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Brief Report

Tourism-Related Pressure on the Freshwater Lens of the Small Coral Island Gili Air, Indonesia

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Abstract: Tourism on Gili Air, a small coral island in Indonesia, has increased significantly. Groundwater is the primary water source on the island. This study aims to estimate the sustainability of groundwater use on this small coral island. It conducts an initial assessment of the freshwater lens system using cost-effective methods to evaluate the available freshwater volume and sustainability of water withdrawals related to tourism. The results and methods can be transferred to other low-lying islands. The results show that Gili Air has a well-developed freshwater lens, estimated to contain 2 million cubic meters of water, with an annual recharge rate four times higher than the water demand of the island's inhabitants. However, our findings suggest that the rapid increase in tourism resulted in unsustainable water withdrawals between 2016 and 2019. Without proper groundwater monitoring and management, this could lead to seawater intrusion into the aquifer.

Keywords: freshwater lens; small coral island; sustainable water use; Indonesia; Lombok

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1. Introduction

On many small islands, groundwater is a scarce and sensitive resource that requires careful management and preservation to ensure its continuous availability [1]. On islands with high tourism, the water quality of groundwater can be affected by tourism-related sewage waters [2], and freshwater demands associated with this industry can significantly strain or surpass available water resources [3]. The unsustainable extraction of groundwater resources can lead to saltwater intrusion and groundwater depletion [4]. Managing groundwater resources effectively requires a thorough understanding of the hydrogeological system [5].

Conceptually, assuming homogeneous aquifer conditions, the groundwater on islands typically occurs as a freshwater lens (FWL) that floats on denser seawater, separated by a transition zone (Figure 1) [3]. Low-lying coral islands like Gili Air usually have a dual-aquifer system where a shallow FWL resides in the upper Holocene sedimentary aquifer, which overlays a lower aquifer of Pleistocene limestone [6–8]. The transition from Holocene sediments to Pleistocene limestone is a remnant of the glacio-eustatic sea level [9] and is referred to as the "Thurber Discontinuity" [10]. The limestone's higher hydraulic conductivity increases the mixing of water masses driven by tidal forces, which hinders the formation of a freshwater lens within the lower aquifer [7,11]. Hence, the thickness and hydraulic conductivity of the upper aquifer determine the dimensions of the freshwater lens together with the groundwater recharge of precipitation that falls on the island's surface. As a result, smaller islands tend to have relatively minor freshwater capacities compared to larger islands. Mixing with seawater in a transition zone followed by subsequent outflow to the ocean is known as fresh submarine groundwater discharge (FSGD) that balances groundwater recharge [12]. The magnitude of FSGD can vary depending on local hydrogeological conditions, rates, and times of groundwater recharge and extraction [13].

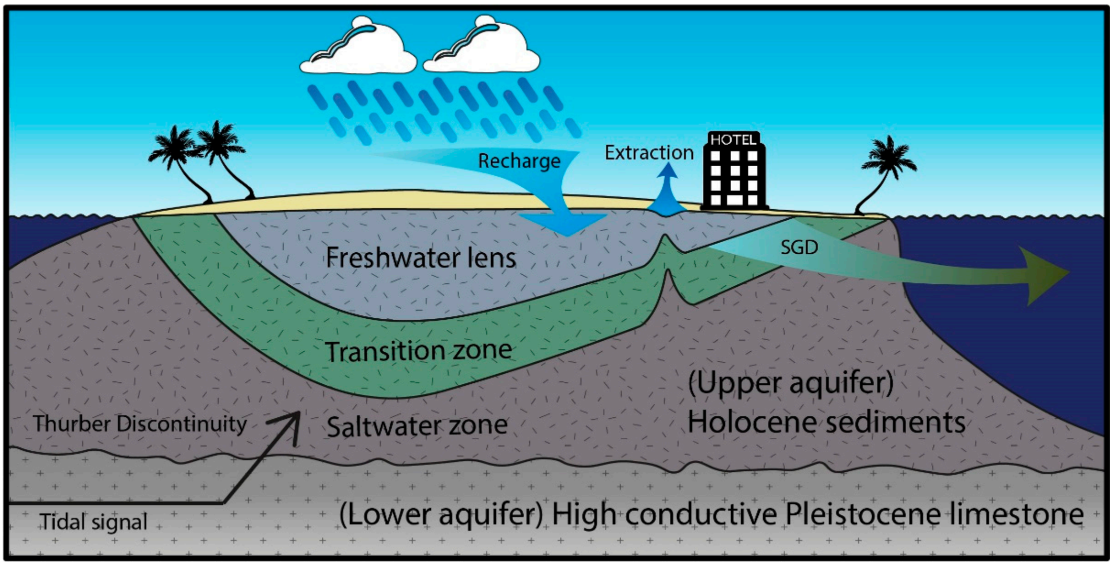

Figure 1. Conceptual model of a coral island's freshwater lens with a surrounding transition zone (modified from [7]).

Here, we assess the distribution, water storage capacity, and annual recharge of the freshwater lens system on Gili Air, West Nusa Tenggara, Indonesia, as well as their determining parameters using simple field methods in order to quantify Gili Air's groundwater resources and estimate the sustainability of the water abstractions in relation to tourism. Additionally, the findings are discussed in light of groundwater withdrawal volumes by the resident population and the tourism sector.

2. Materials and Methods

Study Area

Gili Air is one of three islands on the northwest coast of Lombok, Indonesia (Figure 2). Since the 1970s, backpacker tourism has been prevalent on the island, and it has become the primary economic activity. The number of tourists arriving at Gili Air grew to over 220 thousand visitors per year by 2017 (Figure 2c). The island's tourism industry was affected in 2018 by an earthquake in northern Lombok and in 2020 by the COVID-19 pandemic. The latter led to a significant drop in tourist numbers, but these appear to be recovering quickly. Satellite images reveal a notable increase in the construction of buildings with private swimming pools for tourism during the last decade. A total of 2200 residents and the tourist industry supply themselves with freshwater out of hundreds of dug wells around the island. The following, this study uses the term 'freshwater' for water with a salinity of up to 2.5 PSU (practical salinity units; dimensionless). Additionally, some hotels are connected to a waterpipe from Lombok, which provides an average water volume of 5.6×10^4 m^3 annually, according to information from the water-provider company PDAM.

Gili Air is a low-lying island with a surface area of about 1.7 km^2. A 10 m high hill rises in the eastern central part of the island. Although there has been limited research on the geology of Gili Air, Astjario and Astawa [14] reported that the island's base is composed of pillow lava from subaqueous volcanic activity. On this foundation, a typical coral reef island has formed, with a lower limestone aquifer topped by carbonate sand and silt deposits (Figure 2d).

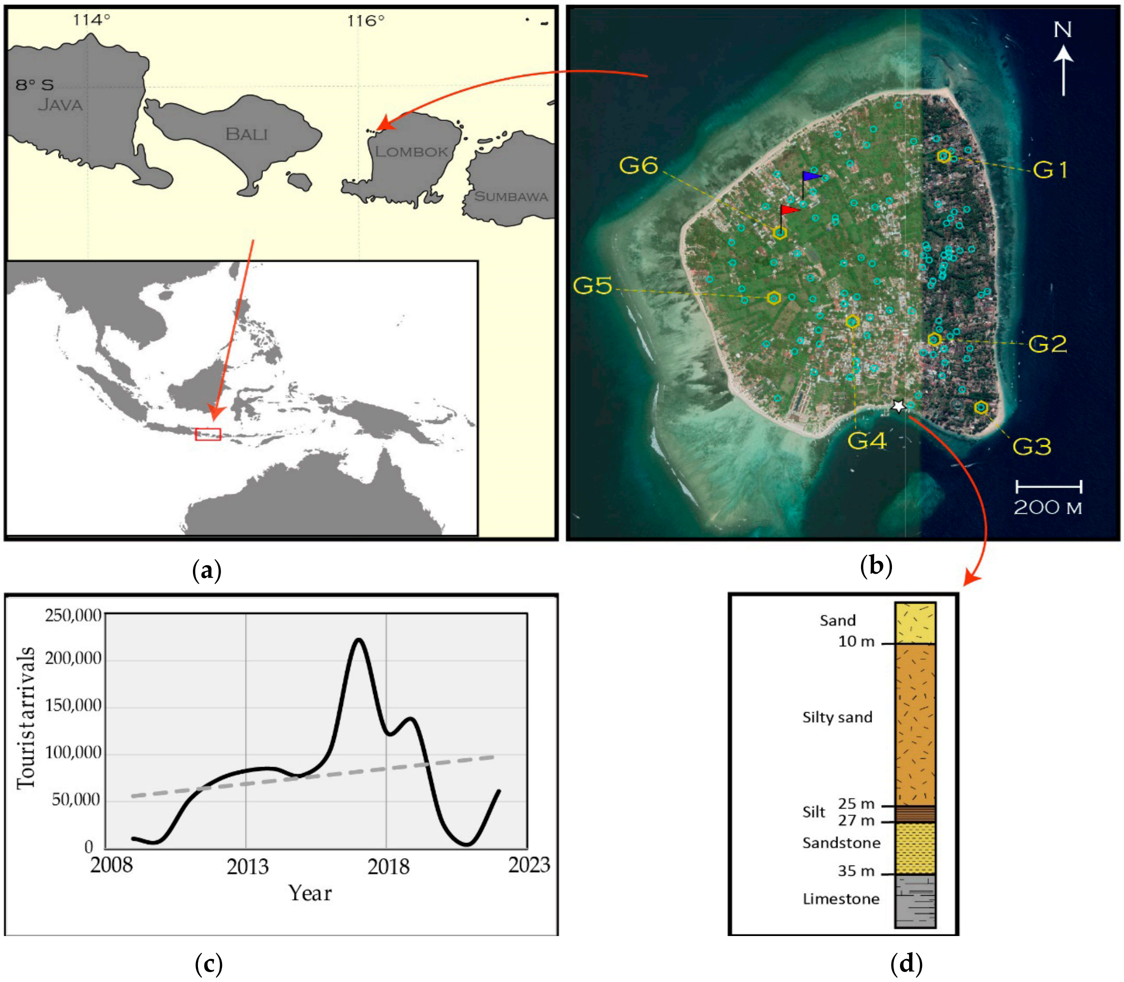

Figure 2. (**a**) Location of Gili Air in Indonesia. (**b**) Satellite image of Gili Air (Google Earth, 4 February 2020) with the following locations: red flag: Meteotime duo weather station; blue flag: Sainlogic weather station. G1–G6: sediment sampling locations. Blue circles: dug well measurement locations. Star: location of drill profile. (**c**) Annual tourist arrivals at Gili Air (Dinas Pariwisata Kabupatem Lombok) 2009–2022. (**d**) Geological interpretation of drill profile previously taken and provided by the civil engineering department of the Universitas Mataram.

3. Data Acquisition

The methods used in this study concentrate on cost-effectiveness and easy reproducibility without the need for expensive equipment, enabling an initial assessment of the freshwater resources of small and circular islands with sedimentary aquifers. This study is based on fieldwork data collected from December 2019 to June 2020. These data form the input parameters for interpolations and algebraic methods to analyze the FWL of Gili Air.

A precipitation dataset was composed of two different measurement series. The first series was recorded at Gili Air (red-flagged location Figure 2b) during the study's fieldwork period, using a TFA-Dostmann Meteotime Duo weather station with a pluviograph to record the precipitation hourly with a 7 mm accuracy. The second series of precipitation measurements, from 2021 to March 2023, was collected daily near the first series location (Figure 2b) using an automated Sainlogic weather station with a 2 mm precipitation accuracy. These data were analyzed on a monthly basis and averaged to mean annual precipitation, which was used for lens thickness calculations and recharge assessment. The complete precipitation dataset includes results from the two measuring series for every month of the year. However, the second measuring series with the Sainlogic weather station experienced data gaps caused by power outages and internet connectivity issues, resulting in only partial availability of data for certain months from 2021 to 2023.

Six samples of the water-bearing upper aquifer were collected from dug well bottoms for a grain size distribution assessment. The samples were derived from different locations around Gili Air (G1–G6; Figure 2b). From the grain size distribution, the hydraulic conductivity was calculated according to [15] for each sample. The sediment samples all meet the necessary requirements of being uniform or moderately uniform sand, have an effective diameter D_{10} between 0.06 mm and 0.6 mm and a coefficient of uniformity of Cu between 1 and 20. Further, the effective porosity was calculated according to [16] to approximate the freshwater volume from the FWL volume, assuming moderate natural compaction of the sediments.

The salinity of 105 dug wells was measured between the end of February and the beginning of June 2020. The well water was sampled with an attached pump or by bucket, considering salinity stratification effects by stirring. Due to the setup, flushing of the wells prior to sampling was not possible. Each location was sampled twice, and each sample was measured three times with a HACH HQ40d multimeter set to HACH salinity and a CDC401 salinity probe with 0.5% accuracy. The salinity well point data were spatially interpolated over the island using the SAGA Universal Kriging method in QGIS 3 with 8–10 minimum–maximum nearest points, a block size of 1, and a 0.00001-degree cell size. This interpolation was used to analyze the freshwater surface distribution of the FWL.

Further data on tourist arrivals per year (Figure 2c), geological depth information (Figure 2d), and inhabitants of Gili Air were acquired from the local administration, Kantor Desa Gili Indah. While percentages and ranges for recharge from precipitation (recharge factor) on small coral islands were derived from a literature review. Piezometric data were also collected, but no accurate topographic information is available to levelize them to the sea level in order to make use of the Ghyben–Herzberg principle [17].

4. Data Processing

Using the software Oracle Crystal Ball (Release 11.1.3), a Monte Carlo simulation was performed with 10,000 iterations to estimate the freshwater lens (FWL) thickness, water volume, and annual recharge. The before-acquired data values, ranges, and assumed distributions served as input parameters. This method allows us to summarize each parameter's individual uncertainties and evaluate the sensitivity of freshwater volume estimations.

The estimation of the lens thickness was accomplished using algebraic methods described by [18] for circular islands and [7]. Both approaches assume steady-state conditions and homogeneous conditions for the upper aquifer. Fetter's [18] method is based on analytical solutions and empirical fits to observations. In order to derive closed-form solutions, the analytical approaches utilized the GHD assumptions, as well as isotropic and homogeneous aquifer conditions, to obtain the necessary simplifications [7]. The FWL thickness (Z_{max}) according to Fetter [18] is calculated with rewritten Equation (1), where $R_e\left(\frac{\mathrm{m}}{\mathrm{a}}\right)$ is the annual recharge, r (m) is the island radius, $k_f\left(\frac{\mathrm{m}}{\mathrm{d}}\right)$ is the hydraulic conductivity of the aquifer sediments, p_f is the freshwater density, and p_s is the saltwater density.

$$Z_{max} = \sqrt{\frac{\frac{R_e}{365} * (r^2)}{2 * k_f * \left\{1 + \left[\frac{p_f}{p_s - p_f}\right]\right\}}} * \frac{p_f}{p_s - p_f} \tag{1}$$

Bailey et al. [7] based their FWL thickness calculation on a numerical model obtained using the variable density, solute finite element code SUTRA [19]. This method accounted for the influences of the reef flat plate and the underlying limestone with higher permeability. The latter can lead to truncation of the FWL due to saltwater mixing. The FWL thickness calculation can be expressed using Equations (2) and (3). Equation (2), where L is the limiting factor, $y_0 = -16.07$ and d = 0.0075 are the fitting model parameters, Z_{TD} is the depth of the limestone aquifer (Thurber Discontinuity), and w is the island width.

$$L = y_0 + (Z_{TD} - y_0) * \left(1 - e^{d*W}\right) \tag{2}$$

And Equation (3), where b is a fitting model parameter depending on the island width, R is the mean annual precipitation ($\frac{\mathrm{m}}{\mathrm{a}}$), and S and C are model-derived factors for hydraulic conductivity and reef flat plate.

$$Z_{max} = L * \left(1 - e^{-bR}\right) * S * C \tag{3}$$

To approximate the mean effective distribution freshwater volume of the FWL (V_W (m^3)) following the lens thickness estimations (2) and (3), an ideal lens shape of a spherical segment is assumed for the FWL. This simplification allowed for the geometrical calculation of the FWL volume as a spherical cap (V_{FWL} (m^3)) with Equation (4), where L_r (m) is the radius of a circle representing the lens surface area.

$$V_{FWL} = \frac{1}{6} * \pi * Z_{max} * \left(3 * {L_r}^2 * {Z_{max}}^2\right) \tag{4}$$

The mean effective freshwater volume of the FWL (V_W (m^3)) is derived by Equation (5), where the FWL volume is multiplied by the effective porosity (n_e) determined by the grain size distribution analysis.

$$V_w = V_{FWL} * n_e \tag{5}$$

Additionally, we used a closed-form solution for circular islands [20] (Equation (6)) to calculate the useable water volume of the FWL in comparison to the water volumes resulting from the previously described method.

$$V_w = \frac{\pi * n_e * \sqrt{2}}{3} * \sqrt{\frac{R_e}{k_f} * \left(1 + \frac{p_f}{p_s - p_f}\right)} * r^3 \tag{6}$$

The closed-form solution calculates the usable water volume of an FWL directly from the input parameters hydraulic conductivity ($\frac{\mathrm{m}}{\mathrm{s}}$), effective porosity (%), recharge ($\frac{\mathrm{m}}{\mathrm{s}}$), and island radius (m). As Chesnaux [20] assumes a uniform recharge and a sharp fresh-saltwater boundary, we used the radius of a circle representing the lens surface area L_r (m) in Equation (6) instead of the island radius r.

The mean annual recharge volume (R_v (m^3)) was calculated using Equation (6), where R represents the mean annual precipitation (m), R_f is the recharge factor for the amount of precipitation recharging into the aquifer, and S_{FWL} represents the FWL surface distribution (m^2).

$$R_v = R * R_f * S_{FWL} \tag{7}$$

Only recharge into the FWL surface area was considered, as recharge into the surface areas of the transition zone at the coast would be transported by the groundwater flow into the ocean. Finally, the results of both methods were averaged for further estimations.

5. Results

5.1. Fieldwork Results

The highest precipitation levels were measured in February and March (Figure 3), while December and January recorded significantly higher precipitation than the drier period of April to November. The mean annual precipitation is estimated to be 1180 mm. Records for the rainy season, January and February, are available for four years, and the precipitation within these months fluctuates by up to 17% when compared to monthly averages. This variability is utilized to calculate the potential range of mean annual precipitation, which is estimated to be between 980 and 1380 mm.

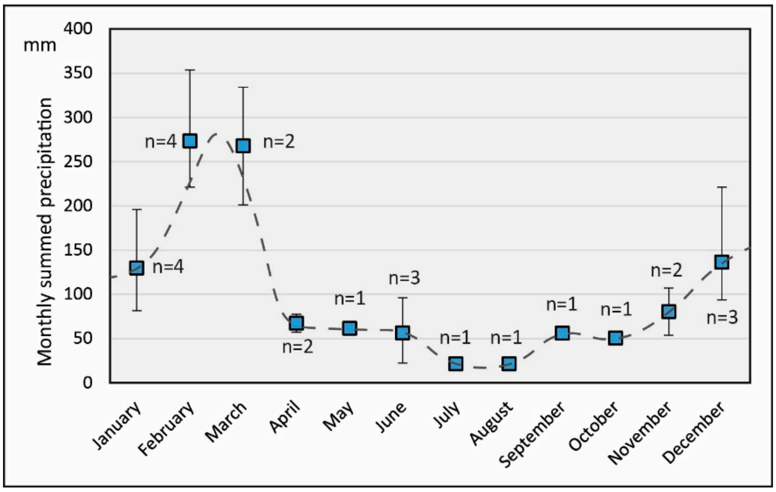

Figure 3. Monthly precipitation records for 2019 to 2023 (the time period when records were available); n = available monthly records.

A review of the literature pertaining to the recharge of eight coral reef islands indicates that their recharge rate is about 30% of precipitation with a standard deviation of 10% [3]. Higher annual rainfall, seasonal rainfall, and lower tree density [21] have been identified as key factors that increase the amount of rainwater recharged into the aquifer, resulting in fewer losses due to evapotranspiration [3].

The hydraulic conductivity values obtained from the grain size analyses ranged from 9.20 to 58.92 $\frac{m}{d}$, with an average of 27.8 $\frac{m}{d}$ (Table 1). The effective porosity values ranged from 27.4 to 35.0%, averaging 29.2%.

Table 1. Results of the upper aquifer sediment grain size analysis, hydraulic conductivity, and effective porosity.

Location	Sediment Classification	d_{10} (mm)	d_{60} (mm)	k_f ($\frac{m}{d}$)	n_e (%)
G1	Fine–Medium sand	0.29	1.76	58.9	35.0
G2	Fine–Medium sand	0.25	1.49	43.7	28.3
G3	Fine sand	0.11	0.41	9.5	28.0
G4	Fine–Medium sand	0.19	0.59	28.7	29.9
G5	Fine–Medium sand	0.12	0.83	9.2	26.7
G6	Fine–Medium sand	0.15	0.79	16.9	27.4
Average		0.18	0.98	27.8	29.2

According to the geological interpretation of the well log provided by the University of Mataram Engineering Department (Figure 2d), the underlying limestone's depth was 34.8 m. On Gili Trawangan, the neighboring island of the study area, the drill data show a depth of 6 m to the underlying limestone. Hence, further data processing was conducted within the range of 6–34.8 m.

The salinity values of the well-log series range from 0.46 to 18 PSU. Out of the wells tested, 53% were found to have a salinity $\leq$ 2.5 PSU, which is here defined as freshwater. The salinity of wells in the eastern and northeastern parts of Gili Air varies significantly within a short distance. The distribution of the interpolated freshwater lens surface covers an area of 0.83 km^2 (Figure 4), equivalent to 48% of the island's surface. This covered area is slightly towards the west of the island's center and southeastern part. The interpolated FWL area includes wells with freshwater, with an uncertainty of 20.5%. Using this uncertainty, the range of the FWL surface ranges from 0.66 to 1 km^2. The radius of a circle that represents the surface area covered by the freshwater lens is estimated to be between 458 and 564 m, with an average value of 514 m.

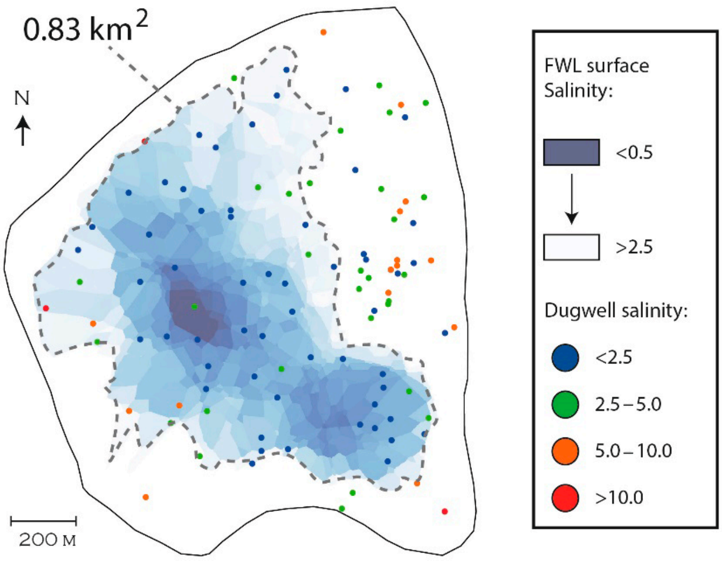

Figure 4. Location and results of the salinity well measurements and resulting interpolation of the freshwater lens surface distribution on Gili Air.

5.2. Monte Carlo Simulation

Table 2 presents the values and range of all input variables utilized in the Monte Carlo simulation. The input variables consist of island width, depth to the Thurber Discontinuity, hydraulic conductivity, the radius of the FWL surface distribution, effective porosity, mean annual precipitation, and the recharge factor. The assumed probability distribution for each input variable is also specified. The output variables comprise the thickness of the FWL according to the Fetter [18] and Bailey et al. [7] calculations, as well as their average freshwater volume according to both methods following Equations (1), (3) and (5), the freshwater volume according to Chesnaux [20] following Equation (6), and the annual recharge amount. For each output variable, the mean value and 90% confidence interval are provided as measures of central tendency and uncertainty, respectively.

Table 2. Inputs and outputs of the Monte Carlo simulation with 10,000 iterations for the calculations of the FWL thickness (Equations (1) and (3)), water volume (Equation (5)), and mean annual recharge volume (Equation (7)).

		Value	**Min**	**Max**	**Distribution Assumption**
Inputs	Island width (m)		1475	1515	Triangular: Max
	Depth to Thurber Discontinuity (m)		6	34.8	Uniform
	Hydraulic conductivity ($\frac{m}{d}$)	27.8	9.2	58.9	Triangular: Value
	FWL surface distribution radius (m)	514	458	564	Triangular: Value
	Effective porosity (%)	29.2	19.3	35	Triangular: Value
	Mean annual precipitation ($\frac{m}{a}$)	1.18	0.98	1.38	Triangular: Value
	Recharge factor	0.4	0.2	0.4	Triangular: Value

Table 2. *Cont.*

		Value	Min	Max	Distribution Assumption
		Average	Certainty Range		Certainty Level
Outputs	FWL thickness (Fetter) (m)	20.82	15.36–28.62		90%
	FWL thickness (Bailey) (m)	16.01	5.84–26.20		90%
	FWL thickness (average) (m)	18.42	12.29–24.73		90%
	Water volume (m^3) (Fetter and Bailey)	2.1×10^6	1.3×10^6–3.1×10^6		90%
	Water volume (m^3) (Chesnaux)	2.6×10^6	2.2×10^6–3×10^6		90%
	Annual recharge volume ($\frac{m^3}{a}$)	3.5×10^5	2.5×10^5–5.4×10^5		90%

6. Discussion

6.1. Input Uncertainties

The rainfall data used in this study are subject to uncertainties associated with a small sample size. The fact that only one complete monthly record is available for several months adds uncertainty to the interannual variation of rainfall. Nevertheless, the data show seasonal precipitation, for which sufficient data are available during the rainy season to compare several years with each other. The recharge factor's triangular distribution assumption includes the enhancing effect of the rain's seasonality on FWL development. Furthermore, the precipitation is recorded only on one side of the island. However, as Gili Air is a low-lying island, the orographic effects are negligible, and minor spatial rainfall variations of 10–20% were observed on other low-lying islands [10]. A more precise analysis of the recharge rate for Gili Air than that derived from the literature would improve the output results.

The upper aquifer sediment properties used in this study were derived from sediment samples of the uppermost layer of water-bearing sediments only, assuming homogeneous conditions. Changes in hydraulic conductivity and effective porosity of the upper aquifer sediments are probable and influence the FWL, which is not represented in this study. Pumping tests were not executed due to the risk of saltwater intrusion. Sediment samples from various depths and locations and slug and bail test in piezometers, combined with a finite element modelling approach, could give a better insight into these influences. Nevertheless, the determined hydraulic conductivity and effective porosity results are within, but at the lower end of, the range considered for other small coral islands of 25 $\frac{m}{d}$–400 $\frac{m}{d}$ [7].

The freshwater lens surface distribution interpolation was derived from salinity measurements in dug wells. Due to their shallow sealing penetration depth, they act like skim wells, making them suitable for this method. The measurements were taken throughout the duration of the rainy season and until its conclusion. This implies that the suggested distribution can be juxtaposed with the peak annual distribution. Further calculations based on this value, e.g., the freshwater volume and annual recharge, are therefore also interpretable as their maximum. The decrease in water withdrawals during the study period, due to the decline in tourists as a result of the Corona pandemic, is likely to amplify the FWL distribution results presented in this study. As fewer dug wells are available in the island's transition zone, measuring points with lower salinity values are generally overrepresented. This was faced by including a boundary condition of 35 salinity along the reef margin. Furthermore, simplifying the elongated form of the FWL distribution to a circle for the geometrical lens volume calculations implies an overestimation of the lens volume.

Further input data include the island form, width, and depth of the lower aquifer. The island's form is known to affect the lens if the island is elongated. The circular shape of Gili Air renders this effect negligible and allows the measurement of its general width. The depth of the lower aquifer is discussed in the next chapter with the freshwater volume sensitivity analysis.

6.2. Uncertainty of the Freshwater Lens Volume

Both methods of evaluating the FWL thickness and the volume calculation [20] consider a sharp interface between fresh and saltwater at 50% of the transition zone. The actual thickness of the lens in water with a salinity of up to 2.5 should be tinner. Applying Fetter's method, the lens thickness result is some meters thicker than Bailey's equation proposed, as the influence of the lower aquifer was not accounted for. Despite this, the average of both equations is utilized. This was supported by Bailey's equation's thin minimum lens thickness, which cannot represent reality as Gili Air's FWL has met the tourism demand until today. To better understand the FWL thickness, in situ salinity measurements from various depths and locations would help, allowing for direct measurement of the lens thickness not only in space but also in time. This would enhance tracking changes in the lens thickness and enable estimating storage changes, recharge behavior, and reactions to extraction adjustments. Geophysical methods such as vertical electrical sounding (VES) can be used to investigate the thickness and geometry of the freshwater lens. During the fieldwork of this study, a VES survey was conducted on Gili Air, but the results showed abruptly rising resistivity values after a few meters and were discarded as unrealistic. This could be due to technical issues or geological factors that caused the injected current to spread horizontally, preventing deeper penetration.

The freshwater volume estimation assumes an ideal lens shape as data on the vertical lens geometry is unavailable; this adds another potential uncertainty to the estimations, while the volume calculation following Chesnaux [20] gives a result within the range calculated along with assuming a lens geometry. The only available drilling data points toward deeper-laying limestone than the FWL is reaching with its purposed thicknesses. Hence, it is improbable that the lens is truncated, and a more trapezoidal geometry is not expected, at least at the southern drilling site. With more spatial knowledge of the limestone information, a volume calculation by dividing the lens into transects and calculating the depths individually could be suggested [22]. The freshwater volume estimation is subject to accumulating uncertainties from both the input parameters and the thickness of the freshwater lens.

The uncertainties of the FWL surface distribution, mean annual precipitation, and recharge factor accumulate for the annual recharge volume. Rainwater infiltrating at the surface-distributed transition zone on the island's coastline is not considered in the recharge estimation, as the general concept of freshwater lens contour lines suggests that this water will flow into the ocean and not into the FWL. Also, additional water quality issues of the freshwater lens that have been observed elsewhere [23], e.g., because of sewage water from tourists, are not considered in this study.

6.3. Lens Development

According to the analysis of the mean annual recharge and water capacity of Gili Air, it can be inferred that the freshwater lens has the potential to retain a water volume equal to 6 years' worth of recharge. This indicates the good drought resilience of Gili Air's freshwater lens. However, this assumption does not take into account the influence of water withdrawals by residents and tourists. Since the local municipality meets its water demand nearly exclusively from groundwater, its water demand is equated with the residential groundwater withdrawal volume. By assuming a water demand of 120 L per day per inhabitant of Gili Air [24], the estimated residential water requirement is 9.5×10^4 m^3, which is about a quarter of the mean annual recharge.

The water demand of the tourism sector is also predominantly satisfied through the use of groundwater sources and can be equated with withdrawal. However, some hotels are supplied with water via a pipeline from Lombok, and this water must be considered when estimating groundwater consumption. Assuming no FSGD occurs and the entire mean annual recharge is available for extraction, this would result in an annual quantity of water equivalent to 3.1×10^5 m^3 (2.1×10^5– 5×10^5 m^3) remaining for the tourism sector. A Monte Carlo simulation with 100.000 iterations was utilized to estimate the number of tourists that the water volume could sustain, using a water requirement estimate of 860 L (ranging from 550 to 1125 L) per day per tourist in Indonesia [25] and a stay of 2–5 days per tourist on Gili Air. This simulation resulted in a median sustainable tourist number per year of 112,000, with a 50% certainty range of 91,000–138,000. The comparison between these numbers and visitor data indicates that in 2017, water consumption was unsustainable given the high number of over 220,000 visitors. Considering losses due to submarine groundwater discharge, it is suspected that the period spanning from 2016 to 2019 with over 100,000 visitors also led to depletion of groundwater, resulting in a reduction of the freshwater capacity and hence lowering the resilience to drought events. Tourism industry data indicate a recovery from the COVID-19 pandemic, and more than 100,000 visitors can be expected in 2023.

Persistent, unbalanced groundwater extraction may result in groundwater salinization, leading to significant issues for the tourism industry and the resident population. This is stressing the groundwater resources, while the shrinking island surface due to climate-change-driven sea-level rises can be suspected to add further stress [26]. Despite the ongoing planning for a new water supply pipeline for Gili Air, the timeline for completion and the full integration of all households into the system remain uncertain. However, it is debatable whether the installation of a supply pipeline would mitigate water withdrawals successfully, as the cost of this water would be high compared to groundwater, which is currently available for free use. Furthermore, the devastating earthquake of 2018 in north Lombok exemplified how rapidly infrastructure can be destroyed, whereas a functional freshwater lens system ensures a dependable supply of fresh water.

7. Conclusions

The aim of this study was to quantify Gili Air's groundwater resources using cost-effective and reproducible methods and estimate the sustainability of the water abstractions in relation to tourism. The purposefully simple methodology naturally entails greater uncertainties and less robustness in the results due to the absence of expensive equipment. Yet, it is particularly important since resources for groundwater assessment are often limited on small islands. The results presented in this study provide insights into the hydrogeology and freshwater lens system of Gili Air. Moreover, they highlight new prospects for management applications concerning Gili Air's groundwater resources. This study provides the first published evaluation of Gili Air's freshwater lens system. The methodological framework can be easily replicated in other small coral island settings, providing valuable insights into the hydrogeology and freshwater lens systems. It is important to note that this study focuses on the effects of water abstraction due to tourism and does not address the consequences of sewage. Nevertheless, the results also highlight areas that require further investigation.

The average annual recharge exceeds the water demand of the resident community approximately fourfold, and the volume of freshwater is estimated to be sufficient to provide resilience against droughts if no tourists were on the island. However, that is not the case, and neither can all recharge be used to the full extent, as losses to the mixing zone must be considered. Since 2016, the impact of tourism may have led to unsustainable freshwater extraction. The COVID-19 pandemic has resulted in a substantial decrease in tourist numbers, providing an opportunity for the partial recovery of freshwater reserves. However, as tourist arrivals are once again on the rise, there is a potential for renewed strain on the freshwater system. Groundwater monitoring and management are therefore recommended to ensure the existence of the fresh groundwater lens under Gili Air.

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