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Unveiling Island Water Demand Patterns: A Multi-Scale Comparative Study in the Maldives

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ABSTRACT *The geographical distribution of islands in the Maldives presents unique water management challenges. Despite similarities, supply water demand patterns vary across islands due to factors such as consumer behaviour, availability of alternative water sources (groundwater, rainwater), and urban density. Current design practices rely on standardised per capita values, potentially leading to over- or under-sized water systems. This research proposes a data-driven approach to establish water demand patterns that consider island characteristics. Operational data from 2023 for three Maldivian islands — HDh. Finey, M. Mulah, and Gn. Fuvahmulah —are analysed, representing contrasting land areas, populations, and urban environments. The analysis shows distinct peak demand times and minimum night flow patterns for the three islands. While the peak demand for the Gn. Fuvahmulah is higher (25 m3/hr) compared to HDh. Finey (10 m3/hr), the per capita water demand is much higher for HDh. Finey(24.45 L/capita/hr) compared to Gn. Fuvahmulah (2.72 L/capita/hr). By identifying the influence of different factors on water demand, the research aims to provide beneficial insights for policymakers, designers, and operators of water management facilities. This information can aid to optimise future water system design, minimise investment costs and enable long-term sustainability. The insights from this study can help to avoid over- or under-capacity developments, leading to lower operational costs and increasing water security for island communities.*

Keywords: Island Water Demand Patterns, Data-Driven Water System Design, Water Management, Sustainable Water Infrastructure

Introduction

The Maldives is among one of the most vulnerable Small Island Developing States (SIDS) with extremely shallow groundwater reservoirs. The thin freshwater lens ranging between 1 to 1.5 meters in depth, is facing severe depletion and increasing salinity. Issues are primarily caused by excessive extraction of groundwater in addition to the impacts of sea-level rise and reduced rainfall (GCF, 2024; Jaleel et al., 2020).

The limited land area, isolated nature, and high population density of most islands limits access to freshwater resources. This increases reliance on alternative supply options such as desalination and rainwater harvesting (Han & Ki, 2010). As a result, the Maldivian government has invested significantly in centralised desalination plants for all inhabited islands. These facilities must adhere as per the design criteria outlined in the "Design Criteria and Technical Specifications: Design and Construction of Water Treatment and Supply System URA 4001:2001"

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by the Utility Regulatory Authority of Maldives.

Despite the development of centralised desalination plants, a comprehensive understanding of island-specific water demand patterns remains limited. Water consumption is dependent on various factors, including consumer behaviour, urban density, and presence of alternative sources (Reyes et al., 2019; Tortajada, 2006)

This aim of this research is to unveil the diversity of water demand patterns in the Maldivian context and offer insights for optimised water system design. Operational data from three geographically, and demographically different Maldivian islands—HDh. Finey, M. Mulah, and Gn. Fuvahmulah—are analysed to identify key patterns in water production and consumption. During the period of study, inhabitants of HDh. Finey received desalinated water at no cost. We aim to understand the factors that influence water demand by analysing daily water consumption variations, similarities, and differences across these islands.

We also explore how water distribution data can be used to assess the health of the water network and identify potential leakages using the concept of Minimum Night flow (MNF) (Alkasseh et al., 2013; AL-Washali et al., 2018). Furthermore, daily power usage patterns, the impact of solar energy on water production, and fluctuation of solar energy over time are analysed in detail for HDh. Finey using the water production, electricity consumption, and solar power consumption data.

Literature Review

The management of water systems effectively relies heavily on monitoring and analysing water demand patterns. These patterns, which accounts for numerous factors including seasonal variations, population growth and behaviour of consumers (Pacchin et al., 2019), along with network models are useful in forecasting the water needs, which in turn allows for timely optimisation and sustenance of water distribution operations (Avni et al., 2015). This is achieved via reduction of water wastage and service disruptions because of water conservation programmes, planned maintenance regimes and other demand-side management strategies that utilize these modelled data (Avni et al., 2015).

One of the key indicators of a healthy water system is Minimum Night Flow (MNF). This is the lowest flow rate at which water is distributed at night, which usually is recorded between 12 am and 4 am (Hayslep et al., 2024). One application of MNF includes its comparison with the baseline flows to detect possible leaks in the network, in turn, reducing water loss. (Negharchi & Shafaghat, 2020). The lower the MNF values are, approaching zero within the duration of the analysis, the healthier the water network is, depicting minimal leaks. However, a consistent threshold of MNF may insinuate a background leak in the water network and requires additional investigation for its corroboration.

Reverse Osmosis desalination technology consumes large amounts of fossil fuels for its power production. Hence, this process is known to contribute to major greenhouse gas emissions and global warming. This is a major challenge for the growing demand for water production using this technology. To address this challenge, fossil fuels can be replaced with other renewable energy sources. Solar power is one of the most promising energy alternatives because it can reduce greenhouse gas emissions ensuring sustainability of the water production system. For a tropical country like the Maldives, which receives ample amounts of sunlight, the reliance on fossil fuels can be reduced with solar powered desalination (Alawad et al., 2023). Despite these benefits, it is estimated that only 1% of the total global desalination is achieved using solar power (Fthenakis et al., 2022).

Modern water management systems require digital data. Digital data enables accessibility, security, and efficiency. This enhances decision-making and operational management(Carriço et al., 2023). This is especially important in the context of SID's like the Maldives. Manual data formats inhibit development as it makes data retrieval and analysis time-consuming and error prone. Digitisation enables real-time monitoring, predictive analytics, and automated reporting, which are critical for optimising water resource management and responding to issues quickly (Rousso et al., 2024). The main challenge for this study also posed to be the digitisation of the data needed for the analysis, due to the heavy reliance on manual data formats such as scanned operational log sheets.

Urbanisation or the shift of population from rural to urban areas tends to have profound implications for water demand and management. As cities grow and population density increases, the demand for water resources also increases. Factors like industrial activities, commercial development, and increased domestic consumption contribute to higher water usage rates in urban areas (Canteiro et al., 2024). Population density can serve as a proxy for urbanisation and can be used to estimate future water demand and plan for infrastructure expansion (Rathnayaka et al., 2016).

Methodology

Data Collection

Data collected from desalination plants operated by Fenaka Corporation Limited on three distinct Maldivian islands are analysed in this study. Data was analysed for periods of one, six, and twelve months, as detailed in Table 1.

Table 1: Details of the islands and data analysed for this study

No.	Island Name	Parameters Analysed	Timeline for Analysis	Population (MBS, 2022)	Land Area(Ha) (MLSA, 2024)
1	H.Dh. Finey (Island)	• Water Demand (m3/hr) • Water Production (m3/hr) • Main grid electricity consumption (kWh) • Solar electricity consumption (kWh)	1 January 2023 – 31 January 2023	409	117.53
2	M. Mulah (Island)	• Water Demand (m3/hr) • (2 hour interval)	1 January 2023 – 30 June 2023	1423	68.33
3	Gn.Fuvahmulah (City)	• Water Demand (m3/hr)	1 January 2023 – 31 December 2023	9166	495.04

Water demand and production data were obtained from totalising water meters installed at the desalination plants. Totalising water meters, similar to household water meters, provide an accurate cumulative flow through the meter, which is more reliable than an instantaneous flow meter for obtaining the total outflow from the desalination plant. Electricity consumption data was sourced from standard electricity meters at the same locations. While no specific calibration was conducted for this study, all meters were tested and calibrated prior to installation.

All the data used in this study was originally stored in scanned handwritten documents in PDF format on Fenaka servers. To facilitate analysis, data for H.Dh. Finey and M. Mulah was manually digitised. Gn. Fuvahmulah data, available in digital PDF format, was converted to Microsoft Excel spreadsheet format and cleaned using Python. Missing data was imputed using daily averages.

Population data and land area data were obtained from the Maldives Bureau of Statistics and the Maldives Land Survey Authority. Population density is used as a proxy for urbanisation for the purpose of this study.

Analysis

Once the data was digitised, Python was used to preprocess and analyse hourly water demand patterns. The data was structured into a pivot table format, with dates as rows and hours in a day as columns. Visualisations were generated using Python's plotting libraries, highlighting average demand patterns by overlaying individual daily trends as faint lines and emphasising the average trend with a bolder line. This approach facilitated the identification of consistent water demand patterns and potential outliers. To evaluate the impact of solar-powered desalination, H.Dh. Finey's water production, electricity consumption, and solar power generation data were analysed in detail, similar to the water demand patterns.

Results and Discussion

Analysis of water demand in Figure 1 for H.Dh. Finey, M. Mulah, and Gn. Fuvahmulah reveals consistent daily patterns with the lowest consumption occurring between 22:00 and 5:00 hrs. All three islands show the lowest consumption between 1:00 and 4:00 hrs. Maximum usage occurs in the afternoon for all islands, though the specific timing and magnitude vary. H.Dh. Finey exhibits three distinct peaks at 8:00, 13:00, and 19:00 hrs. Similarly, Gn. Fuvahmulah also shows three peaks at 13:00, 16:00 and 19:00 hrs, while M. Mulah exhibits two peaks at 14:00 and 20:00 hrs.

It is crucial that we understand these water consumption patterns in order to optimise water resource management. Identifying peak and off-peak hours allows utilities to schedule maintenance activities such that it minimises disruptions to consumers. This information also aids in implementing demand-side management strategies during water shortages or planned outages.

In this regard, from the results of the three islands, it can be determined that, any water rationing activities or maintenance activies which require water services to be discontinued can be carried out during low peak hours, between 22:00 and 5:00 hrs to minimise the impact of those activites on consumers. During peak hours, water pressure can be reduced within the distribution network to conserve water. This approach allows service providers to extend water service in emergency situations, such as when water production falls below consumption or is completely stopped. By strategically rationing water and utilising stored reserves, the service period can be prolonged, ensuring a more equitable distribution of water resources while any issues are resolved within the respective systems.

H.Dh. Finey and M. Mulah demonstrate MNF, indicating a healthy water distribution network with minimal leaks. Gn. Fuvahmulah's consistent low-level demand (approximately 1 m^3/hr - Table 2) for MNF suggests a potential background leak requiring further investigation. This analysis using MNF demonstrates the value of this low-cost, long-term data monitoring in identifying network vulnerabilities and informing maintenance planning. Other methods such as water balance analysis—calculating the difference between water entering the distribution system and the water accounted for or billed—can be used to identify leaks or Non-Revenue Water (NRW) (Kingdom et al., 2006; Liemberger & Wyatt, 2019). However, such an analysis requires significantly more data and is much more time-consuming than the simple MNF analysis conducted in this study. As such MNF analysis can be a highly time-efficient and resource-effective method for service providers to make a baseline assessment of the network health of their water systems.

Table 2 shows that H.Dh. Finey has significantly higher, approximately ten times higher, maximum demand per capita than the other islands. This disparity is attributed to the absence of water billing in H.Dh. Finey, leading to excessive consumption. Additionally, urbanisation appears to correlate with increased per capita consumption, as evidenced by the higher rate in Gn. Fuvahmulah compared to M. Mulah.

Although the population density for Mulah is higher at 20.83 pax/km2, it is categorised as an island by the government. In Gn. Fuvahmulah, the population density is close to that of Mulah but lower with 18.52 pax/km2; however, is categorised as a city by the government. This categorisation is based on the total population of the island. The urbanisation and development associated with being a city is expected to have led to a slightly higher per capita consumption in Gn. Fuvahmulah compared to M. Mulah. Cities tend to have more industrial activities, commercial development, and increased domestic consumption. However, the impact of urbanisation on water usage is significantly less pronounced than the effect of billing for water consumption.

Table 2: Minimum and Maximum Demand per hour and Maximum Demand per hour per capita

No.	Island Name	Population Density(pax/km2)	Minimum Demand (m3/hr) (MNF)	Maximum Demand(m3/hr)	Maximum Demand per Capita (m3/hr/capita)
1	H.Dh. Finey	3.48	0.000	10.000	24.45
2	M. Mulah	20.83	0.006	3.385	2.38
3	Gn. Fuvahmulah	18.52	1.000	25.000	2.72

Analysis of H.Dh. Finey's power consumption and water production data in Figure 2 revealed insights into water production in H.Dh. Finey. Solar power generation typically commences at 6:00 hrs and persists until 20:00 hrs. Fluctuations in solar output throughout the day indicate varying cloud cover conditions.

While an initial assessment suggests that reduced grid electricity consumption during midday correlates with increased solar generation, a deeper analysis reveals that a scheduled daily maintenance period for the desalination plant between

12:00 and 14:00 hrs is the primary factor influencing water production and, consequently, energy demand during this time. The data also shows that due to the consistently high demand in H.Dh. Finey, near-continuous operation of the desalination plant is required, except for the daily maintenance window.

To quantify the contribution of solar energy, calculations indicate that solar power provides approximately 23.1% of the desalination plant's peak energy demand during optimal conditions. Although occasional peaks of solar generation can meet up to 38.5% of the plant's requirements, achieving complete reliance on solar energy would necessitate a four to five-fold increase in current solar capacity.

Limitations

The reliance on physical, handwritten records presented significant challenges for data analysis. This limitation underscores the need for improved data management practices to maximise the value of such critical information.

Figure 1 Water Demand (a) H.Dh. Finey, (b) M. Mulah, & (c) Gn. Fuvahmulah

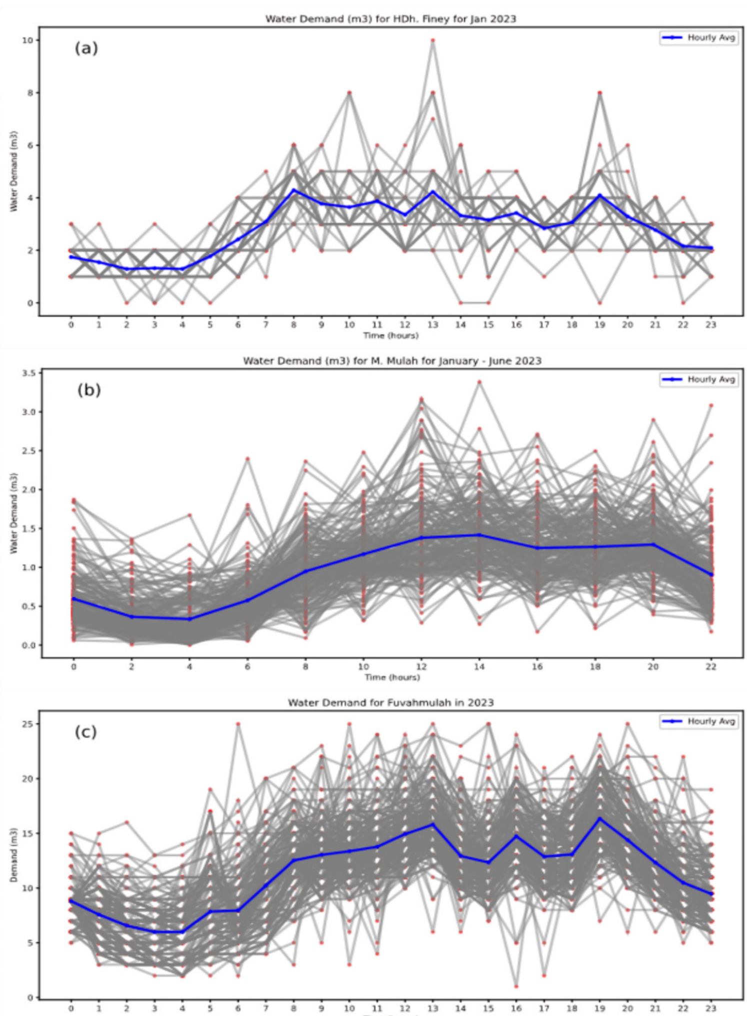
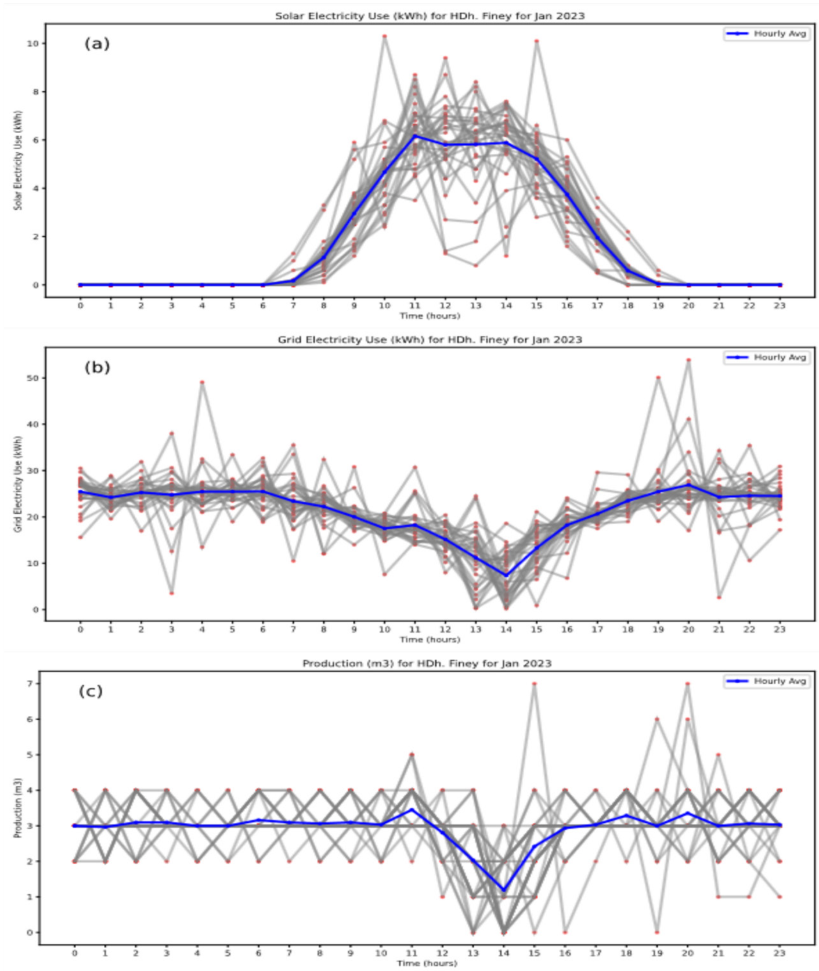


Figure 2: (a) Solar electricity use, (b) Grid electricity use, (c) Water production for H.Dh. Finey



Conclusions and Recommendations

In conclusion, consumer behaviour, particularly billing practices, and urbanisation are key factors influencing per capita water consumption. Consistent daily consumption patterns were observed across all three islands, with the lowest demand between 22:00 and 5:00 hrs. Peak usage occurred in the afternoon, although specific timing and magnitude varied.

MNF analysis was shown to be a simple and powerful tool in identifying the health of water distribution networks. MNF analysis revealed healthy water distribution networks in H.Dh. Finey and M. Mulah, while a potential background leak was identified in Gn. Fuvahmulah.

H.Dh. Finey exhibited significantly higher per capita consumption due to the absence of water billing. Urbanisation also correlated with increased per capita consumption, as observed in Gn. Fuvahmulah compared to M. Mulah.

Integrating renewable energy, such as solar power, can reduce the environmental and economic impacts of water desalination. Solar power contributed approximately 23.1% of the peak energy demand for the desalination plant in H.Dh. Finey. Increasing solar capacity by four to five times would be necessary to achieve complete reliance on solar energy.

Based on these findings, it is recommended to:

1. Invest in digitalisation of water infrastructure data to facilitate real-time monitoring, leak detection, and comprehensive system analysis.
2. Increase the integration of renewable energy generation, especially solar, at desalination plants to reduce energy costs, and address environmental impact and long-term water security by reducing dependency on fossil fuels.
3. Conduct further research to understand the socioeconomic and behavioural drivers of water consumption in island communities.

Conflict of Interest

I hereby declare that I have no conflict of interest related to this research.

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Table 3: List of staff who carried out data collection

No.	Staff Name	Island
1	Hassan Ali	Gn. Fuvahmulah
2	Ahmed Naee	Gn. Fuvahmulah
3	Abdulla Hamdhaan	Gn. Fuvahmulah
4	Ahmed Juman Khalid	Gn. Fuvahmulah
5	Mohamed Rasheed	Gn. Fuvahmulah
6	Karam Ahmed	Gn. Fuvahmulah
7	Ahmed Ali	Gn. Fuvahmulah
8	Ibrahim Shah	Gn. Fuvahmulah
9	Mussad Nizam	Gn. Fuvahmulah
10	Ahmed Hunaif	Gn. Fuvahmulah
11	Aishath Ibrahim	Gn. Fuvahmulah
12	Mohamed Alim	Gn. Fuvahmulah
13	Ali Hussain	Gn. Fuvahmulah
14	Aini Seena Saeed	Gn. Fuvahmulah
15	Siyath Mohamed	Gn. Fuvahmulah
16	Ismail Riza	Gn. Fuvahmulah
17	Mohamed Azaan	Gn. Fuvahmulah
18	Azaan Wafir	Gn. Fuvahmulah

19	Ali Abdul Rahman	M. Mulah
20	Hassan Mohamed	M. Mulah
21	Fathimath Mohamed	M. Mulah
22	Munaz Abdul Rasheed	M. Mulah
23	Ahmed Latheef	M. Mulah
24	Ahmed Ibrahim	M. Mulah
25	Ahmed Miusam	M. Mulah
26	Naveed Ziyaadh	M. Mulah
27	Ali Thohir Hassan	M. Mulah
28	Mohamed Moosa	M. Mulah
29	Fuaadh Mohamed	M. Mulah
30	Ahmed Zaid	H.Dh. Finey
31	Abdulla Ziunadh	H.Dh. Finey
32	Azvaan Thoha	H.Dh. Finey
33	Ahmed Abdulla	H.Dh. Finey
34	Mohamed Irufan	H.Dh. Finey
35	Abdul Raxxag	H.Dh. Finey
36	Ibrahim Hussain	H.Dh. Finey
37	Hassan Rasheed	H.Dh. Finey
38	Saud Ali	H.Dh. Finey

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