ESTIMATION OF IMPACT OF ARTIFICIAL GROUNDWATER RECHARGE IN SMALL ISLANDS USING A NUMERICAL MODELLING APPROACH

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Degree of Master of Science

Department of Civil Engineering

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for the degree Master of Science

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DECLARATION

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Dr. R.L.H.L. Rajapakse Date

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ABSTRACT

Estimation of Impact of Artificial Groundwater Recharge in Small Islands using a Numerical Modelling Approach

There are many small islands all over the world, which face scarcity of drinking water due to low rainfall, high evaporation rate, absence of surface water and salinity in groundwater. Island width, amount of recharge, pumping rates and aquifer properties are the governing factors of freshwater lens volume. Only a certain percentage of rainfall will percolate naturally into the ground and remaining rainwater will reach the sea without recharging the ground. In addition to natural recharge, artificial recharge can be used to increase the freshwater lens volume. In order to identify the effect of artificial recharge in the freshwater lens, the existing conditions of the aquifer and the volume of groundwater should be identified. It can be identified by using geophysical investigations, algebraic models or numerical models.

The objective of this study is to identify the impact of artificial recharge on aquifer condition and groundwater table in small islands by using a numerical modelling approach.

Three islands in the Maldives, namely Dharavandhoo, Henbadhoo and Bodufolhadhoo, which face scarcity of drinking water, were selected for this study. A two-dimensional numerical model was developed by using SUTRA (Model for 2D or 3D Saturated-Unsaturated, Variable-Density Ground-Water Flow With Solute or Energy Transport) with ModelMuse as graphical user interface (GUI). The model simulates the seawater-freshwater interface by using the following approach. Island undergoes a prolonged drought, which causes the water inside the island to become fully saline due to saltwater intrusion. Later, rainwater recharge to the island starts which drives out seawater, raise the water level on the island, and finally a constant freshwater lens develops over time. In the present study, the freshwater level and seawater-freshwater interface level in each island were measured by using electromagnetic surveys (Model: ABEM Terrameter SAS 1000), and aquifer properties were obtained from the literature and in-situ testing. Holocene aquifer hydraulic conductivity was calibrated until the percentage difference between simulated freshwater lens volume and observed freshwater lens volume is less than ±10%. The impact of artificial recharge was identified by increasing the recharge rate in the model by 5% and 10% of annual rainfall and simulating the previously calibrated model, presuming that artificial recharge can be increased to facilitate an additional recharge of 5–10% of annual rainfall.

Observed seawater-freshwater interfaces of the islands in most transects were in lens shape as expected, but interfaces in certain transects have clear upconing effect at particular locations due to over-pumping. The calibrated Holocene aquifer hydraulic conductivity values range from 25 m/day to 45 m/day, which is in the same order of magnitude for atoll island Holocene aquifer hydraulic conductivity values presented in previous studies. The analysis of the effect of artificial recharge indicates that the freshwater lens thickness and volume significantly increased with artificial recharge. With a 5% of annual rainfall as artificial recharge, the freshwater lens thickness of Dharavandhoo, Henbadhoo and Bodufolhadhoo islands increased from 5.2 m to 6.9 m (33%), 2.6 m to 4.0 m (54%) and 1.5 m to 2.7 m (80%), respectively and with a 10% annual rainfall as artificial recharge, it increased to 8 m (53%), 4.9 m (88%) and 3.4 m (127%), respectively.

Based on these results, it can be concluded that the model developed can be effectively used in quantifying the effect of artificial recharge on groundwater volume and artificial recharge will be a sustainable solution to overcome the scarcity of drinking water in small islands.

Keywords: Atolls, Freshwater lens, Maldives islands, SUTRA - Model Muse

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 General

Water is one of the most important natural resources, which is essential for the existence of all living beings. Frequent flooding, drought and contamination of potable freshwater resources are the common issues receiving much attention in water-related management arena nowadays. Population growth, climate change and environmental pollution have resulted in the scarcity of drinking water, aggravating water availability issues in many parts of the world. Many types of research are being carried out today to find advance methods and techniques to solve these water-related issues.

1.1.1 Definition of small islands

Over the world, there are about 50,000 small tropical islands located in Indian, Pacific and Atlantic Oceans and among them, 8,000 are inhabited with people (White, et al., 2007). UNESCO defined small islands as those having land area less than 2,000 km^2 and the width less than 10 km (UNESCO, 1991). Water scarcity is very crucial in these small islands due to low land area. Groundwater is the one and only natural water resource available for drinking and other household activities, where flowing or retaining surface water is rare and difficult to get any in required quantity and quality due to low land area and the unique topography prevailing in these islands.

1.1.2 Coral atolls

Generally, coral sand islands that are located fully or partially enclosing a shallow lagoon in the shape of a ring along with coral reef form an atoll (Bailey & Kivi, 2017). As there is a dual aquifer system (Holocene aquifer lies on top of Pleistocene paleo – karst aquifer) in atoll islands, they are different from other small islands. Atoll formation is a slow process that takes millions of years to develop. Underwater volcanic eruption creates a buildup of lava on the ocean bed, and due to many volcanic eruptions at a particular location again and again, the lava continues to grow until it comes out from the ocean's surface and then an island will be formed from the buildup of lava. Later, hard corals start to build up on the reef of the island. The coral reefs are made up of millions of hard exoskeletons of dead aquatic animals consisting of calcium carbonate. Finally, over time, ocean waves erode parts of the coral reef. The eroded corals become sand that covers up on the existing reef to form tiny island (Wonderpolis). Over 400 atolls exist in the world (Bryan, 1953). As they are not fixed to the earth's rock surface like other continents or land area, due to climate changes like oceanic disturbances, earthquake and sea level rises, their location, size and shape get changed from time to time.

Atolls can be further divided as low-lying atolls and elevated or high atolls. Based on previous studies, high atolls are identified as atolls having elevation greater than 4 m and the rest are classified as low-lying atolls (Pernetta, 1992; Richmond, Mieremet, & Reiss, 1997). In low-lying islands due to their low elevation, water will drain quickly into the sea thus, the existence of surface water in the form of a river or a pond will not be possible. However, in higher islands, there will be a possibility of surface water. According to literature (Barnett & Adger, 2003), Marshall Islands and Tuvalu are the countries that only consist of low-lying atolls while other islands have both low lying and elevated atolls.

1.1.3 Scarcity of drinking water in small islands

Freshwater resources of small islands are very precise, fragile and scarce. These islands situated far from continents and other countries, have unique physical, social, demographic and economic characteristics and often ignored by other countries. Scarcity of natural resources like land, vegetation, freshwater, energy sources and minerals, lack of economic development, frequent natural disasters like tsunami, sea level rise and coastal erosion, their isolation from other countries and distance between their communities, make the hydrological and water resources management of these islands critical (Falkland A. C., 1993). Many developed small islands have very high population densities as most of the people in those islands wants to settle in the developed cities rather than suffering in undeveloped village areas. It causes high stress on the water resources of these cities. The population of Male in the Republic of Maldives is over 50,000 in 1.3 km^2 area (Zahir, 2015). Due to the scenic beauty and isolated nature of these islands, they act as main tourist destinations, which results in many resort development and commercial activities in these tiny islands. Other than over pumping due to high demand, pollution resulting from commercial activities is also another threat, which causes huge stress on freshwater resource management of these islands. Many previous studies on small island freshwater lens condition have concluded that seawater intrusion as well as depletion of freshwater lens have occurred in many islands due to over pumping (Post, Bosserelle, Galvis, Singlaire, & Werner, 2018; Banerjee & Singh, 2011).

In certain worst cases, available freshwater on the island has been depleted or polluted or become fully saline into an extent where off-island sources of water are the only options available. Desalination of seawater from the nearby lagoon area and importation of water from nearby islands or continents will be costly options. The isolated nature of these islands from the nearby land area makes it difficult to supply water from anywhere else. Desalination or reverse osmosis will results in high costs, which will not be possible in these islands. Other than these, natural disasters such as cyclones, earthquakes, volcanic eruptions and storm surges are also common in small islands due to their geo-morphological setting. These disasters will further deplete the freshwater lens and it will take many years to rebuild the depleted freshwater lens again (Chui & Terry, 2012; Holding & Allen, 2015). They are also affected by frequent flooding and droughts due to the change in rainfall pattern. Many research studies have found out that sea level rise due to global warming will be the greatest threat in future on the freshwater lens in small islands (Gingerich, Voss, & Johnson, 2017; Oberle, Swarzenski, & Storlazzi, 2017; Ketabchi, Mahmoodzadeh, & Ashtiani, 2013).

1.1.4 Current measures in small islands to solve drinking water issues

Rainwater harvesting is the common method adapted in small islands for the usage of water in rainy days thereby they safe groundwater for dry season. This method is more efficient in islands which have high and regular rainfall and which is regular like Tavalu Island (Thompson, 1987). Most of the other islands have low rainfall and irregular rainfall pattern. In those islands, rainwater harvesting is used for essential needs like drinking and cooking. For other requirements, groundwater will be used even though its quality is not suitable for drinking. The amount of rainwater that can be saved in a tank is limited and the collected water will evaporate quickly due to high temperature prevailing in these islands therefore, in dry season the community will depend on groundwater for all their needs. Over extraction of groundwater during dry season cause salinity intrusion as well as depletion of freshwater lens.

To solve the water related issue in a community basis some techniques like surface water resources development such as reservoirs, tanks, dams and other storages are being used in some islands (Wilson, 1986; Waterhouse & Petty, 1986). Nevertheless, these techniques are not suitable in small islands due to their unsuitable topography and high costs (Falkland T. , 1999).

1.1.5 Artificial groundwater recharge and fresh water management

Artificial groundwater recharge method is considered as one of the most sustainable ways to solve groundwater issues, especially in small islands. Recharging the ground with available rainwater during the rainy season will help to supply water in dry season without causing freshwater lens depletion due to over-extraction. Implementation of artificial recharge is increasing in countries like Netherlands, Poland, Belgium, Spain, Australia, South Africa, Greece and Switzerland (Krinner & Lallana, 2001).

The main advantages of artificial recharge are the recovery of overexploited aquifers, storage of floodwater and utilization/supply during dry seasons, reduction in land subsidence, provision of continuous municipal water, reduction in groundwater salinity around agricultural fields, and reduction in seawater intrusion around coastal areas. However, there can be various disadvantages due to the artificial recharge such as discharge of nutrients and micro-pollutants which may cause negative longterm impacts on soil and aquifer and it may not be economically feasible if it is not designed, implemented and analysed properly (Siddiqui, 2016).

Many experimental studies have been carried out to identify the impact of artificial recharge. Groundwater storage volume was monitored throughout the recharge period during these studies which concluded that the quantity and quality of groundwater increased with artificial recharge (Kaledhonkar, Singh, Ambast, & Tyagi, 2003). Some studies focused on finding the best method and location for artificial recharge (Saleh, Almasri, & Shaheen, 2009). Based on the climatic and geological conditions of the study area, the most suitable method and location will change.

1.1.6 Brief introduction about the study area

This study was carried out in three small islands in the Maldives that face severe scarcity of drinking water. The location of the Republic of the Maldives is shown in Figure 1.1. It is situated in the Indian Ocean near India and Sri Lanka. There are about 2000 islands and among them, 200 are occupied with people (Alsumaiei & Bailey, 2018). In the Maldives, there are 26 atolls which differ in size and among them, Huvaddu atoll (with an area of 2,800 km^2) is the largest while Thoddoo atoll (with an area of 5.4 km^2) is considered to be the smallest (Karthikheyan, 2010). This state extends from the 8º North to 0º South (Equator), while being bound by Ihavandhippolhu Atoll in the north and Addu Atoll in the south. The capital of the Maldives is Male'. Maximum prevailing ground elevation is 2.4 m above sea level; village Villingili of Addu atoll has the highest elevation point. Elevation of 90% area in the Maldives is less than 1 m (Deng & Bailey, 2016). Most of these areas get adversely affected by recurrent flooding during high tide conditions.

Figure 1.1: Location of the Maldives islands

The climatic condition of the Maldives islands is warm and tropical as it is situated near the equator. The average annual temperature is 28.0° C and the average relative humidity is 80% (Deng & Bailey, 2016). In a previous study, regarding rainfall variation of the Maldives islands (Bailey, Khalil, & Chatikavanij, 2014), rainfall data were collected for various locations from Rainfall Tropical Mission and based on the analysis it was identified that rainfall pattern in the Maldives differs in three regions of 5° N to 10° N, 0° N to 5° N and 5° S to 0° N where the rainfall increases from north to south with an average annual rainfall of 1,715, 1,940, and 2,380 mm, respectively (Deng & Bailey, 2016; Bailey, Khalil, & Chatikavanij, 2014).

Due to the high permeability of island soils, rainwater infiltrates quickly into the soil and due to low elevation, the formation of streams or surface water bodies is not possible in these islands (Urish, 1974), thus these communities depend on a combination of rainwater harvesting, desalinized or reverse osmosis seawater or lagoon water and groundwater for their domestic and manufacturing needs (Bailey, Khalil, & Chatikavanij, 2014). Freshwater lens condition of most of the Maldives islands are under serious risk due to changing climatic pattern, sea-level rise due to global warming (Pernetta, 1992; Lal, Harsawa, & Takahashi, 2002; Moorner, Tooley, & Possnert, 2004), increasing urban population, limited rainwater capacity and contamination (Woodroffe, 2008; Barthiban, 2012).

The atoll islands of the Maldives were also formed by volcanic eruptions which resulted in a hard limestone Pleistocene layer at the bottom and a Holocene sand surface on top of it, with a solution or media discontinuity known as Thurber discontinuity. This discontinuity is located approximately 13-18 m below sea level (Wheatcraft & Buddemeier, 1981; Bailey, Khalil, & Chatikavanij, 2014). Hydrogeological characteristic of the Maldives islands is shown in Figure 1.2. Pleistocene layer's hydraulic conductivity is a hundred times higher than that of Holocene aquifer (Woodroffe & Falkland , 1997; Bailey, Khalil, & Chatikavanij, 2014). Higher hydraulic conductivity of Pleistocene layer is identified as the main reason for the thin freshwater lens in the Maldives islands (Bailey, Khalil, & Chatikavanij, 2014). Aquifer properties of both Holocene and Pleistocene layer are given in Table 1.1.

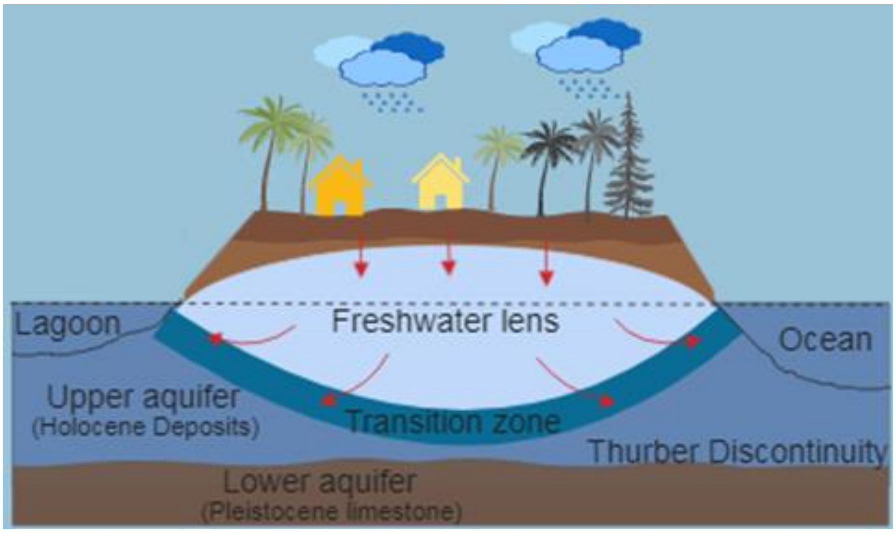


Figure 1.2: Hydrogeological characteristics of Maldives islands

Table 1.1: Aquifer properties of Maldives islands

Aquifer property	Value	Source
Longitudinal dispersivity	6 m	(Griggs & Peterson, 1993)
Transverse dispersivity	0.005 m	(Griggs & Peterson, 1993)
Holocene layer thickness	15 m	(Hamlin & Anthony, 1987)
Holocene horizontal conductivity	75 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Holocene vertical conductivity	5 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Pleistocene horizontal conductivity	5000 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Pleistocene vertical conductivity	1000 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Porosity	0.15	(Anthony, 1997)

1.2 Problem Statement

Scarcity of drinking water is a common problem in small islands all around the world. Artificial groundwater recharging method is adapted by some of the developing islands to solve the water related issues. The knowledge of the impact of artificial recharge on the existing groundwater table is only available to a certain level in certain small islands with the high scarcity of drinking water but the long term impact of artificial recharge on groundwater level and its impact on water resource management is not adequately analysed.

1.3 Objective of the Study

1.3.1 Main objective

To identify the effect of artificial recharge on the freshwater lens of small islands in the Maldives by using numerical modelling method.

1.3.2 Specific objectives

- To conduct a detailed literature study to identify the present state of research on the topic.
- To collect available data required for the study and check for consistency and reliability.
- To develop, calibrate and validate a numerical model for groundwater modelling in the Maldives islands with available data.
- To find out the change in freshwater lens condition due to artificial recharge.
- Sensitivity and uncertainty analyses
- Deriving conclusions and recommendations for the long-term water resources management in small islands.

1.4 Outline of Thesis

There are six chapters in this thesis.

The first chapter presents an introduction to the research topic with problem statement and objectives. The second chapter reviews the literature on methods used in freshwater lens modelling, studies carried out in Maldives islands, knowledge on artificial recharge and identifies the research gap.

Chapter three describes the materials and methods used in the study. It gives details about the study area, collected data sets and the methodology followed in the study. Model selection, model development, calibration of model and method used in calculating freshwater lens volume is also described in this chapter.

The fourth chapter presents the results of data checking, sensitivity analysis, model calibration and effect of artificial recharge. Chapter five discusses the outcomings of the research. The sixth and final chapter provides conclusions based on this study and recommendations for implementation and future research.

2 LITERATURE REVIEW

2.1 General

In order to identify the effect of artificial recharge in the freshwater lens, the existing condition of groundwater and aquifers should be identified. There are many research studies carried out to identify the existing groundwater and aquifer conditions of small islands specifically those facing high scarcity of drinking water mostly in the Maldives (Kivi & Bailey, 2017), China (Zhou X. , 2011; Hu & Jiao, 2010) and Islands in Pacific (Chui & Terry, 2012; Barkey & Bailey, 2017).

2.2 Methods used in Modelling Freshwater Lens

Different methods like geophysical investigations with airborne electromagnetic systems (Costabel, Bernhard, Hourben, & Gunther, 2017; Houben, Noell, Vassolo, & Grissemann, 2014), numerical modelling (Olsen, Bailey, & John, 2010; Holding & Allen, 2015; Szymkiewics, Kawecka, Simunek, & Leterme, 2018) and algebraic modelling (Jenson & Bailey, 2011) are used to identify the existing groundwater level.

2.2.1 Geophysical investigations

Geophysical investigations are the most accurate method to identify the existing groundwater level conditions. The freshwater level will be directly measured in the field by using different techniques and will be interpreted. In the past, the only method to identify the groundwater condition was by using dug wells or bored wells. Nowadays, many novel and advance technologies are being used in order to improve the accuracy and easiness of measurement.

Airborne electromagnetic (AEM) surveys are being used recently to provide underground hydrogeological information like water level, aquifer properties and rock characteristics (Seimen, Esban, & Christiansan, 2009). Airborne surveys have the ability to cover large areas quickly without causing disturbance to local activities and the environment. These methods are less risky and cost effective. In the electromagnetic methods, there will be a transmitter as well as a receiver. Transmitter carries the current in which magnitude varies as a function of time. This current has a similar time dependence magnetic field. Based on Faraday’s Law of Induction, this time varying magnetic field induces a magnetic flux in the ground. These magnetic currents will be detected by the electromagnetic receiver.

The transmitter and receiver do not need to touch the ground; they can be mounted on an aircraft (McNeill, 2006). There are many varieties of Airborne Electromagnetic method like Helicopter Borne Electromagnetics (HEM), Transient Electromagnetics (TEM) and Magnetic Resonance Sounding (MRS). Even though airborne electromagnetic surveys provide many advantages, there are certain drawbacks in this method when compared with traditional methods. Great skill is required in measuring and interpreting the data. As many alterations and calculations are involved in these methods, there will be uncertainties in the measured data that require a validation based on direct observation.

2.2.2 Algebraic modelling

In literature, several methods have been developed to evaluate the thickness of the groundwater lens in the absence of empirical data and to identify the lens condition in future based on certain scenarios like climatic change and disaster situations. Most of the algebraic models are primarily built up by adopting Ghyben-Herzberg principles (Drabbe & Ghyben, 1888; Herzberg, 1901). It is implied in the principle that the ratio between water table above mean sea level and depth to the seawater - freshwater interface below the mean sea level is approximately 1:40 (Robins, 2013). Though this principle assumes that seawater and freshwater are separated by a sharp interface, actually there is a diffusion zone. The Ghyben-Herzberg equation is given by,

$$h = \alpha H \tag{1}$$

where, h is the elevation of the fresh water level above mean sea level, H is the elevation of freshwater - seawater interface below mean sea level and $\alpha = (\rho_s - \rho_f)/\rho_f$ with ρ_s, ρ_o are the densities (kg/m^3) of seawater and freshwater, respectively.

By using Dupuit-Forcheimer assumptions, an algebraic model was developed (Jacob & Henry, 1945), where the lens depth (H) at a distance (x) from the centre of the lens is given by Eq. (2),

$$H^2 = \frac{N(L^2 - x^2)}{K\alpha(1+\alpha)} \tag{2}$$

where, N is the recharge rate, L is lens radius and K is hydraulic conductivity. This equation is valid for single layer aquifers only. Eq. (2) was accordingly modified for infinite strip circular islands with multi-layered aquifers as in Eq. (3) (Fetter, 1972),

$$H^2 = \frac{N[R^2 - r^2]}{2K_{avg}\ \alpha(1+\alpha)} \tag{3}$$

where, R and r are for radius of the island and radial coordinate, respectively. K_{avg} was calculated by using Eq. (4),

$$K_{avg} = \frac{K_1\,(b_1 + h) + K_2\left\{\left(\frac{1}{\alpha}\right)h - b_1\right\}}{h\,(1 + {}^{1}\!/_{\alpha})} \tag{4}$$

where, K_1 and K_2 denote horizontal conductivities of first and second layers, respectively while b_1 is the thickness of the upper aquifer layer below mean sea level (Fetter, 1972). However, it was identified that this equation is valid only when the freshwater lens thickness is confined to the Holocene layer only (Vacher, 1988).

In wide islands, these models over predict the freshwater lens. When the freshwater lens meets Thurber discontinuity point, it will rapidly mix with seawater due to high hydraulic conductivity of Pleistocene layer. To take the effect of Thurber discontinuity an algebraic model was developed (Bailey, Jenson, & Oslen, 2010). Depth of freshwater lens given by Z_{max} is calculated by,

$$Z_{max} = L(1-e^{-bR})SC \tag{5}$$

where, R is the average annual rainfall, b is the factor for the width of the island cross section, S and C are the factors for hydraulic conductivity and L is the upper limit of freshwater lens given by,

$$L = Y_0 + (Z_{TD} - Y_0)\,(1-e^{-dw}) \tag{6}$$

where, Z_{TD} is the depth to Thurber discontinuity, w is the width of the island cross section, Y_0 and d are constant.

Table 2.1 summarises the algebraic equations and the parameters involved in those equations.

Table 2.1: Summary of algebraic models used in freshwater lens modelling

Reference	Equation	Input parameter
(Drabbe & Ghyben, 1888; Herzberg, 1901)	$h = \alpha H$	Density of seawater and freshwater and elevation of seawater - freshwater interface
(Jacob & Henry, 1945)	$H^2 = \frac{N(L^2 - x^2)}{K\alpha(1+\alpha)}$	Recharge rate, lens radius, distance from the centre of the lens, hydraulic conductivity and density of seawater and freshwater
(Fetter, 1972)	$H^2 = \frac{N[R^2 - r^2]}{2K_{avg}\ \alpha(1+\alpha)}$	Recharge rate, radius of island, distance from the center of the lens, hydraulic conductivity and density of seawater and freshwater
(Bailey, Jenson, & Oslen, 2010)	$Z_{max} = L(1-e^{-bR})SC$	Average annual rainfall, factor for width of the island cross section, factors for hydraulic conductivity and upper limit of the freshwater lens

2.2.3 Numerical modelling

Numerical modelling uses some mathematical equations to convert the physical condition and simulate it to find the output. As many complex equations are involved in groundwater flow and solute transport, numerical modelling plays a major role in groundwater studies (Konikow, 2000). Usage of mathematical models came in to practice at the year of 1800 A.D. The development of advanced computers in the 1960s had its impact in each field; same way in groundwater studies also usage of numerical solutions with mathematical models had been identified as a suitable approach to solve many issues in groundwater studies.

Many equations are there in groundwater flow and solute transport. There are two types of numerical modelling, finite difference modelling and finite element modelling. These methods use approximations to solve the differential equations. The accuracy of the output produced by numerical modelling will depend on the quality of the input data, size of grid space and time resolution and the numerical method used in solving the model equation. In history, the first numerical modelling for the freshwater lens dynamic of atoll islands was by Ronald K. Lam in 1974. Finite difference method was used to estimate permeability from tidal data (Lam, 1974). Later, many models were developed. MODFLOW, MT3DMS, SEAWAT and SUTRA are the most common software used in previous studies.

2.2.3.1 Modular Finite Difference Model (MODFLOW)

Modular Finite Difference Flow Model (MODFLOW) is a 3D finite model developed by McDonald and Harbaugh (McDonald & Harbaugh, 1984) of United State Geology Survey in 1984 in FORTRAN 77 (American National Standards Institute, 1978) language (Wang, 2008). It had been updated three times in the name of MODFLOW-88, MODFLOW-96 and MODFLOW-2000. The current version of MODFLOW-2000 is supported by C language also (Wang, 2008). MODFLOW developed by United State Geology Survey is a free public domain software but as it is written in FORTRAN language, the input files have to be given as text, which is time consuming and complex. Many Graphical User Interfaces (GUI) for MODFLOW were developed. Among them, Visual MODFLOW developed by Waterloo Hydrologic Company in 1994 which is a commercial version is the common software used by groundwater modellers. This Graphical User Interface will help to input data by using Excel, Surfer grids, GIS and AutoCAD. Understanding and correcting errors will be easy when a GUI version is used instead of using the source code version.

The MODFLOW software consists of the main program and modules. Modules are further divided into packages. Each package is used to represents the specific flow system of the model. User can select a suitable package for each flow system, for example, flow from or flow into a source. Allocating separate modules and packages helps in adding newly developed modules or packages without altering the existing system.

It can be modelled in 2D or 3D modelling. Block centre finite difference method is used to simulate the groundwater flow. Aquifer layers can be modelled as confined or unconfined.

The main limitation of this model is, it can not be used to simulate thermal and solute transport problems. Thus, it will not be suitable in modelling saltwater intrusion problems, freshwater lens thickness modelling of small islands, etc. Some researchers used a combination of MODFLOW and other software like MT3DMS or SEAWAT in addressing such issues in freshwater lens and solute transport modelling.

The MODFLOW is most commonly used in modelling groundwater flow of large catchment areas where groundwater infiltration and percolation from an aquifer to aquifer are the governing factors (Jyrkama, Mikko, & Jon, 2007; Feng, Juan, Liu, & Zhao, 2010; Faghihi, Neda, Kave, & Babazadeh, 2011). MODFLOW gave successful results in analyzing saltwater intrusion due to over pumping in a coastal aquifer (Rejani, 2008; Zume, Joseph, & Tarhule, 2008), used for designing of dewatering systems (Yang & Qiang, 2009; Surinaidu, 2015) and solving groundwater contamination issues (Rao & Tamma, 2011; Parameswari, Mudgal, & Nelliyat, 2012; Qi-Peng & SHi, 2012).

2.2.3.2 MT3DMS (Modular Three-Dimensional Multispecies Transport Model

MT3DMS (Modular Three-Dimensional Multispecies Transport Model) is a three-dimensional (3-D) transport model developed originally in the name of MT3D by S. S. Papadopulos and Associates, Inc. in 1990 (Zheng C. , 1990) and further developed in 1999 with the help of United State Army Engineer Research and Development Center (Zheng & Wang, 1999).

This model has the capacity to solve advection, dispersion and chemical reactions of dissolved constitutions in groundwater. It uses MODFLOW in the first step to simulate flow and to find heads and cell by cell flux terms. The outputs will be written in a specially formatted file and will be inputted to the MT3DMS and used to simulate transport part of modelling. Different boundary conditions can be created and external sources like sinks can be introduced in the model. Automatic model calibration is available in this software.

The lateral flux exchange from stream to aquifers can not be simulated by using this model (Simon, Bernard, Muerville, & Ruber, 2015) and another limitation of this model is it will not take the effect of density variation in modelling (Zheng, Hill, Cao, & Ma, 2012).

This model was used in many groundwater studies which are related to solute transport (Wu, Lu, Zhang, & Bodvarsson, 2004; Chau & Jiang, 2002; Kourocas & Harter, 2014) like groundwater pollution investigations (Vargese, Alappat, & Sammad, 2015; Ghoraba, Zyedan, & Reshwan, 2012).

2.2.3.3 SEAWAT

As the groundwater level of small islands is influenced by sea level rises, modelling with MODFLOW will not give effective results as it does not give much consideration for variable density groundwater flow and therefore, a new model SEAWAT developed based on MODFLOW and MT3DMS is used in simulating groundwater lens conditions of small islands (Taliby, Pandit, & Heck, 2017). SEAWAT is a coupled version of MODFLOW and MT3DMS developed by United States Geology Survey (USGS). It uses MODFLOW to solve the flow system and MT3DMS to solve the solute transport equations (Guo, 2002).

Since this software is a combination of both MODFLOW and MT3DMS, it is easy to use for the users of MODFLOW and MT3DMS. The new users must first get familiar with these software before using SEAWAT. In most of the situations, many preprocessors can be used to create input files but in certain cases, the input files may have to be written (Christian, Langevien, & Guo, 2006).

The original version of SEAWAT is written in FORTRAN language. The available free GUI interfaces like Model Muse, Model Mate, etc., do not support this software. There is a GUI version of SEAWAT but it is a commercial version.

The SEAWAT is one of the widely used codes to simulate saltwater intrusion (Lathashri & Mahesha, 2015; Guha, 2010) and in modelling freshwater lens of islands (Comte, Join, Banton, & Nicolini, 2014; Bosserelle, Jakovovic, & Post, 2015; Banerjee & Singh, 2011; Pauw, Baaren, Visser, De Louw, & Essink, 2015).

2.2.3.4 SUTRA (Saturated Unsaturated TRAnsport model)

Another model SUTRA (Saturated Unsaturated TRAnsport model) was developed in 1984 (Voss, 1984) by United State Geology Survey. It was developed in the name of SUTRA 2.0, SUTRA 2.1 and SUTRA 2.2.

This model can simulate the saturated or unsaturated flow of constant or varying density groundwater flows. Flow can be either steady-state or transient state. This software does not have its own GUI version but interfaces like Model Muse and Argus ONE can be used to create input and view output of the model.

There are some drawbacks in this software. This model can not simulate multiphase flow and it can not simulate both temperature and solute problem inside one model. It does not have an automatic calibration facility (Voss, 1984).

It is a commonly used software in modelling saltwater intrusion and atoll island freshwater lens (Bailey, Khalil, & Chatikavanij, 2014; Griggs & Peterson, 1993; Bailey & Jenson, 2009; Deng & Bailey, 2016; Gingerich, Voss, & Johnson, 2017).

The Geographical Information System (GIS) is an important tool used in groundwater modelling (Stafford & Michael, 1991; Goodchild, 2014). GIS act as a representing tool to input the spatial information like groundwater level, aquifer properties and elevation data to the model (Sudhakar, Verma, & Soumya, 2016). It helps in modelling by increasing the time efficiency, simplifying data handling, storage and sharing and helps in representing the model output (Zhou & Li, 2011; Russo, Fisher, & Lockwood, 2014).

Summary of the numerical models used in groundwater studies is given in Table 2.2.

Table 2.2: Summary of numerical models used in groundwater studies

Model used	Modelling purpose	References
MODFLOW	Modelling groundwater flow in large catchments	(Jyrkama, Mikko, & Jon, 2007; Feng, Juan, Liu, & Zhao, 2010; Faghihi, Neda, Kave, & Babazadeh, 2011)
MT3DMS	Groundwater flow related to solute transport	(Wu, Lu, Zhang, & Bodvarsson, 2004; Chau & Jiang, 2002; Kourocas & Harter, 2014)
SEAWAT	Saltwater intrusion problems and freshwater lens modelling of atoll islands	(Comte, Join, Banton, & Nicolini, 2014; Bosserelle, Jakovovic, & Post, 2015; Banerjee & Singh, 2011; Pauw, Baaren, Visser, De Louw, & Essink, 2015; Lathashri & Mahesha, 2015)
SUTRA	Freshwater lens modelling of atoll islands and saltwater intrusion problems	(Bailey, Khalil, & Chatikavanij, 2014; Griggs & Peterson, 1993; Bailey & Jenson, 2009; Deng & Bailey, 2016; Gingerich, Voss, & Johnson, 2017)

2.3 Studies Carried out in the Maldives Islands

The existing groundwater studies in the Maldives islands are not adequate to get a clear idea about the present freshwater lens conditions in individual islands and their aquifer properties. Existing aquifer properties of these islands have not been studied properly. The type of aquifers of these islands are identified as Holocene layer and Pleistocene layer and their properties like transmissivity, conductivity and porosity values were obtained from previous studies carried out in Marshall islands (Hamlin & Anthony, 1987) and islands in Federated state of Micronasia (Anthony, 1997) with similar aquifer conditions. Since several past studies (Bailey, Khalil, & Chatikavanij, 2014; Deng & Bailey, 2016; Alsumaiei & Bailey, 2018) in the Maldives islands conducted based on these data have produced successful results, these data are used in this study. Some studies took efforts to measure the freshwater lens thickness and to estimate the freshwater lens volume for certain islands (Falkland T. , 2000; Falkland T. , 2001).

An algebraic model developed in a previous study (Bailey, Jenson, & Oslen, 2010) given by equation (5) and (6) was applied for nine islands with different size in the Maldives (Bailey & Kivi, 2017). The model uses simple steady-state concept and parameters of the model are annual average rainfall, the width of the island along a particular cross-section, hydraulic conductivity and depth of Thurber discontinuity. By using the algebraic model, the freshwater lens thickness along a particular cross-section was calculated and then by using trapezoidal geometry, the freshwater volume of the groundwater lens was calculated. Based on the results, it was identified that the freshwater lens thickness of small islands is governed by the rate of rainfall and hydraulic conductivity value while the freshwater lens thickness of large islands is governed by depth to the Thurber discontinuity. The freshwater lens thickness increases with island width but once it reaches the interaction between Holocene layer and Pleistocene layer, it will mix with seawater quickly due to the higher conductivity of the Pleistocene layer. Even though the depth of Thurber discontinuity is an important parameter in simulating the freshwater lens condition of large islands, measuring it is a costly process, therefore it was assumed as 15 m (Bailey & Kivi, 2017).

In another study, dynamic freshwater lens thickness was simulated by using rainfall data of 14 year period (1998-2011) (Bailey, Khalil, & Chatikavanij, 2014). From the collected rainfall data, the Maldives region was divided into three regions, namely 5º N–10º N, 0–5º N and 0–5º S, and the average annual rainfall values of these regions are 1,715 mm, 1,940 mm, and 2,380 mm, respectively. The southern region has higher rainfall but unfortunately, there are no much islands within this region. Two-dimensional numerical simulation by using SUTRA model was used to simulate the freshwater lens thickness. Daily recharge depth for the model was calculated by using the soil water budget model (Falkland A. C., 1994). Based on the results, it was identified that many of the islands have an adequate freshwater lens but its thickness reduces in the dry season and gets totally depleted in small islands. During the 14 year analysis period, the islands in northern regions (0–5º N and 5º N–10º N) experienced an overall decrease in the freshwater lens while islands in the southern region (0–5º S) experienced an overall increase in freshwater lens thickness.

Sea level rise is the greatest threat for the islands like the Maldives. Some studies were carried out to identify the impact of sea-level rise on the freshwater lens condition of these islands (Alsumaiei & Bailey, 2018; Deng & Bailey, 2016). The recession on the shoreline was calculated by using the researched sea level rise rate (5 mm/yr (Mee, 2011)). Based on the results, it was concluded that smaller islands are more vulnerable due to sea-level rise than the larger islands. Table 2.3 summarises the details about the studies carried out in the Maldives islands.

Table 2.3: Summary of studies carried out in Maldives islands

Title	Source	Findings
Estimating Transient Freshwater Lens Dynamics for Atoll Islands of the Maldives	(Bailey, Khalil, & Chatikavanij, 2014)	Rainfall data of 14 year period (1998-2011) was used to simulate dynamic freshwater lens with observed lens data. Based on the results the islands in northern regions (0–5º N and 5º N–10º N) experience an overall decrease in the freshwater lens while islands in southern region (0–5º S) experience an overall increase in freshwater lens thickness.
Method for Estimating Available Groundwater Volume of Small Coral Islands	(Bailey & Kivi, 2017)	A model was developed to estimate the freshwater lens volume of Islands in the Maldives. Lens volume of large islands is governed by the depth of Thurber discontinuity and that of the small islands is governed by rainfall rate and hydraulic conductivity.
Assessing Groundwater Availability of the Maldives under Future Climate Conditions: Future Groundwater Availability of Maldives	(Deng & Bailey, 2016)	Future rainfall pattern and sea-level rise impact were taken into consideration. Results imply that the lens thickness of small islands (200 m) will decrease by 60% to 100% while that impact is considerably less (12% to 14%) in large islands (400 m).
Quantifying Threats to Groundwater Resources in the Republic of Maldives Part I: Future Rainfall Patterns and Sea Level Rise	(Alsumaiei & Bailey, 2018)	Numerical modelling was carried out for four islands in the Maldives to identify the impact of sea-level rise. Results show that small islands of area less than 0.6 km^2 are more vulnerable and that their freshwater lens volume reduces by 11% to 36% while the large islands are less vulnerable, and the lens volume of large islands reduces only by 8% to 26%.

2.4 Knowledge on Artificial Recharge

Most of those previous studies on artificial recharge are based on qualitative analysis to identify the methods, advantages and disadvantages of artificial recharge (Mukherjee, 2016; Abellan, Rico, & Garcia, 2017). Implementing artificial recharge in a community is an easy process, as the common people can easily understand this sustainable solution and it causes no damage to the community. Artificial recharge helps not only in the dry season by increasing the yield but also in the wet season by reducing flood, landslide risk (not applicable to the Maldives islands) and soil erosion effects. Even though it has many advantages, there are some disadvantages like contamination, clogging of aquifers and economic issues (Mukherjee, 2016).

Many techniques like surface method (ponds, canals, trenches and riverbeds), deep underground systems (wells or boreholes) and induced recharge (pumping wells) are used to facilitate artificial recharging of groundwater. Some of the studies were focused on finding the best method (Mohan & Abraham, 2015) and location (Yaraghi, Haghighi, & Ronkanen, 2017) for artificial recharge. Based on the geological conditions, aquifer properties, land use pattern and rainfall pattern, etc., the best technique will vary. Suitable technique and location must be identified prior to implementing the project to make the artificial recharge efficient. Improper methods and locations will end up in uneconomical and inefficient systems.

Several experimental based research projects have been carried out to find the change in groundwater level due to artificial recharge (Saleh, Almasri, & Shaheen, 2009; Kaledhonkar, Singh, Ambast, & Tyagi, 2003; Igboekwe & Ruth, 2011). In such studies, bored wells were used to monitor the change in groundwater level before and after recharge. From the above studies, it was identified that the groundwater level increases up to a considerable amount with artificial recharge. The effectiveness of artificial recharge varies from region to region. In a previous study to find a solution to overcome seawater flooding event, artificial recharge was identified as a better method, as it helps in reducing the recovery period and improves the quality of water (Gingerich, Voss, & Johnson, 2017). Table 2.4 summarises the details about artificial recharge studies.

Table 2.4: Summary of studies on artificial groundwater recharge

Title	Reference	Description	Findings
Artificial Groundwater Recharge. Review of the Current Knowledge of the Technique	(Abellan, Rico, & Garcia, 2017)	Analyses the knowledge on artificial recharge techniques	Surface methods like trenches, ponds, canals and riverbeds, and deep underground systems like wells or boreholes, and induced recharge by pumping wells are the current techniques used in artificial recharge.
A Review on Artificial Groundwater Recharge in India	(Mukherjee, 2016)	Summarises the methods, advantages and disadvantages of artificial recharge	Need for artificial recharge in India is high. Certain areas have inefficient artificial recharge systems due to lack of research studies carried out in those areas. In some areas, studies were carried out and suitable technique varies from region to region.
Effectiveness of Artificial Recharge Structures in Enhancing Groundwater Storage: A Case Study	(Mohan & Abraham, 2015)	Comparison of the effect of artificial recharge by individual recharge structures and combined recharge structures	Water level increased from 2 m to 3 m in individual structures and 5 m in combined structures.
Artificial Groundwater Recharge in Faria Catchment	(Saleh, Almasri, & Shaheen, 2009)	Finding out the amount and suitable location of artificial recharge	Based on results, artificial recharge contributes to 3.2 MCM (mean monthly discharge in million cubic meters) in addition to natural recharge of 60.3 MCM.
Artificial Groundwater Recharge through Recharge Tube Wells: A Case Study	(Kaledhonkar, Singh, Ambast, & Tyagi, 2003)	Bored well data were used to monitor the change in groundwater level before and after recharge	By the use of recharge tube well, 10.5 l/s average recharge was observed. The water table rose by 33.7 m to 34.4 m and the influence of recharge tube well was in 100 m radius.

Groundwater Recharge through Infiltration Process: A Case Study of Umudike, Southeastern Nigeria	(Igboekwe & Ruth, 2011)	Bored well data were used to monitor the change in groundwater level before and after recharge	Water table before and after artificial recharge was 85 m and 95 m above mean sea level
Seawater flooding events and impact on freshwater lenses of low-lying islands: controlling factors, basic management and mitigation	(Gingerich, Voss, & Johnson, 2017)	Numerical simulation was carried out to identify the effect of artificial recharge in recovery from the seawater flooding event	The recovery period without artificial recharge was 22 months and with artificial recharge was 16.5 months and the quality of water increased with artificial recharge.

2.5 Research Gap

Even though atoll islands face water related issues severe than other countries in continents, due to lack of resources in these small atoll islands, groundwater studies and data required for the studies are lacking in these islands. There are many qualitative studies conducted related to artificial recharge but the long-term effect of artificial recharge on groundwater level and sustainable water resource management, especially in small atoll islands, is not quantitatively analysed adequately.

3 MATERIALS AND METHODOLOGY

3.1 General

The most appropriate research methodology for the study was prepared with the help of a preliminary literature survey to achieve the main aims of the research. A detailed literature survey was conducted to identify the existing condition of the research and to find a suitable method to carry out the research. Data collection and data checking were done to avoid errors in modelling. There were many numerical methods available and the suitable method was identified by undertaking the literature review and by considering the available resources. Model development and sensitivity analysis were conducted prior to model calibration. Model calibration was carried out and the calibrated parameters were validated based on literature findings. Then the amount of recharge was increased by adding artificial recharge and the calibrated model was simulated with total recharge. Finally, the effect of artificial recharge on freshwater lens was identified based on the model output. The methodology followed in this study is given at the end of this chapter in Figure 3.4.

Figure 3.1: Location of selected islands (original in colour)

3.2 Study Area

Three islands, Dharavandhoo, Henbadhoo and Bodufolhadhoo, from the Maldives were selected for this study. Location of the selected islands in the Maldives is shown in Figure 3.1. The Maldives known as the Republic of Maldives is a small island nation in the Asian continent located in the Arabian sea of Indian Ocean. There are about 200 islands, which are inhabited with people. They extend from Ihavandhippodhu atoll in the North to the Addu atoll in the South (Alsumaiei & Bailey, 2018). Male' is the capital and most populated city. Details about the three selected islands are given in Table 3.1. Detail maps of Dharavandhoo, Henbadhoo and Bodufolhadoo are shown in Figure 4.4, 4.12 and 4.14, respectively. Areal map of these islands are given in Appendix A.

Table 3.1: Details of the selected island

Details		**Dharavandhoo**	**Henbadhoo**	**Bodufolhadhoo**
Location	Latitude	5º09’30” N	5º58’03” N	4º11’05” N
	Longitude	73º07’50” E	73º23’36” E	72º42’25” E
Atoll		Baa atoll	Noonu atoll	Ari atoll
Distance from Malé		116.53 km	198 km	81.64 km
Area		65 ha	13.6 ha	11.4 ha
Maximum length		1497 m	466 m	407 m
Maximum width		525 m	343 m	386 m
Population		839	491	608
Number of resorts		11	0	6
Land use pattern	Bare land	69%	41%	53%
	Vegetation cover	24%	37%	26%
	Roof cover	7%	22%	21%
Number of rainwater harvesting units		230	130	100

3.3 Data Collection and Data Checking

Freshwater level and seawater - freshwater interface were obtained by electromagnetic surveys (Model: ABEM Terrameter SAS 1000). To validate the electromagnetic data, the freshwater level obtained from electromagnetic data was compared with that of nearby dug well data. Summary of data collected by the geophysical investigation is shown in Table 3.2. Locations of electromagnetic survey points and dug wells are given in Appendix A. Other than freshwater level and seawater - freshwater interface, many details regarding population, number of houses, land use pattern, water usage, number of resorts and number of rainwater harvesting units were also collected from the islands using community meetings and questionnaire surveys. Summary of those collected data by field surveys is shown in Table 3.1.

Table 3.2: Details of geophysical investigation

Survey type	**Type of data collected**	**Number of points**		
		Dharavandhoo	**Henbadhoo**	**Bodufolhadhoo**
Electro magnetic survey	• Ground elevation • Fresh water level • Seawater-freshwater interface	50	27	24
Measured by using existing dug wells	• Ground elevation • Fresh water level • Water quality	10	5	4

3.4 Model Selection and Development

Suitable model selection is an important step, which must be done carefully to avoid errors and issues during modelling. In a previous study regarding model selection (Marshell, Nott, & Sharma, 2005), it is stated that model performance is not the only factor which governs the model selection. Various factors like the objective of modelling, the experience of the modeller, data availability, capacity of computers, time availability and cost of modelling also need to be taken into consideration.

Various options were taken into consideration for the modelling based on previous studies. The SEAWAT (Comte, Join, Banton, & Nicolini, 2014; Bosserelle, Jakovovic, & Post, 2015; Banerjee & Singh, 2011; Pauw, Baaren, Visser, De Louw, & Essink, 2015; Lathashri & Mahesha, 2015), MODFLOW (Jyrkama, Mikko, & Jon, 2007; Feng, Juan, Liu, & Zhao, 2010; Faghihi, Neda, Kave, & Babazadeh, 2011), MT3DMS (Wu, Lu, Zhang, & Bodvarsson, 2004; Chau & Jiang, 2002; Kourocas & Harter, 2014) and SUTRA (Bailey, Khalil, & Chatikavanij, 2014; Griggs & Peterson, 1993; Bailey & Jenson, 2009; Deng & Bailey, 2016; Gingerich, Voss, & Johnson, 2017) were the software considered for modelling. Based on the preliminary literature review, it was concluded that SEAWAT and SUTRA are the two best options for the freshwater lens modelling in small atoll islands. Graphical User Interface (GUI) is an important part in modelling for both data pre-and post-processing and visualization. It helps to prepare data, run the model and helps to visualize the outputs. Both SEAWAT and

SUTRA model source codes are written in FORTRAN language, which is not easy and not necessary to decode or modify. The SEAWAT has its own GUI version but it is a commercial version. MODEL MUSE is a graphical user interface developed by the US Geology Survey (USGS). It supports SUTRA code. Therefore, SUTRA was selected to develop the model by using MODEL MUSE as the graphical user interface.

3.4.1 Model development

The seawater - freshwater interfaces of the selected islands were simulated by using SUTRA (Saturated Unsaturated TRAnsport) model with Model Muse as the graphical user interface. SUTRA was developed in 1984 (Voss, 1984) by the United States Geological Survey (USGS). It was selected due to its high credibility and it has produced good results in the past studies conducted in similar small coastal islands (Gingerich & Voss, 2005; Oki, 2005), especially in atoll island aquifers (Griggs & Peterson, 1993; Underwood, Peterson, & Voss, 1992; Peterson & Gingerich, 1995; Bailey & Jenson, 2009; Bailey & Kivi, 2017; Bailey, Khalil, & Chatikavanij, 2014) and it is a public domain software. Model Muse was used as a graphical user interface to input parameters and to view the output. It is also developed by the United States Geological Survey (USGS).

Using a two-dimensional finite element mesh, which represents a particular cross section of an atoll island, the SUTRA code models groundwater flow and solute transport within the island ground surface, and using this, the depth of freshwater lens and its thickness was simulated (Bailey, Khalil, & Chatikavanij, 2014). The model uses the following approach to simulate the seawater-freshwater interface. Island undergoes a prolonged drought, without any rainfall, which causes the water table to decline to sea level, and become fully saline due to saltwater intrusion. Later, rainwater recharge to the top of the island surface starts and proceeds at a fixed rate, which drives out seawater, raises the water level on the island, and finally a constant freshwater lens will develop which will be stable with time. The island is considered as a porous media. Flow in the porous media is calculated by using the general form of Darcy's Law given by Eq. (7) and solute transport mechanism is governed by Eq. (8) and Eq. (9),

$$V = \frac{k k_r}{\epsilon S_w \mu} . (P - \rho g) \tag{7}$$

where, V is the average fluid velocity, k and k_r represents the solid matrix permeability and relative permeability to fluid flow, respectively, $\in$ is the porosity, S_w is the water saturation, μ, P, ρ represents fluid viscosity, pressure, density and gravitational acceleration, respectively.

$$\frac{\partial(\in S_w \rho C)}{\partial t} = -f - \underline{\nabla}\,(\in S_w \rho \underline{v} C) + \underline{\nabla}.\,[\in S_w \rho (D_m \underline{I} + \underline{D}).\underline{\nabla}\, C] + \in S_w \rho \Gamma_w + Q_p C \tag{8}$$

$$\frac{\partial[(1-\in)\rho_s Cs]}{\partial t} = +f + (1-\in)\,\rho s \Gamma_s \tag{9}$$

Here, C is the concentration; f represents the volumetric adsorbate source, V is the average fluid velocity, D_m and $\underline{I}$ represents the molecular diffusivity of solute in a porous medium and in solution, $\underline{D}$ is the dispersion tensor, ρ_s represents the density of solid grains in the solid matrix, Cs is the specific concentration of adsorbate on solid grains and Γ_s is the adsorbate mass source.

The unsaturated option available in SUTRA was not applied in the model simulation to avoid complexity, thus the freshwater level above sea level was not simulated by the model (Bailey & Kivi, 2017). It was calculated simply by using Ghyben–Herzberg relation (Drabbe & Ghyben, 1888; Herzberg, 1901; Du, 1828). Based on this relationship, the ratio between the water table above mean sea level and depth to the seawater - freshwater interface below the mean sea level is approximately 1:40. Therefore, the effect of elevation of the water table above sea level in the freshwater lens will be less significant. Ghyben-Herzberg relation is given by,

$$h = \alpha z \tag{10}$$

$$\alpha = \frac{(\rho_s - \rho_0)}{\rho_0} \tag{11}$$

here, h is the elevation of the water table, z is the depth of seawater - freshwater interface, and ρ_0, ρ_s are the density of freshwater and seawater, respectively.

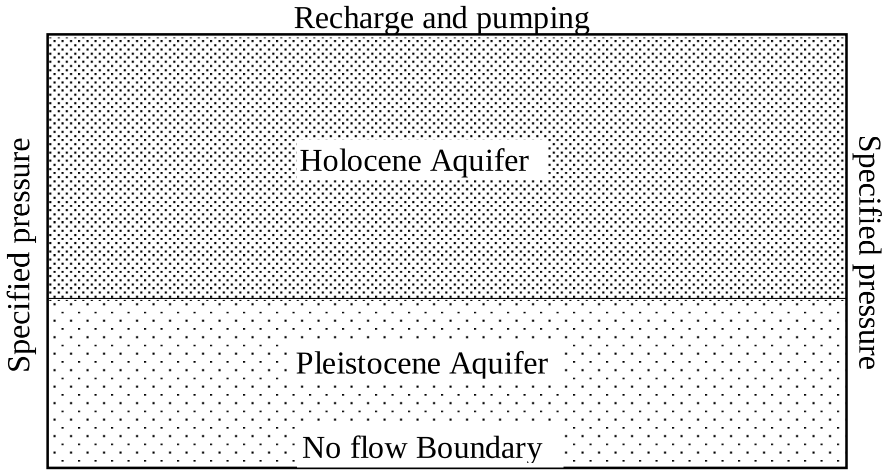


Figure 3.2: Model outline showing locations of no-flow boundary, specified pressure boundary and recharge and pumping

The model outline is shown in Figure 3.2. Specified fluid pressure was assigned at both the ends of the island by using static pressure equation ($P = h\rho g$) where h is the depth of the node from mean sea level, the density of seawater (ρ) was considered as 1025 kg/m^{-3} and gravity (g) was assigned as 9.81 ms^{-2}. Salt concentration was taken as 0.0357 kg$_{salt}$/kg$_{water}$ to represent saltwater. The bottom part of the mesh was bounded as a no-flow boundary where there will be no inflow or outflow. Holocene aquifer properties were assigned to the depth of 15 m and Pleistocene aquifer properties were assigned to 15 m to 25 m depth. Recharge and pumping were assigned to nodes located at the top (Bailey, Khalil, & Chatikavanij, 2014).

Parameters required for the modelling were obtained from previous literature. Initial aquifer parameters are summarized in Table 1.1. Other than these, the specific yield was considered as 0.2 (Griggs & Peterson, 1993) and depth of Thurber discontinuity was considered as 15 m. Annual average recharge was obtained from a previous study carried out by Bailey, Khalil and Chatikavanji in the Maldives over a period of 14 years. They used the soil water budget model of Falkland (Falkland A. C., 1994; Bailey, Khalil, & Chatikavanij, 2014) and summarized the annual average recharge for the three geological regions. The calculated annual average recharge based on this study and pumping rate of each island obtained by field survey presented in Table 3.3, were used in this study to simulate the freshwater lens. Recharge and pumping were assigned uniformly throughout the island. Model development flow chart is shown in Figure 3.3.

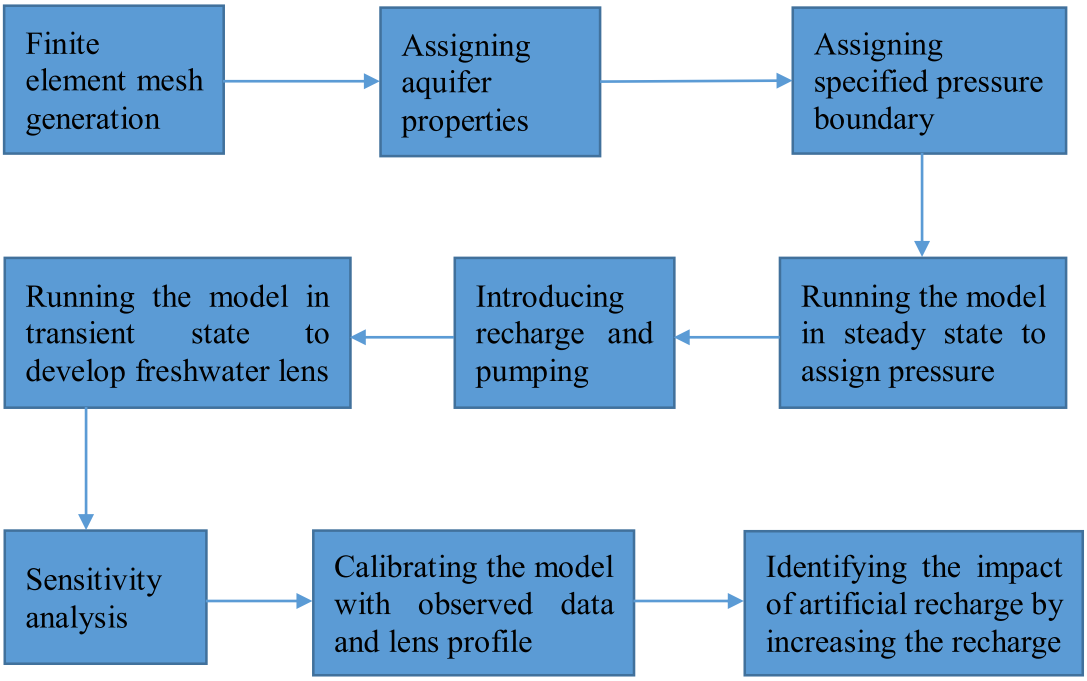


Figure 3.3: Model development flow chart

Table 3.3: Annual recharge and pumping rate of islands

Island	**Geological region**	**Annual rainfall (mm)**	**Annual recharge depth (mm)**	**Percentage recharge (%)**	**Annual pumping rate (mm)**
Dharavandhoo	5° N - 10° N	1715	655	38	143
Henbadhoo	5° N - 10° N	1715	655	38	318
Bodufolhadhoo	0° - 5° N	1940	678	35	400

3.5 Calibration

The objective of the calibration is to have simulated freshwater lens volumes match with the observed freshwater volumes with less than ±10% volume discrepancy. The initial hydraulic conductivity used was 75 m/d as calibrated (Bailey, Khalil, & Chatikavanij, 2014) in a previous two-dimensional modelling of islands in the Maldivian atolls using SUTRA. The hydraulic conductivity was adjusted until the freshwater lens volume estimated by the two-dimensional model matched with the observed lens volume. The calibrated conductivity value was compared with the measured conductivity value from the previous study in the Maldives islands. The depth of Thurber discontinuity was not calibrated as it was concluded that it does not have a major influence on the lens volume (Wallace, 2015). Due to the limited observed data, the calibration was constrained to one parameter. The salt concentration that is suitable for drinking was considered as less than 915 mg/L that is equal to 550 mg/L chloride concentration during field measurement. During the model simulation, the seawater - freshwater interface was taken as 0.00089 kg_{salt}/kg_{water}, which is equivalent to the above mentioned field measurement.

3.6 Freshwater Lens Volume Calculation

Cross sections were selected along the longer axis of the island. The thickness of the freshwater lens was calculated by subtracting the freshwater - seawater interface from the freshwater level. Then, the area of freshwater lens of a particular cross-section was computed by,

$$A = \sum_{i=1}^{np-1} \left(\frac{Z_i + Z_{i+1}}{2}\right) W_i \tag{12}$$

where, *np* is the number of points in that cross-section, *z* is the freshwater lens thickness, and *w* is the distance between two points.

Then, the freshwater lens volume was calculated by computing the volume between those cross-sections using trapezoidal geometry by,

$$V_{lens} = \sum_{n=1}^{nx-1} \left(\frac{A_i + A_{i+1}}{2}\right) L_i S_y \tag{13}$$

where, *nx* is the number of cross-sections used to calculate the freshwater lens; *L* is the perpendicular distance (m) between those cross sections; *Sy* is the specific yield of the aquifer; and *A* is the bulk cross-section area (m^2) of the freshwater lens for a given cross-section (Bailey & Kivi, 2017).

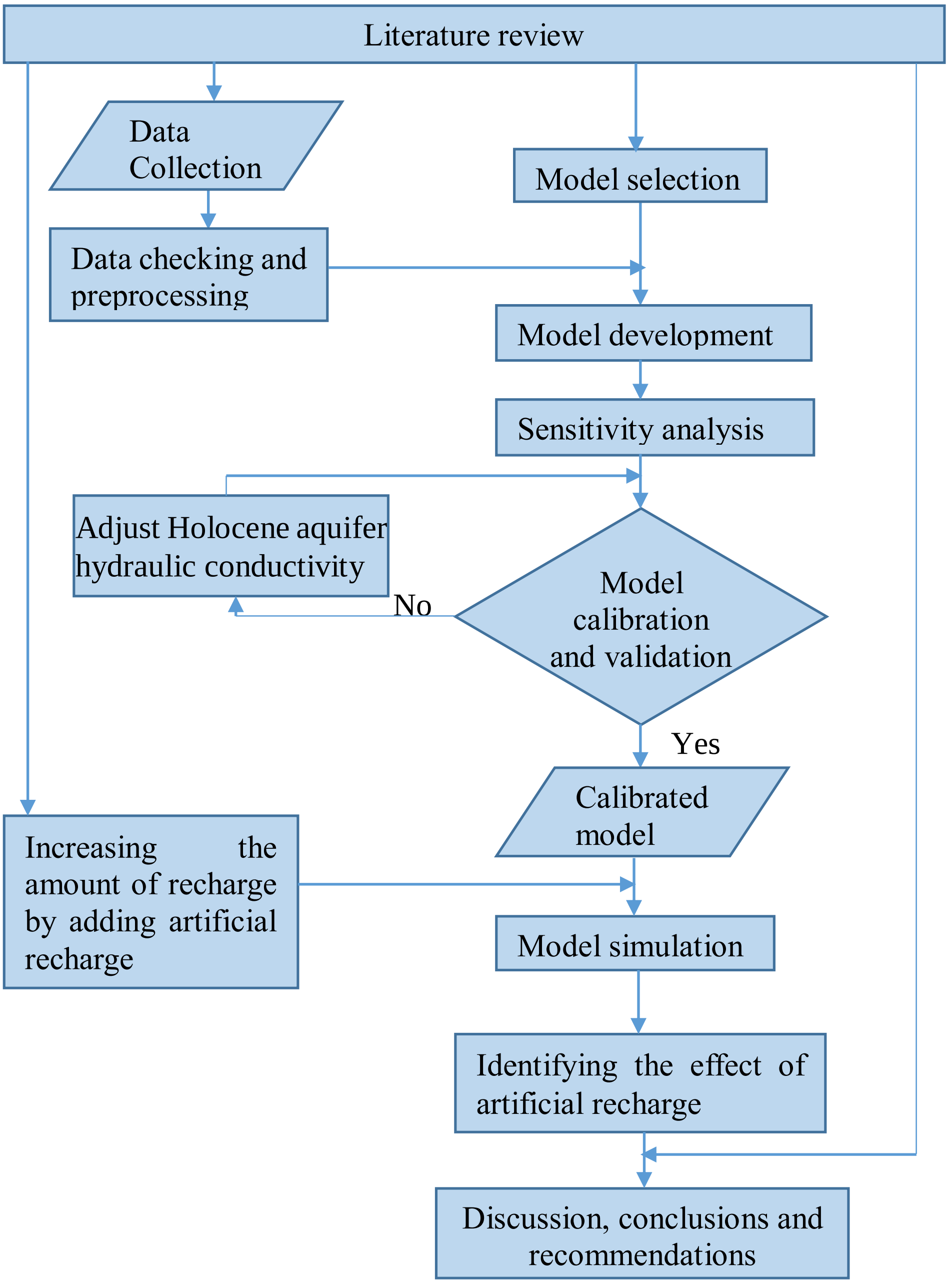


Figure 3.4: Methodology flow chart

4 RESULTS

4.1 Data Checking

Comparison of freshwater level data measured from the electromagnetic survey and nearby dug wells is shown in Figure 4.1. The R^2 value of the trend is 0.96 and based on this, the electromagnetic survey data is validated.

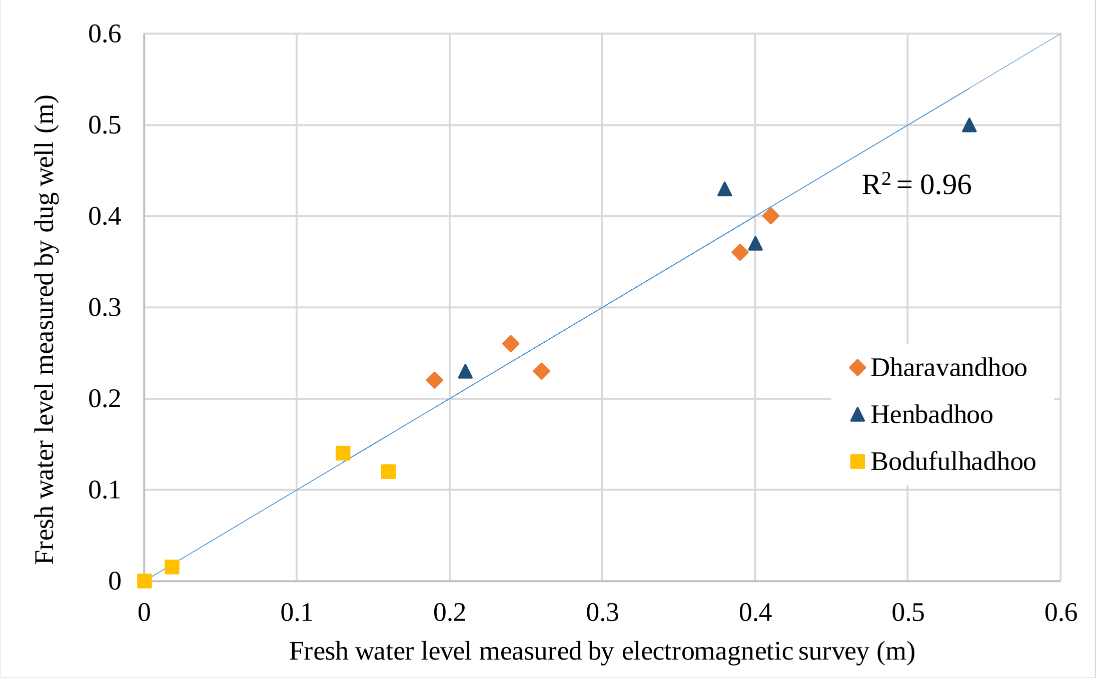


Figure 4.1: Comparison of freshwater level measured from the electromagnetic survey and dug wells

4.2 Initial Parameter Assignment

Initial parameters for the model were selected from the previous literature in the Maldives islands. The parameters summarized in Table 4.1 are assigned to all models to establish baseline condition simulations. In a previous study (Bailey, Khalil, & Chatikavanij, 2014), two-dimensional vertical cross-section SUTRA models were developed to simulate freshwater lens dynamics for some islands in the Maldives. Holocene aquifer hydraulic conductivity was calibrated to produce modelled freshwater lens thickness to match observed lens thickness data. The calibrated hydraulic conductivity was found to be 75 m/day (Bailey, Khalil, & Chatikavanij, 2014). This value has been used as initial hydraulic conductivity for the selected islands. Then, it was calibrated until the modelled freshwater lens volume and observed freshwater lens volume match within ±10% volume variation. A 600 m wide transect was modelled with the following parameters.

Table 4.1: Initial aquifer parameters

Parameter	Value	Source
Longitudinal dispersivity	6 m	(Griggs & Peterson, 1993)
Transverse dispersivity	0.005 m	(Griggs & Peterson, 1993)
Holocene layer thickness	15 m	(Hamlin & Anthony, 1987)
Holocene horizontal conductivity	75 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Holocene vertical conductivity	15 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Pleistocene horizontal conductivity	5000 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Pleistocene vertical conductivity	1000 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Porosity	0.15	(Anthony, 1997)

4.3 Sensitivity Analysis

Sensitivity analysis was performed before calibrating the model to identify the effect of Holocene layer aquifer conductivity and recharge rate on freshwater lens thickness. Hydraulic conductivity values were varied across a range of possible values to cover all potential values as reported by previous modelling studies for atoll islands. Recharge rate was also changed within a certain range and the effect of it on the thickness of the freshwater lens was identified. Figure 4.2 and Figure 4.3 show the sensitivity analysis plot of Holocene aquifer hydraulic conductivity and recharge rate. Based on the sensitivity analysis, it was identified that the hydraulic conductivity has a significant effect on the thickness of freshwater lens where, higher hydraulic conductivity results in a thinner lens and lower hydraulic conductivity results in a thicker lens. Freshwater lens thickness increases linearly with artificial recharge.

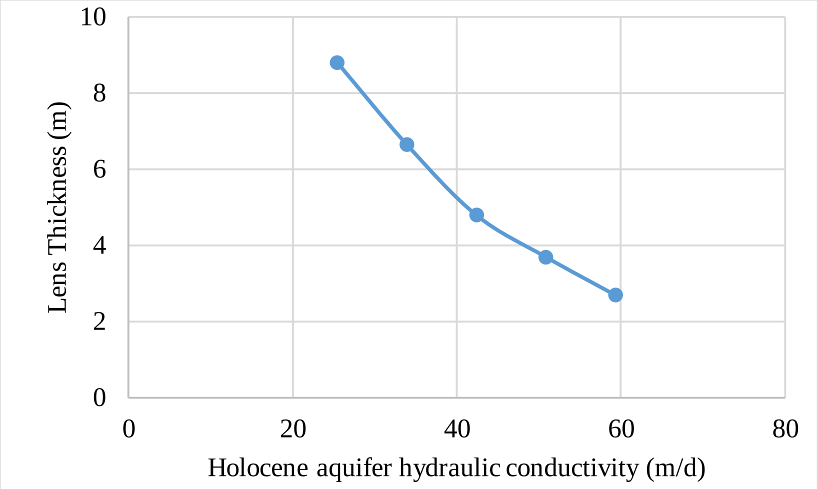


Figure 4.2: Sensitivity analysis plot of hydraulic conductivity

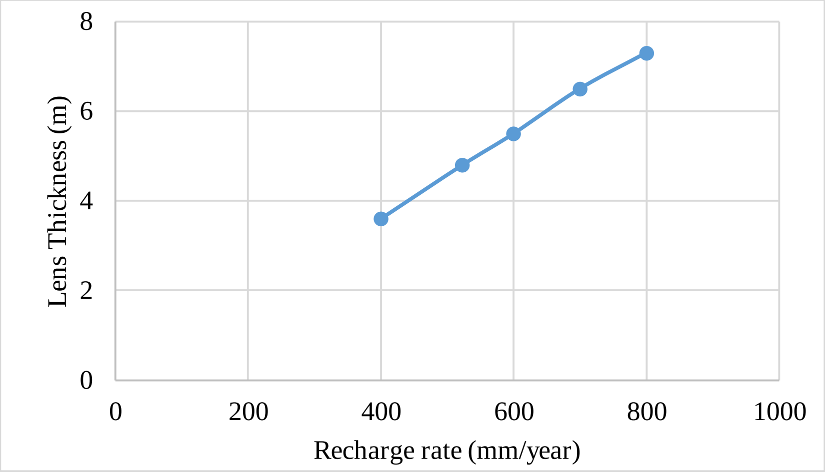


Figure 4.3: Sensitivity analysis plot of recharge rate

4.4 Model Calibration

The initial hydraulic conductivity used was 75 m/d as calibrated in a previous two-dimensional modelling of islands in the Maldivian atolls using SUTRA (Bailey, Khalil, & Chatikavanij, 2014). The hydraulic conductivity was adjusted until the freshwater lens volume estimated by the two-dimensional model matched with the observed lens volumes within ±10% volume discrepancy.

4.4.1 Model calibration for Dharavandhoo Island

Location of Electromagnetic survey points (ER points) of Dharavandhoo Island is shown in Figure 4.4. Two-dimensional modelling was carried out for the six transects shown. Recharge rate for this island was assigned as 655 mm/year (Bailey, Khalil, & Chatikavanij, 2014). Annual extraction based on field survey was 93,564 m^3. It was assigned uniformly throughout the island as 285 mm/year. Calibrated permeability value of Holocene layer was 45.79 m/day. Table 4.2 summarises the parameters assigned for the modelling of Dharavandhoo Island. Figure 4.5 shows the legend of model output and Figures 4.6 to 4.10 [Distance from the centerline (m) in X-axis and Depth (m) in Y-axis, Y-axis is highly exaggerated] show the modelled freshwater lens. Figure 4.11 shows the comparison of observed and simulated seawater - freshwater interface. Calculation of observed and simulated freshwater lens volume is shown in Table 4.3 and Table 4.4. Table 4.5 summarises the observed and simulated freshwater volume.

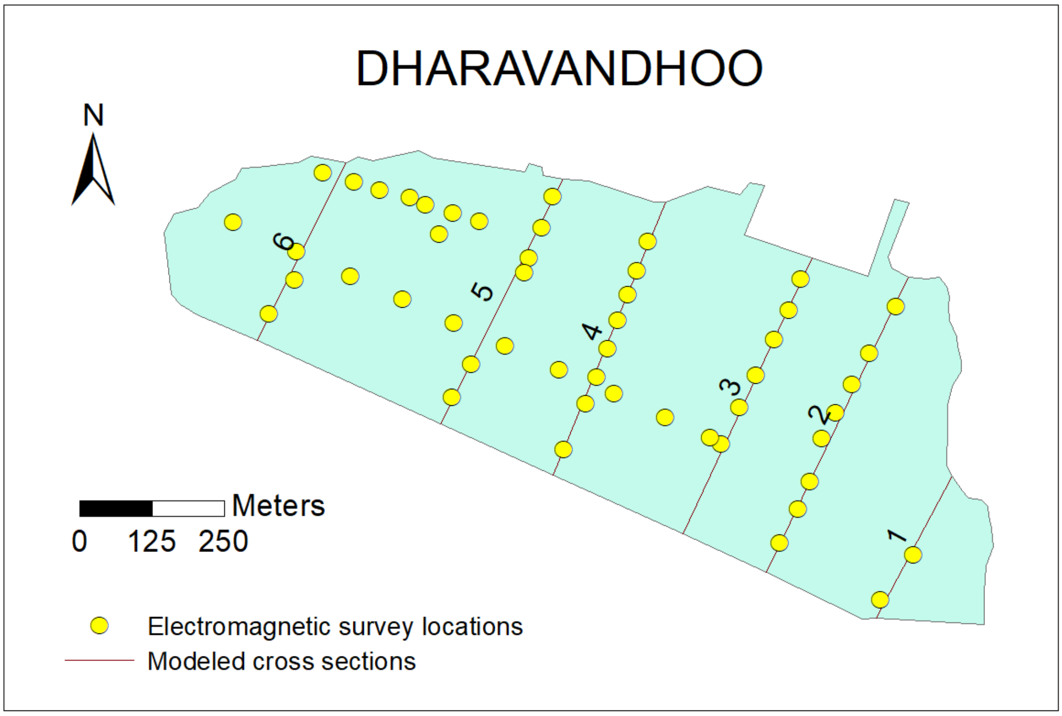


Figure 4.4: Electromagnetic survey locations and the modelled cross-sections of Dharavandhoo Island

Table 4.2: Parameters assigned for the modelling of Dharavandhoo Island

Parameter	**Value**	**Source**
Longitudinal dispersivity	6 m	(Griggs & Peterson, 1993)
Transverse dispersivity	0.005 m	(Griggs & Peterson, 1993)
Holocene layer thickness	15 m	(Hamlin & Anthony, 1987)
Holocene horizontal conductivity	44.9 m/d	Calibrated
Holocene vertical conductivity	9 m/d	Calibrated
Pleistocene horizontal conductivity	5000 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Pleistocene vertical conductivity	1000 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Porosity	0.15	(Anthony, 1997)
Annual recharge	655 mm/yr	(Bailey, Khalil, & Chatikavanij, 2014)
Annual pumping rate	143 mm/yr	Field survey

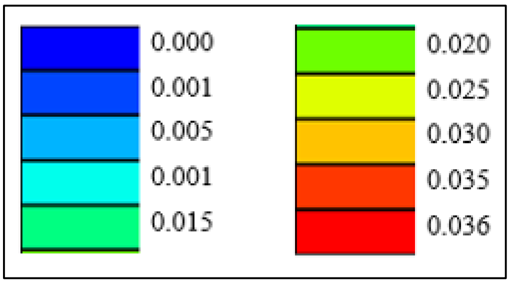


Figure 4.5: Legend of model output (Salinity concentration (kg_{salt} / kg_{water}))

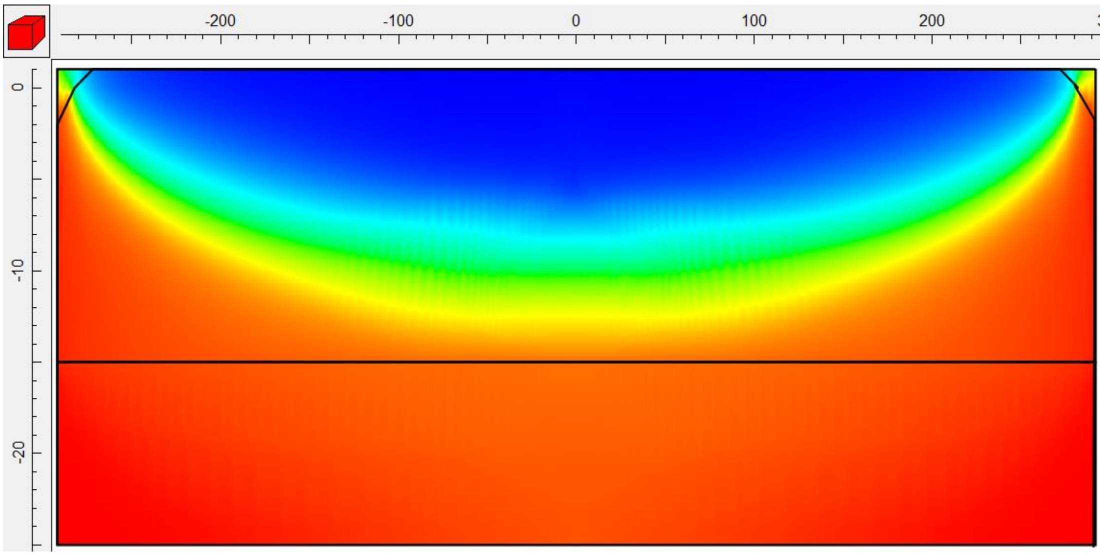


Figure 4.6: Modelled freshwater lens of Dharavandhoo Island in Transect 2

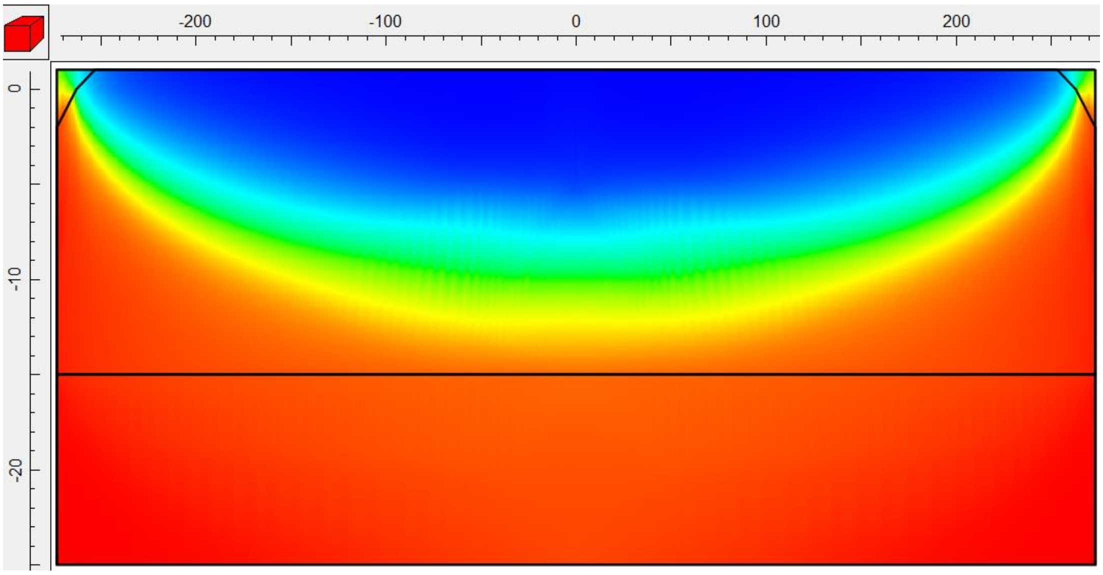


Figure 4.7: Modelled freshwater lens of Dharavandhoo Island in Transect 3

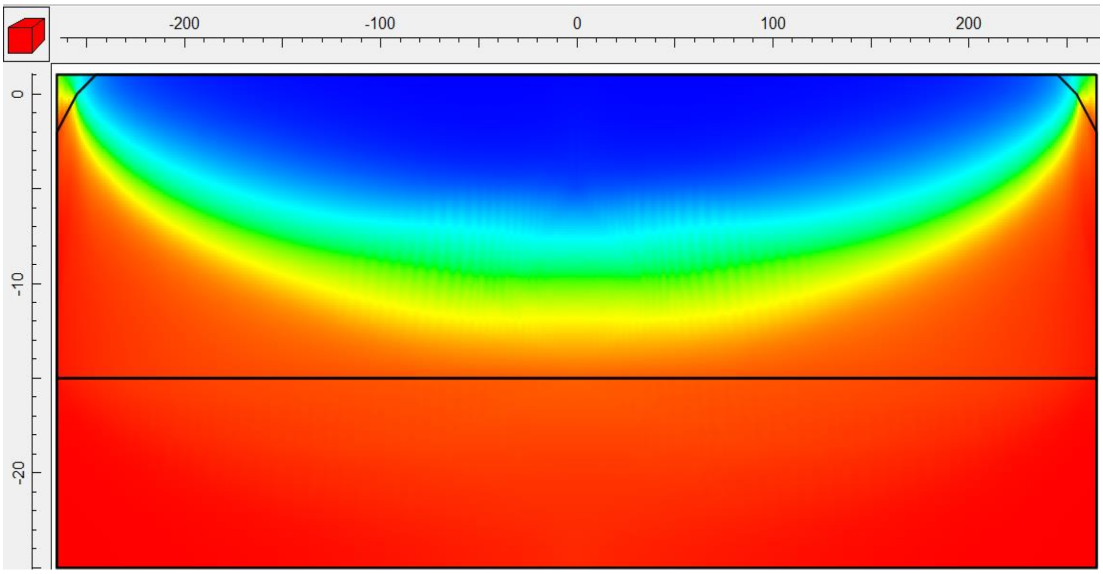


Figure 4.8: Modelled freshwater lens of Dharavandhoo Island in Transect 4

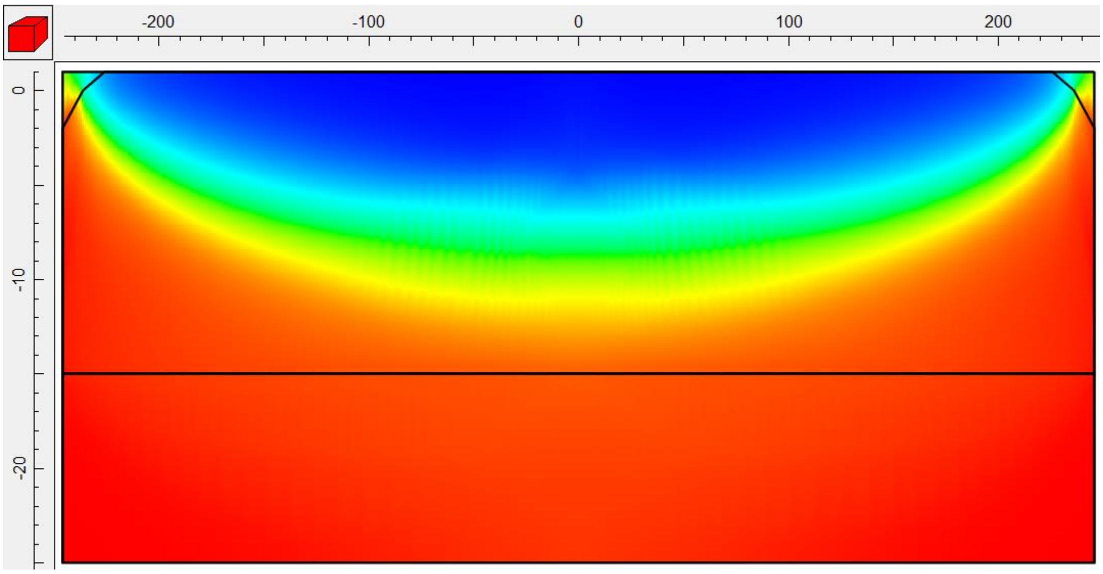


Figure 4.9: Modelled freshwater lens of Dharavandhoo in Transect 5

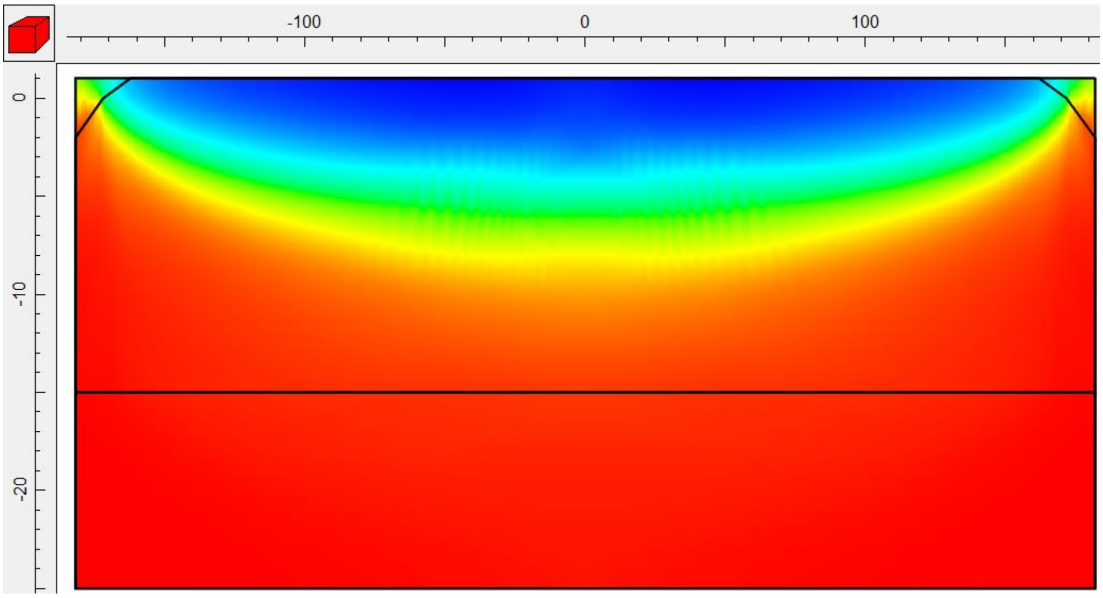


Figure 4.10: Modelled freshwater lens of Dharavandhoo Island in Transect 6.

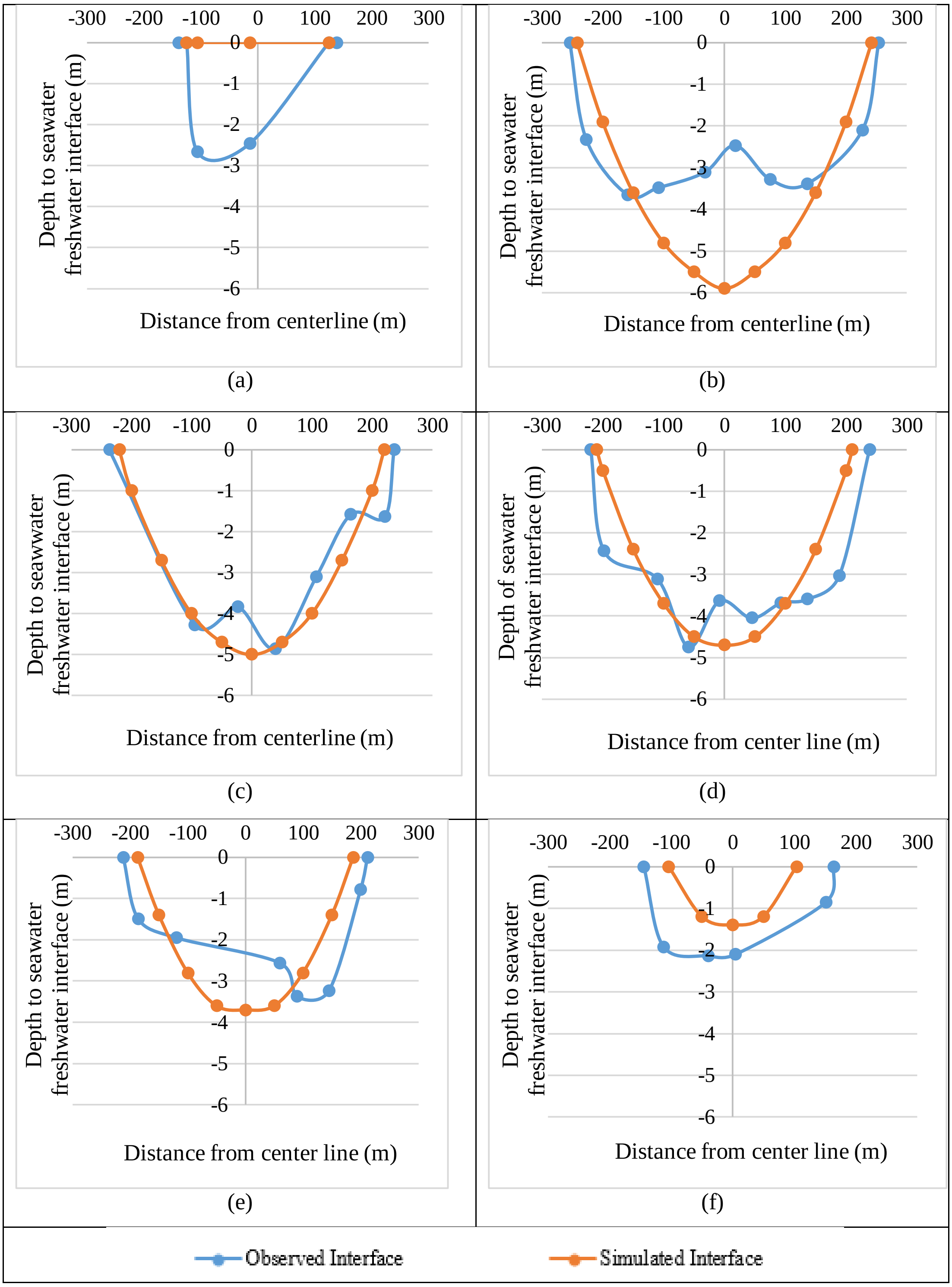


Figure 4.11: Comparison of observed and simulated seawater - freshwater interface of Dharavandhoo Island in Transects 1(a), 2(b), 3(c), 4(d), 5(e) and 6(f) (original in colour)

Table 4.3: Calculation of observed freshwater lens volume of Dharavandhoo Island

Transect	**Distance from center line (m)**	**Depth to seawater-freshwater interface (m)**	**Fresh water level (m)**	**Freshwater lens thickness (m)**	**Area (m^2)**	**Perpendicular distance between the transects (m)**	**Volume (m^3)**
	-139	0	0	0	0		
	-125	0	0	0	26.77		
	-106	-2.66	0.18	2.84	254.69		
	-13	-2.46	0.18	2.64	182.66		
	125	0	0	0	0		
	139	0	0	0	0		
1	Total				464.12	212	39,252.25
	-282	0	0	0	0		
	-254	0	0	0	31.90		
	-227	-2.32	0.07	2.39	207.23		
	-159	-3.65	0.05	3.7	187.95		
	-108	-3.48	0.19	3.67	249.21		
	-32	-3.10	-0.22	2.89	125.96		
	18	-2.47	-0.34	2.13	142.22		
	75	-3.28	-0.44	2.84	175.97		
	136	-3.39	-0.42	2.97	237.22		
	227	-2.10	0.12	2.22	29.75		
	254	0	0	0	0		
	282	0	0	0	0		
2	Total				1387.41	163	46,668.03
	-263	0	0	0	0		
	-237	0	0	0	319.04		
	-95	-4.28	0.23	4.51	313.39		
	-24	-3.84	0.38	4.23	294.95		
	39	-4.86	0.32	5.18	289.90		
	107	-3.10	0.23	3.33	145.51		
	164	-1.58	0.19	1.77	100.13		
	221	-1.64	0.10	1.74	12.72		
	236	0	0	0	0		
	262	0	0	0			
3	Total				1475.66	257	78,993.57
	-255	0	0	0	0		
4	-230	0	0	0	29.05	201	53,066.46

	-208	-2.44	0.22	2.66	263.22		
	-120	-3.11	0.22	3.33	209.17		
	-69	-4.75	0.13	4.88	225.09		
	-18	-3.64	0.30	3.94	215.95		
	35	-4.05	0.24	4.29	199.24		
	83	-3.69	0.31	4.00	172.65		
	126	-3.60	0.38	3.98	197.21		
	179	-3.04	0.41	3.45	86.43		
	229	0	0	0	0		
	255	0	0	0	0		
	Total				1598.02		
	-236	0	0	0	0		
	-212	0	0	0	21.81		
	-186	-1.49	0.17	1.66	121.11		
	-120	-1.95	0.08	2.03	454.50		
	60	-2.56	0.44	3.00	96.49		
	89	-3.37	0.39	3.76	206.30		
	145	-3.23	0.37	3.6	134.61		
	200	-0.78	0.46	1.24	7.29		
	212	0	0	0	0		
	236	0	0	0	0		
5	Total				1042.11	356	56,735.74
	-172	0	0	0	0		
	-155	0	0	0	32.41		
	-123	-1.92	0.14	2.06	159.90		
	-50	-2.14	0.16	2.30	99.76		
	-6	-2.10	0.18	2.28	252.27		
	141	-0.85	0.29	1.14	7.25		
	154	0	0	0	0		
	171	0	0	0	0		
6	Total				551.59	194	10,700.92
Freshwater volume (m^3)							**285,417**

Table 4.4: Calculation of simulated freshwater lens volume of Dharavandhoo Island

Transect	**Distance from center line (m)**	**Depth to seawater-freshwater interface (m)**	**Fresh water level (m)**	**Freshwater lens thickness (m)**	**Area (m^2)**	**Perpendicular distance between the transects (m)**	**Volume (m^3)**
1	No freshwater lens					212	39,959.25
	Total				0		
2	-242	0	0	0	41.32	163	55,370.98
	-200	-1.9	0.07	1.97	142.41		
	-150	-3.6	0.13	3.73	217.50		
	-100	-4.8	0.17	4.97	266.69		
	-50	-5.5	0.20	5.70	295.17		
	0	-5.9	0.21	6.11	295.17		
	50	-5.5	0.20	5.70	266.70		
	100	-4.8	0.17	4.97	217.50		
	150	-3.6	0.13	3.73	142.41		
	200	-1.9	0.07	1.97	41.32		
	242	0	0	0	0		
	Total				1884.87		
3	-220	0	0	0	10.36	257	74,129.70
	-200	-1	0.04	1.04	95.80		
	-150	-2.7	0.10	2.80	173.48		
	-100	-4	0.14	4.14	225.26		
	-50	-4.7	0.17	4.87	251.16		
	0	-5	0.18	5.18	251.16		
	50	-4.7	0.17	4.88	225.26		
	100	-4	0.14	4.14	173.48		
	150	-2.7	0.10	2.80	95.80		
	200	-1	0.04	1.04	10.36		
	220	0	0	0	0		
	Total				1512.12		
4	-210	0	0	0	2.59	201	47,293.36
	-200	-0.5	0.02	0.52	75.09		
	-150	-2.4	0.09	2.49	157.94		

	-100	-3.7	0.13	3.83	212.32		
	-50	-4.5	0.16	4.66	238.21		
	0	-4.7	0.17	4.87	238.21		
	50	-4.5	0.16	4.66	212.32		
	100	-3.7	0.13	3.83	157.94		
	150	-2.4	0.09	2.49	75.08		
	200	-0.5	0.02	0.52	2.59		
	210	0	0	0	0		
	Total				1372.30		
5	-187	0	0	0	26.82	356	42,091.84
	-150	-1.4	0.05	1.45	108.75		
	-100	-2.8	0.10	2.90	165.71		
	-50	-3.6	0.13	3.73	189.02		
	0	-3.7	0.13	3.83	189.02		
	50	-3.6	0.13	3.73	165.71		
	100	-2.8	0.10	2.90	108.75		
	150	-1.4	0.05	1.45	26.82		
	187	0	0	0	0		
	Total				980.60		
6	-172	0	0	0	0	194	3,914.03
	-104	0	0	0	33.56		
	-50	-1.2	0.04	1.24	67.32		
	0	-1.4	0.05	1.45	67.32		
	50	-1.2	0.04	1.24	33.56		
	104	0	0	0	0		
	172	0	0	0	0		
	Total				201.75		
Freshwater Volume (m^3)							**262,759**

Table 4.5: Summary of observed and simulated freshwater lens volume of Dharavandhoo Island

Freshwater lens volume	
Observed volume (m^3)	285,417
Simulated (m^3)	262,759
Percentage difference	7.9 %

4.4.2 Model calibration for Henbadhoo Island

Location of Electromagnetic survey points (ER points) of Henbadhoo Island is shown in Figure 4.12. Two-dimensional modelling was done for the six transects shown. Recharge rate for this island was assigned as 655 mm/year (Bailey, Khalil, & Chatikavanij, 2014). Annual extraction based on field survey was 32,704 m^3. It was assigned uniformly throughout the island as 318 mm/year. Calibrated permeability value of Holocene layer was 25 m/day. Table 4.6 summarises the parameters assigned for the modelling of Henbadhoo Island. Figure 4.13 shows the comparison of observed and simulated seawater - freshwater interface. Calculation of observed and simulated freshwater lens volume is shown in Appendix B. Table 4.7 summarises the observed and simulated freshwater volume.

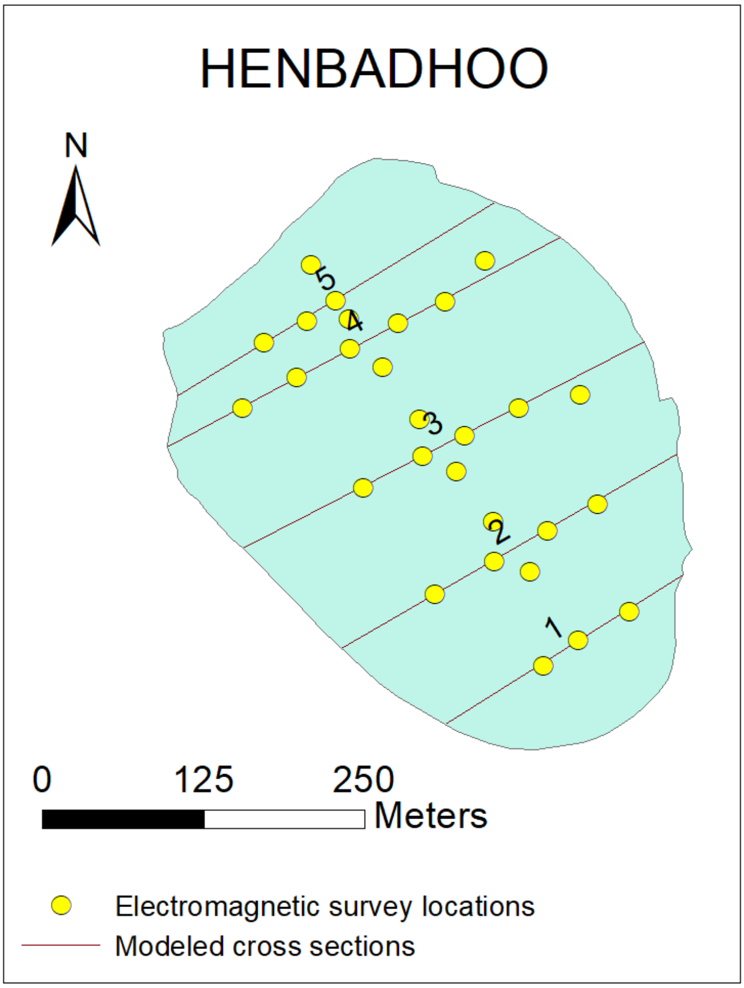


Figure 4.12: Electromagnetic survey locations and modelled cross sections of Henbadhoo Island

Table 4.6: Parameters assigned for the modelling of Henbadhoo Island

Parameter	Value	Source
Longitudinal dispersivity	6 m	(Griggs & Peterson, 1993)
Transverse dispersivity	0.005 m	(Griggs & Peterson, 1993)
Holocene layer thickness	16 m	(Hamlin & Anthony, 1987)
Holocene horizontal conductivity	25 m/d	Calibrated
Holocene vertical conductivity	5 m/d	Calibrated
Pleistocene horizontal conductivity	5000 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Pleistocene vertical conductivity	1000 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Porosity	0.15	(Anthony, 1997)
Annual recharge	655 mm/year	(Bailey, Khalil, & Chatikavanij, 2014)
Annual pumping rate	318 mm/year	Field survey

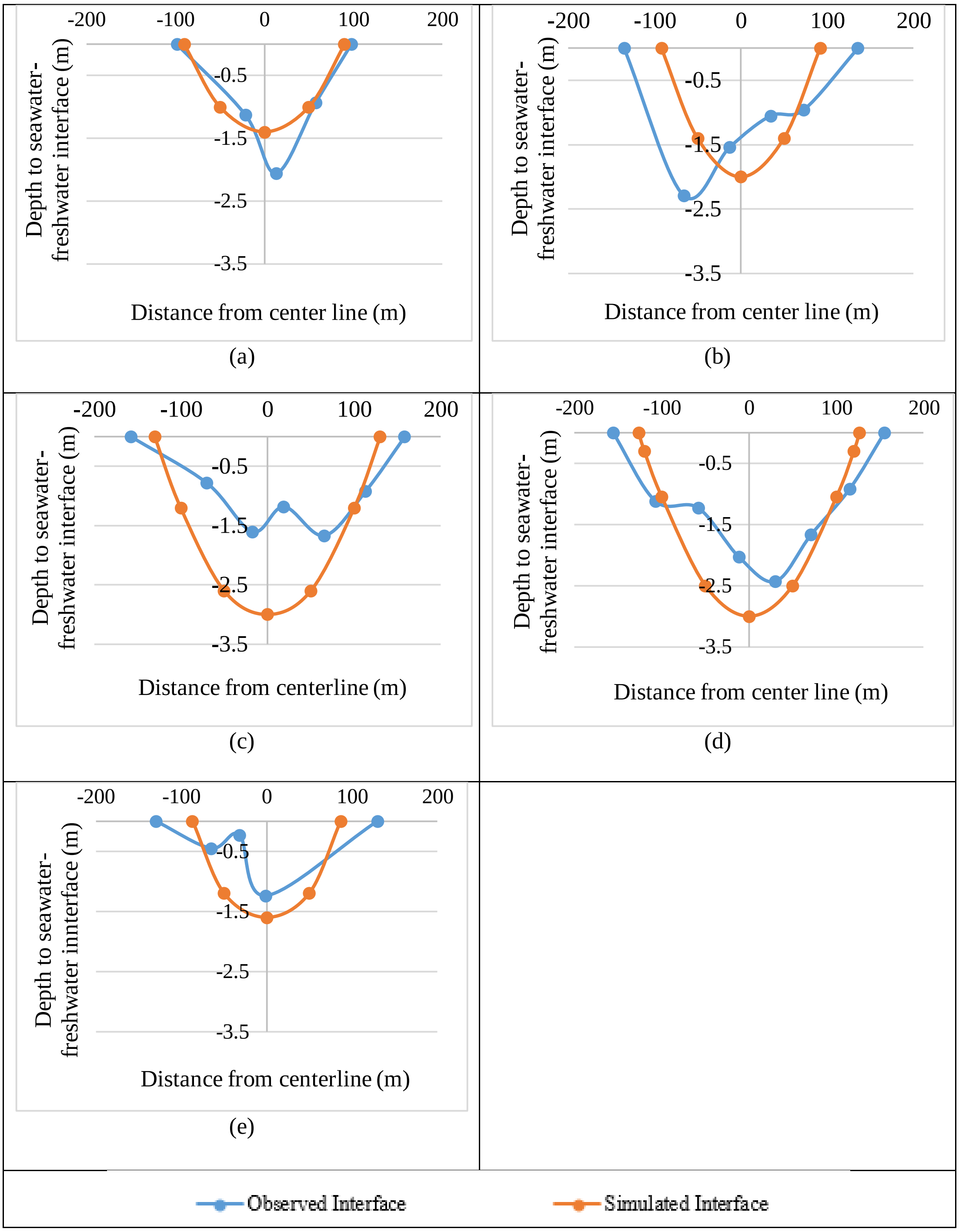


Figure 4.13: Comparison of observed and simulated seawater - freshwater interface of Henbadhoo Island in Transects 1(a), 2(b), 3(c), 4(d) and 5(e) (original in colour)

Table 4.7: Summary of the observed and simulated freshwater volume of Henbadhoo Island

Freshwater lens volume	
Observed Volume (m^3)	27,705
Simulated Volume (m^3)	27,046
Percentage difference	2.4 %

4.4.3 Model calibration for Bodufolhadhoo Island

Location of Electromagnetic survey points (ER points) are shown in Figure 4.14. Two-dimensional modelling was done for the four transects shown. Recharge rate for this island was assigned as 678 mm/year (Bailey, Khalil, & Chatikavanij, 2014). Annual extraction based on field survey was 48,202 m^3. It was assigned uniformly throughout the island as 400 mm/year. Calibrated permeability value of Holocene layer was 38.8 m/day. Table 4.8 summarises the parameters assigned for the modelling of Bodufolhadhoo Island. Figure 4.15 shows the comparison of observed and simulated seawater - freshwater interface. Calculation of observed and simulated freshwater lens volume is shown in Appendix B. Table 4.9 summarises the observed and simulated freshwater volume.

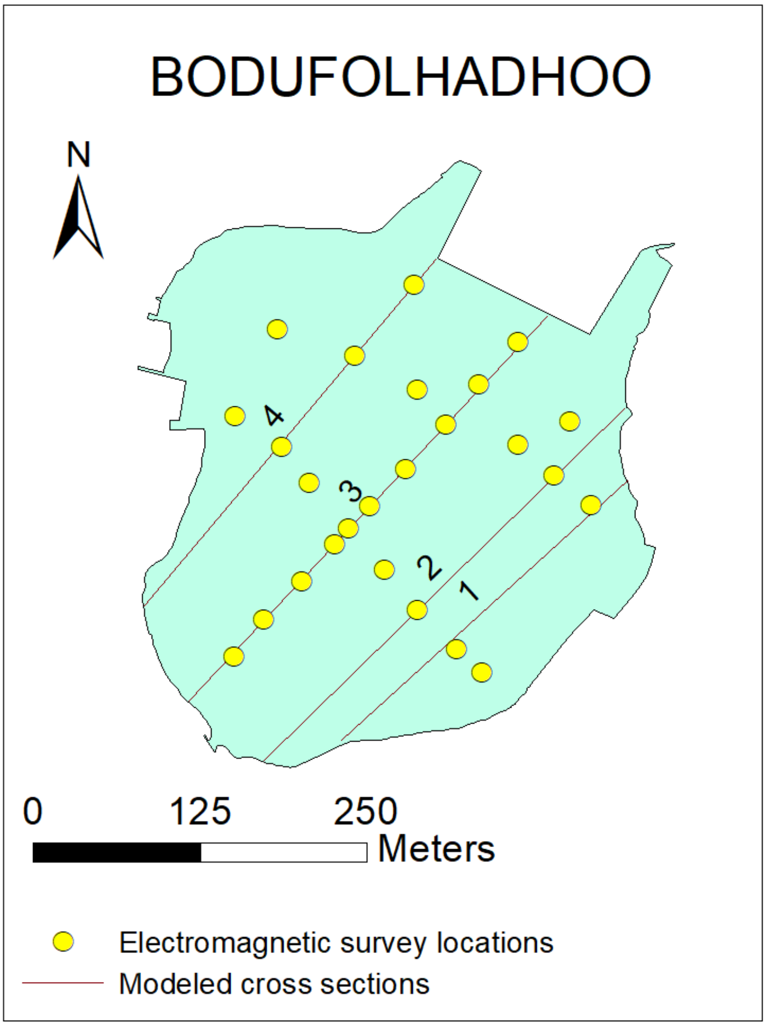
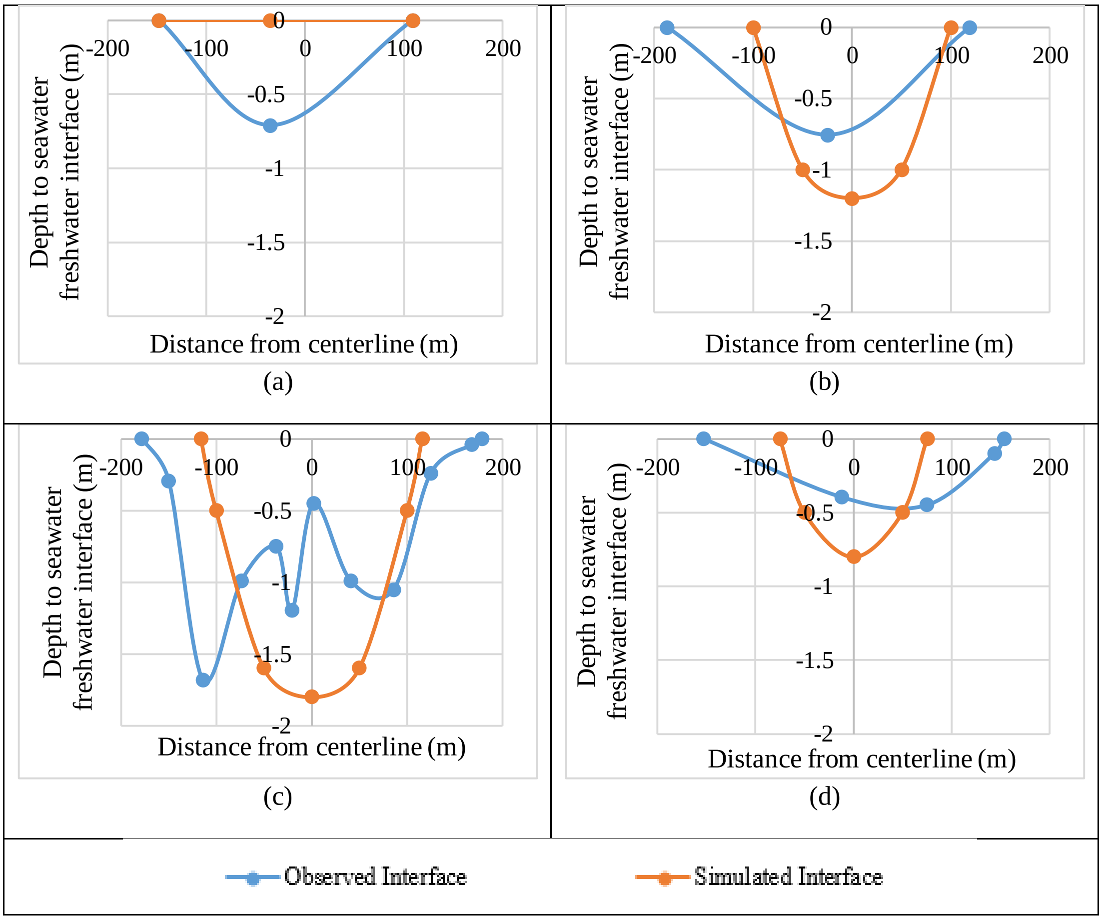


Figure 4.14: Electromagnetic survey locations and modelled cross sections of Bodufolhadhoo Island

Table 4.8: Parameters assigned for the modelling of Bodufolhadhoo Island

Parameter	**Value**	**Source**
Longitudinal dispersivity	6 m	(Griggs & Peterson, 1993)
Transverse dispersivity	0.005 m	(Griggs & Peterson, 1993)
Holocene layer thickness	16 m	(Hamlin & Anthony, 1987)
Holocene horizontal conductivity	38 m/d	Calibrated
Holocene vertical conductivity	7.6 m/d	Calibrated
Pleistocene horizontal conductivity	5000 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Pleistocene vertical conductivity	1000 m/d	(Bailey, Khalil, & Chatikavanij, 2014)
Porosity	0.15	Anthony (1997)
Annual recharge	678 mm/year	(Bailey, Khalil, & Chatikavanij, 2014)
Annual pumping rate	400 mm/year	Field survey



(a)

(b)

(c)

(d)

Figure 4.15: Comparison of observed and simulated seawater - freshwater interface of Bodufolhadhoo Island in Transects 1(a), 2(b), 3(c) and 4(d) (original in colour)

Table 4.9: Summary of observed and simulated freshwater lens volume of Bodufolhadhoo Island

Freshwater lens volume	
Observed Volume (m^3)	8,131
Simulated Volume (m^3)	8,440
Percentage difference	3.8%

4.5 Effect of Artificial Recharge

Effect of artificial recharge was analysed by increasing the present natural recharge by 5% and 10% of annual rainfall assuming that by artificial recharge, additional 5–10% of annual rainfall will be recharged into the ground in addition to natural recharge. Total recharge including annual and artificial recharge was input to the previously calibrated model and the effect of artificial recharge was identified.

4.5.1 Effect of artificial recharge in Dharavandhoo Island

Recharge was increased by 5% and 10% and was input to the previously calibrated model and the effect of artificial recharge was identified. Table 4.10 summarises the total recharge amount with natural and artificial recharge. Figure 4.16 shows the change in seawater - freshwater interface in each transects with artificial recharge. Table 4.11 summarises the change in freshwater lens thickness and freshwater volume with artificial recharge.

Table 4.10: Total recharge with the natural and artificial recharge of Dharavandhoo Island

Percentage of artificial recharge with respect to annual rainfall	Annual rainfall (mm)	Natural recharge (mm)	Artificial recharge (mm)	Total recharge (mm)
5%	1715	655	85.8	740.8
10%	1715	655	171.5	826.5

Table 4.11: Comparison of observed and simulated maximum freshwater lens thickness and freshwater lens volume of Dharavandhoo Island

Percentage of artificial recharge with respect to annual rainfall	Maximum freshwater lens thickness (m)	Freshwater lens volume (m^3)
0%	5.2	285,417
5%	6.9	323,607
10%	8.0	375,527

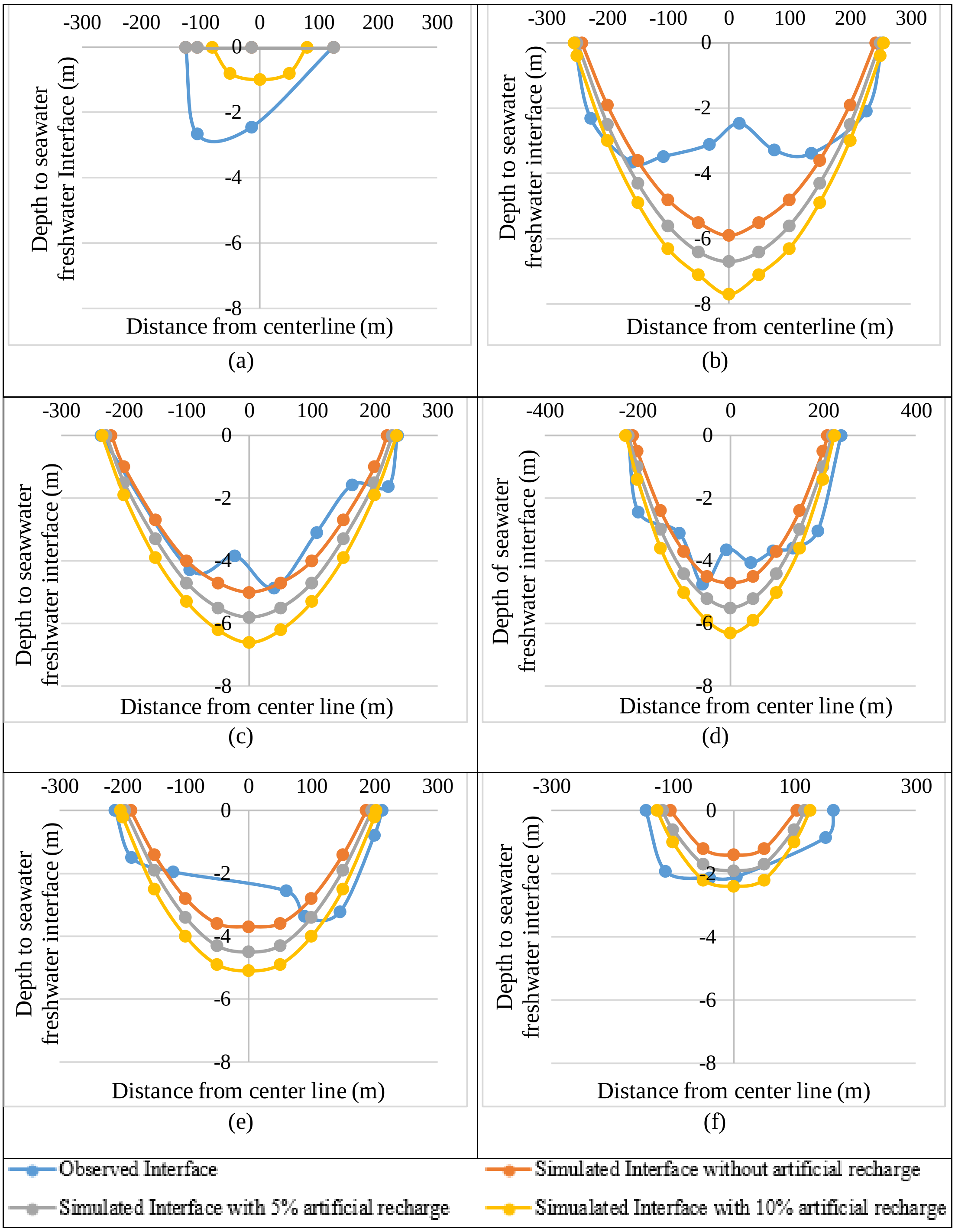


Figure 4.16: Change in seawater - freshwater interface with artificial recharge in Dharavandhoo Island in Transects 1(a), 2(b), 3(c), 4(d), 5(e) & 6(f) (original in colour)

4.5.2 Effect of artificial recharge in Henbadhoo Island

Recharge was increased by 5% and 10% and was input to the previously calibrated model and the effect of artificial recharge was identified. Table 4.12 summarises the total recharge amount with the natural and artificial recharge. Figure 4.17 shows the change in seawater - freshwater interface in each transects with artificial recharge. Table 4.13 summarises the change in freshwater lens thickness and freshwater volume with artificial recharge.

Table 4.12: Total recharge with the natural and artificial recharge of Henbadhoo Island

Percentage of artificial recharge with respect to annual rainfall	**Annual rainfall (mm)**	**Natural recharge (mm)**	**Artificial recharge (mm)**	**Total recharge (mm)**
5%	1715	655	85.8	740.8
10%	1715	655	171.5	826.5

Table 4.13: Comparison of observed and simulated maximum freshwater lens thickness and freshwater lens volume of Henbadhoo Island

Percentage of artificial recharge with respect to annual rainfall	**Maximum freshwater lens thickness (m)**	**Freshwater lens volume (m^3)**
0%	2.6	27,705
5%	4.0	39,836
10%	4.9	52,418

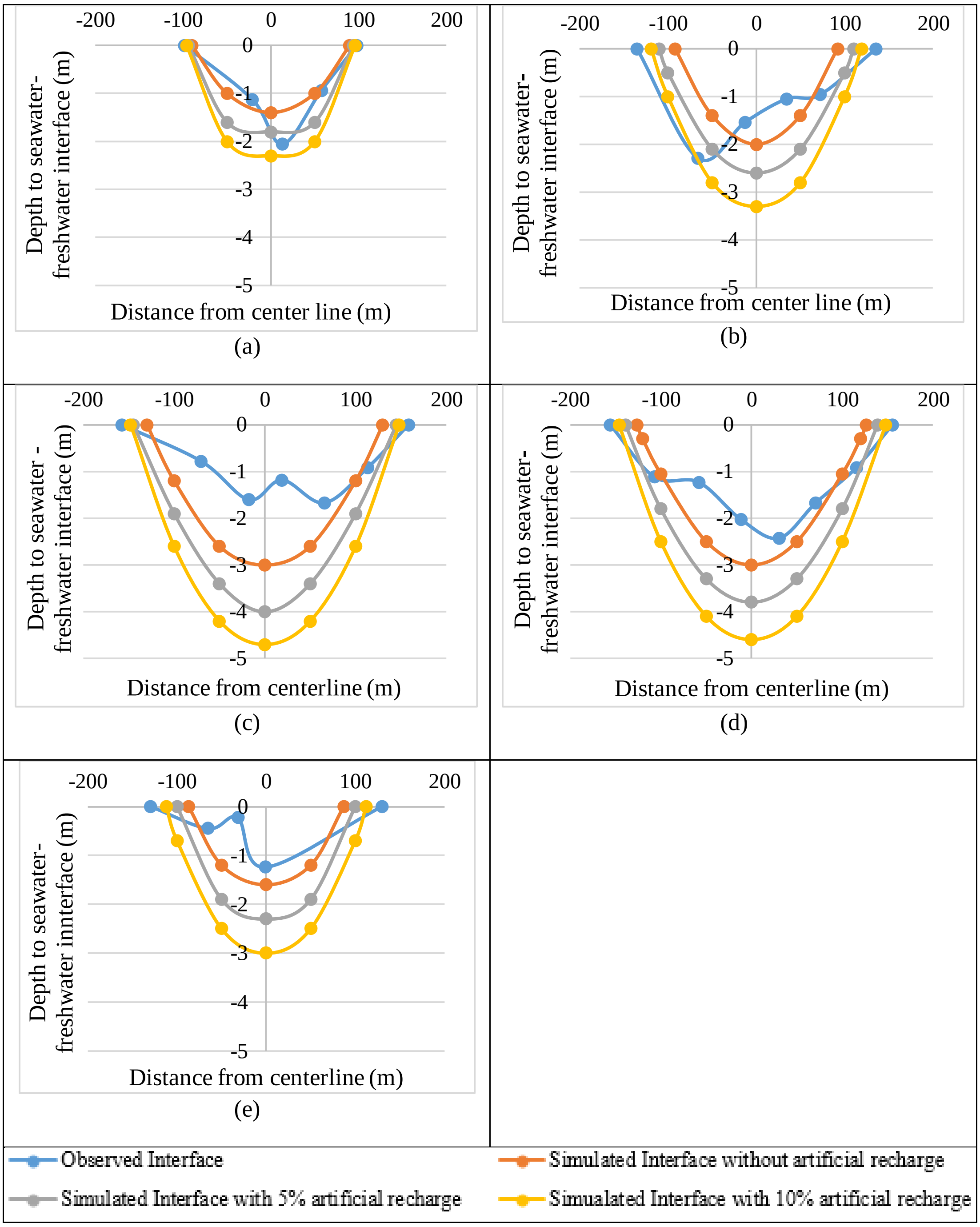


Figure 4.17: Change in seawater - freshwater interface with artificial recharge in Henbadhoo Island in Transects 1(a), 2(b), 3(c), 4(d) & 5(e) (original in colour)

4.5.3 Effect of artificial recharge in Bodufolhadhoo Island

Recharge was increased by 5% and 10% and was input to the previously calibrated model and the effect of artificial recharge was identified. Table 4.14 summarises the total recharge amount with natural and artificial recharge. Figure 4.18 shows the change in seawater - freshwater interface in each transects with artificial recharge. Table 4.15 summarises the change in freshwater lens thickness and freshwater volume with artificial recharge.

Table 4.14: Total recharge with the natural and artificial recharge of Bodufolhadhoo Island

Percentage of artificial recharge with respect to annual rainfall	Annual rainfall (mm)	Natural recharge (mm)	Artificial recharge (mm)	Total recharge (mm)
5%	1940	678	97	775.0
10%	1940	678	194	872.0

Table 4.15: Comparison of observed and simulated maximum freshwater lens thickness and freshwater lens volume of Bodufolhadhoo Island

Percentage of artificial recharge with respect to annual rainfall	Maximum freshwater lens thickness (m)	Freshwater lens volume (m^3)
0%	1.5	8,131
5%	2.7	17,527
10%	3.4	30,366

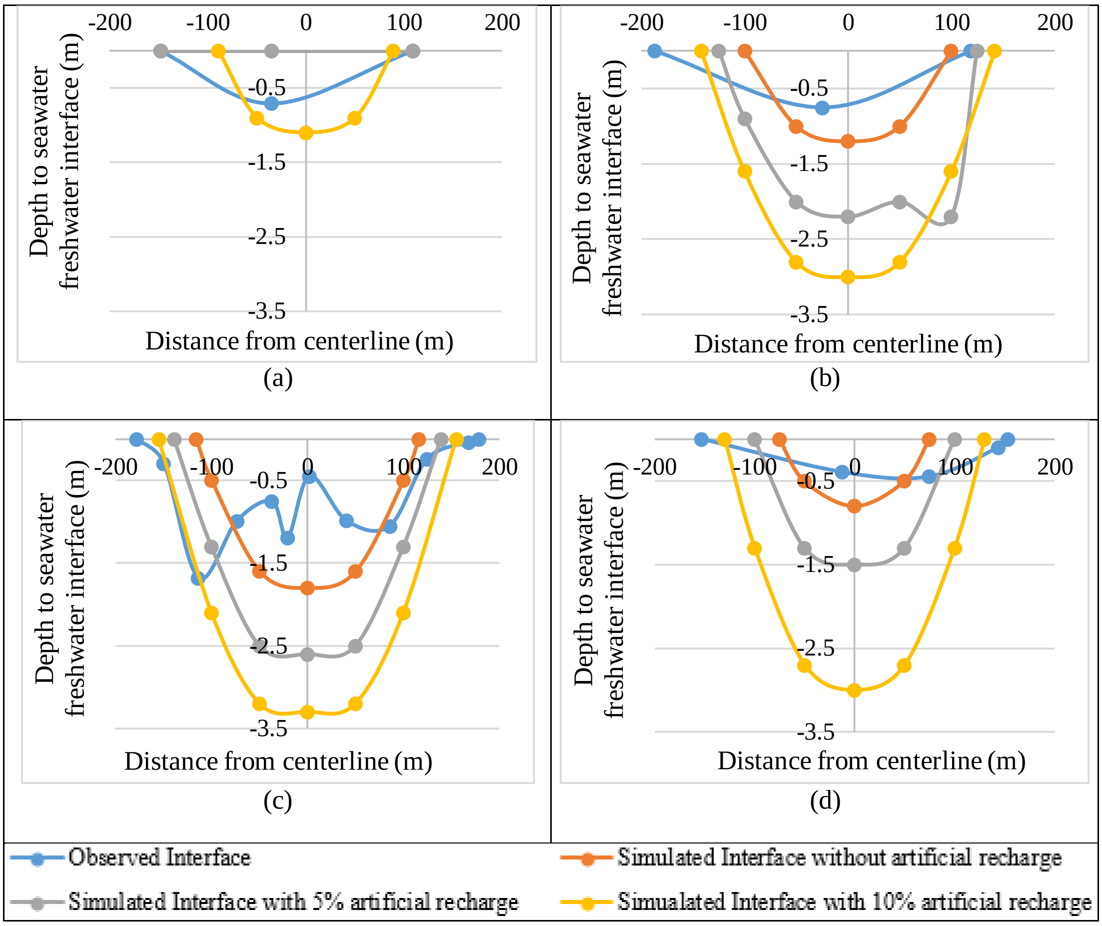


Figure 4.18: Change in seawater - freshwater interface with the artificial recharge in Bodufolhadoo Island in Transects 1(a), 2(b), 3(c) & 4(d) (original in colour)

5 DISCUSSION

5.1 Existing Freshwater Condition of the Islands

Electromagnetic survey data was validated by comparing freshwater levels measured by the electromagnetic survey to that of the nearby dug wells. They matched well with the goodness of fit value (R^2) of 0.96.

Observed seawater - freshwater interfaces of the islands in most of the transects were in lens shape as expected, but interfaces in certain transects have upconing at particular locations. Figure 5.1 to 5.4 show the transects of the islands that have upconing. Over extraction of groundwater at those points is the reason for this (Rumynin, 2011) which will results in depletion of freshwater lens and salinity in freshwater in wells near those locations in future (Rumynin, 2011; Sherif, Kacimov, & Ebraheem, 2012; Kumar, 2006).

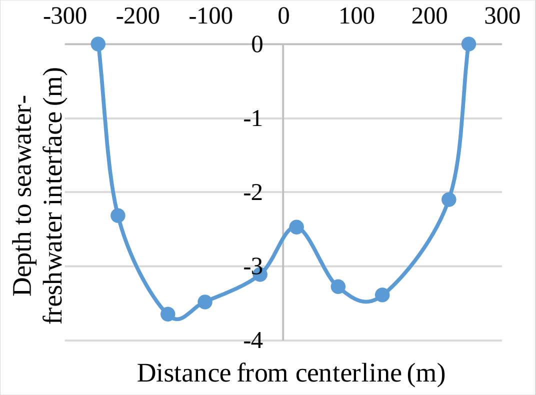


Figure 5.1: Observed seawater - freshwater interface of Dharavandhoo Island in Transect 2

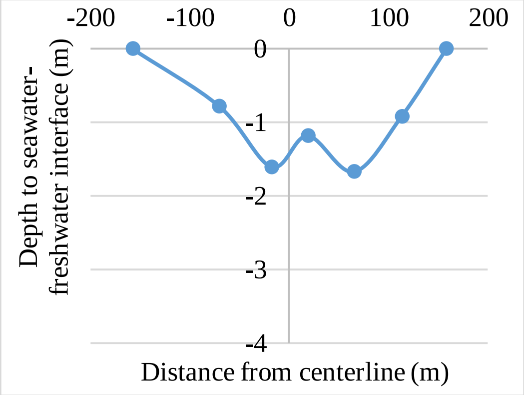


Figure 5.2: Observed seawater - freshwater interface of Henbadhoo Island in Transect 3

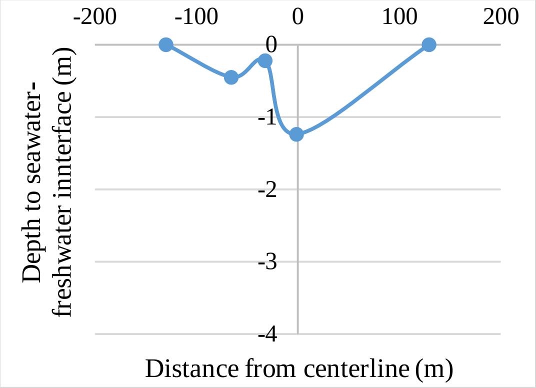


Figure 5.3: Observed seawater - freshwater interface of Henbadhoo Island in Transect 5

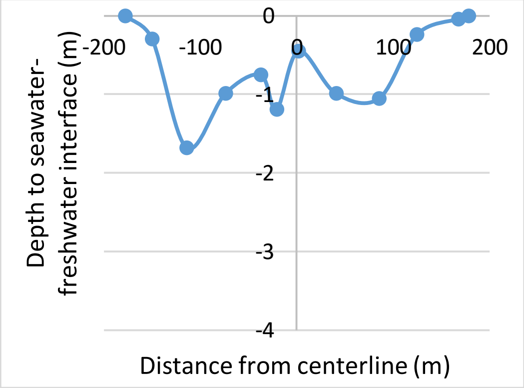


Figure 5.4: Observed seawater - freshwater interface of Bodufolhadhoo Island in Transect 3

5.2 Sensitivity Analysis

Sensitivity analysis results show that freshwater lens thickness is more sensitive to Holocene aquifer hydraulic conductivity. The lens thickness decreases with an increase in conductivity value. In a previous study (Alsumai, 2018) by using three-dimensional numerical modelling in the Maldives Islands, the sensitivity analysis of Holocene aquifer hydraulic conductivity had produced the same results as of this study, that the freshwater lens thickness is much sensitive to the hydraulic conductivity value. Figure 5.5 shows the sensitivity analysis plot of this study and Figure 5.6 is the image of sensitivity analysis of the study conducted by Alsumai (2018).

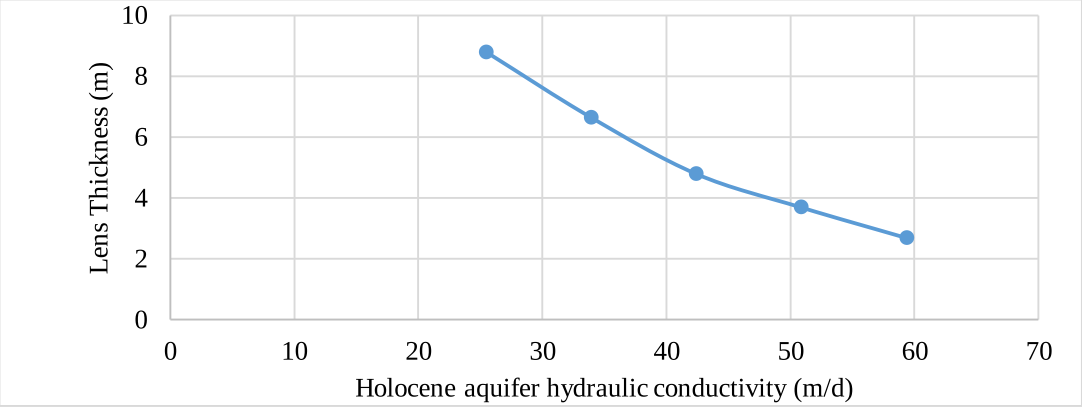


Figure 5.5: Sensitivity analysis plot of Holocene aquifer hydraulic conductivity

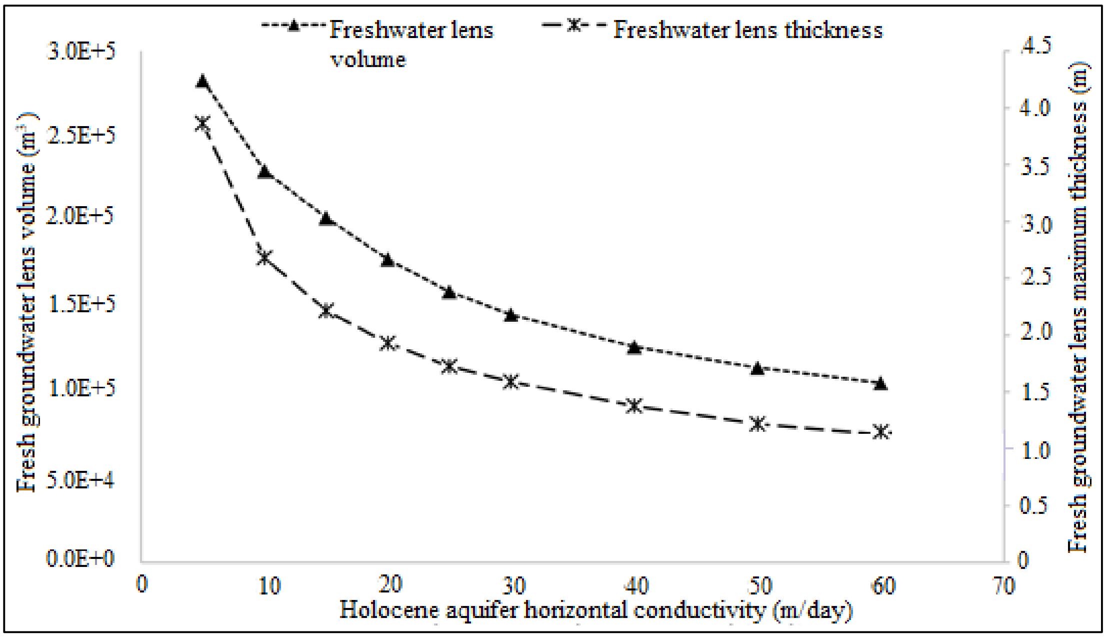


Figure 5.6: Sensitivity analysis plot of Holocene aquifer hydraulic conductivity in a previous study (Alsumai, 2018)

Sensitivity analysis was carried out to identify the impact of recharge rate also. To validate the results, various algebraic models from the literature were taken into consideration. The atoll island lens thickness model (Bailey, Jenson, & Oslen, 2010) given by Eq. (5) matched well with the model output,

$$Z_{max} = L(1-e^{-bR})SC \tag{5}$$

where, R is the average annual rainfall, b is the factor for the width of the island cross section, S and C are the factors for hydraulic conductivity and L is the upper limit of the freshwater lens. These parameters were obtained from the charts and tables provided in the study (Bailey, Jenson, & Oslen, 2010).

Figure 5.7 compares the modelled freshwater lens thickness and the calculated freshwater lens thickness by atoll island lens thickness model.

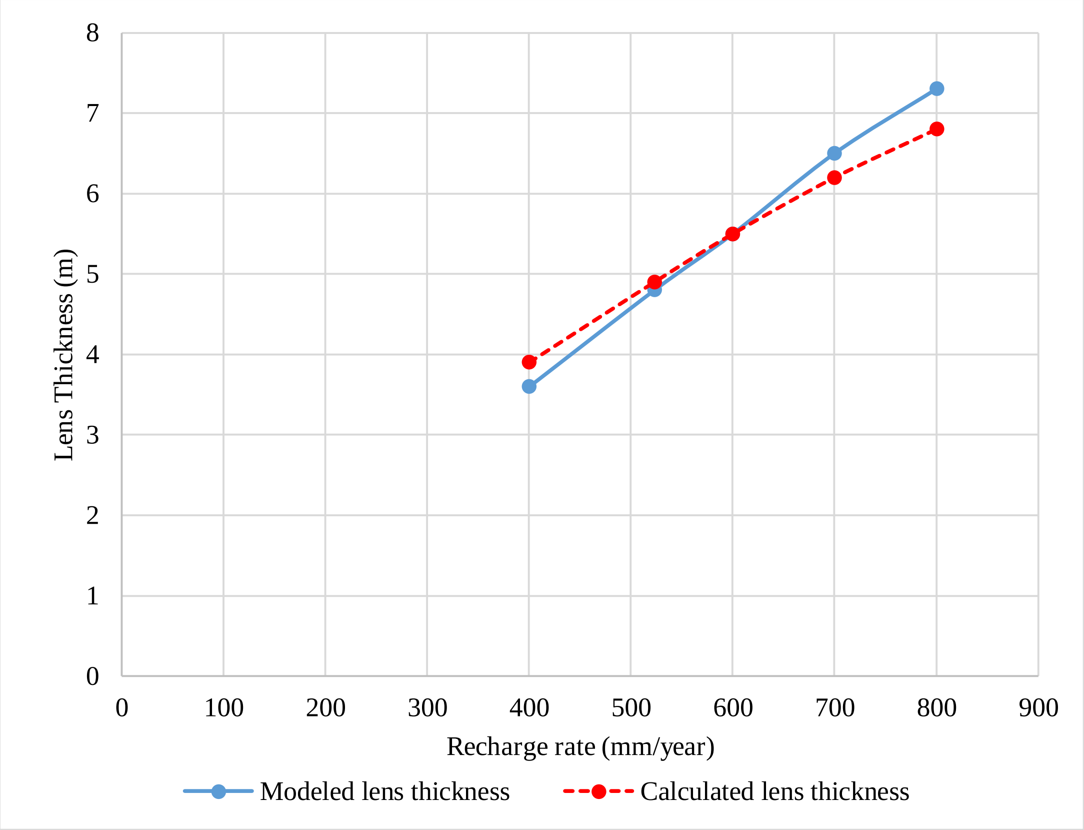


Figure 5.7: Comparison of modelled and calculated freshwater lens thickness

5.3 Model Calibration

Model calibration was achieved by adjusting Holocene aquifer hydraulic conductivity until the modelled freshwater lens volume and the observed freshwater lens volume match within ±10% volume variation. Pumping rate and recharge rate were assigned uniformly throughout the island but in the real situation, the pumping rate will not be actually uniform. Near the coastline, the pumping rate will be low due to lower population density, and in the middle of the island, it will be higher. Land use variation can be seen in the areal maps of the islands provided in Appendix A. Figure 5.8 shows the comparison of modelled and observed seawater - freshwater interface of Dharavandhoo Island. Near the coastline, the model underpredicts the seawater - freshwater interface and in the middle of the island, the model overpredicts it. This could be attributed to pumping variation (Babu, Park, Yoon, & Kula, 2018).

Calibrated hydraulic conductivity values of the three islands range from 25 m/day to 45 m/day, which is inside the range of Holocene aquifer hydraulic conductivity values of atoll islands presented in previous studies (Bailey & Jenson, 2009; Falkland T. , 2000; Falkland T. , 2001). Table 5.1 summarises the observed and simulated freshwater lens thickness, volume and calibrated hydraulic conductivity of all three islands.

Table 5.1: Summary of observed and simulated freshwater lens thickness, volume and calibrated Holocene aquifer hydraulic conductivity value of all three islands

Island	**Freshwater lens Thickness (m)**		**Freshwater Volume (m^3)**			**Holocene aquifer conductivity (m/day)**	
	Observed	**Simulated**	**Observed**	**Simulated**	**Difference (%)**	**Horizontal**	**Vertical**
Dharavandhoo	5.2	6.1	285,417	262,759	7.9	45.0	9.0
Henbadhoo	2.6	3.1	27,705	27,046	2.4	25.0	5.0
Bodufulhudhoo	1.5	1.7	8,131	8,440	3.8	38.0	7.6

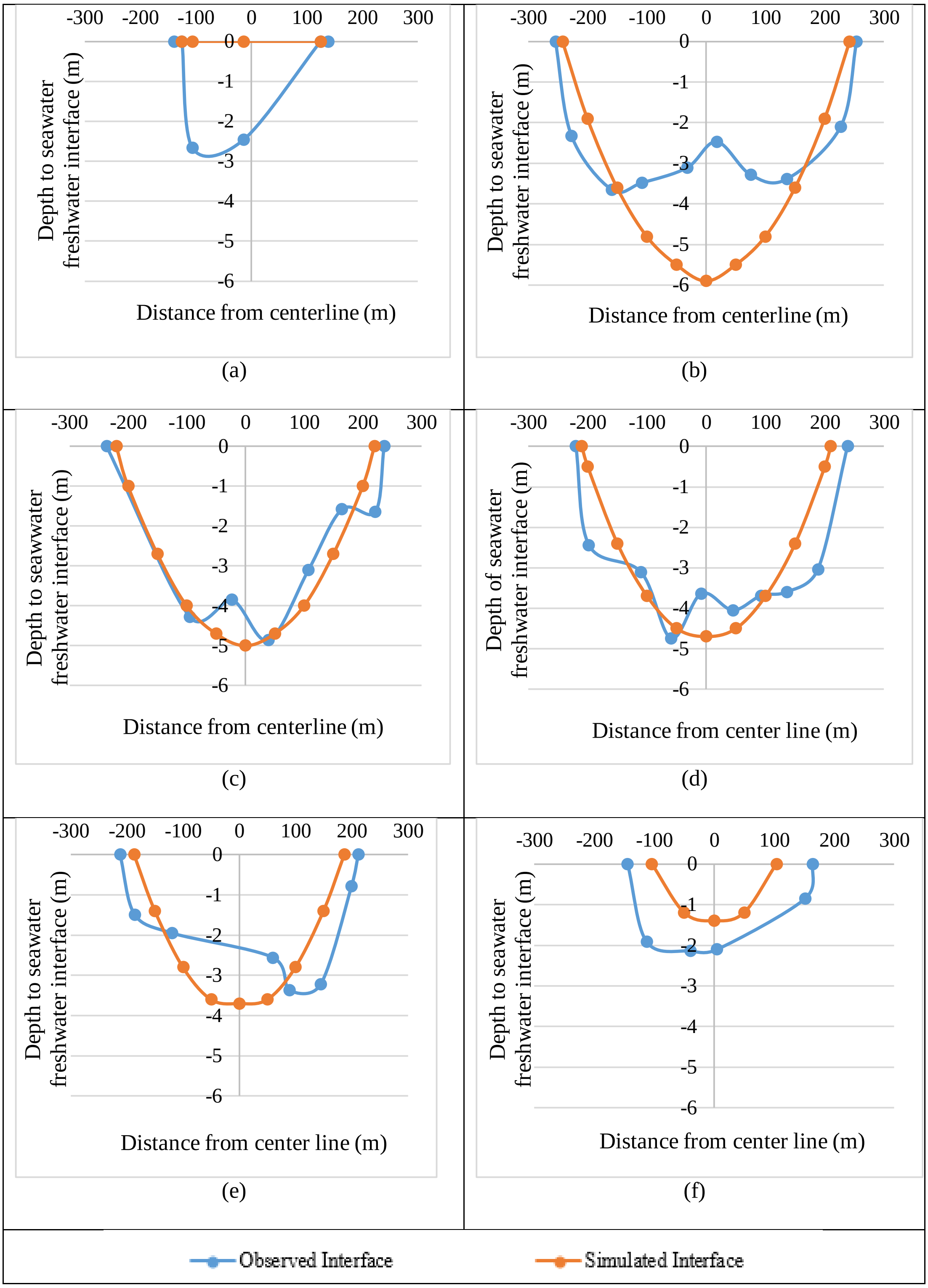


Figure 5.8: Comparison of observed and simulated freshwater lens thickness of Dharavandhoo Island in Transect 1(a), 2(b), 3(c), 4(d), 5(e) and 6(f) (original in colour)

5.4 Effect of Artificial Recharge

Table 5.2 summarises the freshwater lens thickness and volume of all islands with and without artificial recharge. Change in freshwater lens thickness and volume of Dharavandhoo, Henbadhoo and Bodufolhadhoo islands are shown in Figures 5.9 to 5.11. Freshwater lens thickness and volume of all islands increase up to a considerable amount with artificial recharge and therefore, the artificial recharge will be a better and sustainable solution for water related issues in small islands. Most of the previous studies about artificial recharge concluded that artificial recharge increases the quality and quantity of freshwater. In this study, the results also show a good impact on the freshwater lens by artificial recharge.

Table 5.2: Summary of freshwater lens thickness and volume of all islands with and without artificial recharge

Islands	**Without Artificial Recharge**		**With 5% Artificial Recharge**		**With 10% Artificial Recharge**	
	Maximum freshwater lens thickness (m)	**Freshwater lens volume (m^3)**	**Maximum freshwater lens thickness (m)**	**Freshwater lens volume (m^3)**	**Maximum freshwater lens thickness (m)**	**Freshwater lens volume (m^3)**
Dharavandhoo	5.2	285,417	6.9	323,607	8.0	375,527
Henbadhoo	2.6	27,705	4.0	39,836	4.9	52,418
Bodufolhadhoo	1.5	8,131	2.7	17,527	3.4	30,366

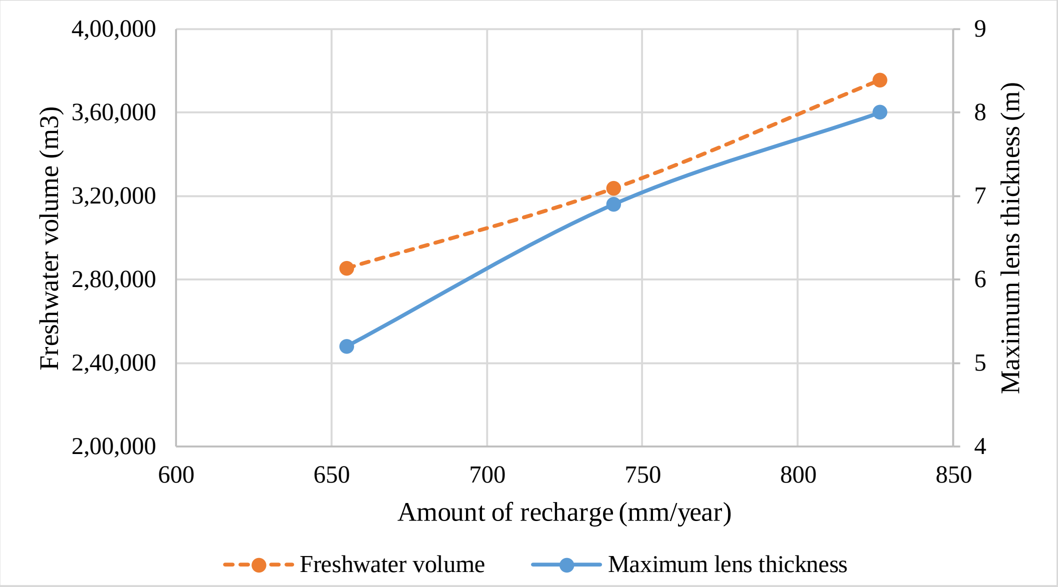


Figure 5.9: Summary of variation of freshwater lens volume and thickness with the artificial recharge in Dharavandhoo Island

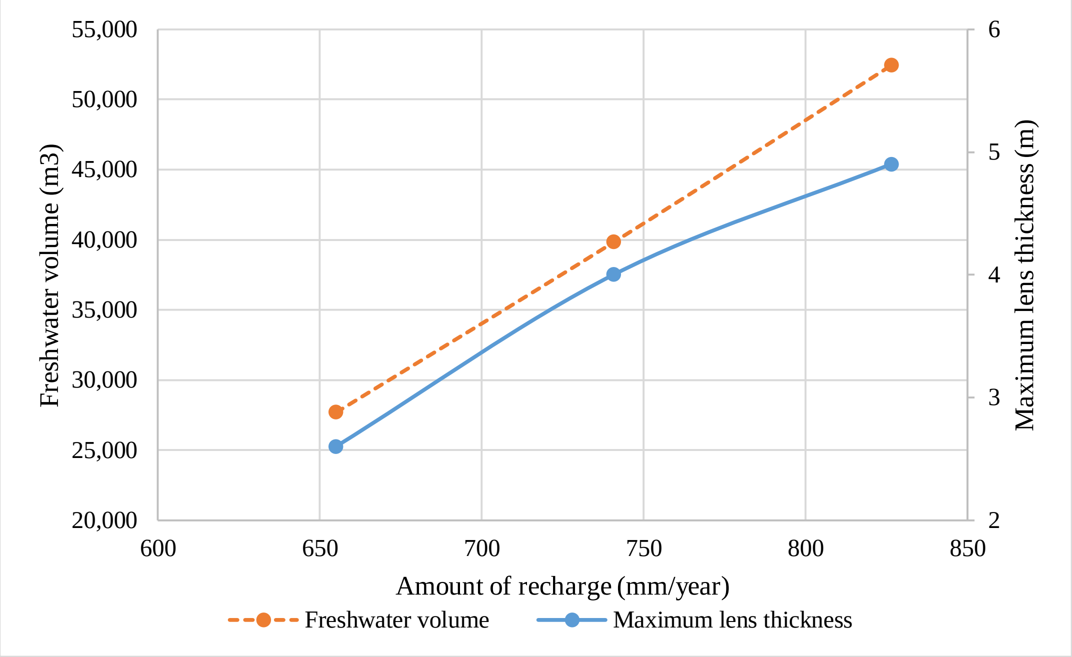


Figure 5.10: Summary of variation of freshwater lens volume and thickness with the artificial recharge in Henabdhoo Island

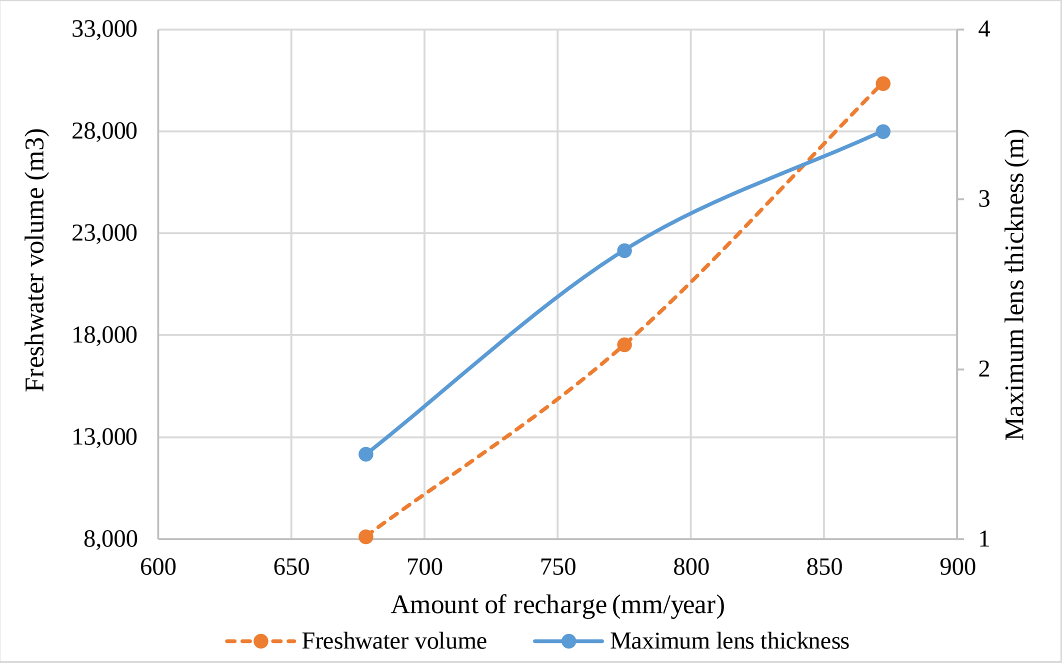


Figure 5.11: Summary of freshwater lens thickness and volume with the artificial recharge in Bodufolhadhoo Island

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Artificial recharge method is a relatively new method in small islands, which needs more research to be carried out focusing on this topic. In this study, the effect of artificial recharge on the freshwater lens of three small islands in the Maldives was analysed by using a numerical modelling approach. Before analysing the effect of artificial recharge, the existing condition of the freshwater lens in selected islands was identified.

Collected electromagnetic survey data was validated by comparing freshwater levels measured by the electromagnetic survey to that of the nearby dug wells. The data sets matched well with the goodness of fit (R^2 value) of 0.96.

Observed seawater - freshwater interfaces of islands in most transects were in lens shape as expected but interfaces in certain transects had upconing at particular locations. Over extraction of groundwater at those points is the reason for this, which might results in depletion of the freshwater lens in future. To avoid this, the pumping rates at these locations should be minimised.

From the sensitivity analysis results, it was identified that freshwater lens thickness is more sensitive to Holocene aquifer hydraulic conductivity. Calibrated hydraulic conductivity values of the three islands were within the range of Holocene aquifer hydraulic conductivity values of atoll islands presented in previous studies.

Analysis of results of the artificial recharge shows that with a 5% of annual rainfall as artificial recharge, the freshwater lens thickness of Dharavandhoo, Henbadhoo and Bodufolhadhoo islands increased from 5.2 m to 6.9 m (33%), 2.6 m to 4.0 m (54%) and 1.5 m to 2.7 m (80%), respectively, leading to a volumetric increase of 38,190 m^3 (13%), 12,131 m^3 (44%), 9,396 m^3 (115%), respectively. With a 10% artificial recharge, the freshwater lens thickness of Dharavandhoo, Henbadhoo and Bodufolhadhoo islands increased from 5.2 m to 8 m (53%), 2.6 m to 4.9 m (88%) and 1.5 m to 3.4 m (127%), respectively, leading to a volumetric increase of 90,110 m^3 (32%), 24,713 m^3 (89%), 22,235 m^3 (273%). From these findings, it can be concluded that artificial recharge will be a sustainable solution to overcome water scarcity issues in small islands.

6.2 Recommendations

In this study, spatial variation of pumping was not taken into consideration. Freshwater lens in small atoll islands is more sensitive to pumping. Its effect should be identified clearly. The pumping rate in each transect can be calculated separately by using land use maps from google earth or by field survey data and the each transect can be modelled with different pumping rate. Further, upconing in certain points can be modelled by assigning high pumping rate at specific nodes, if there is a restaurant/construction site and its water consumption is high, it can be modelled and its effect on the freshwater lens can be identified.

Previous studies have identified that there will be an impact due to sea-level rise and population growth. Further studies can be conducted to identify the combined effect of artificial recharge, sea level rise and population growth.

Relatively high sensitivity to increased recharge was observed in the present study. The proposed 5% and 10% artificial recharge in relation to total annual rainfall will lead to an increase in the present recharge rates by 12-28% in individual islands. It was assumed that this increased recharge will contribute only to increasing the freshwater lens by recharging the ground and pushing down the seawater - freshwater interface. However, the potential losses due to shallow groundwater flow (lateral flow) directly into the sea were not considered in this research. This is an important factor which will affect the sensitivity of freshwater lens thickness and volume by proposed artificial recharge, especially in small islands with a thin freshwater lens. Future studies need to be carried out taking this aspect into consideration.

Further, the depth to the existing groundwater level was not considered when proposing 5% and 10% increase in recharge and estimating the increased lens thickness. This is an important aspect to decide on the most suitable approach for artificial recharge (surface pits, ponds, canals, trenches and riverbeds versus deep underground systems including wells or boreholes, induced recharge wells, etc.) as well as for flood risk control (due to elevated groundwater tables and reduced infiltration rates due to soil oversaturation) and should be investigated further based on individual localities in each island in detailed future studies.

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APPENDICES

Appendix A – Reference Maps of Islands

Figure A 1: Areal map of Dharavandhoo Island

Figure A 2: Areal map of Henbadhoo Island

Figure A 3: Areal map of Bodufolhadhoo Island

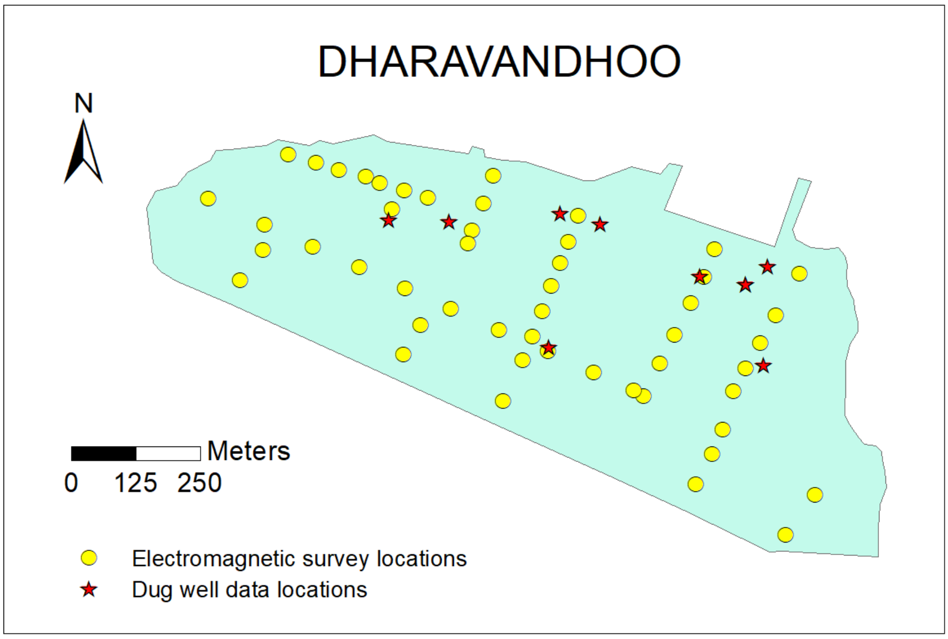

Figure A 4: Electromagnetic survey locations and dug well locations of Dharavndhoo Island

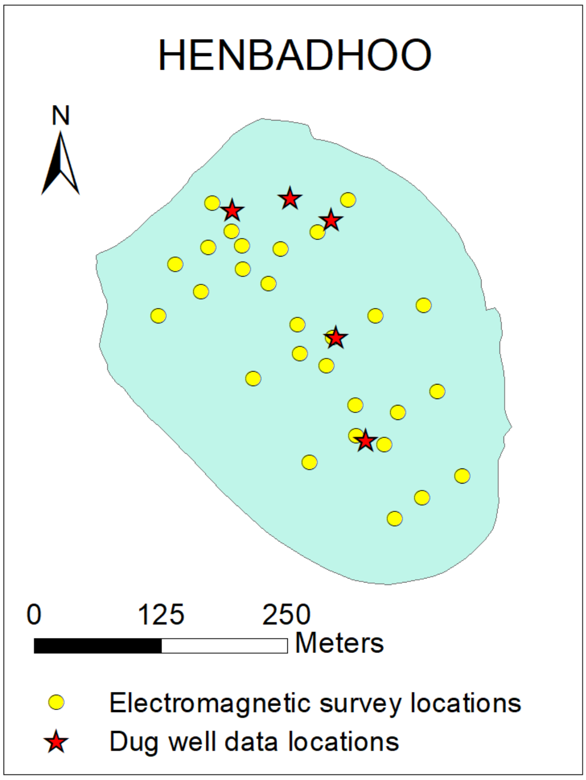

Figure A 5: Electctromagnetic survey locations and dugwell locations of Henbadhoo Island

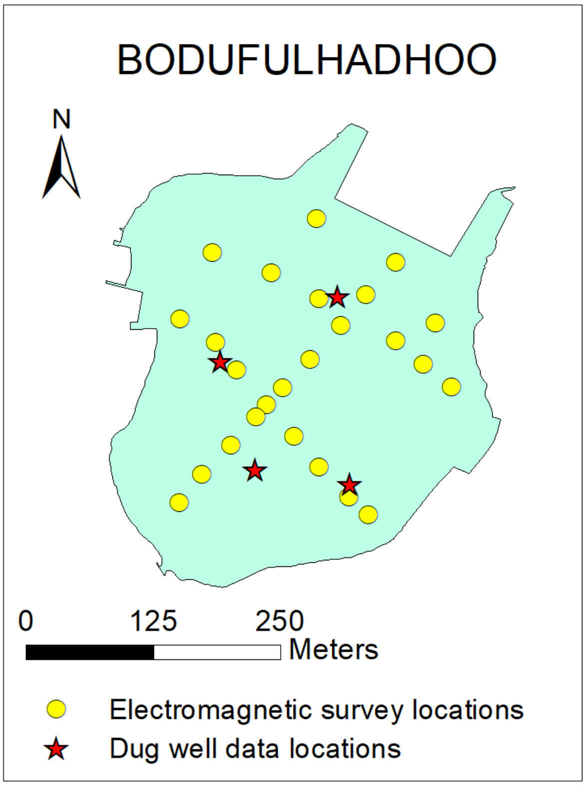

Figure A 6: Electromagnetic survey location and dugwell locations of Bododufolhadhoo Island

Appendix B – Freshwater Lens Volume Calculations

Table B 1: Observed freshwater lens volume calculation of Henbadhoo Island

Transect	Distance from center line (m)	Depth to seawater fresh water interface (m)	Fresh water level (m)	Freshwater lens thickness (m)	Area (m^{2})	Length of transect from previous transect (m)	Volume (m^{3})
1	-109	0	0	0	0		
	-98	0	0	0	54.60		
	-21	-1.13	0.30	1.42	65.12		
	13	-2.06	0.28	2.34	77.35		
	58	-0.93	0.20	1.14	22.77		
	98	0	0	0	0		
	109	0	0	0			
	Total				219.84	73	4,713.88
2	-150	0	0	0	0		
	-135	0	0	0	98.81		
	-66	-2.29	0.58	2.87	131.46		
	-13	-1.54	0.53	2.07	88.33		
	35	-1.05	0.61	1.66	60.05		
	73	-0.96	0.54	1.50	47.25		
	136	0	0	0	0		
	151	0	0	0			
	Total				425.90	86	6,983.62
3	-175	0	0	0	0		
	-157	0	0	0	50.66		
	-70	-0.78	0.38	1.16	79.06		
	-18	-1.60	0.25	1.85	62.76		
	19	-1.18	0.41	1.59	82.41		
	65	-1.67	0.27	1.94	79.88		
	113	-0.92	0.48	1.40	31.39		
	158	0	0	0	0		
	176	0	0	0			
	Total				386.15	97	8,497.60
4	-173	0	0	0	0		
	-156	0	0	0	32.86		
	-107	-1.12	0.24	1.35	73.10		
	-58	-1.23	0.4	1.63	90.51	100	6,777.57

	-11	-2.03	0.22	2.25	102.29		
	30	-2.43	0.21	2.64	92.89		
	71	-1.67	0.27	1.94	72.41		
	116	-0.92	0.38	1.30	25.82		
	155	0	0	0	0		
	173	0	0	0			
	Total				489.89		
5	-144	0	0	0	0		
	-130	0	0	0	24.45		
	-65	-0.45	0.31	0.76	23.41		
	-32	-0.23	0.41	0.64	34.87		
	-1	-1.24	0.37	1.61	105.13		
	130	0	0	0	0		
	144	0	0	0			
	Total				187.87	39	732.68
Freshwater Volume (m^3)							**27,705**

Table B 2: Simulated freshwater lens volume calculation of Henbadhoo Island

Transect	**Distance from center line (m)**	**Depth to seawater freshwater interface (m)**	**Fresh water level (m)**	**Freshwater lens thickness (m)**	**Area (m^2)**	**Length of transect from previous transect (m)**	**Volume (m^3)**
1	-109	0	0	0	0		
	-90	0	0	0	20.71		
	-50	-1	0.04	1.04	62.14		
	0	-1.4	0.05	1.45	62.14		
	50	-1	0.04	1.04	20.71		
	90	0	0	0	0		
	109	0	0	0			
	Total				165.71	73	2,939.57
2	-150	0	0		0		
	-92	0	0	0	30.45		
	-50	-1.4	0.05	1.45	88.03		
	0	-2	0.07	2.07	88.03		
	50	-1.4	0.05	1.45	30.45		
	92	0	0	0	0		
	151	0	0				
	Total				236.97	86	6,544.88

3	-175	0	0		0		
	-130	0	0	0	18.64		
	-100	-1.2	0.04	1.24	98.39		
	-50	-2.6	0.09	2.69	144.99		
	0	-3	0.10	3.10	144.99		
	50	-2.6	0.09	2.69	98.39		
	100	-1.2	0.04	1.24	18.64		
	130	0	0	0	0		
	175	0	0				
	Total				524.06	97	9,920.21
4	-173	0	0		0		
	-126.5	0	0	0	1.00		
	-120	-0.3	0.01	0.31	13.98		
	-100	-1.05	0.04	1.09	91.92		
	-50	-2.5	0.09	2.59	142.41		
	0	-3	0.10	3.11	142.41		
	50	-2.5	0.09	2.59	91.91		
	100	-1.05	0.04	1.09	13.98		
	120	-0.3	0.01	0.31	1.00		
	126.5	0	0	0	0		
	173	0	0				
	Total				498.64	100	6,896.21
5	-144	0	0		0		
	-87	0	0	0	22.99		
	-50	-1.2	0.04	1.24	72.50		
	0	-1.6	0.06	1.66	72.50		
	50	-1.2	0.04	1.24	22.99		
	87	0	0	0	0		
	144	0	0				
	Total				190.98	39	744.83
Freshwater Volume (m^3)							**27,046**

Table B 3: Observed freshwater lens volume calculation of Bodufolhadhoo Island

Transect	**Distance from center line (m)**	**Depth to seawater freshwater interface (m)**	**Fresh water level (m)**	**Freshwater lens thickness (m)**	**Area (m^2)**	**Perpendicular distance between transects (m)**	**Volume (m^3)**
1	-148	0	0	0	40.00		
	-35	-0.71	0	0.71	50.98		
	148	0	0	0			
	Total				90.98	33	681.43
2	-187	0	0	0	61.16		
	-25	-0.76	0	0.76	54.36		
	119	0	0	0	0		
	187	0	0	0			
	Total				115.52	87	3,360.47
3	-198	0	0	0	0		
	-178	0	0	0	0		
	-150	-0.30	-0.30	0	27.10		
	-114	-1.68	-0.17	1.51	53.61		
	-74	-0.99	0.17	1.16	36.55		
	-37	-0.75	0.09	0.84	18.03		
	-21	-1.20	0.15	1.34	22.40		
	2	-0.45	0.16	0.61	35.95		
	41	-0.99	0.26	1.25	50.56		
	86	-1.05	-0.05	0.99	22.87		
	125	-0.24	-0.07	0.17	3.66		
	168	-0.04	-0.04	0	0		
	178	0	0	0	0		
	198	0	0	0			
	Total				270.74	80	2,959.13
4	-170	0	0	0	0		
	-153	0	0	0	37.29		
	-12	-0.40	0.14	0.53	44.64		
	75	-0.45	0.05	0.49	17.21		
	144	0.02	0.02	0	0		
	153	0	0	0	0		
	170	0	0	0			
	Total				99.15	114	1,130.27
Freshwater Volume (m^3)							**8,131.29**

Table B 4: Simulated freshwater lens volume calculation of Bodufolhadhoo Island

Transect	**Distance from center line (m)**	**Depth to seawater-freshwater interface (m)**	**Fresh water level (m)**	**Fresh water lens thickness (m)**	**Area (m^2)**	**Perpendicular distance between the transects (m)**	**Volume (m^3)**
1	No freshwater					33	546.85
2	-187	0	0	0	0		
	-100	0	0	0	0		
	-100	0	0	0	25.90		
	-50	-1	0.04	1.04	56.97		
	0	-1.2	0.04	1.24	56.97		
	50	-1	0.04	1.04	25.90		
	100	0	0	0	0		
	100	0	0	0	0		
	187	0	0	0			
	Total				165.71	87	3,991.70
3	-198	0	0	0	0		
	-116	0	0	0	4.14		
	-100	-0.5	0.018	0.52	54.37		
	-50	-1.6	0.057	1.66	88.03		
	0	-1.8	0.064	1.86	88.03		
	50	-1.6	0.057	1.66	54.37		
	100	-0.5	0.018	0.52	4.14		
	116	0	0	0	0		
	198	0	0	0			
	Total				293.10	80	2,986.96
4	-170	0	0	0	0		
	-75	0	0	0	6.47		
	-50	-0.5	0.018	0.52	33.66		
	0	-0.8	0.029	0.83	33.66		
	50	-0.5	0.018	0.52	6.47		
	75	0	0	0	0		
	170	0	0	0			
	Total				80.27	114	915.04
Freshwater volume (m^3)							**8,440.54**

Table B 5: Freshwater lens volume calculation of Dharavandhoo Island with 5% artificial recharge

Transect	**Distance from center line (m)**	**Depth to seawater-freshwater interface (m)**	**Fresh water level (m)**	**Freshwater lens thickness (m)**	**Area (m^2)**	**Perpendicular distance between the transects (m)**	**Volume (m^3)**
1	No freshwater					212	48,634.40
2	-282	0	0	0	0	163	67,054.94
	-250	0	0	0	64.73		
	-200	-2.5	0.09	2.59	176.07		
	-150	-4.3	0.15	4.45	256.33		
	-100	-5.6	0.20	5.80	310.71		
	-50	-6.4	0.23	6.63	339.19		
	0	-6.7	0.24	6.94	339.19		
	50	-6.4	0.23	6.63	310.71		
	100	-5.6	0.20	5.80	256.34		
	150	-4.3	0.15	4.45	176.07		
	200	-2.5	0.09	2.59	64.73		
	250	0	0	0	0		
	282	0	0	0			
	Total				2294.076		
3	-263	0	0	0	0	257	89,488.00
	-228	0	0	0	21.75		
	-200	-1.5	0.05	1.55	124.28		
	-150	-3.3	0.12	3.42	207.14		
	-100	-4.7	0.17	4.87	264.10		
	-50	-5.5	0.20	5.70	292.59		
	0	-5.8	0.20	6.00	292.59		
	50	-5.5	0.20	5.69	264.10		
	100	-4.7	0.17	4.87	207.14		
	150	-3.3	0.12	3.41	124.28		
	200	-1.5	0.05	1.55	21.75		
	228	0	0	0	0		
	263	0	0	0			
	Total				1819.73		
4	-255	0	0	0	0	201	57,922.81
	-220	0	0	0	10.36		

	-200	-1	0.04	1.04	103.57		
	-150	-3	0.11	3.11	191.60		
	-100	-4.4	0.16	4.56	248.57		
	-50	-5.2	0.19	5.39	277.05		
	0	-5.5	0.20	5.70	277.05		
	50	-5.2	0.19	5.39	248.57		
	100	-4.4	0.16	4.56	191.60		
	150	-3	0.11	3.11	103.57		
	200	-1	0.04	1.04	10.36		
	220	0	0	0	0		
	255	0	0	0			
	Total				1662.30		
5	-236	0	0	0	0	356	54,476.78
	-196	0	0	0	45.26		
	-150	-1.9	0.07	1.97	137.23		
	-100	-3.4	0.12	3.52	199.37		
	-50	-4.3	0.15	4.45	227.85		
	0	-4.5	0.16	4.66	227.85		
	50	-4.3	0.15	4.45	199.37		
	100	-3.4	0.12	3.52	137.23		
	150	-1.9	0.07	1.97	45.26		
	196	0	0	0	0		
	236	0	0	0			
	Total				1219.43		
6	-172	0	0	0	0	194	6,029.78
	-117	0	0	0	5.28		
	-100	-0.6	0.02	0.62	59.55		
	-50	-1.7	0.06	1.76	93.21		
	0	-1.9	0.07	1.97	93.21		
	50	-1.7	0.06	1.76	59.55		
	100	-0.6	0.02	0.62	5.28		
	117	0	0	0	0		
	172	0	0	0			
	Total				310.81		
Freshwater Volume (m^3)							**323,606.72**

Table B 6: Freshwater lens volume calculation of Dharavandhoo Island with 10% artificial recharge

Transect	**Distance from center line (m)**	**Depth to seawater-freshwater interface (m)**	**Fresh water level (m)**	**Freshwater lens thickness (m)**	**Area (m^2)**	**Perpendicular distance between the transects (m)**	**Volume (m^3)**
1	-139	0	0	0	0	212	56,934.09
	-80	0	0	0	12.42		
	-50	-0.8	0.03	0.83	46.60		
	0	-1	0.04	1.03	46.60		
	50	-0.8	0.03	0.83	12.42		
	80	0	0	0	0		
	139	0	0	0			
	Total				59.04		
2	-282	0	0	0	0	163	77,108.12
	-250	-0.4	0.01	0.41	88.03		
	-200	-3	0.10	3.10	204.55		
	-150	-4.9	0.17	5.07	289.99		
	-100	-6.3	0.22	6.52	346.96		
	-50	-7.1	0.25	7.35	383.21		
	0	-7.7	0.27	7.97	383.21		
	50	-7.1	0.25	7.35	346.96		
	100	-6.3	0.22	6.52	289.99		
	150	-4.9	0.17	5.07	204.55		
	200	-3	0.10	3.10	88.03		
	250	-0.4	0.01	0.41	1.04		
	282	0	0	0			
	Total				2626.54		
3	-263	0	0	0	0	257	103,848.14
	-235	0	0	0	34.43		
	-200	-1.9	0.07	1.97	150.17		
	-150	-3.9	0.14	4.04	238.21		
	-100	-5.3	0.19	5.49	297.76		
	-50	-6.2	0.22	6.42	331.42		
	0	-6.6	0.24	6.84	331.42		
	50	-6.2	0.22	6.42	297.76		
	100	-5.3	0.19	5.49	238.21		
	150	-3.9	0.14	4.04	150.18		
	200	-1.9	0.07	1.97	34.44		
	235	0	0	0	0		

	263	0	0	0			
	Total				2104.03		
	-255	0	0	0	0		
	-225	0	0	0	18.12		
	-200	-1.4	0.05	1.45	129.46		
	-150	-3.6	0.13	3.73	222.68		
	-100	-5	0.18	5.18	282.23		
	-50	-5.9	0.21	6.11	315.89		
	0	-6.3	0.22	6.52	315.89		
	50	-5.9	0.21	6.11	282.23		
	100	-5	0.18	5.18	222.68		
	150	-3.6	0.13	3.73	129.46		
	200	-1.4	0.05	1.45	18.12		
	225	0	0	0	0		
	255	0	0	0			
4	Total				1936.76	201	66,778.60
	-236	0	0	0	0		
	-200	-0.2	0.007	0.21	69.91		
	-150	-2.5	0.09	2.59	168.30		
	-100	-4	0.14	4.14	230.44		
	-50	-4.9	0.17	5.07	258.93		
	0	-5.1	0.18	5.28	258.93		
	50	-4.9	0.17	5.07	230.44		
	100	-4	0.14	4.14	168.30		
	150	-2.5	0.09	2.59	69.91		
	200	-0.2	0.007	0.21	0.31		
	236	0	0	0			
5	Total				1385.56	356	63,263.13
	-172	0	0	0	0		
	-126	0	0	0	13.46		
	-100	-1	0.04	1.04	82.86		
	-50	-2.2	0.08	2.28	119.11		
	0	-2.4	0.09	2.49	119.11		
	50	-2.2	0.08	2.28	82.86		
	100	-1	0.04	1.04	13.46		
	126	0	0	0	0		
	172	0	0	0			
6	Total				417.39	194	8,097.31
Freshwater Volume (m^3)							**376,951.16**