in association with

HDH NOLHIVARANFARU ISLAND INFILTRATION GALLERY

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PRELIMINARY INVESTIGATION AND CONCEPT DESIGN REPORT (PROJECT ACTIVITY 2.3 AND 2.4)

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Executive Summary

The report provides an assessment of groundwater conditions in and near the current agricultural plots on the island of HDh. Nolhivaranfaru and provides recommendations for groundwater development for these plots.

This groundwater assessment is part of a project, funded by the United Nations Climate Technology Centre & Network, with the aim of establishing a skimming well gallery system (or “infiltration gallery”) for agricultural use (growing of vegetables and fruit trees) on the island. In this report, the simpler term “gallery” is used to describe either “skimming well gallery” or “infiltration gallery”.

The Consultant team visited Nolhivaranfaru Island from 8 to 11 August 2022 for groundwater investigations. Before the visit, the following work was undertaken:

- Review of two previous groundwater studies for Nolhivaranfaru and nearby islands
- Preliminary assessment of gallery location and length.

The on-site groundwater investigations, which were conducted during the site visit included the following:

- Electromagnetic (EM) surveys in and near the agricultural plots
- Measurements of depths to groundwater level and groundwater salinity (electrical conductivity, EC) at selected wells within the agricultural plots
- Logging of groundwater level and salinity (EC) movements over a 2-day period at a selected well and processing of data.
- Assessment of potential gallery sites.

From MoE (2020) and United Nations (2021), there are 103 plots each with an area of 5,000 square feet (equivalent to approximately 460 m^2). The estimated average groundwater use per plot is about 630 L/day based on 93 active plots. This gives a current average water demand for the 93 plots of approximately 59,000 L/day and a total estimated potential groundwater use for 103 plots of about 65,000 L/day (65 kL/day).

The results from the electromagnetic induction (EM) survey indicate an average fresh groundwater zone thickness of between 6 m and 7 m was present within the agricultural plots. The central (north-south) road showed the best overall results and reflects the proposed location of the gallery.

From water balance analyses, the sustainable yield on an area basis was estimated as 11 kL/day/ha. From this, the length of gallery to supply the full future design pumping rate of 65 kL/day for 103 active lots (unit demand of 630 litres/lot/day) was calculated as approximately 300 m. The length of the gallery estimated and priced in the bid for implementation under the project was 250 m (as it is not possible to estimate actual sustainable yields without the fieldwork investigation data and 250m was considered to represent a reasonable assumption). Based on the calculated sustainable yield of 11 kL/day/ha, the actual allowable pumping rate for the 250m long gallery would be 55 kL/day which equates to 87 active lots at an estimated demand of 630 litres/lot/day. While this yield would be less than than the the ultimate full potential demand, it is also noted that a number of agricultural plots are only farmed for a few months at a time (often in the months approaching Ramadan).

The Concept Design of a 250m long infiltration gallery is outlined in section 3.16 with a concept drawing included in Appendix B. It is noted that at present, the government is investigating the option of providing a tank and reticulation alongside the gallery (refer Kick Off meeting Minutes

Item 3.2) and this would also assist in the future utilisation of the scheme. In addition, should additional funds become available, the Ministry may wish to consider extending the gallery length beyond the 250m allowed for in this contract.

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List of Abbreviations

Abbreviation	Meaning
A&M	Approach & Methodology
AM	Asset Management
AR	Asset Register
BOQ	Bill of Quantities
CEO	Chief Executive Officer
CLO	Community Liaison Officer
COVID-19	Coronavirus disease 2019
CTCN	United Nations Climate Technology and Center Network
DDR	Due-Diligence Report
DED-P2	Detailed Engineering Design Phase 2
DMA	District Metering Area
DN	Diameter Nominal
ECD	Environment & Conservation Division
EIRR	Economic Internal Rate of Return
EMP	Environmental Management Plan
EOT	Extension of Time
EPC	Engineering, Procurement, and Construction
ERP	Enterprise Resource Planning
FIDIC	French: Fédération Internationale Des Ingénieurs-Conseils. English: The International Federation of Consulting Engineers
FIRR	Financial Internal Rate of Return
FS	Feasibility Study
GAP	Gender Action Plan
GIS	Geographic Information Systems
HDE	Hydraulic Design Engineer
HH	Household
HHSQ	Household Survey Questionnaire
IS0	International Standards Organisation

Abbreviation	Meaning
ISS	Informal Settlement Supplies
LOI	Letter of Invitation
MECCT	Ministry of Environment, Climate Change and Technology
MS	Microsoft
NRW	Non-Revenue Water
O&M	Operations and Maintenance
PC	Provincial Capital
PCR	Polymerase Chain Reaction
PD	Project Director
PGs	Provincial Governments
PMU	Project Management Unit
PPP	Public-Private-Partnership
PS	Provisional Sum
PSC	Project Steering Committee
PE	Polyethylene
PVC	Polyvinyl Chloride
RAT	Rapid Antigen Test
STP	Sewage Treatment Plant
TBC	To Be Confirmed
UN	United Nations
WaterGEMS	Water Geospatial Engineering Modelling System
WBS	Work Breakdown Structure
WTP	Water Treatment Plant

1 INTRODUCTION

1.1 General

The report provides an assessment of groundwater conditions in and near the current agricultural plots on the island of HDh. Nolhivaranfaru and provides recommendations for groundwater development for these plots. This groundwater assessment is part of a project, funded by the United Nations Climate Technology Centre & Network, with the aim of establishing a skimming well gallery system (or “infiltration gallery”) for agricultural use (growing of vegetables and fruit trees) on the island. In this report, the simpler term “gallery” is used to describe either “skimming well gallery” or “infiltration gallery”.

The island is located in the Haa Dhaalu Administrative Atoll in the northern part of Maldives. It is located about 280 km north of Malé island and about 3.4 m south of the southern tip of Hdh.Hanimaadhoo. Nolhivaranfaru is approximately 4 km long from the wide northern part to the narrow southern tip. The widest part of the island in the north is approximately 1 km. The width of the island at the central part of the agricultural plots is approximately 630 m. The total area is approximately 170 hectares (ha). The average land elevation is about 1 m above mean sea level (MSL) using data from MoE (2020).

The population of Nolhivaranfaru in 2014 was 1,081 (National Bureau of Statistics, 2014).

The agricultural plots (farms) are located near the middle of the island, south of the urban area of and north of natural vegetation which is largely uncleared. The current area of these plots is approximately 6.5 ha or about 4% of the island area.

From MoE (2020) and United Nations (2021), there are 103 plots each with an area of 5,000 square feet (equivalent to approximately 460 m^2). The estimated average groundwater use per plot is about 630 L/day based on 93 active plots. This gives an estimated potential groundwater use for 103 plots of about 65,000 L/day (65 kL/day). In this report, the term “design pumping rate” is used for the estimated 65 kL/day.

2 CURRENT WATER SUPPLY SYSTEMS

2.1 Existing technologies applied for irrigation in HDh.Nolhivaranfaru Island and similar islands in Maldives

The present agricultural water supply systems generally consist of shallow wells equipped with petrol or electric pumps that draw water from the well and pump to the adjacent crops. A typical installation is shown in the Figure below:

Figure 1 Typical Well and Pump (petrol pump) Installation

The above pumping systems are used to supply water to the crops as shown below:

Figure 2 Typical Irrigation Systems

The water supply systems are typically operated each morning and afternoon or once a day for a limited period. Different farmers adopt different irrigation water usage patterns. It was noted during the site investigation that some of these pumping arrangements can cause significant local water level drawdown in the well while operational (refer Section 3.8). The use of an infiltration gallery will greatly assist in providing a stable, reliable groundwater supply without potential excessive drawdowns associated with pumps in shallow wells pumping at higher flow rates.

Axiomatically the wellbeing of crops depends on water quality. The challenge in population centres is to determine long-term sustainable groundwater extraction rates. Narrow atolls with transmissive aquifers, such as in some atolls in Tuvalu, have limited potential for viable fresh groundwater. For these islands rainwater tanks and desalination appear the only viable options. Sustainable groundwater extraction and use of stored rainwater to maintain freshwater supply throughout droughts is a critical issue for urban areas.

Small land areas in atolls often restrict freshwater supply to mainly basic human needs. The quantity of fresh groundwater contained in lenses depends on atoll width, recharge rate and the ease of transmission of freshwater through the aquifers. Wider islands with high recharge rates and less permeable. Vertically exaggerated cross-section through a low coral island showing the fresh groundwater lens surrounded by seawater.

Often the storage volumes of rainwater tanks are not sufficient to maintain supply in the severe droughts, which are quite frequent, especially in the central Pacific. Sustainable groundwater extraction requires data on recharge rates, demand and the response of freshwater lenses to losses. Sufficiently long monitoring records are available in only a few atolls. Surrogates, such as sea temperature and rainfall inferred from coral cores, provide useful guides to past extreme events. Vulnerability of freshwater in atolls. Natural threats Fresh groundwater in low coral atolls is vulnerable to natural processes and human activities. Drought, storms and climate change affect both quantity and quality of groundwater in atolls. Annual rainfalls in many atolls exhibit large variability due to frequent ENSO-related droughts. Roof catchments and rainwater tanks are generally small and are vulnerable during droughts. Severe droughts have forced the evacuation of some atoll communities in the Pacific. The prediction of, planning for and response to droughts are priorities in small islands. Inundation of low atolls by waves during storms can salinise shallow groundwater. Predicted climate change impacts, particularly sea level rise, therefore causes anxiety.

Living with and managing through current climate variability are continuing challenges that need priority attention. Threats associated with human settlement and wastes. Over pumping of fresh groundwater and inappropriate extraction wells can salinise atoll groundwater. However, biological and chemical pollution of drinking water and its impact on human health are of more concern.

Groundwater contamination caused by sewerage, pigs, crop production. spillage of petroleum products, and seepage from waste dumps occurs in many small islands. The most critical factor influencing groundwater contamination is the depth from the surface to the water table. In atolls this depth is often less than 2 m, and surface contaminants can reach the groundwater in less than 2 h. Swamp taro pits, excavated into water tables, are significant sources of pollution. Faecal contamination of groundwater is a major source of gastroenteritis in atoll communities, causing high infant mortalities and outbreaks of diseases like hepatitis, typhoid and cholera. Domestic wells close to dwellings and pit latrines are especially vulnerable. Defecation on the beach is practiced in many low-density island communities. In higher density populations pit latrines are also used.

It is noted that in Nolhivanafaru Island has a dedeicatyed sewage treatrment plant and the agricultural area is well separated from the living areas of the island.

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2.2 Climate change impact on crop cultivation and production in HDh.Nolhivaranfaru Island and similar islands in the Maldives

The future persistence of atoll islands both as geologic features and as sites of human habitation is uncertain. Anthropogenic climate change is expected to increase sea level and ocean temperature and alter the frequency and intensity of tropical storms (Holdaway et al, 2021). Similarly, changes in ocean temperature and chemistry are expected to reduce the protection services provided by surrounding coral reefs (Sebastian et al, 2019) and reduce the generation of biogenic sediment (Perry et al., 2011), leaving islands vulnerable to shoreline erosion, threatening coastal infrastructure and the stability of the islands themselves (Kench and Webb, 2010). Sea level rise, in concert with changes in ocean swell, is expected to increase the frequency of overtopping and inundation of islands, resulting in damage to infrastructure and the intrusion of saltwater into groundwater reserves (Storlazzi et al., 2018). The exposure to these changing environmental conditions has led to the grim prognosis that many atoll-dwellers will be climate change refugees in the coming decades, as their islands become uninhabitable or even disappear (Betzold, 2015).

Available water either collected or won or obtained through desalination will increase plant diversity and will assist in nutrition security as edible plants are selected and added to the largely marine diet. Commonly the following crops are vicariously grown throughout the atoll states:

Bananas and Plantains (*Musa* spp.)

Betel Nut (*Areca catechu*)

Breadfruit (*Artocarpus altilis*) and other Pacific *Artocarpus* Species

Cassava (*Manihot esculenta*)

Coconut (*Cocos nucifera*)

Kava (*Piper methysticum*)

Noni (*Morinda citrifolia*)

Pandanus (*Pandanus tectorius*)

Sugarcane (*Saccharum officinarum*)

Sweet Potato (*Ipomoea batatas*)

Taro (*Colocasia esculenta*) and other Edible Aroids
Yam (*Dioscorea* spp.)

Reliance on won water – particularly lens or ground water can lead to steady accumulation of minerals particularly wind-blown sea spray.

Climate significantly influences plant response to salinity. Temperature, atmospheric humidity, and air pollution have significant effects on salt tolerance with many crops less salt tolerant when grown under hot, dry conditions. High humidity generally benefits salt sensitive crops more than tolerant crops because increases in salt tolerance result in greater yields.

A strategy in other atoll states to anticipate the effect of this on flora and soil condition has been directed towards the selection of salt-tolerant crops. These including:

Cassytha filiformis – soil conditioner
Citrus x Citrofortunella mitis – edible fruit
Thalassia hemprichii – edible herb

Cassytha filiformis – vine/herb
Thalassia hemprichii – herb/soil conditioner
Xanthosoma sagittifolium – herb/soil conditioner
Asplenium nidus – herb
Ipomoea indica – herb/vine
Hibiscus tiliaceus – ornamental.

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2.3 Status of the Land Use in HDh.Nolhivaranfaru Island and similar islands in the Maldives

Nolhuvaranfaru is a relatively large island in its area (166 ha) in the north of Maldives and is renowned for agricultural activities. Approximately 5000 sqft (0.05ha) of plot has been allocated for households (upon request) free of charge for seasonal crops such as fruits, vegetables, chillies and others. These plots are already cleared of natural vegetation. The approximate combine area of agricultural plots is 3.5 ha.

As of current legal requirement all islands of Maldives are required to prepare a land use plan (20 years horizon) under the decentralization Act (7/2010). Similarly there is a requirement under Land use Plan guidelines of Maldives enforced by Ministry of National Planning ,Housing and Infrastructure (MNPHI), to comply to the guidelines when preparing Land Use Plans (LUPs). Nolhivaranfaru, council has currently contracted a third party (Riyan Pvt Ltd) to prepare a LUP in consultation with the council and all other relevant institutions that will be submitted to MNPHI for approval. According to the Land Use Plan approximately 6.4 ha has currently been allocated from the island for agriculture. This is approximately 4% of the total area of the island. The area allocated for agriculture is approximately same area where current agricultural activity is practiced.

The following figures provides the area where current agricultural activities area practiced and area allocated for agriculture for the proposed LUP (Final draft).

Figure 3 Existing Agricultural Plots (Yellow Rectangle)

Figure 4 Proposed Agricultural Plots as per LUP (Red Rectangle)

Similar islands such as Filladhoo and Uligamu (Ha. Atoll) also have significant levels of agriculture. These islands also have prepared land use plans that have formally allocated agricultural areas. These plans has already approved byy MNPHI (Per. Comm. Riyan Pvt Ltd).

3 GROUNDWATER INVESTIGATIONS

3.1 Outline

Groundwater investigations and analyses were done in accordance with the Proposal (NRW & Lamer, 2021) for Task (Activity) 2.3 “Preliminary investigation in HDh Nolhivaranfaru Island and similar islands in Maldives, and site visit” and part of Task (Activity) 2.4 “Selection of the site to install the infiltration gallery system”.

The investigations included work conducted before the visit to Nolhivaranfaru, groundwater investigations on the island in August 2022 and analysis of data following the visit from 8 to 11th August 2022

Before the visit, the following work was undertaken:

- Review of two previous groundwater studies for Nolhivaranfaru and nearby islands
- Preliminary assessment of gallery location and length.

The on-site groundwater investigations, which were conducted during the period 8th to 11th August, included the following:

- Electromagnetic (EM) surveys in and near the agricultural plots
- Measurements of depths to groundwater level and groundwater salinity (electrical conductivity, EC) at selected wells within the agricultural plots
- Logging of groundwater level and salinity (EC) movements over a 2-day period at a selected well and processing of data.
- Assessment of potential gallery sites.

The opportunity was also taken to search for two multi-level monitoring boreholes that were drilled in the northern part of the island in 2001.

Following the on-site investigations, the following work was completed:

- Analysis of EM data and estimation of fresh groundwater zone thicknesses. It is noted that this zone comprises not only the groundwater itself but also the geological sediments (sands and gravels). The groundwater volume within this zone fills about 30% of the total volume.
- Comparison of recent fresh groundwater zone thicknesses with previous thicknesses obtained in 2019
- Comparison of groundwater depth and EC data from wells within the agricultural plots with a result from the previous study in 2019
- Analysis of groundwater level movements due to the influence of tides and pumping
- Calculation of tidal lag and efficiency at the selected well with data logger
- Analysis of rainfall data
- Estimation of groundwater recharge
- Estimation of sustainable yield
- Assessment of gallery length. location and maximum pumping rate
- Provision of some design details for the gallery and related water infrastructure.

After the investigations above, survey levels relative to MSL were obtained along the central road through the agricultural plot area and at three selected wells adjacent to this road.

Each of the above activities and results are outlined in the sections below.

3.2 Review of Previous Groundwater Studies

Previous studies of groundwater on several islands in Maldives including Nolhivaranfaru are presented in Falkland (2001) and MoE (2020). The earlier study included drilling of two salinity monitoring boreholes in the northern part of the island, an electromagnetic (EM) survey in the northern part of the island (before the agricultural plots were prepared), a survey of groundwater depths and salinities and water quality tests. The later study, conducted in April 2019, which included study in the agricultural plot area, involved an electrical resistivity (ER) survey, survey of groundwater depths and salinities and water quality tests.

Comparison of the results from the two studies is provided in section 3.5.4.

3.3 Agricultural Water resources and Baseline of Infiltration Gallery System

Previous studies of groundwater on several islands in Maldives including Nolhivaranfaru are presented in Falkland (2001) and MoE (2020). The earlier

In order to pump moderate quantities of groundwater from freshwater lenses on small coral islands, such as those in the Maldives, the most appropriate method uses infiltration galleries or "skimming wells" (refer Figure 5~~Figure 5~~). If properly designed, constructed and operated, infiltration galleries can avoid the problems of saline intrusion that can occur due to pumping from wells or vertical boreholes.

Infiltration galleries avoid the problems of excessive drawdown and consequent “upconing” of saline water caused by localised pumping from either wells or boreholes. Galleries effectively skim water from the surface of the lens, thus distributing the pumping over a wide area. Galleries can be constructed with reasonable ease on small coral islands, especially where the water table is relatively shallow, as in the islands of the Maldives. They can be equipped with pumps and are ideal for connection to solar systems where electric power is not available or expensive.

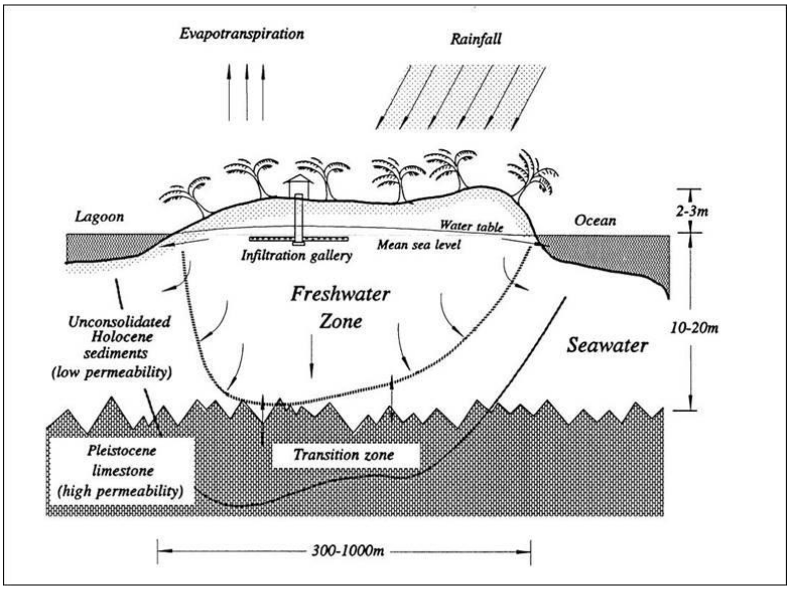

Figure 5 Cross Section through small coral island showing freshwater lens with infiltration gallery (exaggerated vertical scale)

Infiltration galleries generally consist of buried horizontal conduit systems which are permeable to water (for example, PVC slotted pipes). The pipes are laid in trenches dug at or close to mean sea level thus allowing water to be drawn towards one or more pumping wells. The trenches can be dug with a mechanical excavator and/or by hand. Once the gallery pipes are laid, the area is backfilled and the only structures seen above ground level are pump stations and access hole covers.

Infiltration galleries have been constructed and are successfully operating on a number of coral islands including the following:

- Tarawa and Kiritimati atolls, Republic of Kiribati
- South Keeling atoll, Cocos (Keeling) Islands, Australia
- Lifuka island, Ha'apai group, Kingdom of Tonga
- Aitutaki island, Cook Islands
- Majuro and Kwajalein atolls, Republic of Marshall Islands.

It is noted that an infiltration gallery has reportedly been constructed in on Fainu Island in Raa Atoll however the performance data of the gallery is currently not available.

Infiltration galleries are also planned for Kiritimati atoll, Kiribati; other islands in Republic of Marshall Islands and at least one island in Tuvalu.

In summary, infiltration galleries have become a standard technology for pumping fresh groundwater in many coral islands in the Pacific. They have been advocated for use in Maldives islands for many years including in Falkland (2000, 2001a, 2001b, 2004). Infiltration galleries have great potential for sustainably extracting groundwater on many of the larger islands in Maldives especially those which have not been fully developed with housing such as HDh. Nolhivaranfaru.

3.4 Preliminary assessment of gallery location and length

A preliminary assessment of gallery location and length was made based on the results of the ER survey in MoE (2020). This indicated that the north-south road on the western side of the agricultural plots was a possible location. Based on a preliminary assessment of groundwater recharge at tender stage, a gallery length of a 250 m long was estimated to meet the design pumping rate of 65 kL/day (NRW & Lamer, 2021). It is noted that any groundwater recharge estmates is subject to actual field investigation. Further comments regarding the proposed gallery length based on a more detailed assessment are provided in section 3.14.

3.5 Electromagnetic surveys and analysis of data

3.5.1 Purpose, method and locations

During the visit to Nolhivaranfaru, electromagnetic induction (EM) surveys was conducted along roads in and near the agricultural plots to assess fresh groundwater zone thicknesses and determine the preferred location for a gallery from a groundwater perspective. The EM method has been used in previous studies on several islands in Maldives (Falkland, 2000; 2001, 2010a, 2010b, 2010c and 2020d) including on Nolhivaranfaru in 2001 (Falkland, 2001).

The EM equipment used was a Geonics EM34-3 electromagnetic induction meter which comprises a transmitter connected to a transmitter coil and a receiver connected to a receiver coil. The two coils are held by two operators and are linked by a cable. The coils can be spaced apart at defined distances (inter-coil spacings) of 10 m, 20 m or 40 m and the coils can be placed either in a vertical or horizontal position. When the transmitter is switched on, the transmitter coil is energised with an alternating current, which generates a primary magnetic field. This time-varying magnetic field induces small currents in the ground that generate a secondary magnetic field. The secondary magnetic field depends on the inter-coil spacing, the operating frequency and the ground conductivity. Both magnetic fields are sensed by the receiver coil and a reading of apparent conductivity (or "EM conductivity"), based on the ratio of the secondary to the primary magnetic fields, is given. The magnitude of the ground conductivity depends on a number of factors including porosity, pore fluid conductivity, pore surface area, degree of water saturation of sub-surface sediments, temperature and (if present) clay content. Other influences such as buried metallic pipes or electrical cables can alter the natural ground conductivity and result in misleading (high) readings, as these objects can be highly conductive.

For coral islands, the most important factors are the porosity of the coral sediments containing groundwater (effectively the ratio of water volume to total sediment volume) and the pore fluid conductivity (effectively the salinity of the water in the sediments).

The EM surveys were conducted with coils in the horizontal dipole mode (vertical orientation) using an inter-coil spacing of 20 m. Initially, the 10 m inter-coil spacing was also used but it was found that interference from buried electrical cables was affecting readings and hence the 10 m spacing was discontinued for most of the EM survey. The effective depths of exploration (McNeill, 1980) for 10 m and 20 m inter-coil spacings are approximately 7.5 m and 15 m, respectively.

Six EM surveys were conducted in and near the agricultural plots, as follows:

- EM-NOF1: Along east-west road immediately north of agricultural plots from lagoon beach to ocean beach
- EM-NOF2: Along central road in agricultural plots from north to south

- EM-NOF3: Along western road in agricultural plots from north to south
- EM-NOF4: Along east-west road near southern end of agricultural plots
- EM-NOF5: Along eastern road in agricultural plots from south to north
- EM-NOF6: Along east-west road near centre of agricultural plots

The locations of the six EM surveys are shown in Figure 6Figure 6. Re lines are used for the east-west surveys (EM-NOF1, EM-NOF4 and EM-NOF-6) and blue lines are used for the north-south surveys (EM-NOF2, EM-NOF3 and EM-NOF-5). It is noted that only the western end of EM-NOF1 is shown. This EM survey extends to the ocean side at the right side of Figure 6Figure 6.

The first EM survey was conducted on 9^{th} August and the other five were conducted on 10^{th} August.

3.5.2 Results

The results of the six EM surveys are presented in Tables A1 to A6 in Appendix A. These results show:

- Site numbers
- Co-ordinates of each site (in Universal Transverse Mercator, UTM units) using a hand-held GPS receiver
- Distances of each site from the start of the survey (calculated from the co-ordinates)
- Ground conductivity ("EM conductivity") readings in units of millisiemens per metre (mS/m) using 20 m inter-coil spacings for each site
- Estimated fresh groundwater zone thickness for each site
- Comments about the sites.

Figure 6 Image from drone showing agricultural plots and locations of six EM surveys

3.5.3 Estimated fresh groundwater zone thicknesses

The estimated fresh groundwater zone thicknesses in Tables A1 to A6, Appendix A are based on a relationship between EM conductivity readings for the 20 m inter-coil spacing and measured fresh groundwater zone thickness at several multi-level monitoring boreholes in Haa Dhaalu and Haa Alifu islands (refer Figure 7~~Figure 7~~). The measurements of salinity at the monitoring boreholes and EM surveys at the boreholes were conducted in 2001 (Falkland, 2001) and 2005 (GWP Consultants, 2005). The 2001 EM surveys and salinity measurements were conducted at 16 monitoring boreholes including two on Nolhivaranfaru. The 2005 EM surveys and salinity measurements were conducted at 4 monitoring boreholes.

The equation for the line of best fit in Figure 7~~Figure 7~~ was used to estimate the fresh groundwater zone thicknesses in in the Appendix A tables. Also, shown in Figure 7~~Figure 7~~ is the coefficient of determination (R^2), a measure of the 'goodness of fit'. Given the reasonably high R^2 value. the relationship between EM conductivity readings and fresh groundwater zone thicknesses is considered to be quite reasonable.

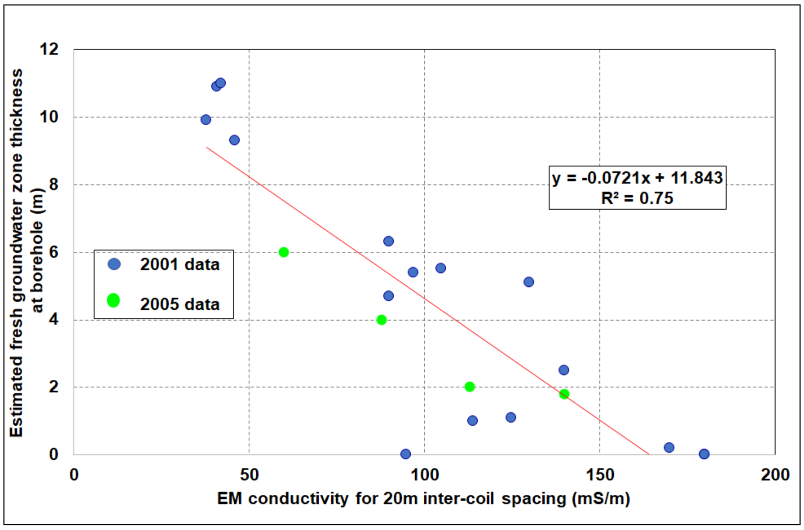

Figure 7 Relationship between EM conductivity readings and estimated fresh groundwater zone thickness for Haa Dhaalu and Haa Alifu islands

Using the data in the Appendix A tables, profiles of estimated fresh groundwater zone thickness along 4 roads were developed. Figure 8~~Figure 6~~ shows the estimated fresh groundwater zone thickness from lagoon beach to ocean beach along the east-west road to north of agricultural plots. Figure 9~~Figure 7~~ shows the estimated fresh groundwater zone thickness along the three north-south roads in the agricultural plots.

The following observations are made about the profile in Figure 8~~Figure 6~~:

- Overall, the variations in estimated fresh groundwater lens thickness along the road from lagoon to ocean show the least thickness near the beaches and the greatest thickness near the centre of the island.
- There are some variations in estimated fresh groundwater zone thickness over short distances on the lagoon side of centre. This is likely to be caused by some interference from buried electrical cables.
- The estimated fresh groundwater zone thickness near the northern ends of the western, central and eastern roads through the agricultural plots varied were 6.1 m, 7.4 m and 8.3 m, respectively.

The following observations are made about the profile in Figure 8~~Figure 6~~:

- The profile for the **western road** shows some variations over short distances which are likely to be due to some interference from buried electrical cables. The maximum, average and minimum estimated fresh groundwater zone thicknesses were 7.4 m, 6.2 m and 5.1 m.
- The profile for the **central road** shows some less variations over short distances than for the western road. The maximum, average and minimum estimated fresh groundwater zone thicknesses were 8.2 m, 7.1 m and 5.8 m which are all greater than for the western road profile.

- The profile for the **eastern road** shows some minimal variations over short distances. The maximum, average and minimum estimated fresh groundwater zone thicknesses were 7.1 m, 6.6 m and 5.7 m which are all greater than for the western road profile.
- All three profiles show a decrease in estimated fresh groundwater zone thickness and a gradual decrease in fresh groundwater zone thickness from north to south

Owing to their short length, profiles are not shown for the two east-west roads in the agricultural plots. However, average fresh groundwater zone thicknesses along the east-west roads in the centre and southern of the agricultural plots were 6.7 m (from two readings) and 6.4 m, respectively. These thicknesses correspond approximately to the average thicknesses of the western, central and eastern roads near the intersections with the two east-west roads.

From the Appendix A tables, profiles in Figure 9Figure 7 and observations above, the estimated fresh groundwater zone thickness is greatest along the central road through the agricultural plots. Hence, from a groundwater perspective, the preferred location for a gallery is the central road. The next location preference is the eastern road. After the initial cross-island EM survey and from the previous ER survey, it was evident that the only realistic location for a gallery was within the area of the agricultural plots. Given this, there was no need to select 2-3 potential areas and the associated decision-making tool (multi criteria analysis). Within the agricultural area, three north-south roads were considered and the central road was selected as the EM survey showed it had the best fresh groundwater thickness.

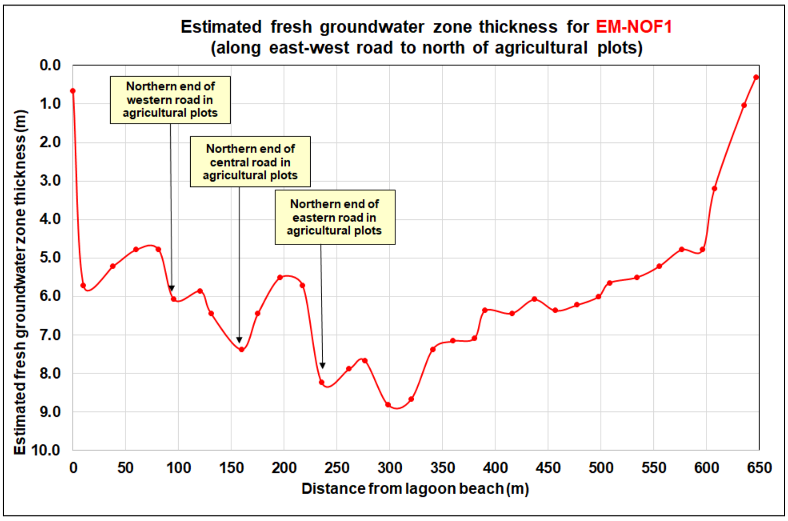

Figure 86 Estimated fresh groundwater zone thickness for EM-NOF1 along east-west road to north of agricultural plots, Nolhivaranfaru

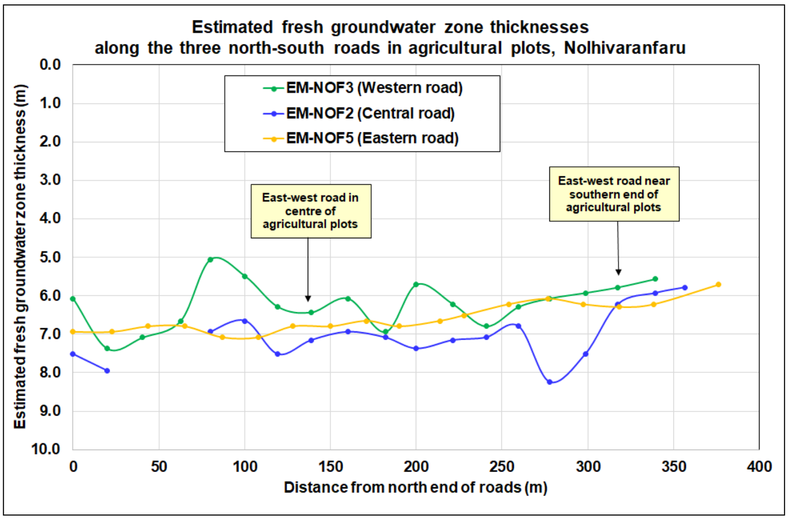

Figure 97 **Estimated fresh groundwater zone thickness along the three north-south roads in agricultural plots, Nolhivaranfaru**

3.5.4 Comparison of fresh groundwater zone thickness with previous results

From the recent EM surveys along the western, central and eastern roads in the agricultural plots, the average fresh groundwater zone thicknesses were between about 6 m and 7 m.

The groundwater survey using the ER method in April 2019 showed the thickest groundwater in the area of the agricultural plots to be about 4 m (MoE, 2020, Figure 4.11). The reason for the difference in results from the two surveys is due to the difference in prior rainfall conditions. Prior to the April 2019 survey, the rainfall was low to very low while prior to the recent survey the rainfall was high to very high depending on the durations of the prior rainfall. Rainfall data from nearby Hanimaadhoo was used to analyse these results and is explained in more detail in section 3.11.3.

3.6 Groundwater depth and salinity at selected wells

Measurements of depths to groundwater level and of groundwater salinity were made at six selected wells within the agricultural plots during the visit. The locations of these wells (1 to 6) are shown in Figure 10Figure 10 and the data is shown in Table 1Table 1. Depth measurements were made with a tape measure and groundwater salinity measurements were made with a calibrated electrical conductivity (EC) meter (TPS WP84).

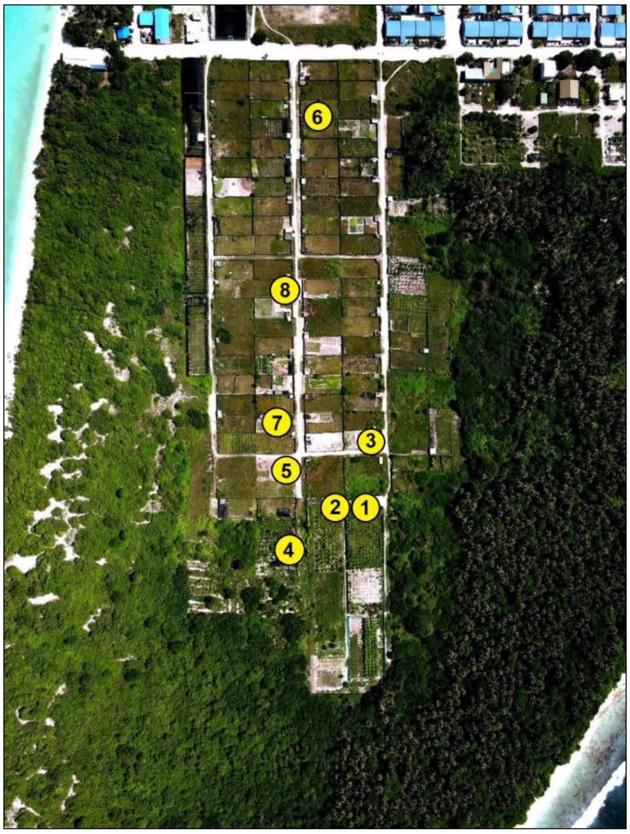

Figure 10 Image from drone showing agricultural plots and eight selected wells

Table 1 Groundwater depths & salinities at selected wells, Nolhivaranfaru

Well No	UTM co-ordinates (zone 43N)		Name	Date & Time	Depth to water (mbgl)	EC (µS/cm) at base	Pump (Yes/No)
	E	N					
1	292279	740364	Nexus farm east well	8-Aug-22 17:20	0.95	565	Yes
2	292268	740364	Nexus farm west well	8-Aug-22 17:30	0.90	570	Yes
3	292297	740409	Honeymoon farm	8-Aug-22 17:30	0.95		Yes
4	292243	740328	Not obtained	10-Aug-22 11:55	0.72	640	Yes
5	292235	740382	Not obtained	10-Aug-22 12:05	0.89	460	No
6	292200	740663	Not obtained	11-Aug-22 10:15	0.77	470	Yes

From the data for wells 1 to 6 in Table 1~~Table 1~~, the following observations are made:

- The average and maximum depths to groundwater level were 0.86 and 0.95 metres below ground level (mbgl), respectively. These depths indicate a shallow groundwater level in the area of the agricultural plots.

- The average and maximum groundwater salinities, as measured in EC units, were 540 µS/cm and 640 µS/cm, respectively. These depths indicate fresh groundwater in the area of the agricultural plots. From previous studies in Maldives islands, the desirable salinity limit for fresh groundwater is 1,500 µS/cm (e.g. Falkland, 2000; 2001).

It is noted that the groundwater salinity values in August 2022 were significantly lower than the one measurement (838 µS/cm) made near the centre of the agricultural plots in April 2019 (MoE, 2020).

3.7 Survey levels along central road and at selected wells

On 17th August, survey levels relative to MSL were obtained along the central road through the agricultural plot area and at three selected wells adjacent to this road. The locations of these wells (5, 7 and 8) are shown in Figure 10Figure 10 and the data is shown in Table 2Table 2. Well No 5 is the same as that included in Table 1Table 1.

Table 2 Ground and groundwater levels relative to MSL at selected wells

Well No	UTM co-ordinates (zone 43N)		Level above MSL (m)		Date & Time	Depth to groundwater (mbgl)
	E	N	Ground	Groundwater		
5	292235	740382	1.045	0.203	17-Aug-22 15:16	0.84
7	292208	740418	0.943	0.260	17-Aug-22 15:18	0.68
8	292203	740533	0.991	0.216	17-Aug-22 15:22	0.78

From the data for the three wells in Table 2Table 2, the following observations are made:

- The average ground level was close to 1.0 m above MSL
- The average groundwater level was 0.23 m above MSL. This seems reasonable for the moderately thick fresh groundwater below sea level.
- The average depth to groundwater was 0.77 mbgl. This is reasonably similar to the average depth of 0.86 mbgl for the 6 wells in Table 1Table 1.

From the 41 levels along the central road (not shown in this report), the following observations are made:

- The ground levels vary between 0.868m and 1.107m above MSL
- The average ground level is 0.87m above MSL.

In summary, the groundwater level is quite shallow and is slightly above MSL at the wells within the agricultural plots.

3.8 Logging of groundwater level & salinity variations at selected well

Groundwater level and salinity (EC) variations were measured over a two-day period using a data logger at the eastern Nexus farm well (No 1 in Figure 10Figure 8). As noted in Table 1Table 1, a pump is installed at this well to irrigate vegetables and fruit trees and vines.

The data logger in the well was a Diver CTD logger which measures combined water and atmospheric pressure. To convert the data to water pressure (or water level) only, a barometric logger (Diver Baro logger) was also used so that the barometric pressure could be subtracted from the combined pressure from the CTD logger. Both loggers were set to record at 1-minute intervals. The CTD logger was installed in the well at 10:16 on 9th August and removed at 09:50 on 11th August.

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Figure 11Figure 9 shows the groundwater levels and EC variations at the well after processing the data from both the CTD and Baro loggers. From the data as summarised in Figure 11Figure 11, the following observations are made:

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- The groundwater variation due to sea level (tidal) variation was about 0.31 m on 10th August.
- The drawdown of the groundwater due to pumping on the afternoons of 9th and 10th August were 0.20 m and 0.38 m, respectively. As no data was available for the actual pumping rates or durations on these days, it can only be assumed that less pumping occurred on 9th August than on the following day.
- The groundwater salinity (EC) remained reasonable (below 700 µS/cm) with a slight increase (about 20 µS/cm) as a result of the pumping followed by a gradual decrease on 10th August. From this limited data, it is apparent that pumping at this well is not having a significant effect on the freshwater lens. However, further data would need to be collected particularly during the drier months of the year to confirm this.

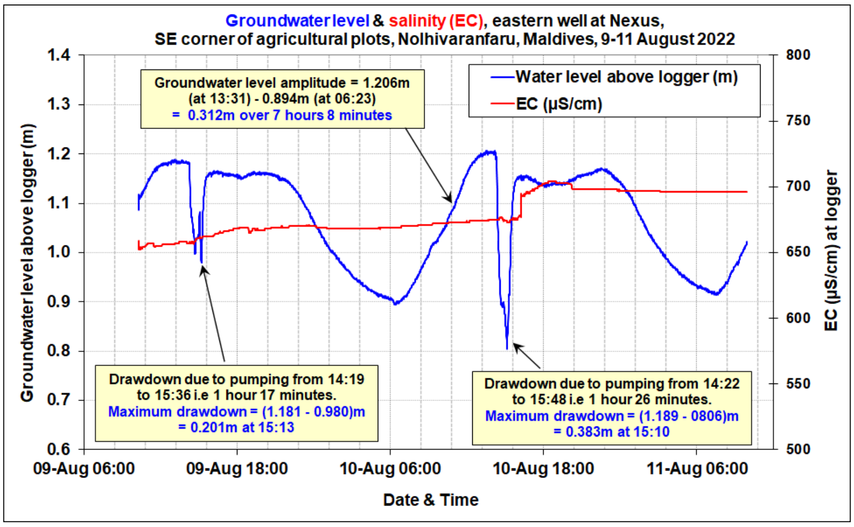

Figure 11 Groundwater level & salinity variations at eastern Nexus farm well 9-11 August 2022

3.9 Groundwater level variations due to sea level variations

Figure 12Figure 10 shows the groundwater level variations at the eastern Nexus farm well together with sea level variations for the period 9th to 11th August 2022. The sea level variations shown in Figure 12Figure 12 are from the August tide prediction chart for the sea level recorder at nearby Hanimaadhoo.

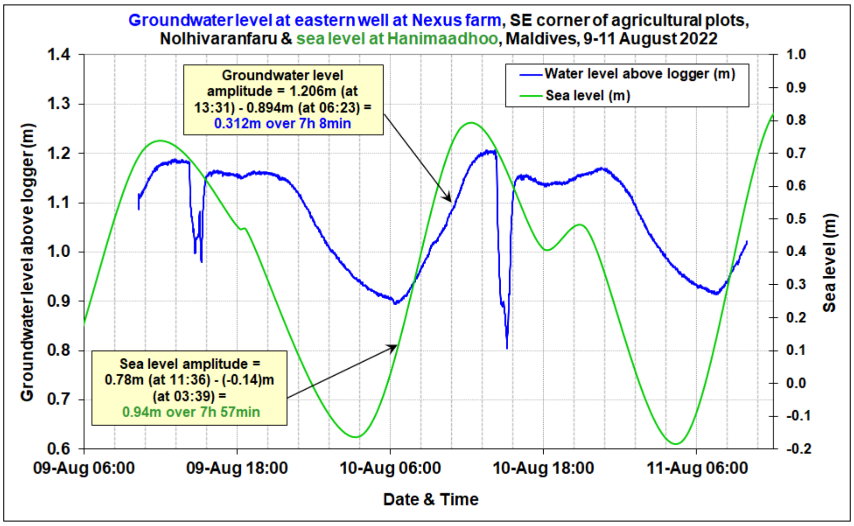

Figure 12 Groundwater level variations at eastern Nexus farm well and sea level variations at Hanimaadhoo, 9-11 August 2022

From the data as summarised in Figure 12~~Figure 12~~, the **tidal lag** (time difference between sea level high or low and corresponding groundwater high or low) and **tidal efficiency** (ratio of amplitude of groundwater movement to sea level movement) were calculated as follows:

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- **Average tidal lag**: approximately 2.5 hours. This lag is similar to other atoll islands where freshwater lenses occur.
- **Average tidal efficiency**: 0.33 (based on two most obvious cycles on 9th & 10th August). This value is moderate compared with other atoll islands where freshwater lenses occur.

The tidal lag and efficiency values indicate the degree of hydraulic connection between the freshwater lens and underlying seawater in the area of the agricultural plots is reasonably low. This is another means of confirming that a reasonable freshwater lens occurs in this part of the island.

3.10 Search for two multi-level monitoring boreholes

A search was made for the two multi-level monitoring boreholes that were drilled in the northern part of the island in 2001 (Falkland, 2001). This search was unsuccessful. It is assumed that one of these boreholes (NOLHIVARANFARU1) was destroyed during construction of a wide road from the harbour to the northern end of the housing area. The second borehole (NOLHIVARANFARU2) is possibly still intact but could not be found owing to dense vegetation on the north side of the road from the housing area to the Feneka utilities area on the eastern side of the island.

3.11 Analysis of rainfall data

3.11.1 Purposes and available data

A review of rainfall data was conducted as rainfall is important to estimate recharge to groundwater. The review also enabled a comparison of prior rainfall conditions leading up to the two groundwater surveys that have been conducted in the area of the agricultural plots (i.e. MoE, 2020 and this current study).

The nearest meteorological station where rainfall and other meteorological parameters are recorded is located at the airport on Hanimaadhoo. Hanimaadhoo rainfall is assumed to be representative of rainfall conditions on Nolhivaranfaru as the distance between the Hanimaadhoo meteorological station and the Nolhivaranfaru agricultural plots is only 8 km.

Daily rainfall data was obtained from the Maldives Meteorological Service in August and September for the period from start of record in June 1991 until July 2002. This data was used to calculate monthly and annual rainfalls.

3.11.2 Summary of annual and monthly rainfall

Figure 13~~Figure 11~~ shows the annual rainfall pattern for the 30-year period 1992-2021 with all data. The average (mean) annual rainfall is 1,775 mm. The maximum and minimum vales are, respectively, 2,240 mm (in 1993) and 1,269 mm (in 2018). The coefficient of variation (Cv) of annual rainfall (standard deviation divided by mean) is 0.16 indicating a relatively low annual variability of rainfall.

On average, the driest months are January to April and the wettest months are June to August (refer Figure 14~~Figure 12~~). The lowest monthly rainfall is zero which has occurred five times during months from January to April in the years 2016 to 2019. The highest monthly rainfall was 541 mm in May 1998.

The Cv's of monthly rainfall vary between 0.41 (for August) and 1.19 (for March). Generally, the highest variability of rainfall occurs in the months with lowest average rainfall and vice versa.

Low rainfall variability is beneficial in terms of recharge as it indicates there are no major fluctuations in recharge to groundwater. Conversely, high variability has the reverse effect on recharge.

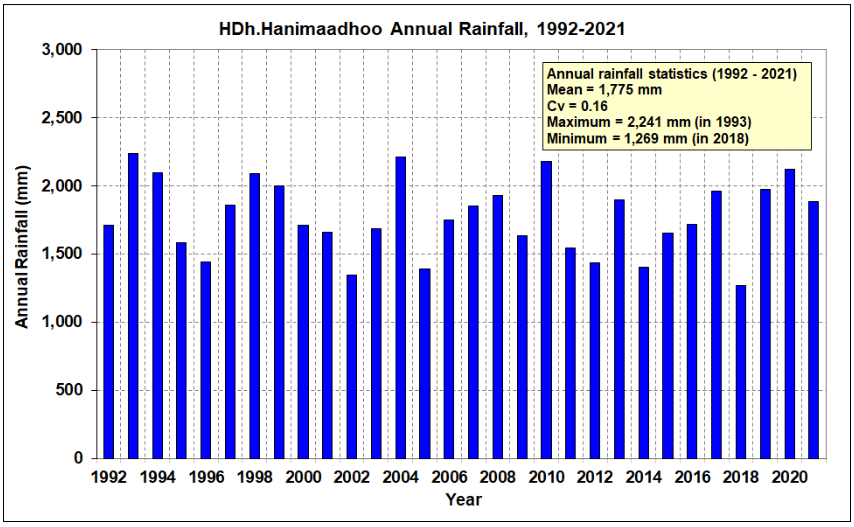

Figure 13 Hanimaadhoo annual rainfall, 1992-2021

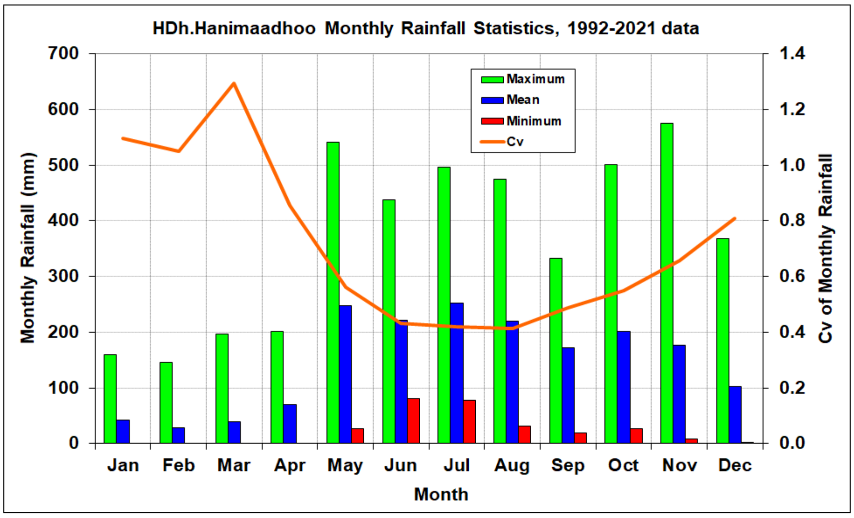

Figure 14 Monthly rainfall statistics, Hanimaadhoo, 1992-2021

3.11.3 Analysis of rainfall prior to groundwater surveys in 2019 & 2022

Of interest to this current study is the rainfall prior to the recent groundwater survey in August 2022 and that conducted in April 2019 (MoE, 2020). To assess this, the decile method (Gibbs and Maher, 1967; White, Falkland and Scott, 1999) was used to rank rainfalls for relevant durations. The durations of most relevance are those close to the hydraulic residence time (or turnover time) of the fresh groundwater. For a freshwater lens with average thickness of 6 m, the available groundwater within the matrix of sediments (sands and gravels) is about 0.3 x 0.6 m = 1.8 m. The average annual groundwater recharge is about 800 mm or 0.8 m (refer section 3.12). The average hydraulic residence time equals the available groundwater divided by the average annual recharge and is therefore about 1.8 m / 0.8 m = 2.2 years. Similarly, if the average freshwater lens thickness is 3 m, the average hydraulic residence time would be 1.1 years. Further details regarding calculation of hydraulic residence time are provided in previous reports including Falkland (2001).

Figure 15~~Figure 13~~, Figure 16~~Figure 14~~ and Figure 17~~Figure 15~~ show the ranking of Hanimaadhoo rainfalls using the decile method for durations of 12 months, 2 years and 3 years over the full period of record. The rankings vary from zero to 100% are calculated and plotted at monthly intervals. Low rankings indicate that low cumulative rainfall has occurred during the period leading up to the selected month. Conversely, high rankings indicate that high cumulative rainfall has occurred. In both figures, horizontal lines showing the 40 and 10 percentiles are included as indicators of, respectively, possible onset of dry periods and critical rainfall levels.

From the data and graphs, the following observations are made:

- For the 12-month duration rainfalls, the rainfall rankings leading up to April 2019 and August 2022 were 3% (very low) and 91% (very high), respectively.
- For the 2-year duration rainfalls, the rainfall rankings leading up to April 2019 and August 2022 were 8% (very low) and 85% (high), respectively.

- For the 3-year duration rainfalls, the rainfall rankings leading up to April 2019 and August 2022 were 25% (moderately low) and 99% (very high), respectively.

In summary, the prior rainfalls to the two groundwater surveys were significantly different with much lower prior rainfalls to the MoE (2020) survey in April 2019 than in the current survey in 2022. This explains the differences in thickness of fresh groundwater from the two groundwater surveys as outlined in section 3.5.4.

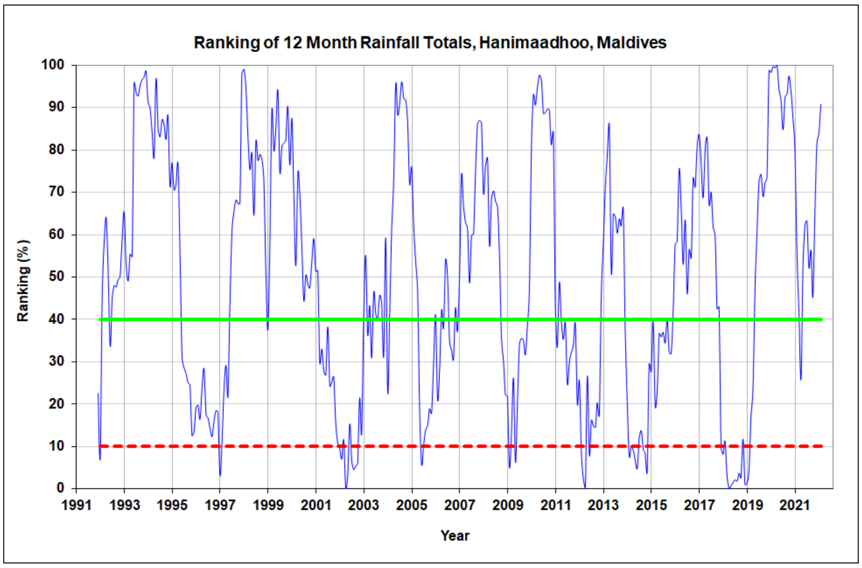

Figure 15 Rainfall Rankings for 12 Month Duration, Hanimaadhoo, June 1991 – July 2022

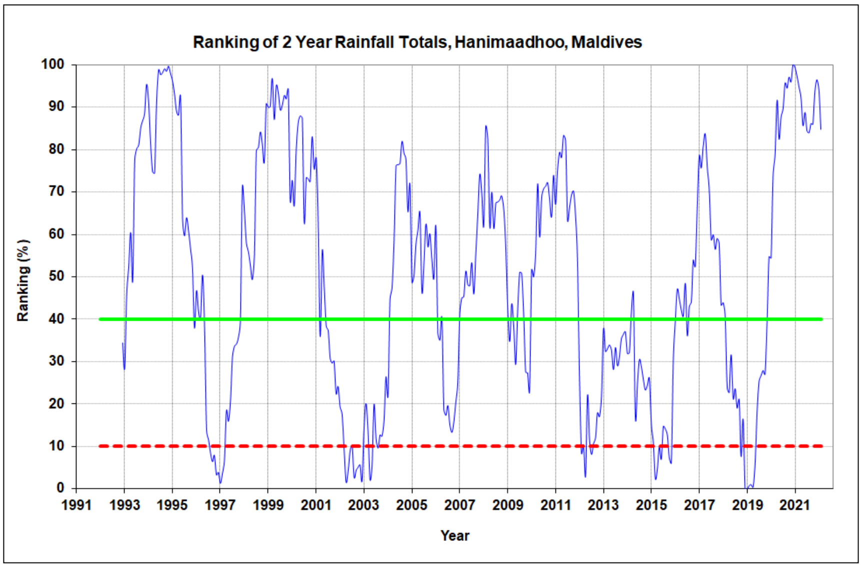

Figure 16 Rainfall Rankings for 2-Year Duration, Hanimaadhoo, June 1991 – July 2022

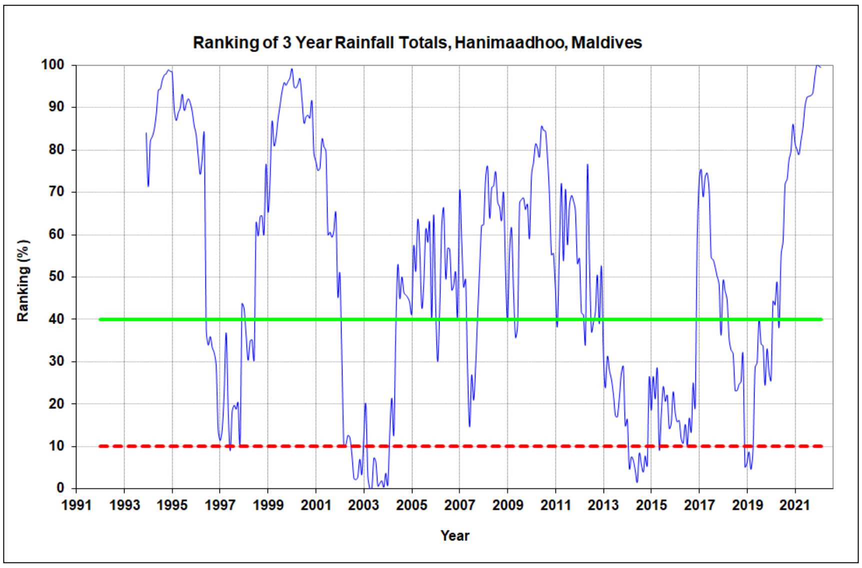

Figure 17 Rainfall Rankings for 3-Year Duration, Hanimaadhoo, June 1991 – July 2022

3.12 Groundwater recharge estimation

A relatively simple method based on a relationship between annual rainfall and recharge provides a reasonable estimate of average recharge. UNESCO (1991) provides such a graph using data from several limestone and coral islands (refer Figure 18~~Figure 18~~).

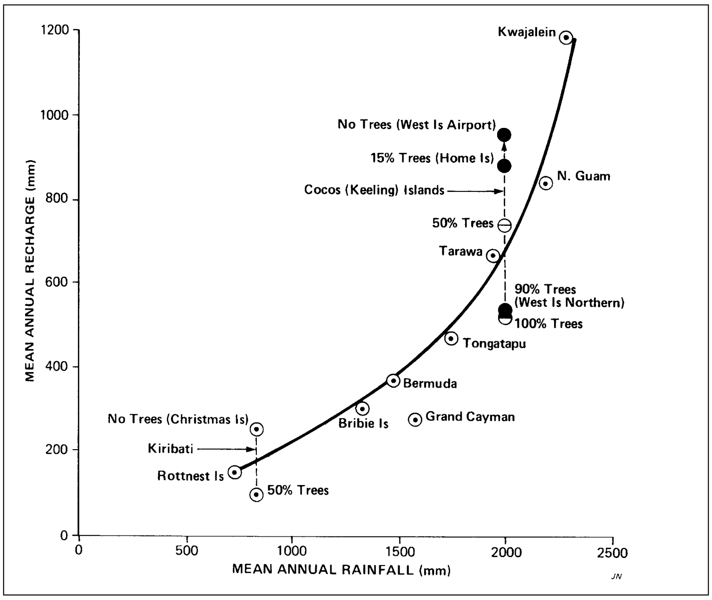

Figure 18 Relationship between annual rainfall and recharge for several islands (from UNESCO, 1991)

Using the average annual rainfall for Nolhivaranfaru of 1,775 mm, the estimated average annual recharge from Figure 18Figure 16 is about 550 mm or approximately 30% of estimated rainfall (or an average recharge-rainfall ratios of 0.3). This provides a reasonable lower limit to the recharge.

More detailed analyses of recharge using a water balance method between monthly rainfall and potential evaporation were conducted in two previous studies for the islands of N.Velidhoo and N.Holhudhoo (Falkland, 2010a; 2010b). These two islands are approximately 115 km and 105 km, respectively, south of Nolhivaranfaru. Monthly rainfall data for Hanimaadhoo for the 18-year period 1992-2009 was used. The average annual rainfall in this shorter period of record was 1,789 mm which is very similar to the 1,775 mm for the 30-year period 1992-2001. As no potential evaporation estimates were available for Maldives, estimates of monthly potential evaporation were based on an average daily potential evaporation rate of 4 mm which is considered reasonable for this latitude. This daily rate is similar to that for the atoll of Tarawa in Kiribati in the Pacific Ocean where a study of groundwater recharge used a calculated daily potential evaporation rate of 3.9 mm. In a more recent groundwater modelling study of Maldives islands under future climatic conditions, a daily potential evaporation rate of 3.5 mm was used (Deng and Bailey, 2017).

For the N.Velidhoo and N.Holhudhoo studies, a number of scenarios using different values for soil moisture zone and the type of vegetation were considered. The scenarios that best correspond to the area in and near the agricultural plots on Nolhivaranfaru, which is largely clear of deep-rooted vegetation, resulted in average recharge-rainfall ratios of 0.45 to 0.47. Further details are provided in Falkland (2010a; 2010b).

During the current study, two further water balance analyses were conducted using the monthly rainfall data for Hanimaadhoo for the longer 30-year period 1992-2021. These analyses used the same soil and water parameters as in the previous analyses and two estimates of daily potential evaporation. These were 4 mm per day as in Falkland (2010a; 2010b) and 3.5 mm as in Deng and Bailey (2017). The results showed average recharge-rainfall ratios of 0.48 and 0.51, respectively. From these results, a reasonable recharge-rainfall ratio for the agricultural plot is 0.5.

Using the average annual rainfall of 1,775 mm and a recharge-rainfall ratio of 0.5, the estimated average annual recharge for areas of Nolhivaranfaru without deep-rooted vegetation including the agricultural plots is close to 890 mm.

3.13 Sustainable yield estimation

The sustainable yield of a groundwater aquifer can be defined as the maximum amount of water that can be extracted on a continuous basis (including during drought periods) without causing long-term depletion of the aquifer or adverse effects on the extracted water. For freshwater lenses on small islands such as Nolhivaranfaru, sustainable yield can be considered as the maximum amount of water that can be extracted on a continuous basis, while maintaining the salinity of the extracted water below the freshwater limit for all purposes (often defined as EC = 2,500 μS/cm).

Freshwater lenses are dynamic groundwater systems and their sustainability depends on both the amount of fresh groundwater in storage and the average recharge rate. Not all recharge can be sustainably extracted, as some of the fresh groundwater inflow is required to flush saline water from the base of the freshwater zone. If all recharge was extracted, freshwater lenses would eventually diminish until no freshwater is available.

The proportion of recharge to groundwater that can be sustainably extracted (or the 'sustainable groundwater yield') is based on many factors including the amount and distribution of the groundwater on the island, the groundwater recharge and the method(s) of groundwater extraction.

Studies on other small island studies (e.g. UNESCO, 1991) have indicated that approximately 25% to 50% of recharge to freshwater lenses can be sustainably extracted. The sustainable yield as a proportion of recharge increases as average annual recharge increases and rainfall variability decreases.

It is noted that for Addu atoll, the sustainable yield was estimated as 35% of recharge in Falkland (2000) based on the fact that rainfall is moderately high and has low variability. For nine selected islands in Haa Dhaal and Haa Alifu atolls, a more conservative estimate for sustainable yield of 30% of recharge was adopted in Falkland (2001a) owing to the lower rainfall in the northern islands than in the southern islands. Given that Nolhivaranfaru is in Haa Dhaal atoll, the sustainable yield estimate of 30% of recharge could be adopted for this island. However, the rainfall records for Hanimaadhoo have a low annual variability based on the Cv of 0.16 over the 30 years of full data. This is a similar Cv to that for Gan in Addu atoll. It is now considered that a higher percentage of 45% could be adopted for Nolhivaranfaru and for Gan.

Using the estimated average annual recharge of 890 mm (refer section 3.12) and a sustainable yield estimate of 45% of recharge, the following sustainable yield estimates are made for the Nolhivaranfaru agricultural plot area in terms of depth and volumetric units and on a per unit area basis:

- The **estimated sustainable yield in depth units is 400 mm per year**. This is equivalent to approximately 23% of the annual average rainfall of 1,775 mm.

- The **average sustainable yield per unit area (hectare) is approximately 11 kL/day/ha**. This per unit area estimate gives a guide to the maximum limit of sustainable pumping.
- For the estimated area of the agricultural plot of approximately 6.5 ha (refer section 1.1), the **estimated sustainable yield is approximately 70 kL/day**.

3.14 Gallery length and pumping rate

The length of the gallery needs to be based on the sustainable yield estimates and also the assumed area of influence of pumping from a gallery. The influence of pumping could be 100 m on each side of the gallery. With this assumption, each 100 m length of gallery would draw fresh groundwater from an area of 2 ha. To stay within the sustainable yield of 11 kL/day/ha, the maximum pumping rate per 100 m of gallery would be 22 kL/day. In order to supply the design pumping rate of 65 kL/day, the gallery length would need to be just under 300 m. However, as the length of the gallery was specified as 250 m in the Proposal (NRW & Lamer, 2021), the allowable maximum pumping rate would need to be reduced to 55 kL/day based on the sustainable yield of 11 kL/day/ha.

It is noted that the maximum pumping rate per metre of gallery is equivalent to 220 L/day/m. By comparison, the allowable maximum pumping rate per metre of gallery is about 230 L/day/m for three galleries on West Island in the Cocos (Keeling) Islands (at latitude 12°11'S and longitude 95°50'S). These galleries are 300 m long each with a maximum pumping rate of 70 kL/day. The average annual rainfall (1,930 mm) on West Island is about 9% greater than on Hanimaadhoo and assumed for Nolhivaranfaru (1,775 mm). However, the variability of rainfall is significantly greater on West Island than on Nolhivaranfaru as shown by a higher Cv of annual rainfall (0.31 compared with 0.16). Thus, the slightly higher rainfall on West Island is offset by a higher variability meaning longer dry periods than on Nolhivaranfaru. This result confirms that the estimated maximum pumping rate for the Nolhivaranfaru gallery is reasonable.

3.15 Multi-Criteria Analysis for the Comparison and Selection of Suitable Sites for Agricultural Infiltration Galleries

3.15.1 Multi-criteria Analysis Methodology

The following multi-criteria analysis has been developed as a high level tool to compare different potential gallery sites so that the most suitable site is selcetd.

It should be noted that in order to apply the multi-criteria analysis, there are two key requirements:

- A geophysical survey at the potential sites must have been completed to determine the thickness of the freshwater lens and potential yield; and
- The potential gallery sites are not to be located where there is obvious commercial/industrial pollution located within 100 metres of the proposed gallery site. Domestic wastewater discharges to groundwater is generally acceptable as the gallery is to be used for agricultural purposes only. However, it is recommended that any sanitation facilities not be within 50 metres of the proposed gallery site.

The above two requirements would eliminate unsuitable options from further analysis.

The following main categories of criteria were developed for the multi-criteria analysis:

1) Technical
2) Environmental; and
3) Financial

Each of these are briefly described below:

Technical Criteria

The key elements regarding the suitability of the potential gallery sites:

a) Average thickness of the groundwater lens

This is a key parameter in comparing potential gallery sites as the reliability of the potential water source primarily depends on lens thickness.

b) Average salinity of groundwater at top of lens

The salinity of the lens is a critical factor for crop use as higher salinity levels may make the groundwater from the lens entirely unsuitable for agriculture or allow only salt tolerant crops to be irrigated.

c) Average depth to freshwater lens

The depth to the freshwater lens is important is this influences construction costs

d) Distance of gallery pump location from farm reticulation system

The proximity of the proposed gallery pump(s) to the irrigation system is important as the longer the distance, the higher capital cost of laying a transmission main to the storage tank and the higher pumping cost.

Environmental Criteria

There are many pollution sources that may affect the use and suitability of an infiltration gallery.

a) Sewage discharging to groundwater

Typically, this pollution source is where septic tanks discharge to the groundwater. This is a significant issue for potable water sources. However, for agricultural infiltration galleries, this is generally not considered to be a critical factor as the water will not be used for human consumption. Direct use of contaminated groundwater onto leafy crops would require washing with clean water before consumption. The majority of crops grown on the islands, however, are not directly irrigated onto the leaves but rather into the soil which mitigates this risk. Drip irrigation to the root zone is an effective means of managing this risk. In particular, the preferred government approach is the treatment of wastewater such as the Sewage Treatment Plant at Nolhivaranfaru which treats wastewater and discharges treated effluent to an ocean outfall.

In general terms, potential gallery sites should be located as far away as practical from any sewage discharges to groundwater.

b) Other wastewater discharging to groundwater

Discharges of trade wastes with potential high concentrations of heavy metals can cause severe damage to the soil and plants and are therefore considered as toxicants. On many islands, there is limited commercial/industrial development and, as such, there is a lower risk. Specific analyses would be necessary for islands where manufacturing facilities are established and trade wastes . In such cases, proper wastewater treatment (sewage treatment plant) is essential. The presence of wastewater contaminants would need to be assessed on an individual basis and in the absence of treatment and location in proximity of a potential gallery site, could lead to an infiltration gallery option not being further considered.

c) Known use of pesticides or herbicides adjacent to gallery position

As the infiltration gallery would be used for agricultural purposes only, the use of pesticides and herbicides do not make the installation of a gallery non-viable. However, the use of such chemicals should be kept to a minimum.

Financial Criteria

a) Capital Costs

The comparison of capital costs between sites is important as some sites will be more expensive to develop than others. In some cases it will not be necessary to calculate the full capital costs for each installation as it will be clear which has the highest/lowest cost to develop based on the proposed locations. For example, the highest capital cost for a gallery on the same island would generally be the one located furthest from the storage tank as it would require the longest transmission main to the storage tank. Note that the capital cost includes the gallery plus the transmission main(s) to the farm irrigation system(s).

b) Operating Costs

The comparison of operating costs between sites is also importan**t**. The operating costs are mainly the pumping costs from the gallery well(s) to the storage tank. Similar to the capital costs, in some cases it will not be necessary to calculate the full pumping costs for each installation as it will be clear which has the highest/lowest cost to operate. For example, the highest operating cost for a gallery on the same island would generally be the one located furthest from the storage tank.

In order to develop a systematic and quantitative method of comparing different sites, a points based rating system was developed. In addition to the points rating system, higher priority criteria were assigned higher weightings due to their higher importance in the assessment process.

The table below shows the proposed multi-criterial assessment system:

Table 3 Multi-Criteria Analysis Scoring System

Item	Category	Points Scoring (1 to 5) Criteria					Points Score	Weighting	SCORE
		1	2	3	4	5			
1	TECHNICAL CRITERIA								
1.1	Average thickness of groundwater lens (m)	<1	>1 - 2	>2 - 5	>5 - 10	>10		25%	
1.2	Average salinity (EC) of groundwater at top of lens (µS/cm)	>1,500	1,000 - 1,500	750 - <1,000	500 - <750	<500		25%	
1.3	Average depth to freshwater lens (m)	>3	2.5 - 3	2 - <2.5	1.5 - <2	<1.5		5%	
1.4	Distance of gallery pump from farm reticulation system (m)	>800	400 - 800	200 - <400	100 - <200	<100		5%	
2	ENVIRONMENTAL CRITERIA								
2.1	Known use of pesticides or herbicides adjacent to gallery position	Everyday use in large quantities	Commonly used (weekly)	Regular use (once a month)	Seldom used (one a year)	No use		10%	
3	FINANCIAL CRITERIA								
3.1	Capital Costs	Highest Cost Option	Between Highest and Average Cost	Average Cost option	Between Average and Lowest Cost	Lowest Cost Option		15%	
3.2	Operating Costs	Highest Cost Option	Between Highest and Average Cost	Average Cost option	Between Average and Lowest Cost	Lowest Cost Option		15%	
								TOTAL SCORE	

3.15.2 Nolhivaranfaru Potential Gallery Locations Assessment

There were three potential gallery sites identified in section 3.5.3, namely:

- Site 1: Western Road
- Site 2: Central Road, and
- Site 3: Eastern Road.

The locations are shown in Figure 19~~Figure 19~~. The multi-crireia approach outlined in section 3.15.1 was then applied to the three potential gallery sites on Nolhivaranfaru Island as shown in the table below:

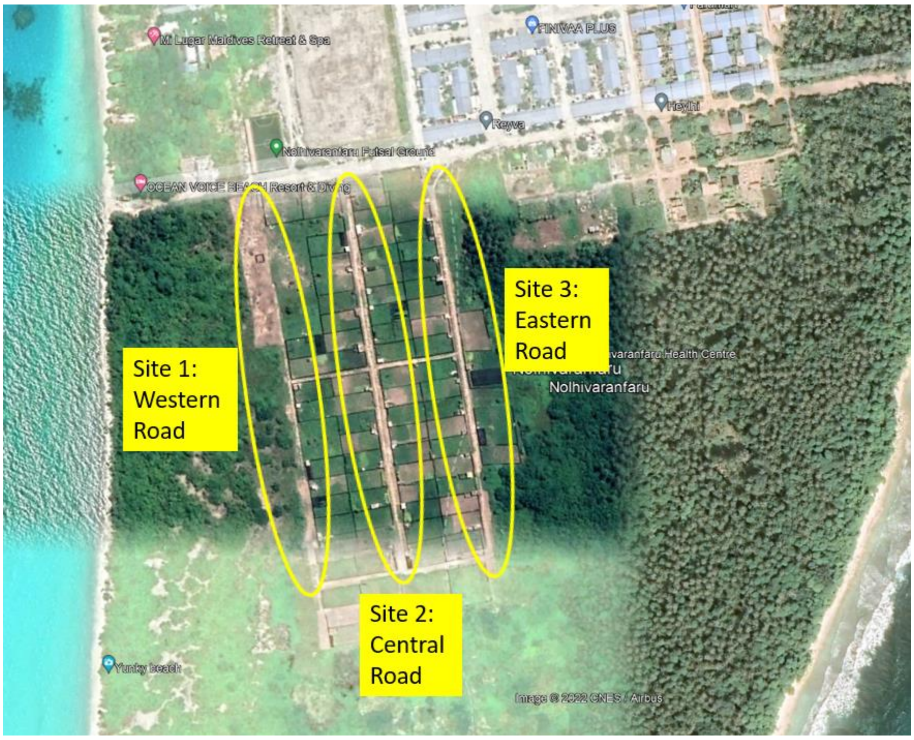

Figure 19 Three Potential Gallery Site Locations on Nolhivaranfaru Island

Table 4 Assessment of Three Potential Nolhivaranfaru Gallery Sites

MULTI CRITERIAL ANALYSIS FOR AGRICULTURAL INFILTRATION GALLERIES AT NOLHIVARANFARU ISLAND							SITE 1: WESTERN ROAD			SITE 2: CENTRAL ROAD			SITE 3: EASTERN ROAD		
Item	**Category**	**Points Scoring (1 to 5) Criteria**					**Points Score**	**Weighting**	**SCORE**	**Points Score**	**Weighting**	**SCORE**	**Points Score**	**Weighting**	**SCORE**
		1	**2**	**3**	**4**	**5**									
1	**TECHNICAL CRITERIA**														
1.1	Average thickness of groundwater lens (m)	<1	>1 - 2	>2 - 5	>5 - 10	>10	4	25%	20	4	25%	20	4	25%	20
1.2	Average salinity (EC) of groundwater at top of lens (µS/cm)	>1,500	1,000 - 1,500	750 - <1,000	500 - <750	<500	4	25%	20	4	25%	20	4	25%	20
1.3	Average depth to freshwater lens (m)	>3	2.5 - 3	2 - <2.5	1.5 - <2	<1.5	5	5%	5	5	5%	5	5	5%	5
1.4	Distance of gallery pump from farm reticulation system (m)	>800	400 - 800	200 - <400	100 - <200	<100	4	5%	4	5	5%	5	4	5%	4
2	**ENVIRONMENTAL CRITERIA**														
2.1	Known use of pesticides or herbicides adjacent to gallery position	Everyday use in large quantities	Commonly used (weekly)	Regular use (once a month)	Seldom used (one a year)	No use	3	10%	6	3	10%	6	3	10%	6
3	**FINANCIAL CRITERIA**														
3.1	Capital Costs	Highest Cost Option	Between Highest and Average Cost	Average Cost option	Between Average and Lowest Cost	Lowest Cost Option	4	15%	12	5	15%	15	4	15%	12
3.2	Operating Costs	Highest Cost Option	Between Highest and Average Cost	Average Cost option	Between Average and Lowest Cost	Lowest Cost Option	4	15%	12	5	15%	15	4	15%	12
								TOTAL SCORE	**79**		**TOTAL SCORE**	**86**		**TOTAL SCORE**	**79**

Notes:

1. Sites 1 and 3 are located approximately equal distances from the proposed future storage tank along the Central Road. As such, they received lower points ratings for item 1.4. Similarly, Sites 1 and 3 have a higher capital and operating cost than Site 2 due to the increased distance from the future storage tank in Central Road and, hence, received lower scores for items 3.1 and 3.2.

It is noted that by applying the above multi-criteria system, the Central Road (Site 2) option was the preferred site for the infiltration gallery.

Although Sites 1 and 3 achieved the same points score, the average thickness of the groundwater lens would decide the preferred option The average thickness of the freshwater lens at Site 3: Eastern Road is 6.6m while the average thickness of the freshwater lens at Site 1:Western Road is 6.2m (refer section 3.5.3) On this basis, Site 3 Eastern Road, would be the second choice and Site 1 would be the least preferred option.

Pumping Cost Estimate

Although a total gallery length of 300m would meet the full projected future water demand, the contract allows only for the construction of a 250m long gallery system. The design flow for a 250m long gallery is 55kL/day.

Based on the "Business" category power tariff of MVR3.75/kWh for monthly power usage, the monthly power cost for the gallery would be **approximately MVR 540/month.**

3.15.3 Gallery Design Concepts and Preferred Concept Design

Infiltration galleries are similar in design in that gallery pipes must be of sufficient length for the design flow to infiltrate through the slotted pipe wall and flow to the pump well. The pipes may therefore be provided in a "linear" (straight line) arrangement where pipes lead to a central pumping well or they may be aligned in a "star" like arrangement where multiple gallery pipes extend radially from the pump well.

The preferred arrangement depends on site conditions where ease of access or manmade or natural obstacles may affect the alignment of the proposed gallery pipe(s).

In the case of Nolhivaranfaru Island, the presence of well laid out roads and agricultural plots indicated that the best approach would be to lay the gallery pipes along the existing roads to avoid disturbing the agricultural plots. Based on the results of the fieldwork conducted, the preferred road was the central road. The presence of a vacant plot approximately half way along the central road meant a "linear" infiltration gallery with a centrally located pump well was the preferred solution.

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It is recommended that the following design features be adopted for the proposed gallery:

- *Length: 250 m.*
- *Location: along the central (north-south) road in the agricultural plots with a central pump well near the east-west road near the centre of the agricultural plots (refer Figure 20~~Figure 20~~). The gallery is shown by the red line with the pump well (shown by the blue circle) offset to the southeast of the road intersection so as to move it away from the roads.*
- *Maximum pumping rate: 55 kL/day.*

3.16 Preliminary design details for gallery and related infrastructure

While design details for the gallery and related water infrastructure can be specified later in the project, some preliminary design details are recommended below:

- The gallery pipes should be slotted 100 mm PVC pipes.

- The base of the gallery pipes should be laid at 0.5 m below MSL. Given the average depth to groundwater level is about 0.85 m (refer Table 1~~Table 1~~), this would mean an excavation depth of about 1.5 mbgl allowing for a 0.15 m thick gravel pack around the gallery pipe.
- A 150 mm wide gravel pack should be placed around the slotted gallery pipes.
- Thick plastic membrane should be placed above the gravel pack before carefully backfilling with excavated material.
- The pump well should be constructed from a ribbed polyethylene sewer manhole such as those at the Feneka sewerage treatment plant on Nolhivaranfaru (or suitable alternative product).
- The two ends of the gallery pipes should be fitted with 100 mm long radius bends and vertical 100 mm pipes to terminate just below surface and be fitted with 100 mm PVC end caps. Concrete blocks should be installed over end caps.
- The energy source for the pump should be electricity and the pump should be operated at a near-continuous low flow rate to minimise pumping effects on the groundwater.
- A flow meter and strainer should be installed on the outlet pipe.
- A tankstand of suitable height with a head tank should be constructed to provide sufficient water pressure to supply each farm (if additional or alternative funding is available).

Figure 20 Image from drone showing proposed location of gallery (shown in red with blue offset pump well)

3.17 Monitoring and Reporting Requirements

Once the gallery is commissioned, it will be necessary to implement an ongoing monitoring program.

The recommended monitoring should include:

- Daily readings of the flow meter on the outlet of the pump
- Weekly measurements of groundwater salinity (EC) using a calibrated EC meter.

The Consultant believes that such monitoring would be beneficial to assess the performance of the gallery on a long term basis. As the Consultant does not have a full time presence on the island during the project, it is assumed that the Island Council would be able to nominate a representative to collect this basic data which the Consultant will then incorporate into the following monthly report during the project monitoring period (Activity 4.2 of the Project).

A monthly report should be prepared for the Island Council on an ongoing basis (during and after the project) with the following data and suitable graphs:

- Table and graph showing total flow for current month and previous months.
- Comments regarding the average daily flow during the month compared with the recommended maximum pumping rate.
- Table and graph showing weekly salinity readings.
- Comments regarding the salinity readings including any trends.
- Monthly rainfall data (for preceding 12 months) from the rainfall gauge at the climate station on Hanimaadhoo (data to be obtained from Maldives Meteorological Service).
- Comments about any obvious changes in salinity as a result of changes in rainfall.
- Comments about the pump operation and any maintenance requirements.

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4 ENVIRONMENTAL AND SOCIAL CONSIDERATIONS

4.1 Proximity to Agricultural Plots

The proposed location for the infiltration gallery is the middle path along the agricultural plots. The farming areas is separated by a 40ft road from the village area. Therefore the galley will be proximal to the village area, however within the farming area.

Figure 21 Figure showIng the agricultural plots with respect to the village including housing, private and public areas (right side of the image)

4.2 Environmental Considerations

The preliminary field investigation visit was made to Nolhivaramfaru from 8-11 August 2022 to explore the potential area for construction of the infiltration gallery to sustainably extract water for farming use. In consultation with the island council, the consultancy team visited the existing farming area allocated for farming.

Approximately 5000sqft of a plot has been allocated for households (upon request) free of charge for seasonal crops such as fruits, vegetables, chillies and others. These plots are already cleared of natural vegetation. The approximate combined area of agricultural plots is 3.5 ha. It is proposed that the gallery to be constructed in the middle path that is completely cleared of the vegetation. Vegetation clearance is therefore not required for this purpose.

Figure 22 Examples of Crops in the Farmed Plots (Papaya)

Figure 23 Examples of Crops in the Farmed Plots (Chilli)

The proposed location of the infiltration gallery is distant to the housing area which also has its own sewage treatment plant and discharges treated effluenbt to the ocean. The proposed infiltration gallery is subject to input of agricultural chemicals (fertilizers), if these are used. As the water will only be used for irrigation (i.e. non-potable use), this is not seen as an issue.

It is also noted that according to the final Draft Land Use Plan (still to be approved), there was only one area allocated where an infiltration gallery system for irrigation purposes could be installed. The selected location complies with this requirement.

4.3 Potential Water sources in HDh.Nolhivaranfaru Island and similar islands in Maldives

The only potable water is groundwater below the ground (approximtately1.5m) which may be developed is a freshwater lens as a result of years of accumulation of rain water underground. Due to the low lying nature of the islands in the Maldives,the island are always vulnerable to inundation from potential rising sea level, storm surges as the average elevation of the islands is approximately 1.5m above MSL. These natural or climate induced treats will continue into the future.

Impacts on the groundwater over the past few decades have resulted from population density based activities such as over extraction of groundwater (salinisation) and pollution from used of septic tanks and soak pits associated sewerage disposal. Currently a sewerage disposal system at a sewerage treatment plant has been established at Nolhivaranfaru where the effluent is disposed to the sea (ocean side of reef) and sludge is processed to be used as organic fertiliser.

Agricultural practices, with chemical fertilisers also have the potential to contaminate the groundwater. It is noted that the water from the gallery is not intended to be used for drinking water purposes however and the possible seepage of pesticides into the groundwater at this isolated location is not considered a health risk to potable water supply which uses rainwater harvesting and a proposed desalination plant.

4.4 Social Considerations

The farming area is used significantly by the farmers of the island. There is currently electricity provided to the farmers to operate electric pumps within some plots to irrigate the farms. During the construction period there may be some concerns of the farmers. These include;

- Access to the farms, especially vehicles used by the farmers due to excavation works; and
- Potential damage to the underground electrical cables during trenching.

The impact of these activities is required to be minimised during the construction period.

4.5 Project Steering Committee Input

The Consultant has undertaken the following key consultation activities to date

- Consultation with the island council members
- Consultation with a number if farmer
- The proposed area for the gallery is within the currently allocated agricultural plots
- The proposed gallery location is is the best practical option for the gallery as other locations are limited by freshwater lens thickness (refer section 3.5.3)

- Council has agreed to this location

Once the preliminary investigation report has been approved, a project steering committee meeting will be held with the committee members.

5 CONCLUSIONS AND RECOMMENDATIONS

The report provides an assessment of groundwater conditions in and near the current agricultural plots on the island of HDh. Nolhivaranfaru and provides recommendations for groundwater development for these plots.

Findings and Conclusions

- The results from the electromagnetic induction (EM) survey indicate an average fresh groundwater zone thickness of between 6 m and 7 m was present within the agricultural plots. The central (north-south) road showed the best overall results.
- A previous survey using electrical resistivity (ER) in April 2019 showed the thickest groundwater in the area of the agricultural plots to be about 4 m The reason for the difference in results from the two surveys is due to the difference in prior rainfall conditions. Prior to the April 2019 survey, the rainfall was very low while prior to the recent survey the rainfall was high to very high depending on the durations of the prior rainfall.
- Measurements of ground and groundwater levels at selected wells and a level survey relative to means sea level (MSL) shows the groundwater to be quite shallow and slightly above MSL within the agricultural plot area.
- Limited data logging of groundwater level and salinity at the Nexus farm eastern well (at southeast corner of the agricultural plots) indicates that the pumping there is not having a significant effect on the freshwater lens. However, further data would need to be collected particularly during the drier months of the year to confirm this.
- Comparison of groundwater level with tidal prediction data and calculated tidal lags and efficiencies indicate the degree of hydraulic connection between the freshwater lens and underlying seawater in the area of the agricultural plots is reasonably low.
- The preferred location for a gallery from a groundwater perspective is the central (north-south) road through the agricultural plots. The next location preference is the north-south road on the eastern side of the agricultural plots.
- From water balance analyses, the sustainable yield on an area basis was estimated as 11 kL/day/ha. From this the length of gallery to supply the full future design pumping rate of 65 kL/day for 103 active lots (unit demand of 630 litres/lot/day) was calculated as approximately 300 m. *The length of the gallery proposed for implementation under the project was estimated and specified as 250 m in the Technical Proposal and priced in the Financial Proposal (NRW & Lamer, 2021). It is noted that it is extremely difficult to estimate actual sustainable yields without the fieldwork investigation data and 250m was considered to represent a reasonable estimate. Based on the sustainable yield of 11 kL/day/ha, the actual allowable pumping rate for the 250m long gallery would be 55 kL/day which equates to 87 active lots at an estimated demand of 630 litres/lot/day.*

Recommendations

It is recommended that the following concept design features be adopted for the proposed gallery:

- Length: 250 m.
- Location: along the central (north-south) road in the agricultural plots with a central pump well.

- Maximum pumping rate: 55 kL/day.

Preliminary design details are recommended below:

- The gallery pipes should be slotted 100 mm PVC pipes.
- The base of the gallery pipes should be laid at 0.5 m below MSL.
- A 150 mm wide gravel pack should be placed around the slotted gallery pipes.
- Thick plastic membrane should be placed above the gravel pack before carefully backfilling with excavated material.
- The pump well should be constructed from a ribbed polyethylene sewer manhole such as those at the Feneka sewerage treatment plant on Nolhivaranfaru.
- The two ends of the gallery pipes should be fitted with 100 mm long radius bends and vertical 100 mm pipes to terminate just below surface and be fitted with 100 mm PVC end caps. Concrete blocks should be installed over end caps.
- The energy source for the pump should be electricity and the pump should be operated at a near-continuous low flow rate to minimise pumping effects on the groundwater.
- A flow meter and strainer should be installed on the outlet pipe.

The proposed concept design of the gallery is shown on the drawing in Appendix B,

If the government is able to provide additional funds then it is proposed that the gallery be extended to 300m length and a tank stand of suitable height with a header tank should be constructed to provide sufficient water pressure to each farm. Alternatively, the project should proceed as planned with the 250m long infiltration gallery and well pump.

APPENDIX A

EM Data and Estimated Fresh Groundwater Zone Thickness

Appendix A

EM data and estimated fresh groundwater zone thicknesses

Table A1 EM-NOF1: Along east-west road immediately north of agricultural plots from lagoon beach to ocean beach, 9 August 2022

Site	UTM co-ordinates (zone 43N)		Distance from start (m)	EM Conductivity for 20m coil spacing (mS/m)	Estimated fresh groundwater zone thickness (m)	Comments
	E	N				
1	292020	740689	0	155	0.7	20m from lagoon edge
2	292029	740693	10	85	5.7	
3	292057	740694	38	92	5.2	
4	292079	740696	60	98	4.8	
5	292100	740698	81	98	4.8	100m from lagoon edge
6	292114	740702	96	80	6.1	At northern end of western road in agricultural plots
7	292138	740709	121	83	5.9	
8	292148	740710	131	75	6.4	
9	292177	740710	160	62	7.4	10m west of northern end of central road in agricultural plots
10	292192	740714	175	75	6.4	
11	292213	740717	196	88	5.5	
12	292234	740720	218	85	5.7	
13	292252	740721	236	50	8.2	Near northern end of eastern road in agricultural plots
14	292278	740720	262	55	7.9	
15	292291	740727	276	58	7.7	
16	292313	740730	299	42	8.8	
17	292334	740735	320	44	8.7	
18	292354	740739	341	62	7.4	
19	292373	740741	360	65	7.2	
20	292393	740746	380	66	7.1	

Site	UTM co-ordinates (zone 43N)		Distance from start (m)	EM Conductivity for 20m coil spacing (mS/m)	Estimated fresh groundwater zone thickness (m)	Comments
	E	N				
21	292403	740746	390	76	6.4	
22	292428	740750	416	75	6.4	
23	292449	740754	437	80	6.1	
24	292469	740756	457	76	6.4	
25	292489	740759	477	78	6.2	
26	292509	740763	498	81	6.0	
27	292519	740766	508	86	5.6	Across T-junction with road to north
28	292545	740769	534	88	5.5	
29	292566	740772	556	92	5.2	
30	292587	740775	577	98	4.8	
31	292606	740781	597	98	4.8	
32	292617	740782	608	120	3.2	
33	292645	740782	636	150	1.0	
34	292656	740780	647	160	0.3	20m from ocean edge

Table A2 EM-NOF2: Along central road in agricultural plots from north to south, 10 August 2022

Site	UTM co-ordinates (zone 43N)		Distance from start (m)	EM Conductivity for 20m coil spacing (mS/m)	Estimated fresh groundwater zone thickness (m)	Comments
	E	N				
1	292185	740696	0	60	7.5	15m south of centreline of east-west road
2	292191	740677	20	54	7.9	
3	292196	740657	41	Very low reading		Reason unknown
4	292199	740635	63	Very high reading		Near buried electrical cable between two electricity boxes
5	292202	740618	80	68	6.9	
6	292205	740598	100	72	6.7	

Site	UTM co-ordinates (zone 43N)		Distance from start (m)	EM Conductivity for 20m coil spacing (mS/m)	Estimated fresh groundwater zone thickness (m)	Comments
	E	N				
7	292207	740579	119	60	7.5	
8	292211	740560	139	65	7.2	Across east-west road with buried electrical cable
9	292215	740539	160	68	6.9	
10	292221	740518	182	66	7.1	
11	292223	740500	200	62	7.4	
12	292226	740479	221	65	7.2	Across buried electrical cable between two electricity boxes
13	292230	740460	241	66	7.1	
14	292230	740441	260	70	6.8	
15	292231	740423	278	50	8.2	
16	292237	740403	299	60	7.5	
17	292237	740384	318	78	6.2	15m south of east-west road
18	292243	740363	339	82	5.9	
19	292242	740346	356	84	5.8	

Table A3 EM-NOF3: Along western road in agricultural plots from north to south, 10 August 2022

Site	UTM co-ordinates (zone 43N)		Distance from start (m)	EM Conductivity for 20m coil spacing (mS/m)	Estimated fresh groundwater zone thickness (m)	Comments
	E	N				
1	292121	740682	0	50	8.2	15m south of centreline of east-west road
2	292124	740661	21	62	7.4	
3	292128	740642	41	66	7.1	
4	292130	740629	54	72	6.7	
5	292134	740601	82	94	5.1	2 photos
6	292138	740582	101	88	5.5	
7	292144	740562	122	77	6.3	
8	292148	740538	147	75	6.4	Across east-west road

Site	UTM co-ordinates (zone 43N)		Distance from start (m)	EM Conductivity for 20m coil spacing (mS/m)	Estimated fresh groundwater zone thickness (m)	Comments
	E	N				
9	292146	740520	165	80	6.1	
10	292149	740501	184	68	6.9	
11	292152	740480	205	85	5.7	
12	292157	740460	226	78	6.2	Across electrical cable between two electricity boxes
13	292164	740440	247	70	6.8	
14	292166	740420	267	77	6.3	
15	292169	740400	287	80	6.1	2 photos
16	292174	740382	306	82	5.9	Across east-west road
17	292178	740359	329	84	5.8	
18	292182	740339	350	87	5.6	

Table A4 EM-NOF4: Along east-west road near southern end of agricultural plots, 10 August 2022

Site	UTM co-ordinates (zone 43N)		Distance from start (m)	EM Conductivity for 20m coil spacing (mS/m)	Estimated fresh groundwater zone thickness (m)	Comments
	E	N				
1	292181	740384	0	82	5.9	T-junction of E-W road & N-S road on west side of agricultural plots
2	292200	740389	20	78	6.2	
3	292221	740390	41	73	6.6	
4	292238	740395	58	74	6.5	
5	292257	740397	77	74	6.5	
6	292279	740402	100	76	6.4	
7	292300	740406	121	75	6.4	T-junction of E-W road & N-S road on east side of agricultural plots

Table A5 EM-NOF5: Along eastern road in agricultural plots from south to north, 10 August 2022

Site	UTM co-ordinates (zone 43N)		Distance from start (m)	EM Conductivity for 20m coil spacing (mS/m)	Estimated fresh groundwater zone thickness (m)	Comments
	E	N				
1	292315	740348	0	85	5.7	
2	292309	740370	23	78	6.2	Next to Nexus farm shed
3	292308	740391	44	77	6.3	
4	292305	740412	65	78	6.2	
5	292303	740434	87	80	6.1	
6	292297	740454	108	78	6.2	
7	292294	740474	128	74	6.5	
8	292294	740496	150	72	6.7	2 photos
9	292288	740516	171	70	6.8	
10	292286	740535	190	72	6.7	Centre of east-west road
11	292281	740558	214	70	6.8	
12	292279	740572	228	70	6.8	
13	292272	740597	254	66	7.1	
14	292270	740620	277	66	7.1	Opposite electricity box on west side
15	292267	740640	297	70	6.8	
16	292260	740660	318	70	6.8	
17	292257	740680	339	68	6.9	
18	292288	740701	376	68	6.9	20m south of centreline of E-W road

Table A6 EM-NOF6: Along east-west road near centre of agricultural plots, 10 August 2022

Site	UTM co-ordinates (zone 43N)		Distance from start (m)	EM Conductivity for 20m coil spacing (mS/m)	Estimated fresh groundwater zone thickness (m)	Comments
	E	N				
1	292276	740384	0	72	6.7	T-junction of E-W road & N-S road on east side of agricultural plots

2	292253	740389	24	70	6.8	
3	292232	740390	45	Unstable reading		Instability here & below caused by buried electrical cables
4	292210	740395	67	Unstable reading		At intersection of E-W road & N-S road in centre of agricultural plots
5	292195	740397	82	Unstable reading		
6	292169	740402	109	Unstable reading		

Appendix B: Concept Design Drawing