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Groundwater mapping of urban and coastal areas in Brunei

Hakimmi Abidin[1], Siti Lieyana Azffri*[1], Emelia Nirus[1], Asri Suhip[2], Afiq Aiman Jaya[2], Stefan Herwig Gödeke[1]

[1] Universiti Brunei Darussalam, Geoscience Programme, Faculty of Science, Jalan Tungku Link, Gadong, BE1410, Bandar Seri Begawan, Brunei Darussalam

[2] Ministry of Development, Public Works Department, Geological and Geotechnical Section, Jalan Lapangan Terbang Lama, Berakas, BB3510, Bandar Seri Begawan, Brunei Darussalam

* Corresponding author

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Abstract: Groundwater mapping plays an important role in effective water resource management, sustainable development, and environmental protection. In the tropical Brunei Darussalam (north Borneo Island), groundwater mapping is yet to be provided. The aim of the study is to provide groundwater mapping of Brunei, particularly for the urban and coastal areas of the Brunei-Muara capital district. The study uses a GIS interpolation technique to generate a groundwater contour map based on groundwater data from 572 sacrificial boreholes located in the study area. Remote sensing data and published maps from secondary sources were digitised in ArcGIS software to produce thematic layers for further hydrological evaluations. Results showed that groundwater levels in the study area are generally high and shallow, ranging from 0 to 18 m below ground level with a mean value of 2.9 m. According to the evaluation of geo-thematic layers and groundwater contours, groundwater flows towards the South China Sea in the coastal areas and towards the Brunei River further inland. Hydraulic gradients towards the South China Sea also vary between 0.004 and 0.08. Thus, assuming surface aquifer thickness in the weathered zone between 10 to 20 m, hydraulic conductivities ranges from $1 \cdot 10^{-5}$ to $1 \cdot 10^{-4}$ m·s^{-1}, a submarine groundwater discharge (SGD) flux between $4.7 \cdot 10^{-7}$ to $4.0 \cdot 10^{-4}$ m^3·s^{-1} per unit width can be estimated for the shallow aquifer. This study provides valuable insights into the groundwater system dynamics so important, which are critical for its future utilisation and protection, aiming to contribute to the national water security in Brunei Darussalam.

Keywords: Brunei, groundwater contour map, groundwater depths, groundwater flow paths, submarine groundwater discharge (*SGD*)

INTRODUCTION

Groundwater is the largest accessible freshwater source on Earth. Millions of people rely on groundwater wells and springs for their daily water needs, particularly in arid and semi-arid regions (Priyan, 2021). Moreover, groundwater is important for industrial processes and irrigation, contributing to food security, economic growth, and development (Giordano and Villholth (eds.), 2007). Furthermore, it is critical in sustaining various wetland ecosystems (Barthel, Rojanschi and Wolf, 2016).

Despite its significance, about a third of the main groundwater reserves worldwide are under constant stress from overexploitation (Nas and Berktay, 2010). Groundwater exploitation, often driven by increasing water demands, has led to the depletion of aquifers in many parts of the world. Declining water levels, land subsidence, and compromised water quality are the consequence of excessive pumping (Llamas and Martinez-Santos, 2005; Dalin *et al.*, 2017). Pollutants from domestic, industrial and agricultural run-offs can infiltrate the subsurface and contaminate aquifers, rendering the groundwater unfit for consumption or other purposes (Wachter *et al.*, 2004; Jia *et al.*, 2020). In addition, the impacts of climate change, including altered precipitation patterns, increased evaporation, and rising temperatures, can disrupt the recharge and availability of groundwater (Green *et al.*, 2011). Therefore, it is important to implement effective management strategies and establish robust monitoring networks to ensure the water security for future generations (Morris *et al.*, 2003).

Regional mapping, such as groundwater mapping, has become increasingly popular over the last five decades, supported by the availability of geospatial data and the use of powerful software such as Geographic Information Systems (GIS) (Jha *et al.*, 2007). GIS is based on the concept of organising information into discrete layers connected by georeferencing in a geographic space (Harder and Brown, 2017). The layers can then be used by geologists or engineers for visualising, analysing, and interpreting geographic data (Johnston *et al.*, 2001; Scot and Janikas, 2010). GIS has also been widely applied for groundwater mapping. A groundwater map provides information on the groundwater system dynamic. It is a useful tool to analyse how groundwater responds to stress from human activities and evaluate processes of groundwater recharge and discharge (Lee *et al.*, 2020). The use of groundwater maps has been particularly important for geological, geotechnical, and environmental investigations. Studies have documented the use of GIS and groundwater mapping to determine groundwater potential zones for domestic, industrial, and agricultural purposes (Etikala *et al.*, 2019; Allafta, Opp and Patra, 2021). Others used GIS to identify zones of contamination from anthropogenic activities (Machiwal, Cloutier and Güler, 2018; Hasan *et al.*, 2019). In general, groundwater mapping improves our understanding of groundwater systems, supporting informed decision-making (Manos *et al.*, 2010).

In tropical Brunei Darussalam, water is primarily supplied from surface water sources (about 99.5%) (FAO, 2011). Furthermore, in the country, the use of groundwater for drinking is limited. Surface water in Brunei is also easily accessible, cheap, and its use is largely subsidised by the government. However, the increasing population and rapid urbanisation are putting increasing stress to the water resource in the country (Suhip *et al.*, 2020). As a result, groundwater use has been subject to research and attracted much attention, particularly in rural and water-scarce areas (Azffri *et al.*, 2022; Azffri, Ibrahim and Gödeke, 2022). Moreover, the study of water quality using geochemical indicators has been limited (Azhar *et al.*, 2019; Gödeke *et al.*, 2020; Azffri *et al.*, 2023). Recent studies have found that the groundwater level in Brunei is generally shallow, up to 20 m below ground level (Azffri, Ibrahim and Gödeke, 2022), and a predicted mean annual recharge rate is 800 mm·y^{-1} (Moeck *et al.*, 2020).

Additionally, the groundwater level in Brunei Darussalam have been assessed by the Public Works Department during urban planning and geotechnical investigations. However, this information has not been part of groundwater mapping. Therefore, this study aims to provide groundwater mapping for the growing urban and coastal areas of the Brunei-Muara capital district, Brunei Darussalam, for hydrological purposes. A groundwater contour map will be generated using the GIS interpolation technique and selected data in ArcGIS software. Remote sensing data, including the digital elevation model (DEM) and aerial photographs, as well as published geology and land cover maps will be used as thematic layers. The groundwater depths, elevations, hydraulic gradient and flow paths will be evaluated and discussed.

STUDY MATERIALS AND METHODS

DESCRIPTION OF STUDY AREA

Brunei Darussalam is a country located on the northern coast of the Borneo Island, Southeast Asia, occupying a total land area of 5,765 km^2 (Fig. 1a) (FAO, 2011). Brunei has four districts. Brunei-Muara, Tutong, and Belait districts are located in the eastern enclave, and the Temburong district makes up the western enclave. The landscape of Brunei is diverse comprising dense rainforests, coastal plains, and hilly terrains. Major rivers, such as the Brunei River and the Tutong River, flow across the country, providing a source of freshwater and serving as important transportation routes (Chuan, 1992). Brunei experiences a tropical climate with high humidity and temperatures that remain relatively constant throughout the year (Hasan, Ratnayake and Shams, 2015). The country is subject to monsoon seasons, with the northeast monsoon bringing heavy rainfall from December to March, while the southwest monsoon brings drier conditions from June to October (BDMD, 2023).

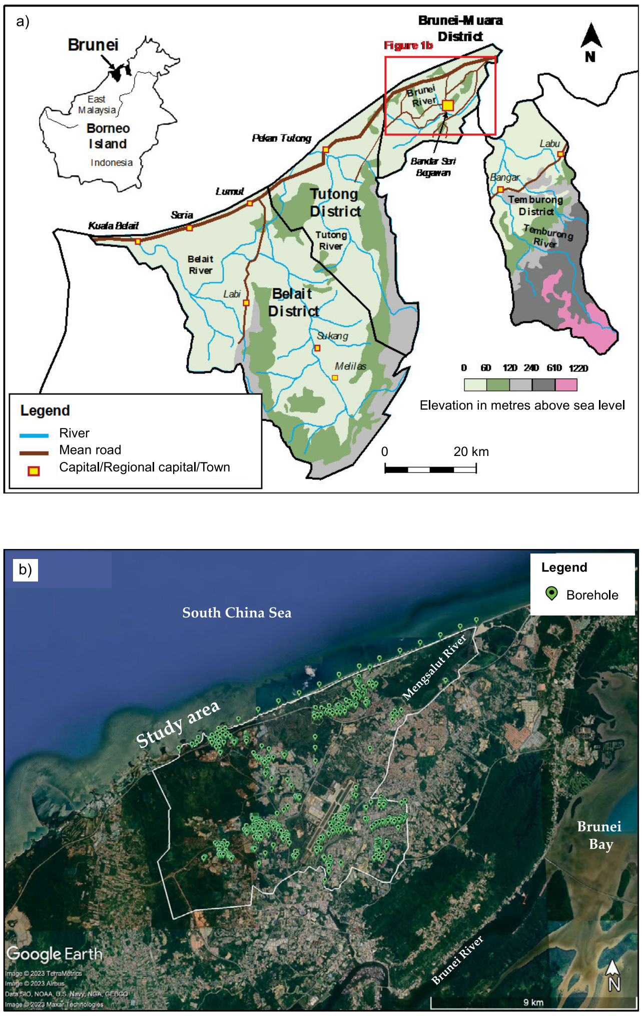

Fig. 1. Study location: a) simplified topographic map of Brunei (inset map (top left) is showing the location of Brunei on Borneo Island); source: Sandal (ed.) (1996), modified; b) map of Brunei-Muara District showing area built-up and location of boreholes in the study area; source: own elaboration based on Google Earth

The study area of 94.3 km^2 (Fig. 1b) is located near the coast in the Brunei-Muara district. As regards demography, the Brunei-Muara is the most populous district of Brunei, with a total population of 289,630 people (2016), which is over 75% of the total country's population (JPKE, 2016). The capital city, Bandar Seri Begawan, is also located near the coast and it is the administrative, cultural, and economic centre of the country (Ng, Shabrina and Buyuklieva, 2022).

Geologically, Brunei is closely tied to the island of Borneo and its geological history spanning millions of years (Sandal (ed.), 1996). From a geological point of view, it consists mainly of sedimentary rock from the Cenozoic era (Fig. 2b). Rock units are divided into the Liang, Seria, Miri, Belait and Setap formations. Their lithologies include sand, shale and coal, which are widespread throughout the country. These rocks were formed by sediment deposition in ancient seas, deltas, and rivers. The geology of the study area is shown in Figure 2.

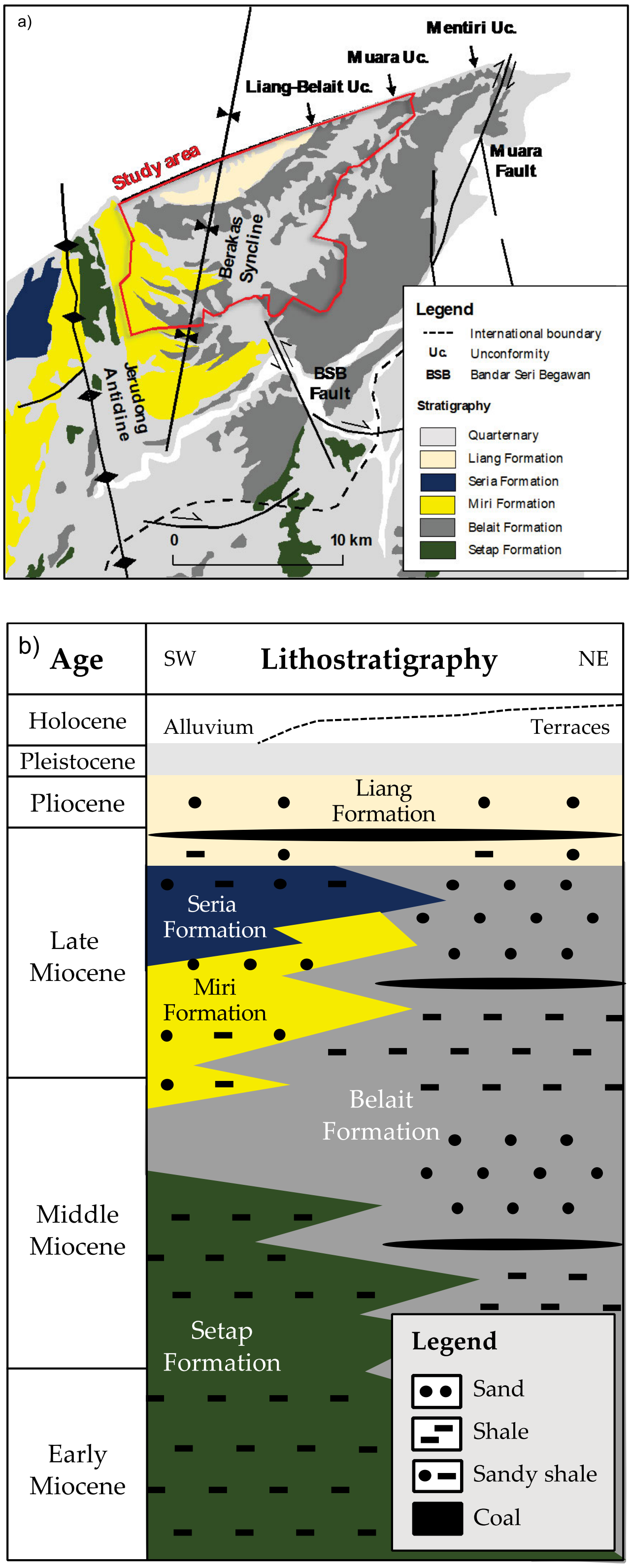

Fig. 2. Geology of the study area: a) simplified geological map of the Brunei-Muara region; source: Morley (2003), modified; b) chrono-lithostratigraphic scheme of onshore Brunei; source: Azffri *et al.* (2023), modified

GIS SOFTWARE

The study used ArcGIS software version 10.7.1 (ESRI, California, USA). ArcGIS is one of the most frequently used GIS software for handling, analysing, and visualising geographical information (Harder and Brown, 2017). The software provides a robust set of tools and functionalities enabling users to work with various types of spatial data, including maps, satellite imagery, aerial photography, and geospatial databases (Johnston *et al.*, 2001; Scott and Janikas, 2010). The methodology proposed for this study involves three main steps: (1) collection of geospatial data, (2) processing and analysing data in ArcGIS, and (3) hydrological evaluations (Fig. 3).

DATA COLLECTION

Borehole and remote sensing datasets used in this study were obtained from the Public Works Department of Brunei Darussalam in the CSV file format (borehole data) and LAS file format (remote sensing data), and displayed in ArcGIS software. A total of 572 sacrificial boreholes made in the study area were used (borehole locations shown in Fig. 1b). The boreholes were commissioned in 1984–2014 for geotechnical investigation of the study area. The boreholes were drilled using a rotary wash boring to maximum depths of up to 30 m below ground level. Borehole data collected for this study include geographical coordinates, surface elevations, and depths to groundwater. Remote sensing (light detection and ranging – LIDAR) data were taken in the study area in 2009, including digital elevation model (DEM) and aerial photographs. Topographic data were presented as 1 km × 1 km tiles. The study used a total of 94 aerial photographs of the area. In addition, published maps include the geology map of Brunei (Sandal (ed.), 1996) and land cover map of Brunei-Muara district (Ng, Shabrina and Buyuklieva, 2022).

DATA ANALYSIS

Statistical analysis

Borehole data were subject to statistical analysis, results of which are given in Table 1. The parameters examined include groundwater level, surface elevation, and calculated groundwater elevation. Their values are minimum, maximum, mean, median, mode, standard deviation and standard error (Tab. 1). Groundwater elevation was calculated by subtracting the surface elevation from depth to groundwater.

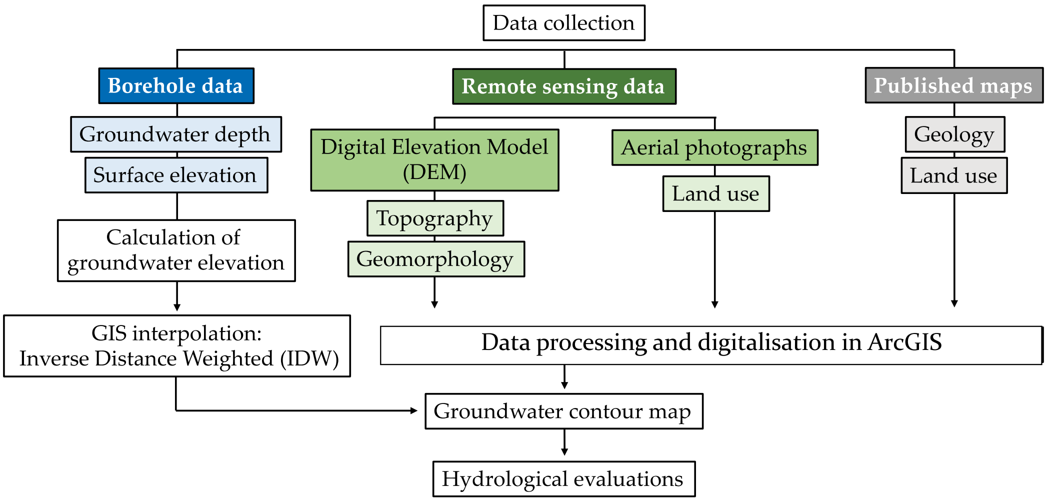

Fig. 3. Methodology used in this study; source: own elaboration

Table 1. Borehole parameters (depth to groundwater and surface elevation) and calculated groundwater elevations in the study area

Statistics	Depth to groundwater (m b.g.l.)	Surface elevation (m a.s.l.)	Groundwater elevation (m a.s.l.)
Minimum	0.0	0.4	–5.1
Maximum	18.0	95.0	94.7
Mean	2.9	22.5	19.6
Median	2.3	18.5	15.5
Mode	3.0	9.8	9.1
Standard deviation	2.2	16.6	15.8
Standard error	0.09	0.69	0.66

Explanations: m b.g.l. = meters below ground level, m a.s.l. = meters above sea level.
Source: own elaboration.

Inverse distance weighted interpolation

The inverse distance weighted interpolation (IDW) interpolation represents a deterministic approach that helps to generate surfaces from observed points (Johnston *et al.*, 2001). It implies that each measured point has a local influence that reduces with distance. It offers higher weights to points that are closest to the predicted location, and the weights decrease as distance increases. Therefore, in a data-sparse region, the IDW interpolation method is preferred to a statistical interpolation method which requires consistent data sets (Mukherjee, Singh and Mukherjee, 2012). The general formula of IDW interpolation was calculated as follows (Johnston *et al.*, 2001):

$$\hat{Z}(S_0) = \sum_{i=0}^{N} \lambda_i Z(S_i) \qquad (1)$$

where: S_0 = unknown location whose predicted value is $\hat{Z}(S_0)$, N = total number of measured data points, λ_i = weights assigned to each measured location, $Z(S_i)$ = observed value at the point S_i.

A cross-validation of this method was performed with Surfer version 22 for groundwater elevations. Results had a mean error of 0.75 m and showed that the IDW interpolation method was the preferred contouring method compared to kriging, nearest neighbour, natural neighbour and local polynomial for this case (Fig. 4).

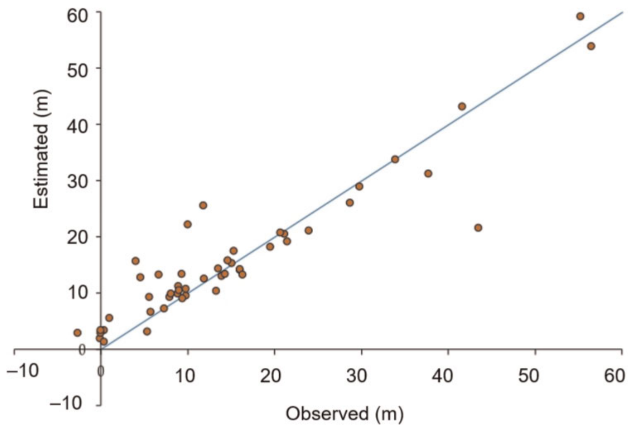

Fig. 4. Computed versus observed depth to groundwater using IDW interpolation for a random 50 datapoints; source: own study

A groundwater contour map of the study area was generated using the IDW interpolation method. Borehole data containing groundwater level information from all boreholes were used for the interpolation. In order to better constrain the interpolation, additional “artificial” boreholes with a groundwater elevation of 0 m a.s.l. were used at the land-sea interface, where it is known whether groundwater flows to the South China Sea (Morris *et al.*, 2003). The generated groundwater contour map shows groundwater elevations expressed in meters above sea level. A contour spatial analyst tool was used to generate the contours, with contour spacing of 3 m. The Polynomial Approximation with Exponential Kernel (PAEK) smoothing algorithm helped improve the cartographic quality of contour lines.

Thematic layers

Groundwater occurrences and movement are the functions of geological, geomorphic and hydrological parameters (Achu, Thomas and Reghanuth, 2020; Fauzia *et al.*, 2021). Hence, each parameter is crucial for understanding the groundwater system dynamics. In the present study, digitised maps and aerial photographs were imported and organised by layers in ArcGIS. Each layer was georeferenced so when stacked on top of each other, the software aligns them correctly to form a complex data map (Johnston *et al.*, 2001; Scott and Janikas, 2010). This study uses the World Geodetic System 1984 (WGS-1984) as the reference coordinate system.

HYDROLOGICAL EVALUATIONS

The understanding of the recharge, storage and flow of groundwater are crucial for a complete evaluation of a groundwater system (Fetter, 2001). In the present study, hydrological features and factors, such as geology, geomorphology and land cover variations, were evaluated and discussed. Groundwater flow paths were determined from high to low groundwater elevations, assuming homogenous isotropic conditions.

RESULTS AND DISCUSSION

DEPTH TO GROUNDWATER

Groundwater levels were observed in 572 sacrificial boreholes in the study area. The depths to groundwater are considered high and shallow, ranging from 0 to 18 m b.g.l., with a mean value of 2.9 m b.g.l. (Tab. 1). The area's surface elevation ranged from 0.4 to 95 m a.s.l., with a mean value of 22.5 m a.s.l. Therefore, the calculated groundwater elevations in the study area ranged from −5.7 to 94.7 m a.s.l, with a mean value of 19.6 m a.s.l. (Tab. 1). The groundwater elevation contour map of the study area is presented in Figure 5.

GROUNDWATER OCCURRENCES, HYDRAULIC GRADIENTS AND FLOW PATHS

Geology

The study area is characterised by sedimentary rock formations ranging from Middle Miocene to recent age (Fig. 2 and Sandal (ed.), 1996). Lithologically, the central portion of the study area is mainly interbedded sandstones and clays of the Belait Formation, which are partly fluvial and shallow marine in their origin. The Miri Formation dominates most of the area in the west. The lithology of Miri Formation is similar to that of the Belait Formation. The coastal portion of the study area is dominated by sands with occasional clays and conglomerates of the mainly fluvial origin Liang Formation. Finally, the southern portion of the study area consists predominantly of sands, silts, and clays of the Quaternary deposits, which are mainly alluvial and fluvial in their origin.

According to Chuan (1992), groundwater sources may be found within the lightly consolidated sands, sandstones and joints of the existing rock formations. The Liang Formation, in particular, is believed to be the most prolific groundwater formation in Brunei. A recent study by Osli, Shalaby and Islam

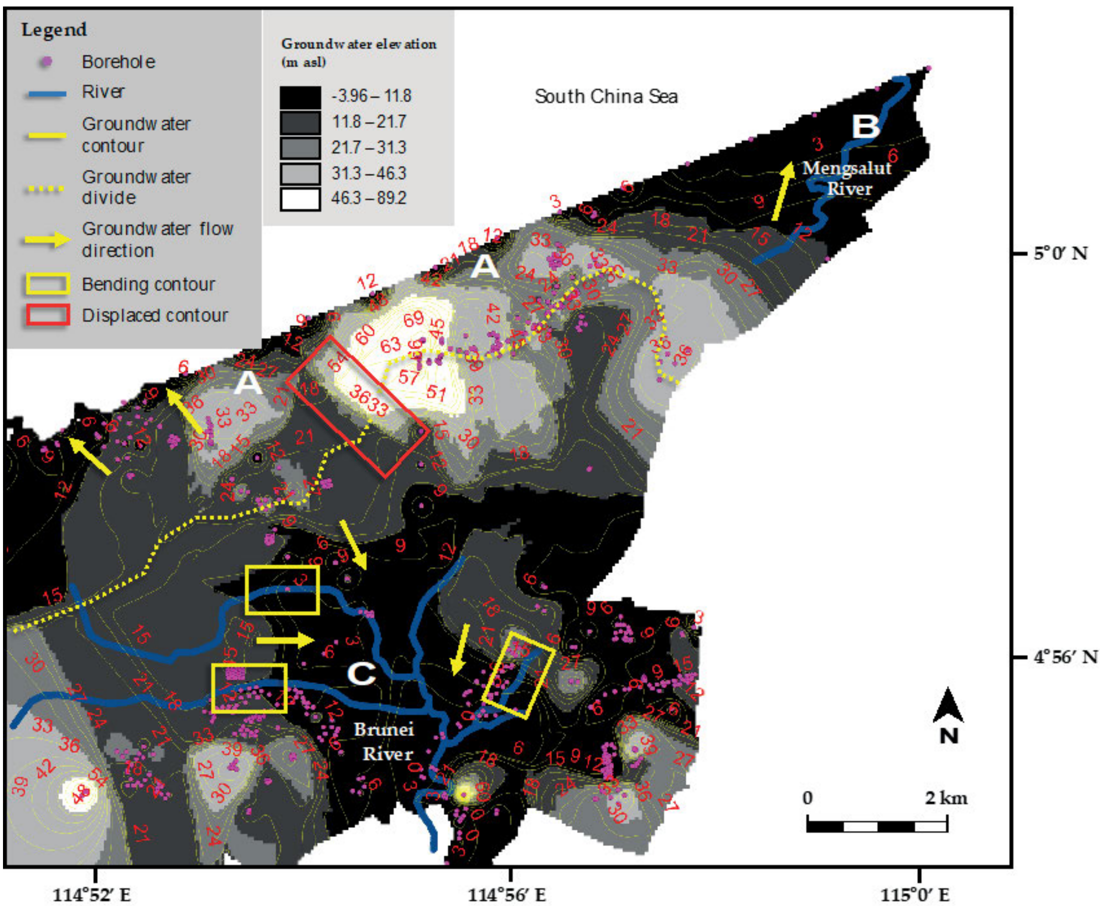

Fig. 5. Groundwater contour map of the study area generated using ArcGIS software; hydrological evaluations are described in this study; source: own study

(2021), showed that the porosity and permeability of sands and sandstones of the Belait and Miri formations were found to reach values of 26.5% and $4.76e^{-12}$ m^2, respectively, suggesting good aquifer potential. Furthermore, floodplain deposits are generally considered to have a high infiltration rate due to the presence of sand and gravel (Suganthi, Elango and Subramanian, 2013).

Structurally, the study area is part of the Berakas syncline, formed during the Middle Miocene to Pliocene period (Fig. 2a). According to Morley *et al.* (2003), three N–S trending structures affect the structural development of this syncline: (1) the Jerudong anticline, (2) the Bandar Seri Begawan (BSB) fault and (3) the Muara fault (Fig. 2a). Folding structures caused the Berakas syncline to display a thinning section towards the Jerudong anticline, while the BSB and Muara faults caused horizontal fractures and discontinuity as well as alter the flow of the Brunei River. Additionally, several unconformities have been identified in the Berakas syncline known as the Liang-Belait, Muara and Mentiri unconformities.

This study has shown the structural complexity of the area as reflected in the groundwater contour map (Fig. 5). In the north-western side of the study area (Fig. 5, red box), the groundwater elevation contour lines appear displaced, showing a clear boundary between high and low groundwater elevations. Based on the geological understanding of the study area, this can be caused by faulting, unconformity or a low permeability unit. Low permeability units are known to cause steep hydraulic gradients and alter fluid flow (Gharbi *et al.*, 2014). Groundwater elevation of the study area also show an increasing trend towards the southwest, which corresponds to the hilly terrains found in the area believed to be part of the Jerudong anticline.

Geomorphology

The present geomorphology of Brunei Darussalam is believed to be the result of a major regression of the sea-level some 5,000 to 6,000 years ago (Bac-Bronowicz and Becek, 2014). The hydro-geomorphological features of the study area have been identified using aerial photographs and topographic maps. Features such as coastal plain, valley fill, and hilly terrains are common near the coast (Fig. 5, areas labelled A). Delta floodplains prevail in the eastern and southern portions of the study area (Fig. 5, area labelled B and C, respectively) with the Mengsalut River identified in the east and the Brunei River in the south.

In the study area, important groundwater flow paths have been identified and these are separated by a groundwater divide (Fig. 5, yellow dotted line). The groundwater elevation above this divide (Fig. 5; areas labelled A) shows a decreasing trend towards the coast, suggesting groundwater movement into the South China Sea. Furthermore, the Mengsalut River provides the main drainage path for ground and surface water into the South China Sea in the eastern portion of the study area. Moreover, the hydraulic gradients towards the South China Sea vary between 0.004 to 0.08. Thus, assuming an aquifer thickness of 10 to 20 m within the weathered zone, and hydraulic conductivities of $1{\cdot}10^{-5}$ to $1{\cdot}10^{-4}$ $m{\cdot}s^{-1}$ (Azffri, Ibrahim and Gödeke, 2022), one can estimate a submarine groundwater discharge (SGD) flux of $4.7{\cdot}10^{-7}$ to $4.0{\cdot}10^{-4}$ $m^3{\cdot}s^{-1}$ per unit width. However, further studies in this regard are needed to confirm these estimates.

The groundwater elevations below the groundwater divide (Fig. 5, area labelled C) have showed decreasing trends towards the south. In this area, the Brunei River provides the main drainage path for ground and surface water into the Brunei Bay (Fig. 1b). Furthermore, the groundwater elevation map of the study area shows bending contour lines along the Brunei River (Fig. 5, yellow boxes), suggesting that it is a gaining river.

Land use / land cover

Identifying land use and land cover patterns is necessary for understanding infiltration and runoff, which are controlled by the nature of surface materials. In the last two decades, urban development in the Brunei capitol district has grown rapidly (Ng, Shabrina and Buyuklieva, 2022). In particular, the study area shows the highest record of urban growth in the country (Fig. 1b). Urban developments include the construction of houses, buildings and roads, which limits the infiltration of rainwater into the ground, thus, reducing potential groundwater recharge. Additionally, the increased runoff from residential, and industrial and agricultural sites can carry pollutants, such as litter, industrial chemicals, fertilisers, and pesticides into nearby surface water bodies. This can indirectly affect groundwater quality (Abdul Aziz, 2005). It was reported that one of the primary sources of pollution of the Brunei River is industrial and domestic wastewater discharge (Kamis *et al.*, 2021; Onifade *et al.*, 2023). If not controlled, the water quality of the Brunei River is likely to further deteriorate with significant increase in population and economic growth.

GROUNDWATER MONITORING FOR SUSTAINABLE WATER RESOURCE MANAGEMENT

Groundwater monitoring is crucial to understanding the availability, sustainability, and health of groundwater resources (Hong *et al.*, 2021). Groundwater monitoring is also fundamental to manage water resources effectively, making informed decisions about water use, and protecting ecosystems that rely on groundwater (Jha *et al.*, 2007). Understanding the fluctuations in groundwater levels over time is useful to identify trends, such as declining levels or seasonal variations (Taylor and Alley, 2001). Authorities could use this information to assess rate of replenishment, identify areas of high recharge, and evaluate the impact of land use practices (Razavi-Termeh, Sadeghi-Niaraki and Choi, 2019). Thus, it is necessary to implement water use restrictions in areas at risk of water degradation.

Regular groundwater monitoring is recommended in Brunei Darussalam for sustainable water resource management. Although groundwater in Brunei is still underexplored and the exploitation of this resource is limited to potable water (FAO, 2011), the impact of overexploitation of this resource is still unknown. Studies found that poor soil compaction and a high groundwater table are the main causes of housing structure failure in Brunei (Ang and Masri, 2019). Therefore, groundwater monitoring and mapping should be carried out in other parts of the country as it will help to identify viable grounds for future urban development. Furthermore, as Rentier *et al.* (2006) noted, the density of groundwater monitoring points should be one monitoring point per 25 km^2 if the groundwater body is perceived to be under stress or otherwise one monitoring point every 100 km^2. Thus, the investigated area in this study should have at least four permanently installed groundwater monitoring wells.

Recent studies have showed that Brunei's water resource is under constant stress and, to some extent, deteriorated by natural and human factors (Azhar *et al.*, 2019; Azffri *et al.*, 2023). The results from sampling and analysis of natural spring waters near the coast (Fig. 5, area A) within the study area were documented in Azhar *et al.* (2019). They showed that the prevalent type is fresh water based on the low sodium-chloride content. Further inland (Fig. 5, area C), the groundwater sample showed a type IV water class, or the calcium-, magnesium-, and bicarbonate-type (Azffri *et al*., 2023). The water was found to be safe for use based on the FAO standard. However, in both studies, the acidic nature of the waters (pH < 4.8) has been reported, which further suggests that treatment of the waters is required before use. It is believed that the groundwater is affected by acid-sulphate soils found in the study area (Grealish and Fitzpatrick, 2013). Furthermore, iron is the most frequently present heavy metal in the Bruneian waters (Abdul Aziz, 2005). Therefore, future studies should include regular water quality monitoring, especially in the growing capital districts.

According to Moeck *et al.* (2020), precipitation rates and seasonality in temperature and precipitation were found to be the major factors in predicting changes in groundwater level and recharge. Therefore, future studies should also try to distinguish groundwater levels between dry and wet seasons, which are expected to differ by around 1 m (Putra *et al*., 2018). The strong reliance of groundwater level and recharge on climate further suggests its vulnerability to predicted climate change.

It was noted that, the groundwater level data used in this study were gathered from borehole investigations conducted in 1984–2014. This might have an effect on bending and displaced groundwater contours. However, we believe that by noting the existing knowledge gaps, we can encourage the hydrogeological community to undertake new research on groundwater mapping in Brunei in order to advance our understanding. Simultaneously, it will provide new public groundwater data available for future use and management.

Sustainable water resource management in Brunei Darussalam requires a comprehensive and integrated approach involving government agencies, industries, institutions and communities (Shams and Napiah, 2019). Moreover, the growing interest for groundwater use from industry and agriculture suggests that a groundwater department should be established in the local government to play a crucial role in developing and implementing regulations, policies, and guidelines for the protection of this precious resource. Coupled with the adoption of advanced water treatment technologies, conservation measures, and exploring alternative sources like desalination and wastewater reuse, these efforts will enhance the resilience and sustainability of water resources in the country.

CONCLUSIONS

Groundwater mapping in Brunei Darussalam is new and has never been conducted before. This study generated a groundwater contour map using groundwater data and GIS interpolation to investigate groundwater levels and flow directions in the urban and coastal areas of the Brunei-Muara District, Brunei Darussalam. Our findings revealed shallow groundwater depths, ranging from 0 to 18 m b.g.l., with a mean value of 2.9 m b.g.l. The groundwater elevations in this study varied from −5.7 to 94.7 m a.s.l., with a mean value of 19.6 m a.s.l. The assessment of geo-thematic layers and groundwater elevations revealed groundwater presence and flow paths enhancing our understanding of the groundwater system dynamics in the study area. In the coastal areas, groundwater flows towards the South China Sea, while the Brunei River provides the main flow path further inland. Future studies should include groundwater mapping and regular monitoring of groundwater levels in other areas of the country, especially in the growing capital districts, to ensure the sustainability of water resources. This work provides the foundation for a hydrogeology map of Brunei which may facilitate future decision-making related to groundwater exploration, land-use planning, and environmental impact assessment.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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