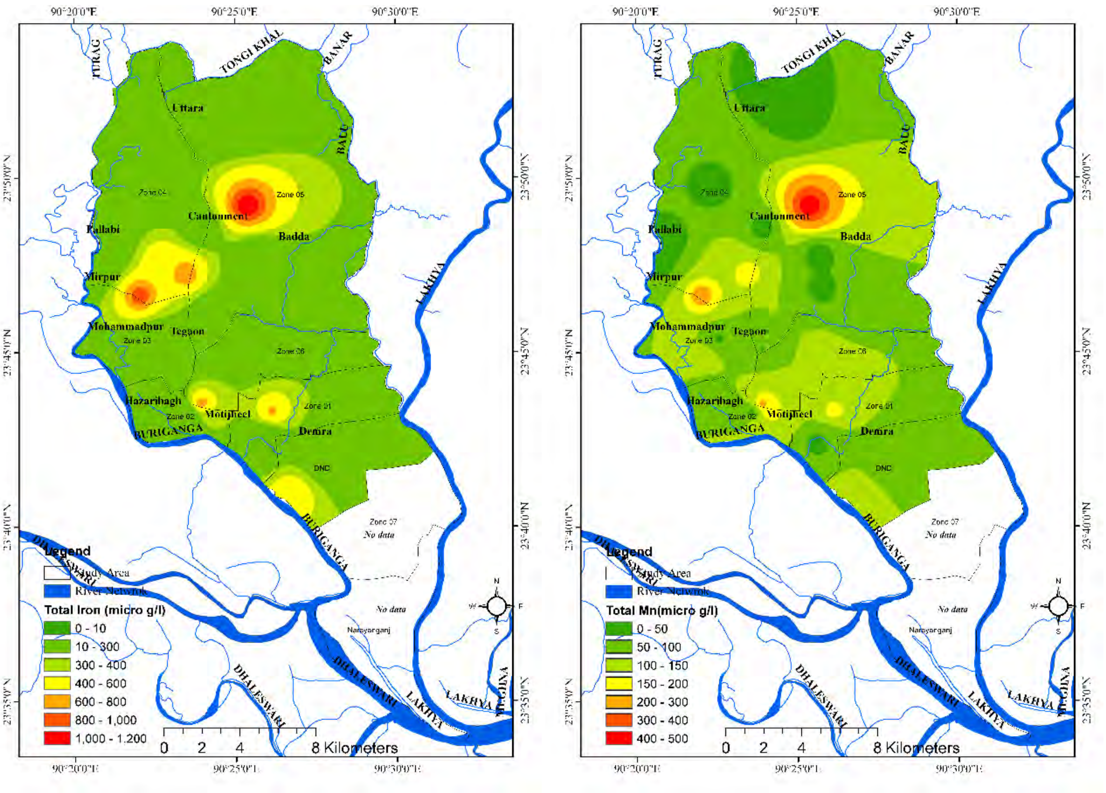


Figure 5.21: Distribution of Fe (left) and Mn (right) in the groundwater of Dhaka City

Significant correlation was observed between Mn and Fe, and between Ca and Mg. From spatial distribution of Ca (Figure 5.22 (left), it is seen that higher Ca concentration exists near the Buriganga River. Maximum concentration is seen as ca. 60 mg/L. In most of the places, NO_3^-concentration is lower than 5 mg/L. Only in one place (near Tejgaon) the concentration is higher. The water sample needs to be rechecked. Dhaka City aquifer is not threatened by $N0_3^-$ till now. Only one sample contains elevated (ca. 20 mg/l) concentration but does not indicate pollution. In most of the places the concentration is below 5 mg/l. All samples are quite below the drinking quality standard (45 mg/l).

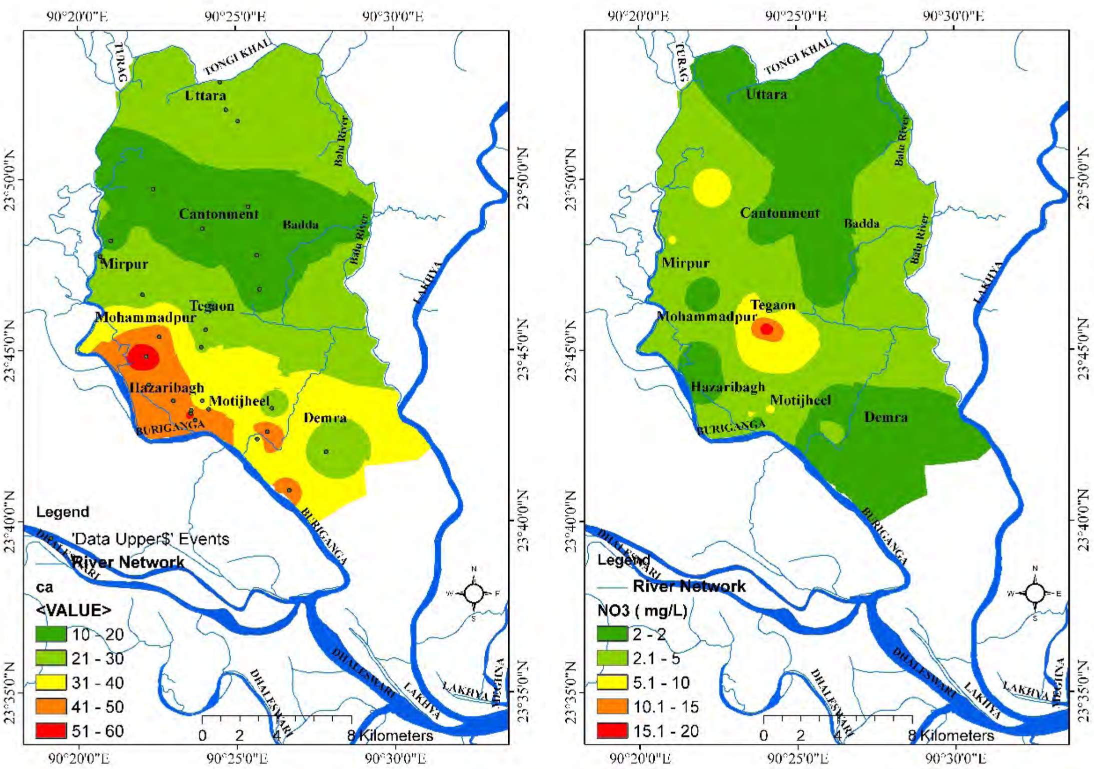


Figure 5.22: Distribution of Ca (left) and NO_3^- (right) in the groundwater of Dhaka City

Table 5.13 presents the standard value of different water quality parameters. Except Fe and Mn, all other parameters are within the standard value, indication almost no hazards in groundwater quality of Dhaka aquifers.

Table 5.13: Drinking water quality standards of EPA, WHO and Bangladesh Standard (BD std): Only important parameters

Drinking Water Quality Standards				Value observed
Parameters (mg/L)	EPA	WHO	BD Std	Upper Dupitila aquifer
Na	175	200*	200*	6 - 43
K	-	-	12	1 - 3
Ca	-	-	75	14 - 61
Mg		50	30 to 35	4 - 28
Cl	250	250	150 to 600	1 - 75
HCO_3		200 to 500		52 - 352
NO_3	45	50*	10	1 - 18
SO_4	250	250	400	0 - 27
As	10 ppb	10 ppb	50 ppb	Below detection
Mn	0.05	0.5	0.1	0.002 – 0.28
Fe	0.3		0.3 to 1	0.01 – 1.05
F	4*	1:5	1	0.08 – 0.26

5.7 Potential of MAR implementation

It is clear from the water resources system analysis (chapter 4) that MAR is a potential response to solve water resources problem in Dhaka city. And, Dhaka city has the potential of MAR implementation. In order to avail the potentiality a number of analysis need to be done and several challenges (such as cost, infrastructure installation etc.) should be faced before any practical application of MAR.

5.7.1 Water Source

However, it is always required to know the critical storm run-off volume in order to design the MAR facility. The following formula was considered to estimate the critical storm run-off volume (Q_c):

$$Q_c= C\times I \times A \text{ x } t_c \qquad (5.2)$$

The value of C is considered as 0.2 (after Bari and Hasan, 2001). The t_c was taken 86 min (after Ahammed et al. 2013). Rainfall intensity, I (100 years and 86 min storm) is 117 mm/hr (after Ahammed et al. 2013). Hence the estimated critical discharge is 800 million L (0.8 million m^3) per 86 min storm event for the entire open spaces. The recharge facilities should be designed considering critical discharge.

Figure 5.23 shows a concept of possible MAR implementation using river water of adequate quality. A MAR scheme for infiltration/Injection of treated storm water in the upper Dupitila aquifer can contain the following elements in addition to regular component of water supply network:

a) MAR technology (such as infiltration basin or injection well) to pour water into the aquifer
b) Water recovery plan
c) Water quality treatment system for storm water prior to injection and recovered water depending on its intended use (potable, non-potable or irrigation)
d) System to monitor groundwater level and abstraction quantity
e) System to monitor the quality of recharged water and recovered water
f) Network for collection of water from river and supply after recovery

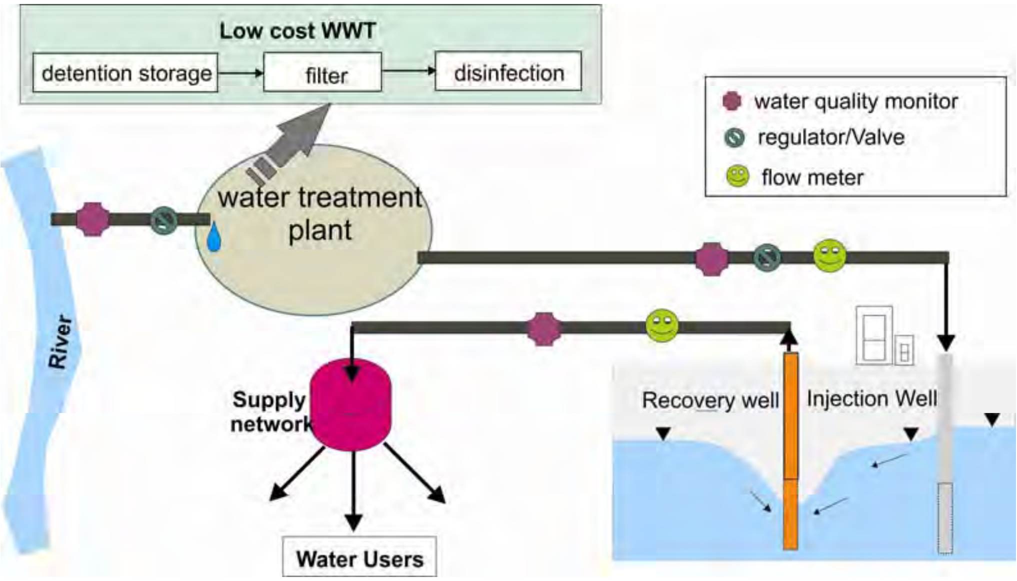


Figure 5.23: A concept of MAR using river water showing principal components that are required.

Figure 5.24 shows a conceptual diagram of reuse of wastewater via MAR. The main challenges are: (a) establishment of WWTP facilities including advanced treatment system, and (2) Recovery of injected water. The dotted lines and the green color boxes indicate required steps to implement MAR using wastewater.

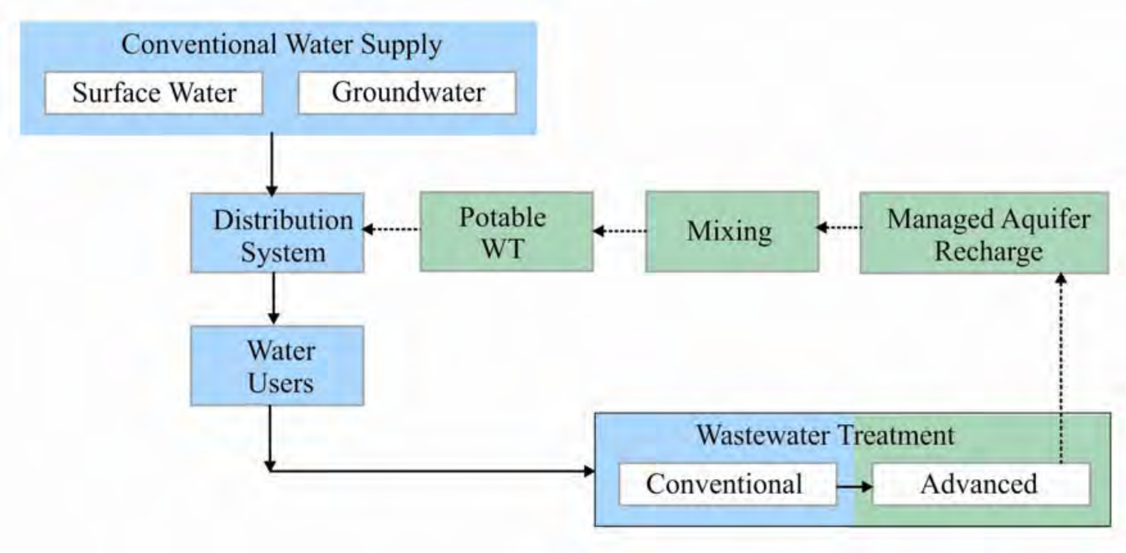


Figure 5.24: Concept of wastewater reuse via MAR in Dhaka City. The solid line and blue color boxes indicate the existing water supply and wastewater treatment system.

After reviewing a number of reports and studies, it can be summarized that two principle factors are of concern with respect to the reuse of wastewater: (1) the treatment process and efficiency of the wastewater treatment plant (WWTP), and (2) huge pollution loads from the industry.

5.7.2 MAR technology

Geological and hydrogeological characteristics of the aquifer of the greater Dhaka region (Dhaka City and its surrounding areas) and their relevance to MAR implication are summarized in Table 5.14. In general, the information in Table 5.14 suggests that with respect to the prevailing aquifer conditions (moderate permeability, thick aquifer, mostly homogenous hydraulic properties, and fresh groundwater), the Plio-Pleistocene deposits are most suitable for a MAR implementation.

According to the hydrogeological investigations, the upper Dupitila Aquifer-1 possesses sufficient storage capacity (ca. 1120 Mm^3), and together with the hydraulic properties of the aquifer (favorable hydraulic conductivities and storage coefficients) allows an implementation of MAR. As the water from the upper Dupitila Aquifer-1 is almost exhausted (Hoque et al. 2007), almost the entire storage capacity is available for recharge. Therefore, the main target aquifer for a MAR implementation in Dhaka City should be the upper Dupitila Aquifer-1. As the Modhupur Clay can neither yield significant amounts of water to wells nor transmit appreciable water to the aquifer below (Sultana et al. 2010), the clay material should be excavated completely in prospective infiltration areas. Alternatively, injection wells could be drilled directly into the aquifer to recharge water.

Characteristics	Aquifer status and application for MAR

5.7.3 Appropriate MAR techniques

Based on the land cover, aquifer thickness, and natural water bodies such as wetlands, canals, and depressions, four different MAR techniques can be suggested for Dhaka City: (1) soil-aquifer treatment (SAT), (2) cascade-type recharge trench/pit, (3) aquifer storage and recovery (ASR) and aquifer storage, transfer, and recovery (ASTR), and (4) use of natural wetlands to recharge the water collected from open spaces. Those techniques and their relevance are described briefly in the following sections.

Table 5.14: Aquifer characteristics relevant to MAR (Dillon and Jiménez, 2008) and their status for the major aquifer systems in the greater Dhaka region.

	Holocene deposit	Pleistocene deposit	Plio-Pleistocene deposit
Confinement	*Unconfined* - Surface infiltration technique is possible. - Vulnerable to surface contamination.	*Semi confined* - Wide range of infiltration mechanism possible	*Semi confined to confined* - Wide range of infiltration mechanism possible
Permeability	*Low to moderate* - Recharge water is more localised. - Higher recovery cost	*Low* - Less dispersion of water - High recovery cost	*Moderate* - Dispersion of water
Thickness	*Thick (ca. 10 m)* - Storage volume might be a major constraint	*Less thick (ca. 48 m)* - Storage volume might be a major constraint	*Thick (>100 m)* - High storage potential
Uniformity of hydraulic properties	*Moderate heterogeneity* - Moderate mixing - Retention times do not vary significantly	*Moderate heterogeneity* - Moderate mixing - Retention times do not vary significantly	*Mainly homogenous* - Minimal mixing - Retention times do not vary significantly
Salinity	*Fresh water* - Unlimited recovery efficiency	*Fresh water* - Unlimited recovery efficiency	*Fresh water* - Unlimited recovery efficiency
Horizontal hydraulic gradient	*Gentle* - Recharge water contained closer to the point of recharge	*Moderate to gentle* -Recharge water contained near to the point of recharge	*Moderate to high* -Recharge water moves away from the point of recharge
Consolidation	Unconsolidated - Clogging could be problem	Semi consolidated - Easy well construction	Slightly compacted and consolidated -Easy well construction

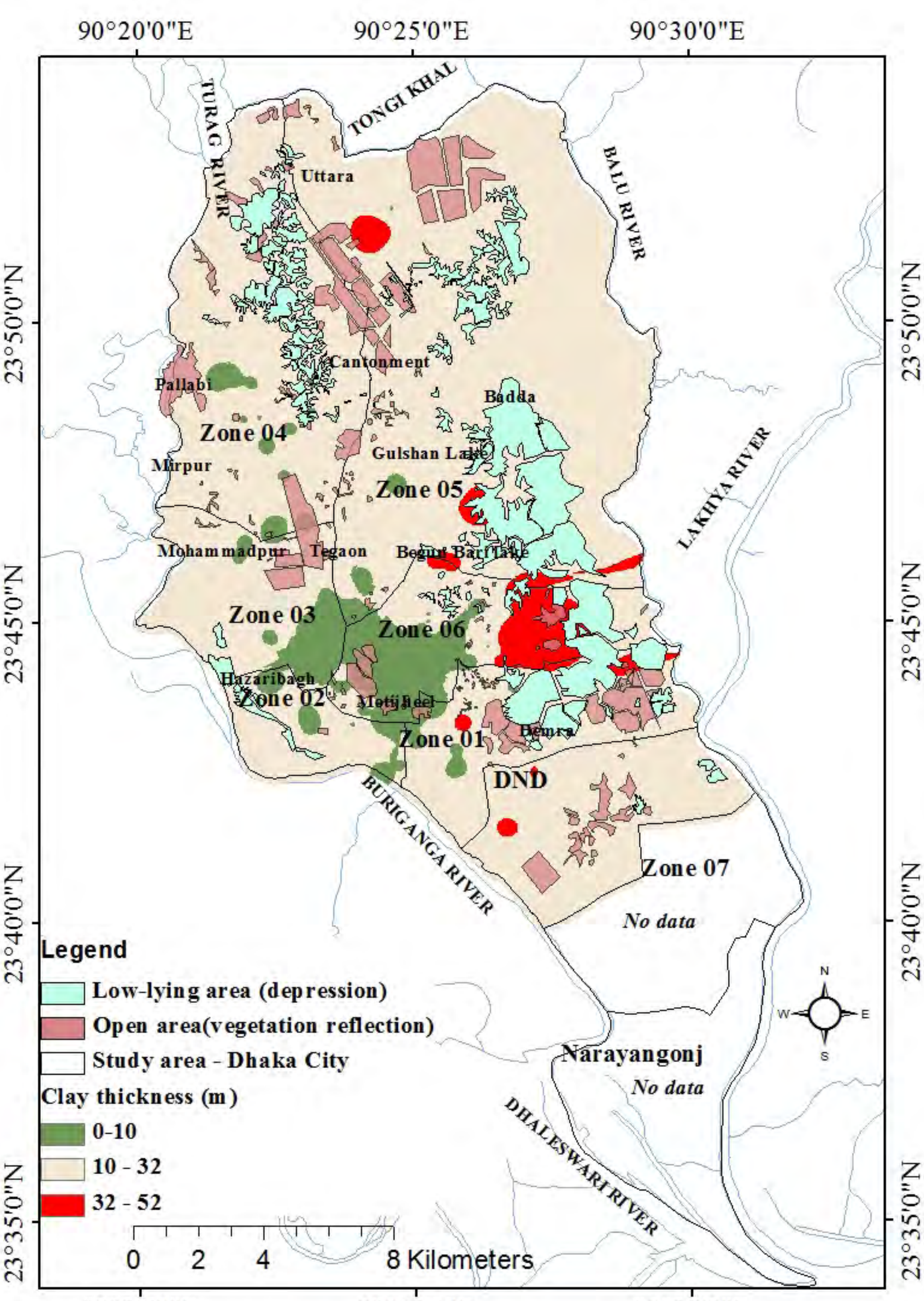


Figure 5.25: MAR site based on the top clay layer thickness, open area and low laying area

(1) Soil-aquifer treatment (SAT)

Implementation of SAT is now a common practice for MAR and is becoming increasingly important (Drewes 2009). SAT is an economical and smart wastewater reuse approach. Since the soil and the aquifer can act as natural filters, SAT systems can remove suspended solids, biodegradable materials, bacteria, viruses, and other microorganisms (Bouwer 1997). SAT is recommended for Dhaka City, where the top subsurface impermeable layer (top soil +clay) thickness varies between 0 m and 8 m, covering approximately 15 km2 area of the city. The groundwater level is deep (the average water table depth at those places is -42 m PWD according to Rahman et al. 2011), the spreading basin (Figure 5.26) will offer water quality improvement, while passing through the thick unsaturated zone.

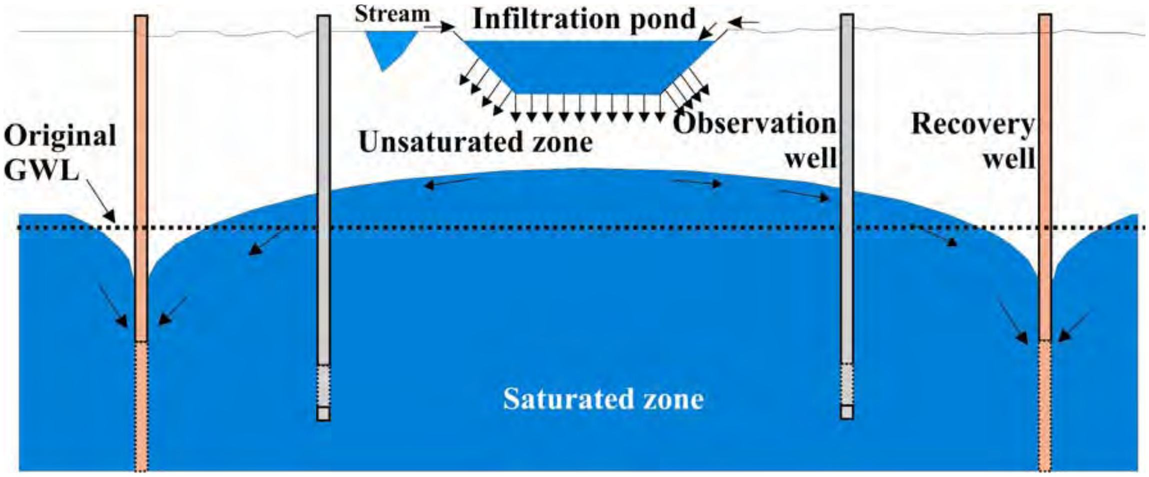


Figure 5.26: Typical SAT layout for Dhaka City

(2) Cascade-type recharge trench and pit

In slackly consolidated material, recharge pits and trenches are used in cases where silty material overlies the aquifer, which occurs at shallow depth (5-15 m) (Bouwer 1996). Recharge structures are constructed in a way such that they just extend to the aquifer (Murray and Tredoux 1998).

In places where the subsurface impermeable layer thickness varies between 10 m and 32 m, covering about 270 km^2 area of the city, recharge pits and trenches are most suitable(Figure 5.27). In order to avoid huge excavation work, cascade type recharge trenches and pits are suggested. Lower parts of the trench (15 to 20 m depth) that are in direct contact with the aquifer might be backfilled with biosand filters (e.g. Noubactep et al. 2009) with a reactive layer containing metallic iron (Fe^0) to offer pre-treatment of the infiltrated water.

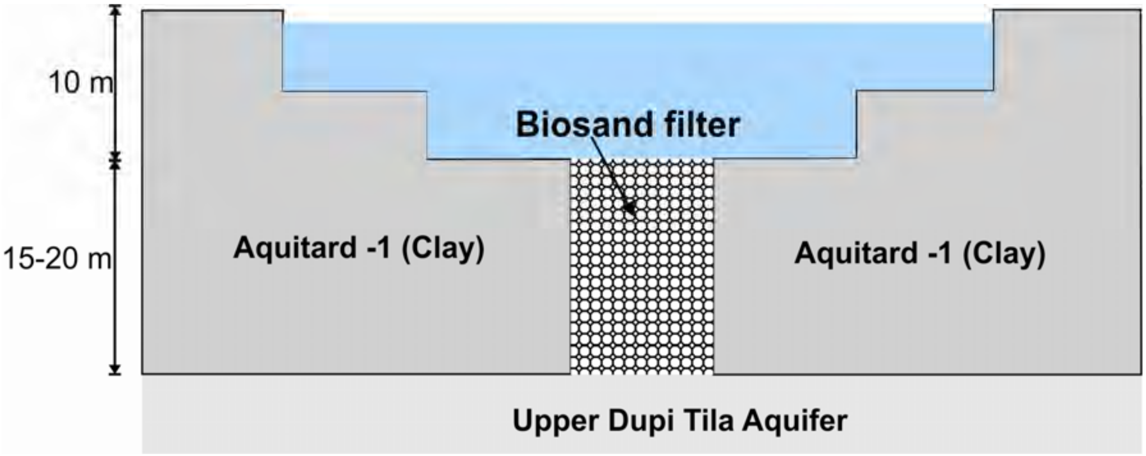


Figure 5.27: A schematic diagram of cascade type recharge trench for Dhaka City

(3) Aquifer storage and recovery (ASR) and aquifer storage, transfer, and recovery (ASTR)

Aquifer storage and recovery (ASR) is a well-known and very often-used MAR technique where land is scarce and where a comparatively thick impermeable layer overlies the target aquifer. High quality water is injected by recharge wells and recovered after certain periods of time (Maliva and Missimer 2010). Water can also be injected into a borehole and recovered by another borehole some distance away. This technique is referred to as aquifer storage transfer and recovery (ASTR). It allows the water to travel a certain distance for the improvement of the water quality ASR and ASTR are suggested, where the subsurface impermeable layer thickness varies between 32 m and 52 m, covering approximately 12 km^2 area of the city (Figure 5.25, and Figure 5.28). Slightly compacted and consolidated aquifer deposits will contribute to an easy well construction (see Table 5.11). The recharge wells are suggested to be installed within the unsaturated zone to take advantage of water quality improvement during downward transport. Sultana (2009) reported about 264 dry and abandoned wells of DWASA. These wells could be used as injection wells at the beginning of the MAR implementation in the city of Dhaka after rehabilitation.

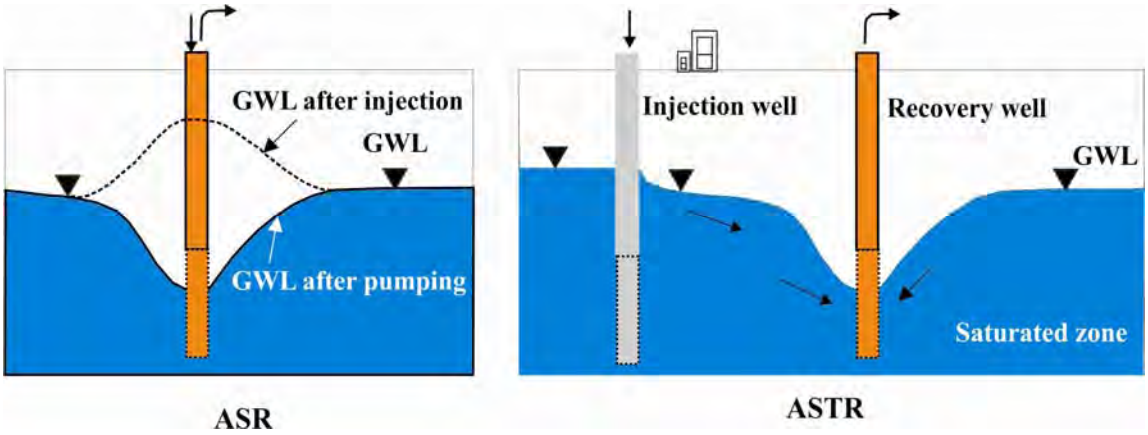


Figure 5.28: A schematic diagram of cascade type recharge trench for Dhaka City

In addition, this technology can be combined with a roof top rainwater harvesting system. Generally, in Dhaka City, the rainwater can be captured from roof catchments and stored in a small reservoir. After filling the reservoir, excess rainwater can be conveyed to the aquifer through a recharge trench or pit and then finally stored in the subsurface (see details in section 4).

(4) Use of existing natural wetlands

The wetlands and water bodies (see Figure 5.25) could be used for MAR after proper development. The water source could be storm water collected from open spaces. This collected storm water could be conveyed to the wetlands by usage of existing storm water drainage systems. The water treatment potential of the wetlands offers a pre-treatment option for the MAR waters (UNESCO-IHP 2005).

The impermeable subsurface layer in the greater Dhaka area, outside the metropolitan Dhaka area, is in some places suitable (thickness less than 6 m) for the construction of spreading basins. The regional groundwater flow direction, from northwest and northeast towards Dhaka City (DWASA 2006), may allow for use of the aquifer’s natural attenuation potential to improve water quality, if the spreading basins are installed in the greater Dhaka area.

5.8 A Model study of RWHS combined with MAR

From the hydrological analysis, it can be concluded that Dhaka City has a sufficient volume of rainwater for MAR. The main challenge is the proper collection and use of this water.

To assess the feasibility of rooftop rainwater harvesting systems for governmental and semi-governmental buildings in Dhaka City, a model study was performed. The 2500 sq m roof area was considered as a model, where harvested rainwater could possibly supply enough water for the general washing purposes. The average water demand at the building is 115 m^3 per month and the roof area is 2,500 m^2(the roof area of BUET Civil Engg building, Rahman (2001)). Both the mass curve method (Nissen-Petersen and Gould, 2000) and Ac –Vc method (IWACO BV, 1981) were used to estimate proper storage volume (Figure 5.29). Conventional statistical analysis methods were applied to check the reliability of water supply from rainwater (Figure 5.30).

From these two methods it can be concluded that about 620 m^3 of storage is required to ensure a water supply at a 115 m^3 $month^{-1}$ demand with a 100% security level (Figure 5.30). The general reliability relationship of water supply for Dhaka City is shown in Figure 5.30. Figure 5.30a shows a reliability curve considering the area 1200 m^2. In the x axis the demand was variedto get reliability with several demand to area ration. Figure 5.30b was prepared using area 2000 m^2. This generalised relationship is also applicable to other roof catchment at Dhaka City. Based on analysis shown in Figure 5.30, the reliability increases with increased roof area for any fixed demand. Required space for the storage volume and related cost are two important issues.

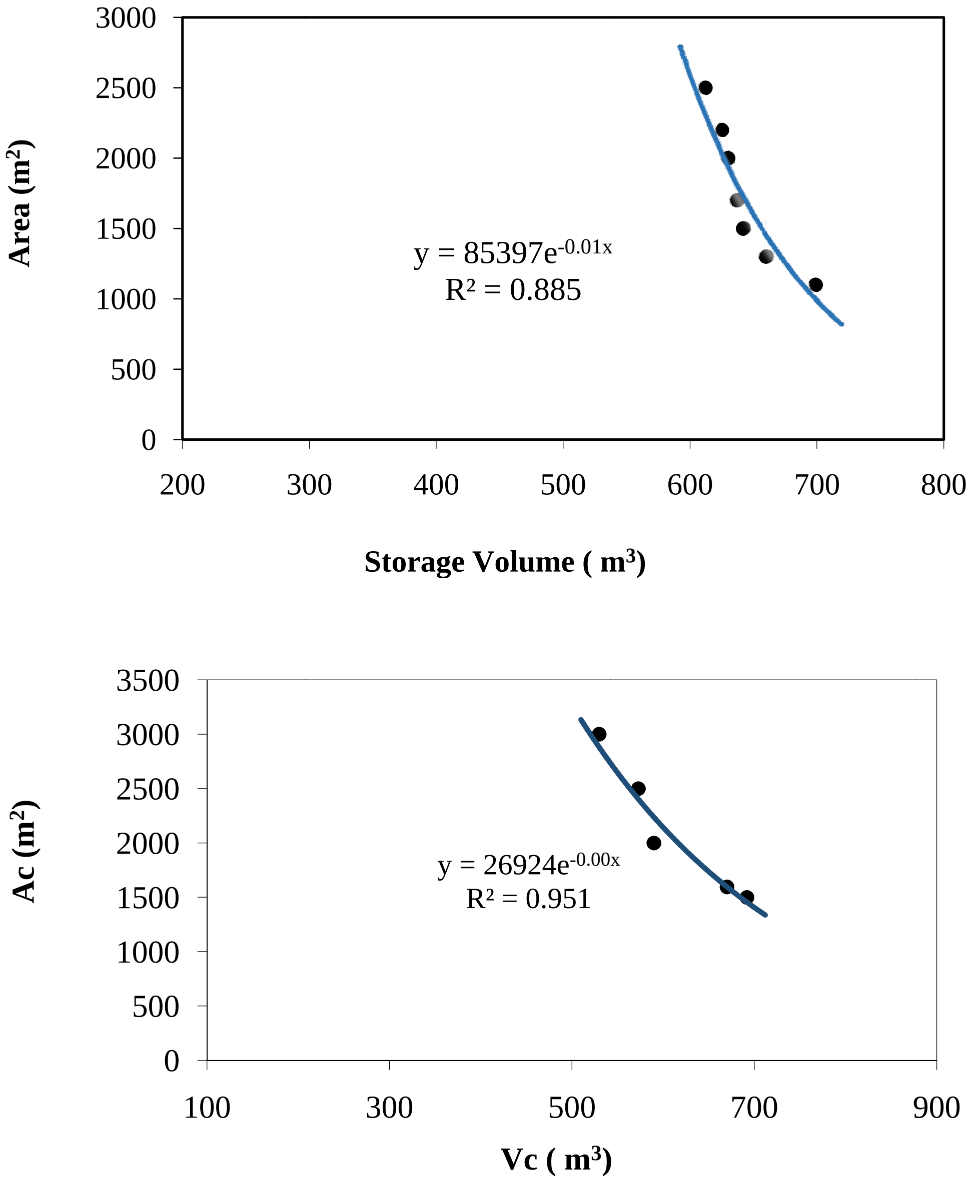


Figure 5.29: Optimal 'storage volume - catchment area' relationship at a constant demand (115 $m^3 month^{-1}$), (a) Mass curve method, (b) Ac – Vc method

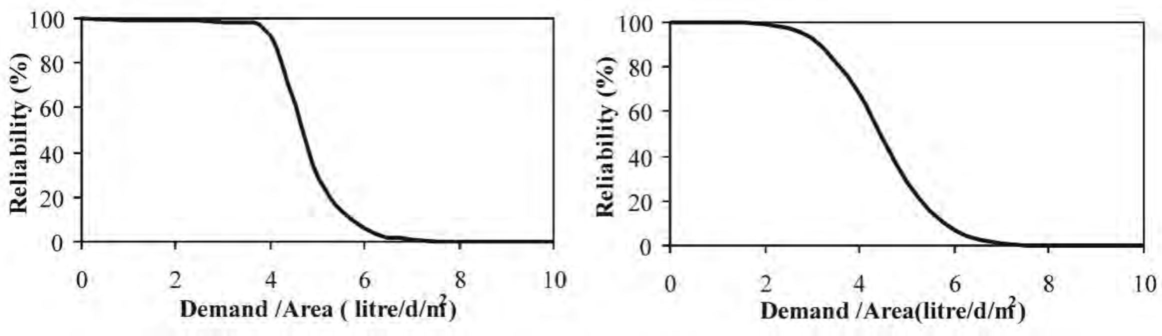


Figure 5.30: General reliability curve for different storage volume per roof area, left: 1200 m^2, right: 2000 m^2

The related cost estimation shows that initial investments are going to be high. Total construction costs for 467 m^3 (80% security level, 2 tank with the dimension of 14.5 m x 5.5 m x 3 m) storage was calculated as approx. TK. 20,00,000. In order to avoid extensive construction costs, a combination of water supply and managed aquifer recharge is most favorable. After considering the immediate need of water, cost effectiveness and necessity of groundwater augmentation, we recommend to use the Rainwater-Storage-Supply and Recharge (RWSSR) concept for places in Dhaka city where roof top rainwater harvesting is possible.

A planned schematic diagram, performed in this study, of the RWSSR concept is shown in Figure 5.31. In the RWSSR concept, rainwater is stored in underground storage tanks (the storage volume is estimated considering a 50% security level for cost-benefit effectiveness) using the available roof area. Therefore, the roof should be prepared for water harvesting beforehand. A portion of the harvested water is used for non-potable use immediately after low cost pre-treatment, such as filtration. When the storage tank if full, excess water is passed through the injection well to recharge the upper Dupitila aquifer. A control valve will regulate the water pathway. The recharge of excess water will increase groundwater resources.

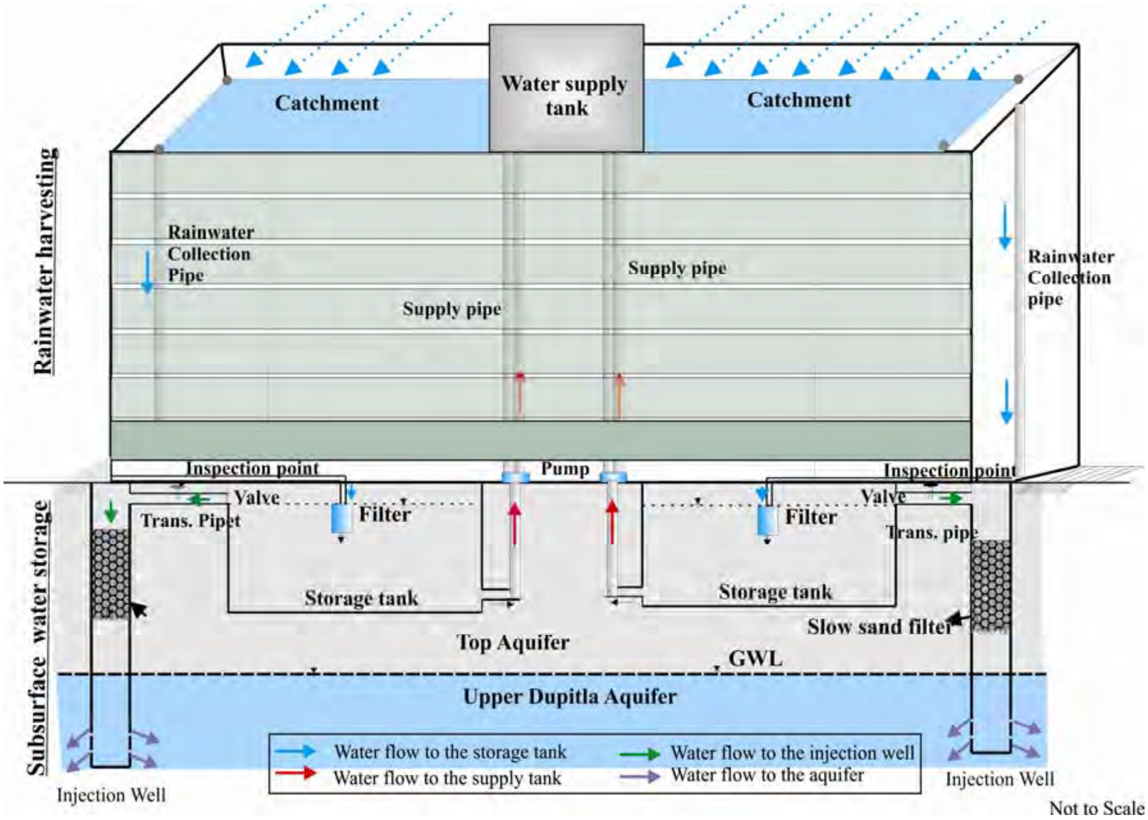


Figure 5.31: Proposed Schematic diagram for Rainwater Storage Supply and Recharge (RWSSR) for a typical building.

5.9 Challenges of MAR implementation

The possible hurdle that should be overcome is to include the urban areas of Dhaka City in the rainwater harvesting system. To prepare the concrete buildings suitable for RWSSR require costs, organisational efforts, public awareness, and the consent of the inhabitants. The initiation of RWSSR can be started from the governmental and semi-governmental buildings under the supervision of the local responsible government authority and the experiences can be transferred to individual house owners.

5.9.1 Technical aspects

Dhaka City has an immense potential of MAR using surface water and treated wastewater. The detailed investigation of pre-treatment of surface and treated wastewater and transport to the MAR locations wasn't studied in detail yet. If we want to use surface run off froMAR, level of pre-treatment will depend largely on the land cover. As the rainwater travel over different land cover, they might contain different sources of pollutant. Hence an intensive water quality monitoring should be planned.

The occurrence and position of fault zones need to be considered during the construction of the aquifer storage and recovery system. A vertical displacement in Zone - 5 (e.g., in Tejgaon area) may be related to the existence of a tectonic fault (see DWASA, 2006). Electrical tomography data (data not shown here) shows that Dhaka City is characterized by incised channels, channel shiftings, channel fill deposits, and overbank deposits up to 125 m depth. The upper aquifers are heterogeneous and may pose difficulties for the implementation of any MAR techniques. Thus, intensive local scale investigations are needed beforehand.

Aquifer pollution is another key concern for MAR implementation in the area. In some places (Hazaribagh, Jatrabari etc.) the aquifer is already polluted with industrial waste and leachate from landfill sites. Migration of pollutants from the rivers to the Upper Dupitila aquifer-1 occurs in direct contact zones. Another source of potential aquifer contamination could be arsenic contaminated groundwater, if spreading basins are situated close to contamination areas.Hence, intensive analysis of the MAR location and technology, supported by groundwater modelling, should be undertaken.

The hydrogeochemical analysis shows that the groundwater of the upper Dupitila aquifer is polluted to a certain degree by anthropogenic activities. Therefore, careful consideration of hydrogeochemical parameters and analysis of the groundwater is required to evaluate potential risks on public health and environmental protection. For example, potential geochemical processes between iron and manganese in groundwater, and oxygen and organic matter in rainwater might play an important role for changes in groundwater quality and aquifer properties (Maliva and Missimer, 2010). The analysis of possible hydrogeochemical reactions and hydrogeochemical modelling with respect to the prevailing aquifer conditions can provide important information on potential changes and risks.

The groundwater of Dhaka City is classified as Ca-Mg-HCO3 type and hence, the precipitation of calcite carbonate may cause the clogging of ASR wells (Maliva and Missimer, 2010). Recharge of rainwater into the aquifer will cause mixing of two waters that may result in a solution, which is either undersaturated or supersaturated with respect to calcite, depending on the Ca concentration and the CO2 partial pressure (Runnels, 1969; Drever, 1997). Hydrogeochemical modelling of the mixing processes is thus required.

Injection of oxygen and organic matter rich storm water firstly reduces the concentration of the major chemical constituents in the upper Dupitila aquifer such as iron, manganese etc. The average pH of rainwater and groundwater is between 6.4 and 7.2, and between 6.0 and 7.6, respectively. Figure 5.32 compares the solubility limit of iron and manganese hydroxides with the Fe and Mn concentrations of the ground water of Dhaka City.

Provided that Fe is present as Fe(II) and Mn as Mn(II) the species will be dissolved in the groundwater. However, the addition of dissolved oxygen (from rainwater) will trigger oxidation processes and cause the precipitation of Fe(III)/ Mn(III) species. Rainwater injection reduces Mn and Fe concentrations by two different mechanisms: (i) dilution, as injected rainwater is basically Fe and Mn free, and (ii) oxidative precipitation. Precipitation of Fe or Mn, e.g. as ferrihydrite and Mn oxides are known to cause clogging of injection wells and affect aquifer properties (van Cuyk et al., 2000; Maliva and Missimer, 2010). In addition, the mobilization of iron, manganese and other metals from the aquifer sediments is another factor that needs intensive monitoring, and hydrogeochemical modelling.

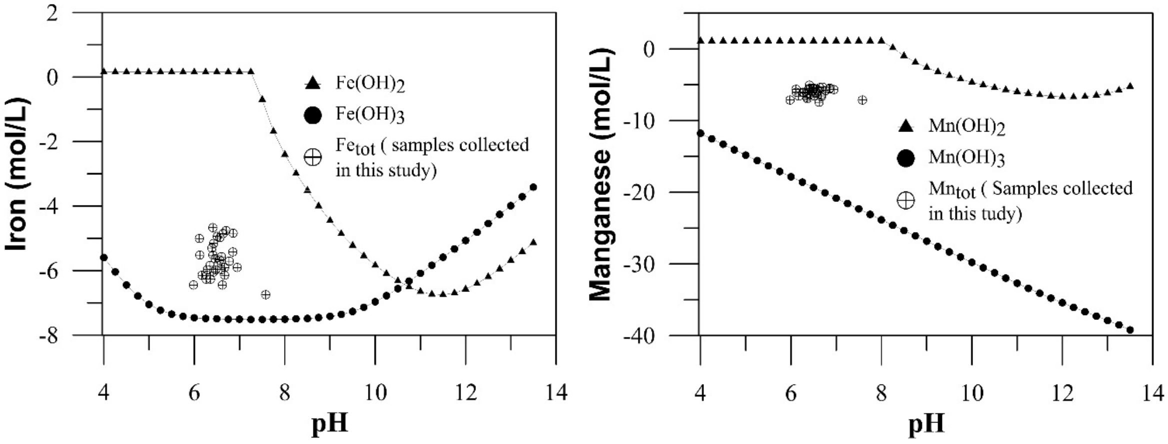


Figure 5.32: Comparison of total concentration of iron and manganese from this study with the solubility data of hydroxides. Hydroxide solubility data are from Lewis (2010).

Groundwater from the upper Dupitila aquifer is not contaminated by arsenic, but mobilization of arsenic from the aquifer sediments can occur when iron (III) oxides are dissolved in the storage zone. In a study that was conducted 30 km south from Dhaka City, arsenic mobility was apparently related to recent inflow of carbon either through organic carbon–driven reduction or displacement by carbonate (Harvey et al., 2002). Artificial recharge water is composed of a mixture of carbon-rich surface water (Harvey et al., 2002) and rainwater that might mobilize arsenic and pollute aquifers that contain arsenic-free groundwater in Dhaka City (Figure 5. 33). Furthermore, the chemical reactions of other environmental protection, and increases in those trace constituents frequently coincide ion Species such as aluminum, silicon, lead etc. are of concern for health and with an increase in iron, manganese, and arsenic (Maliva and Missimer, 2010).

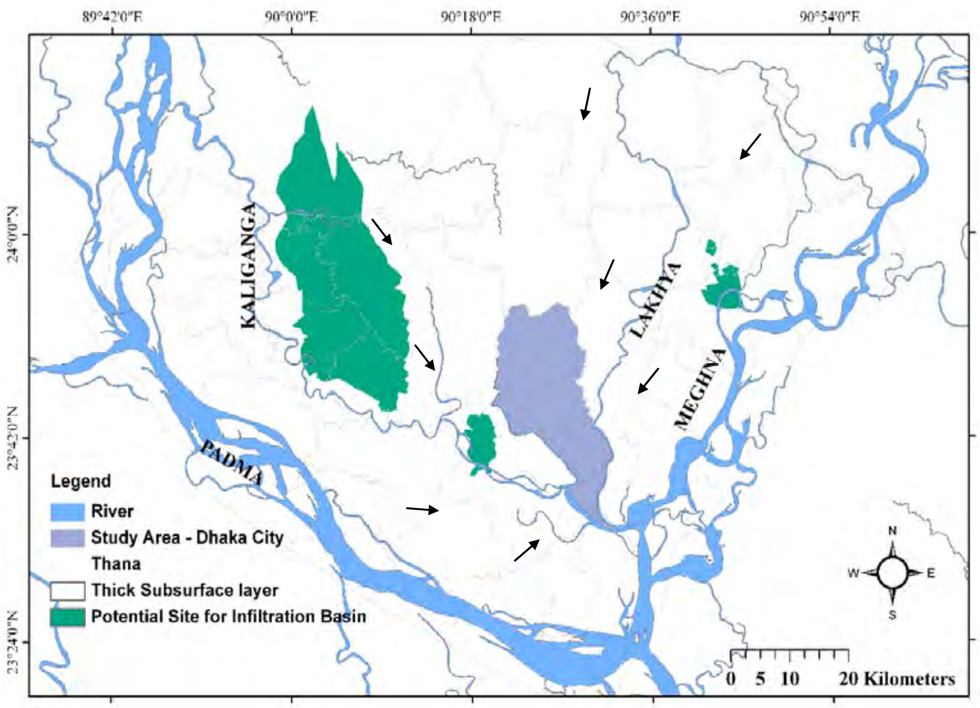


Figure 5.33: Location of possible infiltration site outside of Dhaka based on top surface impermeable layer thickness.

5.9.2 Economic aspects

Cost of Recharge facility is one of the main challenges regarding implementation of MAR in Dhaka city. Motuza et al. (2011) presented a detail cost benefit analysis of for a MAR project by implementing RWSSR concept.

The authors considered a 6 storied building with daily 720 liter water demand for non-drinking purpose. Including underground tank (200 cft) and overhead tank (50 cft) construction cost.

The total cost is Tk. 220,000 for the entire building.
Construction cost of a 6 storied building is around Tk.55400000,
considering 1800 sq. feet area and TK 5000 per sq feet. Hence, construction of a RWHS structure increase only 0.5% of the total cost. Install of RWHS will save ca. Tk.800 per month for the building (Moturza, 2011).

This present thesis also estimated the cost of a RWHS presented in section 5.8. The entire cost of the system is around Tk. 2000000. Higher cost in compared to Motuza et al

(2011) is the increased size of underground tank and construction of injection well. The total cost is also high considering the bill need to pay to DWASA. Total cost saving will be Tk. 3600 (150 m^3*24 Tk per m^3, for commercial use; DWASA (2014)) per month. It indicates that in ca. 45 years the investment will be returned without considering the rate of interest and possible increase in water price. Additional benefit will be gathered due to groundwater recharge which will produce also drinking water in long run. Hence, economically RWHS is a good choice.

The cost of wastewater treatment plan is also high. In Dhaka combine sewage system operates.

So, DWASA needs to treat industrial waste also. The cost of an Effluent Treatment plant (ETP) is 6000000 with a capacity of 50 m^3 / hr (according to Sultana et al., 2013) in addition we need to recharge and distribution facilities which will cost additional cost.

Above all, an ETP has limited service life (15 to 20 years, According to Patricia et al., 2014).

Use of surface water to MAR is also possible but will cost also higher amount money due to construction of treatment plant, water distribution system and MAR facility implementation. RWHS does not require high investment in water distribution system

Considering the above analysis, it is seen that RWHS would be the one of the choice in terms of cost.

5.10 Summary

From the analysis, it is clear that Dhaka city has the potential for implementation of MAR Excess rainwater is comparatively pollution free. So, this might be the first option to use. Though the aquifer possess enough storage capacity, possible risk of pollution should be carefully considered. Reuse of waste water might be another reliable source if proper low cost treatment technology can be implemented.

Injection of recharge water would be the most suitable option due to the following reasons:

(1) Construction of injection well in more easier and convenient than that of infiltration basin and casecade type recharge tecnlogy. It might not be practical to dig 10-15m deep basin.

(2) Maintenance of injection well is easier than pond considering overflow during flooding or heavy monsoon.

(3) During heavy monsoon, the pond might be contaminated by inflow of contaminated sewer water.

(4) Water loss is more in infiltration basin than injection well system.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 General

The scope of this study was to analyse the potential and challenges of MAR implementation in Dhaka city. A number of hydrological and hydrogeological information have been collected and analysed. Several state-of-the art technique were used for analysis. Based on the analysis results this chapter presents overall conclusion and recommendation of the study.

6.2 Conclusions of the study

Crisis of drinking water in the Dhaka city is acute not and with time the scale of problem is increasing. One of the major goals of the national water policy of Bangladesh is to provide safe drinking water to each household in the urban areas (GoB, 1998). Integrated and innovative water management concepts considering conventional and non-conventional water resources are required to achieve this goal in the metropolitan areas of Dhaka City. This study leads to the conclusion that Dhaka City has the prospect to use MAR techniques to conserve excess water during monsoon and use it in dry seasons.

1. Need of MAR in Dhaka City

The water supply and demand situation of Dhaka city clearly indicates that Dhaka city will face huge drinking water supply deficit in near future. Due to over exploitation the extra groundwater exploitation is non-sustainable. Surface water treatment plants are not adequate and become more costly due to continuous pollution of the peripheral rivers.

Hence implementation SW treatment plant is not only adequate for water resources problem solution. Managed aquifer recharge has been proved as a promising response to combat water supply scarcity. It has been practiced world- wide and can also be implemented in Dhaka City.

2. Potential of MAR in Dhaka City

Rainwater can serve 20% to 25% of the total present water demand. Surface water from large rivers and treated effluent can also be a potential source after proper treatment. The Balu-Lakhya River and the Kaliganga River offer better water quality in comparison to the other rivers making these water more suitable for MAR. It should be considered that, during the monsoon, the river water quality improves considerably due to a dilution effect caused by surface run-off. After reviewing wastewater situation it can be e summarised that two principle factors are of concern with respect to the reuse of wastewater: (1) the treatment process and efficiency of the wastewater treatment plant (WWTP), and (2) huge pollution loads from the industry.

The upper Dupitila aquifer possesses suitable characteristics and storage capacities for MAR implementation. The most beneficial results are obtained when MAR is coupled with long-term underground storage and with a water recovery system to supply to individuals and industries. The estimated volume of storage for the upper Dupitila aquifer-1 is about 1120 Mm3, without considering the consolidation due to urbanization, and for the upper Dupitila aquifer-2 it is 2616 Mm3. As the water from the upper Dupitila aquifer-1 is almost exploited, the entire storage capacity is available for MAR.

3. Proper MAR technique and challenges of MAR

In general, three basic MAR techniques, such as SAT (soil aquifer treatment, only in limited spaces), recharge trenches or pits, and ASTR (aquifer storage, transfer, and recovery) can be suitable for Dhaka City. Some modifications may be required to adjust the techniques with respect to water sources and locations and to keep costs low. A minimum separation distance between the injection well and the recovery well is required to get the advantage of natural attenuation for improving groundwater quality. As the production wells of DWASA (Dhaka Water and Sanitation Authority) are densely located, the minimum spacing requirement might be problematic. In this case, the installation of injection wells in the unsaturated zone will allow sufficient time for the recharge water to reach the regional groundwater table.

In some places (e.g., Hazaribagh, Jatrabari) groundwater and aquifers are already polluted by industrial effluent. Hence, the injected water may trigger geochemical processes in the aquifer that might pose additional risks on groundwater quality. Dissolution process in the aquifer, after injection of carbon-rich rainwater, may cause release of arsenic and contaminate the groundwater of Dhaka City. Likely no significant negative impacts on major groundwater quality parameters (e.g. EC, Fe, Mn etc.) are expected after recharge of storm water. The sedimentology and chemistry of Dhaka City aquifers are not well investigated yet and therefore, it is recommended to undertake an intensive survey, accompanied by groundwater modelling, for a better understanding of hydrogeological parameters.

Considering all relative advantages and disadvantages, it can be concluded that RWHS would be first choice to implement in Dhaka City. This study also conclude that Injection of harvested water will be the first choice among the three recharge techniques mentioned here.

6.3 Recommendations for further study

As the storm runoff and surface water that could be utilized for injection has a high probability of being contaminated by microbial pathogens as well as by other contaminants, any water injected into the subsurface should meet water quality criteria to guarantee that the recovered water has the appropriate quality to ensure protection of natural groundwater resources. To evaluate the actual feasibility of using surface water for MAR, detailed studies on water treatment, suitable pre-treatment technologies, and cost-benefit relationships are required.

A groundwater modelling study considering the existing water resources and MAR options is highly required. As the pumping wells are dense situated, without modelling study it would be impossible to plan the recovery water system

As the type, scale, and feasibility of MAR depends on a number of site specific conditions, detailed field studies of the Dhaka region and further basic scientific research are required to select the proper MAR technology, and to explore the mixing of recharge water and groundwater to ascertain the expected MAR project benefits. Hence, better planning and development of a management plan is essential. It is also important that the task and responsibilities are clearly documented within the management plan including clear outlines of accountability and reporting and, specifically, actions to address any non-compliance with these guidelines.

The development of a management plan should be underpinned by a preventive risk management system such as Hazard Analysis and Critical Control Point (HACCP), which is also used by the Australian Drinking Water Guidelines (NRMMC, EPHC, NHMRC, 2009). To adapt the available MAR technologies and to develop proper MAR planning and guidelines appropriate to the conditions in Dhaka City, Bangladesh, related research activities, based on inter-institutional cooperation, should soon be implemented.

Chapter 7

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