Decision Support for Managed Aquifer Recharge (MAR) Project Planning to Mitigate Water Scarcity based on Non-conventional Water Resources

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Executive Summary

The efficient integration into the water resources system and the implementation of Managed Aquifer Recharge (MAR) facilities requires careful planning if the overall water resources management objectives are to be fulfilled. The conjunctive management of surface water, groundwater, and even waste water resources is the aim of any viable MAR system and this is achieved by controlled recharge of these various water resources and, if required, subsequent extraction. MAR is thus part of the Integrated Water Resources Management (IWRM) concept yet until recently, the planning and management of MAR projects have lacked proper decision support and guidelines.

For comprehensive support in MAR project planning under water scarce conditions, an innovative geospatial decision support system (G-DSS) has been developed within the scope of the European Research Project GABARDINE. The G-DSS contains the following system modules: (a) GIS-based DATA management module, (b) DPSIR module, (c) MAR PLANNING module, (d) Spatial Multi-Criteria-Analysis (MCA) module for MAR site selection, and (e) MCA module for comparison and ranking of MAR planning options.

The objective of this dissertation is to present the development of a comprehensive decision framework for the planning of MAR projects under water scarce conditions, within the overall framework of the Gabardine project. A structured and standard planning framework was formulated, which served as a basis for the development of the G-DSS (mentioned above). The modules c, d, and e from the above paragraph were developed and introduced into the G-DSS. Once again, these modules are: (c) MAR PLANNING module, (d) Spatial MCA module for MAR site selection, and (e) MCA module for MAR option comparison and ranking. A further significant contribution was made concerning the development of the DPSIR module (b) of the G-DSS.

The following are descriptions of the G-DSS modules developed under this dissertation:

- The DPSIR (Driver, Pressure, State, Impact and Response) module facilitates the structuring of water resources problems by causal chain analysis and helps to determine potential response(s) and to spatially display the components of the problem.

- The MAR planning module offers the explicit decision steps that are required to plan a project. The planning steps consist of checking the available water quantity and the required water quality. The selection of suitable locations together with relevant MAR technologies and planning options for construction and for project ranking are included.

- An innovative Spatial Multi Criteria Decision Analysis (SMCDA) tool was developed to support MAR site selection, which is considered as a component of the planning tree for the system. The SMCDA tool is non-site specific, adaptive, and comprehensive, and may be applied to any type of site-selection problem.

- The MCA module is able to consider a wide range of criteria and analysis techniques, namely the Analytical Hierarchy Process (AHP) and the Weighted Linear Combination (WLC) to perform the evaluation, comparison, and ranking of MAR planning options

The G-DSS considers important information on the water resources system, such as the water budget as well as the present and future water demand of the area. Integrated into ArcGIS, the G-DSS benefits from GIS procedures for spatial analysis, and the data herein may be processed and displayed. In order to use the modules and related components of the G-DSS, an interactive user-friendly interface was designed in the present work.

In order to validate the newly developed MAR planning framework of the G-DSS and modules, which was created for this dissertation, the following four MAR planning tasks were focused on: (1) MAR pre-feasibility analysis, (2) Site selection and ranking, (3) Analysis, comparison, and ranking of MAR planning and management options, and (4) Soil-Aquifer-Treatment (SAT) system operation and impact

assessment. In total five case studies, one in Bangladesh and three of the GABARDINE project were selected to evaluate the MAR planning tasks (1) to (4):

(1) A MAR pre-feasibility analysis (MAR PLANNING module (c) and MAR planning task 1) in Dhaka, Bangladesh indicates the necessity of an extensive hydrological pre-study and a study of each component of the water resources system. This is important for the development of a tangible planning strategy at the very early stage of MAR project implementation. Dhaka, Bangladesh faces severe water supply problems related to groundwater over-exploitation.

(2A) A practical application of the SMCDA tool (Site selection module (d) and MAR planning task 2) at Querença Silves Aquifer in the Algarve Region indicates the efficiency of spatial MCA as a decision support (DS) tool towards the ranking and final selection of suitable MAR locations.

(2B) A second application of the SMCDA tool at the northern Gaza Coastal Aquifer shows the flexibility of the developed tool. The MAR site and technology selection case study at the Gaza Strip shows that SMCDA analysis substantially benefits from the hydrogeological impact assessment that was supported by mathematical modeling techniques.

(3) MAR management strategies for the northern Gaza strip were compared and ranked based on MCA analysis (MCA module (e) and MAR Planning Task 3). The most relevant decision criteria were selected and quantified in close cooperation with local stakeholders and decision makers. The most promising MAR planning and management strategies were identified.

(4) In Southern Europe, an investigation was undertaken to demonstrate an integrated approach based on field investigations, laboratory and field experiments, and mathematical modeling to understand the impact of aquifer properties on the transport processes of emerging pollutants under soil aquifer treatment (MAR planning task 4). Based on the integrated approach, the study recommends further groundwater monitoring and optimized pond operation.

The present work clearly suggests that the implementation of MAR is not only a local or site specific task, restricted to aquifer storage and water quality attenuation via recharge, but rather is part of a regional IWRM approach on basin scale. The MAR planning framework developed in this study and the conclusions drawn from the case studies facilitate decision makers in dealing with the non-straight forward decision-making process of MAR planning. The MAR planning workflow, an accompanying guideline and the G-DSS with its modules and functionalities, are generally conceptualized and, therefore, are applicable to any water scarcity affected region that is considering MAR implementation.

Zusammenfassung

Die Implementation von Managed Aquifer Recharge (MAR)-Anlagen macht eine sorgfältige Planung zur effizienten Integration in das Wasserressourcensystem und Realisiserung der wesentlichen Wasserbewirtschaftsziele notwendig. MAR-Systeme ermöglichen durch kontrollierte Wassereinleitung in das Aquifersystem und, sofern notwendig, spätere Wiederentnahme das kombinierte Management von Oberflächenwasser, Grundwasser und sogar Abwasserressourcen. Somit leistet MAR einen Beitrag zum Integrierten Management von Wasserressourcen (IWRM). Ungeachtet der Wichtigkeit dieser IWRM Komponente mangelt es der Planung und dem Management von MAR-Projekten bis jetzt an angemessenen Entscheidungshilfen und Richtlinien.

Um die Planung von MAR-Projekten unter Wasserknappheit umfassend zu unterstützen, wurde im Rahmen des europäischen Forschungsprojektes GARBADINE ein innovatives Decision Support System (G-DSS) entworfen, welches die folgenden Systemmodule enthält: (a) GIS basiertes Datenmanagementmodul, (b) DPSIR-Modul, (c) MAR-Planungsmodul, (d) Modul für räumliche multi-kriterielle Analysen (MCA) zur Unterstützung der MAR-Standortsbestimmung sowie (e) ein MCA-Modul für den Vergleich und die Bewertung von MAR-Planungsoptionen.

Ziel der vorliegenden Arbeit war es, ein umfassendes Entscheidungskonzept für die Planung von MAR-Projekten unter Wasserknappheit zu erarbeiten. Ein strukturiertes sowie , standardisiertes Entscheidungskonzept wurde formuliert und als Grundlage für die Entwicklung des G-DSS verwendet. Die oben genannten Module c, d und e wurden im Rahmen dieser Arbeit entwickelt und in das G-DSS integriert. Ein weiterer wesentlicher Beitrag bezieht sich auf die Entwicklung des DPSIR-Moduls. Zur Validierung des G-DSS wurden im Rahmen dieser Arbeit einzelne Planungsschritte auf dem Weg zur MAR-Implementierung im Detail untersucht.

Im Folgenden warden die im Rahmen der Arbeit entwickelten Systemmodule kurz dargestellt:

- Das DPSIR (Driver, Pressure, State, Impact and Response)-Modul ermöglicht durch die Analyse kausaler Zusammenhänge die Strukturierung von Wasserressourcenproblemen und hilft, potentielle „Antwort"-Strategien zu identifizieren und Problemkomponenten aufzuzeigen.

- Im MAR-Planungsmodul können die notwendigen Planungs- und Entscheidungsschritte aufgezeigt und abgearbeitet werden. Die Planungsschritte beziehen sich u.a. auf die Prüfung der Wasserverfügbarkeit und –qaulität. Auch werden durch dieses Modul Entscheidungen zur Standort- und Technologieauswahl sowie die Definition und der Verleich von MAR-Planungsoptionen unterstützt. .

- Zur Unterstützung der MAR-Standortauswahl wurde ein innovatives multikriterielles Verfahren zur Raumanalysse „Spatial Multi-Criteria Decision Analysis" (SMCDA)" ung entwickelt. Das neue SMCDA-Tool ist auf Grund seiner Flexibilität für die Entscheidungsunterstützung bei unterschiedlichen Problemen der Standortauswahl einsetzbar.

- Mit dem MCA-Modul, das für die Bewertung und den Vergleich von MAR-Planungsoptionen entwickelt wurde, können unterschiedliche Entscheidungskriterien und Analysetechniken eingesetzt werden. Dazu zählen beispielsweise der „Analytical Hierarchy Process" (AHP) und „Weighted Linear Combination" (WLC).

Das G-DSS berücksichtigt wichtige Informationen zur Charakterisierung des Wasserressourcensystems, wie die Wasserverfügbarkeit und Wasserbedarfentwicklung in der Region. Auf Grund der ArcGIS-Platform profitiert das G-DSS von verschiedenen Verfahren für räumliche Analysen, die Datenverarbeitung und graphische Darstellung der Ergebnisse deutlich erleichtern. . Das G-DSS verfügt über eine interaktive, intelligente graphische Benutzerbenutzeroberfläche.

Die folgenden vier wichtigen MAR-Planungsaufgaben wurden im Rahmen dieser Arbeit anhand von Fallbeispielen näher untersucht: (1) Beurteilung der Machbarkeit (Pre-Feasibility) von von MAR, (2) Standortsbestimmung und Ranking, (3) Beurteilung, Vergleich und Ranking der MAR-Planungs- und –

Bewirtschaftungsoptionen sowie die (4) Beurteilung des Betriebs- und der Umweltauswirkungen von „Soil-Aquifer-Treatment“ (SAT)-Systemen. Ein Fallbeispiel in Bangladesch und drei Gabardine-Fallstudien wurden zur Untersuchung der oben genannten MAR- Planungsaufgaben (1) bis (4) ausgewählt:

(1) Für Dhaka, Bangladesch, wurde eine MAR-Pre-Feasibility-Studie durchgeführt. Hauptproblem der Wasserversorgung ist die Übernutzung des Grundwassers. Die Studie unterstreicht die Unabdingbarkeit einer umfassenden hydrologischen Vorstudie. Zudem bestätigt sie, wie wichtig die Analyse aller Komponenten des Wasserressourcensystems bereits im frühen Stadium der MAR-Projektplanung ist , um alternative Planungsstrategien rechtzeitig entwerfen und ausreichend bewerten zu können.

(2A) Eine praktische Anwendung des Entscheidungstools zur MAR-Standortauswahl (SMCDA-Tools) am Querença Silves Grundwasserleiter in der Algarve bestätigt die Tauglichkeit des Werkzeugs zur systematischen Identifizierung von Standortalternativen, ihrer Bewertung und abschließenden Auswahl.

(2B) Eine zweite Anwendung des SMCDA-Tools im nördlichen Küstenaquifer des Gazastreifens hebt die Flexibilität des entwickelten Verfahrens hervor. Die MAR-Fallstudie zur Standortbestimmung für Infiltrationsanlagen im Gazastreifen zeigt, dass die SMCDA-Analyse erheblich von einer hydrogeologischer Folgenabschätzung mit Hilfe mathematischer Modelle zur Simulation von Grundwasserströmung und -transport profitiert.

(3) Alternative MAR-Managementstrategien für den nördlichen Gazastreifen wurden mit Hilfe multikriterieller Verfahren auf der Grundlage sozio-ökonomischer und ökologischer Entscheidungskriterien miteinander verglichen und und gemäß ihrer Effizienz bewertet. Die Auswahl der Kriterien erfolgte in enger Kooperation mit lokalen Interessenvertretern und Entscheidungsträgern. Mit Hilfe der entwickelten Verfahren konten die vielversprechendsten MAR-Planungs- und -Bewirtschaftungsoptionen klar identifiziert werden.

(4) Die letzte Fallstudie untersucht den den Einfluss der Aquifereigenschaften auf Transportprozesse unter „Soil Aquifer Treatment“-Bedingungen. An einem semi-ariden Standort in Südeuropa. Verwendet wurde ein integrativer Ansatz, der sowohl Feld- und Laboruntersuchungen als auch mathematische Modellrechnungen berücksichtigt. Auf Grundlage der Ergebnisse des integrativen Ansatzes empfiehlt die Studie weitere Grundwasserbeobachtungen und einen optimierten Betrieb der Infiltrationsbecken.

Die vorliegende Arbeit zeigt, dass die Implementation von MAR nicht als lokale oder fallspezifische Aufgabe zu verstehen ist, sondern vielmehr als Teil eines regionalen IWRM Ansatzes auf Wassereinzugsgebietsebene. Die im Rahmen dieser Studie entworfenen MAR-Planungsstrukturen und die aus den Fallbeispielen gezogenen Schlussfolgerungen tragen zur einer effizienteren Planung von MAR-Anlagen bei. Die entwickelten Konzepte und Modellwerkzeuge wurden so strukturiert, dass sie bei unterschiedlichsten Randbedingungen zur Planung vom MAR-Anlagen in wasserarmen Regionen eingestzt werden können.

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Introduction

1.1 Managed Aquifer Recharge

The world's population is growing fast and the need for water is growing at an even faster pace. About one third of the world's population lives in countries of water stress and if the current trend is maintained, water stress is expected to rise by 66% until 2025 (Kuylenstierna et al., 1997). As water stress or scarcity imposes strong restrictions on humans and natural systems, the vulnerability of water scarce areas to climate variability and possible future climate change is ever more likely. Climate change has been predicted to contribute to decreasing water availability, increasing water quality degradation, and an increase in extreme flood and drought events (Urama and Ozor, 2010; Rusteberg, 2008). In order to assure water supply for future generations, nature conservation and the sensible use of natural resources along with sustainable economic development and environmentally safe and low cost technologies and innovative water resources management practices are urgently needed.

Integrated water resources planning and management (IWRM) as an applied management concept is likely to facilitate the implementation of proper solutions to the above-mentioned problems. Considerable water quality degradation of surface water resources, insufficient precipitation in certain months of the year, and enormous installation costs of surface water harvesting structures put intensive pressure on groundwater resources and lead to irreversible effects on the state of available clean groundwater. This overexploitation and degradation of groundwater resources also causes several other problems, such as salinity intrusions, land subsidence etc., which can be very detrimental to sustainable water resources development.

For better management of existing water resources and to secure water for future generations, aquifers can be used as reservoirs to store water for later use during water scarce periods. Managed Aquifer Recharge (MAR) has been practiced for a number of years in many countries (e.g., in Australia, the USA, Israel) and for a wide variety of water resource management purposes, e.g., for groundwater development in India (CGWB, 2000), rehabilitation of the coastal aquifer in Israel (Abbo and Gev, 2008), prevention and control of surface subsidence in China (Wang et al., 2010), wastewater reuse and storm water management in Australia (Thomas et al., 1997), and Aquifer Storage and Recovery in Arizona, USA (Lluria, 2011). In recent years, substantial progression has been achieved in the scientific understanding of MAR processes and the technologies associated with MAR have been increasingly extended and optimized. However, weak planning remains a major hindrance to the complete and successful adaptation of managed aquifer recharge in areas where it is most needed.

In the new water resources system planning and management strategies, which are steadily becoming more common, MAR does not stand-alone. The successful implementation of MAR requires the careful assessment of many factors. The most important aspects to be considered are: available sources of high quality water, appropriate site assessment, estimation of flow of recharged water, fate of possible emerging pollutants, environmental and socio-economical impacts of the recharge projects, the participation of people, regulation and permitting requirements, as well as government investment and planning. The involvement of these factors makes MAR planning non-straight forward. Though, a number of studies have been performed as to how to successfully integrate the acquisition of data on each of the above-mentioned factors to be taken into consideration, no clear guidelines or planning system has been developed yet. It is now evident that the single most important process for the successful implementation of a MAR project is planning (Maliva and Missimer, 2010) and this now needs the most attention to ensure the future success of MAR.

1.2 Study Background

The effective implementation of MAR projects is a challenge for integrated water resources management in any region because of the combination of surface- and groundwater resources management (Dillon et al., 2007). To guide MAR implementation, greater investment in basic scientific research was recommended in several studies (e.g. Asano, 1985; ASCE, 2001; Gale et al., 2006; Maliva and Missimer, 2010). In the context of national or international water resources planning and management, potential conflicts may arise in MAR projects, particularly where water conservation, allocation, sharing (e.g., trans-boundary aquifers), and water quality protection regulate the major decision making policies. Hence, MAR must be addressed within the broader context of technology, physical and socio-economical factors, institutional arrangements, and decision-making by taking the advantage of available local and regional information and implementing the new technologies. However, the large network of decision makers is not easy to handle, but requires strong and concerted efforts from all those who are involved. A detailed and well-formulated decision making framework can effectively combine all these issues.

A MAR decision-making process should start with the assessment of the viability of the proposed project via an extensive pre-feasibility study i.e., an entry-level desktop study (NRMMC, EPHC, NHMRC, 2009; Hochstrat et al., 2010; Maliva and Missimer, 2010). The pre-feasibility study takes into consideration hydrology, hydrogeology, and a hydrogeochemical analysis of the region, considering site and problem-specific characteristics to tie in with the regulatory aspects of the respective national water policy. As this pre-feasibility assessment facilitates the decision of whether to pursue MAR options or not and to establish project goals, direction, and priorities (Maliva and Missimer, 2010), the assessment should be thorough, complete, and a final document should be prepared at the very early stages of MAR implementation.

The selection of water sources and location for MAR are fundamental requirements of any MAR project. A number of surface and sub-surface characteristics need to be considered during the site selection process for MAR projects. Complex regional characteristics, heterogeneities in surface and/or subsurface characteristics, and variable groundwater qualities make site selection for MAR difficult (Anbazhagan et al., 2005). During the last 20 years a number of studies have been performed to select suitable sites for MAR implementation (e.g., Saraf and Choudhury, 1998; Anbazhagan et al., 2005; Chowdhury et al., 2010). The existing MAR site selection procedures of today are far behind in terms of using modern technologies and decision analysis methods, considering the advancement in site selection methods for other purposes such as waste disposal, priority of land use, etc.

Most of the regulatory directives in the USA, Australia, the UK, Spain, etc. put emphasis on the identification of risk and impact assessment before implementation of any MAR project (e.g. NRMMC, EPHC, NHMRC, 2009; Hochstrat et al., 2010; Gale et al., 2001, etc.). Much technical and analytical progress has been made to determine the possible risks imposed and possible related impacts (environmental, health, social, and economical) in several fields of natural resources management. Advancements in mathematical modeling techniques, multicriteria decision analyses, etc., need to be well explored and adopted in the field of MAR in an integrated way. Above all, the most promising MAR options must be studied in terms of environmental impacts, socio-economic efficiency, as well as their contribution to solutions to the prevailing or future water resources problems.

For the efficient integration of the broad range of technical data, experience, and process information that might be germane to decision making, a common and clear guideline, and decision support system is required in the field of MAR. The main objectives of the specific DSS are to: 1) analyse different operation scenarios, 2) evaluate the consequences of each scenario, using already proven technical and analytical tools (e.g., groundwater model, GIS techniques, Multi-Criteria Analysis, etc.), and 3) to suggest best possible option(s) for assisting specific decision makers, individually or in groups. Presently, such intelligent systems are missing in the field of MAR. Several studies (e.g. Dillon et al., 2001; Asano and Cotruvo, 2006; Amy and Drewes, 2007; Chowdhury et al., 2010) have been performed to meet only a part of the requirements of the whole system. Plans to support MAR project implementation and to combine the acquired knowledge in the IWRM framework, facilitating decision makers to implement MAR projects, are themes, which have to be addressed. Therefore, a comprehensive study is required which has a main focus on the integration of different components and aspects of MAR project implementation in a framework starting from an initial preliminary feasibility assessment to a final MAR project plan, considering both local and regional water resources problems.

1.3 Research Needs

The IWRM concept puts great importance on the fact that all water is part of a greater system, which should be identified in order to approach water resource management holistically. In this respect, MAR is considered an integral part of IWRM. The state-of-art documents for MAR clearly indicate the importance of undertaking research that supports the planning of MAR in a region within the context of IWRM. The major research requirements for MAR are as follows:

- Creating a detailed framework for the planning and management of MAR projects
- Constructing a Decision Support System (DSS) to support planning and management of MAR while combining modern decision analysis techniques
- Building guidelines and a framework for the monitoring of infiltrated water quality under Soil Aquifer Treatment (SAT) while taking underground processes and spatial/temporal behaviour of emerging pollutants into consideration
- Applying mathematical modeling techniques for quantification of the most representative decision criteria under different MAR implementation strategies
- Introducing and implementing state-of-art analysis techniques for socio-economic assessments of different MAR implementation strategies

The research requirements outlined above are based on a critical review of the state-of-art of the MAR planning concept and are the conclusions drawn from the critical review of the literature by the author. In order to meet these requirements the present study was conducted and the objective thereof is outlined in the following section with close respect paid to the above mentioned research requirements.

1.4 Objective of the Present Study

With respect to the already outlined research requirements, the focus of this study and main objective is to offer a decision support (DS) framework for the implementation of MAR projects with non-conventional water resources to combat water scarcity and to provide decision support tools for the decision makers.

The specific objectives of the study are:

- Development of a guideline and workflow for a DS framework for planning and management of MAR in the context of IWRM
- Provide basic concept, data exchange, functionality and interface for G - DSS development
- Formulation of a pre-feasibility assessment to address MAR viability and potential challenges while focusing on an over-exploited and stressed urban aquifer
- Development of a spatial multi-criteria decision analysis (SMCDA) procedure to support the selection of the most suitable location for MAR; the evaluation and the ranking of the selected sites by mathematical modeling
- Study the impacts of the most representative environmental, health, and socio-economic decision criteria of MAR implementation strategies and to select the best strategy based on this

- Design an example of groundwater monitoring network for detection of water quality changes under SAT and propose an optimum pond operation schedule for decision makers, using a process based transport model

The report will explain in detail the efforts made to reach these objectives as well as describe the results and provide an analysis of their significance.

An innovative geospatial decision support system (G-DSS) was developed within the scope of the European Research Project GABARDINE (Rusteberg et al., 2011). The objectives of the present study were set in a way that the outcomes contributed substantially to the development of the innovative G-DSS.

1.5 Outline of the Applied Methodology

A new detailed MAR planning framework, consisting of a detailed flow chart showing MAR planning steps and an accompanying guideline, is the focus of this study. For comprehensive support to the planning of MAR systems in water scarce areas, a structured and standard planning framework was formulated that served as a basis for the detailed development of the G-DSS. Three primary modules were developed in this study and introduced into the G-DSS: (i) MAR PLANNING module, (ii) a spatial MCA module for MAR site selection, and (iii) a MCA module MAR option comparison and ranking. A further significant contribution was made concerning the development of the DPSIR module of the G-DSS. The DPSIR (Driver, Pressure, State, Impact and Response) module facilitates the structuring of water resources problems by causal chain analysis that helps to determine potential response(s) and to spatially display the components of the problem, The MAR PLANNING module offers the explicit decision steps that are required to plan a project. An innovative Spatial Multi Criteria Decision Analysis (SMCDA) tool was developed to support MAR site selection and is considered as a component of the planning tree for the system. The new SMCDA tool functions based on the combination of existing multi-criteria evaluation methods with modern decision analysis techniques. The MCA module, to perform MAR option comparison and ranking, is able to consider a wide range of criteria and analysis techniques, namely the Analytical Hierarchy Process (AHP) and Weighted Linear Combination (WLC). In order to use the modules and related components of the G-DSS, an interactive user-friendly interface was designed in the present study and provided in the G-DSS. Four primary and core steps of MAR planning are: (1) MAR pre-feasibility analysis, (2) Site selection and ranking, (3) MAR option analysis, comparison and ranking, and (4) Soil-Aquifer-Treatment (SAT) system operation and impact assessment. These steps were considered in this dissertation for practical and detailed investigation in one test site in Bangladesh and three test sites of the GABARDINE project.

1.6 Structure of the Thesis

This report consists of ten chapters. In general, chapter 4, 5, 6, 7, 8, and 9 describe the main research works undertaken in this study. All chapters are written in a way that each of them can be read as a stand-alone piece of research including introduction, methodology, results, discussion, conclusion and references. The outlook of each chapter is briefly explained below:

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 study. Additionally, this chapter shows the outlines of the individual methodologies that are an integral part of the overall methodological framework of this study.

Chapter 4 describes the conceptual framework of the G-DSS development for MAR that is followed by an explanation of the G-DSS functionality, supported by figures of the G-DSS interfaces.

Chapter 5 introduces the importance of the preliminary investigations and knowledge requirements that are required for the decision makers before starting any MAR project implementation by giving an example of an overexploited and stressed aquifer in Dhaka, Bangladesh. A combination of regional and local scale investigations and analyses are presented in this chapter.

Chapter 6 describes a new, innovative, and robust Spatial Multi Criteria Decision Analysis (SMCDA) system for the selection of appropriate sites for the implementation of MAR for a groundwater body, in the Algarve region, Portugal.

Chapter 7 evaluates and ranks the selected sites, using the developed Spatial Multi Criteria Analysis methodology described in Chapter 6, supported by groundwater modeling. A simple groundwater body (North Gaza, West Bank) was taken into consideration to establish the hypothesis of a combined procedure of site selection by spatial multi criteria analysis and site ranking by groundwater modeling.

Chapter 8 elaborates the overall MAR project impact assessment and investigation techniques by undertaking environmental, social, and economical criteria quantification studies and performing multi criteria analysis for the strategies' comparison and ranking.

Chapter 9 concentrates on the understanding of the fate and transport of certain emerging pollutants under soil aquifer treatment. The study reveals the local scale water quality changes during MAR. Finally, an example of groundwater monitoring plan and a pond operation are suggested.

Chapter 10 synthesises and concludes the results obtained under different research methodologies in different climatic and geographical conditions for MAR. Further research ideas together with the statement of the limiting factors of this case study are stated.

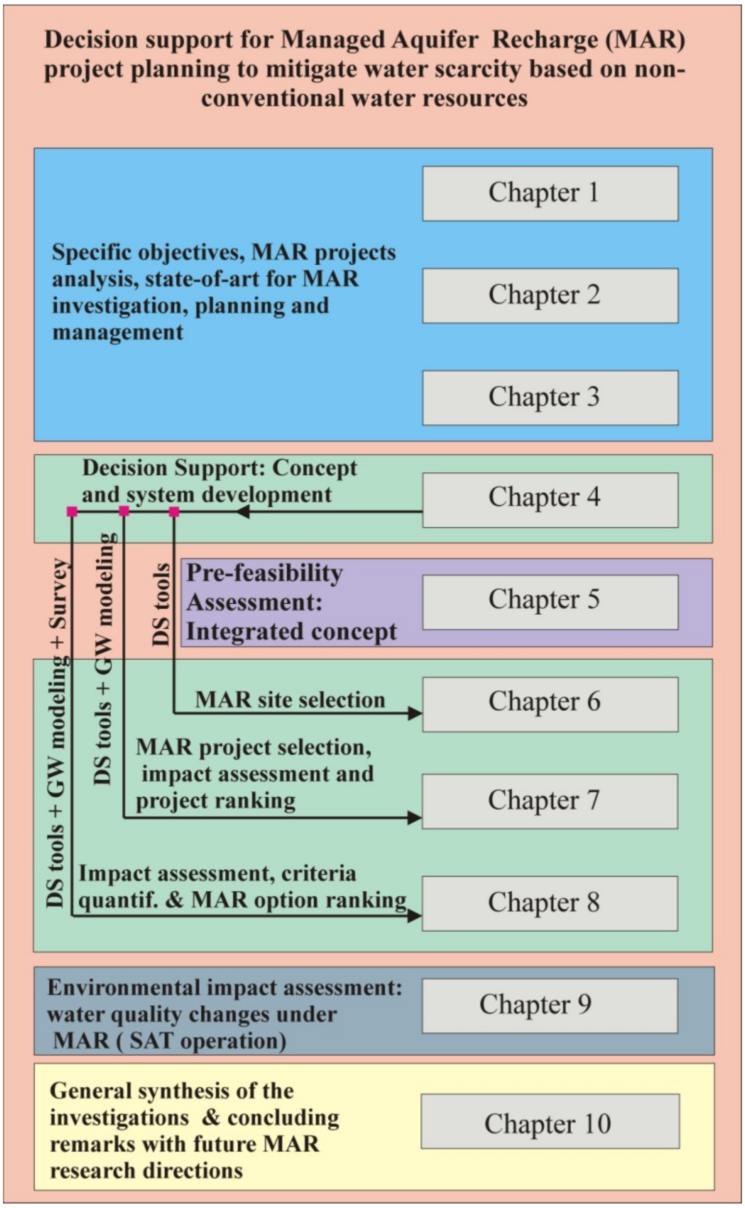

Figure 1.1: General structure and overview of the thesis

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Chapter 2

Managed Aquifer Recharge: State-of-the-Art and Theoretical Background

2.1 Managed Aquifer Recharge: State-of-the-Art

2.1.1 History of managed aquifer recharge

Managed Aquifer Recharge (MAR) is the process of augmentation of the natural movement of surface water into subsurface by technique of construction, by surface spreading of water or by artificially changing natural conditions (Todd, 1980). To enhance the natural supply of groundwater, MAR is becoming increasingly important in groundwater resources management and particularly in situations where the conjunctive use of surface water and groundwater resources is considered (Asano, 1985). MAR in the form of rainwater harvesting and storm water retention has been practiced for millennia in the more arid parts of the world, including the Middle East, India, and the American Southwest (Maliva and Missimer, 2010). In Europe, MAR schemes have been in operation for over one hundred years (Water & Forestry, 2007). 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. Aquifer Storage and Recovery (ASR) was carried out at Mount Gambier, in close proximity to Blue Lake in South Australia, over 100 years ago (DWLBC, 2010). The East London Waterworks Company conducted artificial recharge experimentation in response to the depressurisation of the Chalk and Basal sands aquifer in England (O'Shea et al., 1995). Todd, (1959) indicated that MAR was being widely investigated and implemented by the middle of the 20th century for different purposes. The first successful test of an Aquifer Storage and Recovery (ASR) System with mixing of fresh water in an aquifer containing brackish water appears to have been performed at Camp Peary (Cederstrom, 1947). Cederstorm, (1959) reported that after several years of operation, it might be possible to recover a quantity of fresh water nearly equal to the total quantity recharged. In USA, the first long term ASR project was implemented in Wildwood, New Jersey in 1967 (Lacombe, 1997). 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) reported that Israel had an earlier than the USA successful ASR project implementation, which began in 1955. The author also discussed the existence of a transition zone between the stored and ambient water. Theoretical, experimental, and field studies of ASR and the hydrology of water were performed in the United Arab Emirates and Kuwait (Senay, 1977), in Israel (Bear and Jacobs, 1965) and by Louisiana State University in the United States during the middle of the 1960s and 1970s (e.g., Esmail and Kimbler, 1967; Moulder, 1970; Smith and Hanor, 1975). Pyne (2003) stated that ASR was first used in the USA in 1969 in Wildwood, New Jersey. The first managed aquifer recharge operations in Australia were infiltration basins established in the mid-1960s on the Burdekin Delta, Queensland. These have been operated and maintained continuously for over 40 years and are currently the largest Australian system at 45GL/yr. (Dillon, 2009; Charlesworth et al., 2002). The change of water quality and clogging of pond bed under infiltration has been reported and discussed by Bouwer (1968). Hiusman and Olsthoorn's (1982) book, *Artificial Groundwater Recharge* and Asano's (1985) book, *Artificial Recharge of Groundwater,* provide an important theoretical discussion and some case studies of MAR. 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 10further pilot studies being conducted. Later Pyne, (2005) reported that the number of ASR systems had increased to 72 by March 2005. Review of the MAR history reveals that the important technical issues that are relevant for a successful MAR scheme implementation mentioned today is already reported or addressed in earlier MAR studies or reports and related scientific papers.

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 brief overview on the different technical, management and planning issues of MAR.

2.1.2 Basic requirements to implement managed aquifer recharge (MAR) projects

Every water resources development project has some basic requirements which should be fulfilled before any further planning and implementation of the project. The three very basic requirements for MAR implementation are:

A) Water Source: Availability of non-committed and non conventional water surplus for recharge

B) 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

C) MAR Technology or Methodology: Methodologies should be appropriate to meet the defined objectives and local hydrogeological settings

These three requirements are briefly explained below:

A) Water source

Water source is the one of the basic requirements. The main water sources for MAR are: Surface water, Storm-water runoff, treated effluent, potable water, and imported water (after UNESCO-IHP, 2005).

(a) Surface water

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.

(b) Storm-water runoff

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)

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).

B) MAR location

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. Besides these factors, 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)

C) 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. Incidental recharge from irrigation (excess irrigation)
   - v. 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
   - v. Stream augmentation

(c) Direct subsurface techniques (well, shaft, and borehole recharge)
   - i. Open recharge wells, pits, and shafts
   - ii. Borehole flooding
   - iii. Aquifer Storage and Recovery (ASR)
   - iv. Natural openings, cavity fillings

(d) Indirect recharge (induced recharge)
   - i. Bank infiltration
   - ii. Inter-dune filtration
   - iii. Aquifer modification

(e) Rainwater harvesting

i. Roof top rainwater harvesting

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

(f) Combination of surface and subsurface techniques

i. Basin or percolation tanks with pit shaft or wells

ii. Rooftop Rainwater Storage and recharge of excess rainwater by wells.

The following sections briefly describe the most commonly practiced techniques of MAR that are quite relevant for the study (after UNESCO-IHP, 2005):

(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. 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.

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.

Soil aquifer treatment

Implementation of Soil Aquifer Treatment (SAT) is now a common practice for MAR and will be increasingly important (Drewes, 2009). 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). 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 detailed explanation of removal of organic and inorganic matter during SAT is provided later on in this chapter (section 2.1.6).

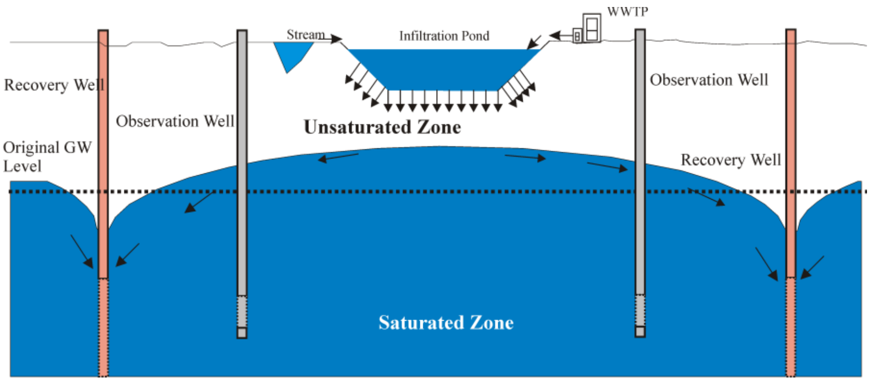

Figure 2.1: Schematic view of Soil Aquifer Treatment

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).

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.

(b) In-channel modifications

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.

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.

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.

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. 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).

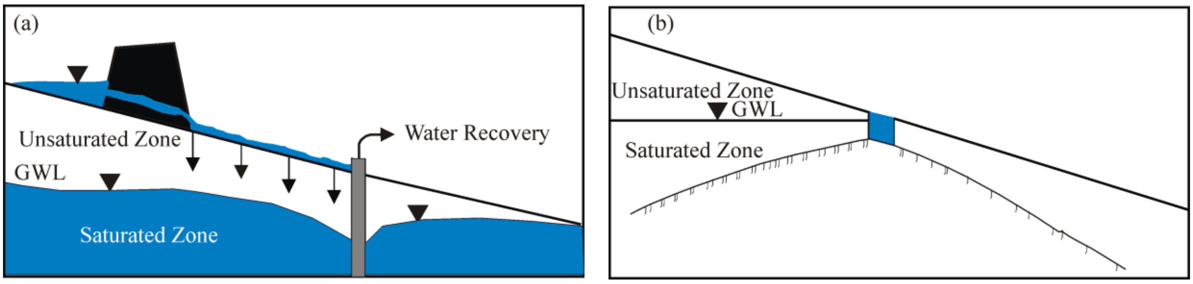

Figure 2.2: Schematic view of (a) leaky dams and recharge release, and (b) sub surface dams (modified after UNESCO-IHP, 2005)

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

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.

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). 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 injectant applied in an ASR system should pass through proper pre-treatment before any injection (UNESCO-IHP, 2005).

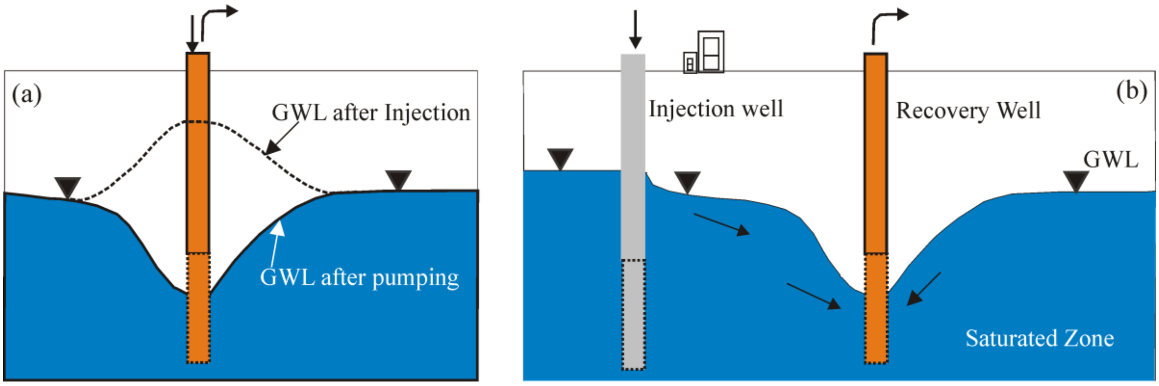

Figure 2.3: Schematic view of (a) ASR and (b) ASTR (modified after UNESCO-IHP, 2005)

(d) Indirect Recharge

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)

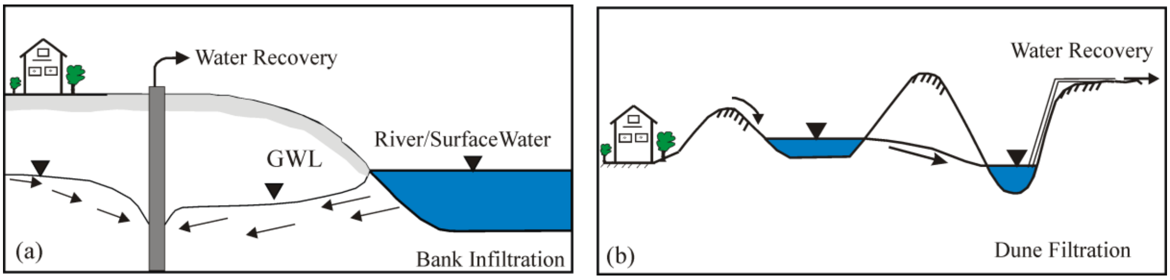

Figure 2.4: Schematic view of (a) Bank infiltration, and (b) Dune filtration (modified after UNESCO-IHP, 2005)

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 2.2b). 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)

Roof top rainwater harvesting

Roof top rainwater harvesting can conserve rainwater for either potable use or for recharge of groundwater. 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.

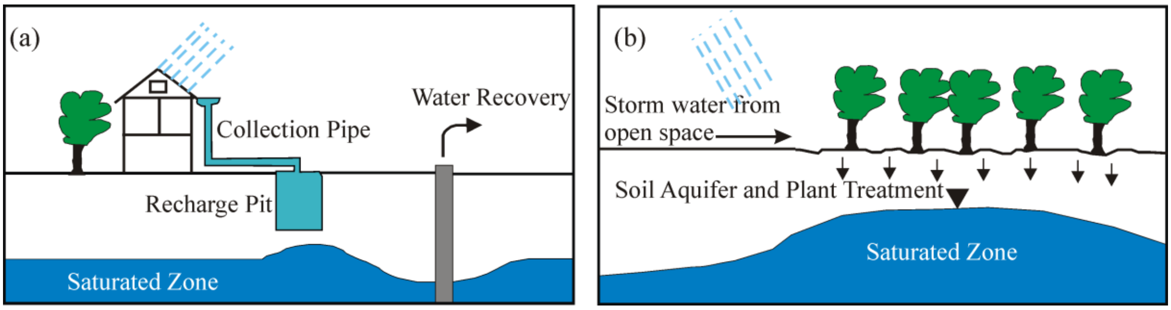

Figure 2.5: Schematic view of (a) Rooftop rainwater harvesting, and (b) Rainwater collection from open spaces and SAT using a wetland. (modified after UNESCO-IHP, 2005)

Open spaces rainwater harvesting

Rainwater harvesting methods using open spaces involve micro-watershed management methods that allow rainwater collection, infiltration, and percolation into the subsurface. 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.

2.1.3 An outlook on Managed Aquifer Recharge projects in the world

This section describes the outlook of the managed aquifer recharge projects in different continents in the world. A total of 93 case studies were analysed that include regional examples, site-specific examples, and pilot projects. Some of the projects have been incorporated to the overall water resources management of the respective area. Some of the projects are focused to solve local water resources problem and some projects aim for scientific understanding of certain issues relevant to the local problems. In order to assess the large amount of information on MAR, published research reports and guideline reports were taken in consideration. Figure 2.6 shows the distribution of the projects analysed in the study. 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. The following section

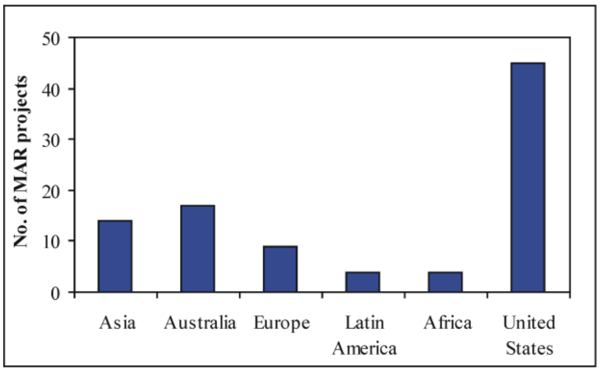

Figure 2.6: Continental and regional distribution of MAR projects analysed in this study

briefly describes worldwide practice of MAR projects in terms of water source, water use, MAR techniques, and aquifer type.

Water source

The source of water varies across the projects and includes surface water (43%), treated effluent (22%), storm water (17%), and mixed type water (18%). From the analysis (Figure 2.7a), it can be concluded that in most cases the water source is surface water because of the availability and the lower pre-treatment requirement. Advanced treatment of wastewater and subsequent injection of treated effluent into the aquifer is now being increasingly practiced. This type of water is mainly used in developed countries. In the United States, most of the current ASR schemes involve potable water (AWWA, 2002). The Dan Region project, the largest artificial recharge project in Israel, uses the treated effluent from Tel Aviv and reuses the stored water for unrestricted irrigation. The use of storm runoff is widely practiced in the countries, which have heavy rainwater during the wet season such as in India. Some MAR projects function by mixing treated effluent with storm water (IGRAC, 2010). However, the quality of source water is now the main determining factor for MAR implementation worldwide.

Use of water / Objective of the project

MAR now plays an important role for the improvement of water supply conditions. In this study, 39% of the projects reviewed aim at improving water supply at the localities. In Germany, 54% of the applications are mostly for drinking water supply (Water & Forestry, 2007). Seasonal storage of water is another main objective of MAR where enough rainfall is available during the wet season. Reclaimed water can be reused for agricultural use after water quality improvement in the aquifer (Figure 2.7b).

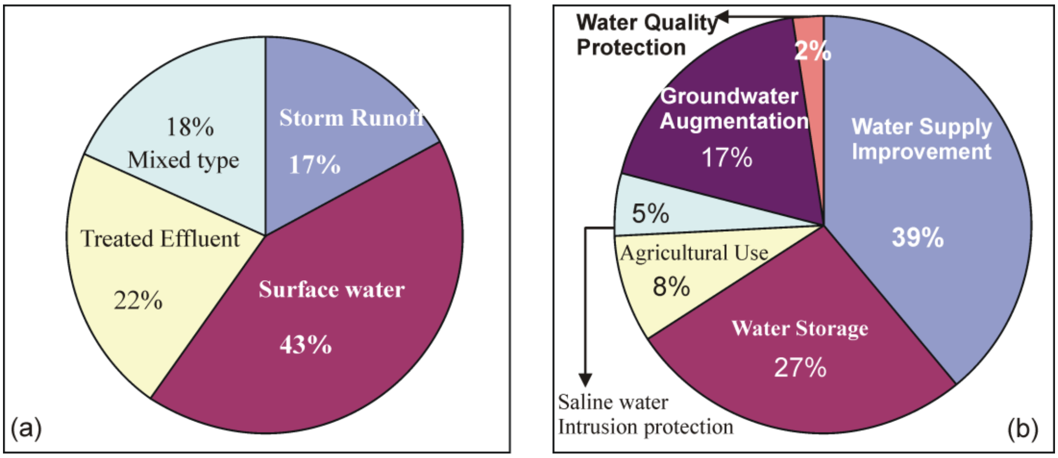

Figure 2.7: (a) Water source for MAR projects and (b) uses of MAR projects

Very few projects are working on the aim of protecting salinity intrusion in the coastal aquifer. In china, most MAR projects are aimed at the enhancement of groundwater resources (Han, 2003). Many projects have been implemented to achieve two or three of the objectives mentioned above. The Burdekin Delta scheme, the oldest and largest infiltration scheme in Australia, provides water for sugarcane areas using surface infiltration techniques. It is also used to prevent salt water intrusion into the aquifer (Narayan et al., 2007).

Aquifer types

In this study, the hydrogeological environments (aquifer type) are grouped into four general categories, namely alluvium, fractured hard rock, consolidated sandstone and carbonate aquifers, according to the description given earlier in section 2.2. 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. 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. MAR projects in fractured rock aquifers exist in India (CGWB, 2000) for transferring the captured storm/surface water over large distances.

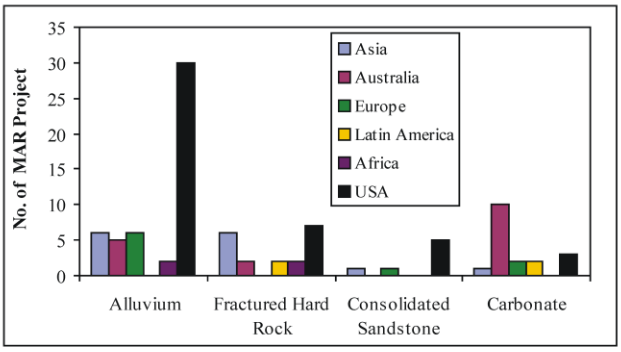

Figure 2.8: Predominant aquifer types for MAR projects in the world.

MAR techniques

The spreading basin is the most popular MAR technique all over the world. The spreading basin offers the most benefit of SAT and it is economical. A number of pilot ponds have been constructed in order to develop site-specific information on the hydrogeology and water quality (e.g. removal of organic matter). ASR using recharge wells is also a well-known MAR technique (see Figure 2.3). Recharge wells are mostly used where a thick impermeable layer exists at the top of the aquifer. Considerable innovative implementation of the ASR scheme and research into ASR has recently been undertaken in Australia and the USA. 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-channel modification and rainwater

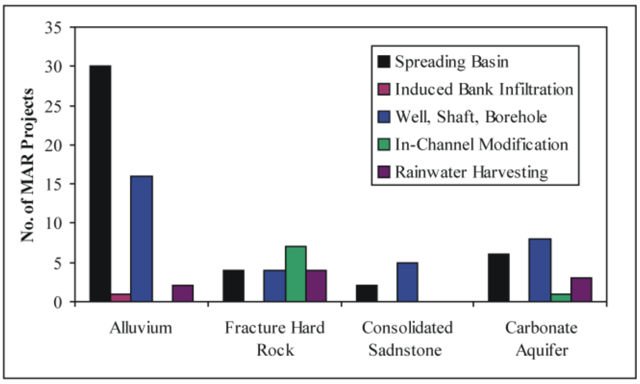

Figure 2.9: Worldwide practiced MAR Techniques in different hydrogeological conditions

harvesting are a commonly practiced technique in the various provinces of India, Pakistan, and Australia. Mostly roof-top harvesting is done in India (CGWB, 2000; UNESCO-IHE, 2005). Roof-top rainwater harvesting is being made mandatory, by amending the building by-laws, in urban areas of India where ground water levels are more than 8 meters below the ground surface or the roof area is more than 100 m^2 (UN-Habitat, 2006; CGWA, 2001).

Lesson learned from the analysis

A number of lessons learned can be drawn from the analysis of the 93 projects. First of all, it can be concluded from the review that MAR can significantly contribute to the water resources problem solution. The main benefits of MAR are: water storage and supply for domestic consumption and irrigation, enhancement of groundwater resources, and the prevention of salinity intrusion and the minimization of environmental damages. Besides the advantages, MAR schemes face a number of problems that should be considered during planning. First of all, well clogging is a problem that many MAR projects in the world have faced. Back flushing of recharge wells and wetting/drying cycles of the infiltrations basin are the main technique to manage clogging problem (Maliva and Missimer, 2010). Depending on the aquifer type, the frequency of back flushing and wetting/drying are set. Little information is available about the GW quality monitoring network. Many documents reviewed suggested implementing a good monitoring network to understand the geochemical processes, well hydraulics, and the degree of water quality improvement. Economics of MAR is another prime issue for MAR implementation. Very few documents reported on the cost-benefit analysis of the MAR projects. Brown et al., (2005) reported that the cost of a cubic meter of recovered water is $1.54 for non-brackish sites while it is $3.56 for the brackish water. The issue of regulation and permit is also a great concern and sometimes frustrating to the ASR operators. One Californian ASR facility requires permits from 14 separate agencies for that facility (Water and Forestry, 2007). The main conclusion drawn from this literature review is that the study of and application of decision support systems for planning and management of MAR projects has been lacking. AWWA, 2002 reported that 89% of the ASR operators were satisfied with their projects. Due to the lack of proper decision and good understanding of the system, a number of projects became unsuccessful in some other countries. The future challenge of MAR is the proper planning and management of projects.

2.1.4 Managed Aquifer Recharge project planning, impact assessment, and Decision Support System (DSS)

Planning of Managed Aquifer Recharge Project

The review of MAR history (see Section 2.1.1), basic requirements of MAR (see Section 2.1.2) and outlook of MAR projects worldwide (see Section 2.1.3) support one important conclusion: MAR does not work everywhere and a number of schemes either failed or did not achieve satisfactory results.

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 favourable 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.

MAR regulatory framework

The principle objective of MAR regulatory framework is to protect the groundwater body from any pollution and to ensure public health safety. As the regulation for environmental protection and public health is different from country to country and state to state, each MAR regulatory framework has been formulated to adopt the relevant local and regional legal issues. The following issues are commonly treated in the existing MAR regulatory frameworks over the world (from NRC, 2008):

- MAR structure (such as infiltration basin, injection well etc.), construction, and pilot testing
- Authorization to inject or infiltrate water in an aquifer
- Recharged water quality requirement
- Authorization to store water and recover water from an aquifer
- Protection of the stored water

The following sections give a very brief description of regulatory requirements MAR in the United

States, Australia, the United Kingdom, France, and Spain.

In the United States, the extraction of water from surface water bodies and aquifers is regulated by the states or by local regulatory agencies. Therefore, the regulation for MAR in the USA is fragmented. A variety of different state, federal, and local regulatory agencies have been working on this issue (Maliva and Missimer, 2010). A number of codes of regulation regarding wastewater reuse have been issued by the California Department of Public health (CDPH, 2008) and these are designed for recharging aquifers designated as a source for drinking water supply (Hochstrat et al., 2010). Therefore, a minimum residence time of 60 days is also specified for water quality improvement (CDPH, 2008). The regulations promote sophisticated pre-treatment before recharge and suggest a strict monitoring program. In general, groundwater law controls the use of groundwater resources in the USA. Key groundwater laws issues related to ASR include authorization for use of the aquifer, ownership of the injected and stored water, and protection of stored water for other aquifer users (Maliva and Missimer, 2010).

The main objective of MAR projects in Australia is to use the recovered water for non potable use using poor quality water (Dillon et al., 2001). Therefore most MAR guidelines are formulated accordingly. Australian water recycling guidelines consist of several documents and have solely advisory character and are not prescriptive (Hochstrat et al., 2010). Instead of setting values for water quality parameters, the documents provide principles and a framework for safe implementation of a MAR scheme using a multi barrier approach as a key concept (Hochstrat et al., 2010). The Australian regulatory approach is practical and flexible because the injected water quality requirements are matched with the actual potential aquifer water uses rather than assuming human consumption (Maliva and Missimer, 2010). It is assumed that aquifer treatment can be taken into consideration that as a means for the recovered water achieving water-quality criteria relevant to its anticipated beneficial use (Dillon and Pavelic, 1996).

An overview of the MAR regulatory issues in the United Kingdom is provided by Gale et al., (2001) and summarized by Maliva and Missimer (2010), which is concisely stated therein. The authorization or licensing of the source water extraction, the quality of the recharged water and potential environmental impacts are addressed in the regulatory documents. A phase approach is employed for the implementation of ASR and no guarantee of approval of future project phase is given. The project developed should ensure that the recharge and discharge of any water is in accordance with the legislative and water & environmental agency requirements. For protecting the environment, the agency will seek to control all recharge and subsequent recovery to ensure effective water resources development. Monitoring, abstraction, and discharge requirements will be established. Under the Groundwater Regulation (1988), an authorization is required for the discharge of listed substances (list I: no entry substances, list II: no pollution by substances) to groundwater. Environmental Impact Appraisals are required to confirm that environmental effects of the proposed MAR project are considered.

The French MAR regulatory frame has been summarized by Ward and Dillon (2009) and concisely presented therein. French water policy relies on regulatory and planning instruments combined with various degrees of negotiated agreement, which is different from the Australian and UK guidelines. Water management is subject to compliance with three levels of water policy: the European Union, the National level, and at the level of the hydrographic basin. The European directive *Eaux Résiduaires Urbaines 1991*, is set down into the French water law of 1992 and is the legislative basis for stormwater and aquifer management. French Water law states for two water management regimes: authorization and declaration. Declaration is less controlled than authorization, and applies when the total harvesting surface area ("superficie totale desservie") is greater than 1ha and less than 20ha. Harvesting approval is granted on submission of documentation. The granting of an 'Authorization' for areas greater than 20ha is conditional on the results of preliminary environmental impact studies and assessments complying with set water condition standards. French water legislation articulates legislative direction and prohibits at the EU, national, and local basin level harvesting, aquifer storage, and extraction applicable to ASR (Ward and Dillon, 2009).

The decree, Royal Decree 1620/2007, of December 7th, establishing legal regulation for the reuse of treated wastewater (R.D. 1620/2007, de 7 de diciembre, por el que se establece el regimen juridico de la reutilizacion de las agues depuradas) and adopted by the Spanish Government describes the various clauses of water reuse regulation and authorization. The decree states various water reuse types, and sets a number of water quality criteria for recovered water. The legal issues also refer to the Groundwater Directive (GWD), established by the European Commission (EC, 2009) in some clauses. The legislation explicitly excludes the reuse of recycled water for potable use (Hochstrat et al., 2010).

From the above discussion, it can be summarized that each regulatory framework concentrates on the protection of groundwater storage zones and public health. The Australian approach to MAR is probably a more science-based, commonsense permitting process, which matches the current and future uses of the storage zone with the appropriate water quality standards (Maliva and Missimer, 2010).

MAR Impact assessment and mathematical modeling

MAR impact assessment is an essential MAR planning step. Environmental and health impacts can be assessed using mathematical modeling. Until now, the implementation of mathematical modeling for

MAR impacts has not been well practiced. Only few examples have been found in the literature on the use of mathematical modeling in the field of MAR. The application of a mathematical model for SAT system analysis covers three aspects: Operation of pond, water flow, and reactive transport. The determination of the operation schedule is required of the decision maker to perform preliminary analysis on SAT systems. Tang et al., (1996) and Li et al., (2000) developed an optimization methodology for operation and design of SAT. The studies developed a SALQR (successive approximation linear quadratic regulator) algorithm to solve the SAT operation problem .The SALQR algorithm was applied to solve the multi-stage non-linear optimal control problem. The SALQR algorithm is a modification of differential dynamic programming (DDP) and is considered for the optimal operation of SAT systems under uncertainty (for description of SALQR see Li et al., (2000) Appendix- A). Unsaturated flow model HYDRUS 1D (Šimůnek et al., 1998) was used to describe the hydraulics and was modified to consider the water quality aspect and the effect of a clogging layer. The HYDRUS 1D model was also subsequently interfaced with SATQR. This combined model was named SATOM (SAT operation model). The optimal operation model determines optimal value of the control variables (e.g. the application time, the drying time) in order to maximize the infiltration. The simulator HYDRUS determines the state of the SAT for these decisions. The combined model closely obtains the global optimal solution. Instead of using SALQR algorithm, the Genetic Algorithm (GA) combined with modified HYDRUS 1D can also obtain global or near global optimal solution, which has been concluded by Tang and Mays (1998). GA is one of the combinational optimization methods. GA has the ability to search large and complex multi-modal decision spaces and can efficiently handle nonconvexities that cause difficulties for traditional optimization method. The authors (Tang and Mays, 1998) developed a combinational scaling method and devised a special evaluation procedure to improve the performance of GA. So, for determining the multi-cycle SAT system operation, a computer model, GASAT, was developed in FORTRAN using the GA procedure and interfaced with the simulator HYDRUS. The comparative study of GASAT with SATCOM reveals that GASAT obtains a better solution, although it requires more CPU time than SATCOM. The main drawback of these two models is that they did not consider water quality issues. The models are 1D and flow and transport simulations are completely dependent on HYDRUS. The optimization models could be coupled with MODFLOW in order to simulate three dimentional flow and transport. Using the MODFLOW code developed by USGS, MODFLOW-SURFACT can analyse flow and contaminant transport using vadose zone flow and transport equations (Panday and Huyakorn, 2008). Under SAT process, the fate and transport of organic and nitrogen species has been studied in limited scale using MODFLOW SURFACT (Kim et al., 2004). The authors concluded that the model successfully described that fate and transport of the key constituents during the wet/dry operation periods in both unsaturated and saturated subsurface environment.

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.

Decision Support System (DSS)

Presently, each IWRM project focuses on a Decision Support System (DSS). Many researchers have long since recommended the use of a DSS in Integrated Water Resources Management Planning. Though DSS started to appear in Water Resources System (WRS) in the mid-1970's, significant progress has only been made in last few years. A number of DSS have been developed specifically for a given basin and are rarely useful for a different system. For flood management issues, CWMS (Fritz et al., 2002), SMS (EMRL, 2004), WMS (EMRL, 2004) etc., for accidental Spill DBAM (van Gils et al., 2004), Riverspill (Samuels et al., 2003), WQModel (Whiteaker, 2004), for water allocation issue; AQUATOOL (Andreu, 2004); DELFT TOOLS (Delft Hydraulics, 2004); MIKE BASIN (DHI, 2008) and MIKE SHE (DHI, 2009), etc, for water quality issue BASINS (USEPA, 2004), MODULUS (Oxley et al., 2004), WISDOM (BMBF, 2010) etc., are available. DSSWRP and MULINO decision support systems (EC, 2006) address integrated water resources management issue. A number of BMBF IWRM projects are now concentrating on the development of DSS (e.g., BMBF, 2009a, BMBF, 2009b; BMBF- MOST, 2010), but most of them are region specific.

No DSS exists regarding the artificial recharge system. Some researchers separately worked on the development of DSS on a specific component of MAR. Ghayoumian et al., (2005) developed a DSS for artificial recharge site selection using GIS. No interactive window with the user and system as well as interface was incorporated to facilitate decision-making. Evaluation of multi criteria was also missing. Dillon et al., (2007) emphasized the improved governance of MAR addressing water allocation and water quality protection. The author discussed the science and technology base necessary to support good guidelines especially for water reuse. A complete flexible, non-site specific and adaptive DSS for MAR project planning is missing.

2.1.5 Mixing of injected water with native groundwater and hydro-geochemical processes and clogging problems under MAR

Mixing of injected water with native groundwater

The main mechanisms for reduced/transformed quality of influent water are dispersion, density stratification and lateral movement down the hydraulic gradient. Mixing occurs at the interface of injected water and native groundwater, and than dispersion occurs in the mixed condition. The degree of mixing is largely dependent on the physical property of the aquifer and partly depends on the type of flow in the aquifer. The mixing between two dissimilar water types (injected water and native groundwater) and interaction with the aquifer minerals can adversely affect MAR schemes by deteriorating the recharged water quality (Herzceg et al., 2004) and may cause pond bed, well, and aquifer clogging (Cuyk et al., 2000). The mixing phenomena may vary in variably saturated zone and saturated zone, as the hydraulics and system behaviour of these zones are quite unsimilar.

Occasionally, the artificial recharge of water may cause "new" reactions to take place, which could lead to the quality of the recovered water being outside of the range of quality spanned by the injection and native water. Major chemical changes to the quality of the injected water are to be expected when one or more of the following conditions are met (after Gale, 2001):

(a) If there is large difference in chemical quality between recharged water and the native water, large differences in pH and redox state can occur

(b) The native ground water or the aquifer material do not posses a sufficient pH buffering capacity

(c) There is large difference in elemental concentrations between the recharged and native water and significant mixing occurs

(d) A change in chemical condition of the water having contact with the aquifer material is able to enhance major or minor chemical reactions

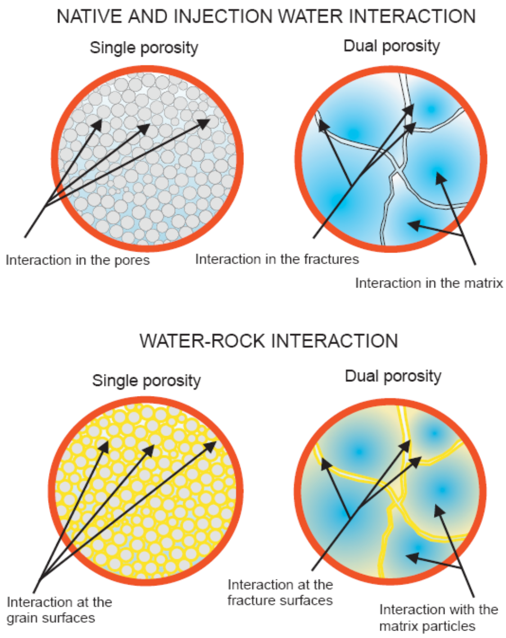

Figure 2.10: Chemical interactions between groundwater and aquifer, which can take place during ASR (Gale, 2001)

The chloride ion is mostly used for determining the mixing ratio of infiltrated water to native groundwater. Equation 1 and 2 show the general equation for calculating mixing ratio of injected water to groundwater using the chloride ion. Herczeg et al, 2004 reported the proportion of injectant estimated using equation 2 ranges from 17% to 100% at the 5 m distance to injection well, 17 to 100% at the 25 m distance to observation borehole, >2% to 12% at 65 m distance, and <2% at 325 m distance. General equations for calculation of mixing ratio are as follows (after Herczeg et al, 2004):

$[Cl^-]_{mix} = X [Cl^-]_{inj} + (1-X) [Cl^-]_{gw}$ 1

$X = ([Cl^-]_{mix} - [Cl^-]_{gw}) / ([Cl^-]_{inj} - [Cl^-]_{gw}$ 2

where ,

$[Cl^-]_{mix}$ is the Cl^- concentrations in the mixed groundwater sample,

$[Cl^-]_{inj}$ is the Cl^- concentrations in the injected water,

$[Cl^-]_{gw}$ is the Cl^- concentrations in the native groundwater sample,

X is the fraction of injected water in the mixtures,

The error in estimating fractions (E_{mix}) ranges from 7-11% based on the square root of the sum of the squares of the respective standard deviations

$E_{mix} = \sqrt{\{(E_{inj})^2 + (E_{gw})^2\}}$ 3

E_{inj} and E_{gw} are the standard deviation of the respective end members.

Carbon absorption study reveals that within 120 m of the infiltration pond, no measurable mixing has been observed. The ration of infiltrated water at a distance 480 m and 700 m were found 88-89% and 55-60% (Kortelainen and Karhu, 2006).

Hydro-geochemical processes under MAR

Hydrochemical characteristics below the infiltration pond develop either saturated or unsaturated conditions and are controlled by the presence or absence of O_2. The highly dynamic changes in the redox environments result in the variably hydraulic behaviour of this infiltration system. High degradation of organic carbon produces more reducing conditions directly below the pond (within 1m) (Drewes, 2009; Greskowiak et al., 2005). The zone of entrapped air may re-oxidize the redox species down gradient, which probably produce the redox condition further downward than the narrow zone below of infiltration pond. The chemical heterogeneity of the sediment and non-uniform flow conditions may be responsible for a non-uniform redox pattern below the pond (Greskowiak et al., 2005). The authors also concluded the following: (1) The C cycling is strongly affected by the occurrence of an unsaturated environment below the pond, (2) When the infiltrated water is relatively warm, the spatial and temporal development of the redox chemistry is strongly linked to the prevailing hydraulic conditions and their dynamics below the basin, (3) seasonal temperature variations may not affect the overall characteristics of the hydraulic system.

If hydraulic loading rate is high or the dosing rate is slow, some constituents of concern, which would normally be treated, may be transported through the vadose zone to the groundwater. A lysimeter study concluded that under certain conditions, infiltration character and soil depth did not exert considerable effect on hydraulic and purification performance (van Cuyk et al., 2001).

Table 2.1 shows some related geochemical reactions that might occur below the pond and /or in the aquifer during MAR implementation. Some of the major geochemical processes that may perturb the long term equilibria or steady state conditions between the groundwater and the aquifer minerals due to ASR schemes are summarized below:

1. As the precipitation of calcium carbonate is a common mechanism of chemical clogging of wells, in general, Calcium carbonate geochemistry is important for ASR systems. The calcite precipitation or dissolution due to the mixing may occur even if both of the water are at or near to saturation (Herczeg et al., 2004)
2. Denitrification is another major redox reaction that depends upon the concentration of nitrate in the injected water. If potable water or rainwater that contains low nitrate, denitrification will be a minor process (Vendarzalm and Le Gal La Salle, 2005)
3. The oxidation of manganese (Mn^{4+}) and iron (Fe^{3+}) species, relatively insoluble in the aquifer system, can produce mobile divalent forms (Mn^{2+} and iron Fe^{2+}) and thus can adversely affect the groundwater quality. Injecting reducing water into an oxidizing aquifer may also lead to the release of iron and manganese by dissolving iron and manganese oxides (Maliva and Missimer, 2010)
4. The sulphate reduction is an important redox reaction in ASR systems, particularly if relatively organic-rich water is recharged in a brackish or saline-water aquifer (Herczeg et al., 2004; Maliva and Missimer, 2010)
5. The fate of the organic material contained in the subsurface environment after recharge is largely dependent on the sorption process and the biodegradability (McCarty et al., 1985)
6. Microbial degradation rather than adsorption may be responsible for the removal or certain pharmaceuticals (Massman et al., 2006)

Table 2.1: Some of the reactions that may occur during artificial recharge of surface water (oxygenated) into an aquifer containing sub-oxic or anaerobic groundwater (after Herczeg et al., 2004 and Greskowiak et al., 2005).

	Chemical reaction	Reaction type
1	O_2 +CH_2O = CO_2 + H_2O	Organic matter oxidation via O_2
2	Fe0OH + CH_2O = Fe^{2+} + HCO_3^-	Organic matter oxidation via Fe (III)
3	SO_4^- + 2CH_2O = H_2S + 2HCO_3^-	SO_4 reduction
4	15/4 O_2 + FeS_2 = 2SO4^{-2} + Fe $(OH)_3$ + 4H^+	Pyrite oxidation via O_2
5	14Fe 3+ + FeS_2 + 8H_2O = 2SO_{4-}^{2} + 16H^+ + 15 Fe2+	Pyrite oxidation via Fe (III) reduction

	Chemical reaction	Reaction type
6	$CO_2 + H_2O + CaCO_3 = HCO_3^- + Ca^{2+}$	Carbonate dissolution
7	$X\text{-}Na_2 + Ca^{2+} = X\text{-}Ca + 2Na^{2+}$	Cation Exchange
8	$Mn^{+2} + 0.5O_2 + H_2O = MnO_2 + 2H^+$	Oxidation
9	$FeS + 2O_2 = SO_4^{2-} + Fe^{2+}$	Oxidation
10	$5CH_2O + 4NO_3^- = H^+ + 5HCO_3^- + 2N_2 + 2\ H_2O$	Organic matter oxidation by nitrate

2.1.6 Fate and transport of organics, and trace organics under SAT

Groundwater recharge with reclaimed wastewater and other sources of water is now being widely practiced in various parts of the world, especially in the arid and semi arid regions. Surface spreading basin (i.e. Soil Aquifer Treatment) is now a common practice for groundwater artificial recharge (Drewes, 2009). Soil Aquifer Treatment (SAT) is an economical and aesthetic wastewater reuse system. Since the soil and the aquifer can act as a natural filter, SAT system can remove suspended solids, biodegradable materials, bacteria, viruses, and other microorganisms (Bouwer, 1997). During SAT, secondary or tertiary treated wastewater infiltrates into the ground from an infiltration basin, percolates through the unsaturated zone, and finally mixes with native groundwater. Soil percolation includes several processes that occur during downward transport in the vadose zone. At the basin – soil interface, the combined effect of sedimentation, filtration, aeration and microbial growth leads to the formation of a biologically active zone that may be impermeable (Bouwer and Rice, 1984). The main problems concerning groundwater quality using reclaimed wastewater are pathogens, total minerals, heavy metals, and stable organic substances (Drewes and Jekel, 1998). Research has shown that a variety of organic compounds including veterinary and human antibiotics, other prescription and non-prescription drugs, widely used household and industrial chemicals including personal care products and products of oil use and combustion, steroids and reproductive hormones (Ternes. 1998, Kolpin et al., 2002), as well as bacterial, viral, and protozoan pathogens (Toze, 1999), can survive conventional wastewater treatment and persist in the aquatic environment. Very little information is available concerning the removal efficiency and removal mechanisms or processes of nitrogen, phosphorus, pharmaceuticals, heavy metals, trace metal, and BOD removal in soil aquifer treatment yet many experimental studies have been performed (laboratory and field) to attempt to ascertain the processes involved in removing organic matter, heavy metals, and other emerging pollutants (Drewes, 2009). The following sections briefly summarize the state of knowledge on the fate of organics and trace organics (e.g. pharmaceuticals) under soil aquifer treatment.

Fate of Organic Matter (OM) under SAT

SAT can effectively treat suspended and dissolved effluent organic matter (EfOM) present in source water. The removal efficiency of organic matter from the effluent was found to be very high under different field conditions with different initial organic contents. At higher concentrations of

TOC/DOC (>10 mg/L) in the infiltrated water, ca. 70-90% removal efficiency was achieved in field investigations (for details Table 2.3). After infiltration, organic matter of wastewater origin gradually transforms into organic matter that more closely resembles background Natural Organic Matter (NOM) (Drewes et al., 2006). Protein-like and soluble microbial products (SMP) may persist in the aquifer even after long travel times (Drewes et al., 2006). The depth of the unsaturated zone has no impact on organic matter removal in a short time of SAT operation (Cha et al., 2005).

About 50-60% of DOC removal during SAT of secondary and tertiary effluents takes place in the top 1.5 m of soil which is most predominantly of an oxic condition (Sharma et al., 2008). Most of the removal of organic matter occurs within the top few centimeters or in the infiltration zone (Drewes, 2009). This is probably due to the abundance and distribution of microbes and their biological activity in the subsurface (Rauch and Drewes, 2005, Nema et al., 2004). A decrease in assimiable organic carbon (AOC) (Kortelainen and Kharu, 2006) and rapid removal of easily biodegradable organic matter during early stages of SAT below the infiltration pond (Fox et al., 2001) suggest a contribution of high microbial activity. Reports from the literature suggest that the microbial biomass (e.g., Holden and Fierer, 2005) is generally highest in surface soils and decreases rapidly with depth (most probably follows power functions) and overall composition of microbial communities changes significantly with soil depth. Mechanical filtration capacity of the top soil layer contributes to the removal of suspended organic matter, which results in a surface clogging layer over time.

Many field and controlled laboratory soil column studies suggest that biodegradation is predominantly the main process of organic matter removal (e.g., Fox et al., 2005; Quanrud et al., 2003b; Drewes and Jekel, 1998). Recent experimentation with 3-D fluorescence excitation/emission has also indicated the highly biologically active processes that occur during SAT (Drewes, 2009). The redox condition in a saturated aquifer may provide a suitable environment for degradation (Vanderzalm et al., 2006). The authors also reported that in addition to aerobic respiration, denitrification is responsible for minerilization of DOC in carbonate aquifers. DOC may be adsorbed on the soil particles (Kortelainen and Kharu. 2006). Humic substances (HS) are relatively resistant to degradation. The important mechanism of removal for HS is attachment to aquifer material followed by microbial degradation (Juhna et al., 2003). So, adsorption is likely less prominent in vadose zone organic carbon removal. Adsorption processes are not sustainable for SAT operation as breakthrough of accumulated organics might occur over the long term. Field and column studies concluded that adsorbed organics are subsequently transformed or degraded and do not accumulate in the soil (Fox et al., 2005). Removal of OC might be a combination of degradation and adsorption processes accompanied by filtration through the upper soil (Idelovitch et al., 2003, Quanrud et al., 2003b). Better understanding is required to differentiate chemo-sorption from physical sorption under SAT. Recently Drewes, 2009 summarised that three mechanisms are responsible for the removal of EfOM in the sub surface. These are: 1) biotransformation and mineralization 2) physical adsorption 3) dilution with local groundwater. Very few studies tried to prove this statement by numerical modelling using either laboratory or field observed data. A first-order macroscopic kinetic model can describe the biodegradation of DOC during SAT.

The infiltration rate, the level of pretreatment, and the soil type have no influence on the biological removal efficiency during SAT. The effluent water quality from SAT largely depends on the travel distance and residence/travel time. Longer travel time will allow breakdown of slowly biodegradable organics (Idelovitch and Michail, 1984). The guidelines proposed by Sharma et al., 2008 state that more than 90% removal of DOC can be achievable when the travel time is more than 50 days (Influent concentration range 2-24 mg/L). Nevertheless, for additional purification of influent treated wastewater, it would be helpful to let the water flow horizontally in the aquifer (saturated zone).

The impact of soil types on SAT operation has been examined by few studies. The removal of organics does not depend predominantly on soil type, although fine-grained soil has little advantage over other soil types (Quanrud et al., 1996). Sharma et al., 2008 suggested that soil type might have an impact on DOC removal and mentioned that sandy loam has better DOC removal efficiency than others.

The persistence or biodegradation of Total Organic Halogens (TOX) or Adsorbable Organic Halogen (AOX) have been poorly investigated. Cometabolism might be the main process of AOX removal (Drewes et al., 1998). On the other hand, sorption to clay mineral and organic matter is concluded to be the main predominant mechanism for AOX removal (Lin et al., 2008; Quanrud et al., 1996).

Table 2.2: Reductions in total organic carbon during SAT of wastewater effluent (extended from Quanrud et al., 2003b) (field and laboratory tests).

Sl. No	Reference	Reduction (%)	C_o (mg/L)	Sediment thickness (m)	Field (F) or Laboratory (L) test	
1	Bouwer et al. 1974	73	10-30	3.3		From Quanrud et al., 2003
2	Bouwer and Rice, 1984	70-71	10.2-11.7	18		
3	Idelovitch and Michail, 1984	82	18	25		
4	Nellor et al. 1984	66	10	2.4		
5	Amy et al. 1993	50[a]	10.8-12 [a]	6.1		
6	Wilson et al. 1995	90	15.12 [a,b]	37		Prepared by the author
7	Drewes and Jekel, 1998	55	15.10 [a]	2	L	
8	Drewes and Fox, 1999	72	5.7	20	F	
9	Fox et al., 2001	>50	5-7	20-30	F	
10	Quanrud et al., 2003	>90	2-16	37	F	
11	Cordy et al., (2004)	>70	8.87[c]	2.4	F	
12	Cha et al., 2005	22-25%	4.5	0,0.5,1	L	
13	Fox et al., 2005	> 50%	6-10[a]	1.5	F	
14	Amy et al., 2007	50-75%	6.1	6	F	
15	Sharma et al., 2007	46-54%[a]	35	2.5	L	
16	Kolehmainen et al., 2007	35-85	10-14		F	
17	Lin et al., 2008	70-90	80-18.9[a]	50-100	F	

[a] dissolved organic carbon; [b] annual averages for two recharge seasons: [C] organic wastewater compounds

Fate of trace organics (EDC and Pharmaceuticals)

Endocryne Disrupting Compounds (EDCs) can be natural hormones or pharmaceuticals, estrogen replacement products, or steriods (Master et al., 2004). The presence of Endocrine Disrupting Compounds (EDCs) is of special concern because these compounds are associated with potential adverse health effects and toxicological effects on aquatic species (Snyder et al., 2004). Consequently, their presence in wastewater leads to the necessity of better understanding their fate and transport during aquifer storage and recovery operations. Mostly secondary treated (biological treatment followed by disinfection) wastewater is used for groundwater replenishment via the surface spreading system . Despite the treatment process, some pharmaceuticals and EDCs persist in treated effluent at very low concentrations (Benotti and Snyder, 2009). Only limited studies have been performed up to now to provide information on the mechanisms for the attenuation of EDCs during SAT. The fate and transport of pharmaceuticals and EDCs in the subsurface are controlled by many factors such as hydrogeological conditions, concentration, pH of recharge water, processes such as advection and dispersion, sorption and desorption, diffusion, microbiological and chemical transformation, pond operation (wetting and drying cycling scheme), etc. Drewes et al. (2002), showed that SAT could efficiently remove anti-inflammatory and lipid-regulating drugs. A period of less than six months of groundwater transport can efficiently remove some pharmaceuticals and Personal Care Products (PCPs), such as Diclofenac, Ibuprofen, Ketoprofen, Naproxen, Fenoprofen and Gemfibrozil, from secondary effluent under SAT. Antiepileptics such as Carbamazepine and Primidone persist in groundwater even after a long period of recharge (Drewes et al., 2003). A 23 day study within a 2.4 m long soil column showed about 70% removal of some organic compounds, but the study demonstrated that under recharge conditions similar to those in arid and semi arid climates, some pharmaceuticals (especially eight compounds: Carbamazepine, Sulfamethaxazole, Benzophenon, 5-methyl-1H-benzotiazole, N,N-diethyl-tolaumide, Tributylphosphate, (Tri- 2-choloroethyl) phosphate, and Cholesterol), pathogens, and other organic wastewater compounds (OWCs) can persist in treated effluent after soil aquifer treatment (Cordy et al., 2004). SAT can remove steriodal hormones. Estriol and testosterene were completely removed (< 0.6 ng/L) only after travel through 1.5m of porous media, where 17β- estradoil was attenuated by 90% at this same condition and was completely removed before reaching the water table. The mobility of these compunds is low in subsurface system. A field experiment was supported by a soil column study under saturated and anoxic flow condition. A 4 m long soil column reported complete removal of these three hormones. The primimary mechanisms for controlling the fate and transport of EDCs and pharmaceuticals are adsorption and biodegradation. (Snyder et al., 2004, Mansell and Drewes, 2004a and Mansell et al., 2004b). Mansell et al., (2004b) reported 79%, 84%, and 98% removal of 17β- estradoil, estriol, and testosterene in a short passage of a soil column (0.30 m). 17β- estradoil is less mobile than others. Column experiments and chemical nonequilibrium miscible-displacement models also imply rapid degradation/transformation of 17β- estradoil in the sorbed phase (Casey et al., 2003). In addtion to sorption processes, transformation might effect the transport of Sulfadiazine (SDZ) in soil. The transport of SDZ mainly depends on the input concentration and pulse duration. For better understanding of transport processes, using laboratory data and mathematical modeling, besides site-kinetic sorption with irreversility, possible transformation reaction, appropriate isotherms and rate laws are important information to have (Wehrhan et al., 2007). Because of the wide range of physiochemical properties (e.g. Log Kow) and microbial transformation mechanisms, it is not easy to understand comprehensively the behaviour of these contaminants in the subsurface environment (Benotti and Snyder, 2009).

2.1.7 Effect of clogging under infiltration pond operation

The formation of a clogging layer at the bottom of the infiltration ponds is a well-known feature. Clogging is caused by a combination of physical (filtration), chemical (precipitation of minerals), and biological (growth of microorganisms or algae) effects (e.g. Schuh, 1990; Rinck-Pfeiffer et al., 2000). Clogging can reduce the infiltration rate by reducing the sediment's hydraulic conductivity and may be responsible for the development of unsaturated zone below the pond (Bouwer, 2002). The low hydraulic conductivity of the clogging layer leads to a dramatic decrease of pressure head along its vertical extent. When a negative pressure head at the lower extent of the clogging layer is reached, the unsaturated zone is developed under the pond and then the layer acts as an additional hydraulic barrier (Bouwer, 2002) and leads to a rapid decrease in the infiltration rate. Once conditions have become unsaturated, the flow follows a vertical hydraulic gradient equal to one, i.e., a vertical pressure gradient equal to zero (Bouwer, 1978). On the other hand wastewater –induced clogging increases the soil biogeochemical activity and can enhance sorption, bio-transformation and inactivation processes (Lowe et al., 2001). A two-dimensional simulation study also shows the physical and biological effects of clogging (Kildsgraad and Engesgraad, 2001). Field studies in different recharge basins and several soil column studies reported on the decrease in infiltration rate and concluded that the biodegradation of organic carbon may produce the clogging. Incident sunlight and retention time of water above the soil surface help to produce an algal layer on the soil surface. An increase of the drying time segment of the wetting/drying cycle may help to desiccate the algal layer (Kopchynski et al., 1996, Quanrud et al., 1996a). A 16 cm soil column experiment concluded that the physical and biological clogging may be reversed by chemical unclogging (calcite dissolution) (Rinck-Pfeiffer et al., 2000). The drying of the infiltration basin may recover the infiltration rate to some extent (up to 64%, reported by Schuh, 1990). In addition to microbiological growth, attachment and detachment are also important processes for creating clogging (Kildsgraad and Engesgraad, 2001). Effluent pre-treatments have no impact on clogging layer development (Kopchynski et al., 1996). The clogging effect is very important to control in order to optimise the operation of infiltration ponds. Mathematical optimization modeling should therefore be considered to address the clogging effect (application time and drying time) (Li et al., 2000).

2.1.8 Managed Aquifer Recharge impact and related risk assessment

MAR projects may impart adverse impacts on environmental and public health and may therefore impact society adversely. Identification of potential risks is a prerequisite to ensure public and environmental health. MAR schemes may neither be socially acceptable nor economically feasible and before implementing any MAR scheme, proper assessment of environmental, health and socio-economic impacts should be undertaken to ensure a beneficial performance.

A. Environmental impact

Environmental Risk Assessment (ERA) and Environmental Impact Assessment (EIA) are two key MAR planning and operation issues that must be considered carefully. "*Environmental risk assessment is the process of evaluating the likelihood of adverse effects in, or transmitted by, the natural environment from hazards that accompany human activities*" as defined by Lohani et al., (1997). The effects from hazards may be on environment, human health, economic welfare, quality of life, and/or the ecosystem. EIA is a prediction based on quantification of cause-effect relationships (Lohani et al., 1997). Major concerns and methods of ERA are explained in the section "Health Impact." This section briefly explains the EIA principles, methods, and its relevance to MAR.

Lohani et al., (1997), summarizes seven main methods to perform EIA, which are: (1) ad hoc method (2) checklist and matrices (3) sectoral guidelines (4) systematic sequential approach (5) networks (6) simulation modeling workshop and (7) Spatial Analysis. The choice of EIA method depends on the scale of the project, information availability, and the scope of the analysis. In this study, a simulation modeling technique was used to quantify the environmental impact.

The requirement of EIA and ERA in the field of MAR implementation has been stated by different researchers (e.g., ASCE, 2001) and is included in the guidelines such as the Australian guideline for MAR (NRMMC, EPHC, NHMRC. 2009). The National Environmental Policy Act (NEPA) of the USA requires the federal agencies to assess the environmental impacts and the states to prepare the Environmental Impact Statements (EIS).

MAR schemes do pose potential impacts to the environment. The impacts are related to a number of factors such as recharge water quality, groundwater quality, hydrogeology of the locality, groundwater movement, catchment processes, etc.

B. Health impact

The water quality of the recovered water of MAR projects should meet the drinking water quality standards or irrigation water quality standards. However, because effluent may contain a wide range of pollutants, an increased health risk can be expected in drinking water from this source. A number of methods are available to assess the health risk or impact of recovered water both qualitatively and quantitatively.

Comparing water-quality with existing standards and quantitative health risk assessment (Cox, 2006) are two main parameter-based approaches for assessing the health risk of recycled water. In the first approach, the concentrations of chemicals and microorganisms approved by risk-based water-quality standards are compared with the concentrations in the recycled water (Thoeye et al., 2003). The approach is based on the assumption that water complying with the standards is safe, because drinking-water standards are made to protect public health. The second approach involves studying each component in the water separately. It is based on the presence of harmful substances and microorganisms in the water, acceptable and infective doses, and estimations of the exposure of the water users. Using these data, the health risk can be calculated and compared with the risk that is agreed to be acceptable. Table 3 describes the different steps in a quantitative health risk assessment (both microbial and chemical).

Table 2.3: Steps in the risk assessment procedure (NRC, 1998)

Sl No	Risk Assessment procedure
1	Hazard identification - involves definition of the human health effects associated with any particular hazard.
2	Dose–response assessment - involves characterization of the relationship between the dose administered and the incidence of the health effect.
3	Exposure assessment - involves determination of the size and nature of the population exposed and the route, amount, and duration of the exposure.
4	Risk characterization or integration of steps (1)–(3) - to estimate the magnitude of the public health problem.

A model based systematic approach is quite helpful to quantify health risk in the decision making process. Figure 2.11 shows the steps for model based health risk characterization.

Hazard Analysis and Critical Control Point (HACCP) is an industry standard preventive risk management system that identifies, evaluates, and controls hazards associated with the production of safe food or water (EPA, 2009). Although the HACCP is primarily developed for the food processing industry, the WHO advocates the use of the HACCP-like principles assessment procedure for water reuse risk assessment. HACCP is also used by the Australian Drinking Water Guidelines (NHMRC, NRMMC 2008).

Static Quantitative Microbial Risk Assessments (QMRA) are commonly prescribed for assessing microbial risks in recycled water systems (WHO, 2006a; Soller and Eisenberg, 2008). Toze et al., (2010) applied the QMRA approach to assess the microbial pathogen risk in the recovered water following infiltration and aquifer passage in Australia. The authors demonstrated the effectiveness of the approach for MAR planning and guidelines.

Though a number of health risk assessments are already developed in different sectors (e.g. drinking water, food industry etc.,), the example of risk assessment techniques for implementation in the field of MAR is scant (Toze et al., 2010). Any MAR guidelines should incorporate appropriate health risk management approaches to avoid any potential human health danger.

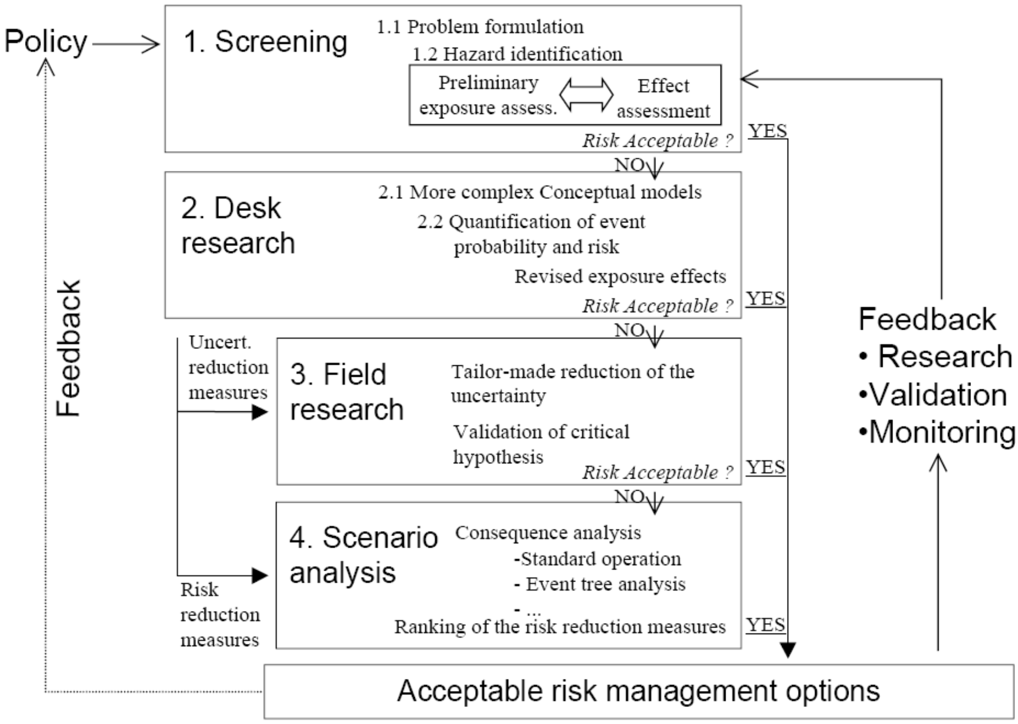

Figure 2.11: A phased approach for model based health risk characterization (Thoeye et al., 2003)

C. Socio-Economical impact

Another great concern of MAR implementation should be the socio-economic impact in the short and long run of the project. This impact becomes more important when the locality is dependent on the agricultural activities and the recovered water is planned to be used for irrigation, such as in the Gaza strip (Naasar et al., 2009).

The economics of the management and use of groundwater is relatively well established by now and seeks to identify the use path(s) that maximize net benefits over time (Burt, 1970; Cummings, 1970; Gisser, 1983). The economics of management and use are focused to a large extent on the different incentives of using the aquifer as a common pool vs. a regulated/privatised stock of water yielding the inefficient use of over-pumping. The economics of MAR has been analyzed early on as well (e.g., Cummings, 1971; Vaux, 1985). The cost of MAR has to be included as well as the cost of unintended side effects (risks of contamination). As the human health risks can be reduced further by applying use restriction, the various alternative uses (landscaping, agricultural uses with/without vegetables eaten raw, drinking water) can be compared (NRC, 1994). The environmental benefit due to groundwater level development should need to be converted to monetary benefit, which is not easy. The application of economic valuation to alternative groundwater uses with managed recharge has been practiced in the USA, such California, and Las Vegas Valley in Navada etc. Donovan et al. (2002) reported that that the benefits of MAR are greater than the costs and there is a net savings of about $700 per year over a 20-year period for non-municipal members of the Ground Water Management Program. Brown, 2005 reported the cost analysis of around 50 ASR sites in brackish aquifer.

The research project WAVES (http://www.usf.uni-kassel.de/waves/) uses a number of indicators to reflect the socio-economic effect of global change on water uses in the Brazilian Northeast, including the change of farming income, but does not develop an economic model of groundwater uses. The EU project RECLAIM WATER (http://www.reclaim-water.org/) has as an extension of a larger number of pre-treatment alternatives, but evaluates them with a risk analysis approach. The EU project GABARDINE (www.gabardine-fp6.org) includes the development of socio-economic indicators, which include a number of economic variables, but it does not aim at a complete economic valuation of the alternative technologies and sources of artificial recharge.

Due to the variability of the factors associated with different stages of a MAR scheme and the resulting complexities, a generic risk assessment is not practical. It is recommended that a case-by-case assessment be undertaken for each proposal.

2.1.9 Multi Criteria Analysis for decision support in the field of MAR

Multi Criteria Analysis (MCA) is the composition of techniques that are potentially capable of improving the transparency, auditability, and analytical rigour of the possible decision and may be applied in many different fields of science and technology (Dunning et al., 2000; Romeo and Rehman, 1987). Originally, MCA was developed to select the best alternative from a set of competing options by analysing the selected criteria that presents the options best. MCA evolved as a tool for decision making in the 1960s and 1970s (Hajkowicz, 2007). Over the years, MCA has received attention by a diverse range of disciplines and has evolved into a wide range of decision aiding techniques (e.g., Munda, 1995). The application of MCA can be for ranking of alternatives, product evaluation, formative evaluation, improvement of negotiation, combined product and process evaluation, structuring of the decision problem and assessment of the overall impacts (Sharifi, 2003). Nowadays, MCA is an established methodology in the professional and scientific community. Overtime, MCA has received particular attention in water resources management. In the field of MAR project planning and management, the application of MAR is scant (Rahman et al., 2010).

Spatial Multicriteria Analysis (SMCA) is another application of MCA, where a number of thematic maps are considered as the criteria and the analysis considers the spatial distribution of the alternatives. The main steps of SMCA are basically similar to traditional MCA analysis so in this report, the general description and the workflow of both (traditional and spatial) MCA are discussed under the same heading.

Many factors need to be considered during the site selection process for MAR projects. Complex regional characteristics, heterogeneities in surface and/or subsurface characteristics, and variable groundwater qualities make site selection for MAR difficult (Anbazhagan et al., 2005). Apart from these hydrogeological considerations, other factors such as political and social factors are important in the decision-making process. National and international water policies, natural conservation regulations, environmental impact assessments, and socio-economic considerations make the site selection procedure complex. Complexity increases when MAR project managers are from different disciplinary backgrounds; this may often lead to disagreements concerning which criteria to give more weight to in the decision-making process. These conflicts always need to be dealt with before the MAR project is implemented. GIS and the traditional DSS alone do not effectively facilitate the implementation of MAR project parameters, which are equally based on complex decision criteria and spatial information (Jun, 2000). GIS based analysis methods are poor in dealing with uncertainty, risks, and potential conflicts; therefore, there is a large possibility of losing important information, which in turn may lead to a poor decision (Bailey et. al., 2003). Multi-criteria Decision Analysis (MCDA) integrated into GIS (SMCDA) provides adequate solution procedures to this problem because the analysis of potential MAR projects may be done more comprehensively and at a lower cost. Variable project sites, risks, MAR techniques, policies, and limits in geological as well as social, environmental, and political realms can easily be considered by the SMCDA approach (Calijuri et al., 2004).

MCDA is helpful in identifying priorities for a given MAR project (Gomes and Lins, 2002). The integration of MCDA techniques with GIS has considerably advanced the traditional map overlay approaches for site suitability analysis (e.g., Malczewski, 1996a; Eastman, 1997). MCDA procedures utilize geographical data, consider the user's preferences, manipulate data, and set preferences according to specified decision rules (Malczewski, 2004). The advantage of integrating GIS with MCDA has been elaborated by many authors (e.g., Malczewski, 1996b; Jun, 2000; Gomes and Lins, 2002; Sharifi and Retsios, 2004). According to Malczewski (2004), the two critical considerations for SMCDA are: (i) the GIS capabilities of data acquisition, storage, retrieval, manipulation, and analysis; and (ii) the MCDA capabilities for combining the geographical data and the manager's preference into unidimensional values of alternative decisions. A number of methodologies have already been developed for SMCDA in different fields of science and engineering to select the best alternatives from a set of competing options (e.g., Sharifi et al., 2006; Zucca et al., 2007).

A brief description of the different steps of both the spatial and non-spatial MCA analysis is given below:

(a) Problem analysis

The first step of starting an MCA procedure is to identify the problem and to analyse it properly because the choice of MCA methods and the steps are also dependent on the problems.

(b) Choice of criteria and subcriteria

Criteria, which give an indication of the appropriateness of the alternatives to achieve the objective, are used to evaluate the objectives of a decision problem. Therefore, the selected criteria should represent accurately the objective of the problem. Sharifi, 2003 stated that the selected criteria must be *SMART* (Specific, Measurable, Attributable, Realistic, and Time bound). CIFOR, (1999) proposed nine attributes for the selection of criteria, which are (1) Relevance (2) Unambiguously related to the assessment goal (3) Precisely defined (4) Diagnostically specific (5) Easy to detect, record and interpret (6) Reliability (7) Sensitive and responsive to the changes in the system (8) Provides a summary or integrative measure over space and time, and (9) Usefulness to users. Therefore, a critical review of the system in the particular field should be performed to select criteria for an MCA analysis.

(c) Hierarchy of criteria and subcriteria

If the number of selected criteria is very large, it is reasonable to subdivide the criteria into groups and/or subgroups. It is advisable to make a three-level hierarchy (cited in Pfeffer, 2002). They found that a hierarchy more than three levels would not increase the insight of the problem. The criteria can be bottom-up or top-down. These two categories can be mixed up by using a computer program. Based on the hierarchical structure concept, Analytical Hierarchy Process (AHP, Saaty 1980) has been developed.

(d) Standardization of Criteria/Subcriteria

The criteria or subcriteria can be measured in different measurement units. For example, slope is measured in percent (%), aquifer thickness is measured in meters, etc. To make all the criteria comparable they have to be standardized (Sharifi and Retsios, 2004). Valuation of the best possible value to 1 or 100 and the worst possible value to 0 will satisfy the goal. A number of techniques are available for standardization, such as the linear scale transformation (Voogd, 1983), the mid-value method (Bodily, 1995), the Evalue method (Beinat, 1997), the convex value function and concave value function (Keeney, 1992), the utility function approach (Eriksen and Keller, 1993), etc. Malczewski, 2000 stated that common practice is to use the standardized score range procedure, which is associated with a non-linearity problem. The author recommended to use value function analysis techniques for standardization. There are several value function analysis techniques, such as the mid value method, the Evalue method, the convex value function and the concave value function etc. Only the value function technique was used in the study.

(e) Relative weight of criteria and subcriteria

The relative importance of the criteria can be achieved by assigning a weight to the criteria. So a relative weight can be defined as a value assigned to an evaluation criterion that indicates its importance relative to other criteria under consideration (Malczewski, 1999). The weights are usually normalized to sum to one. There are a few methods to assign weights to the criteria, such as direct weighting (Hämäläinen and Pöyhönen, 1997), ranking method (Wilcoxon, 1945), rating method (Webster, 2008), pair-wise comparison method (Saaty, 1980), trade-off analysis method (Keeney and Raiffa, 1976), etc. The methods differ in several important ways. Malczewski, 1999 stated that the ranking or rating method is applicable if ease-of-use, time, and cost are involved in generating of weights. On the other hand, pair-wise comparison or the trade-off analysis method is suitable if accuracy and theoretical foundations are major concerns. Empirical applications suggest that the pair-wise comparison method is one of the most effective techniques for spatial decision making including GIS base approaches (Eastman et al., 1993, Malczewski, 1996, Malczewski, 1999). In this present study, the direct weighting method (Hämäläinen and Pöyhönen, 1997) and pair-wise comparison (see section 2.2.3 for description) method are used.

(e) Combination of criteria and subcriteria

The overlay MCDA plays an important role in many GIS applications. Boolean logic and Weighted Linear Combination (WLC) are the most popular decision rules in GIS (e.g., Eastman, 1997; Malczewski and Rinner, 2005) and both can be generalized within the scope of Ordered Weighted Averaging (OWA) (e.g., Malczewski and Rinner, 2005; Malczewski, 2006). In OWA, a number of decision strategy maps can be generated by changing the ordered weights. Several OWA applications have been implemented already (e.g. Rinner and Malczewski, 2002; Calijuri et. al., 2004; Malczewski et al., 2003; Malczewski, 2006). The Analytical Hierarchy Process (AHP), proposed by Saaty (1980), is another well-known procedure. This procedure is important for spatial decision problems with a large number of criteria (Eastman et al., 1993). AHP can be used to combine the priorities for all levels of a “criteria tree,” including the level representing criteria. In this case, a relatively small number of criteria can be evaluated (Jankowski and Richard, 1994; Boroushaki and Malczewski, 2008). The combination of AHP with WLC and/or OWA can provide a more effective and robust MCDA tool for spatial decision problems. Boroushaki and Malczewski (2008) implemented AHP-OWA operators using fuzzy linguistic quantifiers in the GIS environment, which has been proven to be effective.

2.1.10 Spatial Multi Criteria Analysis (SMCA) and its application to MAR

The history of site selection for MAR projects is about 30 years long. The site selection studies reviewed cover local scale (e.g., Kallalia et al., 2007) to regional scale (e.g. Ghayoumian et al., 2007). The detailed State-of-Art of the MAR site selection is given in Chapter 6. However a large gap in research still exists today, considering the advancement in site selection methods for other purposes such as waste disposal, priority of land use etc. The existing MAR site selection procedures of today are far behind in terms of using modern technology and decision analysis methods. Proper selection and combination of surface, subsurface, and regional characteristics need to be included for a complete evaluation. Criteria standardization has not been well adapted. A wide variety of weighting methods need to be practiced. The classical overlay mapping and modeling are the most commonly used methods for site suitability mapping. Therefore, the advantage of SMCDA has not been properly and fully utilised. The trade–off between decisions and rules needs to be included. Above all, no interactive non-site specific and decision tool for MAR site selection has been developed yet.

2.2 Managed Aquifer Recharge: Theoretical Background

2.2.1 Mathematical modelling: Groundwater flow in saturated and unsaturated zone

Visual Modflow

Visual Modflow is a complete and easy-to-use modeling environment for practical applications in three-dimensional groundwater flow and contaminant transport simulations. Visual Modflow uses the USGS Modflow code (Harburg & McDonald, 1996). The authors provided an excellent description of the model and its underlying mathematics, upon which a family of code has been evolved, such as MODPATH (Pollock, 1994). Modflow is a three-dimensional finite difference model, which solves a system of equations describing the major flow and related processes in the hydrological system. The partial-differential equation of groundwater flow used in Modflow can be represented by the equation as shown below:

$$\frac{\partial}{\partial}\left(\quad \right) \quad \left(\quad \right) \quad \left(\quad \right)$$

where,

K_{xx}, K_{yy}, and K_{zz} = Values of hydraulic conductivity along the x, y, and z coordinate axes (L/T);

h = Potentiometric head (L);

W = Volumetric flux per unit volume representing sources and/or sinks of water, with W<0.0 for flow out of the ground-water system, and W>0.0 for flow in (T^{-1});

S_S = Specific storage of the porous material (L^{-1});

The modular and public domain status of Modflow has allowed new capabilities to be added to the original model. The Modflow code is used widely in research and has undergone extensive review.

The detailed description of Modflow is given by Harburg & McDonald, 1996 and thus is not explained here. In this study, visual Modflow (v. 4.3, SWS, 2009) is used for groundwater flow simulation. The Visual MODFLOW interface consists of Input, Run, and Output sections. In the Input section, the user sets up conditions for groundwater flow and contaminant transport models using a graphical interface. In the Run section, the user translates the model conditions created with the Input section into the standard input files for the appropriate models. Overall, Visual MODFLOW is a powerful package that makes model setup and manipulation easy and efficient. The interface is intuitive and easy to use, while giving the user the ability to simulate solute transport, particle tracking, and seawater intrusion (SWS, 2009).

2.2.2 Mathematical modelling: Solute and reactive transport in saturated zone

Solute transport models simulate the movement, mixing and reactions of dissolved constituents in groundwater. Mixing is of obvious concern in MAR systems, as the injected water and the native groundwater possess different chemistry. Solute transport models are built upon or otherwise incorporate a groundwater flow model. A number of solute transport codes, such as MT3DMS (Zheng and Wang, 1999), SEAWAT (Guo and Langevin, 2002), SUTRA (Voss and Provost, 2002), PHT3D (Prommer et al., 2003), FEFLOW (Diersch, 1998) have been developed that have been used or can be used for the simulation of mixing and natural attenuation in aquifers under various MAR operation scenarios. In this study MT3DMS, included in Visual Modflow has been used to simulate reactive transport.

The detailed description of MT3DMS is given by Zheng and Wang, (1999).

2.2.3 Decision support for Managed Aquifer Recharge

Driver, Pressure, State, Impact, Response - DPSIR

The causal chain analysis approach known as the Driver (D), Pressure (P), State (S), Impact (I), Response (R) method is a well known method for identification of the causal chains of certain problems and their potential responses. The DPSIR concept has been developed for describing interactions between society and the environment, starting from the assumption that there is a causal chain between society

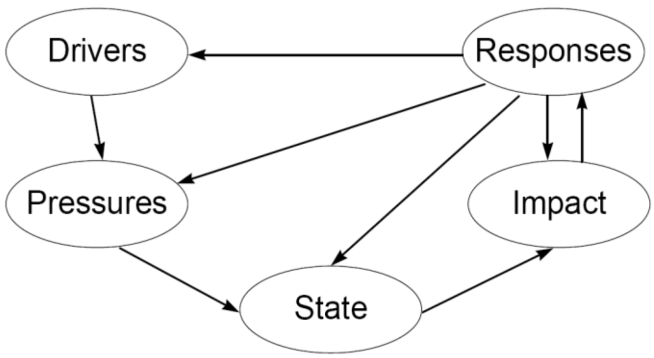

Figure 2.12: The DPSIR framework for causal chain analysis (after EEA, 1999)

and environment. The strategies, 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 environment (OECD 2003). Once the driving forces have been listed, the resulting stress factors (pressures in the DPSIR framework) can be clearly defined as well as their consequences on the water resources system.

Analytical Hierarchy Process (AHP)

AHP was introduced by Saaty, 1980 as a flexible and yet structured methodology for analysing and solving complex decision problems by structuring them into a hierarchical framework. Developing the hierarchical structure, obtaining preference information, estimation of relative weight by pair-wise comparison and construction of overall priority ranking are the main steps of AHP. AHP uses the pairwise comparison for assigning relative weights to each criterion. The AHP and pair-wise comparison procedures have been described in many articles of the literature (e.g., Saaty 2001, Malczewski, 2006).

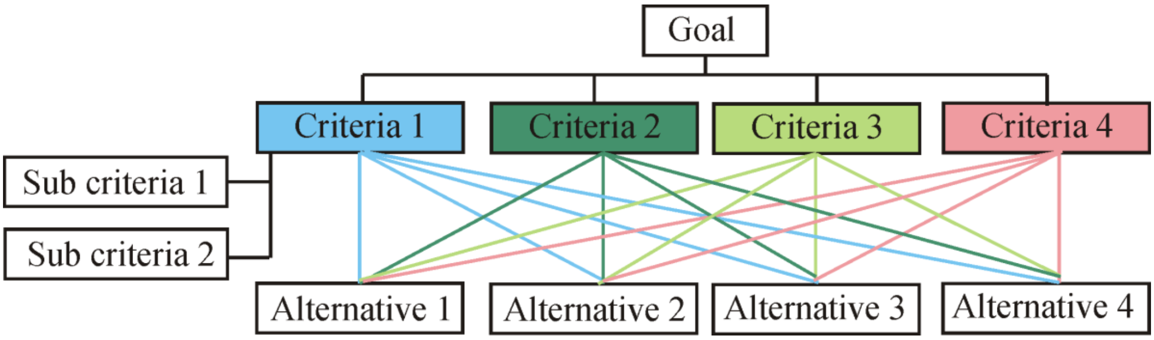

Figure 2.13: Illustrative example of AHP considering 4 criteria and 4 alternatives.

Pair-wise Comparison

This method is used in the Analytical Hierarchy Process (AHP), proposed by Saaty (1980). The method can be used for complex concepts, as only two components are considered each time. Thereby the complexity is reduced. This involves three steps: (1) developing a comparison matrix at each level of the hierarchy, beginning at the top and working down (2) for each element of the hierarchy, the weights are calculated (3) estimation of the consistency ratio (Boroushaki and Malczewski, 2008). The pair-wise comparison is aimed at providing a cardinal scale to evaluate objects according to some subjective preference criteria. Pair-wise comparisons are made on a scale of relative importance (see Table 2.4) where the decision maker has the option to express the preferences between two elements on a ratio scale from equally important (i.e., equivalent to a numeric value of one) to absolute preference (i.e., equivalent to a numeric value of nine) of one element over another. Ratings of decision makers are arranged as numbers in a comparison matrix. Based on this, relative weights for all elements of the hierarchy are calculated with the Eigenvector Method (EVM), indicating the priority level for each element in the hierarchy (Saaty, 2001). Accordingly, priorities for the alternatives are obtained by judgments with respect to each above-level element of the hierarchy.

Their performances are weighted with the relative weights of criteria and subcriteria and are added to an overall priority for each alternative (i.e. how they contribute to the objective), which allows a cardinal ranking of the alternatives (Saaty, 2006).

Table 2.4: The fundamental scale for pairwise comparison (after Saaty, 2008).

Intensity of Importance	Definition	Explanation
1	Equal Important	Two elements contribute equally to the objective.
3	Weak Importance	Experience and judgment slightly favour one element over another.
5	Strong Importance	Experience and judgment strongly favour one element over another.
7	Very Strong Importance	One element is favoured over another; its dominance is demonstrated in practice.
9	Absolute Importance	The evidence favouring one element over another is of the highest possible order of affirmation
Intensities of 2,4,6 and 8 can be used to express intermediate values. Intensities 1.1, 1.2, 1.3 can be used to express the criteria that are very close in importance.		

(i) Weighted Linear Combination (WLC)

WLC is the simplest and most commonly used aggregation method in decision making (Eastman et al., 1993). The method is extensively applied in land use/suitability analysis, site selection, and alternative selection (Han and Kim, 1988; Eastman et al., 1995; Lowry et al., 1995). The method is very easy to implement within the GIS environment using map algebra operations and cartographic modeling (Tomlin, 1990; Berry, 1993). The method is also easy-to-understand and intuitively appealing to decision makers without having too much technical background (Hwang and Yoon, 1981, Massam , 1988). WLC can be expressed as:

$$S(x_i) = \sum \cdot s_i(x_i) \quad \ldots\ldots \quad (4)$$

w_j = normalised weight; $\Sigma\ w_j = 1$; $S_i\,(x_i)$ = standardized criteria function/map

WLC can be combined with GIS capabilities to use for land suitability and site selection studies. After analysing the relative advantages and disadvantages of the GIS/WLC analysis, Malczewski, (2000) suggested that incorporating the value function approach and trade-off analysis into the combined GIS-WLC procedures can substantially improve the decision making process. The greatest disadvantage of the WLC method is that it tends to be an ad hoc procedure with little theoretical foundation to support them (Malczewski, 1999). That is why the sensitivity analysis is an indispensable part of the WLC-process to recognize the stability of the result towards the different weights. Especially regarding site selection for MAR, a close look on how sensitive the method is under different conditions (e.g. hydrogeological, slope) needs to be taken into account to be sure to pick a matching area.

(ii) Ordered Weighted Average (OWA)

OWA is a class of multicriteria combination operators, involving two sets of criteria weights which are “criteria importance weight” and “ordered weight” (Yager, 1988). The concept of fuzzy linguistic quantifiers, introduced by Zadeh (1983), allows the conversion of natural language statements into proper mathematical formulation (Munda, 1995). In this study, the regular increasing monotone quantifier class was considered. Given the criteria weights w_j, the quantifier-guided OWA can be defined as follows (Boroushaki and Malczewski , 2008):

$$OWA(i) = \sum_{j=1} \left(\left(\sum_{k=1} \right)^{\alpha} - \left(\sum_{k=1}^{-1} \right)^{\alpha} \right)_{ij} \text{………………………………………………………………….. (5)}$$

z_{ij} = weighted attribute value; α = parameter for linguistic quantifier
u_k = criteria weight reordered according to z_{ij} ; and j = number of criteria.

OWA involves two sets of weights, the weights of criterion priority and ordered weights. The advantages of ordered weight are that, by changing the ordered weights it is possible to generate a wide range of decision maps. A number of studies in the GIS environment has been performed over the past ten years (e.g. Rinner and Malczewski 2002; Calijuri et al., 2004, Malczewski , 2006). Some of the above mentioned used conventional (quantitative) OWA. Conventional OWA operators are of limited applicability where a large number of criteria are involved (Yager, 1996). For a large set of decision criteria, it is really difficult to satisfy the decision maker’s preferences on the result obtained from combination of criteria maps (Malczewski, 2006). In this situation, the acceptable solution from preference of the decision maker may be specified in terms of some fuzzy linguistic quantifiers such as ‘Most’ of the important criteria are satisfied by an acceptable solution (Yager, 1999). In our study, the Regular Increasing Monotone Quantifier (RIM) (Yager, 1996), a type of proportional quantifier, was used for linguistic quantifiers statement. The simplest and most used methods for defining the parameterised subset on the unit interval was used in this study (Yager, 1996).

$Q(p) = p^{\alpha}, \alpha$ …………………………………………………………………………….. 6

Q(p) represents the fuzzy set interval and it can be applied for generating a whole set of the RIM quantifiers. Table 2.5 shows the selected RIM quantifiers and their characteristics.

Table 2.5: Some properties of the RIM quantifiers for the selected value of α parameters (after Malczewski, 2006)

α	Quantifier (Q)	ORness	Tradeoff	GIS combination Procedure
α→ 0	At least one	1.0	0.0	OWA (OR, MAX)
α = 0.1	At least a few	a	a	OWA
α = 0.5	A few	a	a	OWA
α = 1	Half (identity)	0.5	1.0	OWA (same as WLC)
α = 2	Most	a	a	OWA
α = 10	Almost all	a	a	OWA
α→ ∞	All	0.0	0.0	OWA (AND, MIN)

[a] Problem specific and depends on the number of criteria involved

Malczewski, 2006 combines the advantages of the fuzzy linguistic quantifiers and OWA operator for GIS based multi criteria evaluation procedure with an application for land suitability analysis in the Sinaloa Province on the Pacific Coast of Mexico. The theoretical background of the combination of fuzzy linguistic quantifiers and OWA has been presented by Yager, 1999. OWA allows for a high degree of input variability and trade-off between the importance of input variables (Figure 2.14). Using an α value between 0 to ∞, yields a range of MCE operator in the decision strategy space. α = ∞ (linguistic quantifier is 'all of the criteria satisfies') yields no 'tradeoff' and full 'ANDness'. Decreasing the value of α from larger numbers to 1.0 corresponds to increasing the degree of 'ORness' and 'tradeoff' between selected criteria. When α=1 (linguistic quantifier is 'half of the criteria satisfies'), yield the full 'tradeoff' (WLC) and 'ORness' = 0.5 (Figure 2.14). Decreasing the value of 1 to 0.0 corresponds to increasing the degree of 'ORness' and decreasing the degree of 'tradeoff' between selected criteria (Malczewski, 2006). α=0 (linguistic quantifier is 'at least one of the criteria satisfies') yields no 'tradeoff' and full 'ORness'. The end of the range represents the extreme strategy (high risk).

Combination of AHP-WLC and AHP-OWA procedure

Boroushaki and Malczewski (2008), integrated GIS with an extension of AHP using a quantifier-guided OWA procedure. The authors suggested that GIS-MCE would simplify the definition of decision analysis and the incorporation of qualitative information within the analysis will facilitate descriptive analysis of multiple criteria.

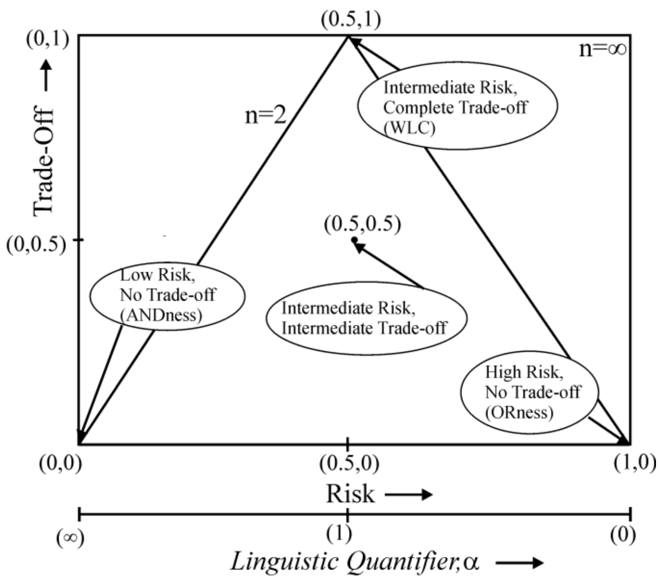

Figure 2.14: The Decision strategy space showing relation between trade-off and risk, n is the number of criteria (modified after Eastman, 2000 and Malczewski, 2006).

The detailed description of AHP combination with OWA is given by Boroushaki and Malczewski (2008). The authors concluded that combination of The Analytical Hierarchy Process (AHP) and OWA, integrated with fuzzy linguistic quantifiers could provide a more powerful multicriteria decision making tool for structuring and solving decision problems.

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Chapter 3

Methodology

3.1 Introduction

Planning and integration of the different components of the water resources system (WRS), which are related to MAR, is critical for successful MAR implementation. Conceptual planning, guidelines, and assessment of logistical possibilities are required to integrate MAR planning options within IWRM. A new detailed MAR planning framework, consisting of a detailed flowchart showing MAR planning steps, a guideline, and a decision support system is the focus of this study. To facilitate in the presentation of the critical steps of MAR project planning in context to this study, five individual case studies from four different geographical locations were undertaken. These case studies focus on the water resource problems of each study area in context to selected appropriate MAR planning steps. An individual methodological framework, including new innovative Spatial Multi Criteria Decision Analysis (SMCDA), geological modeling, groundwater modeling, hydrogeochemical investigations, Multi Criteria Analysis (MCA), etc has been made appropriate for each individual case study. The overall methodology of MAR planning, the individual methodologies, and the major representative steps of the planning are presented in this chapter and respect is paid to the reasoning criteria behind each case study area selection. Case study area selection is summarized in brief statements for each case study and for detailed descriptions of each study area, please see the subsequent relevant chapters.

3.2 Overall Methodology

The conceptual framework for planning and management of MAR is illustrated in Figure 3.1. The principle guidelines for the conceptualisation of MAR planning and management are briefly summarized below:

1. The MAR planning process starts with basin characterization followed by an analysis of the water resources system (WRS) and the existing water resources problem. After identifying the real problem facing the WRS, the first MAR planning task is to identify whether MAR is a potential response. The Driver, Pressure, State, Impact and Response (DPSIR) concept, proposed by the Organization of Economic Co-operation and Development (OECD, 1993) can assist to structure the pertinent problems and to evaluate potential response(s).
2. If MAR is a potential response, then a preliminary feasibility study is required to determine the possibility of MAR in the region. The feasibility study mainly includes the determination of the existing water budget and possible reliable water sources as well as the analysis of the hydrogeological system in order to make decisions concerning the MAR technology to implement and where the best location for MAR infrastructure may be. The feasibility study helps to prepare a conceptual plan, detailed guidelines, and a draft of regulatory aspects of the project. The detailed activities of the feasibility study will vary with the geographical location and extension of the project area, as well as with the existing information and technology (ASCE, 2001).

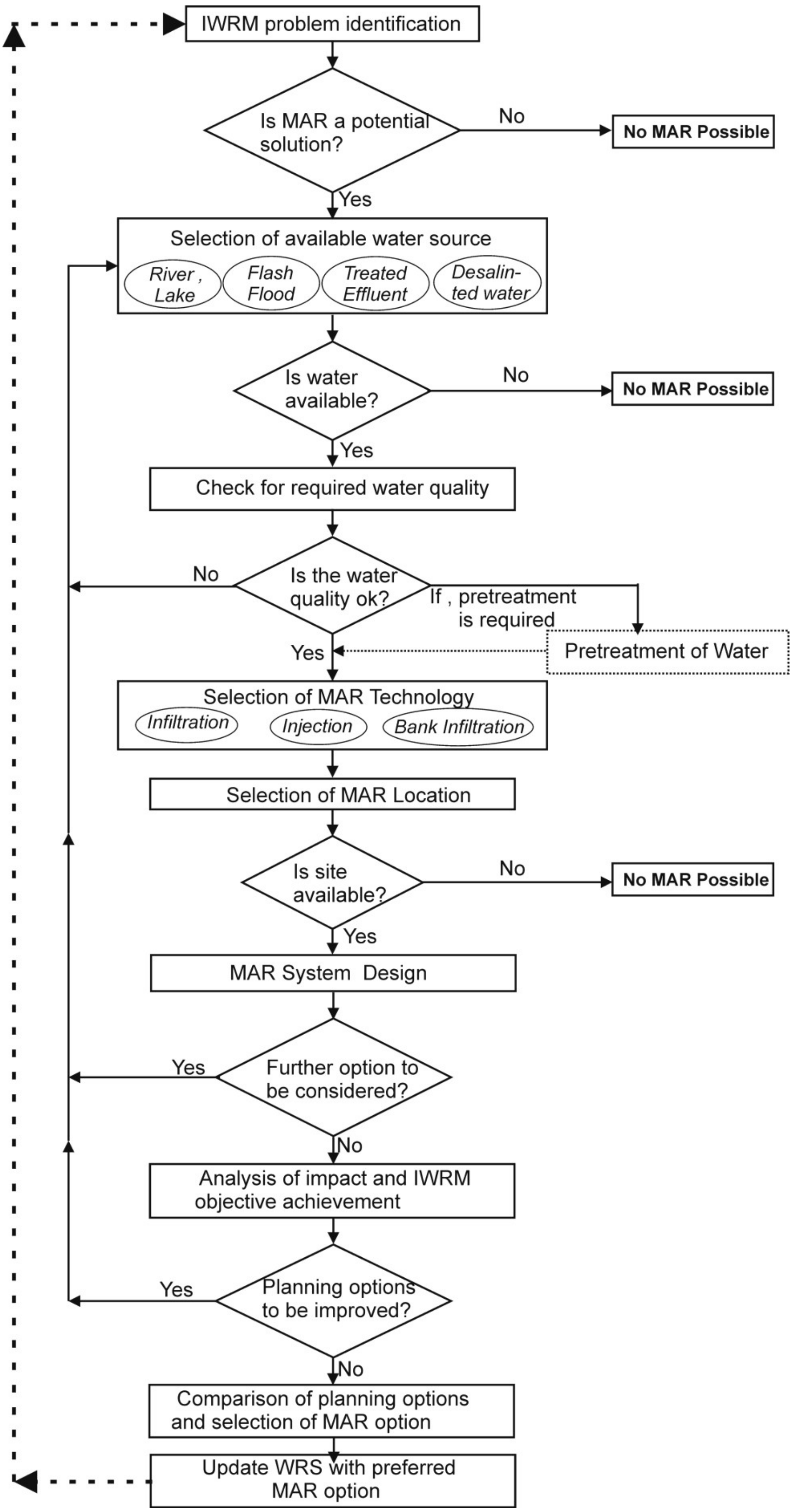

Figure 3.1: Managed aquifer recharge project planning flowchart (modified after Rusteberg et al., 2008)

Section 3.3 illustrates an outline of research efforts for MAR pre-feasibility analysis.

3. After the confirmation of potentiality for a MAR system within a regional and or local WRS, the principle MAR project planning steps in a region include:
    - Clearly determining the water quantity and quality of an area is necessary for an analysis of potential water resources for MAR. Water resources include surface water, storm water, treated effluent, water from flash floods, brackish water, desalinated water, or imported water (see chapter 2, section 2.1.2 for details). The available quantity of non-committed water needs to be verified against the water demand. In order to fulfil the water demand, different water resources can be considered and used simultaneously in the MAR planning.
    - In addition to water quantity, water quality is quite important to avoid further groundwater pollution and the exposing of humans to public health hazards. The water quality parameters should be verified against the WHO standard (WHO, 2006a; WHO, 2006b) or to local guidelines. If the source of water does not meet the water quality standard, then there are two possibilities: (1) discard the water source, or (2) suggest for further pre-treatment. In this case, the cost of further pre-treatment plays an important role in MAR implementation and must be studied in detail.
    - After available water resources are verified, selecting proper technology and finding a suitable place for MAR is the next step. Due to limited appropriate space and conflicts of interest concerning land use, finding a location for MAR is a challenging task. A number of surface and subsurface characteristics need to be considered for selecting suitable sites for MAR. Each MAR technology is suited to its own type of surface and subsurface conditions. A number of MAR techniques, such as infiltration, injection, bank infiltration, etc., are now widely practiced around the world (see chapter 2, section 2.1.2 for details) and these techniques are designed for specific types of land. An investigation therefore requires comprehensive Spatial Multi Criteria Decision Analysis (SMCDA), supported by a hydrogeological study and mathematical modeling. Detailed methodology of the SMCDA and hydrogeological analysis used in this study is given in section 3.4. After selecting the proper location and technology for MAR, a system design is prepared and supplementary hydro-infrastructure is planned.
    - Project options are then prepared for further comprehensive analysis. Different sources of water (with varying quantity and quality), possible uses of recovered water, possible MAR locations, and possible technologies are considered. The MAR options are all created to fulfil the WRS problem solution, which is set in the beginning. The planners are therefore obliged to review alternatives regarding WRS development in their region.
    - Project options are ranked and the best project option is determined for implementation. An analysis of socio-economic and environmental impacts as well as an evaluation of MAR options' performance toward the main water resources management objectives is integral to project ranking. Multi-criteria analysis (MCA) techniques support the decision makers (DMs) in

making the best possible decision by ranking the options. A number of decision criteria, which mostly represent the possible environmental, social, health, and economic factors are considered. The selection of representative decision criteria is a participative process, involving relevant stakeholders, since their opinions, mostly reflected in criteria and options' importance, affects the evaluation of alternative MAR options/strategies (Rusteberg et al., 2011). Project alternative ranking is considered to be the most critical step in the whole planning process. Detailed methodology developed and used in this study for MAR strategy formulation, criteria selection and quantification, and strategy ranking is given in section 3.5.

- For groundwater quality management, risk control, and MAR regulation formulation, the information regarding water quality changes and the fate of emerging pollutants in the underground after recharge is quite important. Emerging pollutants may persist during MAR implementation within the recharged water even after wastewater treatment. The aquifer system can improve the water quality by acting as underground reactor, which is called 'Soil- Aquifer-Treatment (SAT)'. A good and properly designed monitoring network supplies adequate information related to groundwater quality changes, both spatial and temporal. Hence, Mathematical modeling to quantify possible groundwater flow and transport processes and to determine the possible results of the mixing of native water with recharged water is considered by the MAR practitioners. The outline of the local scale integrated approach for simulating SAT operation is given in section 3.6.

4. MAR project alternatives may be determined to be non-feasible long after a project alternative has been implemented and monitoring and environmental analysis have begun. In this case groundwater quality may not have in fact met standards of quality set by environmental regulations. In order to ensure the achievement of regulatory standards, a decision support system (DSS) may be invaluable in this respect. A DSS user may try to improve project performance by slightly changing decision variables related to MAR management (system operation), water recovery, location, and other options before a project is decided upon and the infrastructure is built. After analysis of all the project options with the DSS, determining the contribution of the most preferred project to the overall IWRM goal is performed. With this final step the WRS system analysis with respect to MAR is complete.

For comprehensive support of MAR project planning under water scarce conditions, an innovative geospatial decision support system (G-DSS) was developed within the scope of the European Research Project GABARDINE. The following G-DSS modules were developed and integrated into the GIS platform: (a) Geo DATA-base management module, (b) DPSIR module, (c) MAR PLANNING module (d) a spatial MCA module for MAR site selection, and (e) a MCA module for MAR option comparison and ranking (Rusteberg et al., 2011). For comprehensive support to the planning of MAR-systems in water scarce areas, the above-mentioned planning framework, developed within this dissertation, served as a basis for the complete development of the G-DSS. The modules c, d, and e from the above paragraph were developed and introduced into the G-DSS. Once again, these modules are: (c) MAR PLANNING module, (d) Spatial MCA module for MAR site selection, and (e) MCA module for MAR option comparison and ranking. A further significant contribution was made concerning the development of the DPSIR module (b) of the G-DSS. Chapter 4 gives a detailed description of G-DSS and its interface.

Based on the detailed flow chart, the following four important MAR planning tasks were selected and were subjected of practical and detailed investigation on case study level: (1) MAR pre-feasibility analysis, (2) Site selection and ranking, (3) Analysis, comparison and ranking of MAR planning and management options, and (4) Soil-Aquifer-Treatment (SAT) system operation and impact assessment. A total four detail individual methodology, one for each MAR planning task mentioned above, were developed in this dissertation, which are described in the following sections. To make each methodology independent of other methodologies, water resources problem analysis, can be performed by DPSIR analysis, was maintained as the first step in each analysis.

3.3 MAR Pre-feasibility Study

Figure 3.2 outlines the recommended research efforts and the sequence and type of information which is required to be obtained when performing a MAR viability analysis in a region. As can be seen at the top of Figure 3.2, 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) Hydrogeochemistry.

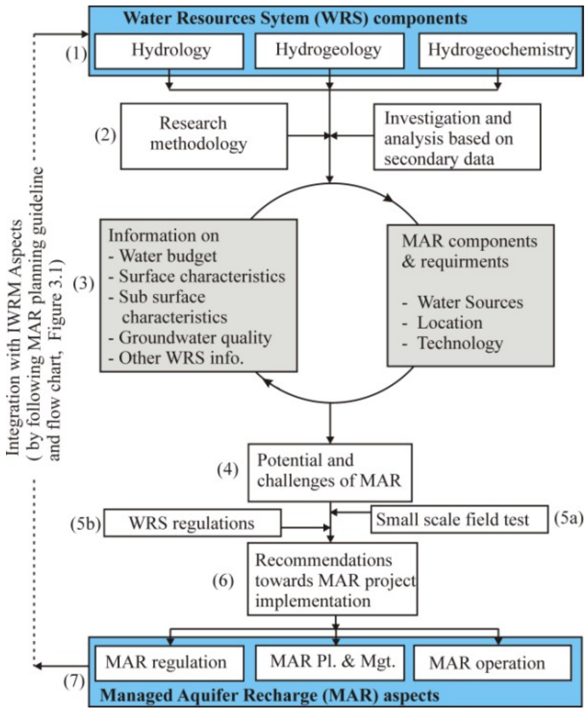

Figure 3.2: General flow diagram for MAR pre-feasibility analysis

The DPSIR concept can assist to structure the pertinent problems and to evaluate potential response(s). 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. Analysis of acquired information is most reliably achieved using state-of-the-art methodologies, such as surface water modeling, water budget analysis, geological modeling, groundwater modeling, and groundwater quality data analysis by the Piper diagram and or geochemical modeling (e.g., PHREEQC). Other state-of-the-art technologies which have not been mentioned also exist and may be implemented as well. 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. The likelihood is high that small-scale field investigations, such as groundwater sampling (i.e., to determine water quality at 'Hot Spots of GW contamination'), will be required to make more solid recommendations for MAR implementation (Step-5a). The WRS should always be carefully considered while preparing the recommendations in order to keep the integration of MAR planning within WRS regulation (Step-5b). Afterwards, the MAR pre-feasibility study continues and recommendations are formulated, which focus mainly on the three main aspects of MAR (Step-6 and Step-7), such as (1) MAR regulation, (2) MAR planning (Pl.) and Management (Mgt.). From this stage and on, the next steps of the MAR planning procedure (Figure 3.1) should be followed. 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.

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.

3.4 MAR Site Suitability Mapping and Site Ranking

The overall methodology of the suggested site suitability procedure and evaluation of suitable sites is shown in Figure 3.3. The flowchart shows the main decision steps for Spatial Multi Criteria Analysis and hydrogeological assessment. In general, the entire process involves five main steps: (1) problem definition and causal chain analysis, (2) constraint mapping, (3) suitability mapping, (4) sensitivity analysis, and (5) site ranking.

The water resources problem analysis is performed in the beginning along with an analysis of the role of MAR as a potential response (Step-1). Analysis is undertaken by the DPSIR concept.

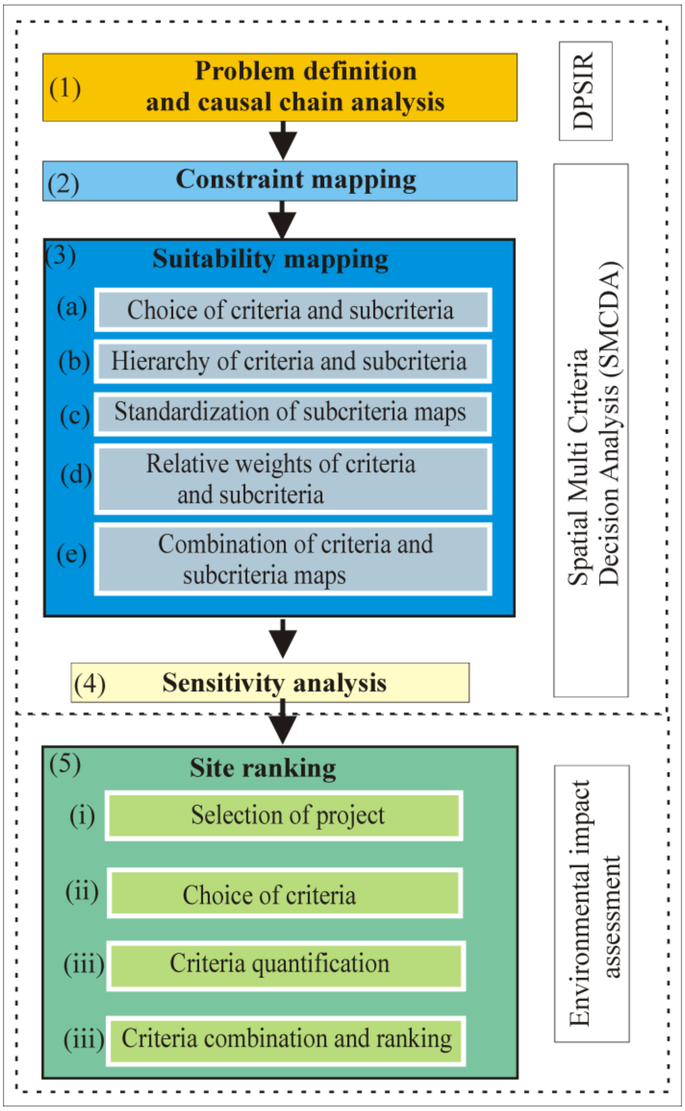

Figure 3.3: General methodology for MAR suitability mapping and site ranking combining (spatial) multi criteria analysis and mathematical modeling.

Constraint mapping (Step-2) allows screening-out of a large number of alternatives, which are deemed non-feasible. This step helps the user to avoid conflicts in decision-making. This constraint map (Step-2) serves as a mask for suitability mapping (Step-3). In the first step of suitability mapping, all relevant surface, subsurface, and regional characteristics are selected (Step-3a). Each characteristic is defined as sub-criteria.

The next step within Step-3 involves the decomposition of the ultimate goal into a hierarchy. The lowest level of the hierarchy is the sub criteria. In the immediate upper level, the sub-criteria are grouped under the main criteria. The combination of the main criteria produces the suitability map, which is the goal of the site suitability mapping, the top level of the hierarchy. The maps are then standardized using a predefined function, e.g. linear, piece-wise linear, step function (Step-3c). Assigning values of importance for each criterion and sub-criterion is then done by assigning a weight to each criterion (Step-3d). After standardization and weighting, the next step is to obtain the overall suitability index of each alternative, which is represented as a cell in the maps. Overlay methods commonly available, are Weighted Linear Combination (WLC) and Ordered Weighted Average (OWA) with fuzzy linguistic quantifiers. By changing the weights of each overlay method and of the linguistic quantifier associated with the objectives and attributes for OWA, a wide range of decision scenarios can be generated. This helps to check the sensitivity of the system with changing weights and linguistic quantifiers (Step-4).

An environmental impact assessment and more specifically, a hydrogeological investigation should be performed to compare the suitable sites (in this study, sites are called “MAR projects”, in Chapter 7) in terms of their impact on the environment, especially on the regional aquifer system (Step-5). After selecting a number of projects, most representative and simplified hydrogeological criteria are selected (Step-5a and 5b). The selected decision criteria quantification can be done by means of mathematical modeling. MCA assists to compare and rank the sites. In the simplified MCA, the criteria values are then combined to choose the best project for implementation.

In this study Weighted Linear Combination (WLC) was used for project ranking and Visual Modflow was used for groundwater modeling.

Based on the above methodology, considering Step-2, Step-3. Step-4, the new SMCDA tool was developed in this dissertation and incorporated in the G-DSS as “Site selection module.” Step-1 and Step-5 were undertaken externally and input to the SMCDA tool.

Two case studies were undertaken by implementing the above-mentioned methodology. In the first case study, in Querença Silves Aquifer, Algarve Region, Portugal, the SMCDA tool was implemented

(Step-2 to Step-4, Figure 3.3). The entire methodology, from Step-1 to Step-5 (Figure 3.3), was implemented in a simple aquifer system in North Gaza, West Bank. Explanations for using two different case study areas are given in section 3.7 in this chapter.

3.5 Analysis, Comparison and Ranking of MAR Planning and Management Options

Figure 3.4 shows the flowchart of the detailed concept of the MAR strategy impact assessment and ranking using a combined approach, called the 'AHP-WLC' method. The flowchart shows the main steps for the development of strategies, quantification of selected criteria, and Multi Criteria Analysis towards the search of a sustainable water resources management plan for MAR implementation. In general, the entire process involves three main steps: (a) water resources strategy development, (b) criteria selection and criteria quantification, and (c) criteria overlay. A brief description of the overall methodology is illustrated in the following figure.

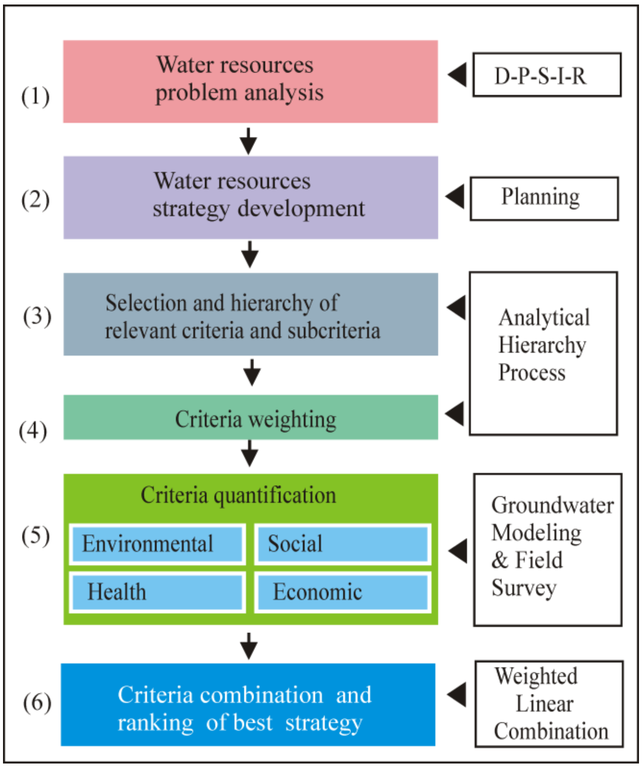

Figure 3.4: Flowchart showing the main steps in performing MAR strategy analysis.

In this method, the water resources problem of the test site is first comprehensively analysed using he DPSIR (Step-1). Depending on the water resources situation (e.g., water budget, potential IWRM measures and alternatives, etc.), alternative strategies for the water resources system are developed (Step-2). Afterwards, a number of most representative decision criteria are selected that represent environmental, health, social, and economical status of the water resources system in the study area (Step-3). The next step starts the Analytical Hierarchy Process (AHP) by decomposing the ultimate goal into a hierarchy. The top of the hierarchy is the goal of the analysis/problem. Each criterion at each level of hierarchy is then assigned an appropriate weight (Step-4). The weights can be derived by discussions with the decision makers, experts, scientists, and stakeholders. Pairwise comparison introduced within the scope of AHP by Saaty, 1980 is useful for criteria weighting. Criteria weighting is followed by criteria quantification. Criteria quantification (Step-5) is considered as being the most important and time consuming step of this methodology. Environmental and water related decision criteria, such as groundwater level rise or mean chloride concentration, are determined by means of groundwater flow and transport models applied over an adequate planning horizon, which is commonly at least 20 years. Economic viability may be judged on the basis of a Cost-Benefit-Analysis (CBA) while social aspects, such as social acceptance or willingness to pay, are quantified by means of a questionnaire survey. After criteria quantification, the criteria are overlain to estimate overall ranking of each strategy (Step-6). WLC method was applied in this study to ranks the the strategies.

The environmental analysis may show that certain MAR options are actually non-feasible, e.g. due to legal environmental constraints and regulations. These options will have to be excluded from further analysis. In general terms, the decision makers may try to improve the set of options by slightly changing decision variables related to MAR management (system operation), water recovery, location, and other variables.

The above methodology was implemented within the G-DSS. Since, the G-DSS does not offer criteria quantification facilities, it was done externally.

In this study, the above-mentioned methodology has been applied in North Gaza, West Bank.

3.6 Soil Aquifer Treatment (SAT) System Operation and Impact Assessment

An investigation concept to simulate SAT operation, to develop a groundwater monitoring plan for SAT, and to design optimal pond operation for the executive agency is developed in this study. This integrated and organized approach is based on the principle of underground processes for certain emerging pollutants in groundwater under the Soil Aquifer Treatment (SAT) condition. Figure 3.5 postulated the integrated concept showing the interrelationship of all relevant activities grouped into some research methodologies such as field activity, laboratory experiment and analysis, and mathematical modeling that should be considered for investigation. Under each fragment of the integrated concept, primary activities are listed. The outcomes of the activities are intended to serve as a detailed planning base for MAR practitioners. Depending on the site-specific hydrological processes, the activities might be supplemented by other activities. The addition of activity under each main research methodology will be a somewhat continuous process, at least through the initial years of a SAT research project. Information gained from each activity will provide a basis for other activities.

The above-mentioned investigation concept was implemented in this dissertation to design a SAT operation in a case study at Southern Europe.

All activities and details shown in Figure 3.5 were not performed in this case study. Field investigation consists of drilling activities, collection of soil samples, and infiltration tests. The collected disturbed and undisturbed soil samples were analysed in the laboratory for grain size analysis and used to understand the soil hydraulic and transport properties, and to perform a tracer test, e.g. a soil column experiment. The chemical analysis results of soil column tracer tests were obtained in this study from a secondary source. The determined and estimated soil hydraulic and transport properties (e.g. hydraulic conductivity, effective porosity, transport velocity, etc.) were used to develop groundwater flow and transport models.

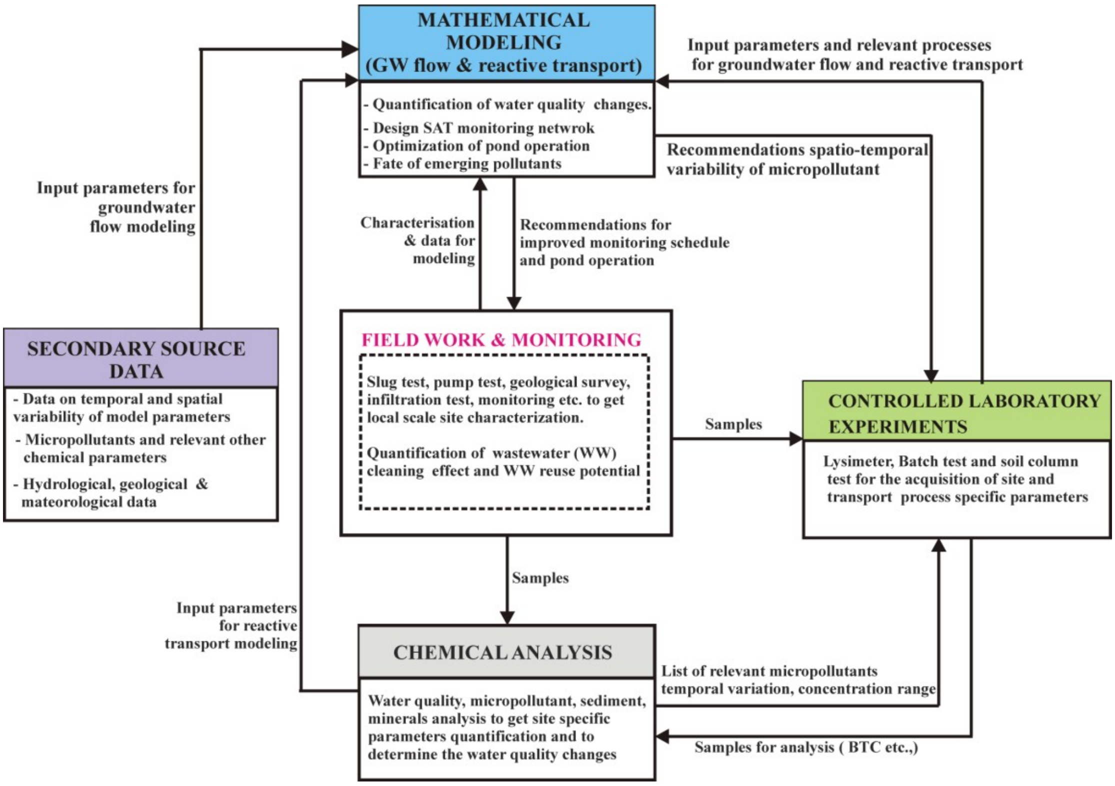

Figure 3.5: Integrated concept for investigation of water quality changes under soil aquifer treatment (SAT) (modified after GABARDINE, 2007**).**

The groundwater flow and transport model was calibrated against the GWL and electrical conductivity from a secondary source field test data. The calibrated groundwater model was then used to simulate the transport process of selected emerging pollutants in the test site. Finally, the model was used to find the optimum pond operation and to develop a groundwater-monitoring network for further application. In all steps of the investigation, secondary data improves the efficiency of the research. In this study, the above-mentioned methodology was applied in a test site in southern Europe.

3.7 Case Study and Site Selection

In total five case studies, one in Bangladesh and three of the GABARDINE project were selected and investigated in this dissertation to evaluate the MAR planning tasks (1) to (4), mentioned at the end of section 3.2, using the developed methodology for each one. The case studies are:

(1) Dhaka City (DHAKA) Case Study: A MAR pre-feasibility investigation, considering the water supply problem of an over-exploited aquifer in Dhaka, Bangladesh (Chapter 5).

(2A) Querença Silves (QURSV) Case Study: A practical application of the SMCDA tool (site selection module) at Querença Silves Aquifer in the Algarve region to prove the efficiency of spatial MCA as DS tool towards the ranking and final selection of suitable MAR locations (Chapter 6).

(2B) North Gaza Site Ranking (NGSIR) Study: A second site selection case study in north Gaza to clearly suggest that SMCDA analysis must be supported by hydrogeological impact assessment for selecting the best MAR technology at specific locations (Chapter 7).

(3) North Gaza MCA (NGMCA) Study: Selection of the most representative decision criteria for MAR management strategies, criteria quantification, and comparison and ranking of the strategies for the north Gaza Strip (Chapter 8).

(4) Local Scale SAT (LOSAT) Case Study: Design of an example of a groundwater monitoring network for detection of water quality changes under SAT and a proposal of an optimum pond operation schedule for decision makers, using a process-based transport model (Chapter 9).

The main criteria for test site selection are the hydrology, the hydrogeology, the state of the existing water resources system, and the prevailing water resource problems. Detailed description of the case study area is given within the relevant chapters. Brief descriptions of the relevance of each test site with respect to the relevant planning steps are given below:

(1) Dhaka City (DHAKA) case study - Dhaka Bangladesh

Dhaka City is facing immense problems of water supply shortage and immediate action is required to find alternative water resources to the current source, which is primarily groundwater. The government of Bangladesh has considered the possible implementation of MAR to help address growing water resource issues in the city. As of up until now, no feasibility study for MAR implementation has been done. A feasibility study is considered to be the first step in any MAR project planning (see section 3.2 and Figure 3.1). The availability of comprehensive hydrological data, hydrogeological information, basic GW quality monitoring data and the water supply problem makes a feasibility study for MAR in Dhaka City possible. A detailed description of the research efforts is shown in section 3.3 and the case study is given in Chapter 5.

(2A) Querença Silves (QURSV) case study- Querença Silves Aquifer, Algarve Region, Portugal

Due to the geographical location, the Algarve Region in southern Portugal is prone to experiencing droughts, and the region has been affected by many droughts over the last few decades. The droughts have caused severe shortages of available water resources. Surface water reservoirs had reached volumes, which were below acceptable levels, and the Querença-Silves aquifer system was overexploited. MAR is considered as a potential strategy to store water during the wet season and to use later during dry periods. Nowadays, selection of a suitable site of an aquifer for an infiltration basin is considered as one of the main MAR planning steps in the Algarve Region The surface and sub-surface characteristics and the available information of the groundwater body makes the Algarve Region an ideal study area for the implementation of SMCDA (Step-2 to Step-4, Figure 3.3). An environmental impact assessment (Step-5 in the methodology) supported by groundwater modeling was not performed for this MAR project due to the complexity of the urban groundwater dynamics, i.e., complexities of groundwater extraction, pollution, solute transport processes, sub-surface complexity, etc.

(2B) North Gaza Site Ranking (NGSIR) study- North Gaza Strip, West Bank

The water resource problems that northern Gaza Strip faces are immense. The habitants suffer from over-exploitation of groundwater resources and pollution due to inadequate wastewater collection, treatment, and disposal. Wastewater reuse will complement the existing water resources and will improve the agricultural water supply condition. Use of reclaimed water for agriculture will make freshwater available for domestic and industrial use. In this respect, MAR is considered a potential response to the current water resources problems in the northern Gaza Strip.

Infiltration of treated wastewater is considered as the first choice for MAR implementation. The aquifer system of Northern Gaza is not complex but is unconfined and phreatic. Hence, the 'NGSIR' case study is suitable to implement and demonstrate the entire methodology (section 3.4 and chapter 7), i.e. an application of the SMCDA tool followed by a hydrogeological investigation and site ranking. Based on the suitable sites and their ranking, decision maker can implement MAR project at the case study area.

(3) North Gaza MCA (NGMCA) study - North Gaza, West Bank

In the water policy of the Gaza Strip, MAR is considered as a potential response to the existing water resources problem. Therefore, the best MAR strategy that is viable for sustainable water resources development at the North Gaza, need to be identified. Based on the wastewater treatment plant construction and reuse of the treated effluent, several strategies can be developed. In order to support the decision maker to formulate viable MAR management strategies, the 'NGMCA' case study was undertaken by following the research concept shown in section 3.5. The 'NGMCA' case study formulate most viable MAR strategies, select the most representative decision criteria and rank the potential MAR strategies by using the developed methodology.

(4) Local Scale SAT (LOSAT) case study – A test site in Southern Europe

A wastewater treatment plant of a city in Southern Europe produces a huge amount of wastewater per day with all effluent being discharged directly into the bay. The continuous operation of the sewage plant during the last years has had a strong negative impact on the quality of the seawater in the bay. Not only is environmental degradation a major issue here, but also the effluent lost to the sea is a waste of a possibly significant water resource. Therefore, the municipality for water supply and sewage treatment has recently decided to determine the feasibility of using the aquifer to store the treated effluent delivered by the wastewater treatment plant. A study was performed to determine the viability of MAR application to the aquifer at the city using secondary treated wastewater. This 'LOSAT' study implemented the integrated concept mentioned in section 3.6 in the case study area to design an example of groundwater monitoring network for detection of water quality changes under SAT and to propose an optimum pond operation schedule for decision makers, using a process based reactive transport model. A detailed description of this case study is given in Chapter 9.

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Chapter 4

GABARDINE Decision Support System (G-DSS) for Managed Aquifer Recharge Project Planning

4.1 Introduction

Based on the concept that a Decision Support System (DSS) may support operational, financial and strategic decisions (Power, 2007), a number of DSS have been developed over time for different sectors of sciences and engineering, marketing, business etc. According to Power (2007), most of the DSS include the following three subsystems: (1) Database, (2) Analysis and Decision-making, and (3) User interface. The system analysis starts with the task of the registration of data in a universal format and subsequent processing, retrieval, and transformation for different problems. The analysis of data is accompanied by the decision makers' preference and related expert advice. The interaction between the system and the decision maker is supported by an adequate graphical user interface. Based on the analysis result and decision maker's plan, the whole cycle is repeated until a satisfying solution is achieved (Marakas, 2004).

In the field of Managed Aquifer Recharge (MAR), comprehensive decision support tools are still needed to support the planning and operation of MAR systems, serving as a response measure to water resources challenges related to water scarcity, groundwater pollution, seawater intrusion as well as groundwater level decrease due to over-exploitation. For comprehensive support to MAR project planning under water scarce conditions, an innovative geospatial decision support system (G-DSS) was developed under the scope of the European Research Project GABARDINE (Rusteberg et al., 2011).

This dissertation is developed within the framework of the Gabardine project and has contributed substantially to the G-DSS development. This chapter presents the basic system structure, functionality, and some of the G-DSS interfacing tools together with the contribution of the present study to the G-DSS development.

4.2 Conceptual Model of the G-DSS

Many DSS have been designed to integrate the capabilities of Geographical Information System (GIS), database management systems, decision-making techniques and expert systems (e.g. Marakas, 2004). It was conceptualised that the G-DSS is a modular system with different degrees of integration and support at each planning step by providing a common framework for interaction and information exchange. Keeping in mind for continuing development, the software system comprises a suite of standard tools, consistent convention and common language for module development (Rahman et al., 2009).

The G-DSS has a modular structure (see Figure 4.1). The detailed descriptions of the modules are given under section 4.3. In addition to the ability of the GIS for displaying the spatial analysis result, the system presents the non-spatial and time series data graphically. Some utility functions were developed to increase the ability of data presentation, consistency checking for MAR planning. These functions improve the analytical scopes within the system. All the components were developed and incorporated in the system as modules. The modules comprise individual components, providing access through standard menus. A user-friendly graphical interface was developed to guide the decision maker through the sequential steps of MAR planning, to switch over and interact with different modules, several decision analysis techniques and utility functions. The G-DSS was implemented under ArcGIS 9.2 environment to facilitate the implementation of spatial analysis procedures and result representation (Rahman et al., 2009). The system is tightly integrated in the ArcMap environment. This instrument is developed as an ArcMap extension, using ArcObjects and VB.Net. ArcObjects is a developer kit for ArcGIS based on Component Object Model (COM). This solution considerably extends the functionalities of ArcMap by implementing the MCDA within the GIS environment by allowing the developer to combine the advantages given by the user interface controls available in the .Net framework with the GIS functionality included with ArcGIS (ESRI). The advantages of customized components by using a COM-Compliant environment such as Visual Studio 2005 are: (1) a wider range of functionalities can be integrated into customisation, (2) codes are not accessible by the user, (3) all aspects of ArcGIS application can be used further, extended, and customized, (4) the customisation can be easily supplied to the client machines (ESRI, 2004; Boroushaki and Malczewski, 2008).

4.3 Modules of G-DSS and other Utility Functions

The following G-DSS modules were developed within the scope of the GABARDINE project and integrated into the GIS platform: (a) Geo DATA-base management module, (b) DPSIR module, (c) MAR PLANNING module (d) a spatial MCA module for MAR site selection, and (e) a MCA module for MAR option comparison and ranking (Rusteberg et al., 2011).

During the process of G-DSS development within the GABARDINE project, present study contributed to the development of the following modules and components, which were incorporated to the G-DSS:

- Development of concept, functionality, and analysis techniques for the following modules: (c) MAR PLANNING module, (d) a spatial MCA module for MAR site selection, and (e) a MCA module MAR option comparison and ranking; and related analysis component of each module
- Concept development to data exchange between the Geo-DATA base management module and these above mentioned three modules
- Assistance to the development of the DPSIR module and its interface
- Provision of the design and concept of the user-friendly interface for the entire G-DSS.

Figure 4.1 shows the G-DSS modular system structure. The so-called toolbox contains a number of software tools and models that have been developed in the context of the GABARDINE project, such as a time series generator, a hydro-budget tool, and a groundwater simulation software etc. These tools are not yet integrated into the G-DSS and therefore, the quantification of decision criteria is still an external process (Rusteberg et al., 2011).

In order to give a clear picture of the entire G-DSS, a brief description of the modules (Figure 4.2) and related components with interface design is given in the following sub-sections:

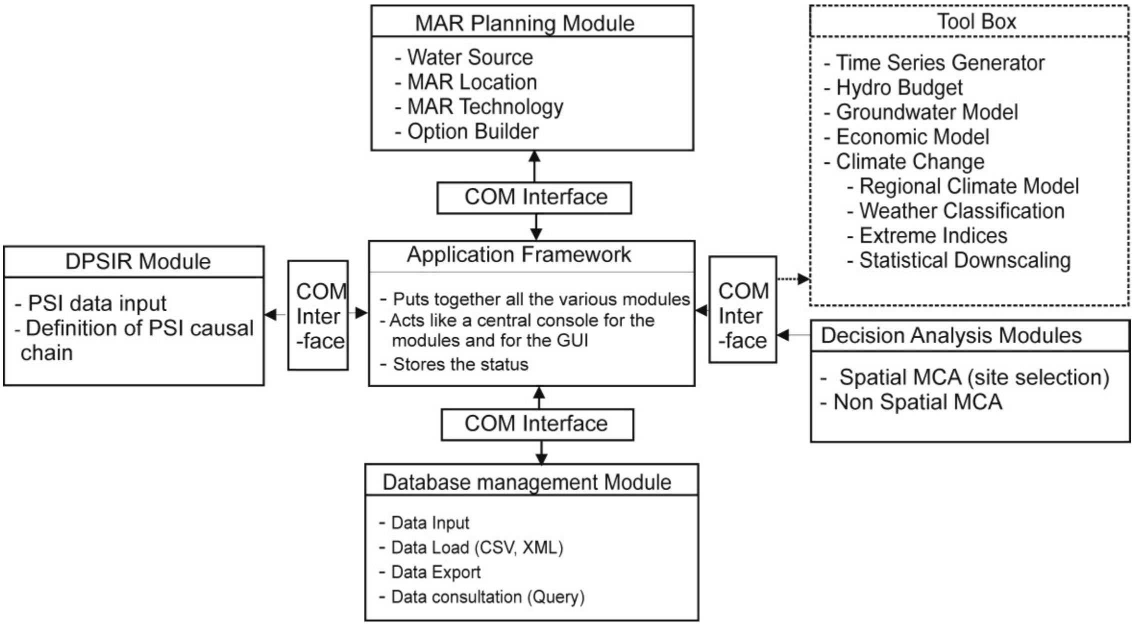


Figure 4.1: Conceptual model for DSS interfacing tool development (Rusteberg et al., 2011)

4.3.1 Database management module

In order to support the effective use of information and data, a geospatial database was included in the system, which was first developed by Wojda et al., 2010. The database was modified and integrated into the system afterwards. As MAR deals with spatial, non-spatial and temporal data, it is necessary to work in a Geographic Information System environment which includes different components, such as data, hardware, software, procedures, operators and analytical problem statements (Meeks and Dasgupta 2004). Spatial and temporal data should be stored in a structured way, in a common geospatial database, which enables not only their management, treatment and analysis, but also the possibility to transfer them to external simulation and modeling systems. The main reasons for

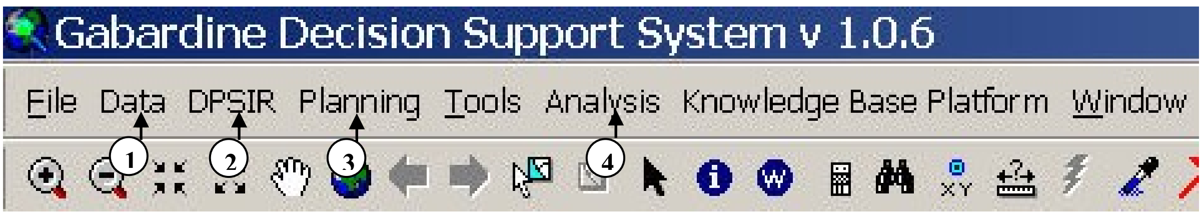


Figure 4.2: Interface showing the different modules of the G-DSS: (1) Data - Geo DATA-base Management module, (2) DPSIR- DPSIR Module, (3) Planning- MAR PLANNING Module, (4) Analysis – Multi-criteria Analysis Module

developing a common geo-database structure are: (1) to assure interoperable data exchanges amongst end users, through programmed protocols such as XML, (2) to have a very well structured data model for MAR system planning and management as well as IWRM (Figure 4.3), (3) to guarantee efficient

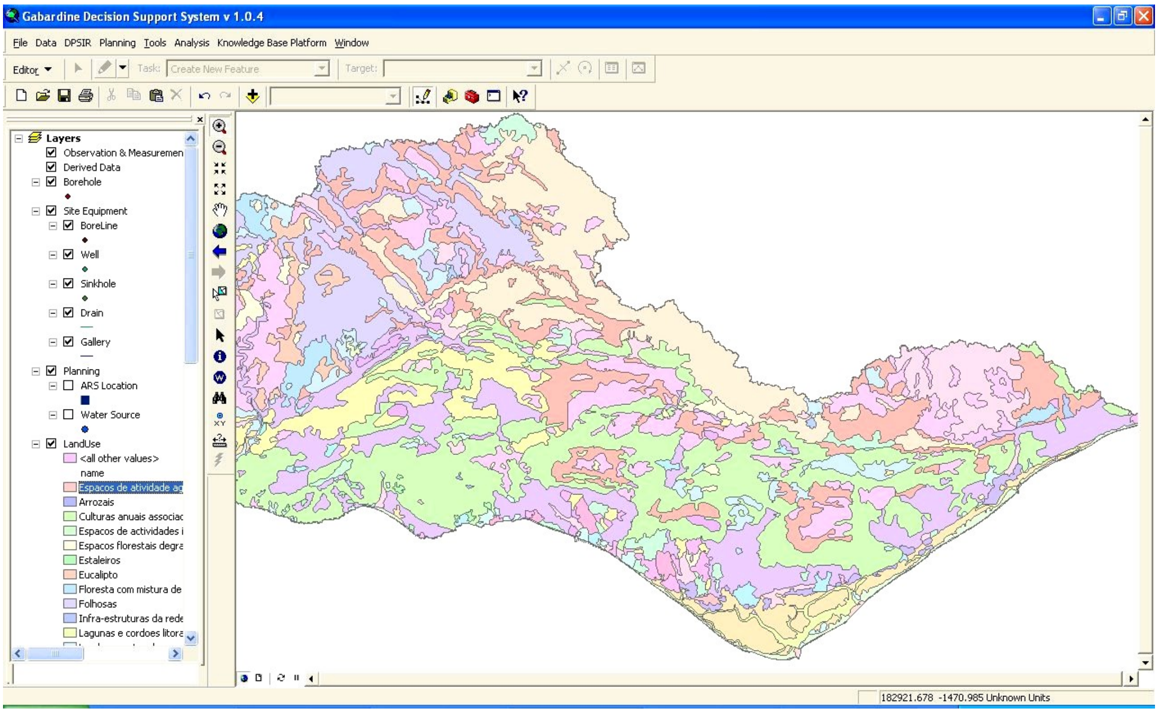


Figure 4.3: Overall database structure interface (left hand menu) (modified after Rusteberg et al., 2011 and Wojda et al., 2006)

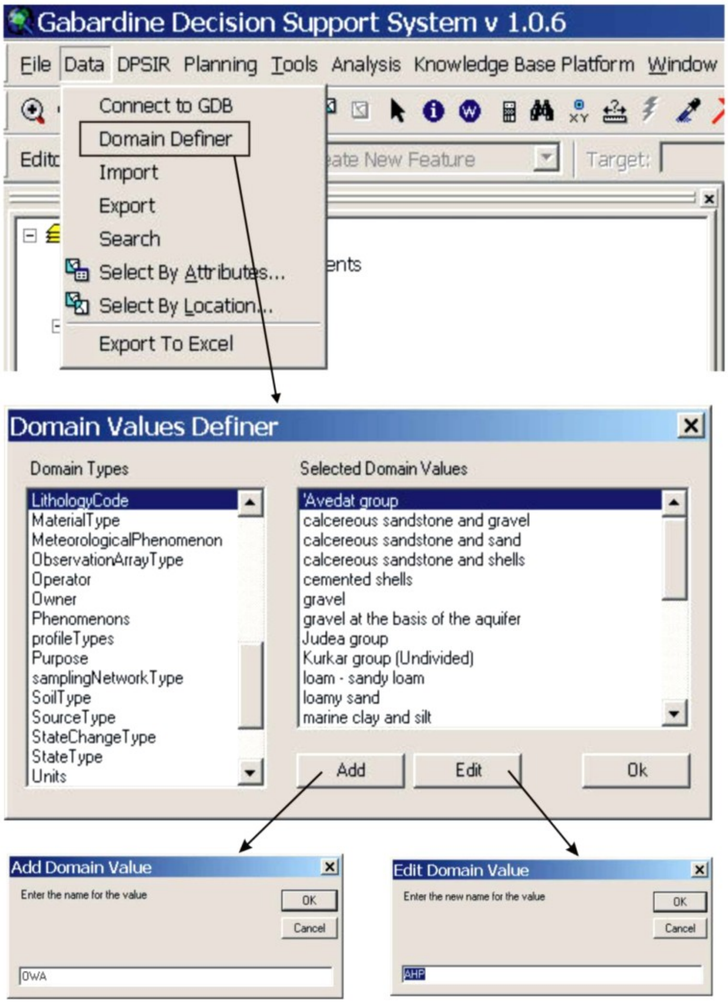
project dissemination and applicability worldwide, and (4) to enable later project integration with international initiatives such as INSPIRE, eContent, WISE, WFD, etc. (Wojda et al., 2006 and 2008). Figure 4.4 shows the interface to export data to the common spreadsheet program 'Excel'.

Taking the above mentioned requirements under consideration, the structure of the geospatial database was developed using a modular project-oriented approach that permits a precise outlook on data and more efficient data management. The solution is transparent for the decision maker, who manages only the sets of data grouped as follows: (1) data description the location of the

Figure 4.4: Export data from geodatabase to excel format

problem, (2) site equipments that are available or constructed for exploring the problem, (3) the results of monitoring or experiments performed using this equipment, (4) different interpretations or derived data, (5) water budget information of the watershed, (6) information for site selection, and (7) storing and handling of data for multi criteria analysis . These groups describe different parts of the environmental problem, and the decision maker does not need to know the internal data structure. The architecture of the Geospatial Database follows international standards concerning geospatial data encoding and transfer. This is reflected in its object-oriented approach supported by the Open Geospatial Consortium (OGC) and the International Organisation for Standardisation (ISO), which enables, for instance, an easy transposition and translation between real-world objects and informatics objects. Furthermore, the conceptual model of data for the Geospatial Database was developed and described using an actual business and industrial standard of the Unified Modelling Language (UML). The conceptual model is also directly implementable in the ArcGIS (Rahman et al., 2009).

Clear structure and unambiguous description following the Geometric profile and platform



Click on domain definer to switch to the Main window to add/edit the domain values.

Domain values definer allows to see the defaults parameters and allows to add or edit

Add or edit new item in the domain definer

Figure 4.5: Interface showing Domain Definer application

independent conceptual data models will facilitate Integrated Water Resources Management and information exchange between different actors from all water related domains. In the case of the DSS, this new conceptual model of data will permit an easy data integration and data exchange by programmed interfaces and eventually assimilation within International Spatial Data Infrastructures (Wojda et al., 2006 and 2008). Additionally, to make the Database more user friendly and flexible, a domain definer was implemented. Through the 'Domain Definer' the user is able to edit and add required parameters into the database (Figure 4.5).

4.3.2 DPSIR module

The Driver (D), Pressure (P), State (S), Impact (I) and Response (R), in short DPSIR, concept was developed for describing interactions between society and the environment (Kristensen, 2004) starting from the assumption that there is a DPSIR causal chain (see Figure 4.6 and Wojda et al., 2006 and 2008). The strategies developed by the European Commission for the implementation of the Water Framework Directive have identified the DPSIR framework as a convenient way to identify stress factors and their effects on the water resources system and groundwater as well. In order to use the G-DSS and to be guided, the water manager needs to proceed in three main steps. First of all, the (multidimensional) problem has to be analysed and structured and this is accomplished using the DPSIR approach. In more detail, at the starting point of the analysis, the water resources related problems are identified. Prior to giving the best response to this problem, the first step is to analyse the problem itself. To do so, the methodology was made compliant with the DPSIR approach, which is a very convenient and appropriate framework for analysing complex environmental problems from a common physical and socio-economical point of view. The problem is analyzed, decomposed and structured in this phase. The

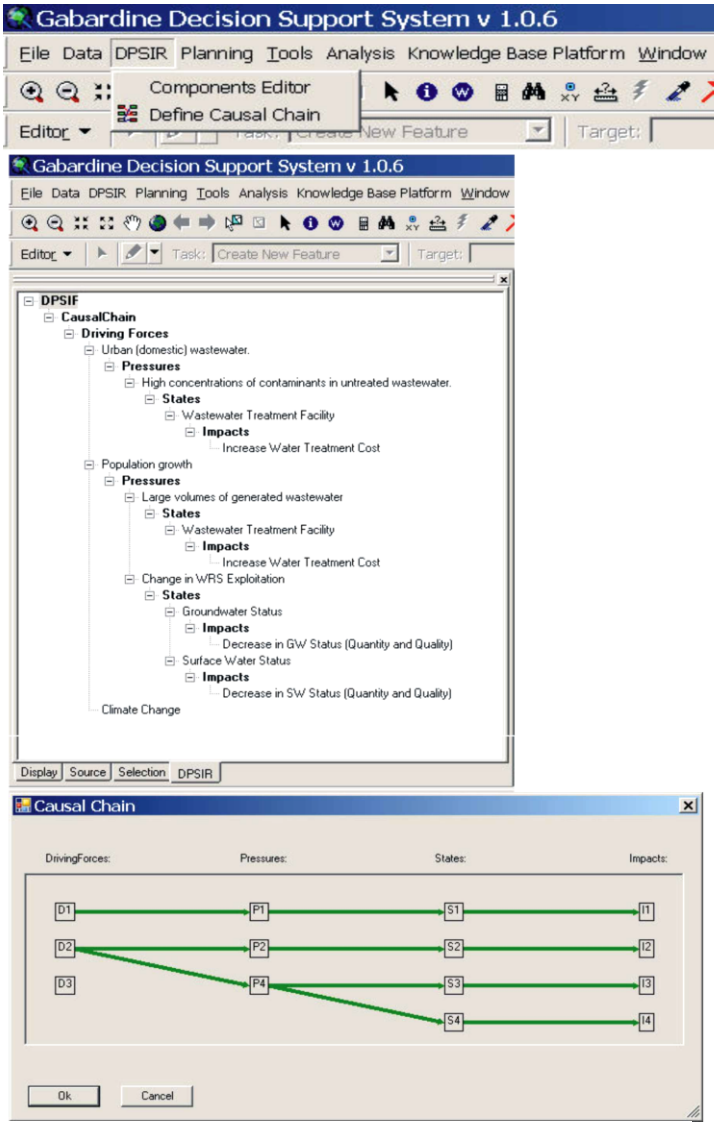


Figure 4.6: Example of DPSIR module implemented in the DSS

next step is to identify potential measures as ‘response’ to the water related problems, which were structurally described in the first phase. It would be possible to screen these responses in order to retain only the feasible ones. In the G-DSS, the measure of “MAR implementation” as a potential response measure to water scarcity was conceptualised, considering different sources of water, at different locations with certain technological, pre-treatment and operational requirements. The DPSIR concept is similar to some extent to the general methodology developed and used in the MULINO project (Giupponi et al., 2004). In addition, the G-DSS provides the spatial visualization of the DPSIR components (Wojda et al., 2006). Figure 4.6 shows an illustrative example of a DPSIR application for water resources management problem analysis at Northern Gaza Strip.

4.3.3 MAR planning module

The MAR planning module is a key module of the decision support system. The module consists of two components, namely watershed info (“Basin Edit”) and ‘Start Planning’ (Figure 4.7). The ‘Basin Edit’ function allows the user to enter relevant information of the study area. The water budget information can be stored in the system through the ‘Water Budget Data’ option (Figure 4.8). The planning module has a tree structure, which appears in the left part of the screen in a windows–like appearance (Figure 4.9). The components of the tree are linked to different analysis techniques, information and modules using the right-hand mouse click option. The planning tree allows the end user to guide through the sequential steps of planning; namely, water source, water quality check, ARS (Artificial Recharge System) location, ARS technology, and option builder. The attributes (e.g., water quantity and quality) of the available water sources (e.g., surface water, treated effluent, imported water etc.,) are implemented at the first step for understanding the overall water availability situation (Figure 4.10) with the status of water quality (Figure 4.11) and for further consideration while making decisions.

Clicking on ‘Planning’ menu allows to navigate ‘Basin Edit’(Figure 4.8) and ‘Start Planning’ options (Figure 4.9)

Figure 4.7: ‘Planning’ menu for MAR planning Module

The system also offers the visualization of time series data in addition to the general advantage of spatial visualization in ArcGIS. The user has the flexibility to add new water sources by clicking on

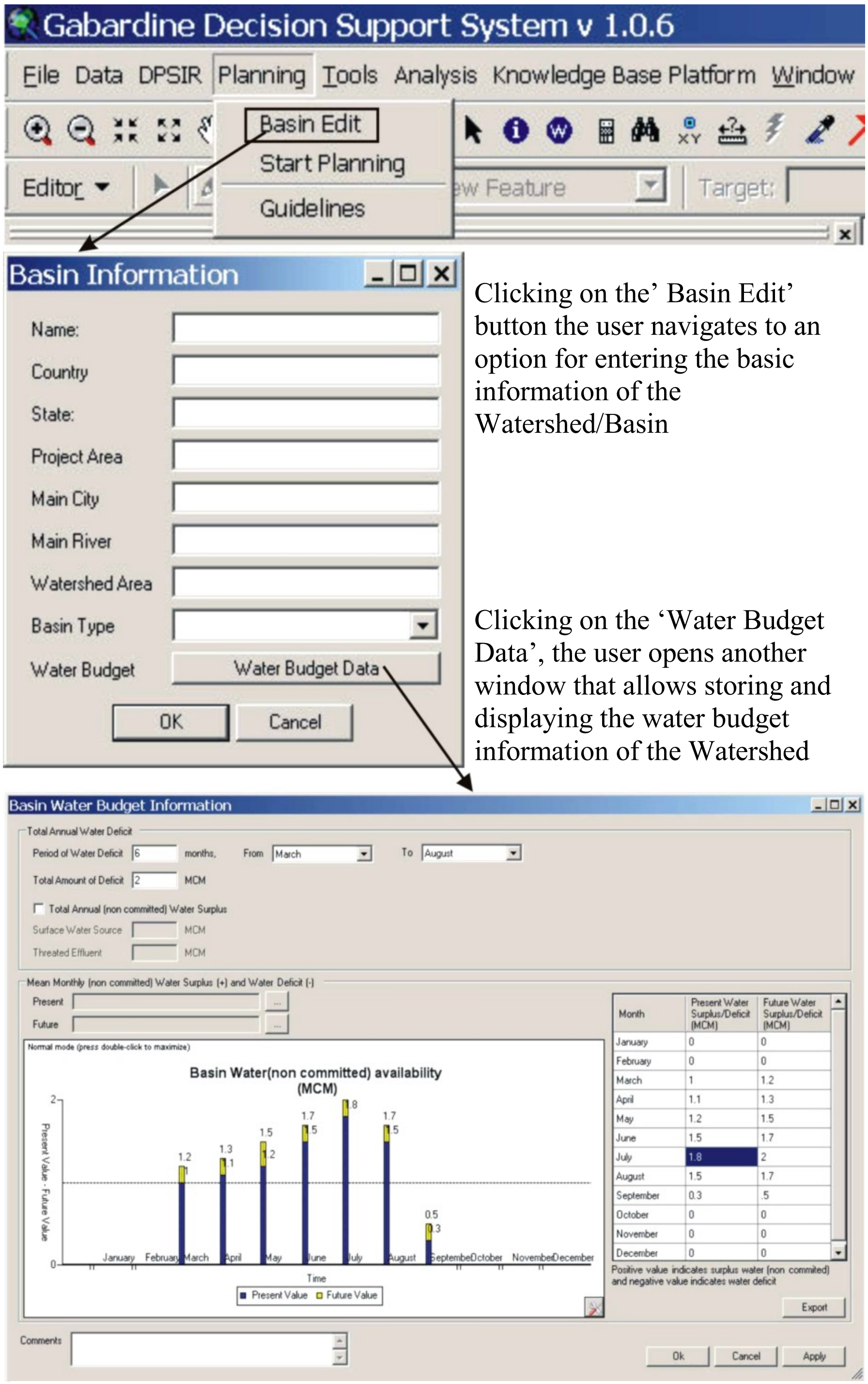


Figure 4.8: 'Basin Edit' options for the watershed

the map and to work with any type of water sources. The availability of water in the watershed can be added to the system to analyse the water budget quantitatively (Figure 4.10). The water quality check allows the user to compare the water quality of the source with standard water quality guidelines/

regulations. The system offers the WHO standard as default for the water quality check. The local guidelines can be compared also in the system.

If the source attends to water quality standards, the system user proceeds with the identification of potential sites for MAR. If the site for MAR system implementation has been already fixed, it can be demarcated in the system with additional general site information asked by the system. If the location is not known, the system offers a method for MAR site selection (described in 4.3.4). Preferred location-wise MAR Technology is assigned together with the location demarcation. General information such as aquifer thickness, distance from the water sources, use of the injected water, etc. for each location can be saved in the database.

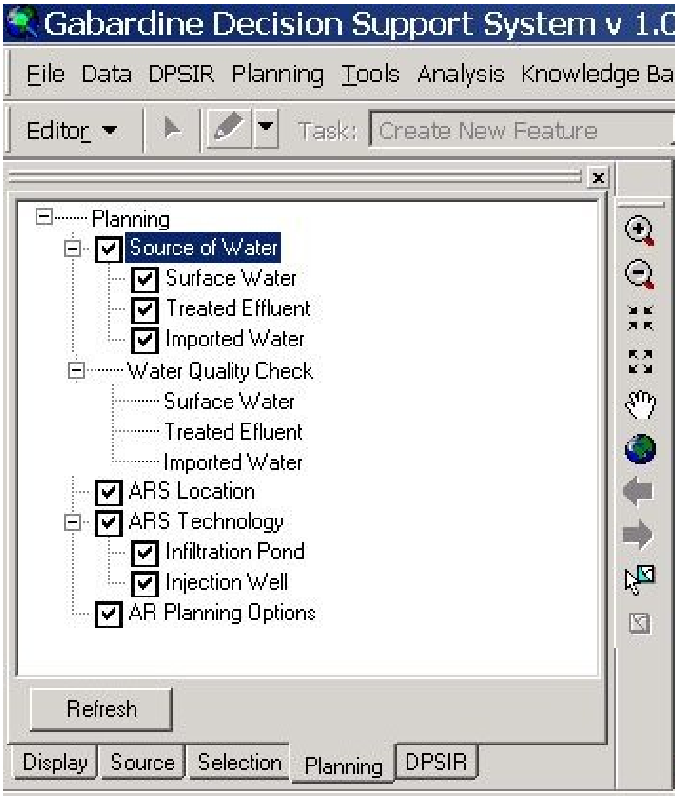


Figure 4.9: MAR 'Planning Tree'

The final step is the definition of a set of alternative MAR planning and management options, supported by the so-called 'Option Builder' under the step 'MAR planning Options' in the planning tree. This step allows the user to define MAR options using the information already given in the preceding steps. Main options components are the water source, MAR location, technology, and annual amount of water to be infiltrated or injected at specific locations. By varying the water source, water quantity, and use of water together with MAR location, the user may generate different MAR project options. These options may be further analysed and ranked based on MCA procedures, given in the decision analysis module. A brief description of the corresponding interface is given under Chapter 4.2.5.

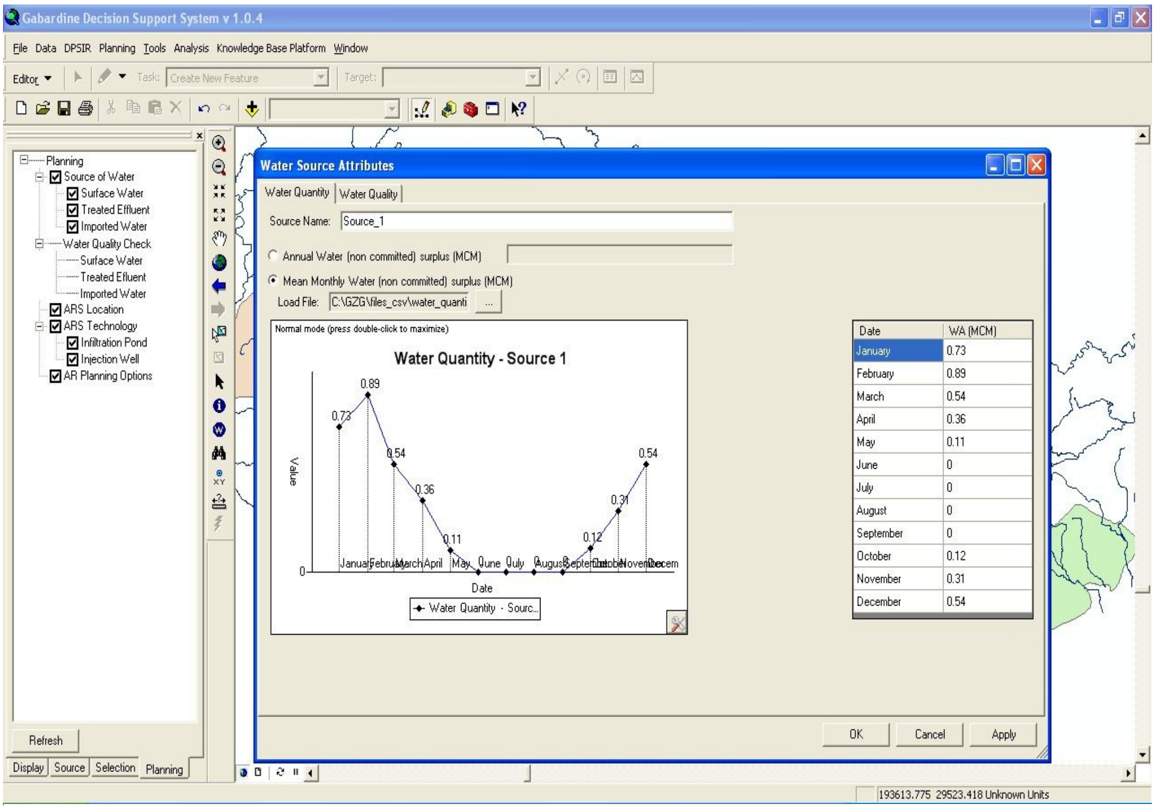


Figure 4.10: 'Water Source' (quantity) attribute in the G-DSS

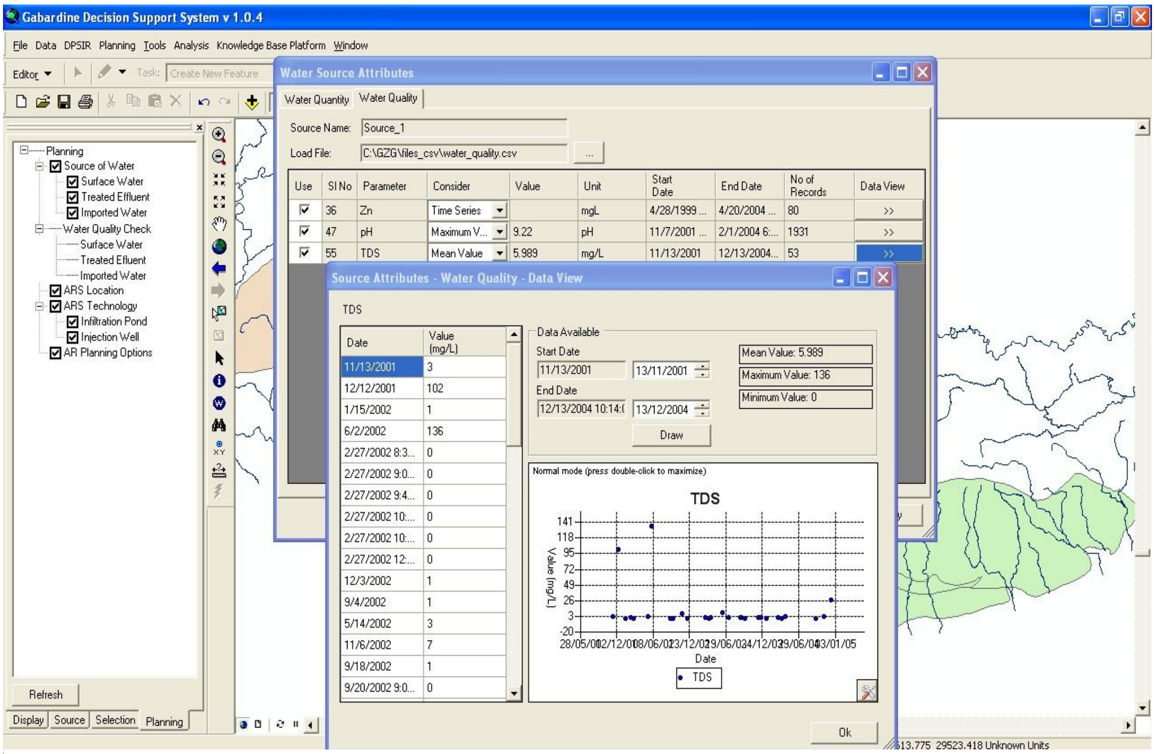


Figure 4.11: 'Water Source' (quality) attribute in the G-DSS

MAR site selection

When the location of the MAR project is not known, the system offers a module which facilitates the user to perform a Spatial Multi Criteria Analysis in order to select potential sites and study their suitability with regards to MAR project implementation (Figure 4.12). The following section gives an overview of the methodology for a site selection tool that was newly developed and describes the interface in details.

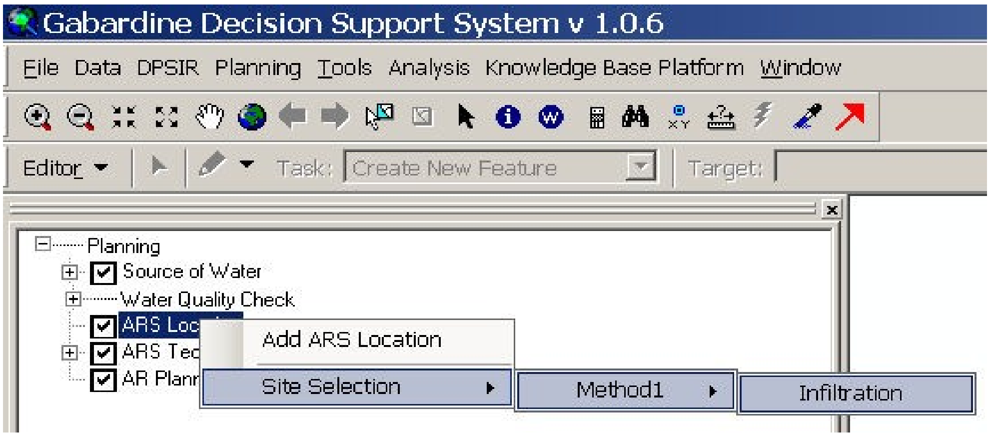


Figure 4.12: Navigation of site selection module from MAR planning tree

A. Constraint mapping

Starting the procedure, the system offers some default criteria to choose and to select the corresponding raster map. New criteria can be added by the user. Both value type and class type map can be handled by the system. The user defines the threshold value for value type criteria and may assign 0 (for non-potential area) or 1 (for potential area) to each class of the class type map. The system then creates a constraint map of each sub-criteria separately (Figure 4.13). The resulting maps may be overlaid and one constraint map can be prepared according to Boolean logic. The constraint maps are added to the ArcGIS document and can be used for further analysis.

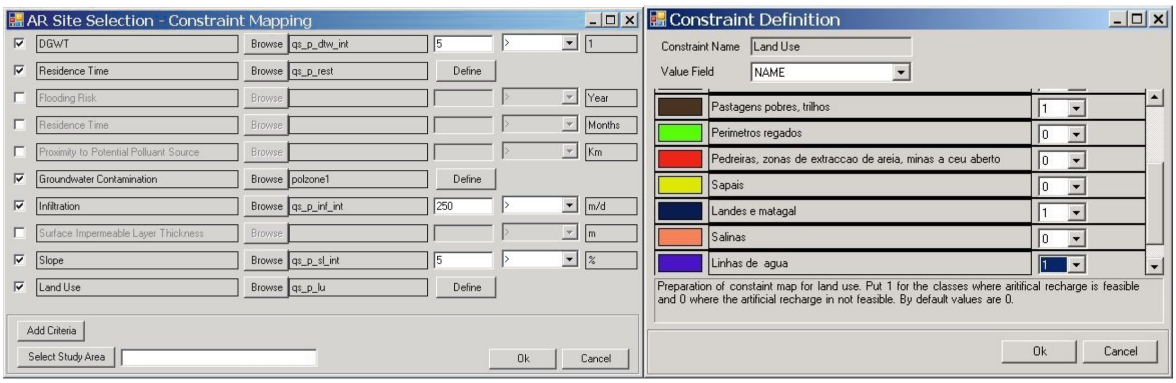


Figure 4.13: Constraint criteria selection and threshold definition for value type maps (left) and for class map (right)

B. Site suitability mapping

Site suitability mapping starts with the preparation of a hierarchical structure by selecting the criteria and sub-criteria for each level and naming the goal of the analysis. The user selects the criteria from the default list. The default criteria are prepared, considering all relevant characteristics that should be included for spatial analysis. Special care was given to avoid any duplication of the criteria/sub-

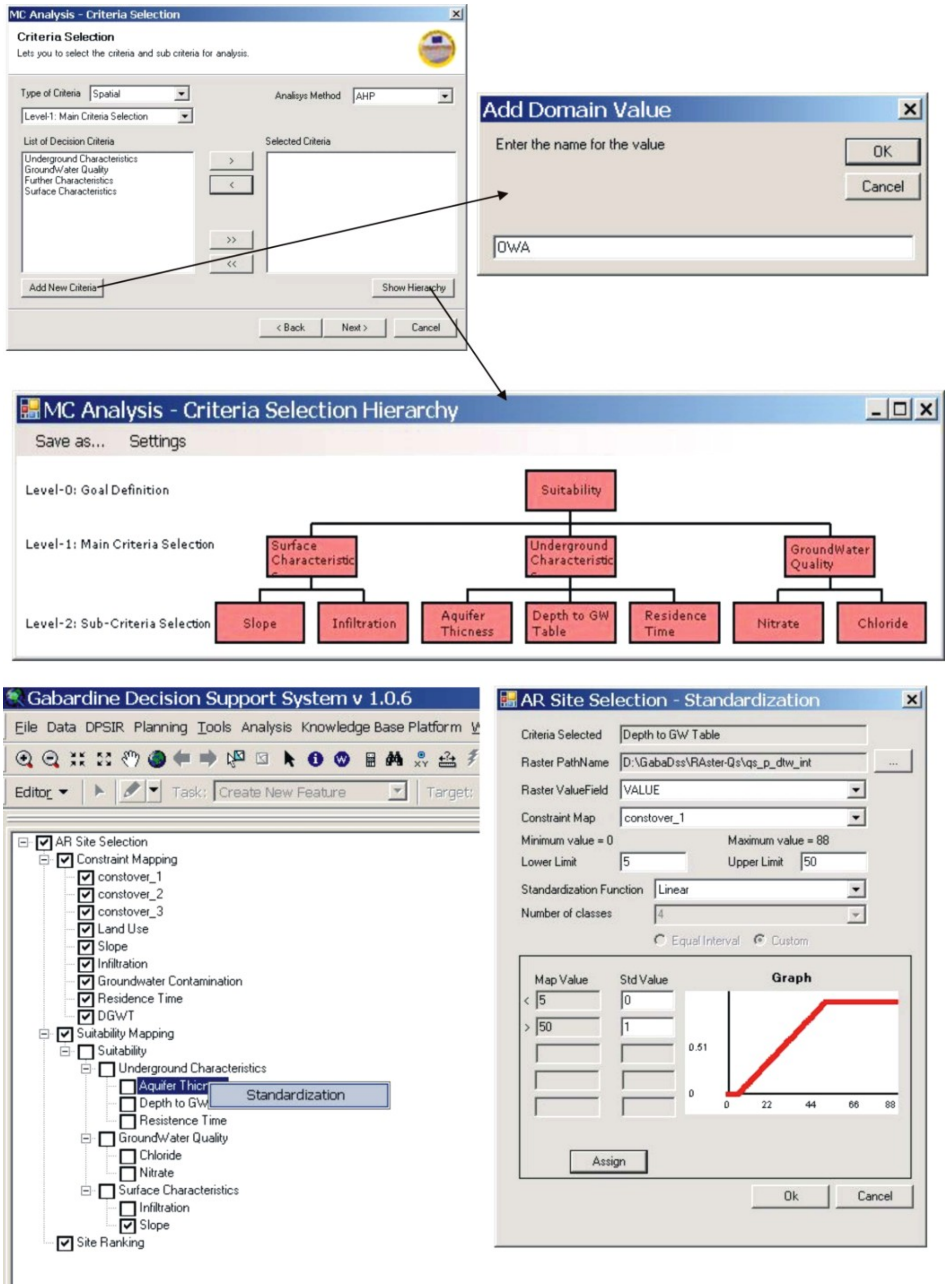


Figure 4.14: Interfaces showing the criteria selection, hierarchy construction and standardization of the thematic maps

criteria in the analysis. New criteria or sub-criteria can also be added easily (Figure 4.14). The user can visualize the hierarchical structure and edit for presentation and reporting purposes. The standardization process follows building of hierarchy. The user selects the criteria, the constraint map, the threshold values, and the preferred standardization function.

The converted function is drawn graphically in the interface for better visualization (Fig 4.14). Overlay command from the criteria tree proceeds to the step of weighting and overlay. The system offers pair-wise comparison and a direct weighting method. The weights of each criterion in each level can be given directly or generated by pair-wise comparison. By applying the pair-wise comparison method, the user can input preferred values using a scale bar. The weights are generated using the specified formula by Saaty, 1980.

Finishing the weighting procedure, the system user reaches the final steps for site suitability mapping

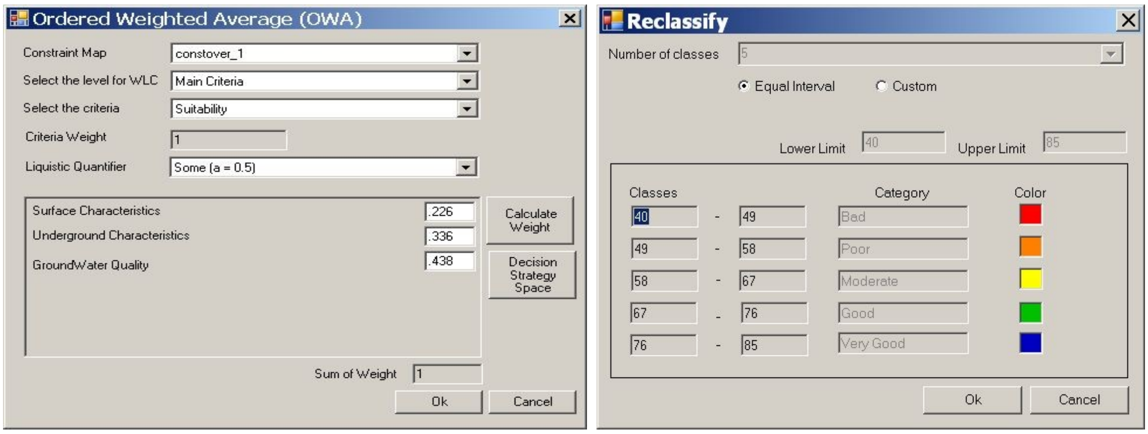


Figure 4.15: Overlay for final suitability analysis (left) and reclassification step of the suitability map (right)

(Figure 4.15, left). Two different overlay procedures are being offered by the system, Weighted Linear Combination (WLC) and Ordered Weighted Average (OWA). In OWA, the linguistic quantifiers are assigned to each level of the overlay. The resulting map is then created and shown as an ArcGIS document. The Analytical Hierarchy Procedure AHP, according to Saaty (1980), supports the construction of a criteria tree as well as the calculation of relative weights of criteria and sub-criteria by pair-wise comparison. After the AHP function of the program is carried out, WLC or OWA are utilized. WLC computes the overall suitability for each alternative or cells using the standardized map, weights, and constraint map. On the other hand, OWA produces the suitability maps by specifying the linguistic quantifier, α (generating a set of ordered weights related to α and combining the generated value for each alternative).

By changing the weights of each overlay method and linguistic quantifier associated with the objectives and attributes for OWA, a wide range of decision scenarios can be generated and the corresponding map layers are added to the map document. This helps to check the sensitivity of the system with changing weights and linguistic quantifiers.

The suitability map can be classified as very good, good, moderate, poor and bad. The system offers five different colors, after Water Framework Directive (WFD), for the five classes (Figure 4.15, right). The user has the opportunity to change the range of class manually.

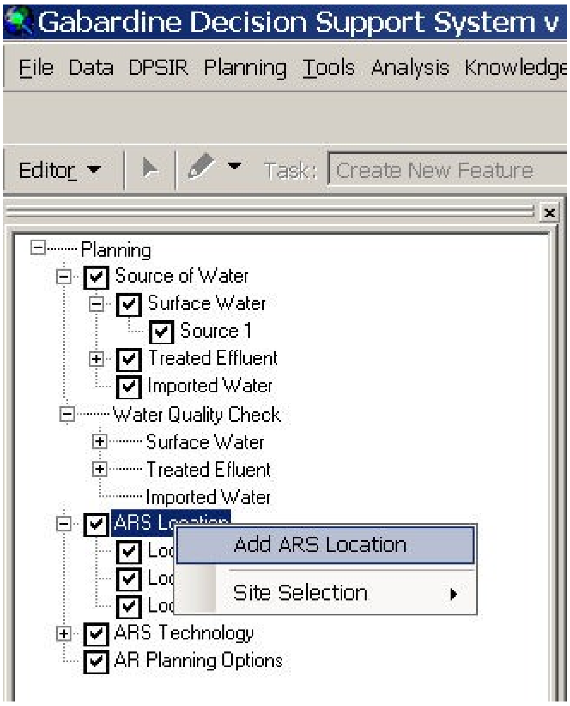
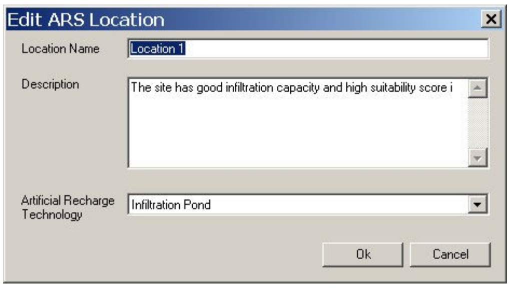


Figure 4.16: Right click option in the site selection tree to include MAR location

The system user may now choose different most-suitable MAR locations according to the location of the available sources of water, taking the required water transfer between sources and selected locations into consideration. The proper technology, such as infiltration pond and or injection well techniques depend on the surface and subsurface condition of the area. The selected most suitable locations will be fixed by using the right click option in the site selection tree and navigating to the positioning of the location on the GIS map (Figure 4.16). The user is asked to give the details of the locations and the technology that will be used at the specific locations (Figure 4.17).



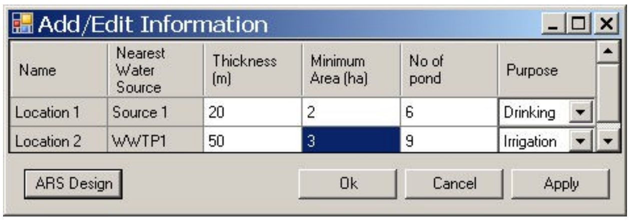


Figure 4.17: Interface showing the input window to include details of the MAR location in the system

4.3.4 Option builder

An important step in the MAR planning process is to prepare different options for MAR implementation in the area under study. A planning option combines potential sources of water with

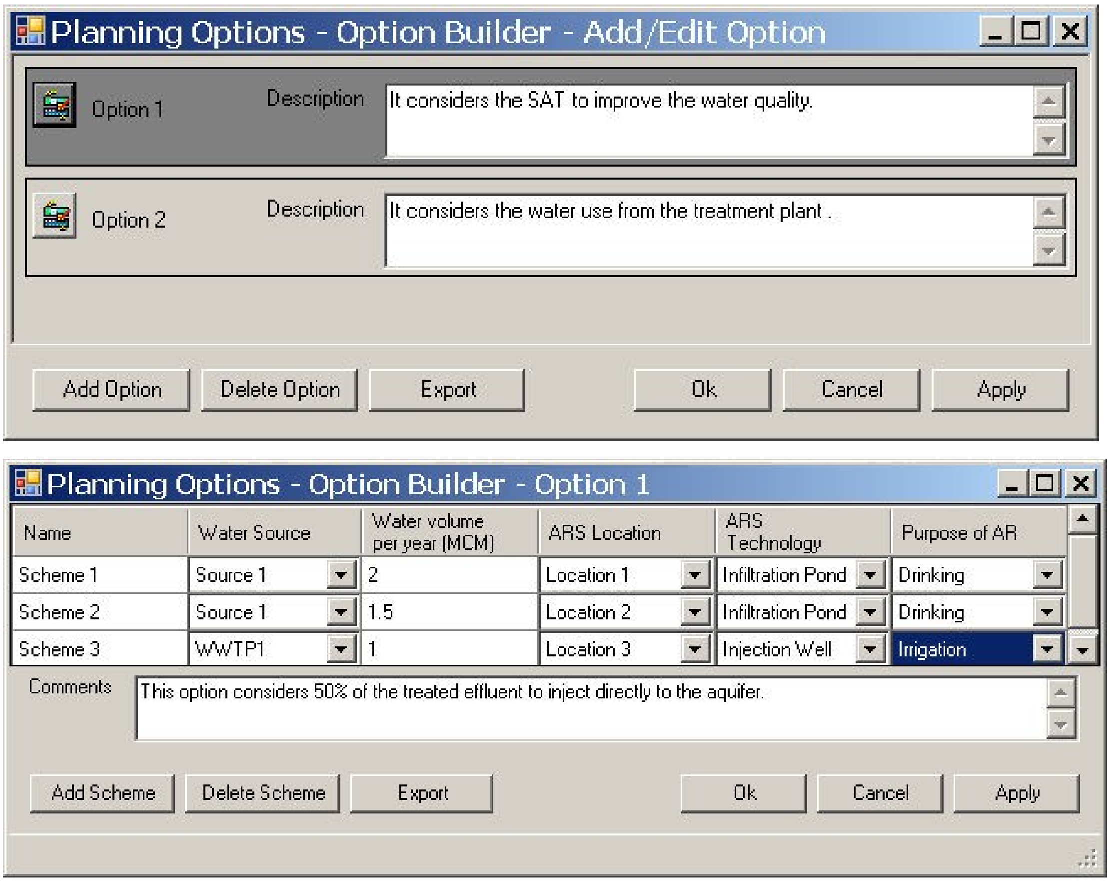


Figure 4.18: The option builder to construct the options and the schemes under each option

annual recharge volumes at specific locations applying proper technology for recharge and recovery for pre-determined uses. The 'options builder' facilitates the development of these options by combining pre-investigated MAR planning elements in an interactive manner based on the left-hand planning menu (Figure 4.18). Different options for the same water source or same recharge location may be considered. These options are linked to the MCA tool. The Decision Analysis Module (Section 4.3.5) reads directly the options, which were prepared by the MAR 'Option Builder'.

4.3.5 Decision analysis module

The selected generally viable MAR planning and management options may be further evaluated and ranked by the means of MCA module. This requires the definition of a set of representative

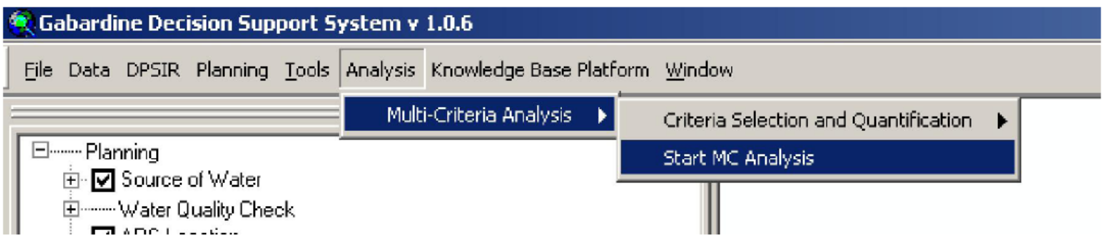


Figure 4.19: MC Analysis, main menu

environmental, health, social, economical, and management criteria by means of a participative process, involving the most relevant stakeholders. The module is accessible through the standard menu option, called 'Analysis' (Figure 4.19).

To start the MCA module, the first condition is to have all the options defined in the planning module. The module will not be functional if this condition is not fulfilled. The first step is to give a project name to the current MCA model that the user wants to define (Figure 4.20). The next step is to choose the second level indicators or criteria. In the application 5 types of second level indicators are defined: Environment, health, social, economy, and management. The user can choose any criteria from the second level for further analysis. The next step is to select third level or lower level criteria (Figure 4.21). A number of criteria are already defined under each second level criterion within the system for the user. At this state of system development, the addition of new criteria is not available due to the restriction of criteria quantification. The quantification of each criterion for the options is not similar. Each criteriion has its own characteristics. To calculate the required values for MCA, the function related to the criteria should be given by the user. Figure 4.22 and Figure 4.23 shows the interface for some MCA input

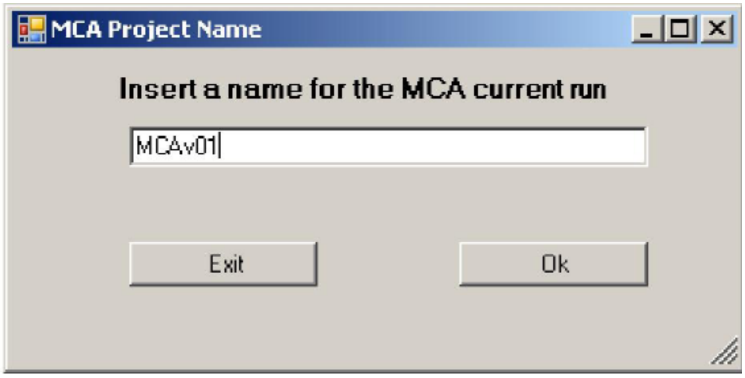


Figure 4.20: Starting interface for the MCA module.

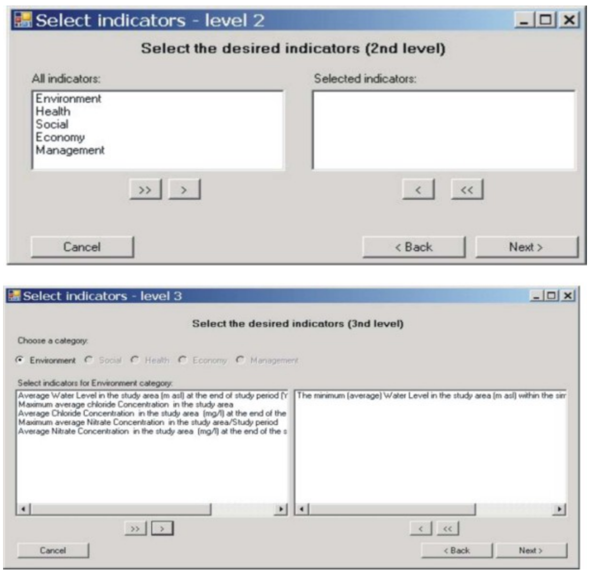


Figure 4.21: Selection of 2nd and 3rd level criteria

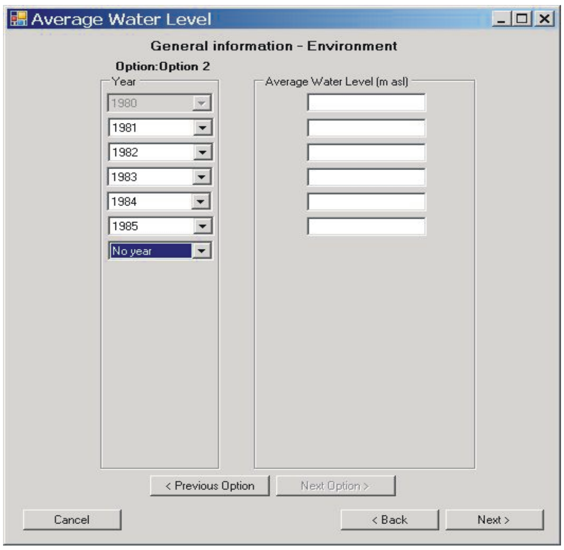


Figure 4.22: Input interface for GWL criteria value

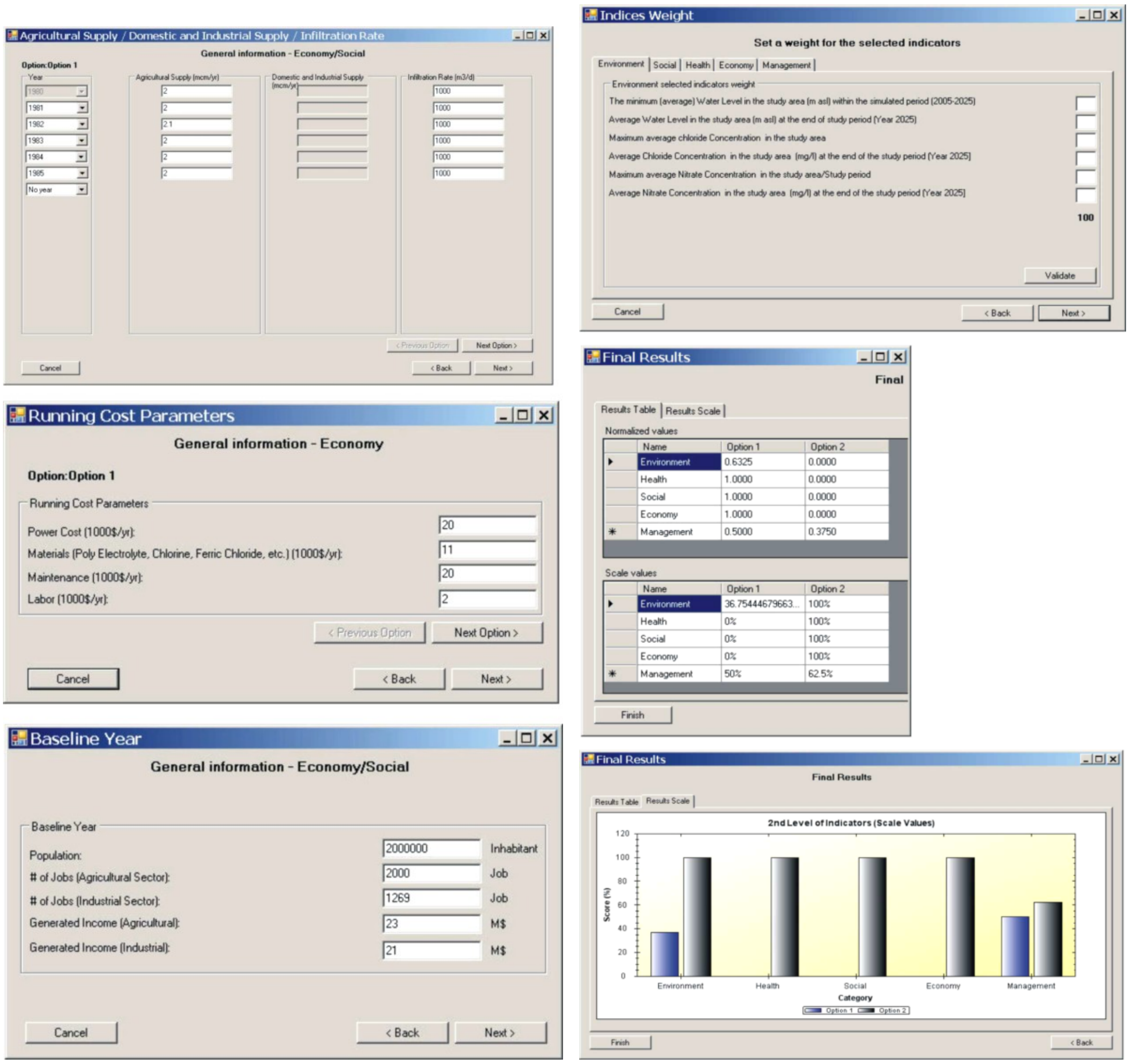


Figure 4.23: Different input interfaces for Multi Criteria Analysis

functions. In the system, 21 criteria were chosen, introducing the required functions for their quantification. The quantification of each criterion is followed by standardization.

4.4 Conclusions and Recommendations

The report presented the main elements of the graphical user interface (GUI) of the Gabardine Decision Support System. User friendliness and flexibility of the GUI guarantee a fully interactive environment which enables the system user to take care of the complex non-straight forward planning and decision making process for MAR implementation. The interfaces were prepared in a way that even the non-technical person could apply the software. Nevertheless, the expert and decision support system should be handled by experienced technicians, since the system involves a number of data processing and handling tasks.

In the G-DSS, the interface allows the user to check and edit the domain values, switch over to the modules and decision analysis techniques, and to store and display the most relevant data and information. The integration of the different interfaces was made to ensure the efficient communication between the worldwide end user and the complex decision analysis techniques.

The G-DSS is an open-end system and new modules are being continuously developed and incorporated. Efforts will be undertaken to integrate further mathematical modeling tools to support Environmental Impact Assessment, especially groundwater modeling software, as well as further decision analysis and optimization techniques.

4.5 References

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Chapter 5

Hydrogeological Investigation towards Managed Aquifer Recharge Implementation for Groundwater Resources Development and to Strengthen Water Supply at Dhaka City, Bangladesh

5.1 Introduction

Increases in the world population, urbanization, industrialization, and non-sustainable practices in agriculture are expected to raise water demands significantly during the next decades (UNEP, 2000). Water resources in certain regions of the globe are already facing demands in excess of available supplies. Therefore, a better water resources management is needed.

The metropolis of Dhaka City, Bangladesh is already confronted with the problem of shortage in water supply (Varis et al., 2006). Historically, Dhaka City has had immense problems related to flooding, waterlogging and drainage congestions during Monsoon (Alam and Rabbani, 2007). Presently, 75% 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 (DWASA, 2010). The population of Dhaka City is presently about 12 million (water supplies by DWASA cover 8.6 million people) 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 (Figure 5.1a).

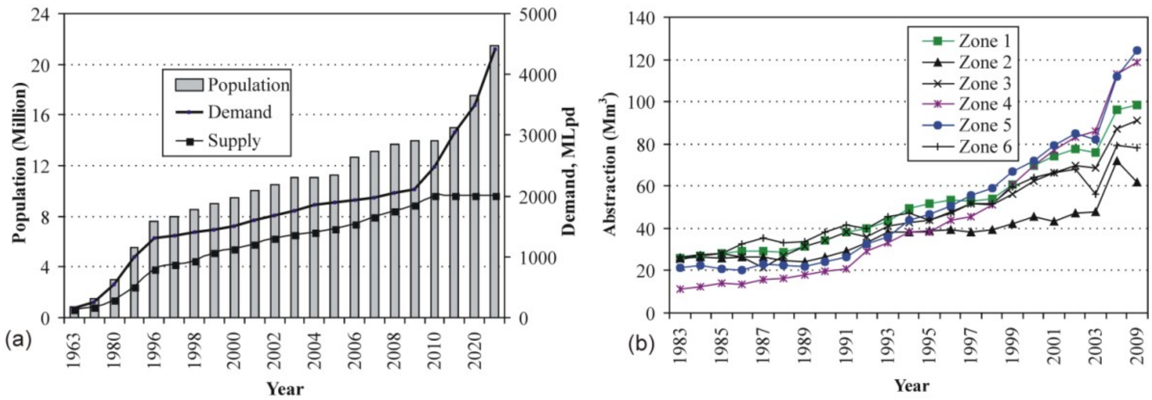

Figure 5.1: (a) Past, present and future water supply and demand scenario for Dhaka City (Source: Population: BBS, (1991); Water supply and demand data until 2010: DWASA, (2010), and DWASA, (2008); Future population, water demand and supply: ADB, (2007). In the figure MLpd is Million Liter per day. **(b) Historical development of groundwater abstraction in six zones of Dhaka.** Abstraction data from year 2004 to year 2008 is missing.

Recently, DWASA has installed high capacity water wells to tap the upper Dupitila aquifer (Haque, 2006). Figure 5.1b shows the increasing trend of groundwater extraction from the aquifer of Dhaka City. In most of the region, groundwater extraction exceeds recharge to the upper Dupitila aquifer. Average groundwater depletion is about 2-3 m/year (Haq, 2006, Akhter et al., 2009), making calls for the alleviation of upper Dupitila aquifer exploitation and the exploration of more suitable and sustainable water resources well-founded.

Besides groundwater, the peripheral rivers are the nearest dependable surface water (SW) source. However, SW is no longer considered as suitable water supply source due to continued pollution (Subramanian, 2004, Kamal et al., 1999). Especially, the river along the Tongi Canal, the Balu River, the Turag River, the Buriganga 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.

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 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). The scope of this chapter is to evaluate the hydrogeological situation in Dhaka City in the context of a planned MAR implementation. The study provides a preliminary hydrogeological feasibility assessment to determine if MAR can be successfully implemented and operated with optimum recovery efficiency. Furthermore, this paper briefly explores potentials, viability, and challenges of a MAR implementation and its contributions to a sustainable groundwater resources development and to a strengthened water supply for Dhaka City.

5.2 Study Area Description

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 5.2).

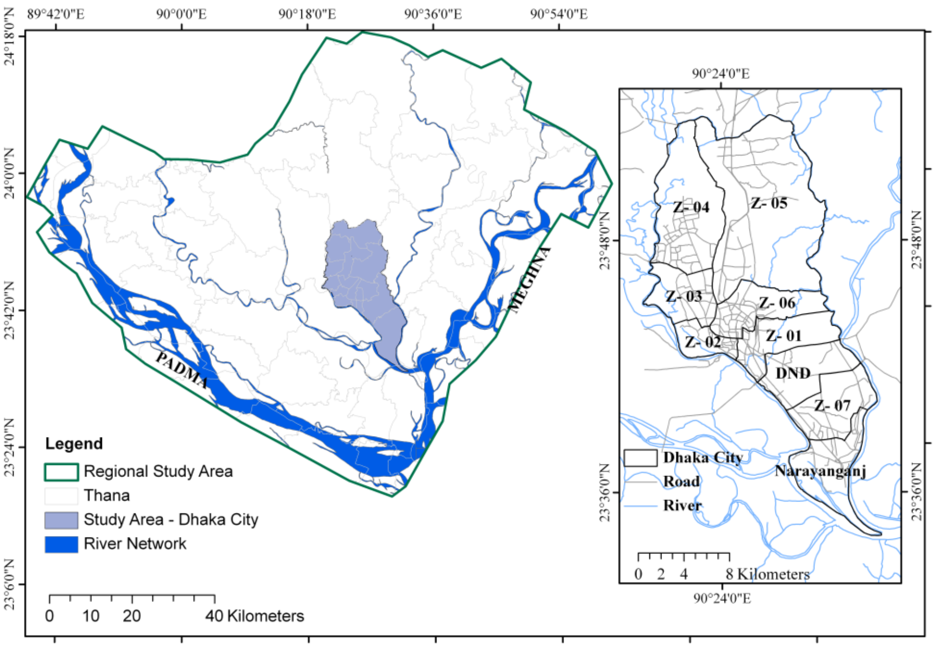

Figure 5.2: Study area map showing regional and local boundaries together with the river network

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 300 and 450 mm. Monthly average temperatures range between 25^0C and 31^0C. Maximum and minimum temperatures are 40 $^{\circ}$C and 6 $^{\circ}$C, respectively. The monthly average humidity and evaporation ranges between 80% and 90%, and 80 and 130 mm, respectively. Table 5.1 shows long-term monthly average climatic parameters in Dhaka City.

Table 5.1: Long-term monthly average climatic parameters of Dhaka City (JICA, 1991; BMD, 2006)

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp. (°C) High	34.2	36.6	40.6	42.3	40.6	38.4	35.2	35.9	35.3	38.8	33.3	31.2
Temp. (°C) Low	5.6	4.5	10.4	15.6	18.4	20.4	21.7	21	22	10.4	10.6	6.7
Average (°C)	18.6	21.5	26.1	28.7	28.9	28.7	28.7	28.7	28.7	27.4	23.6	19.8
Relative Humidity	70.7	66	63	71	79	86	87	86	86	81	75	74
Evaporation (mm)	104	79	81	77	78	83	87	130	118	106	75	105
Rainfall (mm)	7.2	20.3	53.0	127.02	280.2	359.6	360.8	303.0	285.6	165.7	31.4	9.6

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 subdivision were maintained for the analysis purposes, because most of the information is based on the old management zones.

A general description of surface water sources, geology, hydrogeology and aquifer properties of the study area is given in section 5.4 and 5.5.

5.3 Methodology of the Study

For the assessment of the water resources problems of Dhaka City, the Driver (D), Pressure (P), State (S), Impact (I), and Response (R) (DPSIR) concept was applied. The DPSIR (EC, 2002) concept has been developed to evaluate interactions between the society and the environment based on the assumption of a causal connection between society and the environment. 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; EC, 2002). 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. Based on this approach the water resources problem of Dhaka City may be discussed in a structured way.

Secondary data, published and unpublished reports concerning hydrology, hydrogeology and groundwater quality of Dhaka city and its surrounding aquifer, were collected in order to review and analyze the feasibility of MAR in the region. To check water availability and quality, rainfall data (1954-2008) were obtained for Dhaka City from the Bangladesh Meteorological Department (BMD). Surface water discharge data were obtained from the Institute of Water Modeling (IWM). Surface water quality data were obtained from the Department of Environment (DoE), and those data were analysed with respect to water source and quality for MAR.

For the hydrogeological investigation, a total of 400 lithological descriptions of production wells were obtained from DWASA and the Institute of Water Modeling (IWM). The data were used to draw hydrostratigraphic cross-sections and to set up a 3D hydrogeological model. Geophysical information and electrical tomography data were obtained from Dhaka University, and IWM. For hydrogeochemical investigations, a field campaign was performed in September 2010 to collect groundwater samples from DWASA monitoring wells. The collected samples (n = 34) were analysed, using ion chromatography (IC), for major anions and cations (e.g., Ca^+, Mg^+, Na^+, K^+, Cl^-, SO_4^-, NO_3^- etc.) at the University of Goettingen, Department of Applied Geology, Germany. HCO_3^- was measured in the field using the titration technique. Iron (Fe), manganese (Mn), and arsenic (As) were measured at the Bangladesh University of Engineering and Technology (BUET) using an atomic adsorption spectrometer (AAS) (APHA-AWWA-WEF, 1999). In addition to the field campaign, groundwater quality data from a survey that was undertaken by IWM in 2006 were used in this study for in depth understanding of the groundwater quality within the aquifer.

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

5.4 Role of Managed Aquifer Recharge as a Sustainable Solution

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. Based on the research concept explained in section 3.3 in Chapter 3, a detail prefeasibility study was undertaken. The main driving forces on water and the environment in Dhaka City and potential responses were identified, using the DPSIR approach. Figure 5.4 states the main driving forces (D), pressures (P), states (S) impacts (I), and responses (R) at Dhaka City. 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.

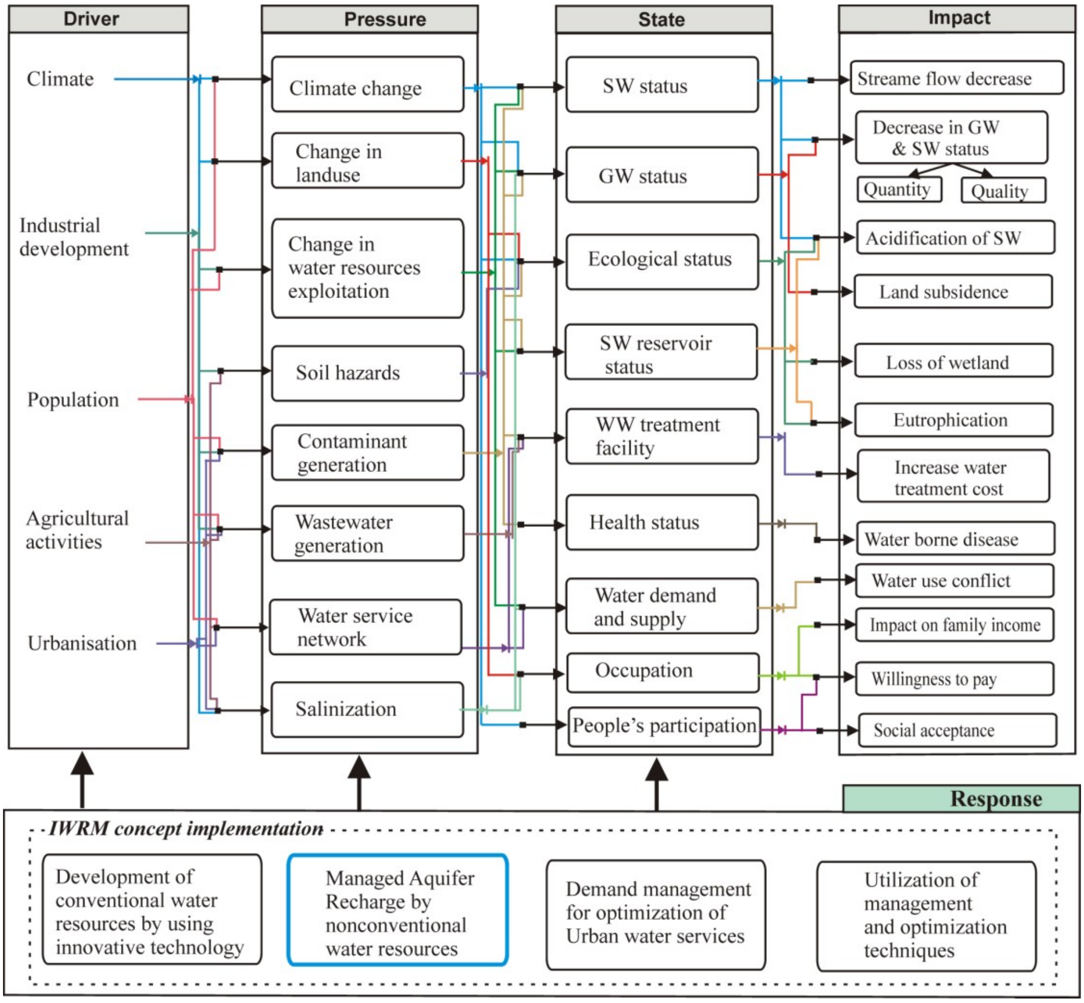

Figure 5.3: DPSIR analysis showing the causal chain of water resources problem in Dhaka city

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.

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. Table 5.2 shows the typical methodologies of MAR and their use in this region, mainly in India.

Table 5.2: Major MAR technology and their implementation in the region (MAR methodology is taken after UNESCO-IHP, 2005)

MAR technology	General Methodologies for MAR	MAR implementation (including implemented, experimental, and planned projects)
Rainwater harvesting	Desiltation of village ponds Field bunds, irrigation fields Roof-top rainwater harvesting	Harayana, West Bengal Colistan (Pakistan) Delhi (India) and Bangladesh
Spreading methods	Infiltration ponds and basins Soil aquifer treatment Controlled flooding Irrigation field recharge	Gujrat, Tamid Nadu (India) Ahmedabad (India)
In-channel modifications	Percolation ponds behind check dams Gabions, nala bunds Sand storage dams Subsurface dams and dykes Leaky dams and recharge release	Assam, Maharastra (India) West Bengal (India) Gujrat, Tamid Nadu (India)
Well, shaft and borehole recharge	Open wells and shafts Aquifer storage and recovery Aquifer storage, treatment, and recovery	Gujrat (India), Kathmandu valley (Nepal)
Induced bank infiltration	Bank infiltration & Inter/dune infiltration	

5.5 Hydrological Investigation for MAR Water Sources

5.5.1 Rainwater harvesting (RWH)

Dhaka City has an average rainfall of 2042 mm (BMD, 2006). 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). There are two potential approaches to implement MAR using rainwater in Dhaka City.

The first approach involves collecting water that is already running off in natural catchment areas. Runoff from urban areas is a significant source for water harvesting and groundwater recharge (Wolf et al., 2007). From May to October, rain is common, and enormous volumes of excess runoff have the potential to be used in MAR. MAR used in this way would not only make use of rainwater as a drinking water source for wet and dry seasons, but would also help to alleviate problems associated with flooding and urban drainage congestion. Open spaces available for rainwater collection in the city have an extent of 14.51 km^2. Considering that 80% of direct runoff can be collected, about 23,216 million litre (ML) per year could be available for underground storage, and 129 MLday^{-1} would be available during the monsoon months (May-October) for immediate use. The surface runoff from paved and unpaved roads could be captured by recharge structures (e.g. check dams, infiltration trenches, ditches or pits etc.). These structures collect runoff-water, which could be injected, using wells or any other technique after pre-treatment, to recharge groundwater (UNESCO-IHP, 2005). In this way, 6.5% of the present water demand could be recharged and stored for long periods of time in the aquifer of Dhaka City.

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 5.3 and Table 5.4 show two different estimations of 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.

Table 5.3: Rainwater harvesting using the roofs of the DWASA water supply connections

City area	Avg. annual rainfall	Total rainfall	Total DWASA water supply connection **	Each roof area*	Total roof area	Yearly total
(km^2)	(m)	(M litre)	Number	(m^2)	(km^2)	(M m^3)
370	2	740,000	271,865	232.34	63.17	149.16

*Source: DWASA.2001; ** DWASA, 2010

Table 5.4: Rainwater harvesting using the roofs of available houses

City area	Avg. annual rainfall	Total rainfall	Total concrete house available for rain water collection *	Each roof area	Total roof area	Yearly total
(km^2)	(m)	(M litre)	Number	(m^2)	(km^2)	(M m^3)
370	2	740,000	678,000	110	74.58	149.16

*Source: BBS, 2006

Considering the total number of water supply connections in Dhaka City (Table 5.3), and if 75% of the average rainfall is harvested, the total annual volume would be 94.76 Mm^3 (94,760 million L yr^{-1}) of water. Another estimation (Table 5.4), considering the total number of concrete houses available for rainwater collection, shows that the amount of harvested rainwater is 149 Mm^3 and if the collection efficiency is 75%, than annually 112 Mm^3 water will be available for use. Both estimations together suggest that ca. 250 MLpd (0.25Mm^3 per day) can be stored for further usage, which is 13% of today's total daily demand. DWASA (2006) estimated that the groundwater-mining rate of the upper Dupitila aquifer is 96.55 Mm^{3}yr^{-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).

5.5.2 Surface water harvesting

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. These rivers contain a significant amount of water, which could be used in MAR. Mathematical modelling studies by DWASA (2006) concluded that withdrawal of water from rivers for water supply purposes is possible (Table 3 and Figure 6), while keeping the local ecology intact, considering 40 % flow for ecological flow-demand in the stream. The study estimated that the change in water depth at Majhina on Lakhya River (Figure 5.6) is only around 0.2 m after withdrawal of 10 m^3/s.

Table 5.5: Water availability at different rivers around Dhaka city (adapted from DWASA, 2006)

River and location	80% dependable flow (m^3/s)
Buriganga at Chandnighat	58.66
Lakhya at Narayanganj	89.31
Lakhya at Majhina	61.4
Kaliganga at Taraghat	13.4
Padma at Mawa	6025
Meghna at Baidder Bazzar	187

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). 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.

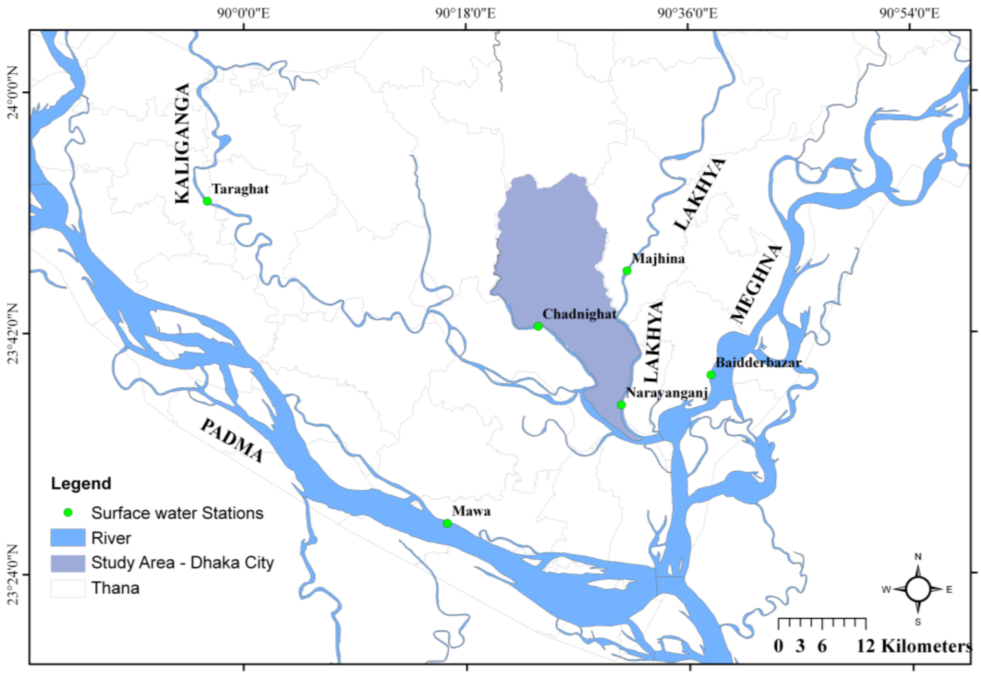

Figure 5.4: Locations of surface water resources assessment in the rivers near Dhaka City

5.5.3 Wastewater reuse

Nowadays, a number of countries are using Wastewater Treatment Plant (WWTP) treated effluent for reuse through artificial groundwater recharge techniques (e.g., Dan region of Shafdan, Israel). In Dhaka City, treated wastewater could 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 wastewater is collected by a combined sewer system and is 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). After reviewing a number of reports and studies, it can be 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 treatment process in the 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). 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.

5.6 Hydrogeological Investigation

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 investigation 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 investigation of Dhaka City and its surrounding area is given in the following sections.

The geology of the study area is characterized by Quaternary alluvial sequences, which commonly show favourable 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 Table 5.6

Table 5.6: Stratigraphy and hydrogeological characteristics of Dhaka City (modified after Morris et al. 2003**)**

Stratigraphic age	Stratigraphic name	Lithology	Thickness (m)	Function in 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
Holocene	Bashabo Formation	(Sand discontinuous)	3–25	Upper Dupitila Aquifer-1
Pleistocene	Madhupur Clay Formation	Silty clay member, Fluvio-deltaic sand	6–25	Aquitard –1
Plio–Pleistocene	Dupi Tila Formation	Dupi Tila clay stones Fluvio–deltaic sands	100–180	Upper Dupitila Aquifer- 2
Miocene	Girujan Clay	Bluish clay	50–100	Aquitard -2

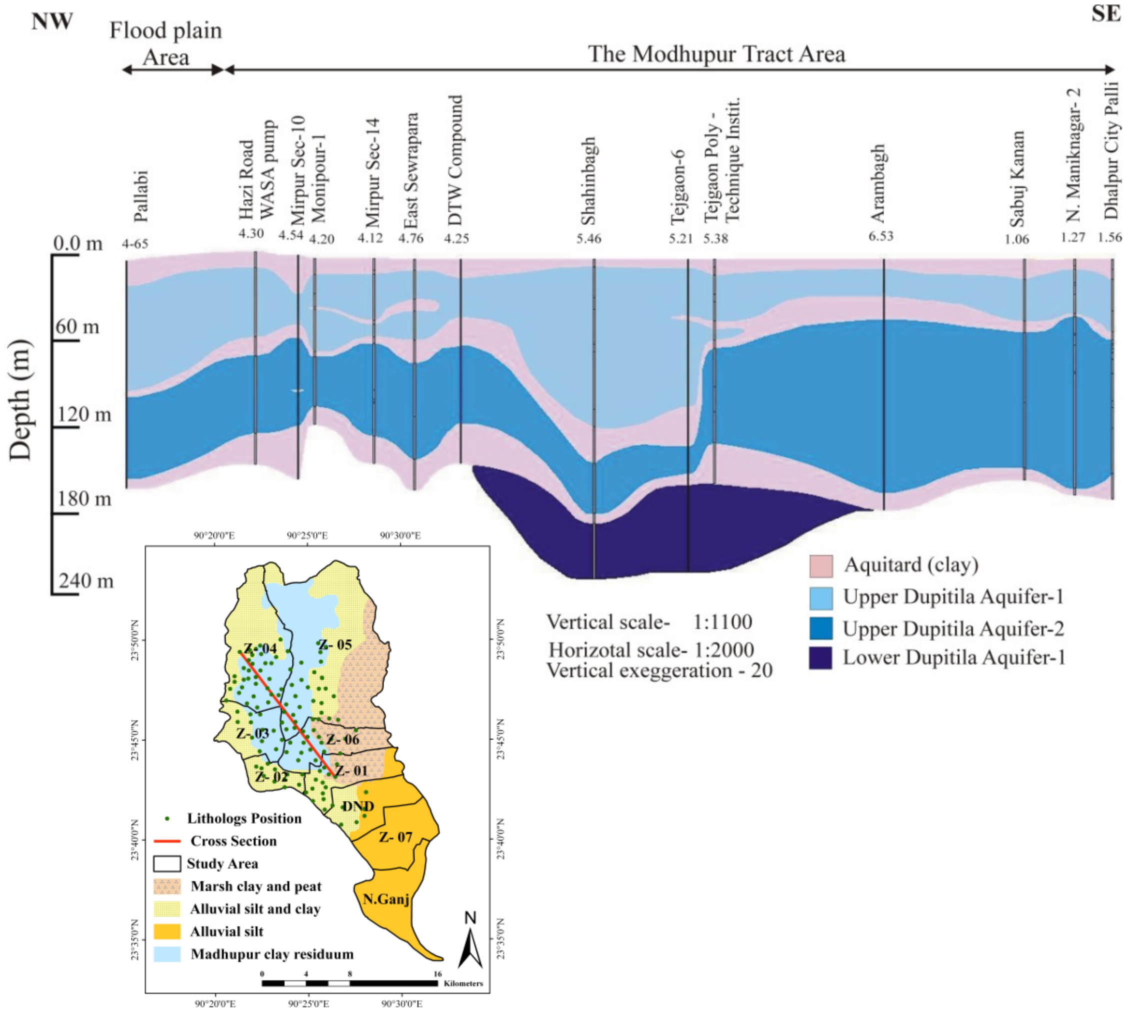

Figure 5.5: North – West (NW) to South – East (SE) oriented cross-section through Zone 4, 5, 6 and 1 of Dhaka City. Detailed description of the Modhupur tract area and flood plain area is given in Table 5.6.

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 400 lithologies and cross-sections, the subsurface geology (within 300 m of depth) of Dhaka city can be generally subdivided into nine layers (Table 5.7). Lithologs and 3D block diagrams 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. 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. As the depths

Table 5.7: Zone-wise average thickness of the different hydrogeological layers in Dhaka City

Hydrogeological layer	Layer average thickness (meter)						
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	N.ganj
Top soil	2.93	2.92	2.71	3.11	2.97	3.02	2.60
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

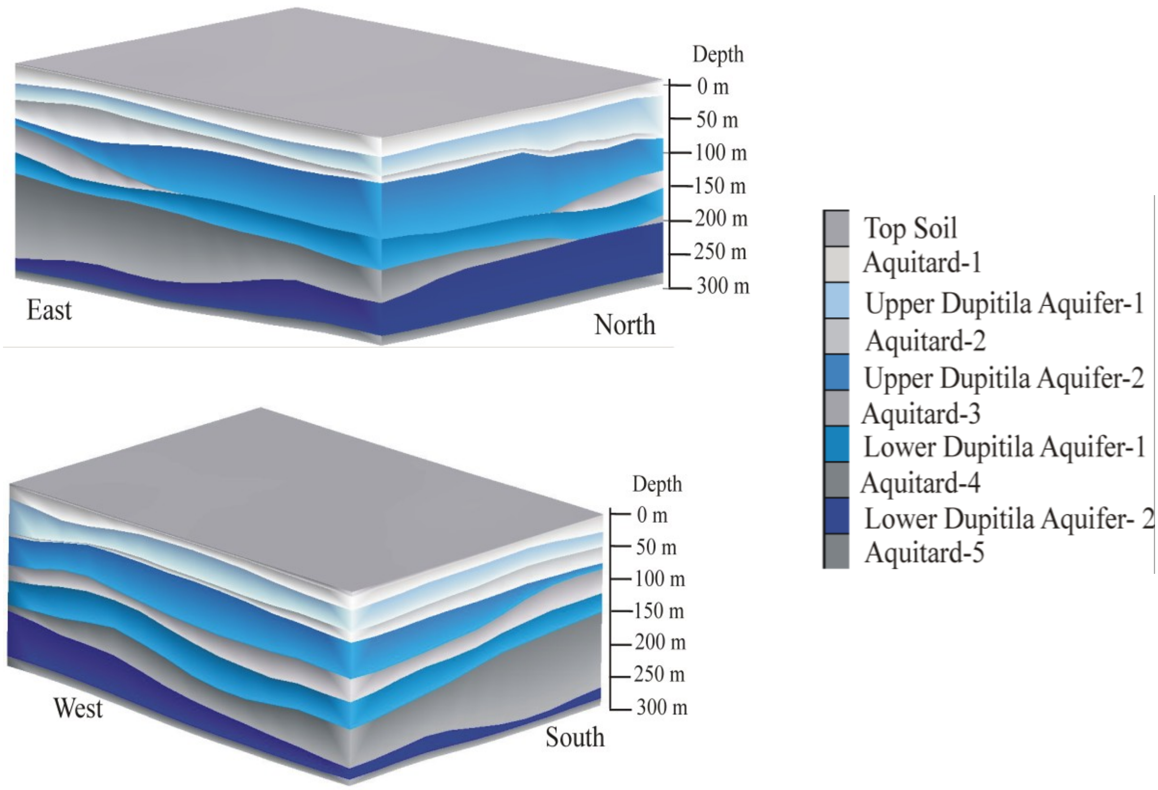

Figure 5. 6: 3-D view of the hydrogeological layers of Dhaka City.

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 aquitards (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 Dupitila aquifer-1. Figure 8 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.

The aquifers of Dhaka City generally possess large transmissivities and storage coefficients (DWASA, 2006). The estimated volume of storage for the upper Dupitila aquifer-1 is about 1500 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. 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 6.22×10^{-5} m/s and 1.98×10^{-4} m/s, and specific yields vary between 0.06 and 0.20. The hydraulic conductivities of the aquifers around Dhaka City range between 8.83×10^{-5} m/s and 9.32×10^{-4} m/s, with an average value of 4.73×10^{-4} m/s, and the specific yields vary between 0.10 and 0.25.

Figure 5.7 gives an overall schematic view of the hydrogeological system considering the situation of the aquifer and the potential sources of pollution.

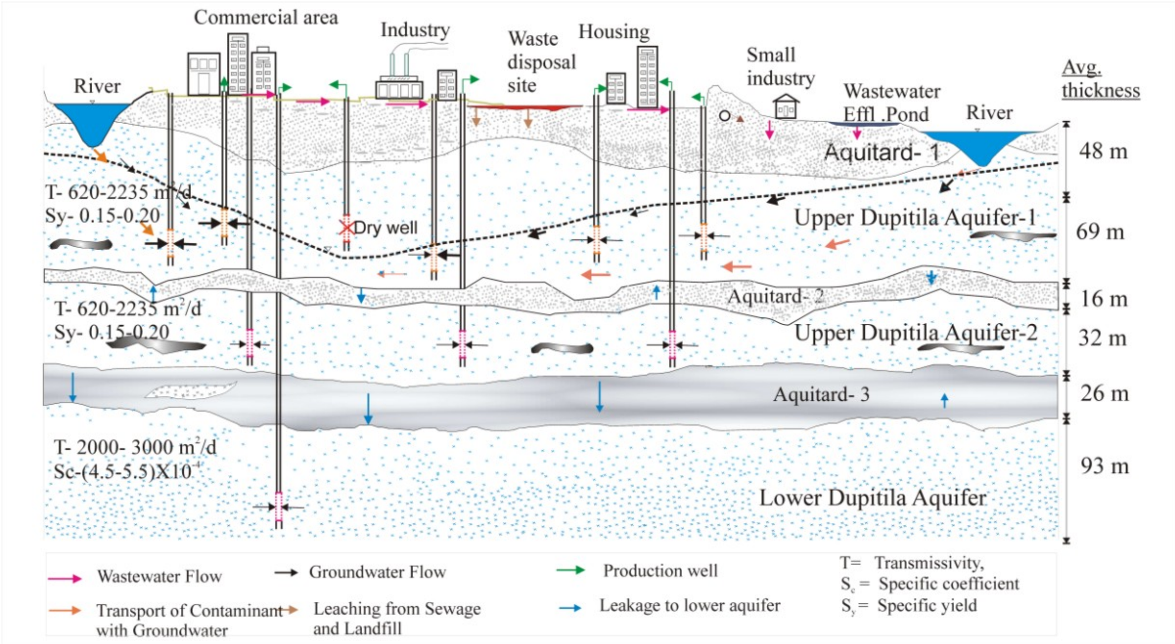

Figure 5.7: Hydrogeological system of Dhaka City - a schematic diagram

5.7 Hydrogeochemical Investigation

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. 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, Figure 5.9) (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 of the area (Saha and Ali, 2001; Zahid et al., 2006).

In order to get spatial and vertical distributions of electrical conductivity (EC) in the aquifer, IWM carried out a survey in 2006 at 228 production wells operated by DWASA. Figure 5.8 and Figure 5.9

(left) 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.

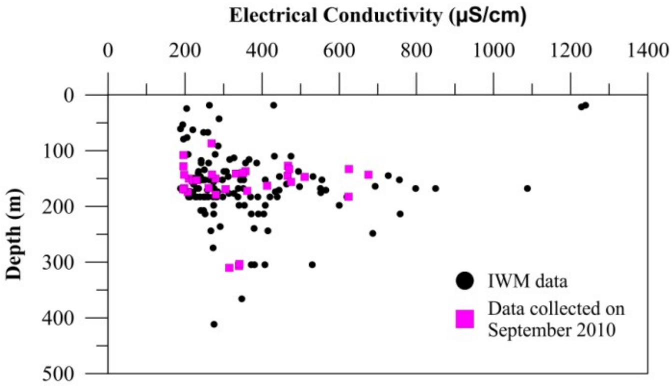

Figure 5.8: Variation of EC with depth in groundwater of Dhaka and Narayanganj. Groundwater samples collected during this study (in September 2010) reveal the same distribution of EC values as in the survey of 2006.

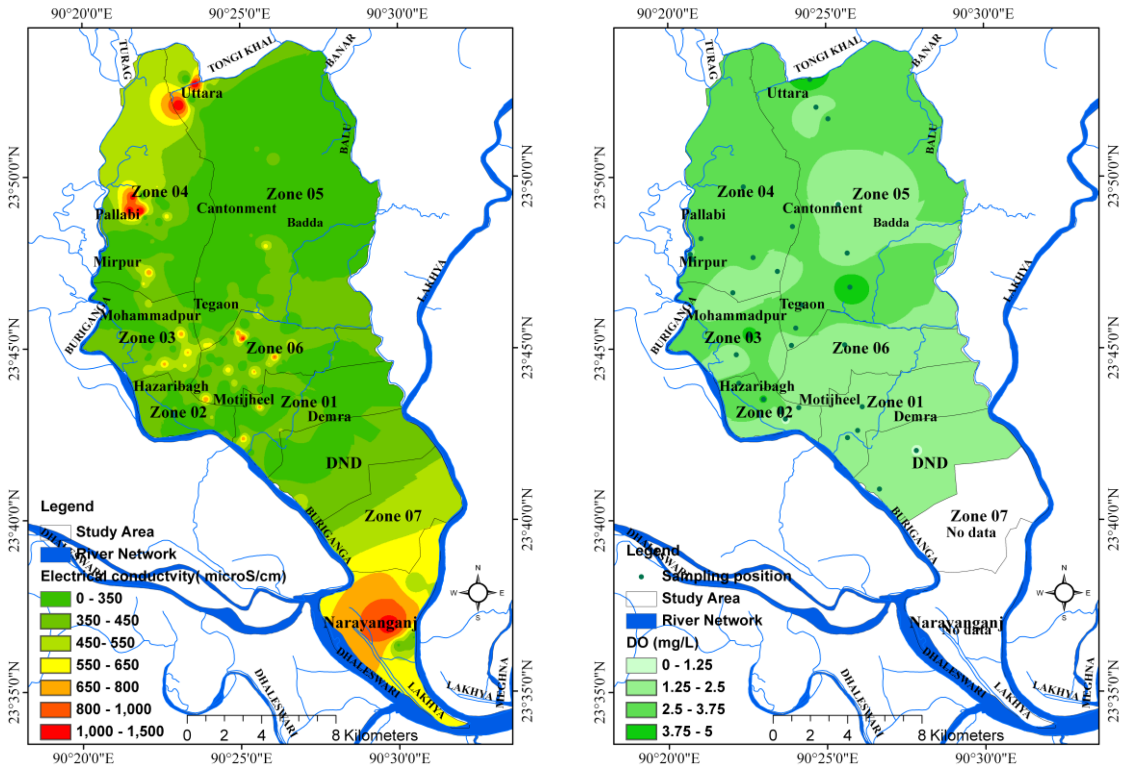

Figure 5.9: Distribution of electrical conductivity (left data: IWM) and dissolved oxygen (right data: sampling campaign in September 2010) in the Dhaka City and Narayanganj groundwater.

Samples collected in September 2010 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). Spatial distribution of DO is shown in Figure 5.9 (right). Data of major ions depict that there is some variation 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. The aquifer of Dhaka City contains predominantly Ca-Mg-HCO_3 type groundwater (Figure 5.10).

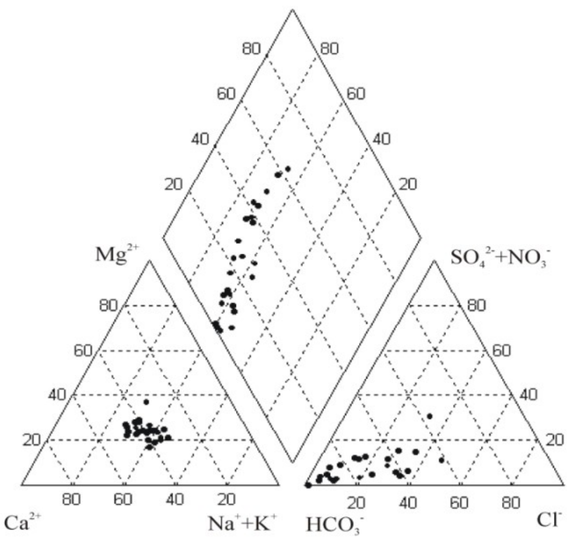

Figure 5.10: Characterization of the groundwater in diagrams after Piper (1944).

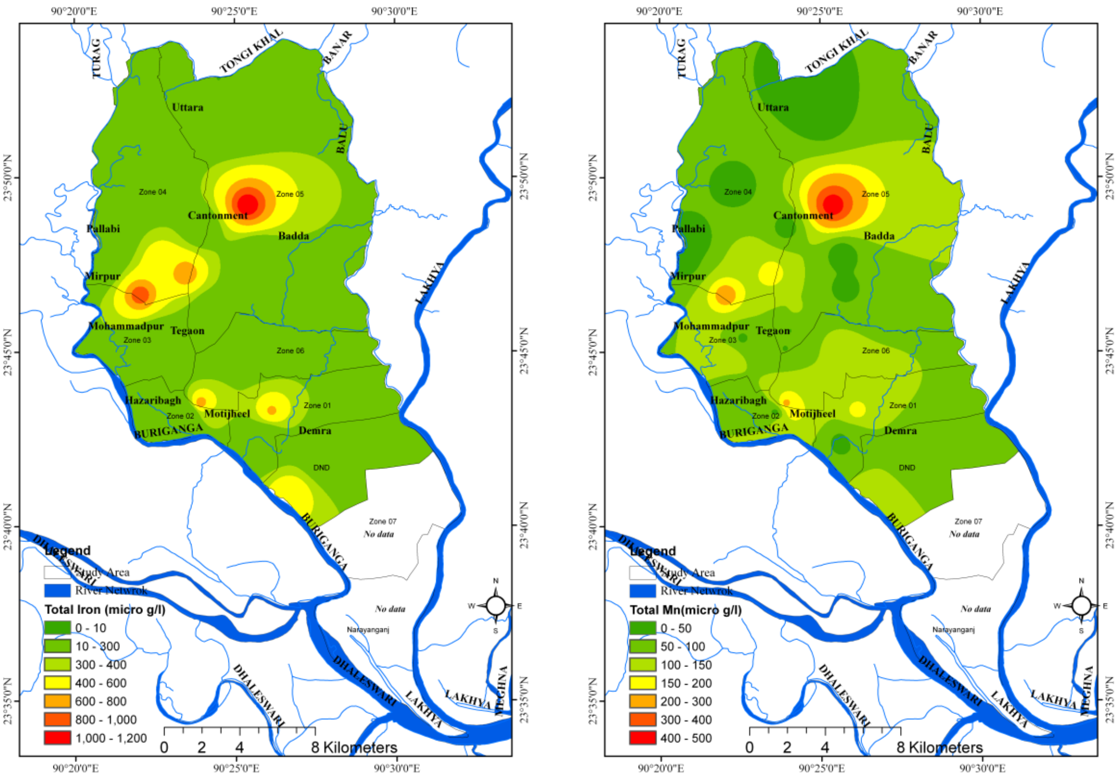

Figure 5.11: Distribution of Fe (left) and Mn (right) in the groundwater of Dhaka City.

Most of the trace elements are below WHO standard values (WHO, 2006) and Bangladesh standards (GoB, 1997), except for iron (Fe) and manganese (Mn). 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. Significant correlation was observed between Mn and Fe, and between Ca and Mg (Figure 5.12).

In order to predict the chemical reactions that might occur in the aquifer under MAR conditions, it is required to determine the saturation state of the native groundwater with respect to certain mineral phases. Calcium carbonate geochemistry is quite important as the precipitation of calcium carbonate may cause clogging of wells (Maliva and Missimer, 2010). Using the computer code PHREEQC (Parkhurst and Appelo, 1999), the saturation index for calcite, one of the main mineral phases of calcium carbonate (Maliva and Missimer, 2010), was estimated. The groundwater of the Dhaka city aquifer is close to saturation for calcite (SI values range between -0.14 and -1.50, with an average of -1.06), except three groundwater samples: at Tejgaon (SI: –2.02), Gudaraghat, Mirpur (SI: –2.16), and Choto Diabari, Mirpur (SI: -1.79). It is important to note that calcite precipitation or dissolution may occur due to the mixing even if both waters (native groundwater and artificially recharged water) are at or close to saturation (Herczeg et al., 2004)

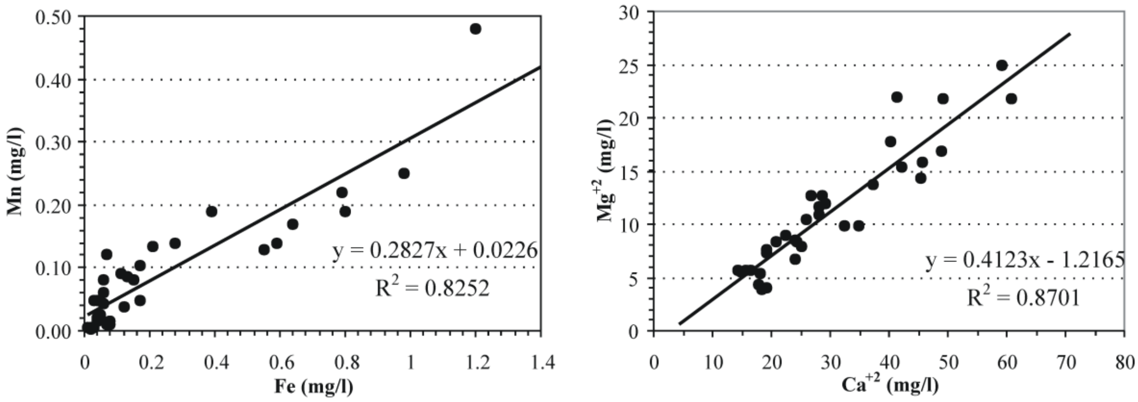

Figure 5.12: Correlation between Fe_{total} and Mn_{total} (left); Ca^{+2} and Mg^{+2} (right) in the groundwater of Dhaka Aquifer.

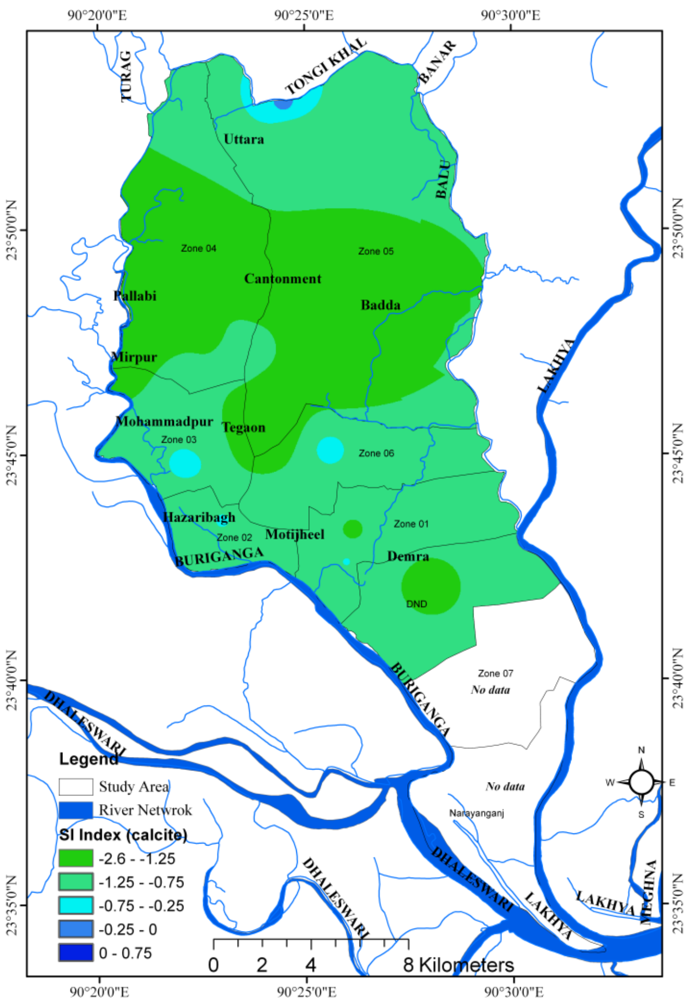

Figure 5.13: Distribution of the SI index with respect to calcite in groundwater of Dhaka City.

5.8 Potential and Challenges of MAR in the Region

The hydrological, hydrogeological and hydrogeochemical investigations clearly show that the water resources system in Dhaka City has the potential for implementing MAR. Several factors, such as possible contamination of the storm water runoff, impermeable surface layer thickness, aquifer contamination etc., call for careful consideration and planning of MAR. The following sections briefly describe the potentials and challenges for MAR regarding the hydrological situation, MAR location and technology (hydrogeology), and possible geochemical changes within the aquifer after recharge.

5.8.1 Water source for 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. A pilot study that considers the Civil Engineering Building of BUET as a model roof area was performed to check the reliability of rooftop rainwater harvesting in Dhaka. Storage volumes of rainwater are calculated by using the mass curve method and the optimal Ac – Vc curve method (Figure 5.14).

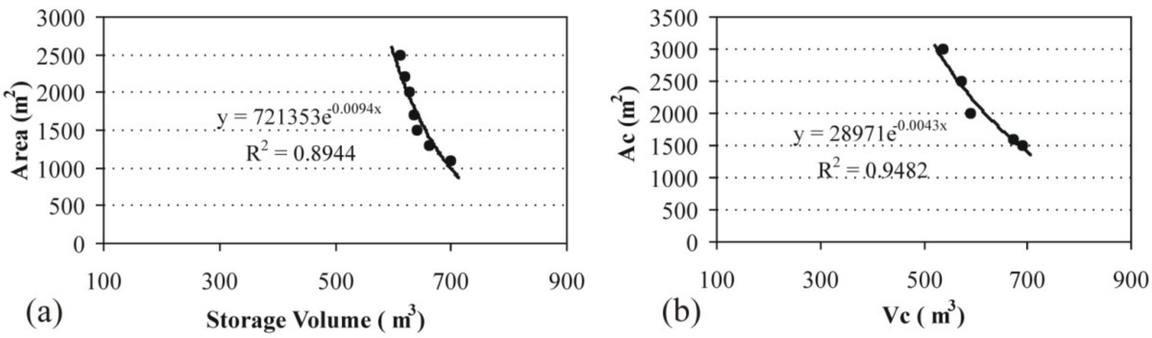

Figure 5.14: Optimal 'storage volume - catchment area' relationship at a constant demand (115 m^3month^{-1}), (a) Mass curve method, (b) Ac – Vc method

From these two methods it can be concluded that about 600 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 5.15). The general reliability relationship of water supply for Dhaka City is shown in Figure 5.16. The generalised relationship is also applicable to other roofs at Dhaka City. Based on analysis shown in Figure 5.16, the reliability increases with increased roof area for any fixed demand. Required space for the storage volume and related cost are two important issues.

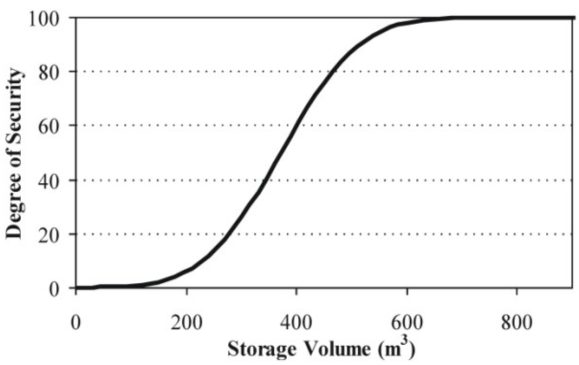

Figure 5.15: Relationship between degree of security and required storage volume

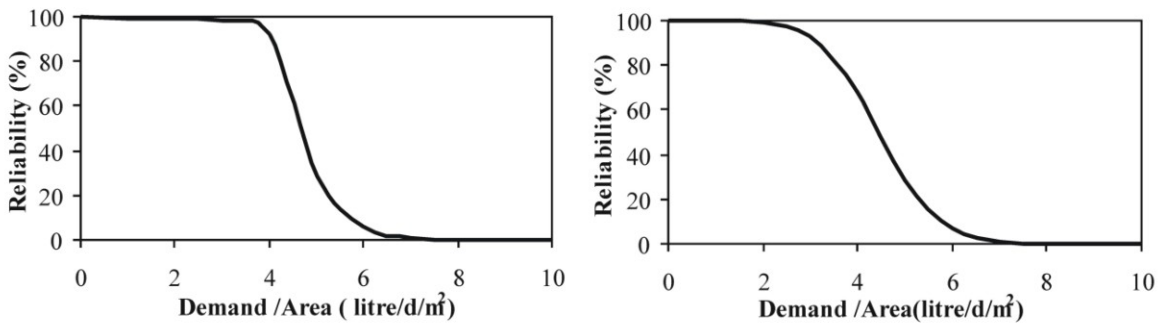

Figure 5.16: General reliability curve for different storage volume per roof area, left: 1000 m^2, right: 2500 m^2

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 Tk. 1,806,542 (approx. 20,000 Euro). In order to avoid extensive construction costs, a combination of water supply and managed aquifer recharge is most favourable. 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.

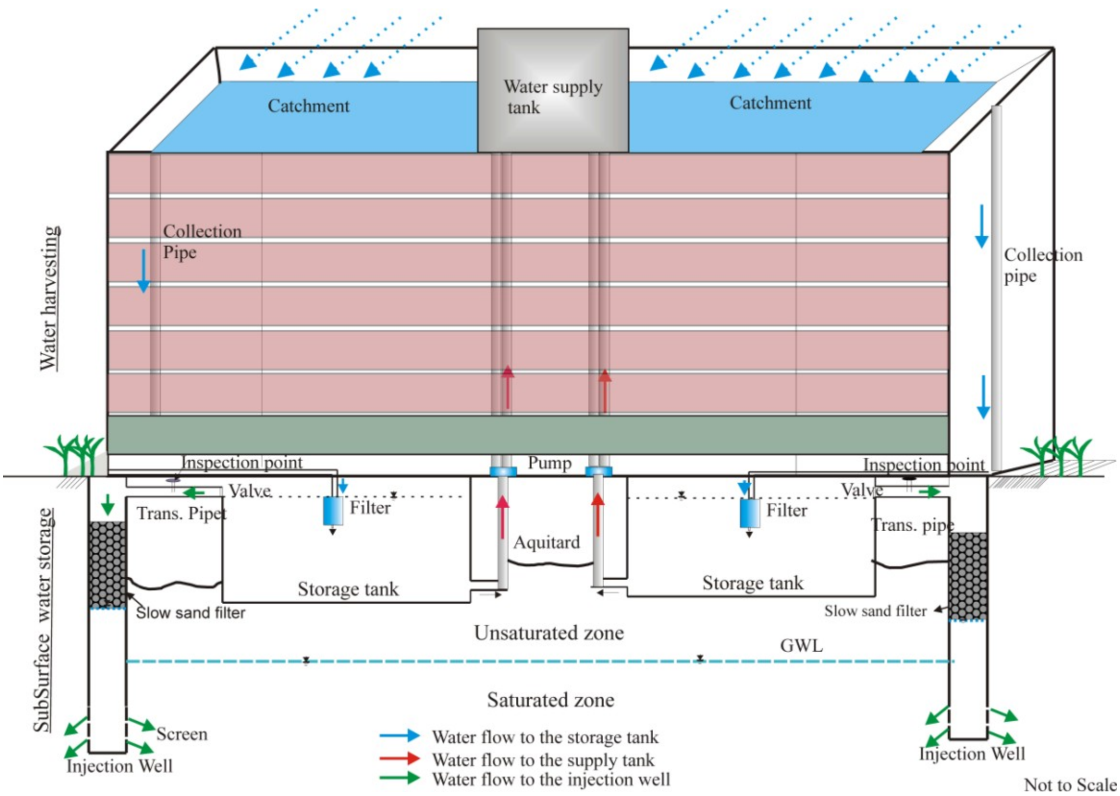

Figure 5.17: Schematic diagram for Rainwater Storage Supply and Recharge (RWSSR) for the civil engineering building at BUET

A schematic diagram of the RWSSR concept is shown in Figure 5.17. 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 area 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 (Dillon et al., 2010). 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 injection well should be filled with slow sand filters to offer some degree of pre-treatment before recharge.

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.

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.

5.8.2 MAR location and technology

After analysing the geology and the hydrogeological systems of Dhaka city and its surrounding area, the characteristics of the aquifer of the greater Dhaka region and its relevance to the MAR implication in the region is summarised in Table 5.8.

The impermeable subsurface layer thickness varies between 8 m and 52 m in Dhaka City. The Modhupur Clay can neither yield significant amounts of water to wells nor transmit appreciable water to the aquifer below (Sultana et al., 2010). Therefore, the clay material should be excavated completely to infiltrate water, or injection wells should be drilled directly into the aquifer to recharge water. From the hydrogeological investigation it seems obvious that the upper Dupitila aquifer possesses enough storage capacity, and that the hydraulic properties of the aquifer such as the hydraulic conductivity and storage coefficient allow an implementation of MAR. Therefore, the main target aquifer for MAR implementation in Dhaka City should be the upper Dupitila aquifer-1. Based on the land cover, aquifer thickness, and natural water bodies such as wetlands, canals, and depressions, the different MAR techniques that can be appropriate for Dhaka City are described in the following section:

Table 5.8: Aquifer characteristics relevant to MAR (Dillon and Jiménez, 2008) and their status for the major aquifer systems in the greater Dhaka region.

Characteristics	***Aquifer status and application for MAR***		
	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 (around 100 m) - Storage volume is no major constraint	Less thick (32 m) - Storage volume might be a major constraint	Thick (>100 m) - High storage potential
Unconformity 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
Lateral hydraulic gradient	Gentle - Recharge water contained closer to the point of recharge	Moderate to Gentle - Recharge water contained near to the point of recharge	Gentle - *Recharge water contained closer to the point of recharge*
Consolidation	Unconsolidated - Clogging could be problem	Semi consolidated - Easy well construction	Slightly compacted and consolidated - Easy well construction

A spreading basin or infiltration pond is recommended for Dhaka City where the top subsurface impermeable layer thickness varies between 0 m and 8 m. As the groundwater level is deep (the average groundwater table depth at those places is -42 m Public Works Datum (PWD), the spreading basin (Figure 5.18a) will offer water quality improvement, while passing through the unsaturated zone. In places where the subsurface impermeable layer thickness varies between 8 m to 30 m, recharge pits and trenches are most suitable. Lower parts of the trench (15 to 20 m depth) that are in direct contact with the aquifer might be backfilled with a slow sand filter and a geotextile filter fabric on top of the backfill (Figure 5.18b). Slow sand filters offer pre-treatment of the infiltrated water during the passage through the sand column (Bouwer, 2002).

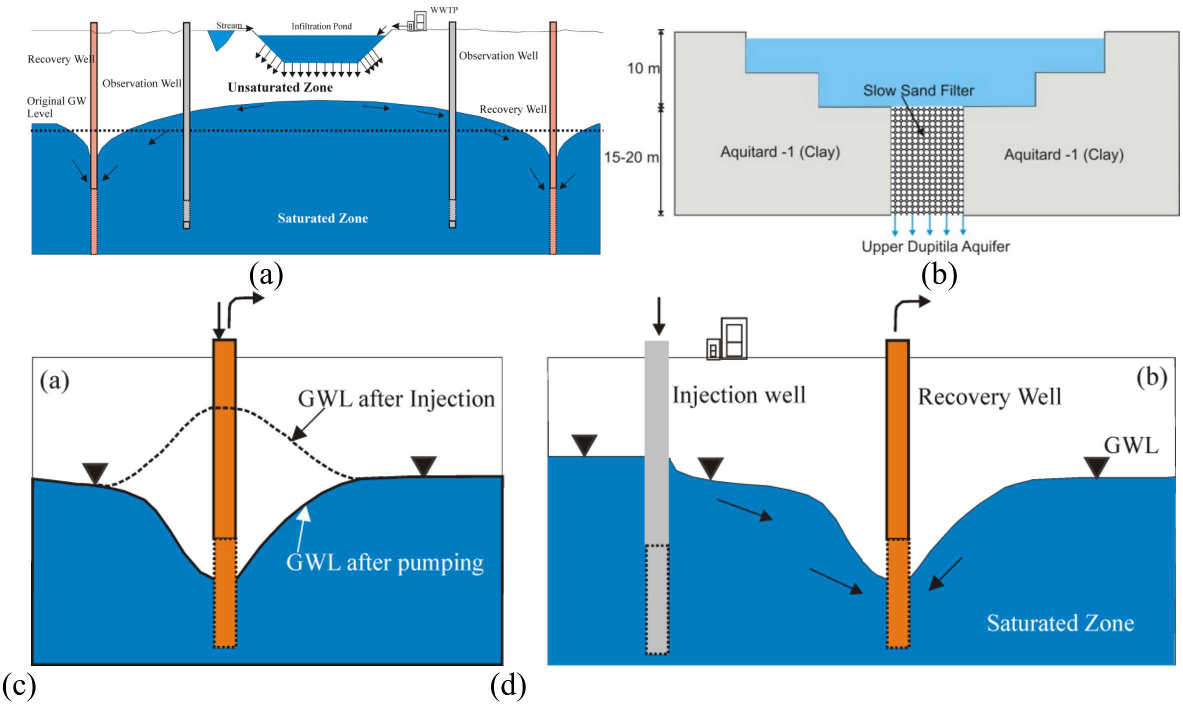

Figure 5.18: Recommended MAR structures: (a) SAT, (b) recharge trench combined with slow sand filter, (c) ASR and (d) ASTR (modified after UNESCO-IHP, 2005)**.**

Aquifer storage and recovery (ASR) and aquifer storage, transfer, and recovery (ASTR) are the most commonly used MAR techniques, where thick subsurface impermeable layers exist (Figure 5.18c and Figure 5.18d). Dry and abandoned wells from DWASA can be used as injection wells at the beginning of the MAR implementation in the city after rehabilitation.

The wetlands and water bodies, such as Begun Bari Khal (See Figure 5.19) can be used for MAR after proper development. The water source for Begun Bari Khal could be storm water collected from open spaces, e.g. in the old airport area and parks nearby the building of the National Parliament (see Figure 5.18). This water could be conveyed to the wetland (distance ca. 3 km) by usage of existing storm water drainage systems. The advantage of the water treatment capacity of the wetlands offers the pre-treatment facility to the MAR waters on-site. The subsurface impermeable layer in the greater Dhaka area is in some places suitable (thickness less than 6 m) for the construction of spreading basins. The regional groundwater flow direction, from North-West and North-East towards Dhaka City (Figure 5.20), 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.

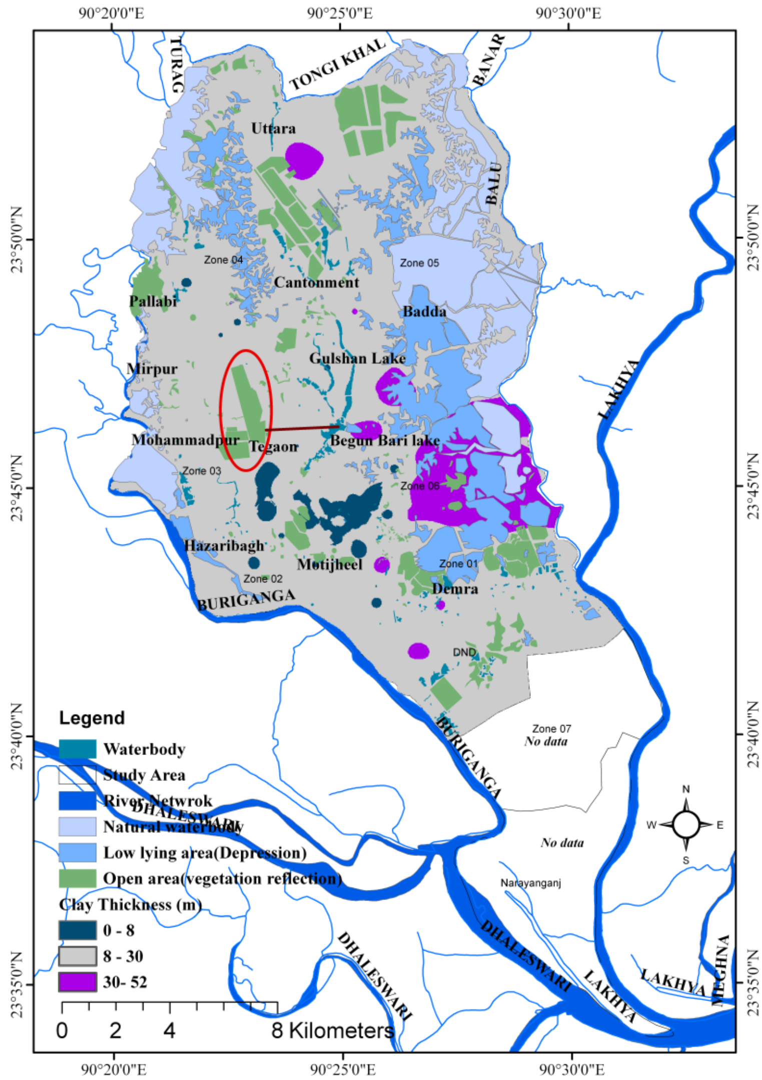

Figure 5.19: Clay thickness, natural water bodies, lowlands, and wetlands in Dhaka City (based on data obtained from Sultana, 2009 and modified afterwards)

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, see Figure 5.5) 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.

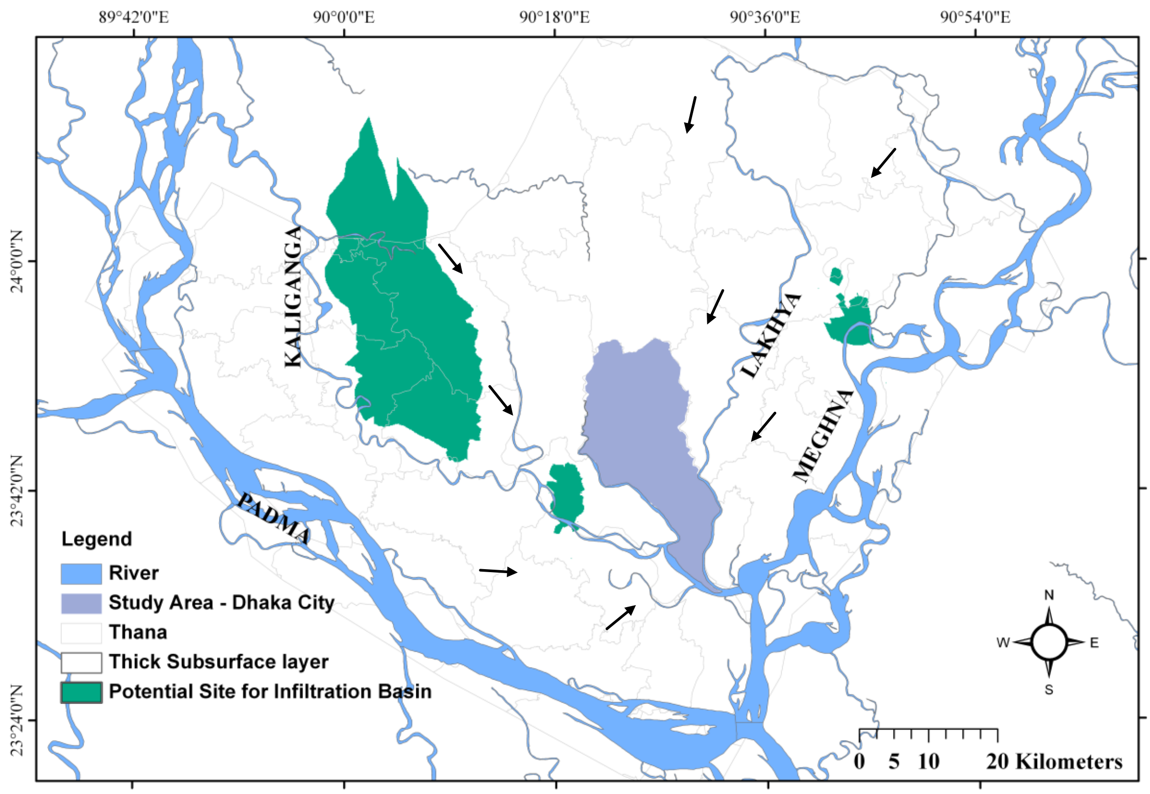

Figure 5.20: Potential site for an infiltration pond in greater Dhaka. The arrows show the regional groundwater flow directions.

5.8.3 Hydrogeochemistry

The hydrogeochemical investigation in section 5.7 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-HCO_3 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

CO_2 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 5.21 compares the solubility limit of iron and manganese hydroxides with the Fe and Mn concentrations of the ground water of Dhaka City.

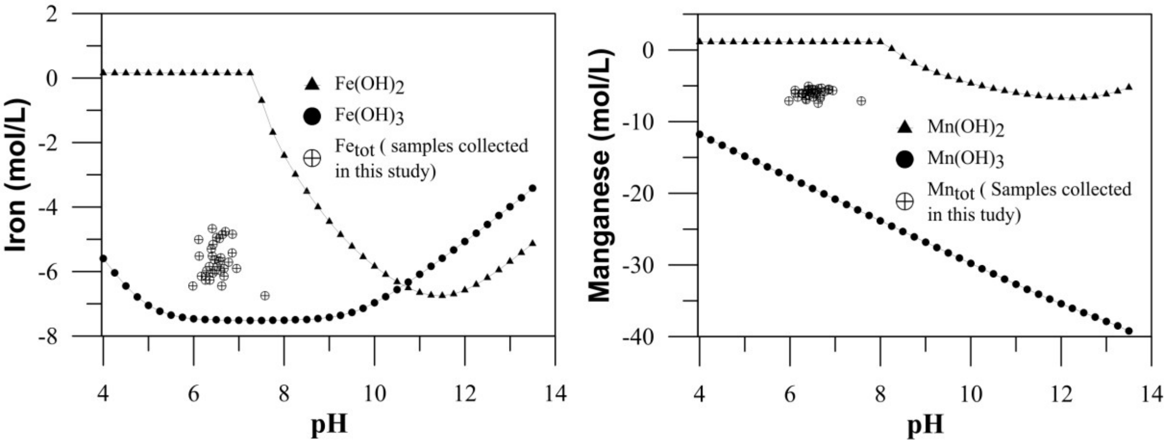

Figure 5.21: Comparison of total concentration of iron and manganese from this study with the solubility data of hydroxides. Hydroxide solubility data are from Lewis (2010).

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.

Groundwater from the upper Dupitila aquifer is not contaminated by arsenic, but mobilisation 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. Furthermore, the chemical reactions of other ion species such as aluminium, silicon, lead etc. are of concern for health and environmental protection, and increases in those trace constituents frequently coincide with an increase in iron, manganese, and arsenic (Maliva and Missimer, 2010).

5.9 Conclusions and Recommendations

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 urban 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. Rainwater can serve 15% to 20% of the total present water demand. Surface water from large rivers and treated effluent can also be a potential source after proper treatment. 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. 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. 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.

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) and / or by Quantitative Microbial Risk Assessments (QMRA) (Toze et al., 2010). 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.

5.10 References

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Chapter 6

A New Spatial Multi-Criteria Decision Support Tool for Site Selection for Implementation of Managed Aquifer Recharge Project

6.1 Introduction

In the field of Water Resources Planning and Management, managed aquifer recharge (MAR) is becoming an important solution for mitigating water scarcity related problems in arid and semi-arid areas. MAR has been practiced throughout the world for the recovery of groundwater levels, improvement of groundwater quality, storage of surface water in the sub-surface, and as a barrier to salinity intrusion. Depending on the water source, water quality, geology, surface conditions, soils, and hydrogeology, a variety of methods have been developed to recharge groundwater (Bouwer, 2002). The spreading basin technique (infiltration) is widely practiced and is useful in areas with high land availability, highly permeable soil, and where the hydrogeology allows for infiltration to an unconfined aquifer (Ghayoumian et al., 2005). Other MAR techniques employing injection wells require less area but a better quality of source water due to the fact that the water is directly injected into the aquifer without taking advantage of natural attenuation processes within the vadose zone. The interdependency of the water quality, MAR location, and technology makes project planning multifaceted and complex.

Many factors need to be considered during the site selection process for MAR projects. Complex regional characteristics, heterogeneities in surface and/or subsurface characteristics, and variable groundwater qualities make site selection for MAR difficult (Anbazhagan et al., 2005). Apart from these hydrogeological considerations, other factors such as political and social factors are important in the decision-making process. National and international water policies, natural conservation regulations, environmental impact assessments, and socio-economic considerations make the site selection procedure complex. Complexity increases when MAR project managers are from different disciplinary backgrounds; this may often lead to disagreements concerning which criteria to give more weight to in the decision-making process. These conflicts always need to be dealt with before the MAR project is implemented. GIS and the traditional Decision Support Systems (DSS) alone do not effectively facilitate the implementation of MAR project parameters, which are equally based on complex decision criteria and spatial information (Jun, 2000). GIS based analysis methods are poor in dealing with uncertainty, risks, and potential conflicts; therefore, there is a large possibility of losing important information, which in turn may lead to a poor decision (Bailey et. al., 2003). Multi-Criteria Decision Analysis (MCDA) integrated into GIS (SMCDA) provide adequate solution procedures to this problem because the analysis of potential MAR projects may be done more comprehensively and at a lower cost. Variable project sites, risks, MAR techniques, policies, and limits in geological as well as social, environmental, and political realms can easily be considered by the SMCDA approach (Calijuri et al., 2004).

MCDA is helpful in identifying priorities for a given MAR project (Gomes and Lins, 2002). The integration of MCDA techniques with GIS has considerably advanced the traditional map overlay approaches for site suitability analysis (e.g. Malczewski, 1996; Eastman, 1997). MCDA procedures utilize geographical data, consider the user's preferences, manipulate data, and set preferences according to specified decision rules (Malczewski, 2004). The advantage of integrating GIS with MCDA has been elaborated by many authors (e.g. Malczewski, 1996; Jun, 2000; Gomes and Lins, 2002; Sharifi and Retsios, 2004). According to Malczewski (2004), the two critical considerations for SMCDA are: (i) the GIS capabilities of data acquisition, storage, retrieval, manipulation, and analysis; and (ii) the MCDA capabilities for combining the geographical data and the manager's preference into unidimensional values of alternative decisions. A number of methodologies have already been developed for SMCDA in different fields of science and engineering to select the best alternatives from a set of competing options (e.g. Sharifi et al., 2006; Zucca et al., 2007).

The overlay MCDA plays an important role in many GIS applications. Boolean logic and Weighted Linear Combination (WLC) are the most popular decision rules in GIS (e.g. Eastman, 1997; Malczewski and Rinner, 2005) and both can be generalised within the scope of Ordered Weighted Averaging (OWA) (e.g. Malczewski and Rinner, 2005; Malczewski, 2006). In OWA, a number of decision strategy maps can be generated by changing the ordered weights. Several OWA applications have been implemented already (e.g. Rinner and Malczewski, 2002; Calijuri et. al., 2004; Malczewski et al., 2003; Malczewski, 2006). The Analytical Hierarchy Process (AHP), proposed by Saaty (1980), is another well-known procedure. This procedure is important for spatial decision problems with a large number of criteria (Eastman et al., 1993). AHP can be used to combine the priorities for all levels of a "criteria tree," including the level representing criteria. In this case, a relatively small number of criteria can be evaluated (Jankowski and Richard, 1994; Boroushaki and Malczewski, 2006). The combination of AHP with WLC and/or OWA can provide a more effective and robust MCDA tool for spatial decision problems. Boroushaki and Malczewski (2008) implemented AHP-OWA operators using fuzzy linguistic quantifiers in the GIS environment, which has been proven to be effective.

An intensive review of the respective literature has indicated that the modern and updated analysis techniques haven't been well investigated and compiled in the field of MAR site selection (see the following section for details). The advantages of the integrated use of GIS and MCDA have been poorly investigated in this field. No structured, non-site specific and flexible decision analysis tool has been developed to date. Therefore, in this study, a methodology has been developed to support the identification of suitable sites by combining modern spatial multi criteria analysis techniques with decision analysis methods. In the process, a new tool has been developed to offer the following:

- A comprehensive framework consisting of AHP, WLC, and OWA analysis techniques for spatial multi criteria analysis for MAR site selection
- A wide range of flexibility and preferences for criteria selection, standardization, and weighting
- An interactive user interface, which offers the standard techniques and leads the user systematically to complete the site selection process.

The following sections include a review on MAR site selection techniques and may be read at any time as needed for review purposes (Section 2). Section 3 is a description of SMCDA for site suitability analysis and includes information on how AHP, suitability mapping, and weighting are involved in the analysis. A brief description on possible sensitivity analysis is mentioned, and is followed by Section 4, which is called 'GIS Based Site Suitability Analysis Tool'. This section along with Section 3 provides distinctive information to MAR site selection and the sections together may be considered to embody the core objective of this paper, which is to explain the development and functionality of a new SMCDA tool for MAR site selection. Section 5 presents the concepts from Section 3, and 4 as applied in the field. The case study presented in Section 5 is on a MAR site selection, which was performed at the Querenca-Silves aquifer system in Portugal. Section 6 provides a summary of conclusions and recommendations to the reader so as to continue progression in the future use and development of MAR site suitability analysis tools such as the one described herein.

6.2 The State-of-the-Art MAR Site Selection Techniques

Only very few studies exist which focus on site selection procedures for Managed Aquifer Recharge (MAR). Respectively, the following three sections differentiate data types (section 6.2.1), present data processing via GIS (section 6.2.2), and give reference to the steps involved in site suitability analysis methods (section 6.2.3) for example, screening of sites, criteria hierarchy and standardization, criteria weighting, overlay, and sensitivity analysis. The three sub-sections of this section are intended to serve as a reference for the basic methods which have been integrated into the SMCDA tool for site suitability analysis of MAR.

6.2.1 Data types

For MAR site selection, different types of data are required. Considerations for data type selection derive from data availability and the objective of the analysis as dependent on each data type. Geological maps, geomorphologic maps, lineament maps (e.g. Saraf and Choudhury, 1998, Jothiprakash et al., 2003, Reddy and Pratap, 2006), slope, infiltration rate (e.g. Ghayoumian et al., 2005, Werz et al., 2009), lineament density, structure, fluvial and denudational geomorphology (e.g. Anbazhagan et al., 2005; Shankar and Mohan, 2005, Chowdhury et al., 2010,), soil texture (e.g. Kalantari et al., 2010, Jotiprakash et al., 2003), and land use (e.g. Brown et al., 2008; Reddy and

Pratap, 2006; Ghayoumian et al., 2007) have been used to provide detailed quantification of surface characteristics. Infiltration rate, transmissivity (e.g. Ghayoumian et al., 2005; Brown et al., 2008), borehole recharge capacity, borehole abstraction capacity, and recharge retention time (Anderson et al., 2005), have been used to quantify subsurface characteristics. Groundwater quality data is usually not paid any attention as being important for site selection (Brown et al., 2008; Ghayoumian et al., 2007; Chowdhury et al., 2010), although it should be due to the nature of MAR as being often involved with water storage and recovery. In addition to surface and sub-surface characteristics, Brown et al., (2008) considered ecological status, road density, power lines, proximity to a water source, and groundwater pollution among other parameters. Wood (1980) considered the possibility of aquifer plugging. Legal aspects together with cost-benefit analyses should also rank among important considerations (O'Hare, 1986). A comprehensive combination of all of these input considerations, however, is absent from the literature of MAR project site characterization.

6.2.2 Data processing

The quantity of spatial data needed to collect, integrate and analyse for MAR project site evaluation is very large and the application of traditional data processing methods for site selection can be very complex and tedious (Anbazhagan et al., 2005). In groundwater management studies, land use suitability mapping and other geographical research, GIS and remote sensing technology have been used separately or in combination to process, integrate, and analyze spatial data (e.g. Krishnamurthy et al., 1996). Use of GIS and remote sensing is also commonly used for MAR site selection studies (e.g. Saraf and Choudhury, 1998; Brown et al., 2008; Ghayoumian et al., 2007; Werz et al., 2009). Anderson et al. (2005) used the mathematical functions implemented in GIS together with spatial analysis operations to calculate retention time and recharge capacity of an aquifer over a wide spatial distribution.

6.2.3 Site suitability analysis methods

In general, the site suitability analysis follows the path: screening of feasible areas → classification of thematic layers → weighting of the criteria → overlaying.

Only few studies have concentrated on screening-out the areas where MAR is actually non-feasible (e.g. Brown et al., 2008, Ghayoumian et al., 2007). Boolean logic is usually used to demarcate feasible and non-feasible areas. Studies mostly concentrate on classifying maps according to relative importance. Each thematic map is classified according to importance of the respectively represented parameters. Linguistic classifiers, such as *very good*, *good*, *suitable*, etc. (e.g. Jothiprakash et al., 2003; Ghayoumian et al., 2005) and value type classifiers such as class 1 to class 4 are implemented in these studies (e.g. Ghayoumian et al., 2007). Step-wise functions are used in different studies in order to standardize thematic maps for aggregation. Ghayoumian et al. (2007) uses membership functions for map standardization. No linear or piece-wise linear function is used in any study for MAR site selection.

Weighting of each criterion is an important factor for spatial multi-criteria analysis. Direct weighting after consultation with experts has mostly been used (e.g. Saraf and Choudhury 1998; Brown et al., 2008). The Analytical Hierarchy Process (AHP), introduced by Saaty (1980), has been recently used by Chowdhury et al., 2010. The advantage of AHP in site selection or spatial multi-criteria analysis is well established (e.g. Jun, 2000; Sharifi et al., 2006) and is therefore implemented in the new tool presented in this report (see section 6.3.3 B).

The most important step for site selection is map overlay. Conventional overlay methods (e.g. Weighted Linear Combination (WLC)) have been practiced in most of the studies for MAR site selection (e.g. Sharaf and Choudhury, 1998). Kallali et al. (2007) used Boolean logic for combining maps. Normal successive intersection of the thematic maps has been used, too (e.g. Jothiprakash et al., 2003). The Ordered Weighted Averaging (OWA) method has not been implemented in any study. It is important to note that combination of AHP-WLC or AHP-OWA has yet to be implemented and is thus presented for the first time in this report (see Chapter 3). Ghayoumian et al. (2005) briefly mentioned the integration of DSS and GIS for MAR site selection, but no special considerations for DSS decision rules or technological descriptions were provided. A spatial knowledge-based decision analysis system for pond site selection has been reported by Shrier er al., 2008. The authors coupled spreadsheet software that facilitates rule processing, with GIS to display spatial data.

Site suitability analysis for MAR is like most other site suitability analyses, but the methods which are best applied are being applied in a unique combination which has not been done until now. The advantage of SMCDA has not been properly and fully utilised in this field. This report presents all the data types and data processing techniques needed for MAR site assessment as well as the familiar yet unique procedure to do so. Also, MAR is a developing field but also has a long and fragmented history. This report is a breakthrough for the field of MAR in the respect that state-of-the art analysis techniques are being compiled and applied in this field and finally more work is being done to ensure the continued implementation of MAR with decreased uncertainty, as demonstrated in the entirety of this paper. This chapter presents for the first time an interactive non-site specific decision tool for MAR site selection.

6.3 The Spatial Multi Criteria Decision Support Method for Site Suitability Analysis

The overall methodology of the new site selection tool is shown in Figure 6.1. This flowchart shows the main decision steps which are implemented for spatial analysis. In general, the entire process involves three main steps: (a) constraint mapping, (b) suitability mapping, and (c) sensitivity analysis.

After preparing the constraint map, AHP is combined with WLC and OWA for the suitability mapping, which is based on standardized subcriteria. The function of AHP is threefold: (1) developing the hierarchy after the selection of criteria (2) doing a pair-wise comparison to assess criteria importance and (3) undergoing construction of the overall composite weight (global weight). Afterward, WLC or OWA operators are used for the final suitability map. These steps, following the MAR problem statement, are described in greater depth below:

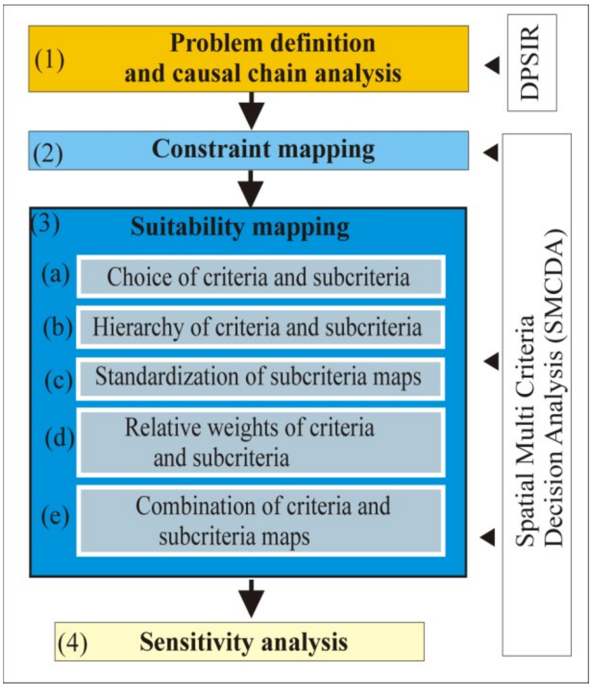


Figure 6.1: The procedure for MAR site suitability mapping

6.3.1 Problem statement

In water resources management, MAR has proven to be an effective response to water scarcity problems. MAR is helpful for the recovery of groundwater levels, the improvement of groundwater quality, and for storage of water and as a barrier against salinity intrusion. The selection of suitable locations for MAR implementation based on proper technologies is one of the primary requirements.

6.3.2 Constraint mapping

The main objective of constraint mapping is to screen out a large number of alternatives which have been deemed as being non-feasible. This step helps the user to avoid conflicts in decision-making. The sites which are of prime interest to other planning projects or which are simply not available or completely non-feasible for MAR implementation are screened out in this step. A conjunctive screening approach was chosen for constraint mapping. Under conjunctive screening, an alternative is accepted if it meets specified thresholds for all evaluation criteria. Figure 6.2 shows the general procedure for constraint mapping. The developed constraint map serves as a mask for suitability mapping.

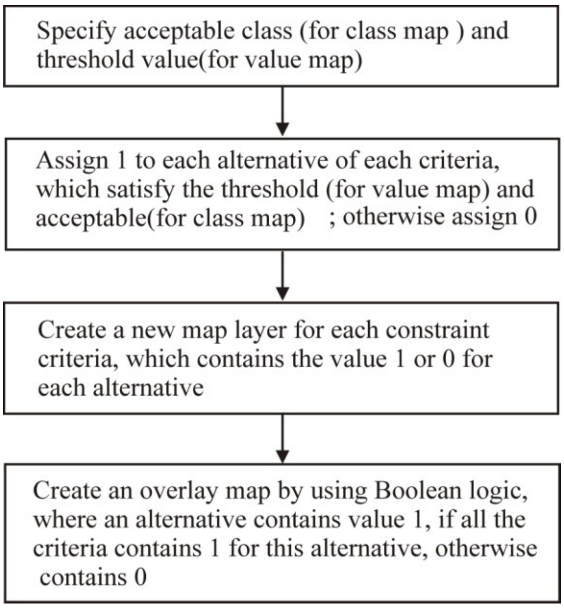


Figure 6.2: Flow chart for constraint mapping

6.3.3 Suitability mapping

(A) Choice of criteria and sub-criteria

In this step, all relevant surface, subsurface, and regional characteristics are selected. Each characteristic is defined as a sub-criterion. The sub-criteria are grouped under the main criteria. The combined main criteria are the "suitability map," which is the goal of the SMCDA.

(B) Hierarchy of criteria and sub-criteria

The role of AHP begins at this step. This step involves the decomposition of the ultimate goal into a three-level hierarchy consisting of sub-criteria of the goal. The top of the hierarchy is the goal of the analysis/problem. The middle level contains more specific criteria with regards to the objective and the bottom level refers to the most specific criteria. The sub-criteria in the lowest level are related to the main criteria in the middle level, while the top level relates to the "suitability map" (see Figure 6.12). The sub-criteria are represented by thematic maps or attributes. The model's user-interface allows the user to construct the hierarchy or "criteria tree."

(C) Standardization of sub-criteria maps

Each sub-criterion in the criteria tree is represented by a map of different types such as a classified map (e.g. land use) or a value map (e.g. slope, infiltration). For decision analysis, the values and classes of all the maps should be converted to a common scale to reduce the dimensionality. Such conversion is called standardization (Sharifi and Retsios, 2004). Different standardization methods may be applied to different maps. This model offers linear, piece-wise linear, and step functions for standardization. The outcome of the function is always a value between 0 and 1. The function is chosen in such a way that cells in a map that are highly suitable for achieving the goal obtain high standardized values and less suitable grids obtain low values.

(D) Relative weights of criteria and sub-criteria

The next step in the site selection procedure is assigning values of importance for all criteria and sub-criteria, which is done by assigning a weight to each criterion. Different weighting methods are available. Pair-wise comparison and direct weighting are used here. The sub-criteria under each main criterion are compared amongst themselves and a weight is assigned to each one. The main criteria are also evaluated in this way.

(E) Combination of criteria and sub-criteria maps

After standardization and weighting, the next step is to obtain the overall suitability index of each alternative. The index value is given to the cells of the map. Overlay methods available are WLC and OWA with fuzzy linguistic quantifiers. WLC is the most simple and the most commonly used aggregation method in spatial analysis (Eastman et al., 1993).

WLC, $S(x_i) = \sum w_i \cdot s_i(x_i)$ (7)

w_i = normalised weight; $\Sigma w_i = 1$; $s_i(x_i)$ = standardized criteria function/map

OWA is a class of multicriteria combination operators, involving two sets of criteria weights, which are "criteria importance weight" and "ordered weight" (Yager, 1988). The concept of fuzzy linguistic quantifiers, introduced by Zadeh (1983), allows the conversion of natural language statements into proper mathematical formulation (Munda, 1995). In this study, the regular increasing monotone quantifier class was considered. Given the criteria weights, w_i, the quantifier-guided OWA can be defined as follows (Boroushaki and Malczewski, 2008):

$$OWA(i) = \sum_{j=1} \left(\left(\sum_{k=1}^{j} \right)^{\alpha} - \left(\sum_{k=1}^{j-1} \right)^{\alpha} \right)_{ij} \qquad (8)$$

z_{ij} = weighted attribute value
α = parameter for linguistic quantifier
u_k = criteria weight reordered according to z_{ij}
j = number of criteria

OWA allows for a high degree of input variability and for the trade-off of importance among input variables (Figure 6.3). When $\alpha = 0$ (linguistic quantifier categorized as "*at least one criterion satisfies*"), the result yields no trade-off and full ORness; when $\alpha = \infty$ (linguistic quantifier categorized as "*all criteria satisfy*"), the result yields no trade-off and full ANDness. Using α value between 0 to ∞, yields a range of MCE operators in the decision strategy space. When $\alpha = 1$ (linguistic quantifier is categorized as "*half of the criteria satisfy*"), the results yields the full trade-off (WLC) (Figure 6.3).

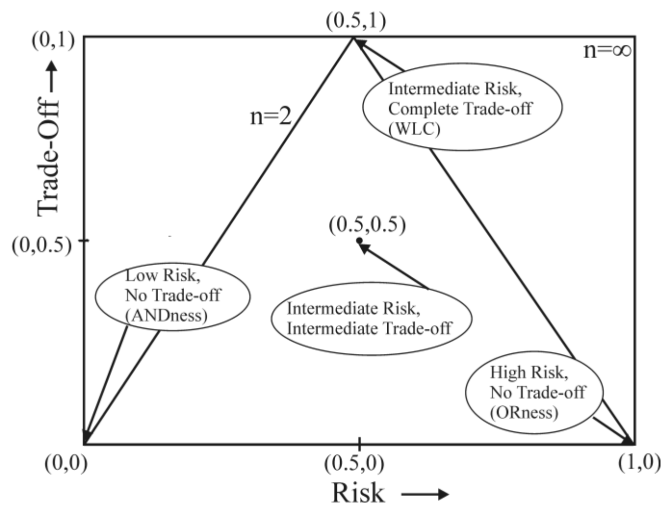


Figure 6.3: The decision strategy space showing relation between trade-off and risk, n is the number of criteria (modified after Eastman, 2000 and Malczewski, 2006)

The detailed description of AHP combination with OWA is given by Boroushaki and Malczewski (2008).

6.3.4 Sensitivity analysis

A sensitivity analysis may be undertaken by the user in order to study the robustness of the suitability map with respect to the linguistic quantifier (α). The new SMCDA tool also permits assessment of site suitability as respective to the influence of the application of different weighting schemes and standardization. In this respect, sensitivity analyses are useful where uncertainty exists in the construction of hierarchy and in the assignment of relative importance (Store and Kangas, 2001).

6.4 GIS Based Site Suitability Analysis Tool

6.4.1 Overall system framework

The site suitability analysis tool extension is tightly integrated in the ArcMap environment. This instrument is developed as an ArcMap extension, using ArcObjects and VB.Net. ArcObjects is a developer kit for ArcGIS based on Component Object Model (COM). This solution considerably extends the functionalities of ArcMap by implementing the MCDA within the GIS environment by allowing the developer to combine the advantages given by the user interface controls available in the .Net framework with the GIS functionality included with ArcGIS (ESRI). The advantages of customized components by using a COM-Compliant environment such as Visual Studio 2005 are: (1) a wider range of functionalities can be integrated into customisation, (2) codes are not accessible by the user, (3) all aspects of ArcGIS application can be used further, extended, and customized, (4) the customisation can be easily supplied to the client machines (ESRI, 2004; Boroushaki and Malczewski, 2008). Figure 6.4 shows the overall system development.

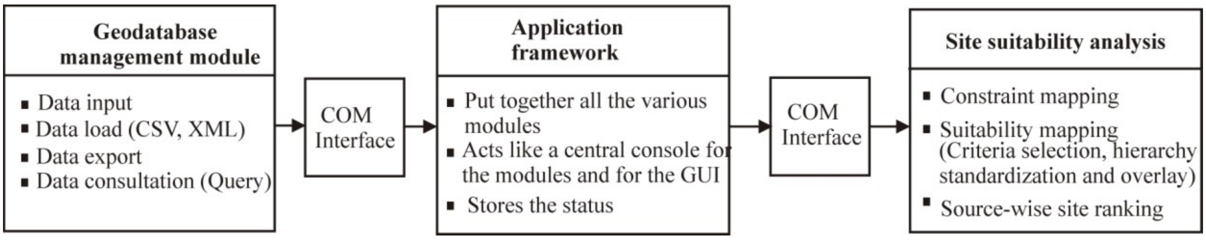


Figure 6.4: Structure of the site selection tool developed in the ArcGIS environment

The model has been incorporated into the table of contents of ArcGIS as the ‘Site Selection’ option. By activating the tab, the user can access the main steps of the site selection instruments: ‘Constraint Mapping’, ‘Site Suitability Mapping’, and ‘Site Ranking’. Further options related to each main step (Figure 6.5) derive from this one.

The supporting database structure is an ArcGIS Personal Geodatabase (ESRI). The geodatabase can store, beside the geographical data, data behavior rules such as domains, relationship classes, and custom behavior. The geodatabase management module is composed of two sections: (i) Data Input/Output and (ii) Spatial/Time dependent query and visualization. The geodatabase management module focuses on designing the user screens, so these match the different sections of the data model. This component includes the following subcomponents:

- Data access subcomponent, which contains functions for database connection, data reading, and database update
- Data model objects, which are used for storing the data in memory while the application is running. These data model objects abstract the feature classes and the tables in the geodatabase and mimic the relationships between them
- Interface components, which include the user screens that provide user access to the data stored in the data model objects. The user can input data through a list of standard user interface controls, such as text boxes, combo boxes, data grids, etc.

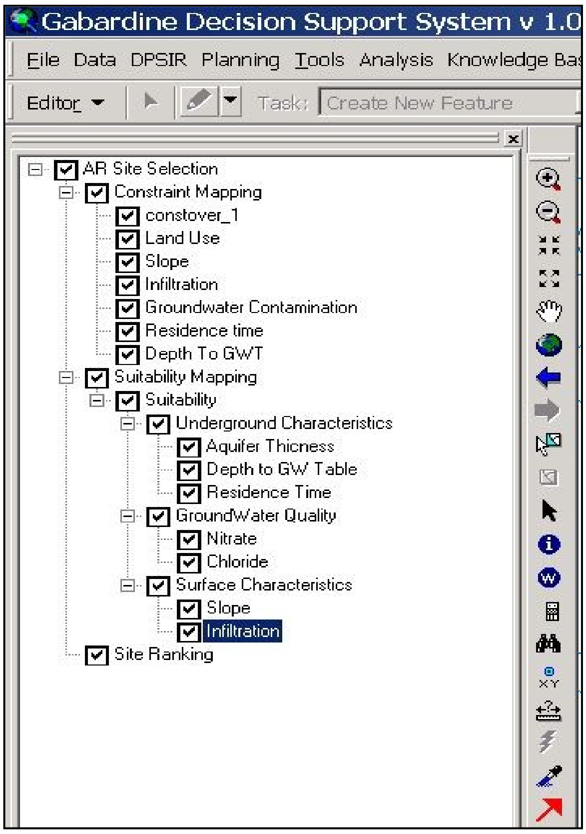


Figure 6.5: Exemplary table of contents in ArcGIS Display for the site suitability analysis, incorporated to Gabardine DSS

The personal geodatabase format was considered suitable for the scale of the current application; however, the format can be easily upgraded for further developments to an ArcSDE (ESRI) geodatabase. The ArcSDE allows connecting ArcGIS and the Site Suitability Analysis Tool interface to future database versions developed using other Spatial Relational Database Management System (RDBMS) software like Oracle, SQLServer, IBM-DB2, and others.

6.4.2 Site suitability mapping

This first step offers default criteria for choosing and selecting the corresponding raster map to generate a constraint map. The default constraint criteria have been selected after a close discussion within a consortium consisting of a number of international experts from different organisations (e.g. LNEC - National Laboratory for Civil Engineering, Portugal; University of Liege, Belgium; EWRE - Environmental & Water Resources Engineering Limited, Israel; University of Nottingham, UK; PHG - Palestinian Hydrology Group, Palestine; GeohidroConsult, Romania; University of Goettingen, Germany, etc.). Moreover, new constraint criteria may be added by the user (Figure 6.6). Both value type and class type map can be handled by the system. The user defines the threshold value for value type criteria and to each class of the class type map; the user may assign a zero for a non-potential area or a one for a potential area. The system then creates a constraint map of each sub-criteria separately. Afterwards, the maps may be overlain and one constraint map may be prepared with Boolean logic. The constraint maps are added to the ArcGIS document and can be used for further analysis.

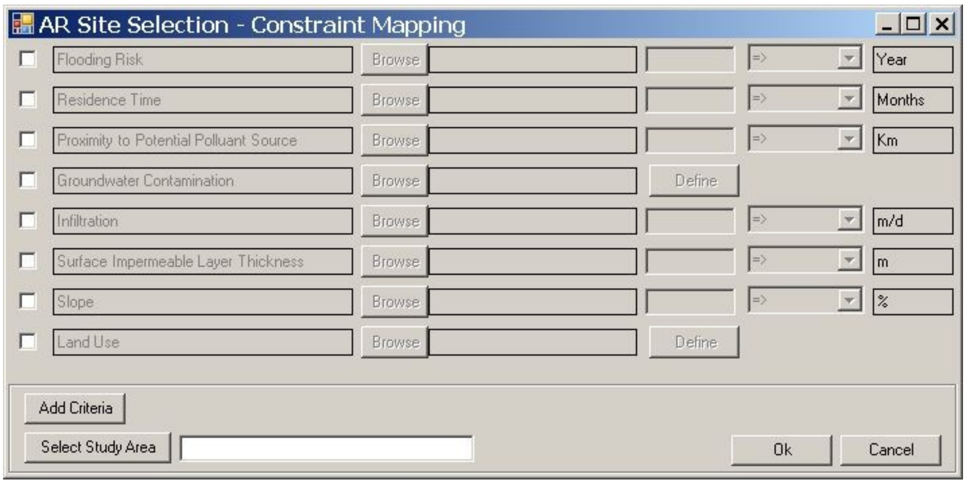


Figure 6.6: Interface to select constraint criteria and assign the threshold

Site suitability mapping starts with the preparation of a hierarchical structure, which is performed by selecting criteria and sub-criteria for each level. The user selects the criteria from the default list. The default criteria are prepared, considering all relevant characteristics that should be included for the spatial analysis. Special care has been given to avoid any duplication of the criteria/sub-criteria. New criteria or sub-criteria can also be easily added via the user-interface. The user can visualize the hierarchical structure and edit for presentation and reporting purposes. The standardization process follows the building of hierarchy. The user selects the criteria, the constraint map, the threshold values, and the preferred standardization function. For a better visualization, the converted function is drawn graphically in the interface (Figure 6.7). The overlay command of the criteria tree proceeds to the step of weighting and overlay. The system offers

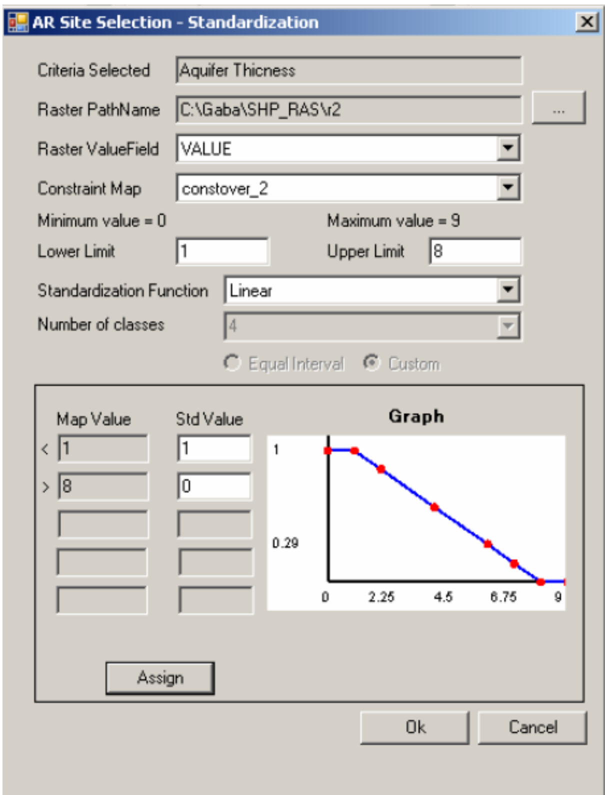


Figure 6.7: Standardization procedure

the pair-wise comparison and the direct weighting methods. The weights of each criterion in each level can be given directly or can be generated by the pair-wise comparison method. In the pair-wise comparison method, the user can input preferred values using a scale bar. The weights are generated using the specified formula by Saaty (1980).

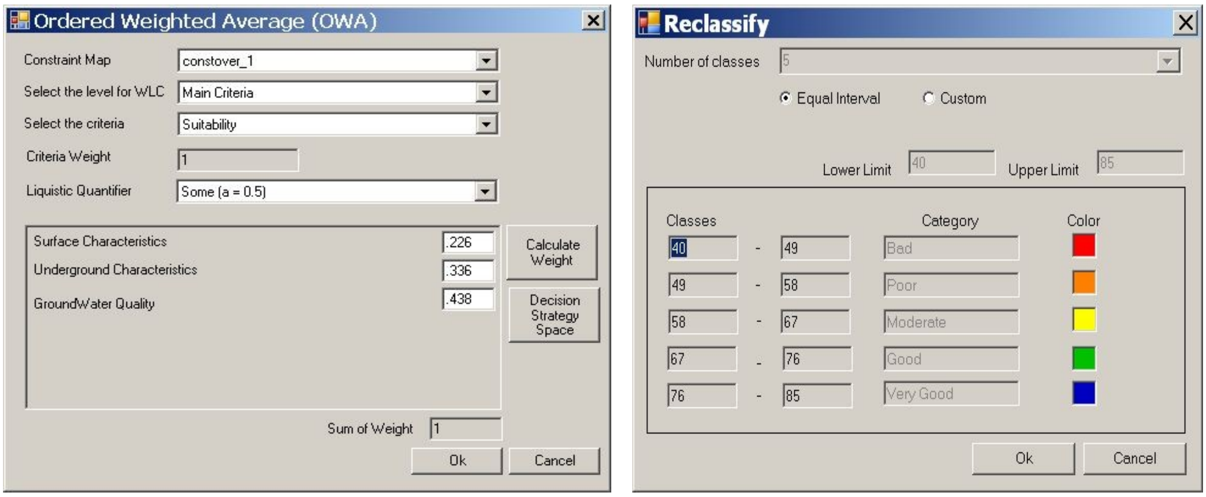


Figure 6.8: The overlay for the suitability analysis (left) and the reclassification step of the suitability map (right)

After finishing the weighting procedure, the user reaches the final steps of the site suitability mapping (Figure 6.8). The user chooses an overlay procedure, either WLC or OWA. In the OWA procedure, the linguistic quantifiers are assigned to each level of overlay. The resulting map is then created and shown in ArcGIS format. The role of the AHP function is the construction of a criteria tree as well as to calculate the relative weights of the criteria and of the sub-criteria by pair-wise comparison. After applying the AHP, the WLC or OWA are used. WLC computes the overall suitability for each alternative or cells using the standardized map, weights, and constraint map. OWA produces the suitability maps by specifying the linguistic quantifier (a set of ordered weights are generated, which are related to α; the generated values for each alternative are combined).

By changing the weights of each overlay method and of the linguistic quantifier associated with the objectives and attributes for OWA, a wide range of decision scenarios can be generated and the corresponding map layers are added to the map document. This helps to check the sensitivity of the system with changing weights and linguistic quantifiers.

Areas on the suitability map can be classified as very good, good, moderate, poor, and bad. The system offers five different colours for the five classes (Figure 6.8), taking into account the colour code for ecological status classification proposed by the Water Framework Directive (WFD) (Water Framework Directive, 2003). The user has the opportunity to change the range of class manually.

The third step is a spatial analysis of the optimal MAR locations with respect to water source locations. In a user-defined buffer zone spatial query, the most favorable MAR locations based on proximity to water source are chosen. The result is a raster map, which shows the optimal MAR locations that satisfy the user chosen distance to proximal potential sources of water.

6.5 A Case Study- MAR Site Selection for Querença-Silves Aquifer System

6.5.1 Problem description

Due to the geographical location, the Algarve region in southern Portugal is prone for experiencing droughts, and the region has been affected by many droughts over the last few decades. The hydrological year of 2004/2005 was extremely dry in all of the Portuguese mainland and especially in the Algarve region. The drought caused severe problems, considering the availability of water resources. Surface water reservoirs reached volumes that were below acceptable levels, and the Querença-Silves aquifer system was over-exploited (Figure 6.9). The aquifer system of Querença - Silves is a major source of drinking water to the urban areas within the Algarve region. The Arade Dam is considered to be the most important drinking water source. The dam is located downstream of the Arade river. More than 50 hm^3 of river water per year are lost to the sea and in dry years there is a shortage of water resources. (Lobo-Ferreira and Oliveira, 2007). MAR is considered as a potential strategy to store water during the wet season and use it during dry periods. The overall planning and management of MAR consists of: selection of water source, location of infiltration basin, and location for recovery of the infiltrated water. This study focuses on suitability mapping for the implementation of infiltration ponds for aquifer recharge.

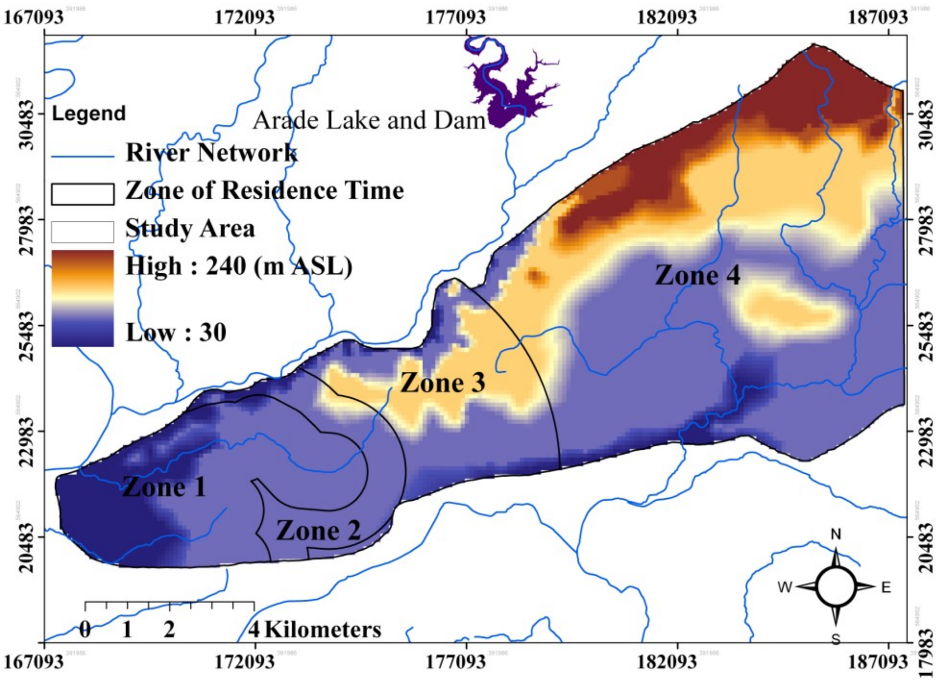


Figure 6.9: Study area (Querenca Silves Aquifer) map

6.5.2 General characteristics of the test site

The Querença-Silves Aquifer System is a 318 km^2 aquifer system, the largest of the Algarve, located in the municipalities of Silves, Loulé, Lagoa and Albufeira (Central Algarve). The aquifer is mainly composed by karstified Lower Jurassic (Lias-Dogger) dolomite structures. The southwestern part of the aquifer is mainly unconfined. The general groundwater flow direction is from Northeast to Southwest. According to the characterization of the Querença-Silves aquifer system (Almeida et al., 2000), the hydraulic parameters are heterogeneous and aquifer productivity values are high. The transmissivity values range between 83 and 30,000 m^2/day and the storage coefficient ranges from $5*10^{-3}$ to $3*10^{-2}$. INAG (2001) presents the recharge value as being 220±54 mm/year. This represents a percentage of precipitation of around 40±10%. Monteiro (2005) obtained an average recharge of 292.5 mm/year. These are average values using the average precipitation values in the area, therefore when the precipitation is much smaller (e.g. the hydrological year of 2004/2005, when precipitation was more than half the average) the recharge is also much lower. Analysing 69 wells of the aquifer for the year 2002, a withdrawal rate of 19.5 mm/year was computed as being possible to meet the water demand of Silves, Lagoa, Albufeira and Loulé. This value was higher during the drought years of 2004-2005.

In this study, only the southwestern part of the Querença-Silves Aquifer is being taken into account due to geology and aquifer properties. The groundwater catchment area is 114 km^2. For analysis purposes, the study area has been divided into four zones (Figure 6.9), according to the residence time of groundwater in the aquifer. These are: Zone I (residence time is less than 6 months), Zone II (residence time is 6 months to 1 year), Zone III (residence time is 1 year to 3 years) and Zone IV (residence time is greater than 3 years). These zones are overlain in each constraint and suitability map so as to assess suitable MAR sites according to the residence time zonation. Results of GIS analysis and of groundwater modeling have been used as spatial input information for MAR site selection procedure.

6.5.3 Selection of criteria for spatial analysis

After discussion with local and international experts and institutions and under the prevailing site characteristics and study objectives, two different sets of criteria were selected: a) criteria for constraint mapping and b) criteria for suitability mapping. Some important criteria were selected for both cases after analysing their importance and relevance. Table 6.1 lists the selected criteria for constraint and suitability mapping, showing the relevance and the usefulness of each criterion for MAR site suitability mapping.

Table 6.1: **List of criteria chosen for constraint mapping and suitability mapping and their relevance to MAR site selection**

Criteria	In the Analysis, used for	Description
Land use	Constraint mapping	The existing land use provides information about the land availability for MAR. For example, areas that are under commercial and industrial use, are non-feasible areas for MAR implementation.
Slope (topography)	Constraint mapping and Suitability mapping	Higher slopes do not permit the implementation of infiltration basins. Furthermore, water runoff is directly related to slope angle Flat areas allow high infiltration and is suitable for aquifer recharge. The lower the value, the higher the priority.
Infiltration rate (soil)	Constraint mapping and Suitability mapping	Infiltration rate of the soil control the penetration of surface water into an aquifer system. Soils with high infiltration capacity are more suitable than those of low infiltration capacity
Sub-Surface Impermeable layer thickness	Constraint mapping and Suitability mapping	The thickness of impermeable layer should not be high, otherwise the excavation costs would be high. The lower the value, the more suitable the place.
Groundwater depth	Constraint mapping and Suitability mapping	In terms of water quality improvement by natural attenuation processes, considerable unsaturated zone thickness is preferred. A deeper groundwater level benefits of the natural attenuation capacity at the studied location.
Distance to groundwater pollution source	Constraint mapping	The place of MAR should have a sufficient distance from groundwater pollution sources.
Aquifer thickness	Suitability mapping	Suitable sites should have high thickness values. Transmissivity and aquifer storage volume depends on the aquifer thickness. The higher the value, the higher the priority.
GW quality (chloride and nitrate)	Suitability mapping	The groundwater quality should be adequate at the place of recharge, except the objective of the MAR is to improve the groundwater quality. The parameter to be considered depend on the groundwater quality at the area .
Residence time	Constraint mapping and Suitability mapping	The residence time of the infiltrated water in the aquifer should be sufficient to be able to use the aquifer as water transfer and recovery system.

6.5.4 Constraint mapping

In order to screen out the non-feasible areas, constraint mapping was undertaken at an early stage. Table 6.2 shows the list of criteria and their threshold values for screening. For the land use map, land class feasibility was defined separately (Table 6.3).

Table 6.2: Defined threshold values (discarding conditions) of the selected criteria for MAR constraint mapping

Criteria Name	Threshold value	Explanation
Land use	-	See Table 3
Infiltration rate (soil)	25 cm/day	The areas where infiltration rate is greater than 25cm/day are considered as potential area.
Groundwater depth	5 meters	The places where groundwater depth is greater than 5m are considered as potential sites.
GW pollution sources	500 meters	The places which are within the radius of 500m of groundwater pollution sources are rejected
Residence time	6 months	A residence time of at least 6 months should be guaranteed.
Slope (topography)	5%	MAR is feasible for areas with less than 5% slope.

Table 6.3: Categorization of the land use types at the study area for MAR constraint mapping

Land use Type	Threshold
Agricultural systems, agricultural areas outside irrigation perimeters, irrigated areas, quarries / stone pits, marshy place, salt-pit, isolated urban areas	Non- Feasible (value is 0)
Permanent crops, orchard, poor pasture / grasslands, natural vegetation, underwood, rivers (water in lines to build check dams, and infiltrate)	Feasible (value is 1)

The threshold values for each constraint criteria are chosen so that criteria values or classes should satisfy the minimum requirement of MAR implementation such as, infiltration basin construction, water quality improvement by using unsaturated zone, aquifer storage capacity etc. For example, the threshold value for residence time used was 6 months, as most of the international standard guidelines for MAR (CDPH, 2008; NRMMC, EPHC, NHMRC, 2009) suggest to keep the water in the aquifer at least 6 months for water quality improvement.

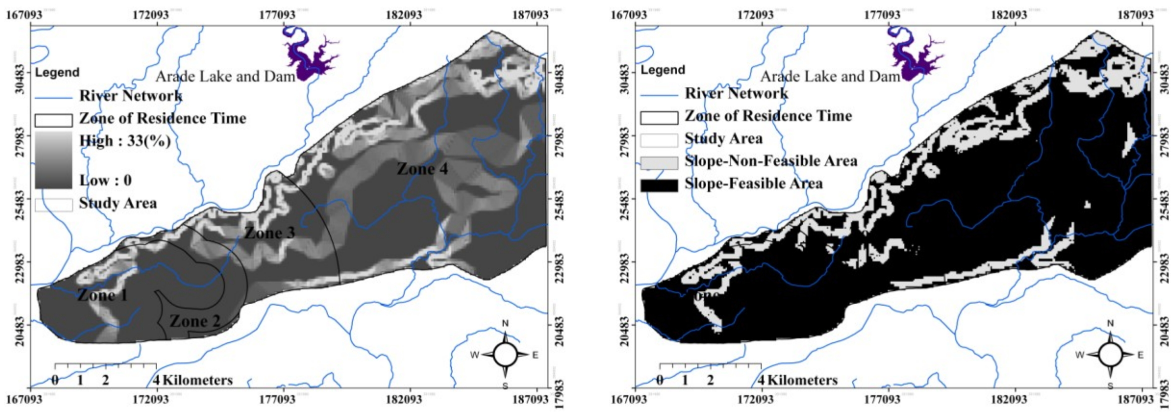


Figure 6.10: Thematic map of slope (left) and it's converted constraint map (right)

After defining the threshold values for each criterion, the thematic map of each constraint criterion has been converted to a constraint map. Figure 6.10 shows the thematic map of slope and the converted constraint map. All the converted thematic maps were overlain by conjunctive screening to achieve the final constraint map (Figure 6.11). This constraint map was used later as a mask for suitability mapping.

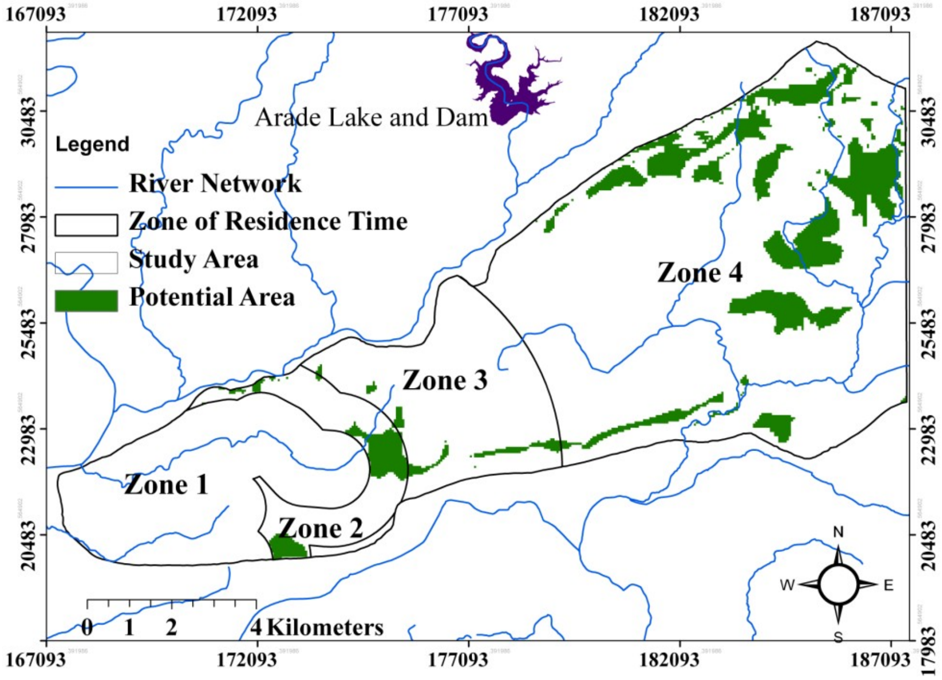


Figure 6.11: Constraint map for suitability mapping

6.5.5 Suitability mapping

After analysing all available data and site characteristics, sub-criteria were selected according to their characteristics, and the main hierarchical structure was prepared (Figure 6.12). The sub-criteria, or thematic layers, were standardized. Three value functions, such as linear, piece-wise linear, and step-wise linear functions were used for this approach (Figure 6.13).

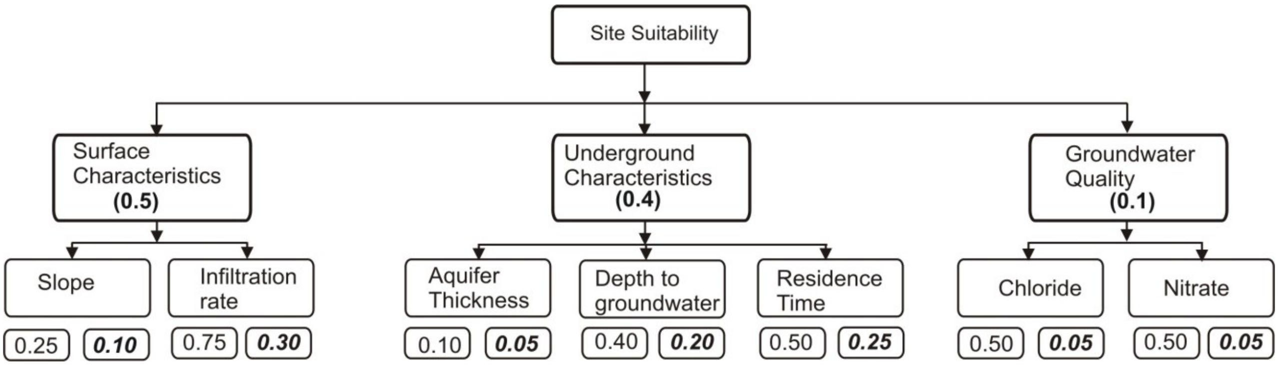


Figure 6.12: Criteria for suitability mapping and hierarchical structure (In bracket the weights local and global are given, bold and italic number to indicate the global weights)

The importance of each sub-criterion has been calculated using pair-wise comparisons and this is shown in Figure 6.12. Infiltration rate of the soil, residence time of groundwater, and depth to groundwater were given highest priority in the analysis. Groundwater quality was a low priority criterion because of low variability of groundwater quality over the entire area. The weighted criteria were then overlaid by two state-of-the-art overlay procedures: WLC and OWA.

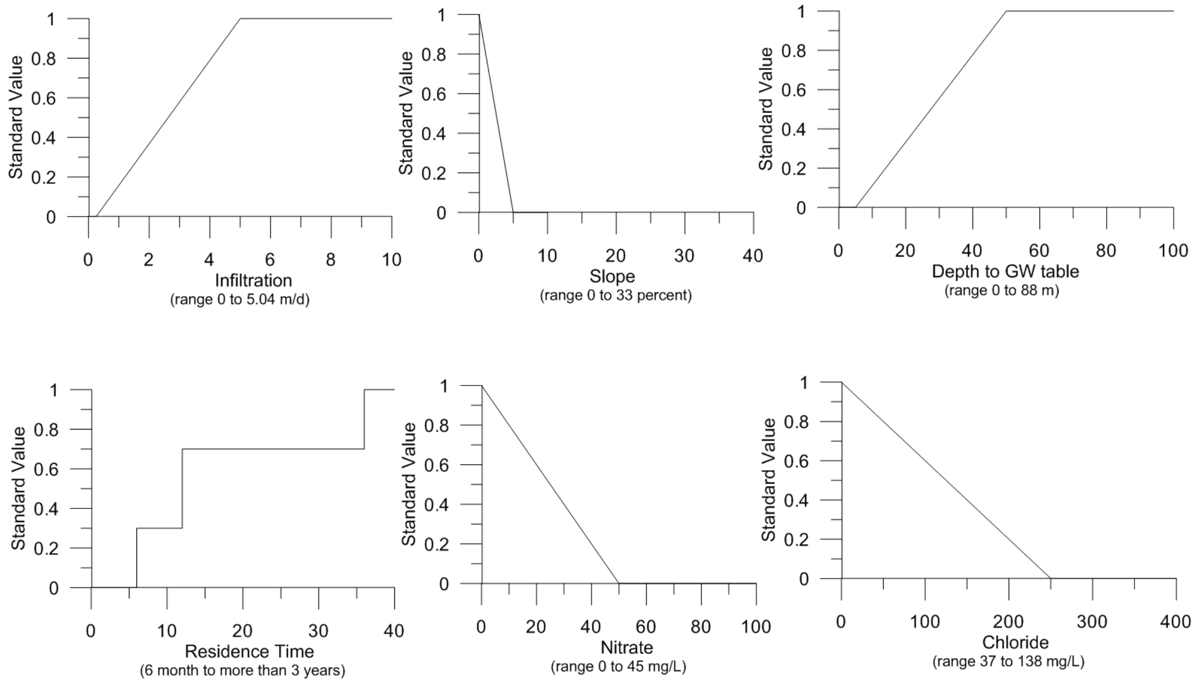


Figure 6.13: Procedure for criteria standardization used in this study (range indicates the limit of the criteria value present in the study area)

Figure 6.15 shows the suitable sites for MAR in the region using the WLC method. Figure 6.16 shows suitability maps using the OWA procedure. The map shows the suitable places under the following decision condition: “half” of the important criteria are satisfied by an acceptable alternative. According to the definition of the OWA, when $\alpha = 1$, the output should comply with the WLC output.

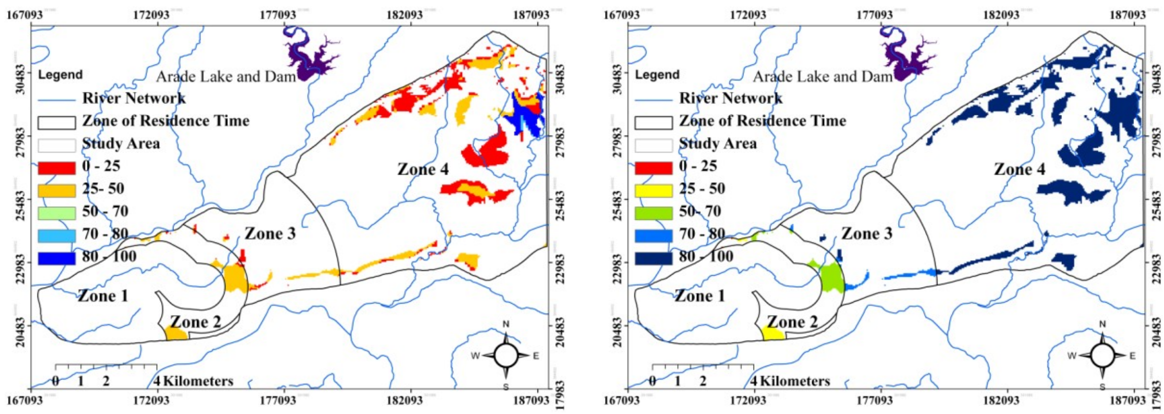


Figure 6.14: Weighted linear combination map for considering surface characteristics (Left) and underground characteristics (right)

6.5.6 Sensitivity analysis

A sensitivity analysis was done which indicates a significant change in site suitability based on changes in risk acceptance of the decision maker (see details in Figure 6.3). In this way, different decision maker's attitudes may be simulated and considered in the MAR planning process, contributing to the integrated management of water resources. A sensitivity analysis has been performed to demonstrate the effect of the decision rules on the site selection procedure. Given the standardized map and corresponding criterion weight, we have chosen four fuzzy linguistic quantifiers: *at least a few* ($\alpha = 0.1$), *a few* (($\alpha = 0.5$); *most* ($\alpha = 2$) and *almost all* ($\alpha = 10$). The corresponding OWA maps are shown in Figure 6.17.

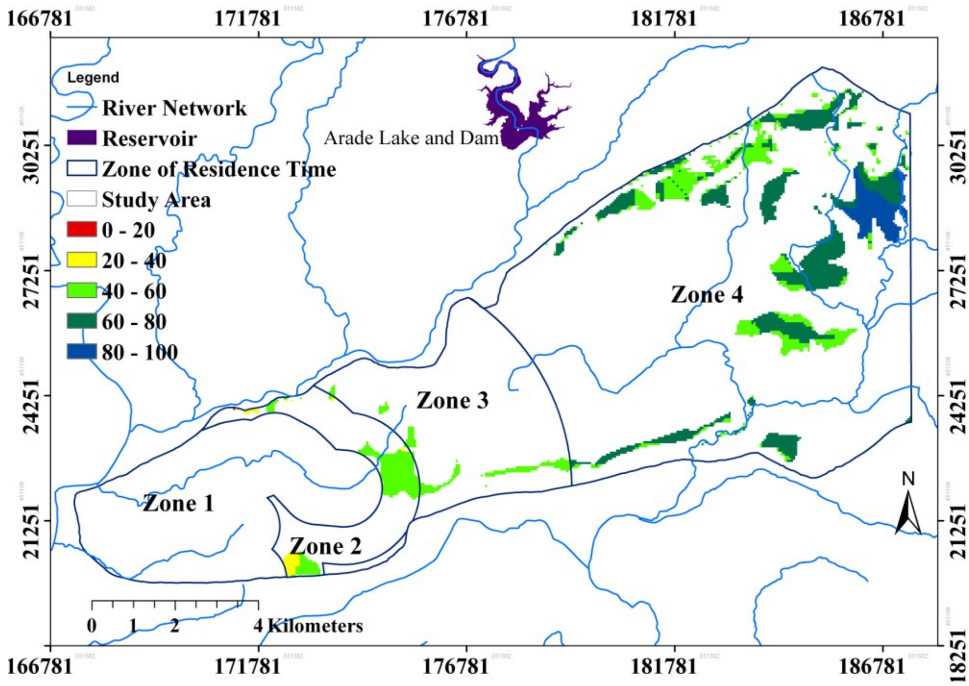


Figure 6. 15: Site suitability for MAR based on WLC

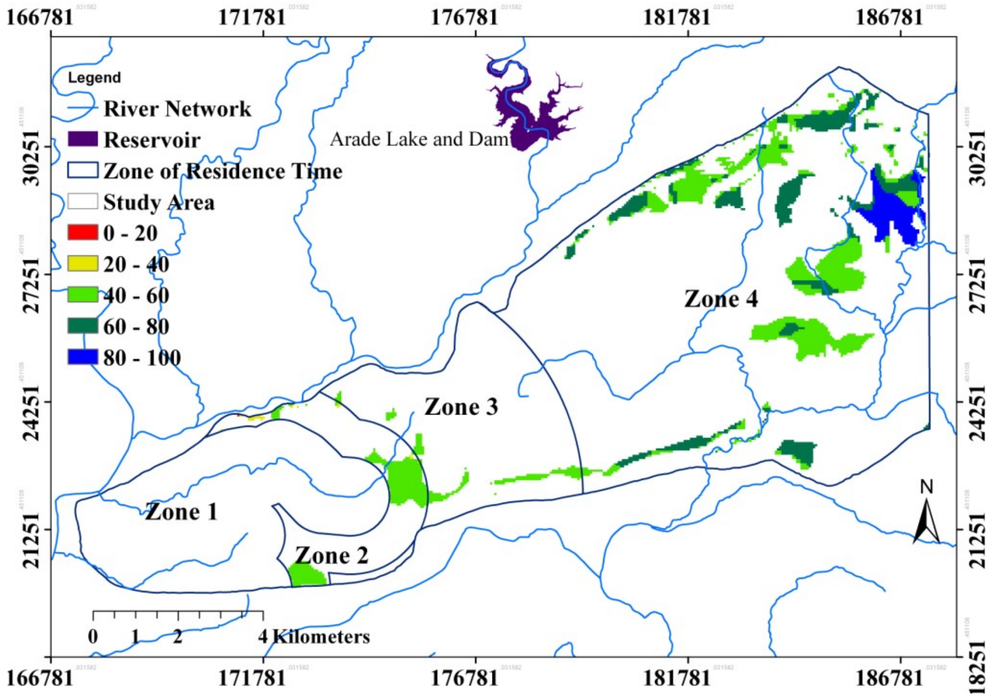
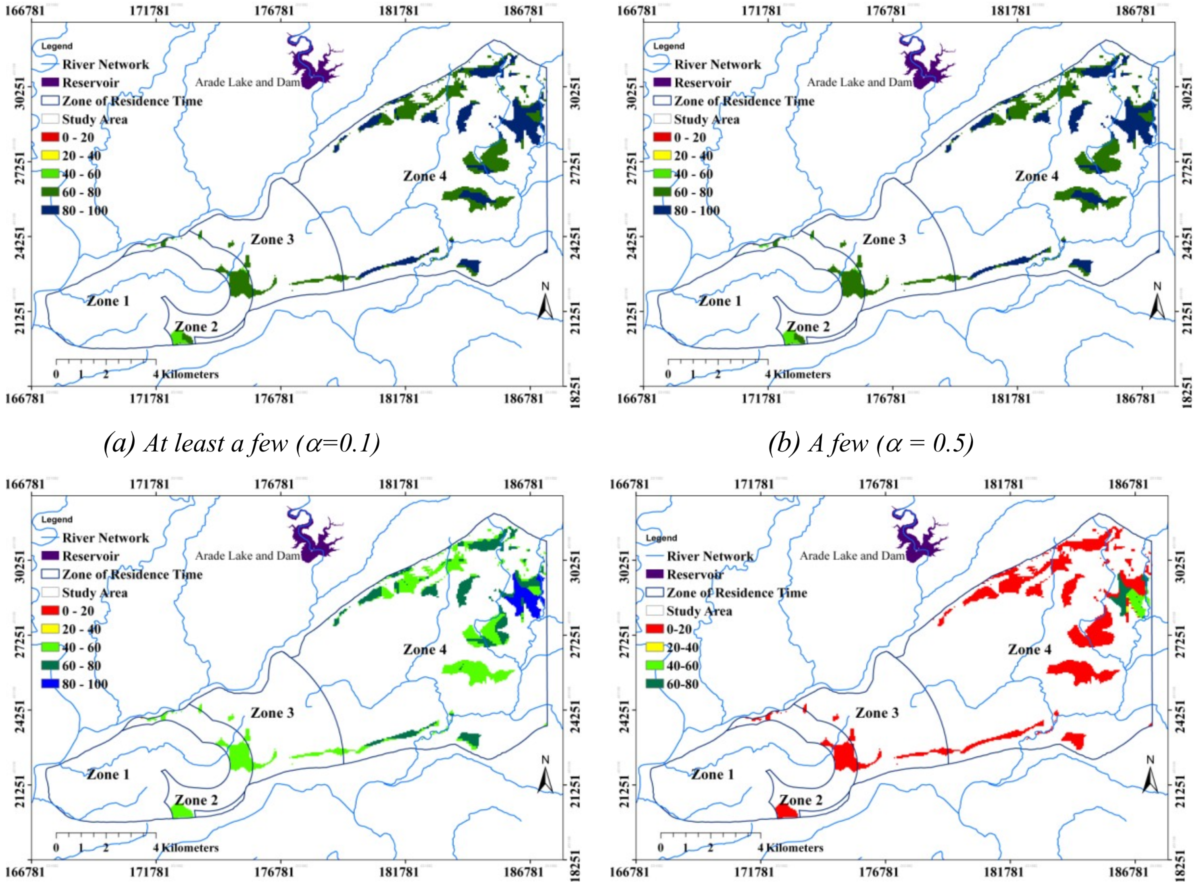


Figure 6.16: Site suitability map using OWA method α = 1 decision rule. The α value assigned same to each level of the hierarchy.

6.5.7 Results and Discussion

The constraint map (Figure 6.11) generated by the Boolean logic overlay method shows that only 11.2% of the total study area is feasible for construction of infiltration ponds to recharge groundwater. Land use and infiltration capacity of the soil are the main constraints for the potential site selection. Most of the potential sites are located in Zone 4, which is characterized by a higher groundwater residence time. The overall suitability map shows the relative ranking of the potential sites, generated by constraint mapping, according to the criteria importance. The suitability scores indicate the relative site ranking alternative to construct an infiltration basin. High suitability scores indicate the site is highly suitable for MAR. It is evident from the suitability analysis (Figure 6.14) that considering only surface characteristics, the study area offers just few adequate locations for the implementation of infiltration basins. In contrast to that, the study shows good suitability for aquifer recharge with regards to the generally feasible areas, considering the prevailing underground characteristics. According to the overall suitability score (Figure 6.15 and Figure 6.16) 1% of the total aquifer is very good (suitability score 80-100), 3.2 % is good (suitability score 60-80), 6.4 % is moderate (suitability score 40-60), and 0.6% is poor for MAR. The rest 88.8% of the aquifer surface is not suitable at all due to the constraints of MAR implementation. The most suitable areas are situated on agricultural land which have high infiltration capacity soil (infiltration rate ranges between 2.7 m/d and 5 m/d) with very flat topography (slope is 0%), and which do not require additional excavation efforts. The groundwater table under the agricultural land is about 70 m below the land surface, which provides a sufficient unsaturated zone thickness to assure water quality improvement. The groundwater quality is also moderate at the high suitability scores places. Since the regional groundwater flow direction is northeast to southwest, the infiltrated water may be easily transferred downstream from the highly suitable area in the northeastern part of the study area by using the natural groundwater flow of the aquifer as the water transfer system. The water may then be pumped in Zones 1 and 2 where drinking water pumping wells are already installed. The distance to the Arade Dam, the potential water source for MAR, is about. 8.5 km away from the highly suitable areas. This distance may incur extra water transportation costs. An approximately 27 ha area is categorised as “Good” which is only 3 km away from the Arade Dam. The groundwater table is 60 m deep and groundwater quality is moderate. In this location, the infiltration rate is relatively low. Here, a comparative study and pilot experiment may be desirable in order to make the final decision on an infiltration basin.

The sensitivity analysis indicates a change in site suitability due to varying risk acceptance of the decision maker (Figure 6.3). In this way, different decision makers' attitudes have been simulated and may always be considered in the MAR planning process. This unique capability of the new SMCDA tool contributes to the greater integration of the management of various water resources. The sensitivity analysis (Figure 6.17) also indicates the significant impact that decision rules have on site suitability mapping. The first map of Figure 6.17a indicates the best possible site suitability. This is the most optimistic decision strategy (*at least a few criteria should satisfy*) of the decision maker. Under this strategy, almost the entire feasible area (10.8% of the total area) falls into the category “very good.” When increasing the value of α (or reducing the risk) the suitable areas which are categorized as “very good” are reduced in number The last map (Figure 6.17d) shows the worst-case scenario according to the decision rules. In this decision strategy (*almost all criteria should satisfy*), no place is categorized as being ‘very good’, rather 9.7% of the total area is categorized as being ‘bad’. From the four alternative maps presented in Figure 6.17 together with the map presented in Figure 6.16, one may notice that the fuzzy quantifier based OWA approach is able to simulate a wide range of decision maker's preferences regarding MAR implementation.



(a) *At least a few (α=0.1)*

(b) *A few (α = 0.5)*

(c) *Most (α=2)*

(d) *All most all (α = 10)*

Figure 6.17: Sensitivity analysis showing the change of site suitability according to the change of decision rule; The α value assigned same to each level of the hierarchy

6.6 Conclusions and Recommendations

This paper mainly demonstrates the new suggested GIS based spatial multi-criteria decision analysis software tool for the site ranking to implement MAR projects. Site selection analysis involves a number of criteria, alternatives and decision factors, resulting in a complex decision environment. With this new tool, the decision steps are explicitly given to the user according to the overall analysis procedure in order to tackle an unstructured problem. Standard criteria and decision rules are offered to the user in order to reduce the analysis efforts and the risk of ignoring relevant decision criteria. The considered hierarchical framework of AHP promotes clear thinking and better understanding of the problem together with reducing errors in importance judgment. Pair-wise comparison permits the checking of consistency to the user's input weight. Decision makers are able to obtain a wide range of decision strategies and scenarios by changing linguistic quantifiers, in the incorporated OWA method (Yager et al., 1988). In order to show the efficiency of the tool, a case study has been performed in Querenca Silves Aquifer, Portugal. Provided default criteria, explicit decision steps, and flexibility in varying criteria standardization and overlay, are found to be very beneficial.

According to the analysis results from the case study, there are just few areas, 11.2 % of the total aquifer, where the implementation of infiltration ponds would be feasible. Non-adequate surface characteristics cause further restrictions for MAR implementation. On the contrary, the underground characteristics, studied for the feasible areas, are adequate for the MAR implementation by means of infiltration technologies. The overall suitability maps, in both methods, suggest installing the infiltration ponds in Zone 4. The high suitability areas are characterized by adequate unsaturated zone thickness, which is very important for water quality improvement. The groundwater quality is also moderate. In order to obtain more locations for infiltration ponds, better analysis of restrictions with regards to land use and soil type is recommended. Decisions with regards to the selection of optimal locations for the installation of water recovery wells and groundwater protection should be supported by groundwater flow and transport modeling, while checking the actual flow path of the infiltrated water and the impact of water pollution sources. Besides this, some other in-situ parameters, such as soil salinity, organic carbon content, and sediment chemistry can be studied further in order to rank the alternatives according to the potential of further water quality improvement. Some socio-economic criteria, recharge and recovery water transportation cost, cost of excavation, etc. can be taken into consideration for further study. Above all, the local agency can verify the analysis result while implementing MAR on the test site.

The SMCDA tool can be further developed to offer more decision analysis techniques to the end user. In the future, a number of standardization functions (e.g., concave, convex, sigmoidal functions etc), weighting methods (such as ranking method, rating method etc.), and overlay methods (e.g., fuzzy additive weighting method, composite programming etc,), will be added to the existing SMCDA tool. The new spatial multi-criteria analysis tool, due to its non-site specific, adaptive and comprehensive concept may serve as a complementary element for any GIS based Water Resources Management support system. By altering the input criteria and using the relevant dataset and decision rules, this spatial multicriteria analysis tool can be applied to a wide range of disciplines, such as groundwater vulnerability assessment, land use planning, site selection for waste disposal etc. Multi-objective decision analysis techniques can be added to this tool easily. The tool has been already implemented in the Gabardine DSS, a comprehensive GIS based decision support tool for MAR planning and management (Rusteberg et al., 2008).

6.7 References

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Chapter 7

Site Suitability Mapping and Managed Aquifer Recharge Site Ranking Supported by Mathematical Modeling at Northern Gaza Coastal Aquifer

7.1 Introduction

The Gaza Strip is located on the south-eastern coast of the Mediterranean Sea. It is located in the transitional zone between a temperate Mediterranean climate in the west and north, and an arid desert climate of the Sinai Peninsula in the east and south. Seventy percent of the population of the Gaza Strip lives below the poverty line and the 2009 estimate of the unemployment rate is 40% (CIA, 2010). One surface water body exists in Gaza, due to the Beit Lahia Wastewater Treatment Plant (BLWWTP), but no permanent natural surface water bodies exist in North Gaza or any part of the Gaza Strip. Due to the absence of surface water, groundwater is the sole source of water for all uses in North Gaza (Shomar, 2006). In 2003, 150 million cubic meters of groundwater was pumped from 4,100 wells to meet domestic, industrial, and agricultural uses for all of the Gaza Strip (Al-Yaqubi et al., 2007). All wells tap into what is known as the Coastal Aquifer, a relatively shallow elongated coastal aquifer which extends from the Sinai Desert at the Gaza-Egypt border to Haifa, Israel (Qahman and Zhou, 2001). The Coastal Aquifer supplies water not only to North Gaza but also the rest of the Gaza Strip and Israel. The Coastal Aquifer has historically been over-exploited (Qahman and Zhou, 2001), and water quality has deteriorated increasingly over time (Al-Yaqubi et al., 2007).

These water resources problems have consequences on the agricultural productivity and affect the regional economy. In order to guarantee sustainability of regional development, Managed Aquifer Recharge (MAR) is considered as a potential response to the current water resources problems in the area (Rusteberg et al., 2010). Considering the hydrological situation of the area, treated effluent is considered as the main water source for MAR. Managed aquifer recharge (MAR) with reclaimed wastewater and other sources of water is now being widely practiced in various parts of the world, especially in the arid and semiarid regions (IAH-MAR, 2003). Depending on the water source, water quality, geology, surface conditions, soils, and hydrogeology, a variety of methods have been developed to recharge groundwater (Bouwer, 2002). Soil Aquifer Treatment (SAT) is an economical and aesthetic wastewater reuse approach (Lee et al., 2004). 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, 1987, cited in Lee et al., 2004). Considering the soil and sub-surface geology, this infiltration technique is considered to be the most suitable MAR technique for the study area.

A number of surface and sub-surface characteristics need to be considered during the site selection process for MAR projects. Complex regional characteristics, heterogeneities in surface and/or subsurface characteristics, and variable groundwater qualities make site selection for MAR difficult (Anbazhagan et al., 2005). During the last 20 years a number of studies have been performed to select suitable sites for MAR implementation (e.g. Saraf and Choudhury, 1998, Anbazhagan et al., 2005; Chowdhury et al., 2010) . The existing MAR site selection procedures of today are far behind in terms of using modern technology and decision analysis methods, considering the advancement in site selection methods for other purposes such as waste disposal, priority of land use etc. An extensive literature review postulates that, in general, the site suitability analysis follows the path: screening of feasible areas → classification of thematic layers → standardisation of the maps → weighting of the criteria → overlaying. Proper selection and combination of surface, subsurface, and regional characteristics need to be included for a complete evaluation. Wide range of criteria standardization function has not been well adapted. A wide variety of weighting methods need to be practiced in the field of MAR. The classical overlay mapping and modeling are the most commonly used methods for site suitability mapping. Boolean logic and Weighted Linear Combination (WLC) are the most popular decision rules in GIS (e.g., Eastman, 1997; Malczewski and Rinner, 2005) and were used in different studies. These two method can be generalised within the scope of Ordered Weighted Averaging (OWA) (e.g., Malczewski and Rinner, 2005; Malczewski, 2006). In OWA, a number of decision strategy maps can be generated by changing the ordered weights. Several OWA applications have been implemented already (e.g. Rinner and Malczewski, 2002; Calijuri et. al., 2004; Malczewski et al., 2003; Malczewski, 2006) but application in the field of MAR is missing. The combination of AHP with WLC and/or OWA can provide a more effective and robust MCDA tool for spatial decision problems. The Analytical Hierarchy Process (AHP), proposed by Saaty (1980), can be used to combine the priorities for all levels of a "criteria tree," including the level representing criteria (Eastman et al., 1993). In this case, a relatively small number of criteria can be evaluated simultaneously (Jankowski and Richard, 1994; Boroushaki and Malczewski, 2008). The combination of AHP with WLC and/or OWA can provide a more effective and robust MCDA tool for spatial decision problems. Boroushaki and Malczewski (2008) implemented AHP-OWA operators using fuzzy linguistic quantifiers in the GIS environment, which has proven to be effective. AHP method has been applied in the field of MAR by several studies (e.g., Anane et al., 2008, Chowdhury et al., 2010) and the application of AHP-OWA is applied by Rahman et al., 2010 (see chapter 6). Rahman et al., 2010 proposed a non-site specific, adaptive, and comprehensive site selection tool that is proven effective and useful and therefore has been applied in this study.

The success of MAR project largely depends on the hydrogeological condition of the project area (ASCE, 2001). The hydrogeological conditions vary from place to place and thus control the groundwater flow, transport processes and regional groundwater situation. Moreover, the infiltration of water may change the general groundwater flow direction by increasing GW level gradient that might halt the fresh water flow from nearby catchment or sea water intrusion from the coast. Hence, the suitable sites should be investigated and ranked according to their impact on the prevailing hydrogeological condition. Still now, no study has been performed that considers the advance SMCDA procedure for site suitability mapping and afterwards rank the highly suitable sites by applying hydrogeological impact assessment (groundwater modeling).

The objective of this chapter is to present the integrated and holistic procedure for MAR site suitability analysis in North Gaza. This chapter also ranks some selected MAR locations through hydrogeological assessment supported by mathematical modeling and multi criteria analysis.

7.2 Study Area Description

North Gaza is the northernmost of five geographical Governorates of the disputed territory known as the Gaza Strip. As of July 2010, the estimated total population in the Gaza Strip is 1,604,238 people (CIA, 2010). The land area is 365 km^2, making the Gaza Strip one of the most densely populated regions in the world (Shomar, 2005c, PCBS, 2006). The population in North Gaza is particularly dense and includes the cities of Beit Lahia, Beit Hanoun, Jabalia, and Jabalia Refugee Camp, and directly abutting these cities is Gaza City, which is the largest city in the Gaza Strip and is where the Gaza Strip derives its name. In the Gaza Strip, 50% of the land is cultivated for agriculture and supports an agricultural industry which is possibly the only significant contributor to the economy of North Gaza (CIA, 2010). Here, flowers, strawberries, and vegetables are grown, often in irrigated greenhouses or in openly irrigated fields (Shomar et al., 2005a). The average annual temperature is 20°C, with relatively wet and mild winters, and hot and dry summers. The heat and dryness of the summers goes from May to September, with average temperatures in the hottest month, August, being 27 °C (Goldreich, 2003). The average annual rainfall is 200-400 mm, with most rain falling in the months of December and January (IMS, 1990).

The landscape in North Gaza is characterized by densely populated urban areas surrounded by cultivated farmland, orchards, and indoor growing facilities such as greenhouses. Close to the northern border, Israeli settlements exist and open areas with no classifiable land use. Soils are sandy to gravely and have high permeability. According to Al Agha (1997), a coastal 1-2 km wide belt of 20-40 m tall sand dunes exists. However, upon detailed study of satellite images provided by Google Maps©, the width of the sand dune belt is approximately 100-500 m (Google, 2010). Two types of soils exist in North Gaza. These are Arenosolic Rhegosols, which exist by the coast and extend roughly to the middle of North Gaza, and Luvisols/Xerosols, which are present on the roughly eastern half of North Gaza (Shomar, 2005c). Landforms characteristic for the Arenosolic Rhegosols are active steep dunes, undulating stabilized dunes and calcareous ridges. Dominant land use on these soils are irrigated horticulture in greenhouses, tunnel houses, and open fields as well as non-irrigated vegetables and fruits, such as grapes (Shomar et al., 2005a, Shomar, 2005c). Luvisols and Xerosols are found together in the eastern part of the region and are found in ancient alluvial valleys, depressions, and slopes. Citrus orchards and non-irrigated crops and vegetables are grown here (Shomar et al., 2005a, Shomar, 2005c).

The Coastal Aquifer extends north to south from Haifa to the Sinai Coast and North Gaza aquifer is a part of it. The aquifer is composed of layers of loess, dune sand, calcareous sandstone, sandstone, and silt (Melloul and Collin, 2000; Qahman and Zhou, 2001). The shallow vadose zone is mostly sand and gravel and is highly permeable (Shomar et al., 2005b). Some perched water tables can be found locally due to anomalous clay layers (MEnA, 2000). Larger and more consistent clay layers at the coast and extending 2-5 km inland, divide the Coastal Aquifer into several confined sub aquifers (Shomar et al., 2005b).

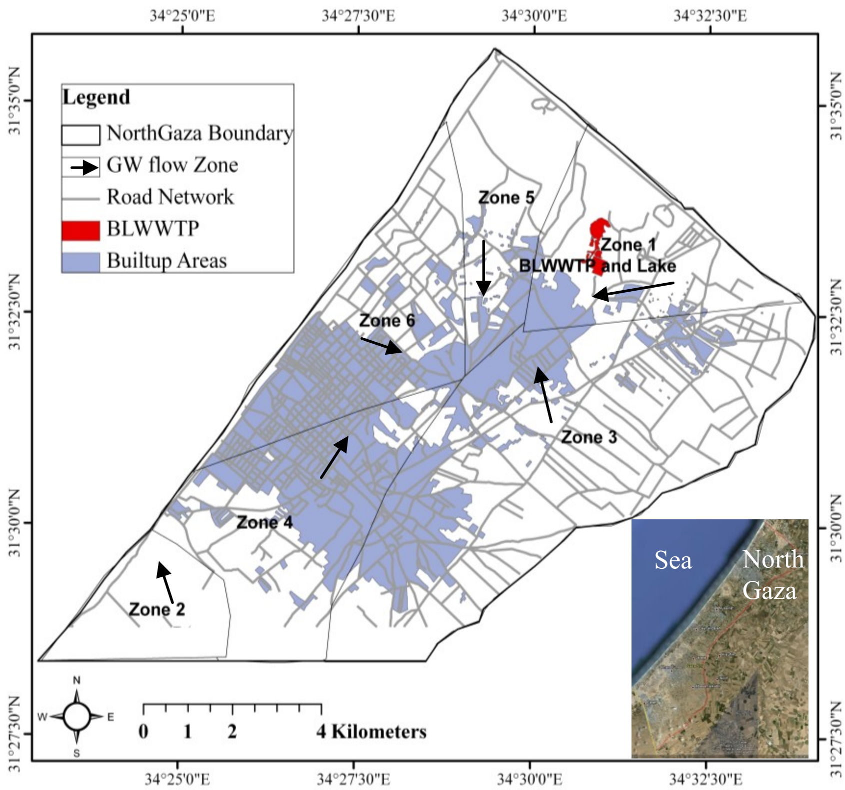


Figure 7.1: Study area map (Data Source: PHG**).** Inset picture from Google Earth**.**

Beyond this distance, to the east, the aquifer is unconfined due to the absence of any clay layers (Qahman and Zhou, 2001; Shomar et al., 2008). The Kurkar Group is the name of the various Pleistocene Epoch deposits that comprise the aquifer and is about 200 meters thick in Gaza City and only 100 m thick in the southern most part of Gaza. The average thickness at the coast is 150-200 m (Shomar et al., 2005b). At the eastern border with Israel, the average thickness is 40-50 m (Qahman and Zhou, 2001). Below the Coastal Aquifer is the Saqiya Formation. This is an impermeable layer 1 km thick and of the Tertiary period. The composition of the Saqiya Formation is marine clay, shale, and marl (Qahman and Zhou, 2001; Shomar et al., 2008). In North Gaza, the GWL in the center of the area is lower than the other parts of the area. So, in this part of the coastal aquifer, the main GW flow direction is towards the center of North Gaza (see Figure 7.1)

7.3 Methods

The overall methodology of the suggested site suitability procedure and evaluation of suitable sites is shown in Figure 7.2. This method is an extended version of the earlier proposed methodology, in Rahman et al., 2010 and in Chapter 6, for site selection. Site ranking using mathematical modeling is done separately and added to the main workflow. The flowchart (Figure 7.2) shows the main decision steps for spatial analysis and hydrogeological assessment. In general, the entire process involves four main steps: (a) constraint mapping, (b) suitability mapping, (c) sensitivity analysis, and (d) site ranking. A brief description of the overall methodology is as follows, after Rahman et al., (2010) (see chapter 6 for details):

The main objective of constraint mapping is to screen out a large number of alternatives, which are deemed non-feasible. This step helps the user to avoid conflicts in decision-making. This constraint map serves as a mask for suitability mapping. In the first step of suitability mapping, all relevant surface, subsurface, and regional characteristics are selected. Each characteristic is defined as sub-criteria. The sub-criteria are grouped under the main criteria. The combination of the main criteria produces the "suitability map," which is the goal of the site suitability mapping. Next step involves the decomposition of the ultimate goal into a three-level hierarchy. The top of the hierarchy is the goal of the analysis/problem. The middle level is more specific criteria of the objective and the bottom level is the most specific criteria. The sub-criteria in the lowest level are related to the main criteria in the middle level. All levels combined are the "suitability map" (see Figure 7.5). The sub-criteria are represented by thematic maps or attributes. The next step in the site selection procedure is assigning values of importance for each criteria and sub-criteria, which is done by assigning a weight to each criterion. Different weighting methods are available. Pair-wise comparison and direct weighting are used here. The sub-criteria under each main criterion are compared amongst themselves and a weight is assigned to each one. The main criteria are also evaluated in this way. Before selecting the final weights at the main criteria level for the overlay, a

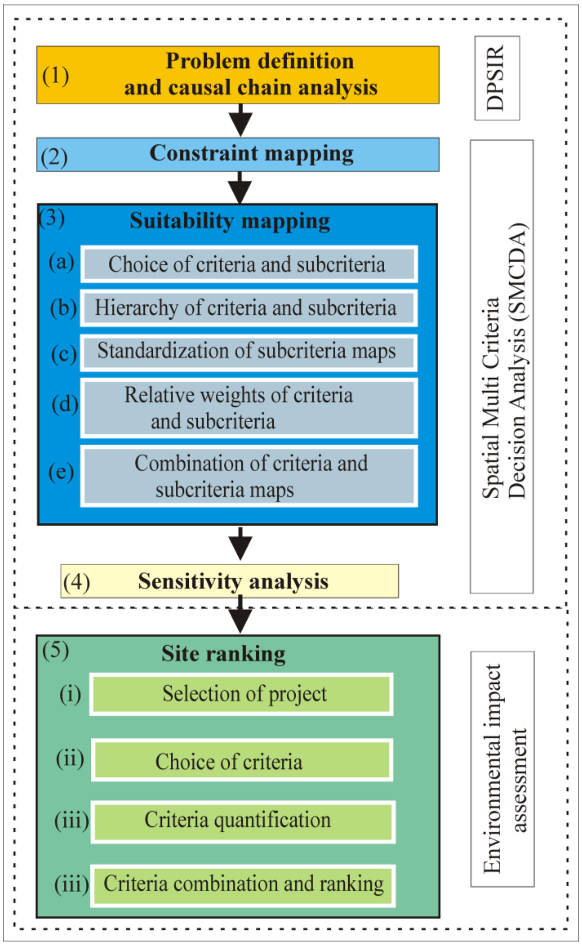


Figure 7.2: Overall methodology

simple sensitivity analysis is performed by changing the weighting. Each step of the sensitivity analysis, one main criterion is given the highest importance and the weights for other are maintained low and equal. In this study we called this procedure as 'scheme analysis'. From the scheme analysis the final weighting and relative importance are selected. As the scheme analysis is a s approach of selecting final weighting of the criteria, it is not included in the flowchart (Figure 7.2) to make the methodology more simple. The maps are standardized using linear and step- wise functions. After standardization and weighting, the next step is to obtain the overall suitability scores (ranges between 0 and 100) of each alternative, which is represented as a cell in the maps. Overlay methods available are Weighted Linear Combination (WLC) and Ordered Weighted Average (OWA) with fuzzy linguistic quantifiers. WLC is the most simple and the most commonly used aggregation method in spatial analysis (Eastman et al., 1993).

$$\text{WLC, } S(x_i) = \sum w_i \cdot s_i(x_i) \quad (9)$$

w_i = normalised weight; $\Sigma w_i = 1$; $s_i(x_i)$ = standardized criteria function/map

OWA is a class of multicriteria combination operators, involving two sets of criteria weights, which are "criteria importance weight" and "ordered weight" (Yager, 1988). The concept of fuzzy linguistic quantifiers, introduced by Zadeh (1983), allows the conversion of natural language statements into proper mathematical formulation (Munda, 1995). In this study, the regular increasing monotone quantifier class was considered. Given the criteria weights w_j, and order weights, the quantifier-guided OWA can be defined as follows (Boroushaki and Malczewski, 2008):

$$OWA_{(i)} = \sum_{j=1} \left(\left(\sum_{k=1}^{j} u_k \right)^{\alpha} - \left(\sum_{k=1}^{j-1} u_k \right)^{\alpha} \right) z_{ij} \quad (10)$$

z_{ij} = weighted attribute value

α = parameter for linguistic quantifier

u_k = criteria weight reordered according to Z_{ij}

j = number of criteria

OWA allows for a high degree of input variability and for the trade-off of importance among input variables (Figure 7.3). When $\alpha = 0$ (linguistic quantifier categorized as "*at least one criterion satisfies*"), the result yields no trade-off and full ORness; when $\alpha = \infty$ (linguistic quantifier categorized

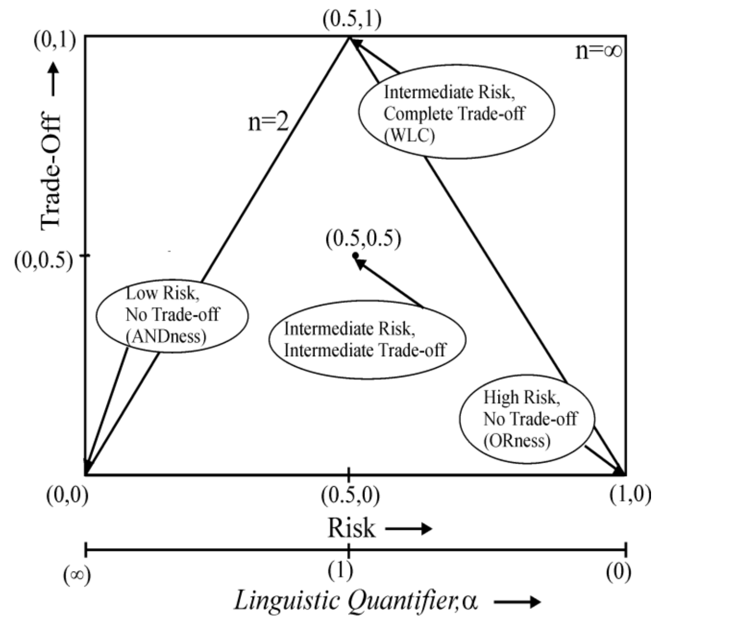


Figure 7.3: The decision strategy space showing the relationship between trade-off and risk, n is the number of criteria (modified from Eastman, 2000 and Malczewski, 2006)

as "*all criteria satisfy*"), the result yields no trade-off and full ANDness. Using an α value between 0 to ∞, yields a range of MCE operators in the decision strategy space. When α = 1 (linguistic quantifier is categorized as "*half of the criteria satisfy*"), the results yields the full trade-off (WLC) (Figure 7.3). The detailed description of AHP combination with OWA is given by Boroushaki and Malczewski (2008).

Based on the OWA concept and fuzzy linguistic quantifiers, represented by an α-value, variations in a sensitivity analysis may be undertaken by the end user in order to study the robustness of the suitability mapping with regards to the fuzzy linguistic quantifier, the α parameter. The model also permits the study of robustness of identified MAR sites with regards to different weighting schemes and standardization. The sensitivity analysis is useful where uncertainty exists in the construction of hierarchy and in the assignment of relative importance (Store and Kangas, 2001).

Depending on the suitability score (ranges between 0 and 100), some locations (designated as 'Project') were selected for environmental impact assessment, more specifically hydrogeological investigation. In this study, a groundwater model was used for a hydrogeological investigation. Based on the hydrogeological investigation, a simple MCA analysis was performed to rank the projects.

7.4 Detailed Description of Analysis

(1) Problem definition and causal chain analysis

The water resource problems that the Gaza Strip faces are immense. North Gaza's, as well as the whole population of the Gaza Strip, face many economical, environmental, and social problems such as desertification, salination of fresh water resources, untreated sewage issues, water-borne disease, soil degradation and most significantly, the depletion of groundwater resources (CIA, 2010). Problems concerning agriculture such as soil salination, aquifer over-exploitation, and groundwater contamination with chemicals such as nitrate have arisen due to inadequate water supplies, absence of water re-use systems such as Managed Aquifer Recharge (MAR), and lack of proper water resources planning. Overall, the mentioned water resources problems are the cause for many of the Gaza Strip's environmental and economic woes. With the aim to analyse the existing water resources problems of the study area, causal chain analysis using the Driver (D), Pressure (P), State (S), Impact (I) and Response (R), in short DPSIR, methodology was used.

The DPSIR concept has been developed for describing interactions between society and the environment (Kristensen, 2004; OECD, 2003), starting from the assumption that there is a causal chain between the two. The strategies, developed by the European Commission for the implementation of the Water Framework Directive, have identified the DPSIR framework as being a convenient way to identify stress factors and their effects on groundwater (OECD, 1993; OECD, 2003). The water resources problems of North Gaza were analyzed, decomposed, and structured in this method in order to find the potential response of the problem. Figure 7.4 shows the DPSIR analysis for the Northern Gaza Strip.

In brief, the water resources system of North Gaza is affected by two main drivers: population and urbanization. These drivers cause certain pressures on groundwater exploitation, wastewater status, land use change, salinization, etc. Consequently, these pressures put impacts on groundwater resources, either by reducing the availability or by deteriorating the quality for further use. The total causal chain on surface water is negligible as there are no surface water resources in the area. Due to scarcity of conventional water resources and availability of effluent water, MAR using treated effluent is considered as the most potential response to the existing water supply problems of the area.

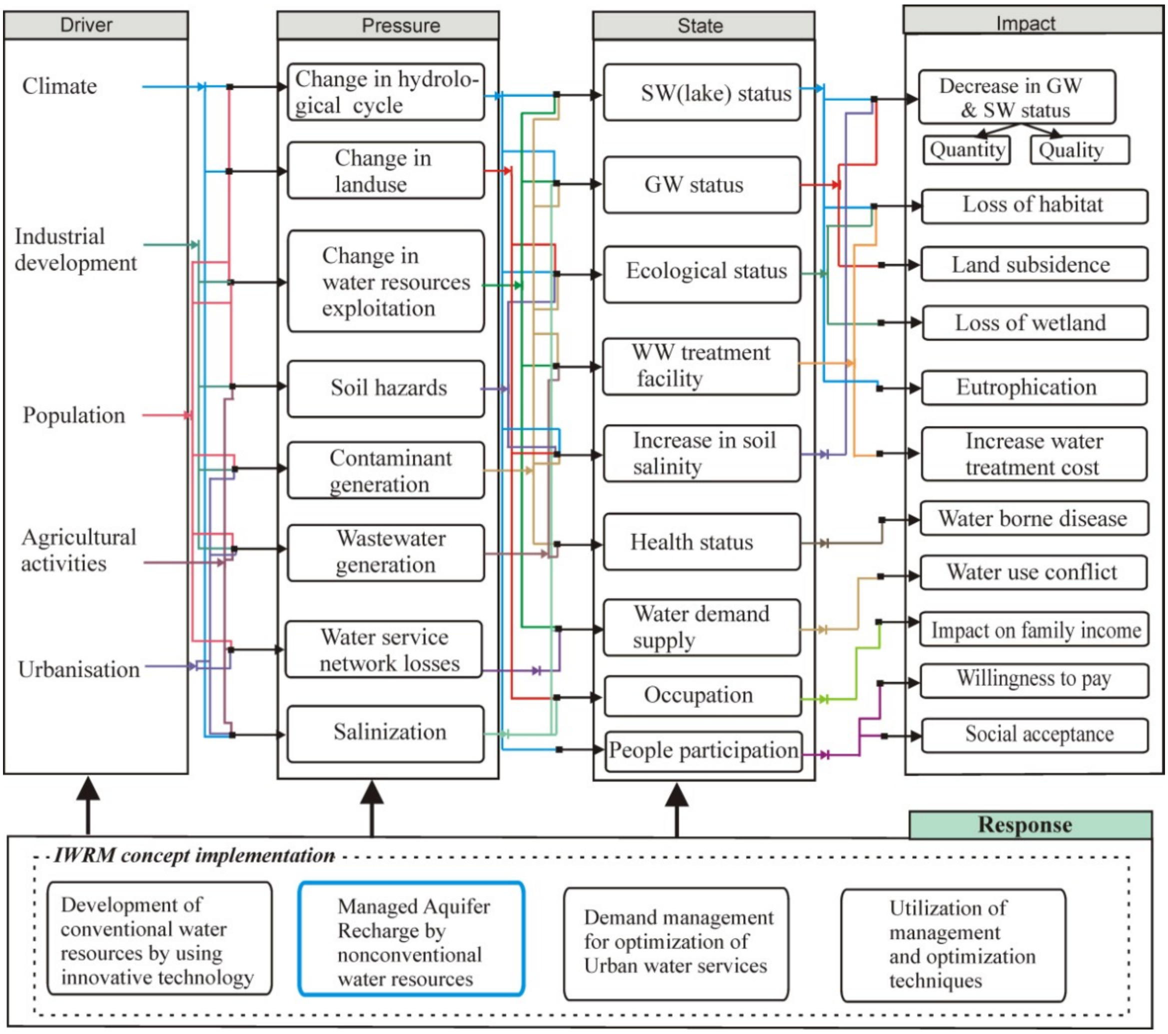


Figure 7.4: DPSIR framework for the Northern Gaza water resources problems

(2) Constraint mapping

The study area is 108 sq km and has been divided into six zones for analysis and discussion, according to the groundwater flow. In order to screen out the non-feasible areas, constraint mapping was performed early on. Table 7.1 shows the list of criteria and their threshold values for screening the suitable places in north Gaza.

Table 7.1: List of constraint criteria together with threshold value

Criteria name	Threshold value	Explanation
Slope	< 3 %	The areas which have less than 3% slope are desirable for MAR.
Groundwater flow zones	Zone 3,4 5, and 6	The groundwater flow zones are considered feasible for MAR as the water from these zones does not pass through the pollution source or does not go to the sea directly.
Land use		Built up area, natural forest, and planted forest are considered non-feasible for MAR.
Aquifer thickness	10 m	The places where aquifer thickness is more than 10 m are considered feasible for MAR.
Distance to the lake	1 km	The places, which are 1 km away from the existing lake (pollution source) are considered as potential areas.
Water table depth	10 m	To get the benefit of soil aquifer treatment, the places where depth to aquifer is greater than 10 m are considered potential areas.

After defining threshold values for each criterion, the thematic map of each constraint criterion was converted to a constraint map using Boolean logic. All the converted thematic maps were overlaid (by conjunctive screening) to have a final constraint map (Figure 7.9). This constraint map was used later as a mask for suitability mapping. All thematic maps were obtained from the Palestine Hydrology Group (PHG).

(3) Suitability mapping

After analysing all available data and site characteristics, the nine sub criteria such as slope, infiltration, nitrate and chloride concentration, aquifer thickness, water table depth, groundwater flow zones, distance to the lake, and cost of effluent transfer, were selected. The sub criteria maps of North Gaza were obtained from PHG.

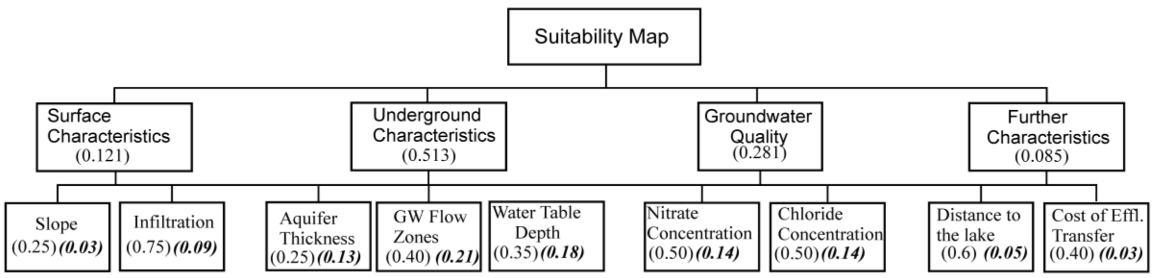


Figure 7.5: Criteria hierarchy and weights (local and global weights are in italic and bold, respectively) for suitability mapping.

The sub-criteria (in other words, the thematic layers) were than standardized. Two value functions, such as linear and step-wise linear functions were used for the approach (Figure 7.6). Each of the main criteria and sub-criteria was assigned a weight according to its importance. The weighted criteria were then overlaid. Weighted Linear Combination (WLC) method was used in this study. Suitability mapping was done in two steps, such as scheme analysis and final suitability mapping.

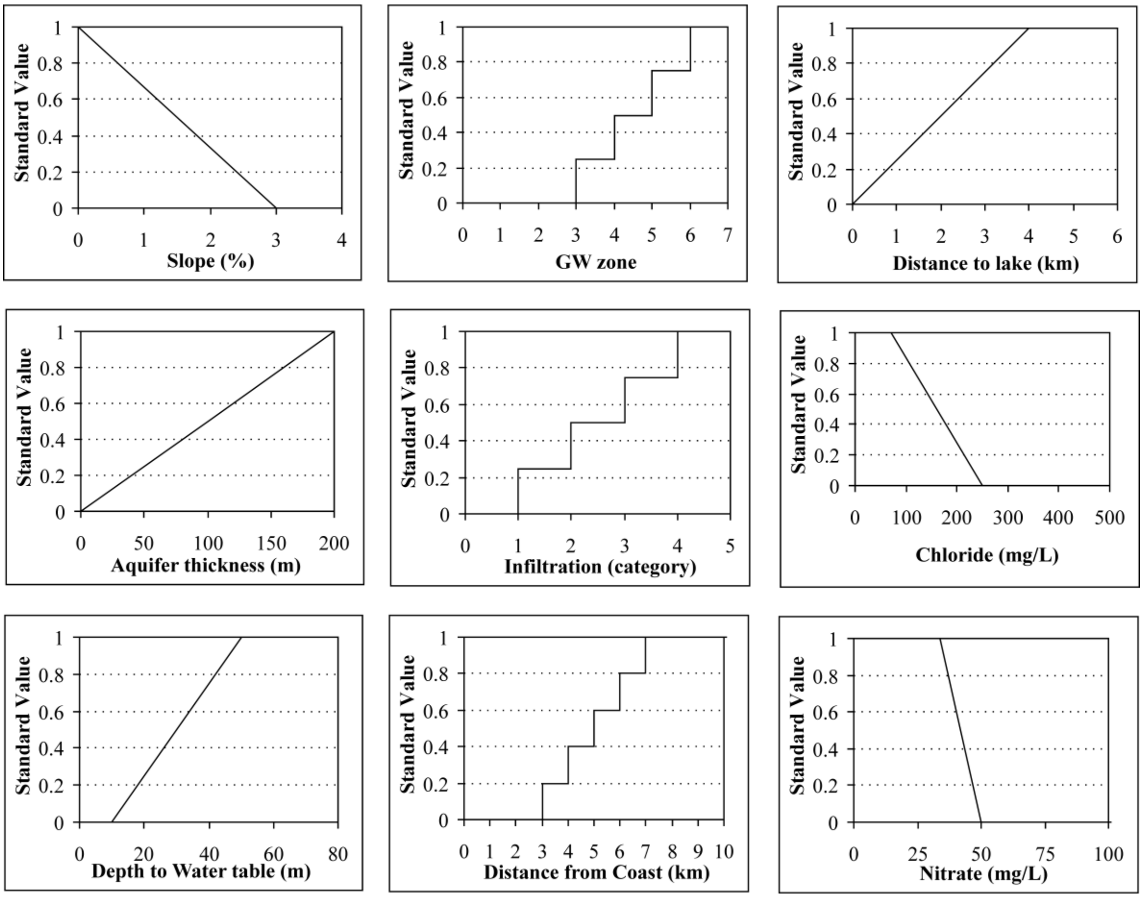


Figure 7.6: The standardized functions, for different sub-criteria, used in this case study

3a.Scheme analysis

Five MAR schemes were prepared by varying the importance of the main criteria. The main objective of the scheme analysis was to investigate the influence of weighting on the site suitability. In general, in each scheme one of the main criteria was given prime interest and the rest were of equal importance. The weights of the subcriteria were maintained as being the same for all schemes. Table 7.2 shows the weights for each main criterion and underlying sub criterion.

3b.Criteria overlay

After checking all results of the schemes, a participative process was undertaken among the local stakeholders and experts. Based on the discussion, a new scheme (Scheme - 6) was developed and weights for the main criteria were calculated by pair wise comparison (Table 7.3 and Figure 7.5).

Table 7.2: Weighting of the different schemes

Main Criteria	Sub-Criteria	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Surface Characteristics		**0. 25**	**0.625**	**0.125**	**0.125**	**0.125**
	Slope	0.25	0.25	0.25	0.25	0.25
	Infiltration	0.75	0.75	0.75	0.75	0.75
Underground Characteristics		**0.25**	**0.125**	**0.625**	**0.125**	**0.125**
	Aquifer thickness	0.25	0.25	0.25	0.25	0.25
	GW flow zones	0.4	0.4	0.4	0.4	0.4
	Water table depth	0.35	0.35	0.35	0.35	0.35
Groundwater Quality		**0.25**	**0.125**	**0.125**	**0.625**	**0.125**
	Nitrate	0.5	0.5	0.5	0.5	0.5
	Chloride	0.5	0.5	0.5	0.5	0.5
Further Characteristics		**0.25**	**0.125**	**0.125**	**0.125**	**0.625**
	Distance to the lake	0.6	0.6	0.6	0.6	0.6
	Cost effluent transfer	0.4	0.4	0.4	0.4	0.4

In Scheme- 6, the underground characteristics were defined as the most significant because the storage capacity of the aquifer and the flow direction of the groundwater are the most relevant criteria for constructing aquifer recharge basins in the study area. The second most important criterion is the groundwater quality, because no already clean fresh water reservoirs should become contaminated by the infiltrated water. The surface characteristics were the third most important, due to small elevation differences; however, infiltration does play a role for the basins. Farther characteristics were ranked as being the least important.

Table 7.3: Pair wise comparison weighting for the resulting final scheme based on WLC.

Main criteria level	Surface characteristics	Underground characteristics	Groundwater quality	Further characteristics	Relative importance
Surface Characteristics	1	$^1/_5$	⅓	2	0.121
Underground Characteristics	5	1	2	5	0.513
Groundwater Quality	3	½	1	3	0.281
Further Characteristics	½	$^1/_5$	⅓	1	0.085

(4) Sensitivity Analysis

Based on the OWA method, a sensitivity analysis was performed by changing the α values of the main criteria. The main criteria and subcriteria importance was kept same as used in the WLC overlay. When α = 1, OWA creates the same overlay as WLC (Figure 7.9). Further, six suitability maps were created based on the following selected value of fuzzy quantifiers; at least one ($\alpha = 0$), at least a few ($\alpha = 0$), a few ($\alpha = 0.5$), most ($\alpha = 2$), almost all ($\alpha = 10$) and all ($\alpha = 1000$) (Figure 7.10).

<u>(5) Site Ranking</u>

(i) Selection of project

Five locations here referred to as MAR 'Projects', with high suitability scores (72-78) were chosen (Figure 7.9) within North Gaza. In addition to the five projects, one project that has a relatively low suitability score (49-51) was also considered for evaluation in order to check the hydrogeological impact and compare with other projects. This comparison, comparing project that has high suitability score with a project that has low suitability score by hydrogeological impact analysis, will give an in-depth idea of the spatial analysis methods implementation for site selection. Six environmental criteria that mostly represent the hydrogeological condition of the north Gaza strip were selected for project comparison by MCA (Table 7.4).

(ii) Impact assessment

Groundwater Model:

A transient groundwater flow model was developed using visual Modflow software (v.2009; SWS, 2009) and its integrated modules, were used to quantify the six environmental criteria in this study. Visual Modflow uses the finite difference code of MODFLOW (Harburg & McDonald, 1988). The three integrated modules, namely MODFLOW (groundwater flow model), ZONE BUDGET (water budget within user defined Zones), MT3DMS (Solute Transport) were used in the study. Relevant data and GIS maps to develop the model were obtained from PHG. The model area was discretized into a grid of 100 by 100 m square cells enclosing an area of 191.28 km^2 in the northern part of the Gaza Strip. The model domain was made larger than the area of interest to minimize the effects of model boundaries on the simulation result (Figure 7.7). The aquifer of North Gaza is unconfined and phreatic. One aquifer system was used in the study.

Aquifer properties such as hydraulic and vertical conductivity, specific yield, and storage coefficient were defined initially from the report EMCC, (2006). K_{xy} was set with a value of 50 m/day in the proximity of the proposed infiltration site and 30 m/day in the rest of the model domain. K_z was set for one tenth of K_{xy}. S_y was considered to be 0.2. Effective porosity (n_e) and total porosity were set to be 0.25 and 0.35, respectively. Little adjustment for the above mentioned parameters were made during the calibration of the transient model. Initial conditions in terms of groundwater hydraulic heads were specified for the model. Existing hydraulic heads of the monitoring wells were used to generate an initial condition contour map. Initial groundwater level varied 2.66 m to –3.41 m. The boundary conditions for the model are as follows: North and South – no flow boundary; West -

constant boundary (0 m above sea level (ASL)), and East - constant head boundary, varying from 10 m in the south to 19 m ASL in the north. The bottom and upper boundaries are no flow boundaries. For the model simulation, the water requirement and abstraction data from the years 2000 to 2003 were used. There are 1,061 abstraction wells within the model domain; out of these, 45 are domestic wells. The abstraction data were obtained from PHG.

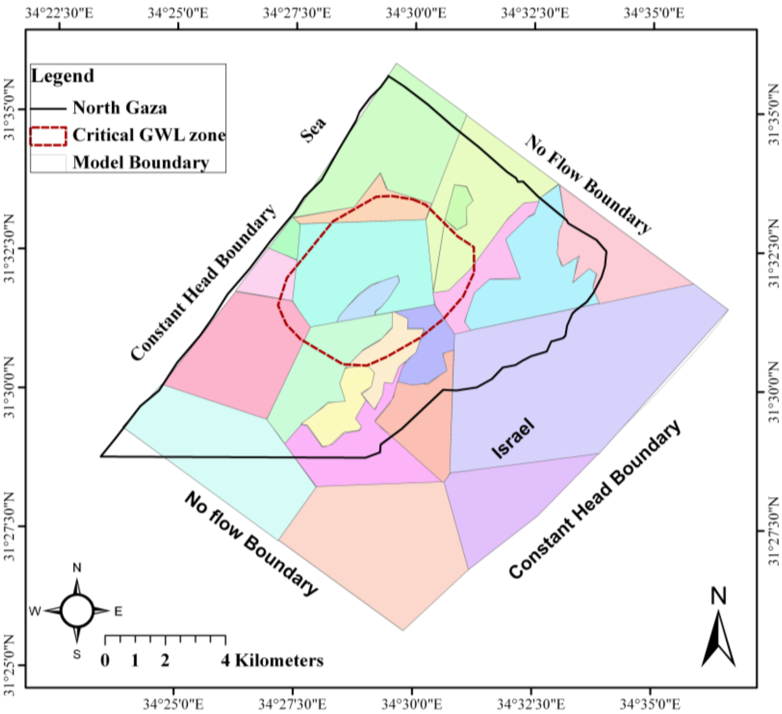


Figure 7.7: Model boundary and the North Gaza area showing the recharge zones used in the flow model.

As usual, rain contributes the major portion of natural recharge in North Gaza. Besides rain, irrigation return flow (25% of the agricultural use) and recharge from domestic use (30% of the domestic use) were also considered. The simulation period data were taken from the years 2000 to 2003. The model was calibrated against the observed groundwater level data at five monitoring wells. Figure 7.8 shows two example of calibration plots.

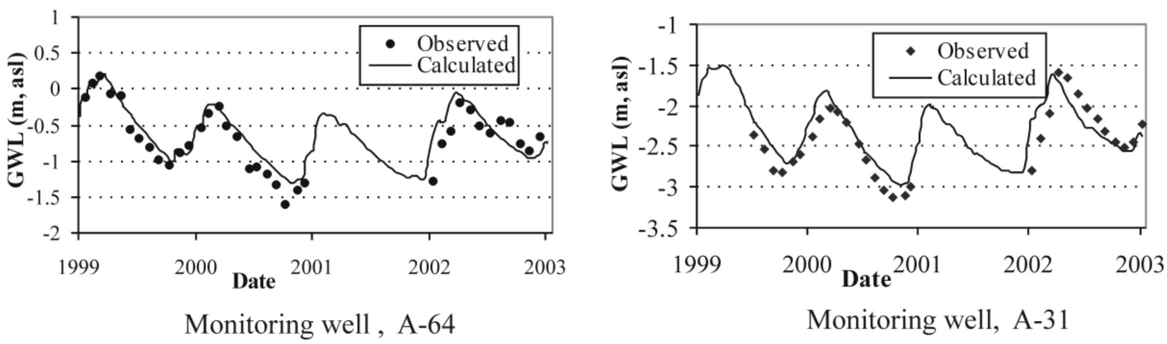


Figure 7.8: Two exemplary calibration plots.

Simulation of groundwater model for project evaluation criteria quantification:

The calibrated flow model was run for the duration of years 2003 to 2040. The calibrated parameters were maintained the same for the whole duration. Agricultural abstractions were maintained the same but domestic abstraction was changed, adjusted for the projected future increase in demand. The maximum limit of projected abstraction rate for each domestic well was taken as 4,110 m^3/day (data source PHG). The impact on the GWL was estimated, considering the most GWL depleted areas, where GWL is -2 m to -4 m ASL (see Figure 7.7, 'critical GWL zone'). Infiltration pond infiltration rate is assumed as follows: infiltration starts in 2008 with a rate of 9.7 Mm^3/year, steadily increasing to 2025 at a rate of 0.8 Mm^3/year (from Sadah et al., 2009b). From the years 2026 to 2040, the infiltration rate is assumed to be constant at 23.7 Mm^3/year.

(iii) Project evaluation and ranking

A simplified MCA was performed in order to rank the projects. Table 7.4 gives the overview of the selected criteria.

Table 7.4: List of criteria with brief description

Criteria and group	Criteria description	Explanation
Criteria 01	Average inflow from Israel to North Gaza (Mm^3/year) within the study period (2005-2040).	Identifies the relative impact of freshwater flow to the study area during MAR implementation.
Criteria 02	Inflow from Israel to North Gaza (Mm^3) at end of study period (2040).	Identifies the relative impact of freshwater flow to the study area during MAR implementation at the end of the analysis period.
Criteria 03	Average inflow from sea to North Gaza (Mm^3/year) within the study period (2005-2040).	Identifies relative flow from sea to study area during MAR implementation.
Criteria 04	Inflow from sea to North Gaza (Mm^3) at the end of study period (2040).	Identifies flow from sea to study area during MAR implementation at the end of the analysis period.
Criteria 05	Average GWL in study area (m ASL) within the study period (2005-2040).	Identifies the relative development of groundwater level in the most groundwater depleted areas during MAR implementation.
Criteria 06	Average GWL in the study area (m ASL) at the end of study period (2040).	Identifies change in GWL at the most groundwater depleted areas due to infiltration at the end of the analysis period.

7.5 Results and Discussion

7.5.1 Site suitability mapping

The areas which are not feasible for MAR were screened out by constraint mapping. Figure 7.9 shows an example of constraint mapping taking 'Land use map' into consideration. The overall constraint map (Figure 7.10) shows that about 50% of the study area was found to have potential and was thus analysed for suitability mapping. Among the selected criteria, the built-up areas, groundwater flow direction, and pollution zones are main constraints for MAR site selection. It is apparent from the constraint mapping that a large and continuous feasible area for infiltration basin construction exists area near the Israelian border.

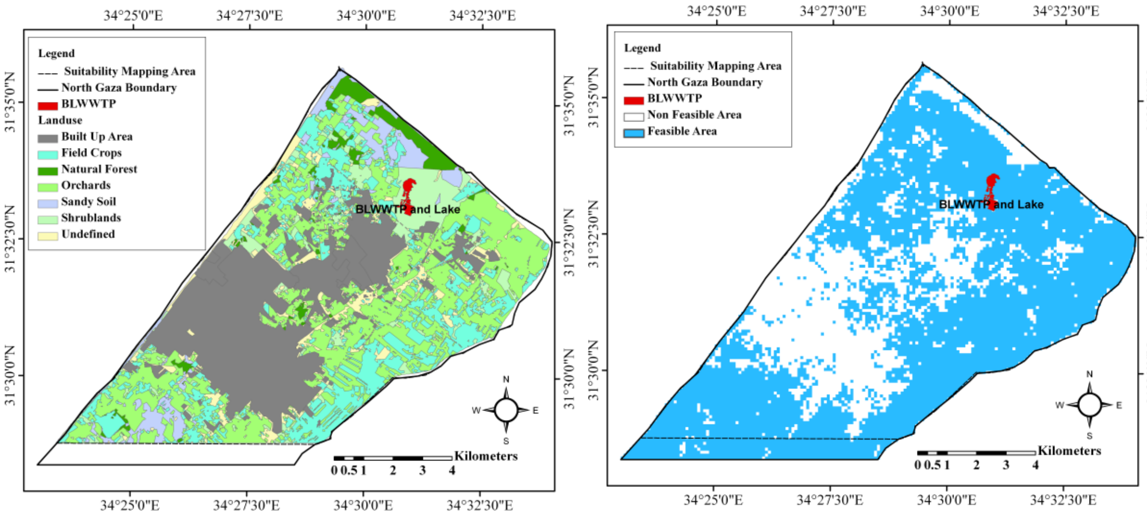


Figure 7.9: Land use map, before (left) and after constraint mapping (right).

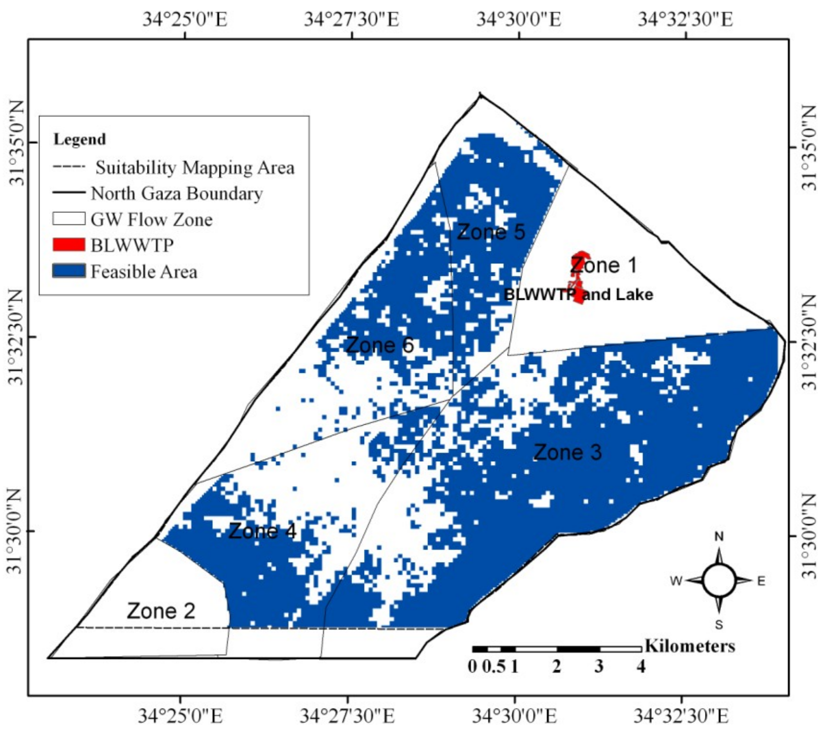


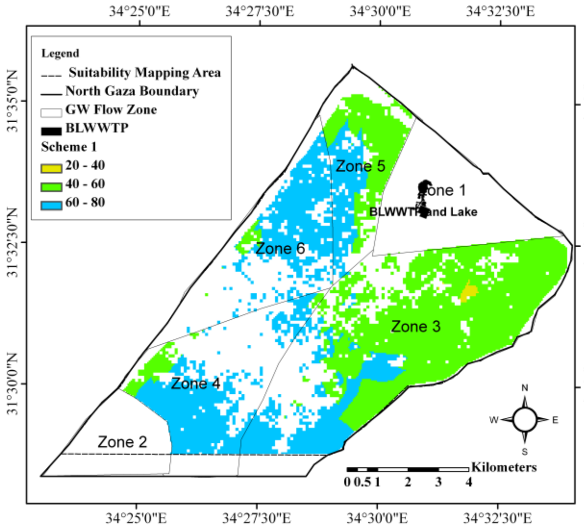
Figure 7.10: Overall constraint map for the northern Gaza Strip

For the suitability analysis, AHP was combined with WLC and OWA overlay methods. The suitability scores are classified as 'very good' (80-100), 'good' (60-80), 'moderate' (40-60), 'poor' (20-40), and 'bad' (0-20). Figure 7.11 shows the suitability maps of Scheme-1 to Scheme-5 and Table 7.5 shows the area distribution of each suitability class under each scheme. The scheme which attaches equal importance to all main criteria (Scheme-1) shows an equal distribution of the total areas that achieve the scores ‘good and ‘moderate’. Factors which contributed to high suitability scores (e.g. ‘very good’ and ‘good’) were desirable surface characteristics (e.g. Scheme-2) and underground characteristics (e.g. Scheme-3). Other than schemes 2 and 3, no other schemes provided areas which were categorised as ‘very good.’ About 45% of the study area was found to be ‘good’ under the condition that underground characteristics of the study area are most relevant for the site selection analysis (Scheme-3). In fact, underground characteristics do control, to a large extent, MAR success. The groundwater quality-dominating scheme (Scheme-4) indicates that fewer areas are highly suitable, though this aspect is quite relevant to the existing aquifer condition of the area. The scheme analysis, in general, shows that a final suitability scheme should reflect the actual importance of the criteria relative to the actual conditions of the field as well as the requirements and relevance for MAR implementation.

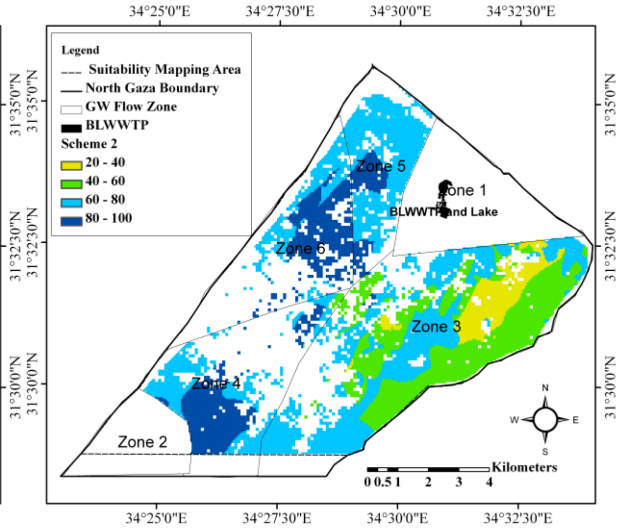
Table 7.5: Area [km²] of the different schemes in relation to the suitability class.

Class	Scale	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Bad	0 - 20	-	-	-	0.01	-
Poor	20 - 40	0.01	1.70	-	27.85	-
Moderate	40 - 60	27.86	15.17	6.62	19.11	33.40
Good	60 - 80	26.13	23.63	45.30	7.03	20.60
Very good	80 - 100	-	13.51	2.09	-	-

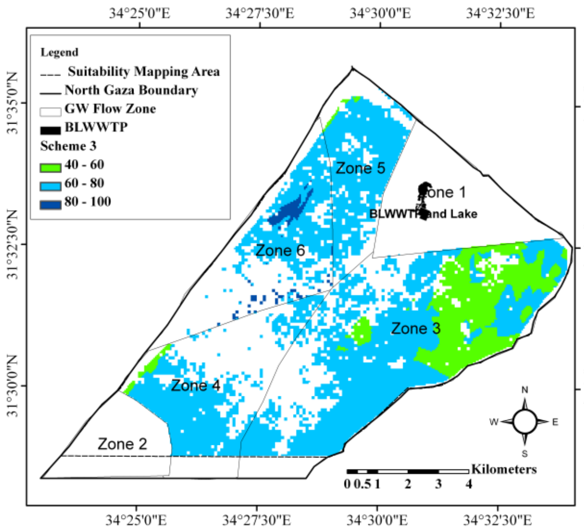
Scheme- 6 (Figure 7.12) represents the final suitability mapping. About 25% of the total study area is classified as ‘good’ for MAR and 25% percent is ‘moderate’. From suitability mapping observations, most suitable places are located near the coast where the soil is highly permeable (data is not shown here) and water flows from the coast to the centre of the study area. Also some ‘good’ locations are seen in south and southeast North Gaza, where scrublands, orchards, and field crops are the predominant land use. The soils of these locations are medium to highly permeable. These places are advantageous because they are far away from the already existing groundwater pollution zone around the lake, deriving from the “Beit Lahia Lake.” The southeast part of the study area is also far away from the coast, so less opportunity exists for flow of infiltrated water to the sea. On the other hand, at these locations, the chloride concentration is quite high (ranging from 559 mg/L to 807 mg/L), which may possibly jeopardise the MAR project in North Gaza. Due to these considerations, selection of one or two MAR project locations is not straight forward even after performing a number of sophisticated spatial analyses, as just described.



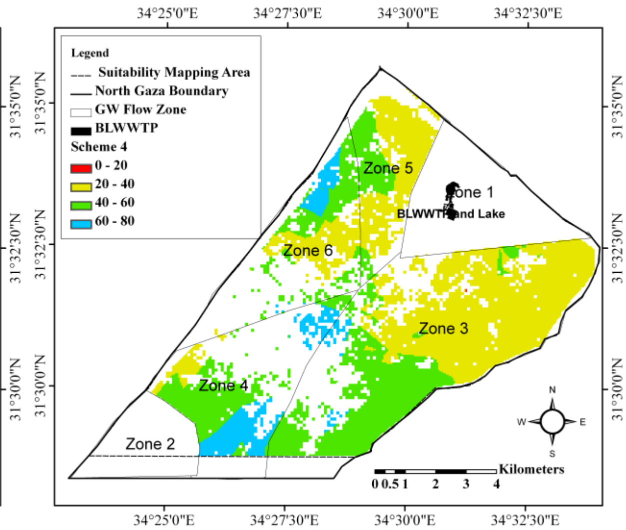
a) Scheme - 1



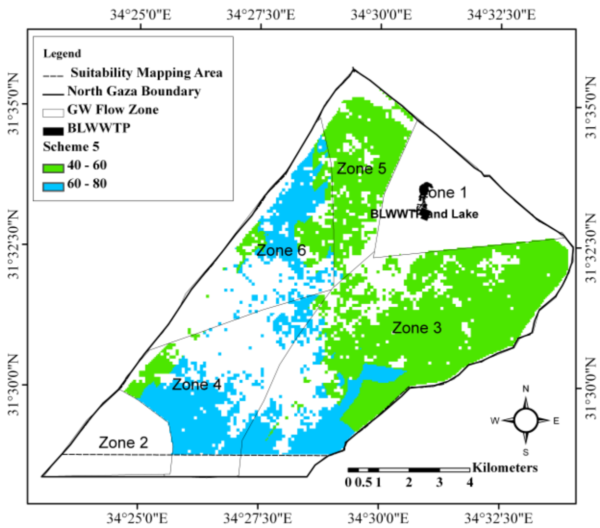
b) Scheme - 2



c) Scheme - 3



d) Scheme - 4



e) Scheme - 5

Figure 7.11: Site suitability maps: Scheme-1 to Scheme-5

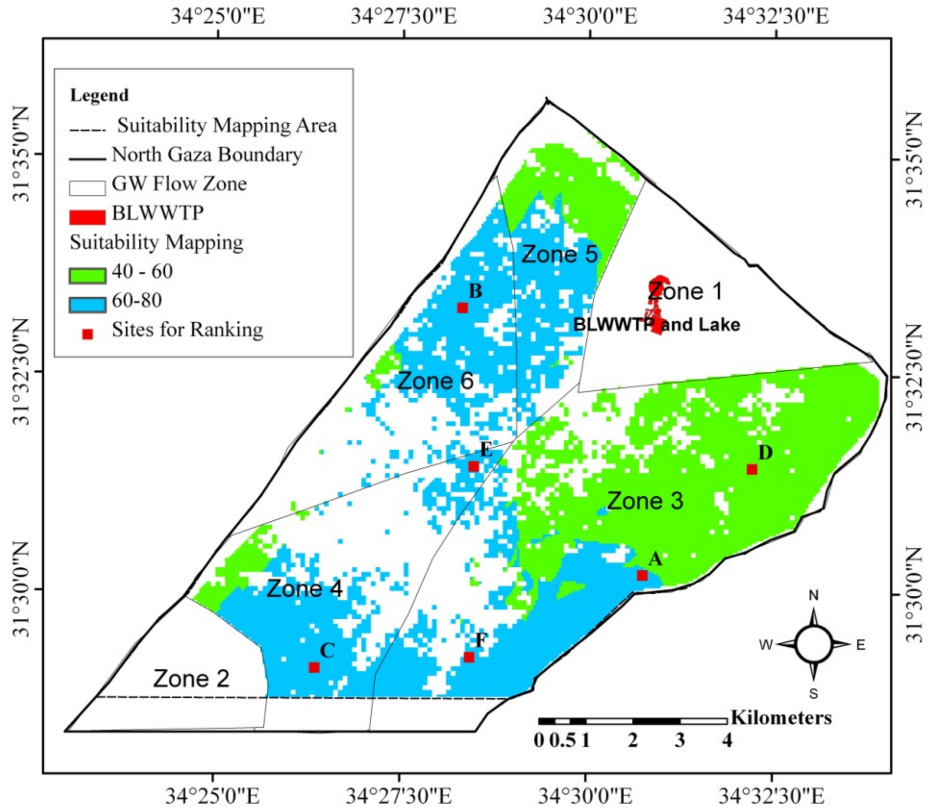


Figure 7.12: Overall site suitability map (both WLC and OWA method) , Scheme- 6

Decision rules on site suitability mapping are made more robust by performing a sensitivity analysis, as described previously. OWA method was used for the sensitivity analysis and the fuzzy linguistic quantifier (α) was used as the variable. Figure 7.13 shows six alternate suitable maps for MAR implementation in North Gaza. Each map is associated with a linguistic quantifier (α) and a measure of trade-off. The suitability map associated with the fuzzy linguistic quantifier 'at least one' ($\alpha = 0$) represents the best case scenario (the optimistic strategy of the decision maker), whereas the fuzzy linguistic quantifier 'all' ($\alpha = 1000$) represents the worst case scenario (the pessimistic characteristic of the decision maker). This means that under the optimistic strategy almost all feasible areas are 'very good' for MAR implementation and under the pessimistic strategy no suitable place for MAR implementation exists. From the six suitability maps, one can easily see how suitable sites for MAR are subjective to changes of decision makers' preferences and specifications, which reflect the inherent aspects, e.g. the integrated and holistic approach, of MAR site selection.

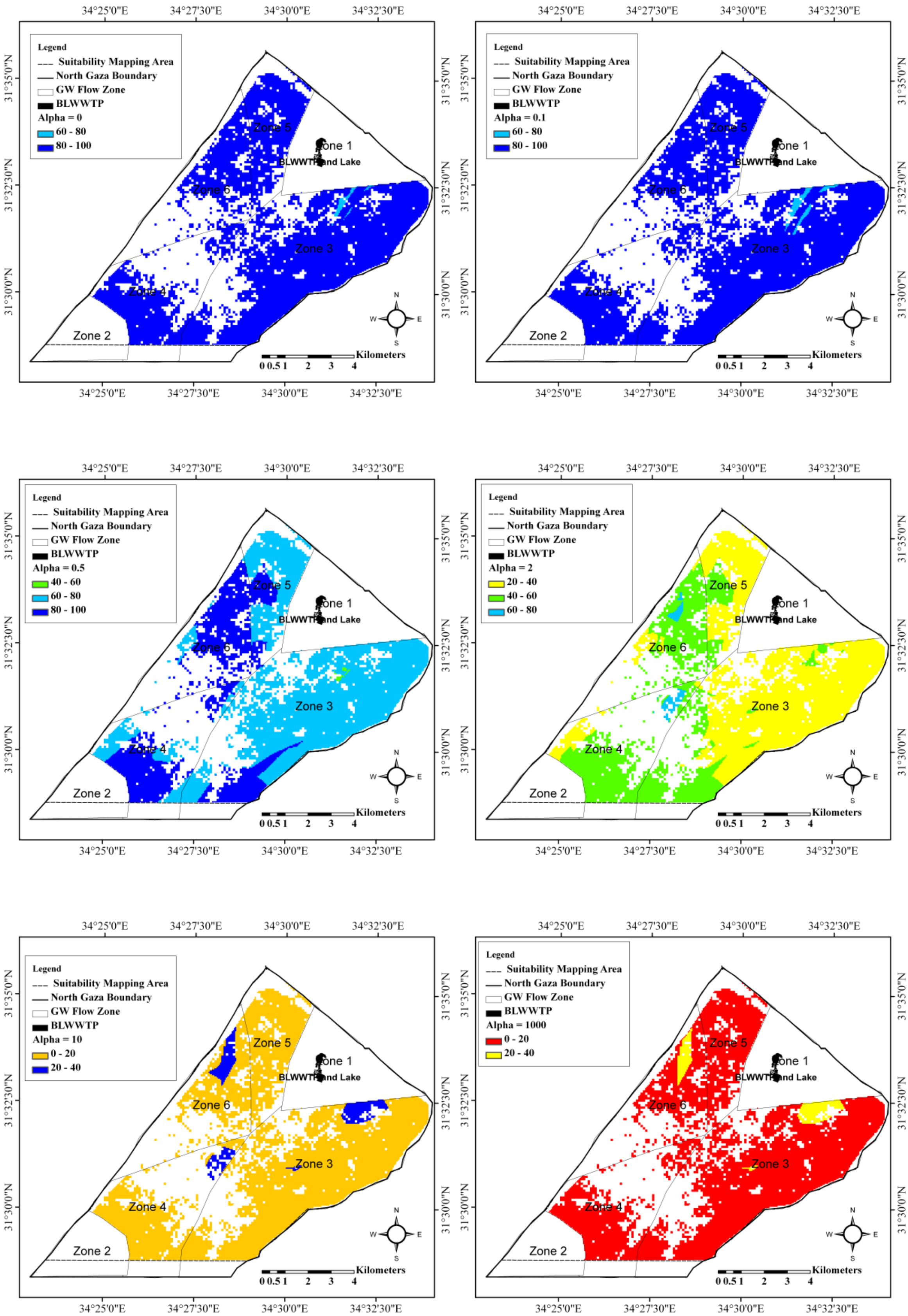


Figure 7.13: Sensitivity analysis using OWA overlay method

7.5.2 Hydrogeological evaluation and ranking of MAR projects

A total of six projects were selected for ranking using the multicriteria analysis (MCA) method. The suitability scores of five projects (A, B, C, E, F) are between 72 and 78 (see Figure 7.10). A sixth projects, D, has a lower suitability score (43-49). The aim of including a lower suitability score location is to compare its hydrogeological performance against the high scored projects.

Three basic factors were considered for ranking the six selected projects. These factors are groundwater level, inflow of freshwater from Israel, and inflow from sea. The positioning of the infrastructure of each project alternative and the corresponding groundwater flow direction has a strong influence on subsequent regional groundwater development. The installation of an infiltration pond near the Israel/north Gaza border may possibly lead to unrecoverable infiltration water losses. Table 7.6 shows the normalised matrix of the quantified criteria for the selected projects. We considered GWL (criteria 5 and 6) as the most important criteria and the importance of the other criteria were kept equal.

Project B, far from the Israelian border, performs best to allow fresh water flow from Israel to the study area (Criteria 1 and 2). In case of Project D, the groundwater mound below and around the infiltration pond, and the groundwater flow parallel to the boarder (Figure 7.14) results in minimal freshwater flow from Israelian area, and is the lowest among the project alternatives. The GWL rise at the centre of the study area is relatively greater by Project E implementation as compared to others projects (Criteria 3 and 4). Project alternative E contributes maximally to halt groundwater flow from sea (Table 7.6). Project B, though located with closer proximity to the sea than Project 'E', has greater groundwater flow toward the sea compared to Project alternative E (Criteria 3 and 4) (see the flow direction in Figure 7.14). Due to the close distance to the sea, Project B losses huge volume of water to the sea. In case of Project E, water inflow from the sea is low due to its contribution to the GWL rise in the entire area, i.e., hydraulic gradient with respect to the sea level is the lowest among the all project alternatives. The flow direction of groundwater under the infiltration condition of Project alternative A, shows that water flows very fast towards the center of study area and contribute substantially towards GWL increase in the study area.

Table 7.6: Normalised matrix of the quantified value of each criteria for MCA

Level 1	Scale	A	B	C	D	E	F	Weight
Criteria 01	'1' indicates best performance and '0' is the worst performance	0.47	1.00	0.48	0.00	0.23	0.65	0.15
Criteria 02		0.41	1.00	0.68	0.00	0.51	0.64	0.15
Criteria 03		0.61	0.95	0.32	0.66	1.00	0.00	0.15
Criteria 04		0.65	0.82	0.00	0.51	1.00	0.23	0.15
Criteria 05		0.94	0.20	0.00	0.75	1.00	0.41	0.2
Criteria 06		1.00	0.05	0.00	0.83	0.95	0.31	0.2

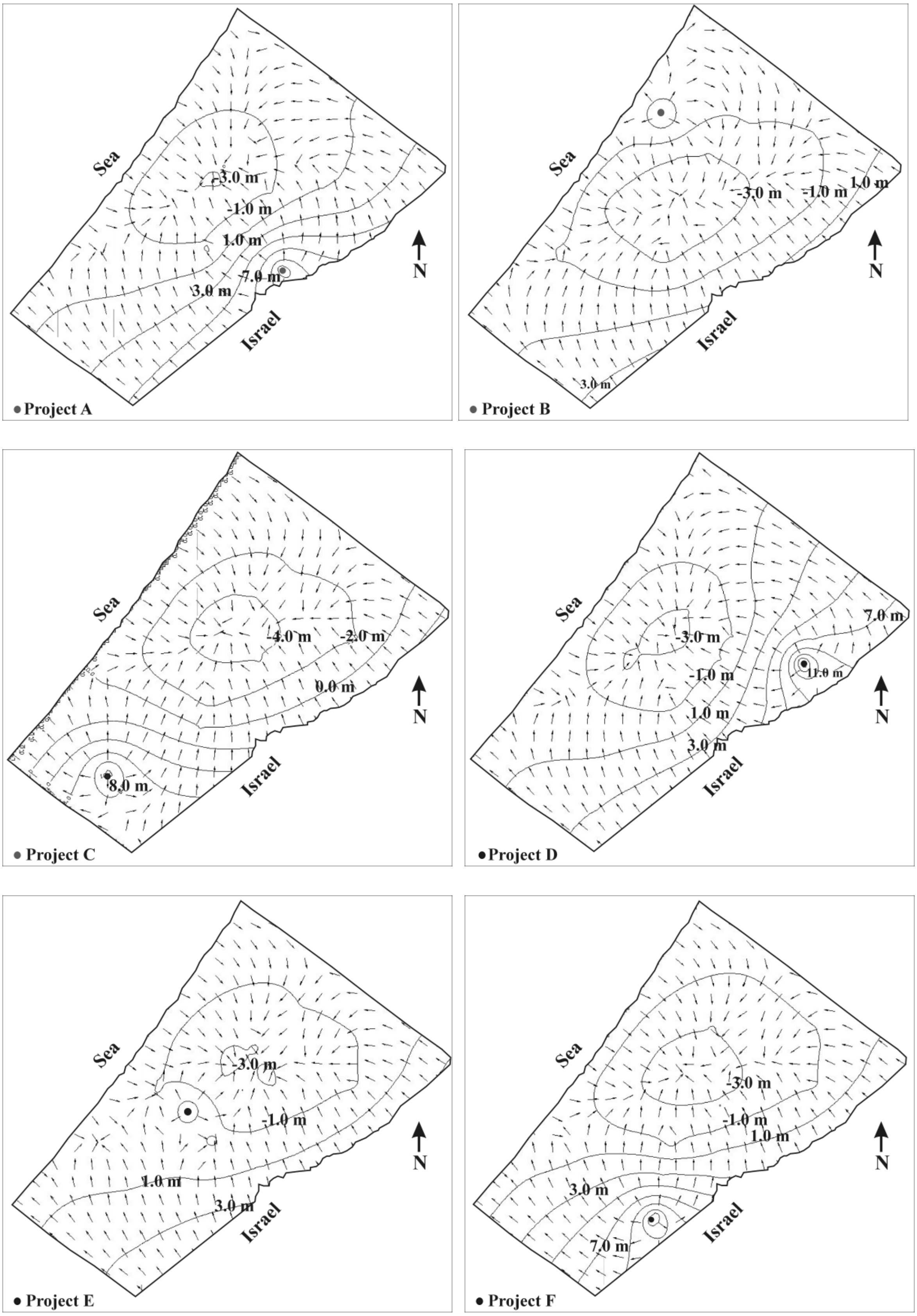


Figure 7.14: Groundwater level and flow direction at North Gaza with respect to the infiltration scenarios of six different locations.

The Project alternative C is located close to the southern border of North Gaza. Groundwater flow from this location is mainly directed seaward (Figure 7.14), making project alternative C not desirable due to the overwhelming proportion of infiltrated water being lost to the sea.

To find the ranking of the selected projects, MCA was performed using WLC. Figure 7.15 shows the performance of the projects. Project E has the highest performance among the six projects followed by Project A, B, D, F, and C. Interesting to observe is that Project D has a better performance over Project C and Project F, though Project D has a lower suitability score. This is due to the direction of groundwater flow, which results in a high GWL increase and water flow from the Sea or Israel. The groundwater level in the study area also controls, due to a change in GWL gradient, the inflow from the sea and the flow from the Gaza/Israel border.

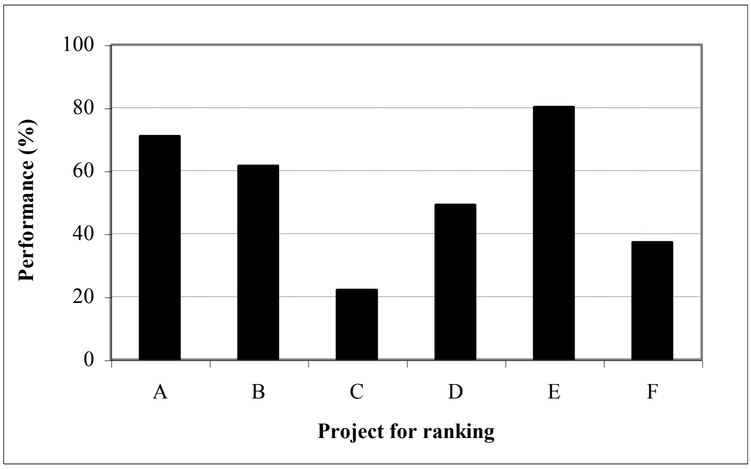


Figure 7.15: Overall ranking of the MAR projects in North Gaza

7.6 Conclusions and Recommendations

In order to assess site suitability for MAR implementation in North Gaza, suitability mapping was performed and ranking of 'very good' locations based on suitability scores was undertaken. A wide range of thematic maps were compiled together with local experts and decision makers' suggestions, reflecting criteria weighting and the large-scale effort involved in conducting a spatial MCA. After screening the non-feasible areas, the combined AHP-WLC spatial MCA shows that the 'good' locations (suitability score 70-80) are located near the coast and southern side of the study area. At the centre of the study area, some places are also categorised as 'good' but space for infiltration recharge facilities might not be adequate there. The 'good' locations are characterised by medium to good infiltration capacity of the overlying soil, enough thickness of unsaturated zone, good aquifer storage, and favourable groundwater flow direction. The chloride and nitrate distribution in the aquifer, used as indicators to represent GW quality in this study, were not always desirable at the 'good' locations. Beside the groundwater level rise and dilution of groundwater, injection of treated wastewater at the places near the coast will be useful to prevent the salinity intrusion from the sea. The location of the existing infiltration ponds, constructed near the new North Gaza Wastewater Treatment Plant, lies on the category ‘good’ according to the suitability scores. The sensitivity analysis, performed by AHP-OWA combined method, simulates the decision maker’s strategies for suitability mapping to implement MAR projects and shows the robustness of the procedure used for this SMCDA. From the six suitability maps (Figure 7.13), one can easily visualize and understand the change of suitable sites for MAR with the change of decision maker’s preference and specifications. So after judging the necessity of the MAR implementation, the decision maker might choose one of the suitability maps, which reflects the decision rule. These might be important in managing conflicting interests among various decision-making aspects and parties. Social-economic criteria related to MAR site selection were not considered due to lack of data.

A hydrogeological evaluation of some selected locations, referred to in the study as ‘Project’, suggests that implementation of MAR projects at the centre of North Gaza, i.e., Project E, is the best option. Overall considerations included, Project E is not recommended due to space limitation for MAR facilities, being close to urban settlements/infrastructure. With this in mind, Project A is considered as being the best option. In fact, a new infiltration pond is already constructed at the site location. Despite having a lower suitability score than Project C, Project D performs hydrogeologically better than project C. This implies that a hydrogeological investigation should be combined with the spatial analysis techniques for site selection to optimise MAR project implementation.

During the hydrogeological evaluation of the projects, no criterion regarding the groundwater quality in the aquifer was considered. Inspite of the better quality of infiltrated water coming from the wastewater treatment plant, this study recommends to perform comprehensive investigation and monitoring of groundwater quality before any MAR project implementation. Besides this, some in-situ parameters, such as soil salinity, organic carbon content, and sediment chemistry can be studied further in order to rank the alternatives according to the efficiency of water quality improvement considering SAT. It is recommended to verify the analysis results by the local project executing institution during the implementation of the MAR project. Nevertheless, this study is one of the pioneer examples for MAR site selection that applies the innovative procedure for spatial multi criteria analysis and evaluates the outcome using a well established mathematical modeling technique. Hence, this approach can be, in general, can be applied worldwide where MAR site selection is required.

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Chapter 8

Environmental, Health, Economic and Social Impact Assessment of Alternative MAR Strategies based on Wastewater Towards Sustainable Development of Water Resources in Northern Gaza

8.1 Introduction

The Gaza Strip, located on the eastern coast of the Mediterranean Sea, is a region facing severe water resource problems. The climate here provides for approximately 200-400 mm/yr of rainfall, with an average of 300 mm/yr, and high temperatures throughout most of the year (Al Agha, 1997). Due to the hot and dry climate, little surface water is available. Water supply relies mostly on groundwater resources located in the Northern Coastal Aquifer of Gaza. This aquifer provides for 97% of the total water to the people of Gaza Strip (Sánchez-Vila and Barbieri 2007). The current rates of abstraction far exceed natural recharge rates, which has lead to a sustained drawdown of the groundwater level over time. Concerns involving saltwater intrusion into the aquifer have risen due to the increased levels of chloride found in the abstracted water. Located at Northern Gaza Strip is the Beit Lahia Wastewater Treatment Plant (BLWWTP), which has been dysfunctional for some time now and is creating severe problems for the public health and the environment (Afifi, 2009). The overloading of the BLWWTP has lead to a complex picture which has complicated the initial problem of groundwater exploitation. The poor management of the BLWWTP and the incomplete treatment and improper disposal of its effluent has caused serious environmental, socio-economic, political and agricultural impacts for people of Gaza.

A three-phase 20-year project involving the construction of a new WWTP further to the south near the Israel boarder and a pipeline connecting the effluent to the new proposed infiltration basin is in progress (EMCC, 2006). The new WWTP will involve Managed Aquifer Recharge (MAR) of effluents and a pipeline connecting the effluent lake and generated water in the northern area to the new WWTP (World Bank, 2008). The Palestinian Water Authority (PWA) along with international support have decided to use practical, already established Managed Aquifer Recharge (MAR) technologies such as infiltration ponds with Soil-Aquifer-treatment (SAT) to replenish the coastal aquifer in order to meet the continually rising demand of water for domestic, industrial, and agricultural use in this water-parched region (Tubail et al., 2004; Nassar et al., 2010).

A number of MAR projects are known to exist in many countries in Europe and Latin America, as well as the USA, Mediterranean countries, the Middle East, South Africa, Australia, and Southeast Asia (Asano, 1985). These projects have been implemented to solve different water resources problems and MAR is considered as an integral part of IWRM. Like the IWRM concept, the objective of MAR is to apply a holistic approach to water resources management problems and its interaction with other sectors of the water resources system, society, and natural processes is inherently strong (Milgrom et al., 2009). Proper planning of MAR projects is important for successful application and can lead to significant risk reduction (e.g., environmental, health etc) and overall project cost reduction by potentially reducing uncertainties during project implementation. Proper planning requires impartiality in the evaluation of MAR options, considering explicit assessment of feasibility and cost–effectiveness (Maliva and Missimer, 2010). During the planning of a MAR project, a number of alternatives and multiple and conflicting criteria need to be evaluated and quantified. A Multi-criteria Analysis (MCA) will be the final phase for the decision makers before arriving to a concrete decision for the option selection (Giupponni et al., 2004). The MCA analysis ranks the performance of alternative decision options against multiple criteria, which must be carefully quantified using different state-of-art tools and methods (Hajkowicz and Collins, 2007).

The following report is on how several strategies for the implementation and management of MAR in the Northern Gaza Strip were quantitatively analyzed based on their potential impacts on agriculture, environment, society, and the economy. All strategies were compared to each other and ranked according to their capability to promote sustainable development at the Northern Gaza Strip. This report also describes the best MAR strategy for the sustainable development of Northern Gaza Strip.

8.2 Study Area

With an area of 365 km^2 and a population of roughly 1.6 million (CIA, 2010), the Gaza Strip is located on the southwestern part of Palestine at the Mediterranean Coast on the edge of the Sinai Peninsula (Figure 8.1). The soil type in the area is mainly Loessial arid brown soil, regosols, sand regosols and arid brown soil. 97% of water used in Northern Gaza is from the Northern Coastal Aquifer (Shomar et al., 2006). This aquifer is composed of Pleistocene marine sand, sandstone, and intercalated clay layers.

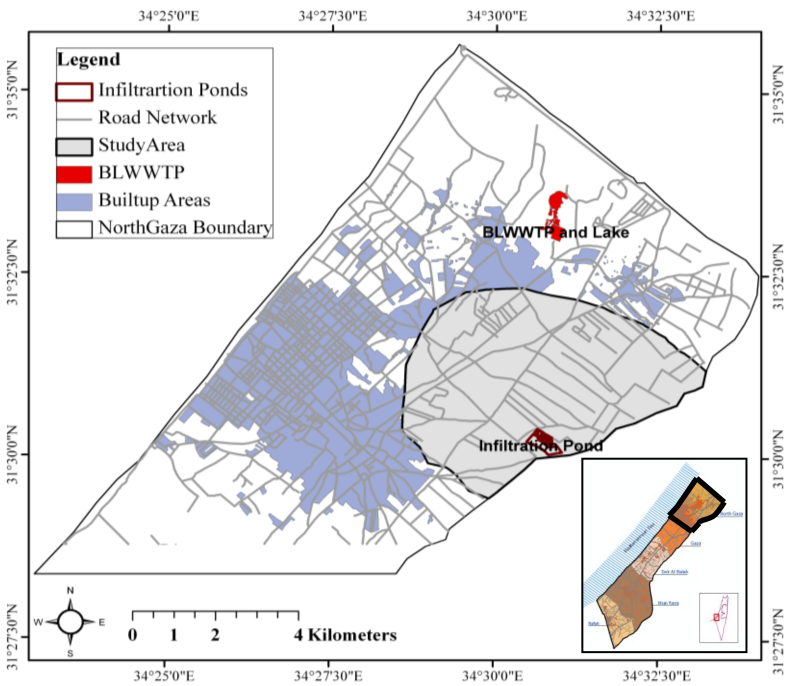


Figure 8.1: Study area map showing the wastewater treatment plants. The new proposed wastewater treatment plant is close to the new infiltration ponds.

Around 1,016 agricultural wells correspond to a pumping of 49.2 MCM/year and 45 domestics wells abstract around 42.3 MCM/year (Rabi et al., 2009). Average natural recharge is 47 MCM/yr. The net groundwater exploitation has resulted in a decline of groundwater level and more brine is being mixed into the aquifer, causing increased chloride concentration with time.

In this study, a part of North Gaza was considered to analyse and compare MAR strategies (Figure 1). This area is the 'area of influence' of the infiltrated water at the end of 2040, considering the infiltration at the new infiltration ponds started at the beginning of 2008. The area was demarcated by using a groundwater flow and transport model. So in the following sections, 'study area' represents the 'area of influence' for infiltration of water using the infiltration ponds near the North Gaza Wastewater Treatment Plant (NGWWTP) (see Figure 8.1).

8.3 Description of Methodology of the Study

The overall methodology of this study is shown in Figure 8.2. The flowchart shows the main steps for the development of strategies and the quantification of selected criteria as well as a multi criteria analysis towards the ranking of MAR strategies for sustainable water resources management plan. In general, the entire process involves three main steps: (a) water resources strategy development (b) criteria selection and criteria quantification, and (c) MCA analysis. A brief description of the application of this methodology at the Northern Gaza Strip is as follows:

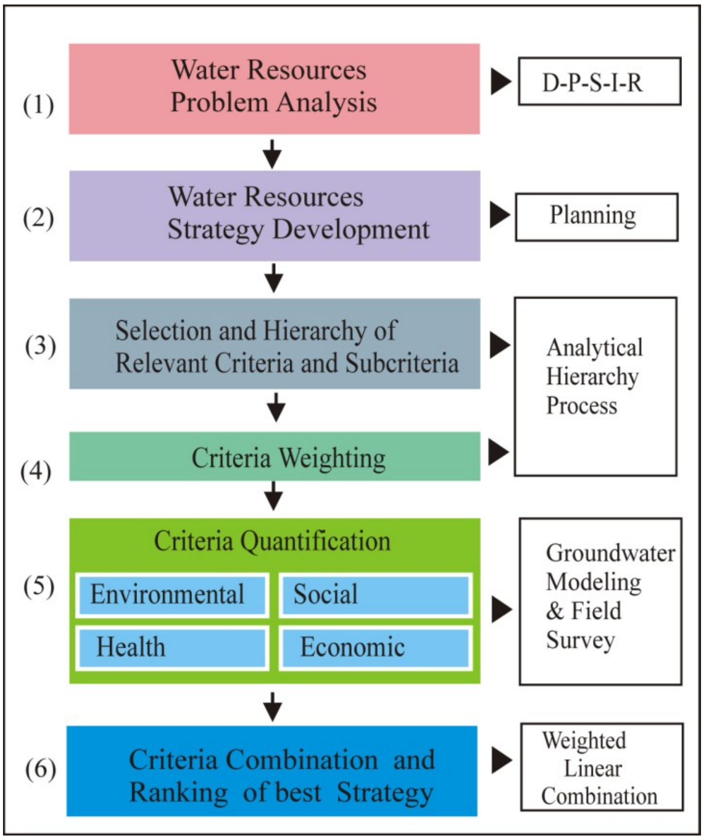


Figure 8.2: Overall methodology of the study

(1) Water Resources Problem Analysis

The water resource problems that North Gaza faces are immense. The people of North Gaza suffer from overexploitation of groundwater resources and pollution due to inadequate wastewater collection, treatment, and disposal. The overexploitation of groundwater resources in the Gaza Strip refers to the unsustainable extraction rate of groundwater from the Coastal Aquifer of Northern Gaza. Currently, the Coastal Aquifer is facing severe quality and quantity problems, which are a result of excessive exploration, resulting in a water deficit between natural recharge and extraction of about 40 to 50 MCM/yr. The water deficit for 2020 is expected to increase to 100 MCM/yr, if the "Do Nothing Approach" to water management in the Gaza Strip is followed until then (Sadah et al., 2009a).

The Gaza Strip faces water quality and quantity problems from the point of view of the unsustainable use of the sole water resource, which is the coastal aquifer. Increased salinity is reason enough for many people not to drink the water. Currently, Gaza's main industry, agriculture, is suffering due to salinization of agricultural wells. Additionally, Gaza suffers health problems due to increasing water pollution mainly by wastewater. This refers especially to infants becoming sick due to bacteria loads into the aquifer (Rusteberg et al., 2010). Currently, major attention is being given by Gaza Strip authorities to combat wastewater contamination as well as decreasing groundwater levels. The contamination by wastewater of North Gaza Strip can be directly linked to the current wastewater treatment system, which exists there. Sewage is collected by a sewer system and piped to the Beit Lahiya (old) wastewater treatment plant (BLWWTP) (Figure 1). Wastewater has been disposed of at the BLWWTP since the late 1970's when the plant was constructed. The initial design of the BLWWTP was for the residents in the municipality of Jabalya (IUG/CDG/ONEP, 2002). At the time 50,000 people lived in this municipality and the maximum wastewater generation was estimated to be 5,000 m^3/day. This volume was the value incorporated into the design of the BLWWTP. Due to the fact that the BLWWTP is now connected to several other municipalities and one refugee camp, the BLWWTP now receives 18,000 m^3 of wastewater per day, over three times the volume of the designed capacity of the system (World Bank, 2008). 180,000 people live in these municipalities which now have their wastewater being treated at the lagoon treatment system, the BLWWTP. These municipalities include Jabalya, Beit Hanoun, Beit Lahiya, Umm Al Nasr, and the Jabalya Refugee Camp (Enshassi, 2000).

The BLWWTP was designed to be a system of aerobic and anaerobic lagoons, without any treatment facility (Alfarra, 2004). Initially, the effluent from the BLWWTP should have been reused for agricultural purposes. Since this has not been realized, the effluent of the final polishing lagoon was to be discharged directly to the sand outside of the BLWWTP compound, owing to the fact that no previously existing surface water bodies were present in the area. With increased population and the loading of the WWTP over its designed limits, effluent slowly began ponding above the sand, due to the creation of a slowly permeable to impermeable layer. Subsequently, the ponds agglomerated and now a lake with the approximate volume of 1.5 MCM is present (Ferreira et al., 2006). The lake is supported by sand dams that have been continuously built up in order to contain the rising water level, making a large area to the west of the lake vulnerable to flooding due to potential collapse of the sand dam (Melad, 2000). The Palestinian Water Authority (PWA), responsible for environmental and health protection has taken other emergency measures in order to avoid inundation of communities within Beit Lahiya. Now, the BLWWTP is blocked due to the height of the lake and treatment is at an all-time minimum. In March 2007, five thousand people were affected and six people died due to a dam break at the BLWWTP (Ferreira et al., 2006). Further use of the BLWWTP is likely to contribute to catastrophes such as the one in March 2007, together with further water quality degradation by faecal matter. Odor emissions from the lake also disturb those who live in the area. Archaeological sites from the Roman-Byzantine Empire exist near the effluent lake and are also endangered by a potential dam collapse (Ferreira et al., 2006; Sadah et al., 2009a).

The poverty level in Gaza is high and many cannot afford the costs of water treatment or desalinisation (Sadah et al., 2009d). Treated wastewater reuse will complement the existing water resources and will improve the water agricultural supply condition. Use of reclaimed water for agriculture will make freshwater available for domestic and industrial use. Hence, MAR is considered a potential response to the current water resources problem in the Northern Gaza Strip.

(2) Water Resources Strategy Development

Based on the water resources problem analysis and considering the water resources management plans for the years 2005 to 2025 (EMCC, 2006; Rusteberg et al., 2010; Sadah et al., 2009a), the following four MAR strategies were established in this study (Table 8.1).

Table 8.1: MAR management strategies towards the development of water resources at the Northern Gaza Strip

Strategy No.	Plan for Water Resources Development	Scenario
Sc-1	Do Nothing	No MAR
Sc-2	Phase 1: Construction of infiltration ponds and pipeline	Use the water from the BLWTTP
Sc-3	Phase 2: Construction of the NGWWTP	Infiltration of better quality water from the new treatment plant
Sc-4	Phase 3: Extension of the NGWWTP	Infiltration of better quality water and increase in infiltration volume from the new treatment plant.

The water management strategies presented in Table 8.1 considers 3 phases in terms of wastewater resources development at the case study area. Strategy no.1 (Sc-1) represents the scenario if nothing has been implemented to the existing water resources structure and no further planning has been considered. Strategy no.2 (Sc-2) is linked with the first phase. This phase considers the diversion of the water from the BLWWTP to the newly constructed infiltration basin, which is located close to the foreseen position of the new North Gaza Wastewater Treatment Plant (NGWWTP) at the Israelian border. The diversion of water will be done by pressure pipeline and the effluent will then infiltrate into the aquifer. Strategy no.3 (Sc-3) considers the scenario if the diverted water will be treated in the NGWWTP and then infiltrated into the aquifer. The effluent quality is better than the water used for infiltration in Sc-2. In Phase 3, the NGWWTP is designed to increase the treatment capacity of around 24 MCM per year in 2025 It indicates in Sc-3, the effluent water quality is better than that in Sc-2. Strategy no.4 (Sc-4) considers infiltration of this extra volume of treated water to the aquifer. In general, Sc-2, Sc-3, and Sc-4 are considered as MAR management strategies.

During the analysis and quantification of all the strategies, the current water withdrawal for agriculture was assumed to be constant. Domestic water demand was assumed to increase, according to the estimated demand increase (after Sadah et al., 2009c). The strategies were evaluated considering a 36-year life span (year 2005- year 2040) of a MAR project.

(3) Selection of relevant criteria and hierarchy construction

A total of 19 most representative decision criteria were selected in close cooperation with Palestinian researchers and authorities as well as further relevant stakeholders. A wide range of indicators were considered for the selection of criteria. The criteria were grouped into four categories, namely environmental, social, health, and economic. Table 8.3 shows the list of criteria with a brief explanation.

Table 8.2: List of selected most representative decision criteria with brief description (modified after Sadah et al., 2009c; Sadah et al., 2009d)

Criteria and group	Criteria description	Explanation
Criteria 01 (Environmental)	The average GWL in the study area (m ASL) within the study period (Year 2005-2040)	This criterion measures the relative development of groundwater level during the MAR implementation in the study area.
Criteria 02 (Environmental)	Average GWL in the study area (m ASL) at the end of study period (Year 2040)	This criterion measures the change of GWL due to infiltration at the end of the analysis period.
Criteria 03 (Environmental)	Average chloride concentration (mg/L) in the study area within the study period (Year 2005-2040)	This criterion measures the relative change of groundwater quality (chloride) during the MAR implementation in the study area.
Criteria 04 (Environmental)	Average chloride concentration (mg/L) in the study area at the end of the study period (Year 2040)	This criterion has been used to reflect the change in groundwater quality (chloride) as a result of artificial recharge at the end of study period.
Criteria 05 (Environmental)	Average nitrate concentration (mg/L) in the study area within the study period (Year 2005-2040)	This criterion measures the relative change of groundwater quality (nitrate) during the MAR implementation in the study area.

Criteria and group	Criteria description	Explanation
Criteria 06 (Environmental)	Average nitrate concentration (mg/L) in the study area at the end of the study period (Year 2040)	This criterion has been used to reflect the change in groundwater quality (nitrate) as a result of artificial recharge at the end of study period.
Criteria 07 (Health)	Average chloride concentration (mg/L) in domestic wells within the study period (Year 2005-2040)	This criterion measures the relative change of domestic water quality (chloride) during the MAR implementation in the study area
Criteria 08 (Health)	Average chloride concentration (mg/L) in domestic wells in the study area at the end of the study period (Year 2040)	This criterion has been used to reflect the change in domestic water quality (chloride) as a result of artificial recharge at the end of study period.
Criteria 09 (Health)	Average nitrate concentration (mg/L) in domestic wells within the study period (Year 2005-2040)	This criterion measures the relative change of domestic water quality (nitrate) during the MAR implementation in the study area.
Criteria 10 (Health)	Average nitrate concentration (mg/L) in domestic wells in the study area at the end of the study period (Year 2040)	This criterion has been used to reflect the change in domestic water quality (nitrate) as a result of artificial recharge at the end of study period.
Criteria 11 (Social)	Social acceptance	Measure the social acceptance to use artificially recharged water for domestic, agricultural and industrial purposes.
Criteria 12 (Social)	Level of convenience	Measures the level of convenience of the public from the MAR strategies. This indicator is a function of a set of sub-indicators (smell, personal safety, noise, attractiveness, comfort).
Criteria 13 (Social)	Satisfaction with available water quantity for different uses	Measures the level of public's satisfaction with the quantity of supplied water.
Criteria 14 (Social)	Satisfaction with domestic water quality	Measures the level of the user's satisfaction with the quality of the domestic water supply.
Criteria 15 (Social)	Contribution to employment	Measures the number of jobs created/lost in agricultural sector.
Criteria 16 (Social)	Contribution to generated income	Measures the increase/decrease in income generated per capita. The indicator measures long-term trends of income generated as result of wastewater reuse in agricultural sector.
Criteria 17 (Social)	Willingness to pay	Measures the public's monetary participation for wastewater reuse for water supply.
Criteria 18 (Economical)	Affordability to pay	Measures the affordability of the users to pay for the agricultural water supply.
Criteria 19 (Economical)	Cost – Benefit	This indicator measures the present value of the net cash flows. It indicates whether the project should be accepted or rejected strictly on economical terms considering direct benefits of the MAR implementation.

Figure 8.3 shows the four-level hierarchical structure of the categories and criteria. The Analytical Hierarchy Process (AHP), proposed by Saaty (1980), is a multicriteria analysis technique that enables the explicit ranking of tangible and intangible factors against each other for the purpose of decision-making or conflict resolution. It combines qualitative and quantitative approaches. This procedure is important for decision problems with a large number of criteria (Eastman et al., 1993). The AHP can be used to combine the priority for all levels of a 'criteria tree,' including the level representing criteria. In this case, a relatively small number of criteria can be evaluated (Jankowski and Richard, 1994; Boroushaki and Malczewski, 2008).

Developing the hierarchical structure (Figure 8.3), obtaining preference information, estimation of relative weight (local and global) by pair wise comparison, and construction of overall priority ranking are the main steps of AHP.

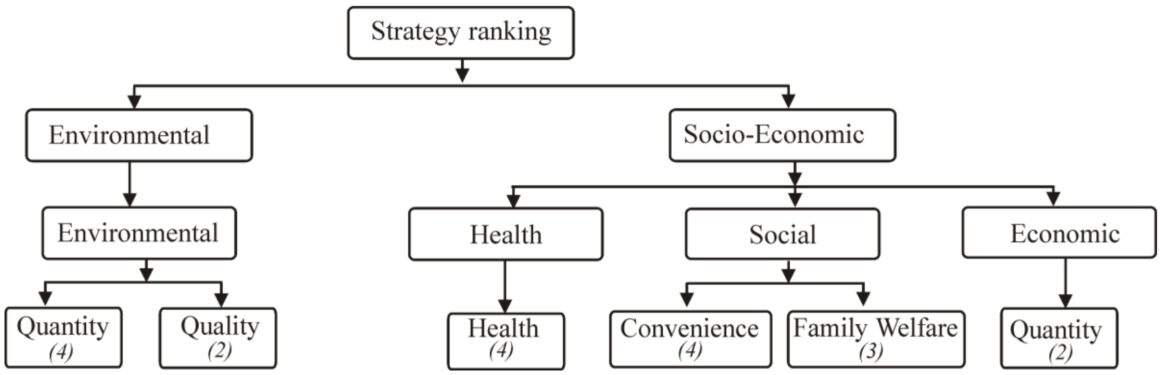


Figure 8.3: Criteria selection and hierarchy. Italic numbers indicate the number of criteria associated to each item at the fourth level.

(4) Criteria Weighting

Relevant importance of each criterion was defined in close cooperation with local scientist, decision makers and stakeholders. Pairwise comparison method, proposed by Saaty 1980, was used to transfer the linguistic importance to numeric value and relative weights were estimated. Net benefit and groundwater quantity (environmental criteria) were considered as most important criteria. At level 2 all four categories were considered equal important for MAR planning and management.

(5) Criteria Quantification

Criteria quantification is a necessary step before any multi-criteria analysis. The selected criteria (Table 3) were quantified using several state-of-art analysis techniques. A brief explanation of the criteria quantification techniques is given below.

Quantification of Environmental Criteria

The selected environmental criteria refer to the groundwater quality and quantity status. These criteria were quantified using a groundwater modeling technique. A groundwater flow and transport model, developed in this case study using visual Modflow (version 4.3, SWS, 2009) and its integrated modules, were used to quantify the six environmental criteria in this study. Visual Modflow uses the finite difference code of MODFLOW (Harburg & McDonald, 1996). The three integrated modules, namely MODFLOW (groundwater flow model), ZONE BUDGET (water budget within user defines Zones), MT3DMS (Solute Transport, Zheng and Wang, 1999) were used in the study. The model area was discretized into a grid of 100 by 100 m square cells enclosing an area of 191.28 km^2 in the northern part of the Gaza Strip. The model domain is taken larger than the area of interest to minimize the effects of model boundaries in the simulation result (Figure 8.4). A detailed description of the model development is given in Chapter 7.

Quantification of Health Criteria

The four health related criteria refer to the water quality status at the domestic water supply wells. The developed groundwater flow and transport model was also used to quantify the health criteria for the analysis. The water quality in the domestic wells depends on the quality of infiltrated water, quality of

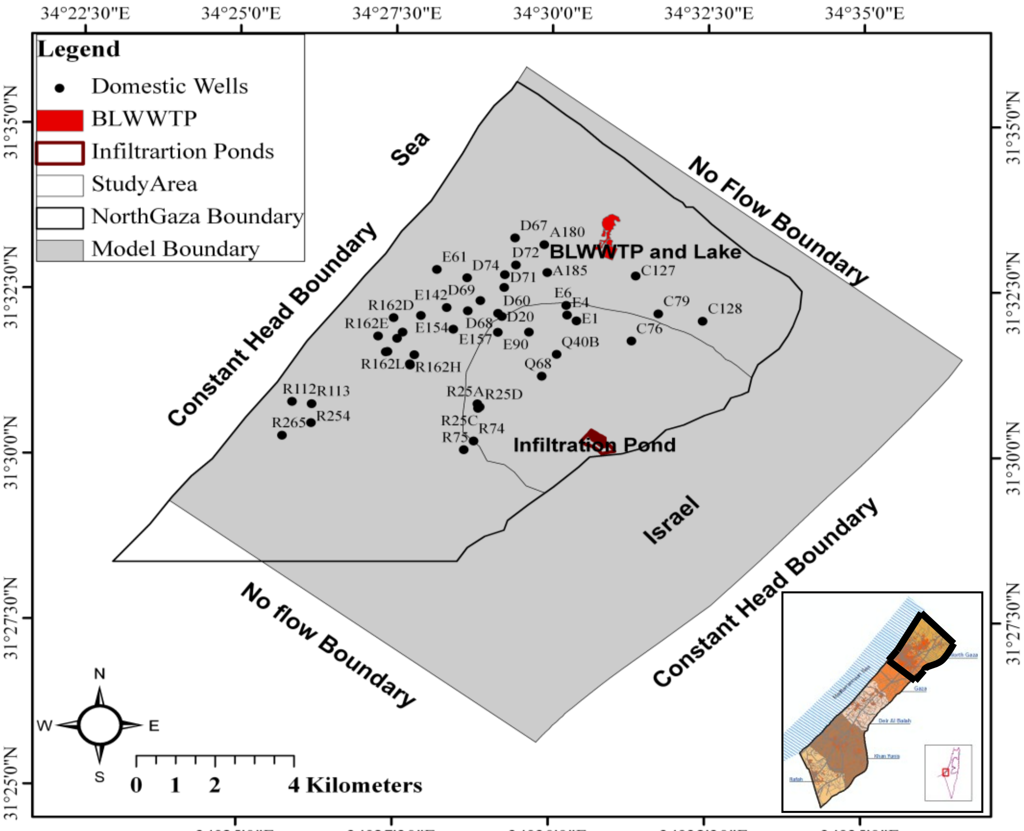


Figure 8.4: Map showing model area, north Gaza boundary, study area, and domestic water supply wells.

native groundwater and the seasons (winter and summer). These three aspects were well adapted in the model.

A brief description of the model simulation for the quantification of the environmental and health criteria is given below:

Model simulation for the environmental and health criteria quantification for different strategies:

The calibrated flow model was run for each strategy for the duration of the years 2003 to 2040. The calibrated parameters were maintained the same for the whole duration. Agricultural abstractions were maintained the same but domestic abstraction was changed during the simulation period.

Chloride: The initial concentration of chloride was taken from the trend analysis, studied by EXACT (2000), considering the data from year 1984 to year 1998. The chloride concentration of the infiltrated water was considered to be the same as that in the wastewater lake at BLWWTP. The chloride concentration used in the model and during the entire modeling period was 250 mg/l (Sadah et al., 2009a). The effect of chloride concentration changes as the volume of infiltrated water changes in different scenarios.

Nitrate: Alike chloride, the initial concentration of nitrate was taken from the trend analysis, studied by EXACT (2000), considering the data from year 1984 to year 1998. The nitrate quality of the infiltrated water was calculated based on the following assumptions (after Sadah et al., 2009c):

Water from the partially treated wastewater lake in BLWWTP (Sc-1 and Sc-2): the Total Kjeldahl Nitrogen (TKN), which was measured regularly, was used to quantify the nitrate concentration reaching the aquifer as follows:

During the summer: the TKN concentration is 75 mg/L (measured) and it was considered that 90% is in the form of nitrate (NO_3-N), i.e. 67.5 mg/L. Also, it was assumed that 20% of the nitrate is denitrified before reaching the infiltration basins and that about 15-20% were considered as additional removal during infiltration. This means that the nitrate concentration of the infiltrated water reaching the groundwater is reduced to 43 mg/L.

During the winter: the TKN concentration is 31 mg/L (measured) and it was considered that 85% is in the form of nitrate (NO_3-N), i.e. 26.3 mg/L. Also, it was assumed that 15% of the nitrate is denitrified before reaching the infiltration basins and that about 15-20% were considered as additional removal during infiltration. This means that the nitrate concentration of the infiltrated water reaching the groundwater is reduced to 19 mg/L.

Water from the NGWWTP (In Sc-3 and Sc-4) : it is assumed that an additional 60% of the nitrate would be removed due the establishment of the NGWWTP, which will be designed for higher wastewater purification capacity. This means that the nitrate concentration reaching the groundwater is 17 mg/L and 7.5 mg/L during the summer and winter seasons respectively.

Table 8.3: Infiltration volume, chloride and nitrate concentration of the infiltrated water used in the groundwater model simulations for the four strategies (after Sadah et al., 2009c)

	Infiltration Water Volume (Mm^3/year)				Chloride (mg/L) in the infiltrated water				Nitrate (mg/L) in the infiltrated water			
Year	Sc-1	Sc-2	Sc-3	Sc-4	Sc-1	Sc-2	Sc-3	Sc-4	Sc-1	Sc-2	Sc-3	Sc-4
2004	Base condition[1]	0	0	0	Base condition[2]	Base condition (559-857)			Base condition[2]	Base condition (20-107)		
2005		0	0	0								
2006		0	0	0								
2007		0	0	0								
2008		9.7	9.7	9.7		250	250	250		19-43	19-43	19-43
2009		10.5	10.5	10.5		250	250	250		19-43	19-43	19-43
2010		11.3	11.3	11.3		250	250	250		19-43	19-43	19-43
2011		12.2	12.2	12.2		250	250	250		19-43	19-43	19-43
2012		13	13	13		250	250	250		19-43	7.5 - 17	7.5 - 17
2013		13	13	13.8		250	250	250		19-43	7.5 - 17	7.5 - 17
2014		13	13	14.6		250	250	250		19-43	7.5 - 17	7.5 - 17
2015		13	13	15.5		250	250	250		19-43	7.5 - 17	7.5 - 17
2016		13	13	16.3		250	250	250		19-43	7.5 - 17	7.5 - 17
2017		13	13	17.1		250	250	250		19-43	7.5 - 17	7.5 - 17
2018		13	13	17.9		250	250	250		19-43	7.5 - 17	7.5 - 17
2019		13	13	18.8		250	250	250		19-43	7.5 - 17	7.5 - 17
2020		13	13	19.6		250	250	250		19-43	7.5 - 17	7.5 - 17
2021		13	13	20.4		250	250	250		19-43	7.5 - 17	7.5 - 17
2022		13	13	21.3		250	250	250		19-43	7.5 - 17	7.5 - 17
2023		13	13	22.1		250	250	250		19-43	7.5 - 17	7.5 - 17
2024		13	13	22.9		250	250	250		19-43	7.5 - 17	7.5 - 17
2025		13	13	23.7		250	250	250		19-43	7.5 - 17	7.5 - 17
2026 - 2040		13	13	23.7		250	250	250		19-43	7.5 - 17	7.5 - 17

[1] Considering no infiltration and maintaining the natural recharge of the base condition used in model simulation 2000-2003.

[2] Considering no infiltration and maintaining the chloride and nitrate source considering the same land use used in simulation model 2000-2003

The strategies did not consider any further withdrawal of infiltrated water for agricultural production; rather we assumed that the stored water, after maintaining the groundwater level that is seen at the end of 2007 (See Figure 8.5), would be available for further recovery at suitable places for irrigation offering water trade-off by leaving more freshwater for domestic use.

Quantification of Social Criteria

All information that were required for social criteria quantification were obtained from Palestinian Hydrology Group (PHG). A questionnaire survey was performed by PHG to get the social aspect of the MAR strategies. The questionnaire was prepared in such a way that it includes criteria that would measure the anticipated level of convenience, perceptions on willingness to use the recharged water for different purposes and the fees that the user would be willing to pay for the supply and the expected level of satisfaction from the quantity and quality of water supplied from each option. A total of 76 questionnaires, after performing a statistical analysis considering the population, were filled out by the locals in the area.

Quantification of Economic Criteria

Cost benefit analysis and other socio-economic factors should be critically analysed prior to implementation of any development project. In our study, two economic criteria were considered (see Table 8.2). Criteria 18 has was quantified using the surveyed data. For Criteria 19 estimation, net cost and benefit, the following factors were considered (modified after Sadah et al., 2009b):

1. The infiltration starts in 2008 with 9.7 MCM of treated water and with an increase of infiltration by 0.08 MCM per year according to the strategies (Table 3).
2. The estimated O & M cost (water transfer, pumping of water, cleaning of infiltration basin etc) for MAR is $\$0.14/m^3$.
3. The cost of abstracting recharged water by wells is $\$0.11/m^3$.
4. The cost of the land for the infiltration basin is $100,000 and was considered at the beginning of 2005, as the ponds were planned to be constructed in this year.
5. The cost of construction of the 9 infiltration ponds and water-pumping infrastructure is $4,000,000 and was considered in the estimation at the beginning of 2005.
6. In this study, the net benefit was calculated based on the amount of water that is stored within the aquifer in addition to maintaining the GWL that is observed at January 01, 2008 (see Figure 5).
7. The net return from the stored water were estimated considering the people's willingness to pay ($\$0.37/m^3$)
8. The discount rate to calculate net present value was assumed to be 10% and will be kept constant over all years of the project.

It was assumed that the installation costs and the water treatment cost of the effluent supply system from the treatment plant would be covered by donor funding. The cost can be recovered by the tariff set for the drinking water supply. The new treatment plant and treatment of wastewater is planned to avoid environmental risk at Beit Lahiya. In the economic model, no cost for wastewater treatment facilities was considered, as the local authority already considered this cost during the economic feasibility of the NGWWTP (EMCC, 2006).

The estimation was done using simple economical model using Microsoft Excel. For net present value calculation equation 1 was used:

$$NPV = \sum_{t=}^{T} \quad t) - \;(t) - \;)M(t)/(1+ \;)^{n} \qquad (1)$$

Here, t is the time after the start of the construction of the project; B(t) are the benefits during year t; I(t) are the investments during year t ; OM(t) is the operation and maintenance cost during year t; i is discount rate (-); T is the time horizon – number of years to be considered for the Cost-Benefit Analysis (CBA); and n is the number of year.

(6) MCA to rank the strategies

The strategy comparison and ranking analysis encompasses two multi-criteria analysis techniques: Analytical Hierarchy Process (AHP) and Weighted Linear Combination (WLC). The role of AHP, mentioned earlier, was to construct the hierarchy and estimation of relative weight after getting the preference information. WLC combines the criteria and provides the ranking. The WLC procedure is described are discussed below briefly:

Weighted Linear Combination (WLC)

WLC is the most simple, and commonly used aggregation method in decision analysis (Eastman et al., 1993).

$$\text{WLC, } S(x_i) = \sum \quad \cdot s_j(x_i) \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; \mathbf{(1)}$$

where,

w_j = is a normalised weight, and $\Sigma\, w_j = 1$

$s_j\,(x_i)$ is the standardized criteria function/map

8.4 Results Analysis and Discussion

Environmental Criteria - Groundwater quantity (criteria 1 and 2)

The calibrated groundwater flow model was used for the long-term simulation of the four strategies. The infiltration rate that was used for the different strategies is given in Table 8.4. The maximum influence area, in Figure 8.4 is shown as ‘Study area’, of the infiltrated water is around 25 sq km taking the full implementation of the phase-III under consideration (Sc-4). The simulations show that the maximum average

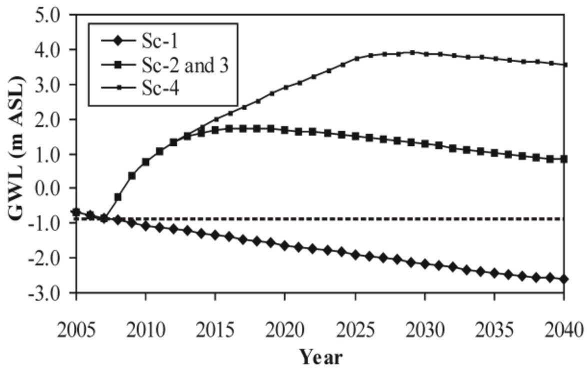


Figure 8.5: Average water level in the study area during year 2005 to year 2040 for the four strategies. The dotted line shows the GWL considering no more mining after 2007. This line was taken as the base line to calculate additional storage made by infiltration strategies.

GWL rise in the study area is 6 m by the year 2028 with respect to 'Do nothing' (Sc-1). At the end of 2040, the GWL are estimated to be –2.61 m, 0.81 m, and 3.57 m for Sc-1, Sc-2 & 3, and Sc-4, respectively. Sc-4 indicates higher groundwater development than the other three strategies. The Sc-1 ('Do Nothing') approach indicates continuous groundwater level mining overtime. The 'zone budget' analysis of the model shows that 3%-5% of the infiltrated water may flow to Israel each year under the simulation condition of Sc-2 and Sc-3, whereas this outflow was estimated 7%-15% per year for Sc-4. The inflow to the study area from the Israel side will be reduced by 20%, 20% and 30% for Sc-2, Sc-3, and Sc-4 respectively. Among the four strategies, simulation results of Sc-4 show better conditions in terms of inflow from the sea to North Gaza. In general, the problem of water flow from sea will remain under control by the infiltration of all MAR strategies.

Environmental Criteria - Groundwater quality (criteria 3 to 6)

Figure 8.6 (left) shows the average chloride concentration in the study area for the four strategies. It is clear from the figure that 'Do Nothing' (Sc-1) strategy will lead to groundwater quality decrease, in terms of chloride, overtime. The simulation result for Sc-4 shows a significant chloride concentration decrease in the study area in comparison to Sc-2 and Sc-3. The model results show the average chloride concentrations at the end of 2040 are 522 mg/L, 426 mg/L, and 400 mg/L for Sc-1, Sc-2 &3, and Sc-4 respectively.

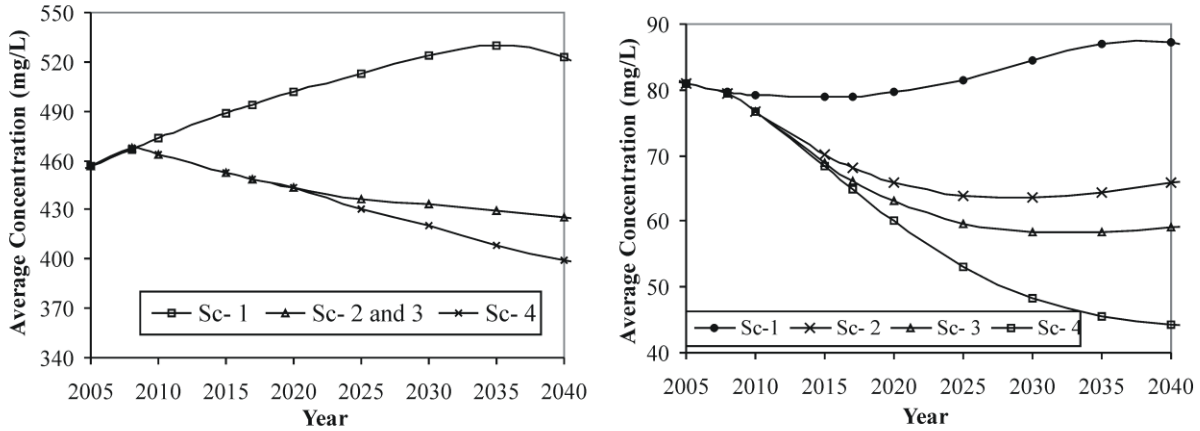


Figure 8.6: Average chloride (left) and nitrate (right) concentration in the groundwater of the study area during the years 2003 to 2040 for the four strategies.

Figure 8.6 (right) shows the average nitrate (expressed as NO_3-N) concentration in the study area for the four strategies. The newly infiltrated water will push away the native groundwater and replace it. So, the nitrate concentration in groundwater at the study area mainly depends on the nitrate concentration in the infiltration water. It is clear from the Figure 8.6 that 'Do Nothing' (Sc-1) strategy will lead to the groundwater quality decrease overtime, in terms of nitrate also. The model results for Sc-4 show a significant nitrate concentration decrease in the study area in comparison to Sc-2 and Sc-3. Dilution and denitrification have been assumed to be the main processes for nitrate reduction in the model simulation. The average nitrate concentrations at the end of 2040 are 82.27 mg/L, 67 mg/L, 59 mg/L, and 44 mg/L for Sc-1, Sc-2, Sc-3, and Sc-4, respectively.

The long-term effect of groundwater flow might also control the groundwater quality in the study area as the distribution of chloride and nitrate in North Gaza and nearby Israel border is complex. The comparatively better quality groundwater possibly enters to the study area from the nearby area due to the change of groundwater flow direction under the MAR implementation strategies.

Health Criteria Quantification

A total of ten domestic wells are located within the study area (see Figure 8.4). The impact of managed aquifer recharge project on domestic wells is very sensitive to the population living in the area. The flow direction of the infiltrated water will impact the domestic wells. By analysing the chloride concentrations in all domestic wells and comparing them with 'Do Nothing' scenario, observations show that the impact on chloride concentrations in all wells will be almost the same. Figure 8.7 shows the average chloride content of the ten domestic wells for the four strategies until the year 2040. In general, a sharp increase in chloride concentration in all domestic wells except Q40B, Q68, and E4 was observed for the three infiltration strategies during the years 2027 to 2030 and then the chloride concentration also decreases sharply (Figure 8.8).

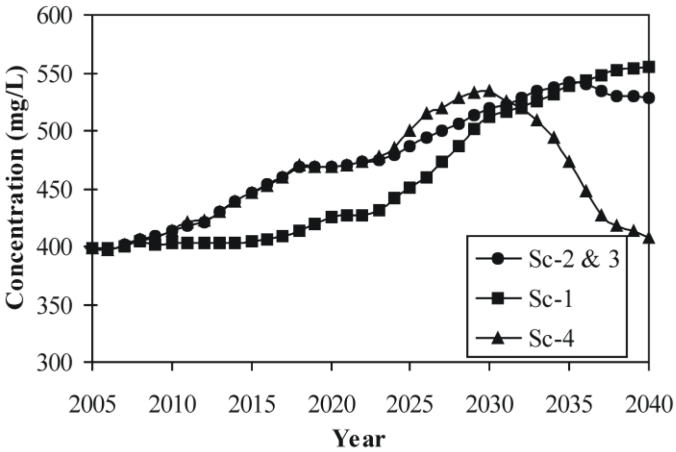


Figure 8.7: Average chloride concentration in the ten domestic wells for the entire simulation period (Year 2005-2040)

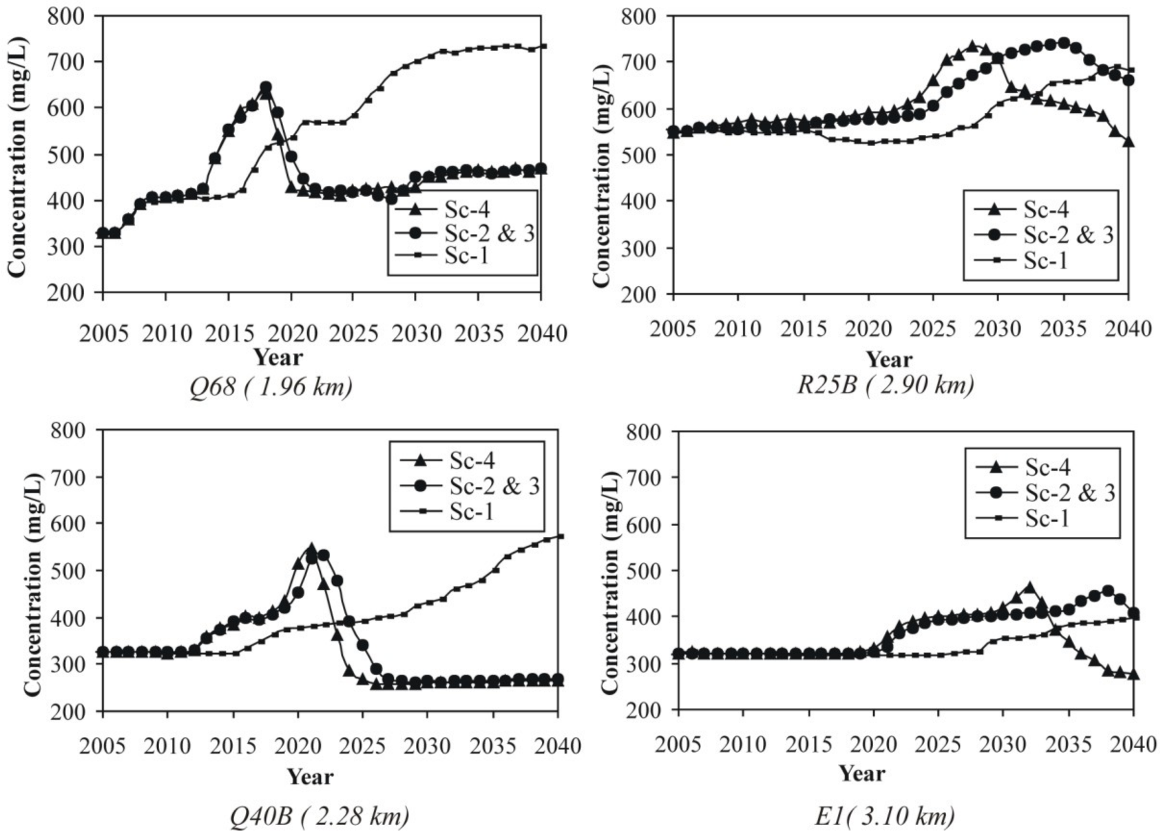


Figure 8.8: Chloride concentration in the selected domestic wells for the whole simulation period (year 2005-2040). The distance of the wells from the edge of the infiltration basin is given in parentheses.

In Q40B, Q68, and E4, the sharp increase was observed at the early stages of the simulation, i.e. the years 2015-2022. The increasing trend in the domestic well chloride concentration is due to the infiltration of wastewater and groundwater flow. In general, the nearby aquifer of the wells and the aquifer beneath the infiltration basin contain higher chloride concentration. So the infiltrated water pushes this water towards the domestic wells and the chloride concentration rises at the wells. Overtime, the infiltrated water replaces the worse quality water and the chloride concentrations at the wells decrease. The nitrate concentration of the places where the domestic wells are located is comparatively higher than the nitrate concentration below the infiltration pond and the infiltrated water (Figure 8.9). The nitrate concentration in all domestic wells will be slightly improved except wells E1, E4, and RC1 (see Figure 8.10). In wells E1, E4, and RC1, the nitrate concentrations will be higher

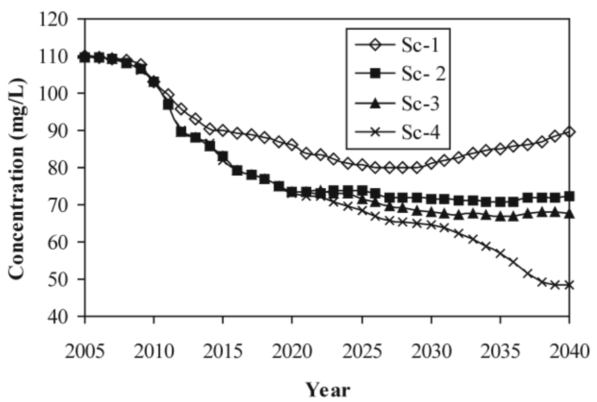


Figure 8.9: Average nitrate concentration in the ten domestic wells for the entire simulation period (Year 2005-2040)

during the period of management (year 2025) because these wells are located in a zone where nitrate concentration is lower than the nearby zone in the direction of groundwater flow. The infiltrated water will push the relatively contaminated water towards these three wells. At the end of the management period, the better quality infiltrated water will reach these two wells and the nitrate concentration will be decreased.

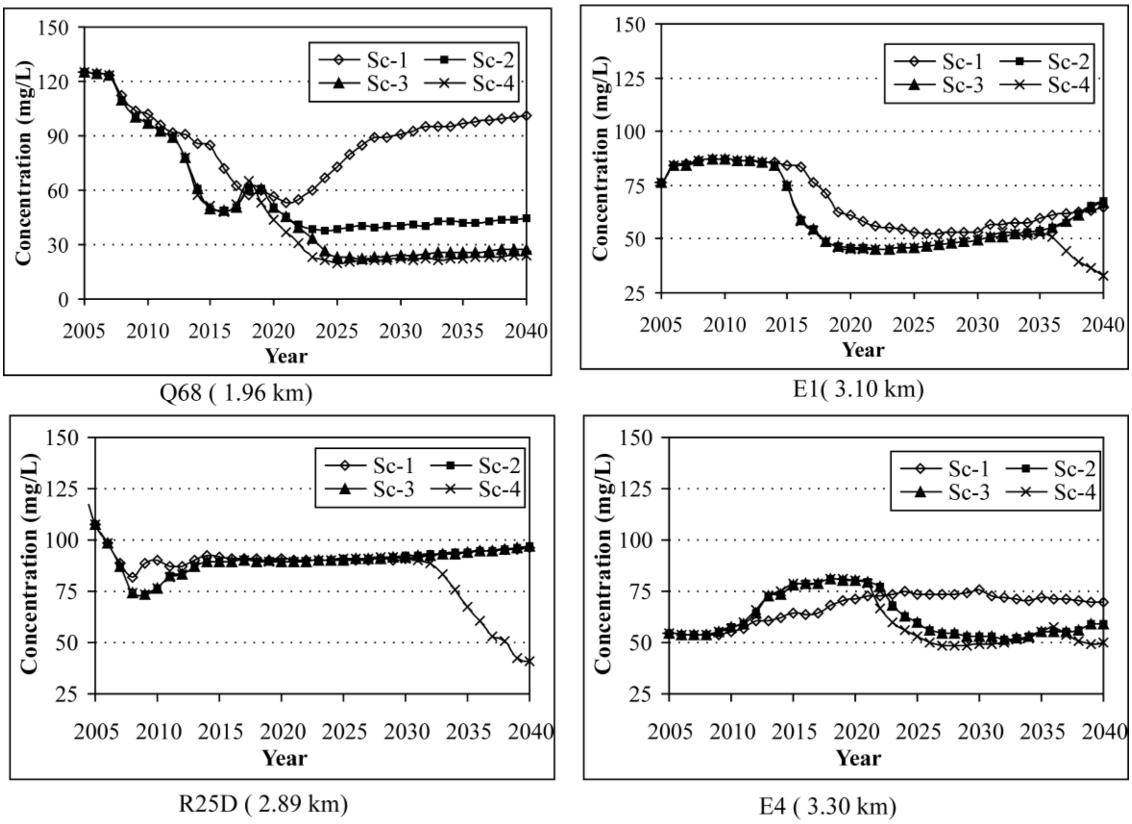


Figure 8.10: Nitrate concentration in the selected domestic wells for the whole simulation period (year 2005-2040). The distance of the wells from the edge of the infiltration basin is given in parentheses.

Social Criteria Quantification

In this study, a field survey was conducted by the Palestinian Hydrology Group (PHG) in order to quantify the social criteria. A questionnaire was prepared and the field survey was conducted in the study area in order to know the social opinions for the different strategies of MAR implementation. In general, the inhabitants are willing to pay more if fully treated wastewater is reused (Figure 8.11). The survey results indicate that the distribution of acceptance and satisfaction of the public is more or less equal between the MAR strategies (Figure

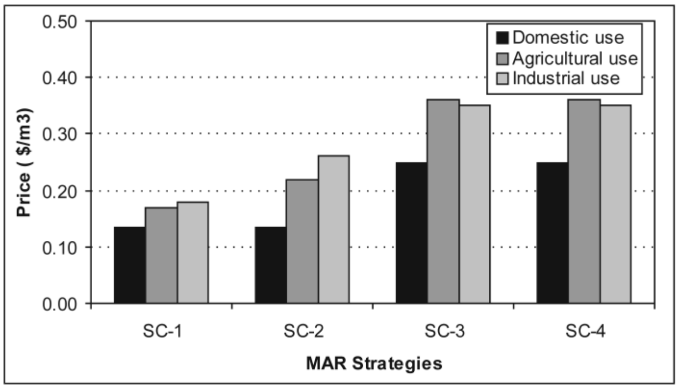
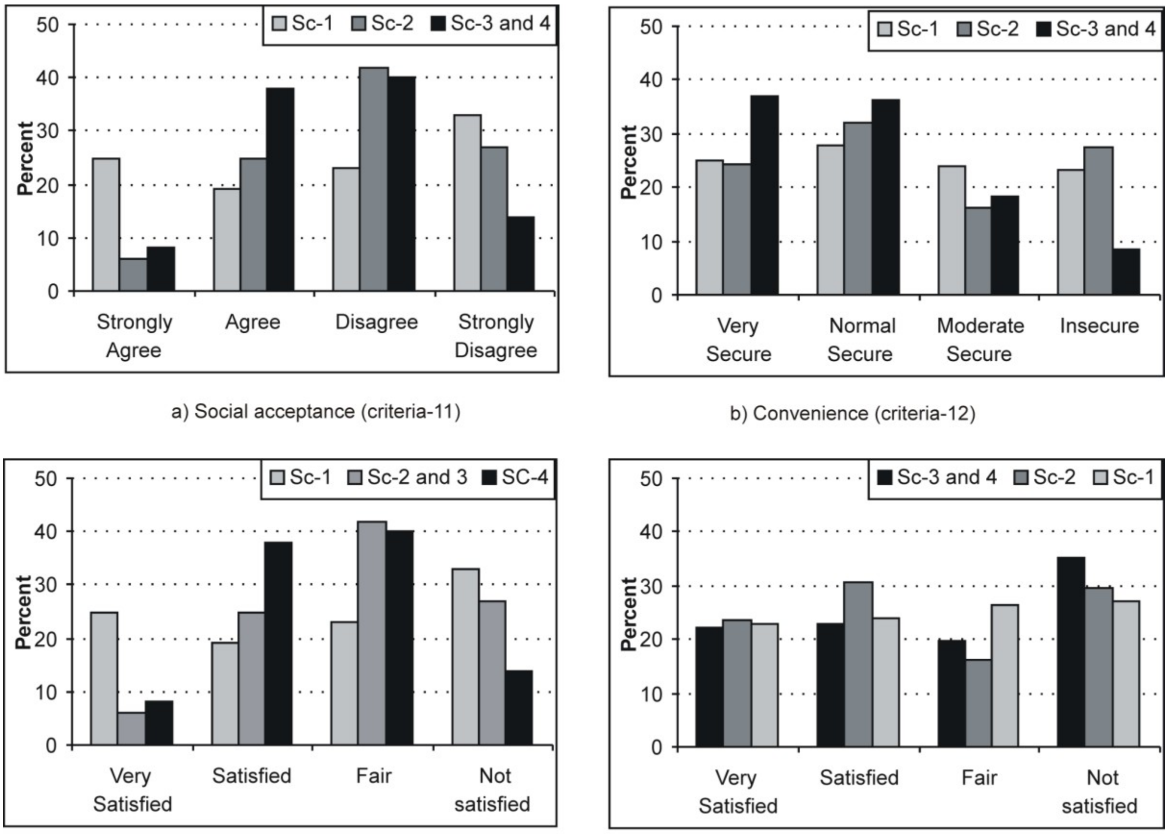


Figure 8.11: Willingness to pay of the respondents for the MAR strategies for different usage

8.12). Results also show that respondents are willing to pay very little for the infiltrated water regardless of use and claim to be able to afford very small fees. Respondents do not agree to use the infiltrated water for domestic purposes but is much more accepting of possibly using this water for agricultural or industrial purposes. The reuse of treated wastewater for irrigated agriculture would save fresh water for drinking water supply and subsequently may solve some environmental problems. In terms of satisfaction with the quality of the water supply, perceptions range from being satisfied to fairly satisfied with Scenario 3 and 4 having the greatest level of satisfaction (Figure 8.13).



a) Social acceptance (criteria-11)

b) Convenience (criteria-12)

c) Satisfaction with Water Quantity (criteria -13)

d) Satisfaction with Water Quality(criteria-14)

Figure 8.12: People's response to the MAR strategies in the study area

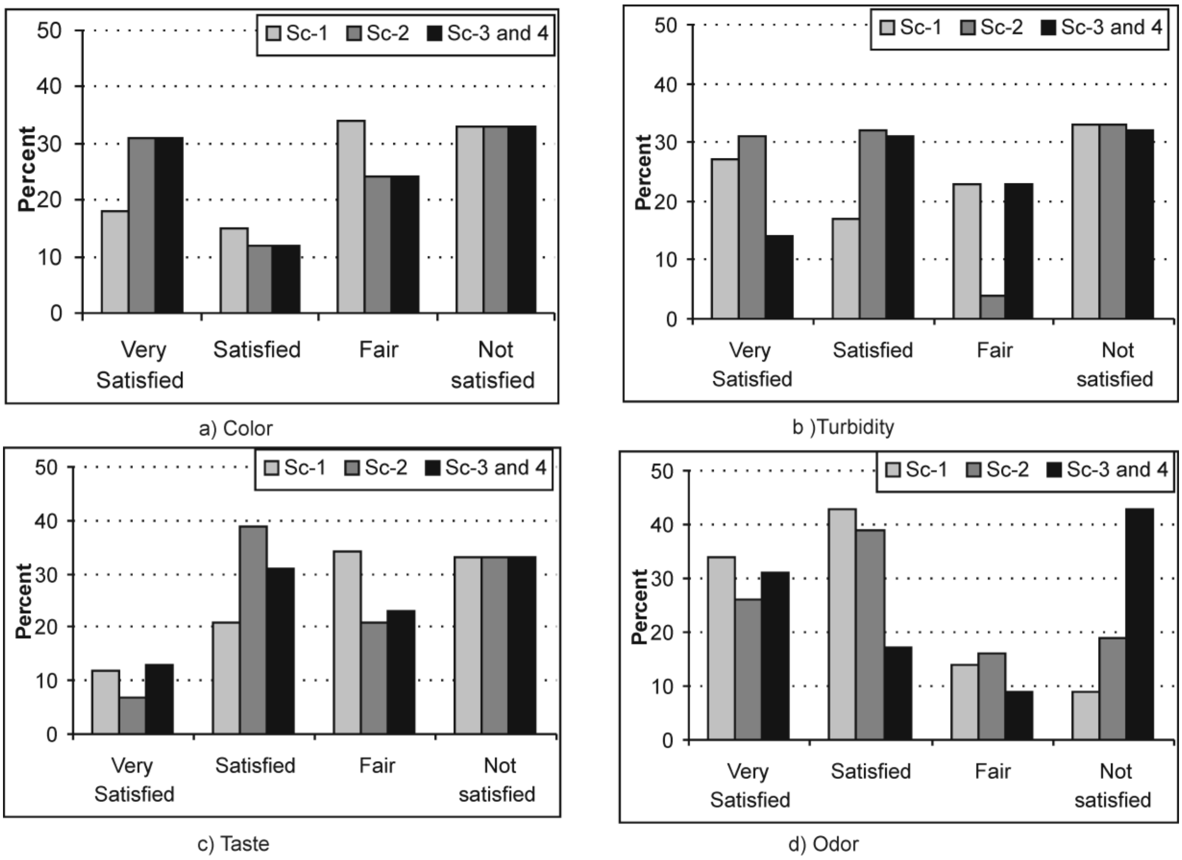


Figure 8.13: Social satisfaction with the supplied water quality of different MAR strategies for several water quality parameters.

Economic Criteria Quantification

In the study area most of the people depend on agriculture, and many youths and women participate in agricultural activities. Hence it is important to review carefully the water price (tariffs) for project feasibility. In general, reuse of wastewater will offer the release of corresponding resources and will help to expand the overall irrigated area by providing more water to irrigate lands, in effect, triggering economic improvements in the lives of the farmers. The cash flow analysis shows that the implementation of a MAR strategy would be beneficial after year 2022 (Sc-4) and year 2024 (Sc-2 & 3) (Figure 8.14). Sc-4 returns the most benefit due to its extended amount of infiltration volume even after year 2012 (see Table 8.3).

Beside the above mentioned benefits, more indirect benefits may be gained from improving groundwater quality. These are increased safety and the benefits generated from freeing the land that the current effluent lagoon occupies as well as the other subjective benefits related to seawater intrusion.

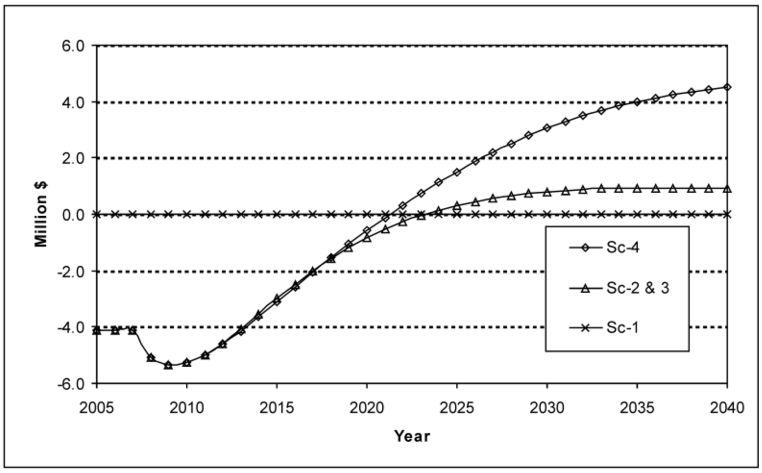


Figure 8.14: Cash flow analysis for the four MAR strategies

Multicriteria Analysis

After quantification of all the criteria, the normalized matrix was prepared for MCA analysis (Table 4). Figure 8.15 shows the ranking of alternative strategies using combined Analytical Hierarchy Process (AHP) and weighted linear combination (WLC) analysis techniques, according to the main criteria groups (Level 2 in the hierarchy).

Table 8.4: Normalized matrix of the quantified value of each criteria for MCA. In 1 to 0 scale '1' indicates the best performance while '0' indicates the worst performance.

Level 1	Sc-1	Sc-2	Sc-3	Sc -4	Global Weight	Level 2	Level 3	Level 4
Criteria 01	0.00	0.66	0.66	1.00	0.03	Environmental	Environmental	Strategy Ranking
Criteria 02	0.00	0.56	0.56	1.00	0.09	Environmental		
Criteria 03	0.00	0.88	0.88	1.00	0.03	Environmental		
Criteria 04	0.00	0.79	0.79	1.00	0.04	Environmental		
Criteria 05	0.00	0.61	0.75	1.00	0.03	Environmental		
Criteria 06	0.00	0.50	0.65	1.00	0.04	Environmental		
Criteria 07	1.00	0.00	0.00	0.59	0.05	Health	Socio-Economic	
Criteria 08	0.00	0.17	0.17	1.00	0.07	Health		
Criteria 09	0.00	0.64	0.72	1.00	0.05	Health		
Criteria 10	0.00	0.39	0.63	1.00	0.07	Health		
Criteria 11	0.96	0.00	1.00	1.00	0.02	Social		
Criteria 12	0.02	0.00	1.00	1.00	0.01	Social		
Criteria 13	0.33	0.00	1.00	1.00	0.03	Social		
Criteria 14	1.00	1.00	0.00	0.00	0.03	Social		
Criteria 15	0.00	0.63	0.63	1.00	0.07	Social		
Criteria 16	0.00	0.60	0.60	1.00	0.07	Social		
Criteria 17	1.00	0.80	0.00	0.00	0.04	Social		
Criteria 18	1.00	0.22	0.00	0.00	0.05	Economic		
Criteria 19	0.00	0.21	0.21	1.00	0.20	Economic		

Considering social and economic criteria, Sc-2 shows better performance compared to Sc-3. People's affordability, convenience, and acceptance of wastewater seem important for the ranking. The results show that Sc-4 is the best-ranked option.

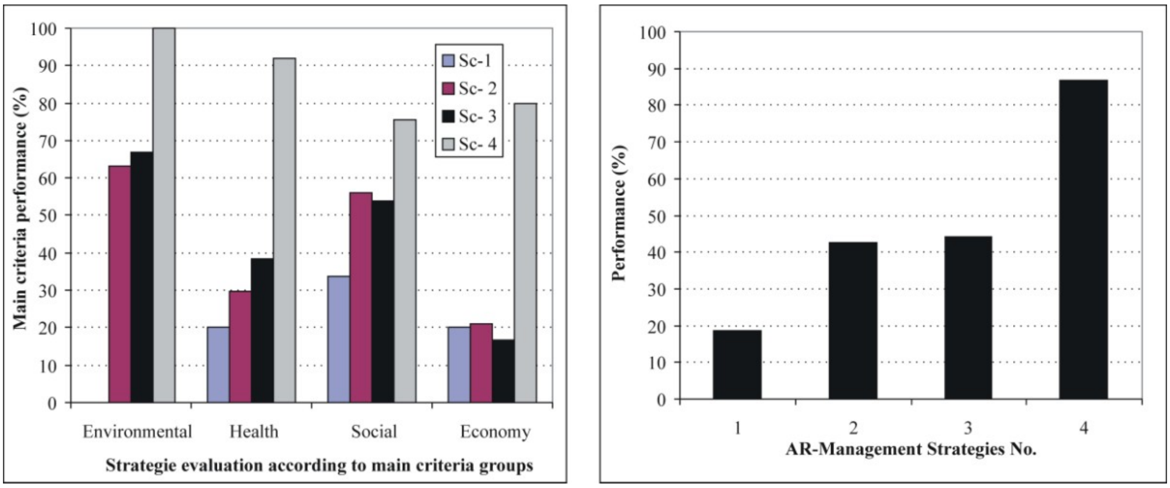


Figure 8.15: Ranking of the strategies using AHP-WLC combination. Left: Ranking according to main criteria group (level 2). Right: Overall ranking of the strategies (at Level 4).

In order to check the impact of criteria selection and robustness of the entire methodology, another AHP-WLC analysis was performed using only eight criteria, which are the most important and relevant for the strategies' evaluations. Table 8.5 shows the normalised matrix of the quantified eight criteria. The criteria value ware derived from the detail analysis of the 19 criteria, mentioned above. Groundwater level recovery was given the most priority. Figure 16 ranking the strategies based on main criteria group (left) and overall performance of them (right). This analysis shows similar results to those mentioned earlier. In general, both MCA-methods show similar results.

Table 8.5: Normalized matrix of the quantified value of eight simplified criteria for MCA. In 1 to 0 scales, '1' indicates the best performance while '0' indicates the worst performance.

Level 1	Sc-1	Sc-2	Sc-3	Sc-4	Global weight	Level 2	Level 3	Level 4
GW level recovery	0.00	0.58	0.58	1.00	0.3	Environm-ental	Environ-mental	Overall ranking
GW Quality improvement	0.00	0.68	0.76	1.00	0.1			
Chloride concentration at Domestic wells	0.00	0.17	0.17	1.00	0.05	Health	Socio-econimic	
Nitrate concentration at Domestic wells	0.00	0.39	0.63	1.00	0.05			
Contribution to the generated income	0.00	0.60	0.60	1.00	0.06	Social		
Social acceptance	0.96	0.00	1.00	1.00	0.04			
Net Cost	1.0.	0.20	0.20	0.00	0.2	Economic		
Net benefit	0.00	0.73	0.73	1.00	0.2			

The criteria and preference structure represented by the weights do not significantly change the ranking order. Strategy no.4 is always ranked first and can be considered a stable solution.

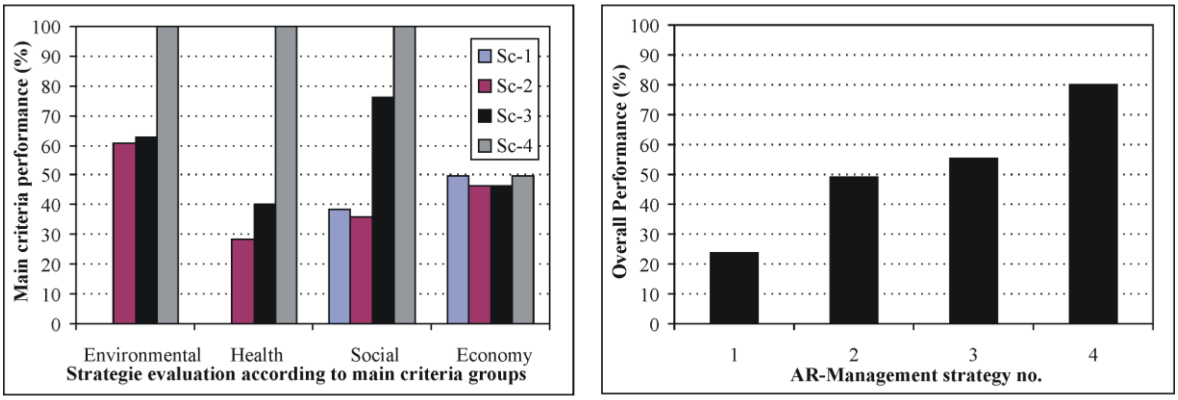


Figure 8.16: Ranking of the strategies using AHP-WLC combination considering only eight important criteria. Left: Ranking according to main criteria group (level 2). Right: Overall ranking of the strategies.

8.5 Conclusions and Recommendations

In order to increase water supply and to combat water scarcity, water pollution, and health problems at the Northern Gaza Strip, appropriate water resources planning and management measures are urgently required. Reuse of the treated effluent will provide an alternative to groundwater for irrigation and will result in increasing the availability of freshwater for domestic and industrial use. The reuse of treated effluent has already been adapted in the national Water Policy for the Gaza Strip (Nassar, 2009). The present study shows that the so-called "Do Nothing Approach" is not a real option for Northern Gaza, contributing to further groundwater level dropping and groundwater quality deterioration, and increasing the health risk for the population of Gaza. The performance analysis of the developed water resources planning and management strategies clearly shows that managed aquifer recharge by means of infiltration ponds with proper treatment is a viable response to the increasing water resources problems of the region.

All strategies except Sc-1 show that MAR will definitely halt the declining trend of groundwater level and store water in the aquifer for further use. Implementation of Sc-4 will offer storage in the aquifer with a maximum value of 23 MCM per year after the full implementation of north Gaza wastewater treatment plant (NGWWTP), phase–III (year 2025). Fresh water flow from Israel will be reduced due to project implementation. Infiltrated water will improve significantly the groundwater quality, in terms of chloride, in all MAR implementation strategies. Regarding nitrate, the relatively high concentration in the partially treated water will have a negative impact on aquifer water quality. Thus fully treated water is desired. In order to keep receiving optimum benefit, optimal pond operation based on practical experiences and regular cleaning of the pond is required. Ten domestic wells will be affected over time due to push of relatively bad quality groundwater towards the wells. But over the course of time, the bad quality water will be replaced by the infiltrated water. Special care for water recovery should therefore be planned to protect the existing domestic wells. Another option could be to use the affected domestic wells for agricultural use and use the nearby unaffected wells for domestic water supply. The groundwater model simulations demarcate a zone of ca. 200 m from the edge of the infiltration basins receiving the infiltrated water with a residence time shorter than 6 months. Regarding pathogenic bacteria, residence time of more than 6 months is recommended (e.g., CDPH, 2008). In the study area, no domestic wells exist within this 200 m. Nevertheless, regular water quality monitoring of abstracted water and efficient recovery wells should be considered. Social indicators show that people are not interested in using the treated effluent for domestic use but intend to use it for agricultural or industrial use. The respondents are not willing to pay much for the reuse. A tremendous effort is required to increase the public awareness for the wastewater reuse. The survey results indicate that the inhabitants are willing to pay a maximum $0.37/m^3 to use wastewater for irrigation. Considering this unit price of water, the project will start to give benefit from the year 2022 (Sc-4) and from the year 2024 (Sc-2 & 3) to the implementation agency. Adequate water pricing should be made considering the level of income and economic feasibility of the MAR project.

Further investments should be undertaken for better maintenance and to further extend the wastewater collection network as well as the capacity of the NGWWTP at the Israelian border, accompanying the rapidly increasing wastewater production. Furthermore, managed aquifer recharge contributes to the control of seawater intrusion and groundwater salinity. In this study, MAR is seen as not only a solution to the water supply and groundwater quality issue, but also as a solution to the effluent lake problem. By using MAR, the wastewater is naturally filtered by the sediments in the unsaturated zone, after sufficient resident time in the underground and water improvement by natural attenuation, and will be monitored adequately by observation wells (Bouwer, 2002). The water then can be reused to meet agricultural demand, leaving more fresh water for domestic use.

Due to the unavailability of scientific data, a variable-density groundwater flow model was not considered in this case study. As the objective of the study is not to quantify salinity intrusion, rather compare different management scenarios, the fresh water flow model is sufficient. In order to investigate the effect of MAR strategies on salinity intrusion in the coastal aquifer, a variable-density groundwater flow model is recommended. The comparison of water management options showed that increasing investments in wastewater collection, treatment, and later groundwater artificial recharge results in increasing water management strategy performance with regards to the considered environmental, social, and health criteria. Obvious drawbacks are the investments for infrastructure and their impact on economic feasibility. This should be discussed in greater depth and should be based on comprehensive CBA that should refer to cost minimization and the related environmental and health benefits, which are fundamental to guarantee the sustainable development of the Gaza Strip.

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Chapter 9

Influence of Aquifer Properties on the Water Quality Changes during Infiltration of Treated Wastewater

9.1 Introduction

Managed Aquifer Recharge (MAR) with reclaimed wastewater and other sources of water is now being widely practiced in various parts of the world, especially in arid and semiarid regions. Implementation of surface spreading basins, i.e. Soil Aquifer Treatment (SAT), is a common practice for MAR (Drewes, 2009). 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). In a MAR operation using infiltration ponds different zones of influence can be observed that are relevant for determining the extent of the attenuation zone, and for positioning of observation and recovery wells (Dillion, 2009). The schematic view of a SAT system and zones of influence are given in Figure 9.1.

During SAT, secondary or tertiary treated wastewater infiltrates into the subsurface from an infiltration basin, continues to percolate through the unsaturated zone and then finally mixes with native groundwater. The transport of solutes involves several processes within the unsaturated and saturated subsurface zones. At the basin – soil interface, the combined effects of sedimentation, filtration, aeration, and microbial growth may lead to the formation of a biologically active zone that may become less permeable (Bouwer and Rice, 1984), yielding a reduced infiltration rate with time. Overall, physico-chemical and biological processes acting within the unsaturated and saturated subsurface zones may provide pollutant concentrations below regulatory limits at the point of compliance, e.g. a groundwater recovery well.

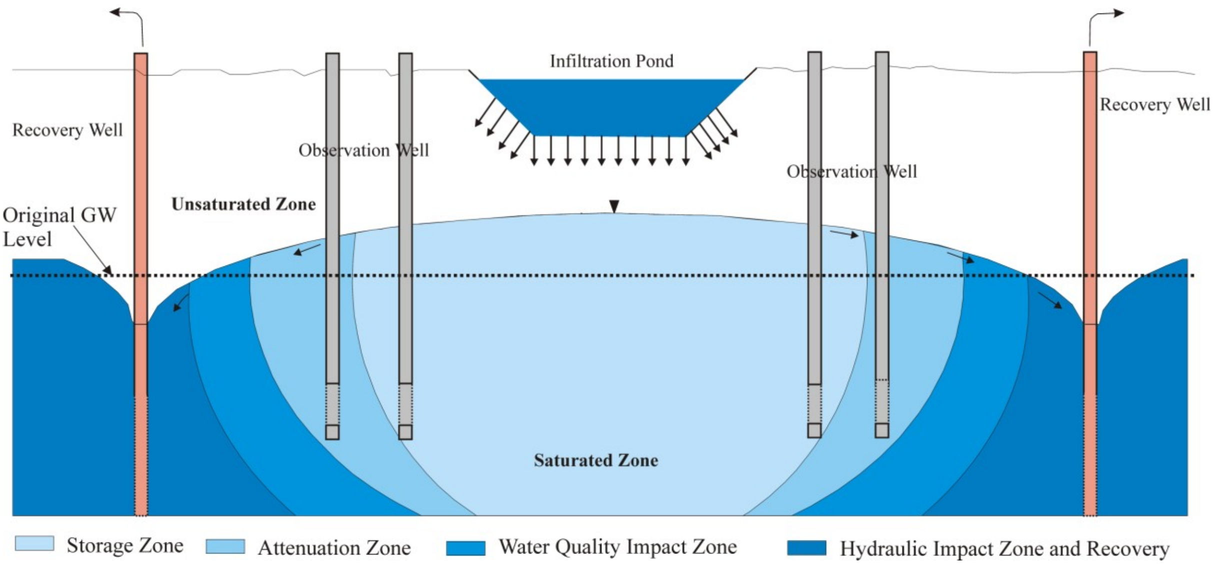

Figure 9.1: Schematic view of the infiltration and recovery installations, and zones of influence in a MAR operation. Zones of influence adapted from Dillon (2009)

Up to now, the impact of subsurface properties on SAT operations has been examined just by a few studies. Removal of organics does not depend on soil type, though fine-grained soil has a small advantage compared to other soil types (Quanrud et al., 1996). Later on, a review study by Sharma et al. (2008) suggested that the soil type might have an impact on dissolved organic carbon (DOC) removal. Sandy loam has better DOC removal efficiency than others. The influence of aquifer properties on endocrine disrupting compounds (EDC) removal has not been well investigated yet.

Research has shown that a variety of organic compounds including veterinary and human antibiotics, other prescription and non-prescription drugs, widely used household and industrial chemicals including personal care products, and products from oil use and combustion, steroids and reproductive hormones (Ternes, 1998, Kolpin et al., 2002), as well as bacterial, viral, and protozoan pathogens (Toze, 1999), can survive conventional waste water treatment and persist in the aquatic environment. The presence of Endocrine Disrupting Compounds (EDCs) is of special concern because these compounds are associated with potential adverse health effects and toxicological effects on aquatic species (Snyder et al., 2004). Consequently, their presence in wastewater leads to the necessity of better understanding their fate and transport during aquifer storage and recovery operations. Despite the treatment process some pharmaceuticals and EDCs persist in treated effluent at very low concentrations (Benotti and Snyder, 2009). Only limited studies have been performed up to now to provide information on the mechanism for the attenuation of EDCs during SAT. The fate and transport of pharmaceuticals and EDCs in the subsurface are controlled by many factors such as hydrogeological conditions, concentration, pH of recharge water, processes such as advection and dispersion, sorption and desorption, diffusion, microbiological and chemical transformation, pond operation (wetting and drying cycling scheme), etc. Drewes et al. (2002) proved that SAT could efficiently remove anti-inflammatory and lipid-regulating drugs. A period of less than six months of groundwater transport can efficiently remove some pharmaceuticals and Personal Care Products (PCPs), such as Diclofenac, Ibuprofen, Ketoprofen, Naproxen, Fenoprofen and Gemfibrozil, from secondary effluent under SAT. Antiepileptics such as Carbamazepine and Primidone persist in groundwater even after a long time of recharge (Drewes et al., 2003). A 23-days study within a 2.4 m long soil column showed about 70% removal of some organic compounds, but the study demonstrated that under recharge conditions similar to those in arid and semi arid climates, some pharmaceuticals (especially eight compounds: Carbamazepine, Sulfamethaxazole, Benzophenon, 5-methyl-1H-benzotiazole, N,N-diethyl-tolaumide, Tributylphosphate, (Tri- 2-choloroethyl) phosphate, and Cholesterol), pathogens, and other organic wastewater compounds (OWCs) can persist in treated effluent after soil aquifer treatment (Cordy et al., 2004).

For a better understanding of transport processes, employing laboratory data and mathematical modelling, information on kinetic sorption with irreversibility, possible transformation reactions, appropriate isotherms and rate laws is important (Wehrhan et al., 2007). Because of the wide range of physico-chemical properties (e.g. log K_{ow}) and microbial transformation mechanisms, it is not easy to understand comprehensively the behaviour of these contaminants within the subsurface environment

(Benotti and Snyder, 2009). Mathematical modeling combined with field studies can improve the knowledge about the fate and transport of the emerging pollutants.

The implementation of mathematical modeling for SAT system analysis has not been well practiced yet. The application of a mathematical model for SAT system analysis covers three aspects: pond operation, water flow and reactive transport. Determination of an operation scheme is required for the decision maker to perform a preliminary analysis of SAT systems. Some studies (e.g., Tang et al., 1996; Li et al., 2000) focused on the optimization of pond operation for MAR, but little emphasis was given to investigate the combined effect of water quality changes and pond operation.

The wastewater treatment plant within the study area (in Southern Europe) considered here treats 180,000 m^3 of wastewater per day with all of the effluent being discharged direclty into an adjacent bay. The continuous operation of a sewage plant during the last years has had a strong negative impact on the quality of the seawater in the bay. Not only is environmental degradation a major issue here, but also the waste of a significant water resource. Therefore the responsibles for water supply and sewage teatment have now decided to check the feasibility of using the aquifer to store the treated effluent delivered by the wastewater treatment plant. A study has been performed to check the viability of MAR applied to the aquifer at the study area, using secondary treated wastewater. Test site characterization, infiltration tests, a field campaign for the understanding the fate of selected emerging pollutants (Nödler et al., 2010), as well as mathematical modeling to simulate the flow and transport processes within the aquifer have been performed up to now.

The main objective of the present study is to simulate the subsurface transport of selected pharmaceuticals during SAT at the test site. This has been performed by detailed field investigations and mathematical modeling of relevant transport processes. Finally, a detailed groundwater monitoring plan for a future SAT implementation at the test site is adressed.

9.2 Description of the Test Site

The test site, having an area of 2 km^2, is located in Southern Europe. Based on observations from satellite images and topographic maps, the site is most likely situated on an old point bar of a river, which lies between the main channel of the a river and an old paleochannel. The aquifer is attributed to the prograding deltas of two rivers rivers. The subsurface is mainly composed of neogene limestones, sandstones and conglomerates overlain by pleistocene and holocene alluvial deposits. The aquifer system extends to depths between 30 m to 120 m. The aquifer was providing water for urban and industrial use in the city . Since 2003 the aquifer is no longer exploited for urban and industrial purposes. The aquifer is unconfined and characterized by a large degree of heterogeneity, as it is located within the zone of meandering channels of the two different rivers. Aquifer hydraulic conductivity is relatively high, ranging between $6.7x10^{-4}$ m/s and $2.55x10^{-3}$ m/s (GABARDINE, 2008).

9.3 Materials and Methods

9.3.1 Test site characterization and experimental setup

For a better understanding of the local subsurface stratigraphic and hydraulic conditions, three drillings (D1, D2 and D3, see Figure 9.2) were performed in a triangular setup spanning a distance of 50 – 100 m between them. Undisturbed samples were retrieved at location D1. After drilling, three piezometers (P1, PD2 and PD3, see Figure 9.2) were installed (Rahman et al., 2010). During the drilling campaign, 33 undisturbed soil samples were collected from drilling D1 and analysed for soil chemical and physical properties. Detailed grain size analyses were performed. In addition, the mineral composition of selected soil samples was investigated in the laboratory.

Two experimental infiltration ponds were then constructed at both sides of piezometer P1. Each experimental infiltration pond is 18 m long, 9 m wide, and has a depth of 2 m. The bed surface area of each pond is 10 m X 5 m (Figure 9.2).

Figure 9.2b shows the monitoring network layout. Three monitoring wells (P1, PD2, and PD3) are 12 m deep, screened from 6 m to 12 m above sea level (ASL), and six wells (P2, P3, P4, P5, P6, P7 and Px) are 6 m deep, screened from 3 m to 6 m ASL.

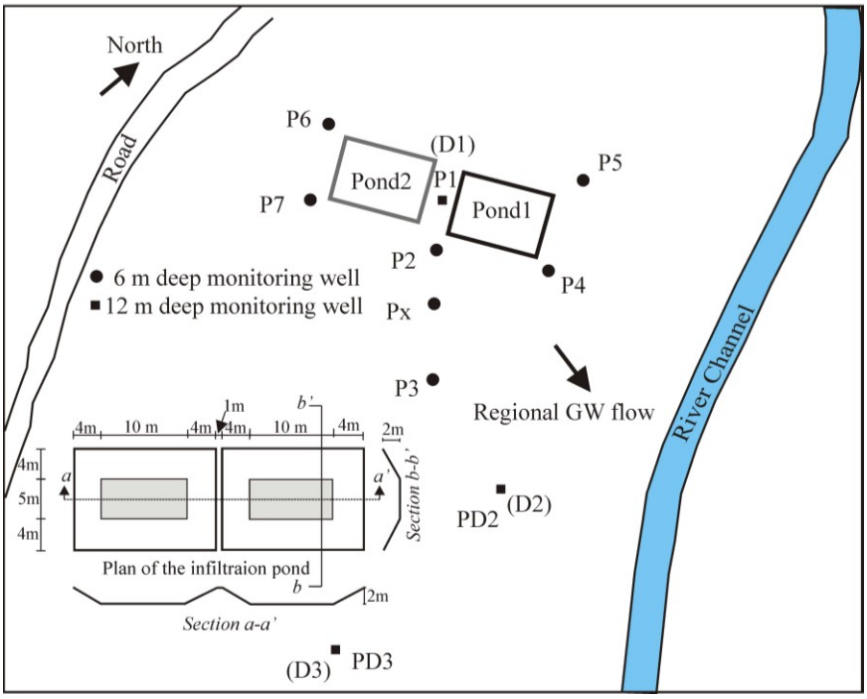

Figure 9.2: Experimental setup showing the position of the piezometers relative to the infiltration ponds and design details of the ponds (pond 1 was used for the field experiments, (Nödler et al., 2009)**.**

9.3.2 Soil column tracer study

Undisturbed soil samples were collected from the infiltration pond bed in a 1041 cm^3 stainless steel cylinder (15 cm height, 9.4 cm inside diameter). In a soil column testing apparatus, stainless steel porous plates were placed between the soil and two stainless steel end caps. The porous plates aimed at avoiding washing out of soil fines. Only glass, Teflon and stainless steel were used for the construction of the experimental apparatus to minimize adsorption. Figure 9.3 shows the simplified layout of the soil column experimental setup.

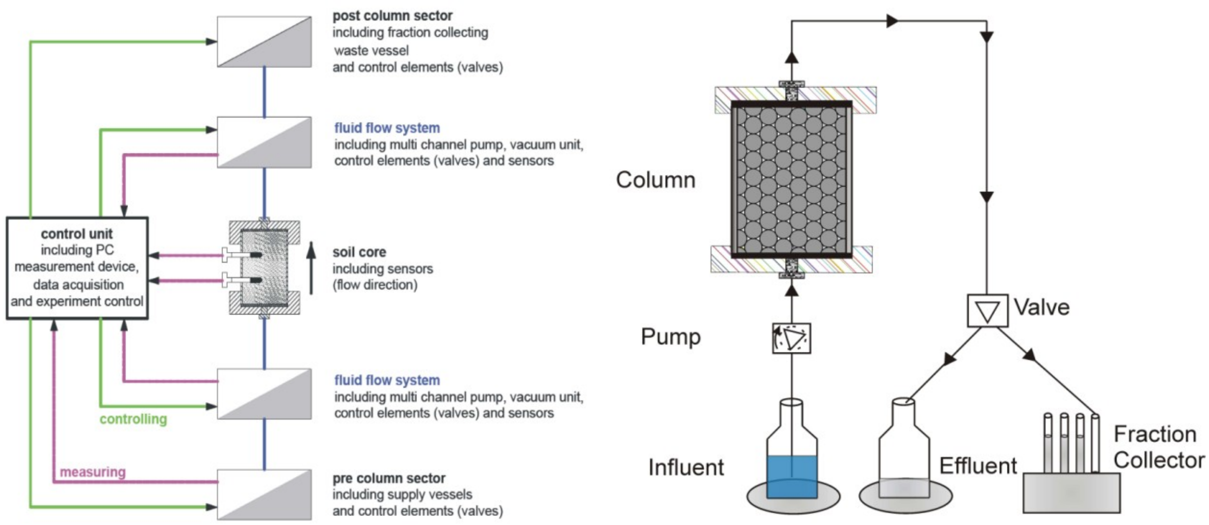

Figure 9.3: Schematic presentation soil column experimental setup: (a) instrumental layout (EMC, 2007) (b) experimental setup.

The soil column was slowly wetted, from the bottom to the top, over a 36-h period with a flow rate of 2 ml/min using deionized water. This was done to reduce the amount of entrapped air, to saturate the soil, to condition the column, and to maintain the soil structure. After conditioning of the soil, an input solution containing two conservative tracers, bromide and chloride, was applied to the soil, from the bottom to the top. A constant flow of 2 ml/min was maintained throughout the experiment. The initial concentrations of chloride and bromide were 99.334 mg/L and 99.108 mg/L, respectively. The effluent fraction was collected every 10 min using an automated fraction collector.

The stock solution and the effluent fractions were analysed for chloride and bromide. Concentrations of bromide and chloride were measured using ion chromatography.

9.3.3 Field investigations

A 30-days field campaign was performed at the test site in order to investigate water quality changes during SAT (Nödler et al., 2009, Nödler et al., 2010). Groundwater levels in the monitoring wells and occurrence of selected pharmaceuticals were monitored. Tap water was applied for infiltration in order to pre-flush the system and to study desorption of selected xenobiotics. Secondary treated effluent (STE) was applied to determine the breakthrough and to study the behaviour of the pharmaceuticals. Table 9.1 summarizes the water injection scheme for the SAT experiments.

Table 9.1: Overview of the infiltration experiments in the test site (after Nödler et al., 2009)

Experiment	Matrix	Purpose	Volume [m^3]	Duration [h]
Ex. 0	Tap Water	Pre-Flush	2761	~ 290
Ex. 1	Secondary treated effluent (STE)	Determination of breakthrough	553	72
Ex. 2	Tap Water	Desorption of pharmaceuticals	425	45
Ex. 3	STE	Behavior of pharmaceuticals	1170	195
Total			4909	

9.3.4 Mathematical modeling

1D modeling of the soil column experiment

The computer code Studio of Analytical Models for solving the Convection Dispersion Equation, STANMOD (Šimůnek et al., 1999), version 2.2, was used to evaluate the tracer experimental data. STANMOD uses the CXTFIT 2.0 code for the estimation of transport parameters from laboratory or field tracer experiments by inversely fitting an analytical solution to the observed data (e.g. Toride et al., 1995; results see below).

2D modeling of the field experiments

A groundwater flow and transport model of the artificial recharge test site was set up employing Visual Modflow software (v.2009; SWS, 2009). Visual Modflow uses the finite difference code MODFLOW (Harbaugh and McDonald, 1996) to simulate groundwater flow. Due to lack of a complete subsurface characterization, the model has characteristics of a principal model, is however based on field data as far as possible and available. The code MT3DMS (Zheng and Wang, 1999) was used to simulate the reactive transport processes in the subsurface. The model involves a two-dimensional vertical cross-sectional domain (150 m x 12 m). Due to an assumption of symmetry, only a half-domain has been modeled. The horizontal grid size ranges from 0.25 m to 1 m with grid refinement around the pond perimeters. The geological layers, along the z axis, were discretized using the drill log information. The groundwater flow is from left to right, according to the regional groundwater flow within the test site. Boundary conditions for flow are a constant head at the right boundary and no flow at the left, bottom, and upper boundaries. At the pond bed surface, a time variable flux boundary was used (Figure 9.4).

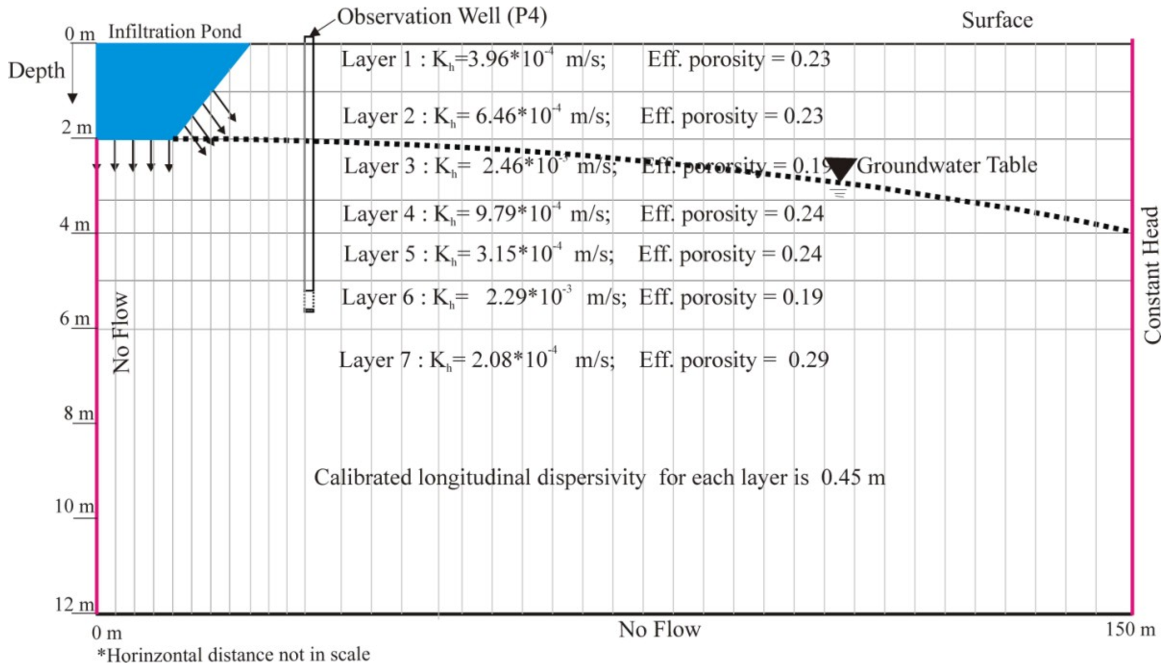

Figure 9.4: 2D model domain, boundary and calibrated parameters

For transport, the boundaries at the left, bottom, and top surface are no flux boundaries. At the pond, a point source concentration boundary was used. The flow, transport, and reaction parameters were obtained from the results of the analyses of collected soil samples, laboratory analyses, output of the 1D soil column model and scientific literature. The model was calibrated using observed groundwater levels and electrical conductivity data obtained at the test site. The calibrated groundwater flow and transport model was used afterwards to study the effect of aquifer properties on the transport behavior of pollutants that persist in the treated effluent. Diazepam is prescribed for gastrointestinal disorders (Ochs et al., 1981) and occasionally detected within the treated effluent of the sewage treatment plan close to the test site (Nödler et al., 2009). On the other hand, Diazepam is generally not present in groundwater (Oppel et al., 2004), therefore Diazepam can act as a tracer to understand the transport processes considering the prevailing aquifer properties at the test site.

Table 9.2: Physiochemical properties of the pharmaceutical used in the study

Compound	**Water Solubility [a] (mg/L)**	**log K_{ow}[a]**	**Use**
Diazepam	220	2.82	Anti-anxiety

[a] SciFinder Predicted values (pH 7-8 at 25° C) unless otherwise noted.

The distribution coefficient between organic carbon and water (log K_{oc}) of Diazepam was estimated using eq. 1, 2 and 3. The octanol/water partitioning coefficients (log K_{ow}) was taken from Table 9.2. Average value of log K_{oc} was used in eq. 4 to calculate K_d , which is 0.12L/Kg. This K_d value was used in the model to simulate the transport of Diazepam in the test site. The retardation factor (R) was obtained using eq. 5 (Table 9.3).

Table 9.3: List of equations used in this study to calculate the log K_{ow} and R for Diazepam

Eq. number	Equations	Reference
1	$\log K_{oc} = 1.0 \log K_{ow} - 0.21$	Karickhoff et al., 1979
2	$\log K_{oc} = 0.72 \log K_{ow} + 0.49$	Schwarzenbach and Westall, 1981
3	$\log K_{oc} = 0.989 \log K_{ow} - 0.346$	Karickhoff, 1981
4	$K_d = K_{oc} . f_{oc}$	Appelo and Postma, 2005
5	$R = 1 + \rho_b . K_d / \theta$	Bear and Verruijt, 1978

In the table, f_{oc} is the fraction of organic carbon, ρ_b is the bulk density and θ the effective porosity.

9.4 Results and Discussion

9.4.1 Field investigations

The investigated stratigraphy reveals a silty surface layer of varying thickness between 0.5 - 1.3 m, a heterogeneous sand body with silt/clay lenses of about 6 - 7 m thickness, and fine to medium sand with minor silt fractions below. During drilling, a series of infiltration tests were performed at different depths to provide a first characterization of the infiltration capacity of the sand layer, which was found to be high enough for the construction of the infiltration ponds. Infiltration rates range from $2x10^{-4}$ m/sec to $2.5x10^{-4}$ m/sec where P1 is located. The historical (February 2007 - September 2008) piezometric level confirms 2m to 2.5 m unsaturated zone, which may be useful for further investigation of unsaturated zone behaviour during infiltration.

The grain size distributions show that the soil particles are uniformly distributed. From the soil texture triangle, it can be concluded that the soil sample represents sandy loam. The three main hydrofacies of the samples are fine sand, medium sand, and silt. The hydraulic conductivities at different depths, calculated using an empirical formula (Beyer, 1964), range between $2.3x10^{-8}$ m/s and $1.4x10^{-4}$ m/s. From the sediment material composition analysis, it was found that quartz mineral grains are dominant in the zone of high hydraulic conductivity (Table 9.4). The samples contain only low percentages of organic matter. Total organic carbon in the relatively high conductivity zone is relatively low (Table 9.5).

Table 9.4: Mineral composition of soil sample 10 (depth 3.65 m to 4 m below ground level)

Description	Coarse grained fraction of medium sand	Fine grained fraction of medium sand
Quartz	80	75
Muskovite	-	3
Mufites	8	18
Clay minerals	-	3
Carbonate	No	No
Undefined	7	1
Relation gravel : sand : silt : clay of the sample is 5 : 80 : 13 : 2 (in %)		
Hydraulic conductivity is 2.8 X 10^{-5} m/s (based on Hydrus 1-D, v 2.0, Šimůnek et al., 1998)		

Table 9.5: Organic content of soil samples at different depths

Sample No.	Depth below surface (in m)	Percent of sand, silt and clay	C_{org} (total, in percent)
1	0 - 0.60	78 : 21 : 1	0.2
12	4.60 - 5.00	66 : 31 : 3	< 0.10
14	6.00 - 6.25	91 : 8 : 1	< 0.10
28	9.5 - 10.00	47 : 43 : 10	1.1

Monitoring of groundwater levels in piezometers P1, PD2 and PD3 shows that there is no relevant seasonal variability of the groundwater levels (GWL) (Figure 9.5) and groundwater flow direction and the groundwater level isoline maps indicate, despite the coarseness of the monitoring well network, that the groundwater at the test site flows in the direction of PD2, which is close to the river (Figure 9.6). This direction also matches with the regional groundwater flow direction, obtained from Ferreira et al. (2006).

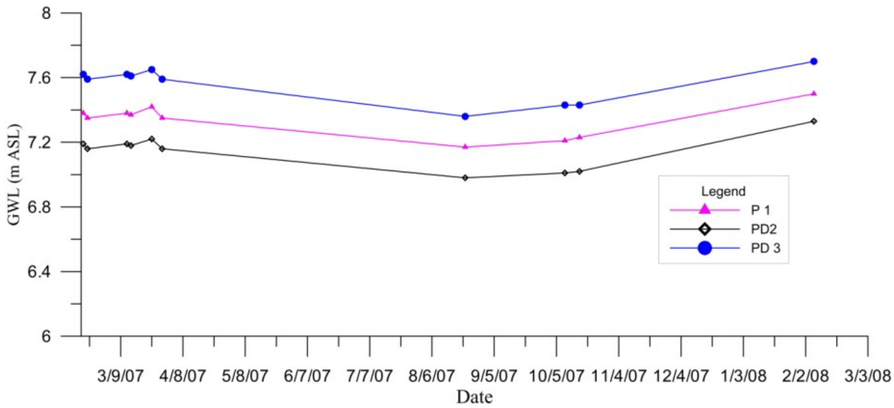

Figure 9.5: Monitoring of groundwater level data at the test site

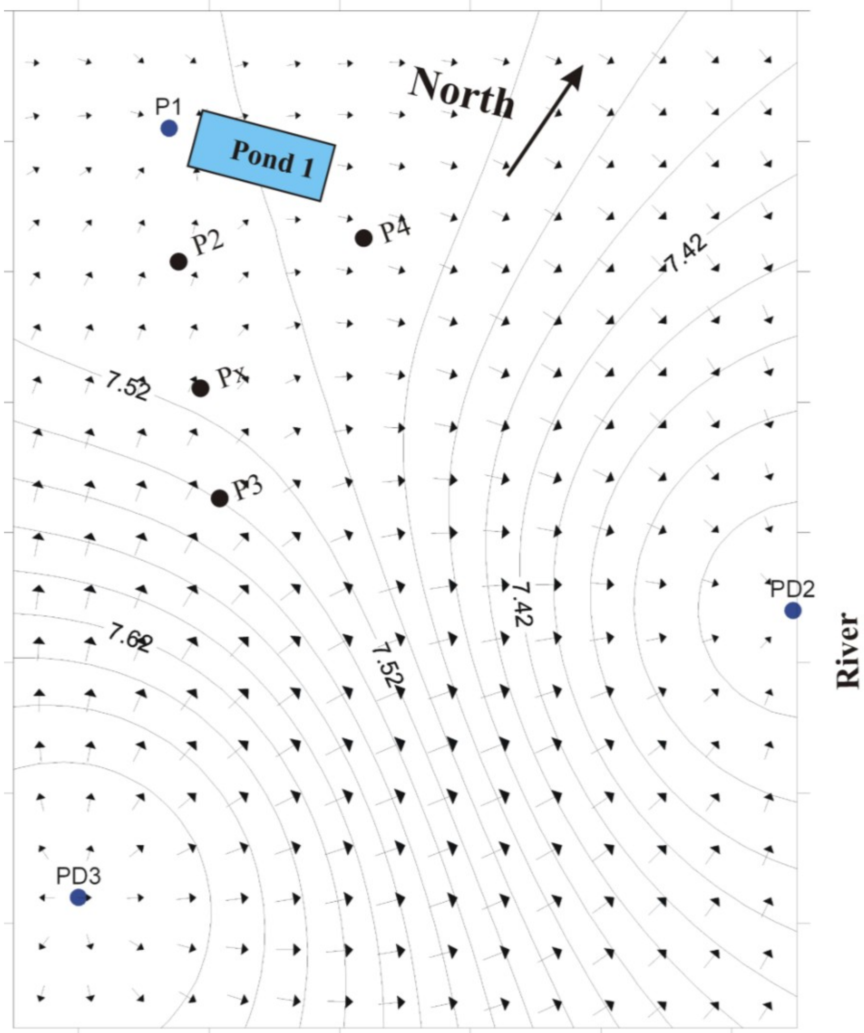

Figure 9.6: Groundwater flow direction at the test site in March 2008.

9.4.2 Soil column tracer study

The breakthrough curves (BTCs) of chloride and bromide obtained from the soil column experiment are shown in Figure 9.7a. Chloride and bromide ions were transported through soil columns basically by an advective-dispersive process, because these ions were considered as non-reactive tracers. They were neither sorbing nor chemically/ biologically altered by the soil or aquifer medium (Levy and Chambers, 1987; Freyberg, 1986).

9.4.3 Modeling study

1D modeling of the soil column experiment

Figure 9.7b and Figure 9.7c show the inverse analytical modeling output obtained from the application of STANMOD to the measured tracer breakthrough curves.

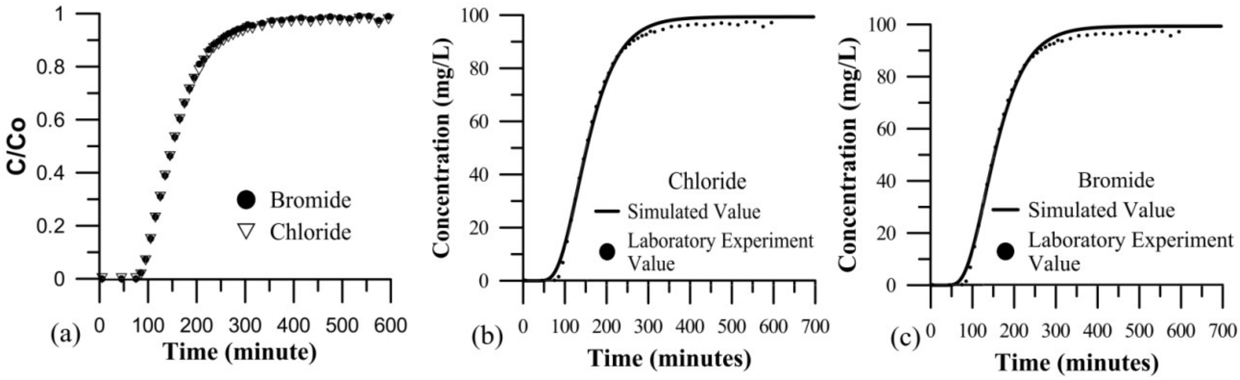

Figure 9.7: a) Breakthrough curves of chloride and bromide in the soil column experiment. Model output for the soil column tracer experiment: b) chloride, c) bromide

Values of the transport parameters velocity, dispersion coefficient, effective porosity, and dispersivity are presented in Table 9.6. A dispersivity of approximately 1 cm is observed in the laboratory column. The transport velocity ranges from 1.53×10^{-5} - 1.55×10^{-5} m/s. The calculated average effective porosity amounts to 29%.

Table 9.6: Estimated flow and transport parameters

No.	Item	Chloride	Bromide
1	Darcy velocity (m/s)	4.5×10^{-6}	4.5×10^{-6}
2	Transport velocity (m/s)	1.531×10^{-5}	1.546×10^{-5}
3	Effective porosity (%)	29.37	29.09
4	Dispersion coefficient (cm^2/min)	0.104	0.107
5	Dispersivity (cm)	1.08	1.07

2D flow and transport modeling

The groundwater flow model was calibrated using the observed groundwater level data at well P4 (see Figure 9.2) situated at 15.5 m distance from the left side boundary of the model domain. Two highly conductive layers below the pond bed surface were identified (see Figure 9.4). The transport model was calibrated using observed electric conductivity data (Nödler et al., 2009) at monitoring wells P2 and P4, which are situated at 13.5 m and 15.5 m distance from the left side boundary of the model domain, respectively (Figure 9.4). Figure 9.8 shows the good agreement of observed and simulated electrical conductivity value at monitoring wells P2 and P4, respectively.

Throughout the calibration process, it was found that the parameter sensitivities were highly variable. Hydraulic conductivity, effective porosity and distribution coefficient (K_d) value had major impact on the simulation result. Storage and dispersivity did not show any significant impact on the simulation outcomes. The calibrated model was then used to simulate the scenario analysis (Figure 9.10).

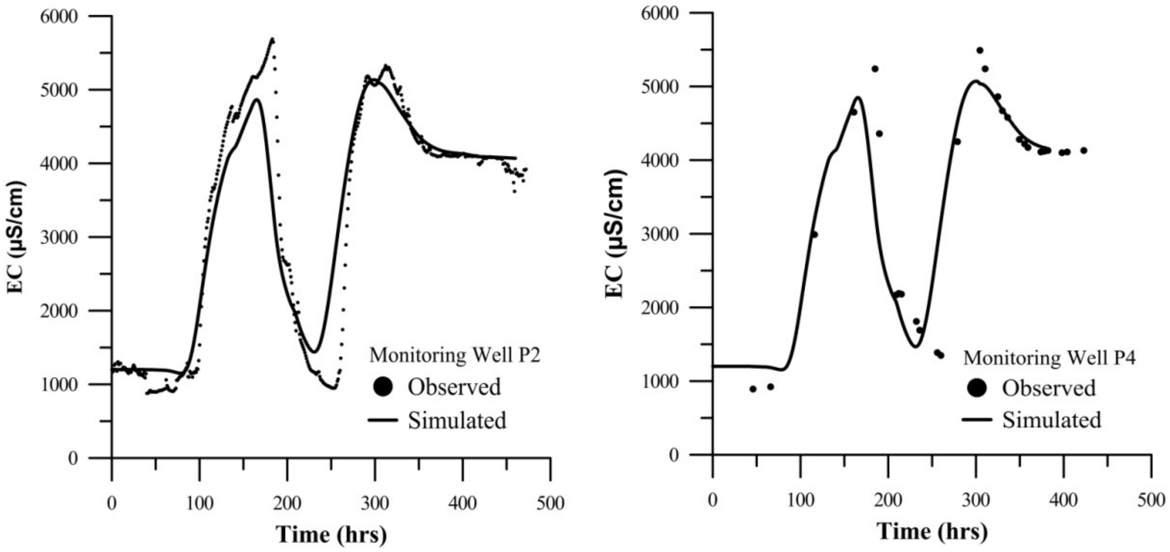

Figure 9.8: Observed and modelled breakthrough curves of electrical conductivity at well P2 and P4 (observed data after Nödler et al., 2009).

9.5 Groundwater Monitoring Framework for further Experiments and Analysis

The above-mentioned flow and transport model was set up considering isotropy as well as uniform hydraulic conductivity and specific yield in horizontal direction within the model domain. Longitudinal dispersivity and sorption coefficients were taken uniform within the entire model domain. For a better understanding of the attenuation of emerging pollutants, an estimation of transport parameters at a higher level of detail is required. A control volume monitoring well network is shown in Figure 9.9, which will be used in future for a more detailed investigation of transport phenomena at the test site. As the longitudinal dispersivity is relatively low (0.4 m), a relatively dense monitoring network is suggested to be able to quantify transverse dispersion also (Figure 9.8).

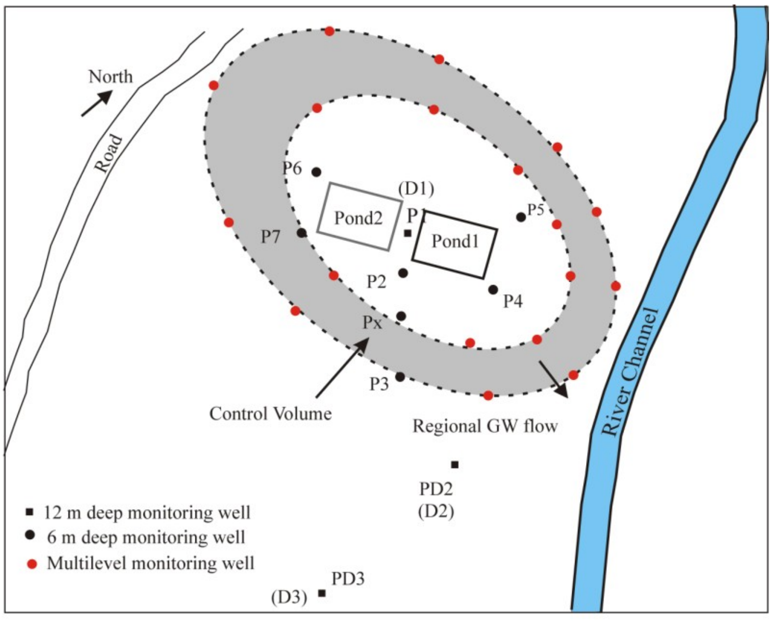

Figure 9.9: Design of an improved monitoring well network for the test site

A scenario simulation was performed to check the effects of heterogeneity in vertical direction. Diazepam was used as a reactive tracer. The input concentration of Diazepam was 12 µg/L and was applied for 15 minutes in the infiltration pond. Figure 9.10 shows the simulated concentration of Diazepam at five different depths at four observation points. The breakthrough curves obtained at layer 4 (see Figure 9.4) at a distance of 45 m and 60 m from the pond center show two peaks. The hydraulic conductivity of this layer is 4 times lower than that of the overlying layer (layer 3), and porosity is 1.25 times higher. As dispersivity and K_d are same within both the layers, the differences of hydraulic conductivity and porosity obviously control the spreading behaviour of Diazepam in such a layered aquifer. The peak concentration appears earlier in layer 3 than in layer 4, due to the fact that the vertical velocity (average value is 2.31×10^{-4} m/s) and horizontal velocity (average value is

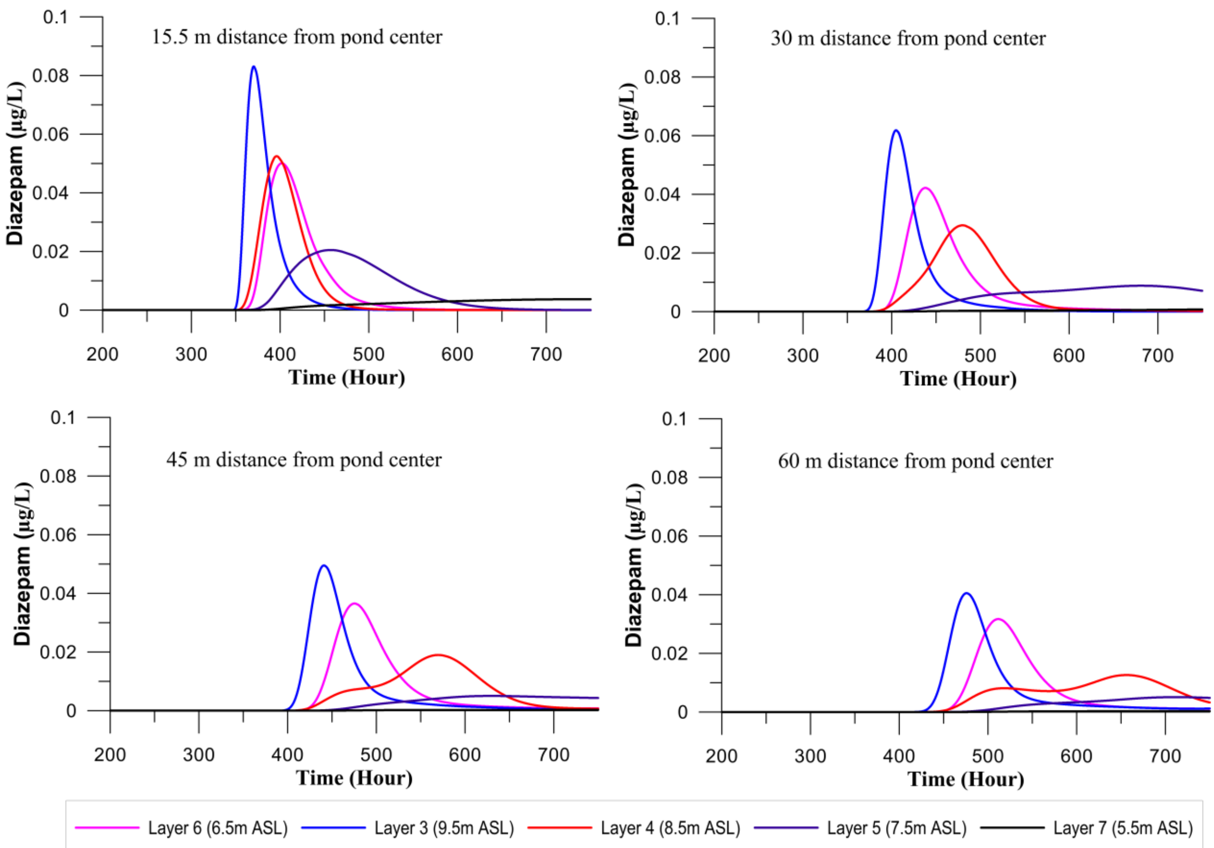

Figure 9.10: Simulated concentration of Diazepam at different depths in different monitoring wells

1.97×10^{-4} m/s) of groundwater within layer 3 are higher than those within layer 4 (average vertical and horizontal velocities are 1.27×10^{-5} m/s and 6.07×10^{-5} m/s, respectively). Within layer 4, the first peak appears due to the horizontal movement of Diazepam with groundwater and the second peak appears due to the vertical leakage from the layer above. On the other hand, as the vertical leakage from layer 4 to layer 5 is relatively low and the horizontal velocity within layer 5 (average value is 1.92×10^{-5} m/s) is lower than within the overlying layer, only one but wide peak is seen.

The scenario simulations clearly demonstrate the need for high resolution monitoring data to be able to explain the relevance and impact of subsurface parameters on the spreading processes. Multilevel sampling will be required to investigate the transport behaviour in three dimensions. Therefore, Figure 9.11 shows a conceptual multilevel monitoring network setup for the test site, allowing further field experimental campaigns and long term 3D monitoring of MAR schemes.

During the field experiment at the test site it was difficult to maintain the pond water level stable throughout the experimental period due to inadequate information on an optimal injection rate to keep the pond water level stable (Nödler et al., 2009). Therefore the calibrated model was used to find an optimal rate of injection to fill the pond and keep the water level stable. No pond bottom clogging was observed during the 30 days of the experiment (Nödler et al., 2009), and therefore clogging was not considered within the model simulation.

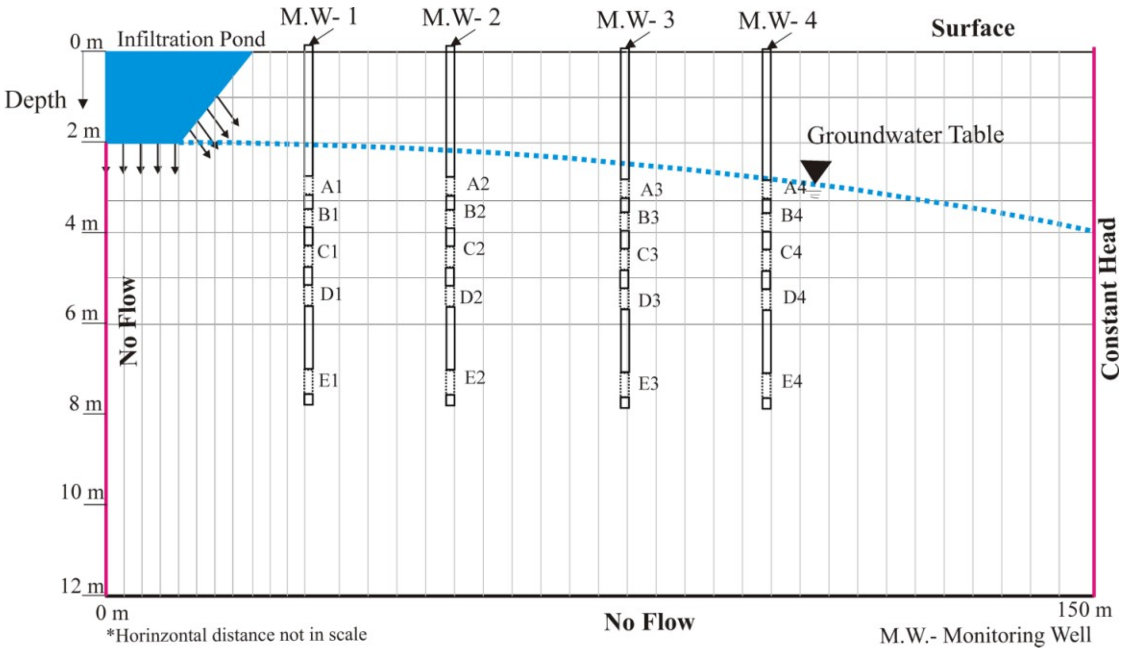

Figure 9.11: Suggested improved 3D monitoring layout showing multilevel sampling positions

The simulation results suggest that an injection of water at a rate of 133.2 m^3/hr for 12 hrs will fill the pond, and an injection rate 0.65 m^3/hr will maintain the pond water level stable. For future infiltration experiments, in order to obtain reliable breakthrough curves at the monitoring wells, we suggest to maintain at least 1 months of flooding, followed by a drainage and drying phase to maintain the attenuation potential and infiltration capacity of the SAT system (Figure 9.12).

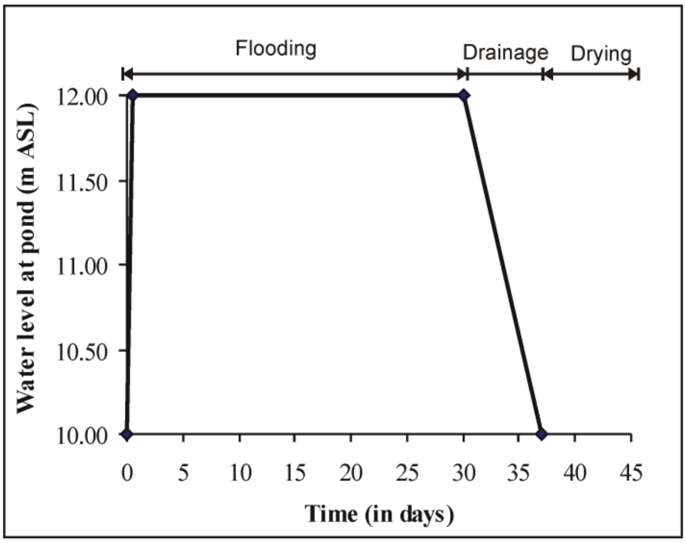

Figure 9.12: Optimal pond operation for further field experiments at the test site

Anoxic conditions develop during flooding of the infiltration pond, leading to a decrease of aerobic biological activity and to an increased clogging at the pond bed (Kopchynski et al., 1996). This clogging may partly enhance sorption, biotransformation and inactivation processes by an increased biogeochemical activity (Ausland, 1998; van Cuyk et al., 2001), however the infiltration rate may be significantly reduced. Drying of the soil surface desiccates the clogging layer, allows aerobic biological activity to restart (Greskowiak et al., 2005), and finally, the infiltration capacity of the pond bed is improved again.

9.6 Summary and Conclusions

This research paper demonstrates an integrated approach based on field investigations, laboratory and field experiments, and mathematical modeling to understand the impact of aquifer properties on the transport processes of pharmaceuticals under soil aquifer treatment measures at a test site. The investigations have revealed that the test site has a sandy aquifer with relatively high hydraulic conductivity. The presence of an unsaturated zone is advantageous for installation of infiltration ponds. The high hydraulic conductivity layers, with quartz being the dominating mineral component, have a low organic carbon content, resulting in a relatively low retardation of the considered pollutants. The developed numerical groundwater flow and transport model is able to reproduce the flow and transport behaviour observed at the test site.

The numerical model was used to determine an optimal pond operation strategy and to investigate micropollutant transport within the aquifer. A pond operation scheme, with 37 days of water being in the recharge basin, including 1 week drainage, is suggested. Afterwards, 1 week drying is recommended, without considering clogging of the pond bed. Indeed, no clogging was observed during the field experiments. Cyclic flooding, drainage and drying of the pond should improve infiltration rates and should control the presence of aerobic or anoxic conditions beneath the pond bed.

The calibrated and validated numerical model can act as an important tool to quantify the degree of attenuation of the micropollutants present in the treated effluent and can help to recommend and design further treatment steps before recharging the effluent into the subsurface.

More experimental and theoretical work is needed to understand the processes of some emerging pollutants that persist in the recharged water even after secondary or tertiary treatment. Hence, a denser monitoring network with multilevel sampling wells is recommended for the test site (Figure 9.10 and 9.11). A possible change of attenuation behavior due to seasonality should also be considered, as it is of importance for the long-term performance of a MAR system. Furthermore, the aquifer properties may change due to adsorption and biofouling, which results in clogging of the aquifer, and changes of porosity and hydraulic conductivity (van Cuyk et al., 2001).

The model will be further developed and used for development of additional pond operation scenarios, considering clogging effects as well as water quality changes during infiltration, and to assess the attenuation of other pollutants observed.

As a river is very close to the infiltration pond at the test site, just 125 m away, most likely the infiltrated water will be discharged to the river before any recovery. Considering 6 months residence time of water within the aquifer required for water quality improvement (CDPH, 2008), the test site is not appropriate for practical implementation of MAR. However, the site represents, in general, the alluvium aquifer system properties (Ferreira et al., 2006). Therefore the site can be used for further experimental and design optimization purposes. The already gathered information together with further experiences will be helpful for the decision makers, allowing planning of future MAR measures in the region.

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Chapter 10

General Synthesis, Conclusion and Future Perspectives

10.1 General Synthesis and Conclusions

The implementation of a managed aquifer recharge (MAR) project requires careful planning for efficient integration into the water resources system and for achievement of the overall water resources management objectives. No standardized MAR planning framework is available, considering all state-of-art decision analysis techniques as combined with integrated investigation approaches. Very little attention has been given to embed overall IWRM objectives into the planning procedure of MAR. This study comprehensively reviews the existing planning procedures for MAR and other water resources projects. Additionally, 93 different MAR projects from around the world were reviewed and a summary was synthesized to determine the most important MAR implementation factors. Besides these MAR projects, a number of related documents in the field of MAR and related fields in natural science were analysed to determine the shortcomings in MAR planning, management, and operation. Based on the gathered information, a comprehensive MAR planning framework was developed. A MAR planning framework is considered here as the nucleus for the entire study. In support of the potential decision maker to follow the framework, new innovative tools were developed. Based on the framework, five case studies were planned and performed, and results were compared. The following sections briefly present the general synthesis and conclusions of the entire study.

Decision Support for MAR planning and Management

For comprehensive support in the implementation and operation of MAR projects under water scarce conditions, an innovative geospatial decision support system (G-DSS) was developed within the scope of GABARDINE (Rusteberg et al., 2011). The following G-DSS modules were developed in the present study and integrated into the G-DSS: (i) MAR PLANNING module, (ii) a spatial MCA module for MAR site selection, and (iii) a MCA module for MAR option comparison and ranking. Beside the three modules, this study contributed substantially to the development of the DPSIR module of the G-DSS. The DPSIR module facilitates the structuring of existing water resources problems and supports the identification of potential responses. The artificial recharge planning module explicitly supports the decision steps that are required for project planning. The main planning steps include water quantity and quality checks of the available water resources as well as the selection of suitable locations together with recommendable MAR technology and definition of MAR project options for project comparison and ranking. The site selection module offers new and comprehensive spatial MCA methods to support the identification of suitable sites for the implementation of MAR projects. The MCA tool for project analysis and ranking considers a wide range of criteria and different analysis techniques, namely the Analytical Hierarchy Process (AHP) and the Weighted Linear Combination (WLC) method among others. The system supports the characterization of the water resources system on a basin level, covering water availability and demand analysis according to present state and future regional development, and providing a wide range of functions for graphical data representation of the relevant temporal and spatial data.

The system was implemented under ArcGIS environment to facilitate the implementation of spatial analysis procedures and results representation. In order to use the modules and related components of the G-DSS, an interactive interface was designed in the present study and provided in the G-DSS, which is user-friendly and helpful.

The following four important MAR planning tasks were selected and were subject of practical and detailed investigation on the case study level: (1) MAR pre-feasibility analysis, (2) Site selection and ranking, (3) Analysis, comparison and ranking of MAR planning and management options, and (4) Soil-Aquifer-Treatment (SAT) system operation and impact assessment. In total five case studies, one in Bangladesh and three of the GABARDINE project were selected to evaluate the MAR tasks (1) to (4):

(1) Dhaka City (DHAKA) Case Study, (2A) Querença Silves (QURSV) Case Study, (2B) North Gaza Site Ranking (NGSIR) Study, (3) North Gaza MCA (NGMCA) Study, and (4) Local Scale SAT Study (LSAT).

1. Dhaka City (DHAKA) Case Study: Pre-feasibility study for checking the viability of MAR projects

The MAR pre-feasibility study is considered to be the first step towards the implementation of any MAR project (Maliva and Missimer, 2010). A MAR prefeasibility study accounts for the hydrological components, such as water demand and supply, water sources and availability of non-committed water; hydrogeological characteristics, such as useful storage, available facilities of injection/infiltration; hydrogeochemical interaction of the recharged water with the native groundwater; and economical and regulatory aspects in the project area. Therefore, a number of technical, geographical, regulatory and legal pieces of information need to be collected and analysed to prepare a useful document for MAR practitioners. The document helps the decision maker to set up a policy for *Go/NoGo* decision-making.

By giving a real example of an over exploited and stressed aquifer in Dhaka, Bangladesh, the integrated investigations show the extensiveness of pre-feasibility studies and establishes the importance of taking each component of the water resources system, at local and regional scale, into consideration in order to come up with an appropriate MAR planning decision. The hydrological investigation confirms that rainwater harvesting can be more effective and economical when it is combined with MAR. The Dhaka City aquifer has a capacity to store recharged water, but geochemical processes were not identified due to the lack of mineralogical and sedimentological information from the aquifer. Mixing of artificially recharged water with native groundwater is an important process and a MAR pre-feasibility study should always focus on this issue as well. Though, a pre-feasibility study cannot give a reliable answer to all questions related to MAR implementation, especially with regards to potential impacts. However, the aim of the 'DHAKA' case study is to highlight, which information is necessary in the MAR planning process and thus this case study emphasizes prime research requirements that assist in the continuing pursuit of the realization of the MAR project in the Dhaka City region. From the 'DHAKA' case study, it is clear that for MAR a number of institutional involvements are required. Government interest and inter-institutional cooperation is therefore of primary importance to ensure the success of a MAR project. On the other hand, this multi-institutional involvement may make the decision-making process complex and time consuming.

The results of the 'DHAKA' case study are site specific and will therefore be different from the potential results of other areas. But this specific case study is an excellent example of an integrated approach that considers all components of local and regional water resources systems for MAR viability assessment, which can generally be applicable and practicable at any climatic and geographic condition around the world. Moreover, key assessment techniques, technical evaluations, and regulatory issues can be gathered, assessed, adjusted, improved, and transferred to other projects with similar hydro(geo)logical environments.

2A. Querença Silves (QURSV) Case Study: Spatial Multi criteria analysis for MAR site suitability mapping

The most basic requirement for a MAR scheme is land upon which to construct the MAR structure, monitoring network, and surface infrastructure. Complex regional characteristics, heterogeneities in surface and/or subsurface characteristics, and variable groundwater qualities make site selections for MAR difficult. The construction of MAR is even more challenging, when a number of competing agencies are involved in land acquisition, especially in urban and suburban areas. Hence, a decision support tool for MAR site suitability is quite essential. A new spatial multi-criteria decision analysis (SMCDA) tool for selecting suitable sites for MAR systems was developed. The new SMCDA tool is based on the combination of existing multi-criteria evaluation methods with modern decision analysis techniques. More specifically, non-compensatory screening, criteria standardization and weighting, and the Analytical Hierarchy Process (AHP) were combined with Weighted Linear Combination (WLC) and Ordered Weighted Averaging (OWA). The SMCDA tool offers some predetermined default criteria and standard methods to increase the trade-off between ease-of-use and efficiency. Integrated into ArcGIS, the tool has the advantage of using GIS tools for spatial analysis, and therein data may be processed and displayed. For the demonstration of the robustness of the new tool, the 'QURSV' case study was planned and executed at the Algarve Region in Portugal.

According to analysis results from the 'QURSV' case study, there are just a few areas, 11.2 % of the total aquifer, where the implementation of infiltration ponds would be feasible. Non-adequate surface characteristics cause further restrictions for MAR implementation. On the contrary, the underground characteristics, studied for the feasible areas, are adequate for the MAR implementation by means of infiltration technologies. The overall suitability maps, suggest installing the infiltration ponds in Zone 4 where the residence time of groundwater is more than three years. The high suitability areas, only 1% of the total area, are characterized by adequate unsaturated zone thickness, which is very important for water quality improvement. In order to obtain more locations for infiltration ponds, better analysis of restrictions with regard to land use and soil type is recommended.

Specific aspects of the tool such as built-in default criteria, explicit decision steps, and flexibility in choosing different options were key features, which benefited the 'QURSV' case study. The efficiency of the SMCDA tool in the decision making process for selecting suitable sites for MAR was also demonstrated through the 'QURSV' case study and in the same manner, can be applicable to any other place around the world for MAR site selection. Moreover, the tool is non-site specific, adaptive, and comprehensive, and may be applied to any type of water resources site selection problem.

2B. North Gaza MAR Site Ranking (NGSIR) Study: Site Suitability mapping and MAR site raking supported by groundwater modeling

It is important to note that the success of a MAR scheme largely depends on the hydrogeological condition of the study area, considering local and regional aquifer stratigraphy, lithology, extent and properties (ASCE, 2001). With this in consideration, potential sites must be assessed and ranked considering two phases of MAR project implementation. The first phase is site selection before MAR project implementation as based on the SMCDA procedure and the second phase is the ranking of best suitable places, obtained from the SMCDA, by using mathematical modelling. The second phase represents the synthetic case of the post MAR implementation phase. The model produces the simulated scenario of MAR in the selected locations considering a project life of at least about 20-50 years.

Considering a simple groundwater body in the northern Gaza coastal aquifer, an integrated approach – SMCDA analysis followed by a simple MCA analysis supported by groundwater modelling - was undertaken considering a project life until 2040. The 'NGSIR' case study demonstrates that the highly suitable places, screened and demarcated by SMCDA do not always have hydrogeologically favourable conditions. The analysis shows that infiltration water changes flow pattern of the area and hence, poses a difference in hydraulic conditions under a specific MAR location, before and after the onset of an infiltration operation. Groundwater model results demonstrate that depending on the position of the infiltration basin, the changes in groundwater level also contribute to the change of fresh water or saline water flow from the surrounding Israelian area or sea.

Therefore, it can be concluded that the hydrogeological impact assessment supported by mathematical modeling should be combined with SMCDA to get the optimum benefit of technology and information, and to minimize environmental risks for the best decision-making concerning MAR technology specific site selection.

3. North Gaza MCA (NGMCA) Study: Environmental, health, social and economical impact assessment and option comparison to rank the best MAR options

A substantial part of the most worldwide regulatory issues related to water reuse programs is devoted to minimizing environmental pollution, especially groundwater pollution, to ensure no risk to human health, and to maximize the benefit. Therefore, it is a prerequisite to perform environmental, social, health, and economical impact assessments of all the viable MAR options before implementation of any MAR project. A number of criteria need to be addressed for each sector. From the quantification of each criterion, ranking of the best options can be performed and thus the decision maker is able to pursue the best MAR project.

An extensive criteria selection, each criterion quantification by groundwater modeling and socio-economic survey and ranking of MAR management strategies were undertaken at the North Gaza Strip, where reuse of the treated effluent can provide an alternative to groundwater for irrigation. The MAR strategies were formulated based on the planned national water policy. The ‘NGMCA’ case study shows that the so-called “Do Nothing Approach” is not a real option for Gaza, as it contributes to further groundwater level dropping and groundwater quality deterioration, and increases the health risk for the Palestinian population. The performance analysis of the developed MAR strategies clearly shows that managed aquifer recharge by means of infiltration ponds with proper treatment is a viable response to the increasing water resources problems of the region. In general, the study distilled the most important and representative criteria that need to be considered. The required quantification procedure of representative criteria and the technical analysis required to quantify the criteria to complete a thorough analysis, evaluation, and ranking of most promising options of MAR was identified.

The experience gained from this study consolidates a basis to assist with planning of a MAR project, to evaluate economic and social acceptance of MAR options with respect to alternatives and to develop a policy framework consistent with the national water policy. It is hoped that the North Gaza experience will be useful not only to the other parts of the Gaza strip but also to the entire region such as the Lower Jordan Valley towards a sustainable development of urban and rural water resources.

4. Local Scale SAT Study (LOSAT): Groundwater monitoring plan and pond operation for SAT implementation

The integrated and organized approach of the field tests, laboratory experiments and analysis, and mathematical modeling shows the effectiveness of the implementation of state-of-the-art technology, which exists in other fields of natural science and in MAR project operation. The 'LOSAT' case study proposed a groundwater-monitoring plan based on water quality changes and temporal-spatial behaviour of certain emerging pollutants under SAT operations. A multi-level monitoring network is recommended to understand the transport of persistent pollutants in a layered aquifer system. An integrated investigation of the test site provides a scientific foundation to underpin infiltration pond operations and the detailed plan of the monitoring installation for further experiments and MAR implementation.

The overall outcome of the 'LOSAT' case study is the development of an integrated and organized approach that is necessary for intelligent short and long term SAT planning and operation. Decision making considerations include the ability to operate the infiltration ponds optimally, to identify water quality improvement, to observe spatial and temporal variability of micro-pollutants, and to evaluate and control potential sources of groundwater contamination during SAT system operation. The approach is helpful for the decision makers charged for planning of SAT operation and providing funds for priority research areas and to MAR practitioners responsible for the conception, design, and operation of SAT. Following this evolving outline, the regulatory and research groups can proceed in an orderly fashion toward planning and management of a successful SAT operation.

In General, the entire study, comprising G-DSS development and case studies, clearly suggest that the implementation of MAR is not only a local or site specific task, restricted to aquifer storage and water quality attenuation via recharge, but rather is part of a regional basin scale IWRM approach. The MAR planning framework developed under this study and the conclusions drawn from the case studies certainly facilitate the decision maker in dealing with the MAR non-straight forward decision-making process. The MAR planning workflow, an accompanying guideline, and the G-DSS with its modules and functionalities are general and therefore, can be applicable to any region concerned with MAR.

10.2 Further Perspectives

The detailed case studies and intensive investigations resulted in new perspectives that may be beneficial for future studies. Some key issues are discussed below:

The G-DSS can be considered as an open-end system and new modules can be continuously developed and incorporated. Efforts with respect to future DSS developments should be dedicated to the interconnection of the mathematical models and tools to support impact and risk assessment as well as the representative decision criteria quantification.

The MAR site selection module can be coupled with groundwater flow and transport modeling to achieve a more comprehensive approach for the selection process concerning the best locations of the MAR infiltration basins, as well as the locations of recovery wells and areas of groundwater protection. The module can be further developed to offer more decision analysis techniques to the end user. A number of standardization functions (e.g., concave, convex, sigmoidal functions, etc), weighting methods (such as ranking method, rating method, etc.), and overlay methods (e.g., fuzzy additive weighting method, composite programming, etc,) can be added to the existing SMCDA tool.

To support the decision maker for SAT system implementation, a guiding document should be developed, which may be referred to as "SAT implementation white paper" consists of a number of flowcharts, rule curves, and regulations, which will be supportive to the decision maker. The contents of the document should be supported by intensive reactive process-based groundwater modeling studies considering SAT performance variables such as water quality, pollutants' nature, recharge volume, hydrodynamic dispersion, aquifer heterogeneity, sediment and mineral compositions. A number of simulations produced by changing variables can create the required charts, flow diagrams, and guidelines for the proposed document. Brown et al., (2005) developed a performance matrix for ASR project planning in brackish water sites. The framework can be modified and incorporated to the produce by the above-mentioned "SAT implementation white paper."

During the performance of the case studies, some issues are just considered superficially and probably need further investigation. In case of 'DHAKA' case study, due to lack of sediment and mineral composition data of the upper Dupitila aquifer, geochemical process and possible mixing of recharged water with native water could not be analysed properly. Some sediment and mineral composition analyses together with isotope analyses will definitely improve the hydrogeochemical assessment of this particular study. Second, in case of SMCDA, the sub-criteria only considered the surface and sub-surface criteria, such as in 'QURSV' case study. At the final stage of analysis, incorporation of socio-economic criteria may be beneficial. Third, In 'NGSIR' case study, groundwater quality changes due to artificial recharge weren't included in the MCA analysis and should be considered in further studies. Fourth, in the 'NGMCA' case study, the conclusions drawn from groundwater flow models in the North Gaza strip don't consider any information on possible saline water intrusion. Due to the lack of data and access to the study area, a variable density groundwater flow model could not be developed. In order to quantify the contribution of MAR projects to control salinity intrusions, the application of a variable density groundwater flow model is recommended.

The MAR planning framework and related case studies do not consider regulatory aspects. Regulatory issues should consider the investigation outputs and deliver the direction of further impacts and risk assessments. The close interaction between regulatory knowledge and technological expertise is an important requirement for continued research on MAR implementation in the case study areas.

Figure 10.1, a flow diagram for the MAR research strategy, shows the intimate relationships among the research methodologies, which is the key issue to handle the MAR implementation integrated way. The research strategy is subdivided into a series of concerns or activities under each research methodology, such as mathematical modeling, laboratory experiments, field investigations, etc. New methodologies or activities may be added where required. A decision support system is considered as the core and final outcome of the MAR research strategy. The DSS receives information, guidelines, and threshold values from several research activities and provide feedback to these activities/methodologies for further research requirement. For example, the DSS formulate options/ scenarios for MAR implementation and through mathematical modeling study the impact of the scenarios can be determined. The quantified values can be than used for MCA analysis to rank the MAR options. Decision makers can involve in the MCA analysis by providing their importance criteria. Finally, the DSS will rank the best option for MAR implementation.

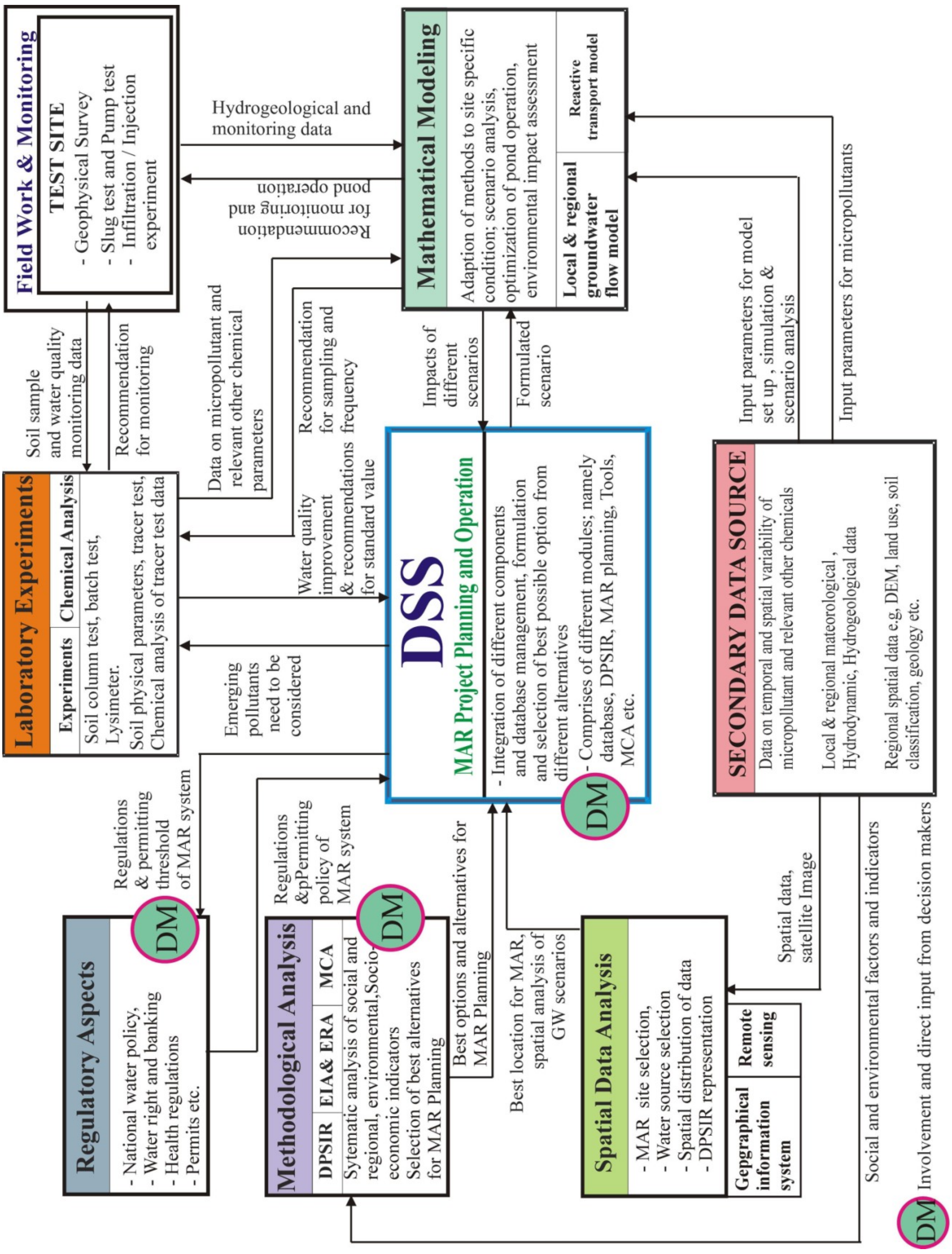

Figure 10.1: Future perspectives for DSS system towards sustainable MAR planning and management, showing the integration of different components of natural system, and analysis techniques and methodologies.

10.3 References

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Education

From May 2007 to date:
PhD: at Department of Applied Geology, Geoscience Center, Georg-August-Universität, Göttingen, Germany.

From September 2004 to September 2006:
M. Sc. in “Technology and Resource Management in the Tropics and Subtropics”: at Institute for Technology in the Tropics (ITT), University of Applied Sciences Cologne

From October 2001 to May 2004:
M, Sc. In Environmental Engineering from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh

From March 1996 to August 2001 :
B.Sc. in Civil Engineering from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh

Employment record

Year	**Employer**	**Position & Responsibility**
May 2007 to date	Georg-August-Universität, Göttingen, Germany	Scientific employee Development of Mathematical model, Decision Support System Development, Assist to project coordination, Activity, management and financial report writing
October 2006 to April 2007	Institute of Water Modelling (IWM), Bangladesh	Junior Specialist Development of Mathematical Model, Conduct Hydrographic, Topographic and Hydrometric data processing, Assist Report and proposal writing
September to November 2005	Aggerverband, Gummersbach, Germany	Internship Development of network model using ArcGIS, Assist in digitizing, mapping, pipe networking

October 2002 to May 2004	Institute of Water Modelling (IWM), Bangladesh	Junior Engineer Development of Mathematical Model, Conduct Hydrographic, Topographic and Hydrometric data processing, Assist Report Writing
January 2002 to September 2002	Department of Civil Engg., Bangladesh University of Engineering and Technology	Research Assistance Literature Review, Preparation of Experiment Methodology, Data Analysis, Report Preparation
August 2001 to December 2001	Intex Limited (Private Consulting Firm)	Design Engineer Supervision and Design of Construction