Hydrogeochemical Investigation and Estimation of Aquifer Properties at Dhaka University Campus

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ABSTRACT: The University of Dhaka has its own water supply system and entirely relies on groundwater. Ten groundwater samples were collected from 10 production wells of 120-320 m depth across the University campus from upper and lower Dupi Tila aquifers. The pH values revealed that water is mildly acidic to neutral and electrical conductivity (EC) values ranging from 325 to 654 µS/cm, indicating fresh groundwater. The total hardness (TH) of the samples ranges from 76-203 mg/L, suggesting moderately hard to very hard water. Of the ten groundwater samples, nine are of Ca-Mg-HCO_3 type, whereas one shows Ca-Na-HCO_3 type of groundwater. The saturation indices show that the groundwater samples are near-saturated for calcite, dolomite, gypsum, siderite, and rhodochrosite, indicating the low potential for dissolution-precipitation of these mineral. Notably, the results of WQI indicate that all the wells are safe for drinking. As of July 2023, the groundwater level was 72 m below ground level with a declination rate of 2.8 m/year. The estimated hydraulic conductivity values of 20 to 90 m/day and transmissivity values of 637 to 2740 m²/day suggest better permeability and water transmission potential within the lower aquifer. These results provide essential information for the university authority to implement appropriate strategies for efficient groundwater management.

Keywords: Groundwater; Major Ions; Water Quality; Hydraulic Conductivity; Transmissivity

INTRODUCTION

Dhaka University represents the highest echelon of academic excellence and operates its independent water supply system. Like other areas of Dhaka, the university relies entirely on groundwater, sourcing 11.4 million litres of water daily from 10 deep tube wells. The water supply management system of Dhaka University is far better than that of DWASA (Dhaka Water Supply and Sewage Authority) (Afroz, 2010). The primary objective of analyzing water quality is to confirm its safety for consumption. Also, it aids in identifying potential issues or deterioration in water quality that may cause adverse health or environmental impacts. A thread of literature on the groundwater quality of Dhaka city is available (Ahmed et al., 1998; Ahmed et al., 2004; DWASA, 2006; Hoque et al., 2007; Burgess et al., 2011; Islam et al., 2017). Unfortunately, there is no record of any thorough investigation into the water quality, availability, and management system of the Dhaka University campus. Only a few fragmented research efforts have been carried out in the Dhaka University area (Sharif, 1996; Nahar, 2009; Afroz, 2010). Characterization of aquifer condition and hydraulic conductivity (K) estimation was carried out at the campus (Nahar, 2009). The results of an investigation on the microbiological quality of groundwater at the site of abstraction in the southern part of Dhaka city by Khan et al. (2004), which included some water samples from the university campus, show that pathogens contaminate the samples (total coliform 10 to 130 cfu per 100ml and total bacteria 2600 to 45000 cfu/100ml) and felt to be outside the acceptable limit of the WHO. However, the water quality met the WHO and DoE potable water permissible limits (Nahar, 2009). An investigation on the assessment of the water quality and supply management system of the Dhaka University Campus was conducted (Afroz, 2010). However, the study was confined to water quality issues, specifically physicochemical parameters. Since then, the hydrogeochemistry of the groundwater of this campus has not been studied, and no estimation has been done on aquifer properties.

To address these gaps, this research aimed to understand the hydrochemical characteristics of groundwater and geochemical behavior, assess the water quality, and estimate the key aquifer properties, i.e., hydraulic conductivity (K) and transmissivity (T) of this campus. To achieve these, a two-fold approach has been

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adopted in this study – encompassing the analysis of hydrochemical parameters of groundwater samples and grain size analysis of the aquifer sediment samples for the estimation of K and T.

Study Area

The study area is in the southwestern part of Dhaka city and lies between 23º47.5´N to 23º42´N latitude and 90º21´E to 90º25´E longitude (Fig. 1). The campus area falls within the jurisdiction of Shahbagh Thana in the Dhaka metropolitan area. It is characterized by relatively small and predominantly plain land with minimal geomorphic attributes. Within this landscape, several large ponds, such as Shahidullah Hall Pond, Jagannath Hall Pond, and the Faculty of Fine Arts Pond, have been artificially excavated and are hydrogeological significant for recharging the upper aquifer system. The long-term total annual rainfall recorded in Dhaka city is in access of 2000 mm (Ahmed et al., 2010). It is supposed to be recharging the upper aquifer beneath the campus through the ponds and green area, and it has never experienced floods as it is situated on high land.

Geology and Hydrogeology

The study area is located on the western fringe of Madhupur Tract, a Pleistocene uplifted block (Miah and Bazlee, 1968). In major parts of Dhaka city, beneath a thin layer of soil, the Madhupur clay formation of the Pleistocene age, which is composed of fine sand, silt, and clay, irregularly overlies the Dupi Tila formation of the Plio-Pleistocene age, that mainly comprises of sandstone and claystone. Table 1 presents the stratigraphy of the Madhupur tract area in Dhaka city (Hoque, 2004), as Dhaka University falls within this area. The main aquifer beneath the Madhupur Tract is the Dupi Tila Formation, which acts as a multilayer leaky aquifer system, effectively restricted by the Madhupur Clay Formation. Four aquifers and four aquitards have been encountered in Dhaka. Among the aquifers, the first and the second are

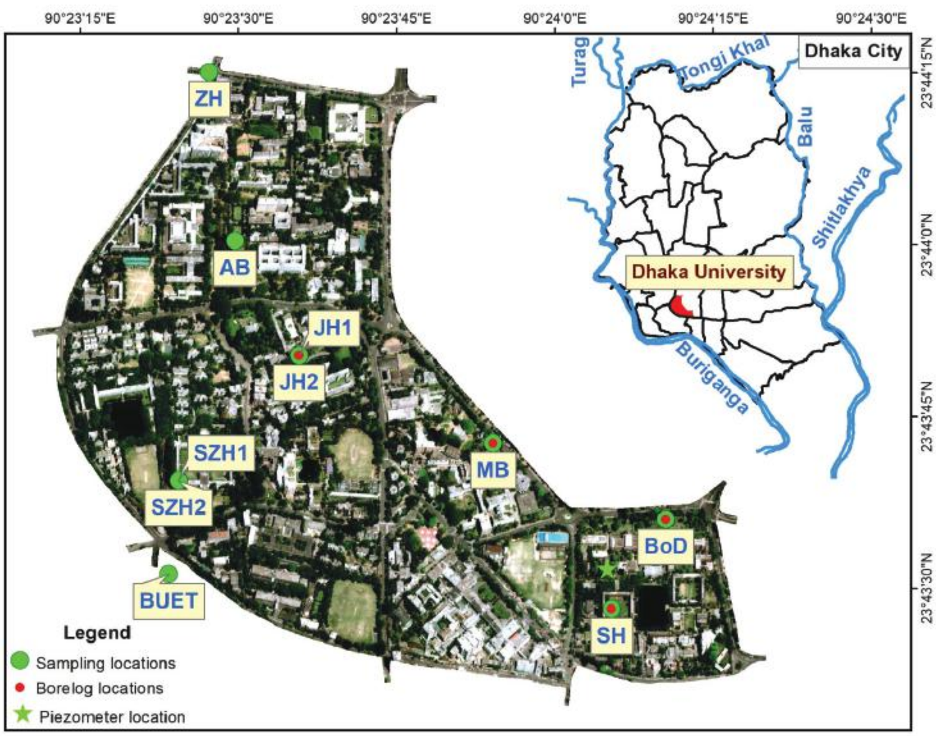

Figure 1: The Locations of Groundwater Sampling along with Borelog Locations Across the Dhaka University Campus, and the Inset Map Showing the Location of the University in Dhaka City

Table 1: Stratigraphy of Madhupur Tract Area in Dhaka City. (after Hoque, 2004)

Stratigraphic age	Stratigraphic Name	Lithology	Thickness (m)	Function in Aquifer system
Recent	Low land alluvium	Swamp, Levee and Riverbed sediments	0-5	Upper aquitard
Holocene	Bashabo Formation	Sand (discontinuous)	3-25	Aquifer
Pleistocene	Madhupur Clay Formation	Silty Clay Member, Fluvio-delaic sands.	6-25	Upper aquitard
Plio-Pleiestocene	Dupi Tila Formation	Dupi Tila Clay stones Fluvio-deltaic sands	100-180	Potential Aquifer
Miocene	Girujan Clay	Bluish Clay	50-100	Known lower aquitard

from the Upper Dupi Tila formation, and the third and fourth are from the Lower (deep) Dupi Tila formation (Sultana, 2009). The aquifer is highly productive, with an average transmissivity of 1850 m^2/day, indicating substantial transmission capacity (Morris et al., 2003). Findings from a long-term aquifer test on the Lower Dupi Tila aquifer suggest that the Storativity (S) is 0.00239, and the hydraulic conductivity (K) is 27.09 m/day (Hossain et al., 2007). Various aquifer tests and bore log data indicate that these aquifers are hydraulically connected (Hoque, 2004). Due to intensive abstraction from the deeper aquifer, the groundwater level is declining rapidly, with the highest decline rate of 5.74 m/year in the south-central part of the city (Islam et al., 2021). A cone of depression has developed in the deep aquifer in the center of the city, with a maximum groundwater level of 64 m below, while in the campus area, it ranges from 40 to 50 m below the ground level (Moshfika et al., 2022). The groundwater quality in this area is more likely to deteriorate due to induced recharge from a polluted segment of the Buriganga River and recharge from contaminated urban areas (Hoque et al., 2014). However, until now, groundwater quality is good and arsenic-free (Charles et al., 2021).

MATERIALS AND METHODS

Secondary Data Collection

Groundwater level data of one-hour intervals from the piezometer installed in the deep aquifer (244 m deep) at the premise of the Department of Geology were collected. These data were sourced from the Bangladesh Water Development Board (BWDB), and an Excel spreadsheet was used to construct a groundwater-level hydrograph. Bore log data were collected from the Dhaka University Engineering Department. The collected data produced a visual illustration for interpreting aquifer sediment.

Groundwater Sample Collection and Laboratory Analysis

A total of ten groundwater samples were collected from ten individual production wells of 120 m -320 m depth distributed in the study area following the standard water sampling protocol (Rainwater and Thatcher, 1960). This sampling was conducted in two phases: eight samples were obtained in September 2022, one (BUET) in January 2023, and the final sample was collected in June 2023 from the newly operational deep tubewell (BoD) that began production a few days before sampling (Fig. 1).

Groundwater samples were collected in 100 mL plastic bottles and rinsed with groundwater beforehand. A 0.45 μm membrane filter was used to filter out the suspended particles. An acidified (with concentrated HNO_3^-) and a non-acidified sample were collected separately from each well and labeled correctly. The samples were then brought to the Geochemistry Laboratory of the Department of Geology, University of Dhaka, for chemical analyses and were preserved at a controlled temperature.

Different on-site water parameters, including EC, pH, Eh, and Temperature, were measured using a pocket EC meter (HANNA, model DIST HI 198300/4) and pH meter (HANNA. model HI 98127)``. In the geochemistry laboratory, the acidified water samples were analyzed for cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Mn^{2+}) using an Atomic Absorption Spectrometer (GBC Australia, model-SavantAA∑) and anions (Cl^-, SO_4^{2-}, NO_3^-, NO_2^-, F^-, Br^-, PO_4^{3-}) using Ion Chromatography (US, model-DIONEX ICS 1100). The non-acidified water samples were analyzed for HCO_3^- ion using the titration method with the aid of sulfuric acid. It should be noted that trace ion arsenic (As) was neither tested in the field site nor the lab since previous studies have already established that the groundwater of Dhaka city abstracted from the Dupi Tila aquifer is not contaminated by arsenic (Charles et al., 2021). Total hardness (TH) in mg/L as CaCO3 was calculated from the concentrations of Ca^{2+} and Mg^{2+} in mg/L by using the following equation (1) (Todd, 1980).

$$TH = 2.5\,(Ca^{2+}) + 4.1\,(Mg^{2+}) \qquad (1)$$

The ionic balance was calculated to estimate the accuracy of chemical analysis. The ionic charge balance error (ICBE) equation was used for this purpose; concentrations of all the ions were converted from mg/L to meq/L unit.

$$ICBE\ (\%) = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} \times 100 \qquad (2)$$

The ionic balance for all ten water samples was within ±10%, usually considered an acceptable range (Domenico and Schwartz, 1990).

Geochemical Modeling

The geochemical model PHREEQC interactive 3.0 for Windows (Parkhurst and Appelo, 1999) has been used to determine the saturation indices (SIs) of the minerals - calcite, dolomite, and siderite in the analyzed water samples. The phreeqc.dat database was used during this geochemical modelling.

Water Quality Index (WQI) for Drinking

Water Quality Index (WQI) has been calculated (Table 2) by assigning weightage for each parameter (pH, TDS, TH, Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe^{2+}, Mn^{2+}, HCO_3^-, SO_4^{2-}, Cl^-, F^-, Br^-, NO_3^-, NO_2^- and PO_4^-) depending on their significance for risk to human health; e.g., a value of 5 posing a high risk to human health, 3 concerning aesthetics and moderate risk to human health, and 1 posing low risk to human health and less concerning aesthetics (Table 2) (WHO, 2017). The presence of arsenic (As) in groundwater is considered a grave water quality concern for human health (Ahmed et al., 2004), but as was not included in the calculation of WQI as it was not analyzed and evident to be absent in Dhaka groundwater (Charles et al., 2021). This evaluation did not include Total coliform count because coliform is considered zero as the sampling was carried out directly from the pumping well.

Table 2: Water Quality Parameters According to the Drinking Water Quality Guidelines (DPHE; WHO, 2017) and Their Assigned and Calculated Relative Weights Used to Evaluate WQI

Water quality parameter	**Unit**	**Standard (Si)**	**Weight (wi)**	**Relative Weight (Wi)**
NO_3^-	mg/l	10	5	0.102
NO_2^-	mg/l	< 1	5	0.102
F^-	mg/l	1	5	0.102
TDS	mg/l	1000	3	0.061
[1]TH	mg/l	200 – 500	3	0.061
[1]pH	-	6.5 – 8.5	3	0.061
SO_4^{2-}	mg/l	400	3	0.061
Cl^-	mg/l	600	3	0.061
Ca^{2+}	mg/l	75	3	0.061
Mg^{2+}	mg/l	35	3	0.061
Fe^{2+}	mg/l	1	3	0.061
Mn^{2+}	mg/l	0.1	3	0.061
Na^+	mg/l	200	3	0.061
PO_4^{3-}	mg/l	6	1	0.020
HCO_3^-	mg/l	200	1	0.020
Br^-	mg/l	6	1	0.020
K^+	mg/l	12	1	0.020
Total			**49**	**1.000**

[1]pH standard 7 and TH standard 350 mg/l were considered for this assessment.

The relative weight (Wi) and the quality rating (Qi) were calculated for each parameter using the equation (3) and (4). Then, the WQI was determined using equation (5) (Adimalla and Taloor, 2020; Baba et al., 2020; Nawrin et al., 2022).

$$Wi = \frac{wi}{\sum_{i=1}^{n} wi} \qquad (3)$$

where, Wi = Relative weight, wi = weight for each parameter, i = individual parameter, n = total number of parameters.

$$Qi = \frac{Ci}{Si} \times 100 \qquad (4)$$

where Qi = quality rating, Ci = concentration of each groundwater quality parameter, Si = water quality standard for each parameter, and i = individual parameter. The drinking water standards for Bangladesh have been considered for almost all parameters (DPHE); only for Bromide (Br^-) was the WHO standard for drinking water (WHO, 2017) applied since this parameter is not enlisted in Bangladesh Standards.

$$WQI = \sum_{i}^{n} QiWi \qquad (5)$$

where, Qi = Quality rating, Wi = Relative weight, n = total number of parameters, i = individual parameter.

Finally, the calculated WQI values were divided into five categories based on the suitability of groundwater for drinking uses, for instance: excellent (<50), good (50-100), poor (101-200), very poor (201-300) and unsuitable for drinking purpose (>300) (Adimalla and Taloor, 2020; El Baba et al., 2020; Nawrin et al., 2022).

Sediment Sample Collection

Ten sediment samples were collected from the screen depth (850-950 ft or 59.1 -289.6 m) of the well of the Botany Department (BoD) for analyzing the grain-size distribution. The sediment samples were obtained from depths ranging from 850 ft (259.1 m) to 950 ft (289.6 m) with 10 ft (3.05 m) intervals. The sediment samples were stored in clean Ziploc bags so they were not contaminated or mixed with other samples, and the bags were labeled with the appropriate information, including depth. The samples were then taken to the Sedimentary Petrology Laboratory of the Geology Department.

Grain Size Analysis

The grain size analysis aimed to estimate the proportion of each size of the grains that make up the sediment of the aquifer. A hundred grams of dried sediment samples were sieved following the standard method using phi (Φ) sieve intervals with 1, 1.5, 2, 2.5, 3, 3.5, 4, and 4.5. The result of the sieve analysis is presented in Table 3. From the grain size analysis data, a standard histogram and cumulative curve (Fig. 2) were prepared, and statistical parameters were computed based on the formulae and verbal scale proposed by Folk (1974).

Empirical Formulae for Estimation of K

Hydraulic conductivity (K) can be roughly determined by grain size analysis of samples (Cheng and Chen, 2007) using an empirical equation. Vukovic and Soro (1992) came up with a common formula after studying various empirical methods:

$$K = \frac{g}{v} \cdot C \cdot f(n) \cdot d_e^2 \qquad (6)$$

Where *g* = acceleration due to gravity, *v* = kinematic viscosity, *C* = sorting coefficient, *f(n)* = porosity function, and d_e = effective grain diameter. The kinematic viscosity (*v*) is related to dynamic viscosity (μ) and the fluid (water) density (ρ) as follows:

$$v = \frac{\mu}{\rho} \qquad (7)$$

C, f(n) values depend on the different methods used in the grain size analysis. According to Vukovic and Soro (1992), porosity (*n*) may be derived from the empirical relationship with the coefficient of grain uniformity (*U*) as follows:

$$n = 0.255\left(1 + 0.8^{U}\right) \qquad (8)$$

where *U* is the coefficient of grain uniformity and is given by:

$$U = \left(\frac{d_{60}}{d_{10}}\right) \qquad (9)$$

Here, d_{60} and d_{10} in the formula represent the grain diameter in (mm)

Former studies have presented the following formulae,

$$K = \frac{g}{v} \times 6 \times 10^{-4} \left[1 + 10\left(n - 0.26\right)\right] d_{10}^{2} \quad (10)$$

Hazen formula was developed earlier to estimate the K even-sized sand, but later, it was seen that it is also applicable for fine sand to gravel size. However, a uniformity coefficient of less than 5 and an effective grain size between 0.1 and 3mm are desirable for this case.

Estimation of K from cumulative curve

From the cumulative curve of the grain-size distribution (Fig. 2, left), the samples were classified, the diameters of grain size D_{10}, D_{20}, $D_{50,}$ and D_{60} were determined, and the coefficients of uniformity and porosity.

Table 3: Grain Size Distribution Data Obtained from Sieve Analysis

Mesh	Aperture in phi	Aperture in millimeter	Weight Retained (g)	Weight %	Cumulative Weight %	Wentworth Size Class
35	1	0.495	5.15	5.16	5.16	Coarse SAND
45	1.5	0.351	24.4	24.46	29.62	Medium SAND
60	2	0.250	25.01	25.07	54.70	
80	2.5	0.177	22.66	22.72	77.41	Fine SAND
120	3	0.124	16.49	16.53	93.94	
170	3.5	0.088	4.94	4.95	98.90	Very Fine SAND
230	4	0.063	0.97	0.97	99.87	
Pan	4.5	<0.063	0.13	0.13	100.00	Silt + Clay
		Total Weight(g):	99.75			
		Sieve Loss(g):	0.25			

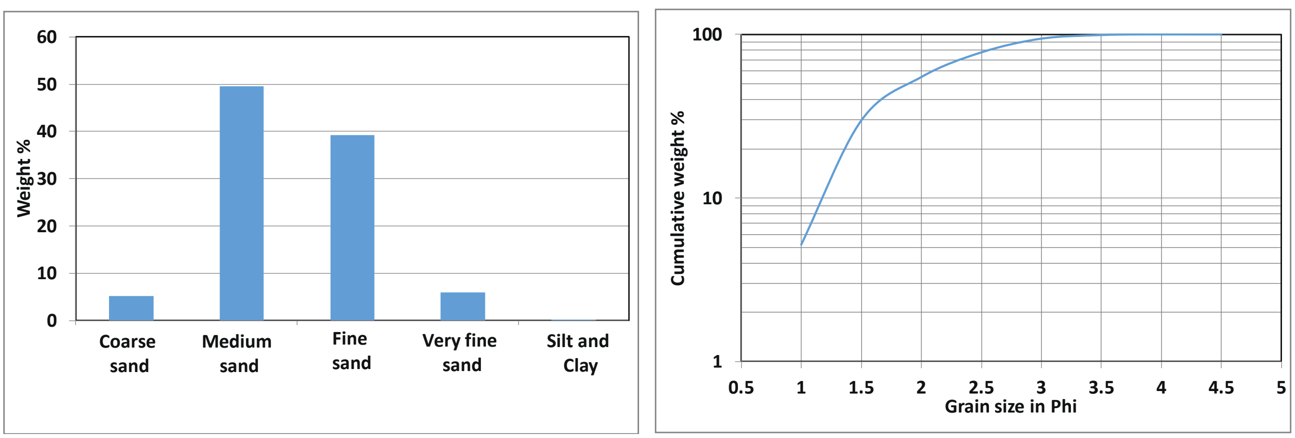

Figure 2: Histogram Showing the Weight Percentage (Left) and a Graph Showing Cumulative Weight Percentage vs. Grain Size in Phi (Right)

Table 4: Estimation of Diameters of Grain Size D_{10}, D_{20}, $D_{50,}$ and D_{60} in mm and Statistical Parameters

Percentile		Grain Size in Phi	Grain Size in mm	Kinematic Viscosity(v)	Co. of Grain Uniformity(U)	Porosity(n)
ø5		1	0.500	9.03E-07	2.29739671	0.421199784
ø16		1.25	0.420			
ø40	d_{60}	1.6	0.330	Inclusive Graphic Standard Deviation, σ_I in Phi		0.641
ø50	d_{50}	1.8	0.287	Inclusive Graphic Standard Deviation, σ_I in mm		0.641
ø80	d_{20}	2.5	0.177	Graphic Mean (Mz) in mm		0.291
ø84		2.6	0.165			
ø90	d_{10}	2.8	0.144			
ø95		3	0.125			

were estimated using equations (Table 4). All the outcomes, from which K was determined using the aforementioned Hazen formulae, are shown in Table 5.

Table 5*:* Estimation of K Using Empirical Hazen Equation and Corresponding to T

Site	Depth from (m)	Depth to (m)	Lithology	Hydraulic Conductivity (K) (m/day)	Aquifer Thickness	Transmissivity (T) (m/d)
Botany Dept (BoD)	259.08	262.13	Fine to medium sand	27.34	30.48 m	833.25
	262.13	265.18	Fine to medium sand	30.36		925.43
	265.18	268.22	Fine to medium sand	39.77		1212.30
	268.22	271.27	Fine to medium sand	20.91		637.38
	271.27	274.32	Fine to medium sand	43.98		1340.59
	274.32	277.37	Fine to medium sand	29.57		901.40
	277.37	280.42	Fine to medium sand	42.20		1286.33
	280.42	283.46	Fine to medium sand	89.92		2740.62
	283.46	286.51	Fine to medium sand	42.20		1286.33
	286.51	289.56	Fine to medium sand	62.20		1895.88

Estimation of Aquifer Transmissivity (T)

An aquifer's transmissivity value (T) can be derived from its hydraulic conductivity if the thickness of the aquifer is known since they are directly related.

T = Kb Where   b= Saturated thickness

Table 5 shows the value of transmissivity estimated from k (Hazen method).

RESULTS AND DISCUSSIONS

Interpretation of Borelogs

The lithology of the borelogs in Figure 3 shows that sediments are mostly fine to medium sand with occasional gravels and small amounts of clay and silty clay. The aquifer seems confined since the layer is topped by clay and silty clay. In all borelogs the sediment colour is yellowish brown upto 120 m depth (upper aquifer) and light gray to dark gray colour upto the explored depth (lower aquifer) except in BoD in which sediments more than 220 m depth are yellowish brown colour.

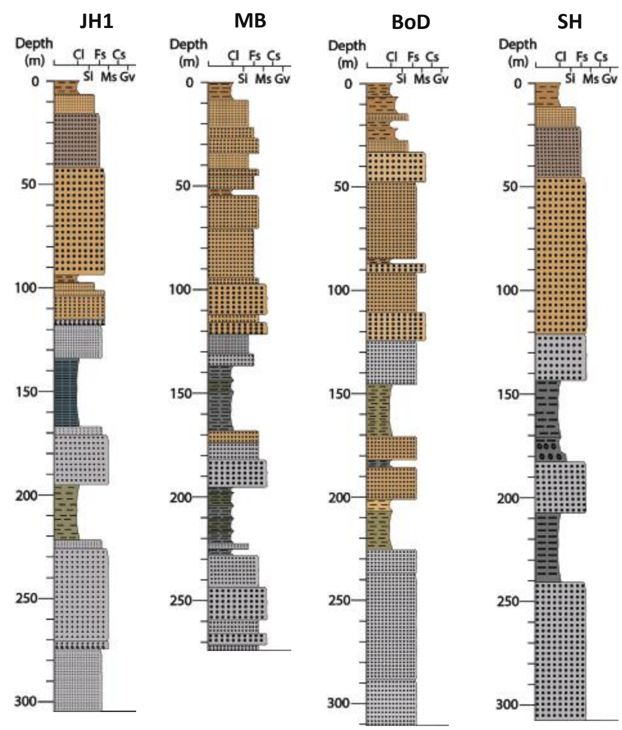

Figure 3: Borelog Data Collected from Production Wells Near Dhaka University; Cl Indicates Clay, Si Indicates Silt, Fs Indicates Fine Sand, Ms Indicates Medium Sand, Cs Indicates Coarse Sand, and Gv Indicates Gravel (See Figure 1 for Locations)

Interpretation of Groundwater Level Hydrograph

The high-frequency groundwater level hydrograph (Fig. 4) of the deep aquifer at Dept of Geology, DU: (GT2642009) from a 244m deep piezometer displays a distinctive annual pattern. Figure 4 shows that the hydrograph initiates with a peak at the beginning of each year, followed by a gradual decline, and then transitions into a predominantly stable curve with minor fluctuations. An observable declining trend is evident despite the short data from January 2021 to July 2023, with a declination rate of 2.8 m/year. Unlike other parts of the country, this hydrograph does not show the lowest groundwater water level during July and August, when rainfall is at its maximum, similar to other parts of Dhaka. This deviation can be attributed to the proximity and configuration of the production wells (Fig. 1). The production wells are closely spaced (Fig. 1), and there are interferences in the pumping during the end of the year; the pumps do not operate to the extent of the rest of the year due to winter vacation. Therefore, the lower values at the year's commencement likely result from pumping recovery. Also, water demand is low in winter compared to summer, which is evident from the DWASA wells. As the year progresses, these inputs diminish, gradually declining and showing the highest value during April-May (dry season). The minor fluctuations may arise from variable pumping rates, occasional shifts in precipitation, or localized hydrological events. This recurring pattern suggests a regularity in the hydrological regime, with the annual cycle significantly shaping the hydrograph's behavior. The current groundwater level (July 2023) is 72 m below ground level, which alarms further groundwater development on the campus.

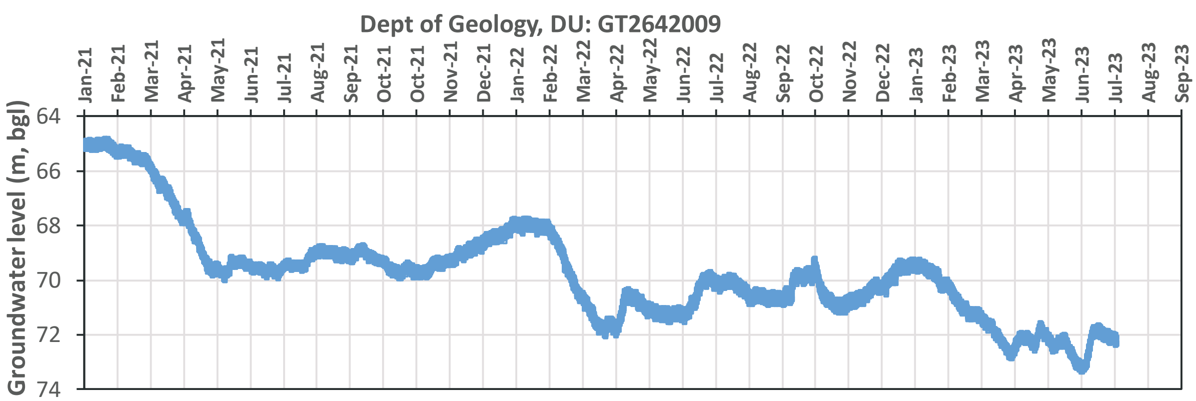

Figure 4: A Hydrograph Showing Fluctuation of Groundwater Level below Ground Surface

Physicochemical Characterization of Groundwater

In this dataset, the pH values range from 6.1 to 7.16, indicating that most samples are slightly acidic to neutral. These values generally fall within acceptable limits for various applications. Electrical conductivity (EC) indicates the total dissolved solid in water, with higher EC values reflecting higher ionic concentration (Hem, 1985). The EC value of the study area ranges from 325 µS/cm to 654 µS/cm, suggesting that most samples have a low to moderate level of dissolved salts or ions, and all are within the freshwater range. EC shows a linear relationship with depth, i.e., EC decreases with depth (Fig. 5). Eh, values at these locations range from -69 to 110 millivolts, indicating the aquifer is in a slightly reduced oxidizing condition. The total hardness (TH) of the samples ranges from 76-203 mg/L. Based on the TH values (WHO, 2010), the groundwater of Dhaka University's production wells is 30% (3 samples) moderately hard water, 50% (5 samples) hard water, and 20% (2 samples) very hard. Usually, soft and acidic groundwater promotes the corrosion of metal wells or pipes compared to hard water (Facey and Smith, 1995; WHO, 2017). Since none (0%) of the sample was soft water, there is less risk of corrosion of water supply equipment in the study area.

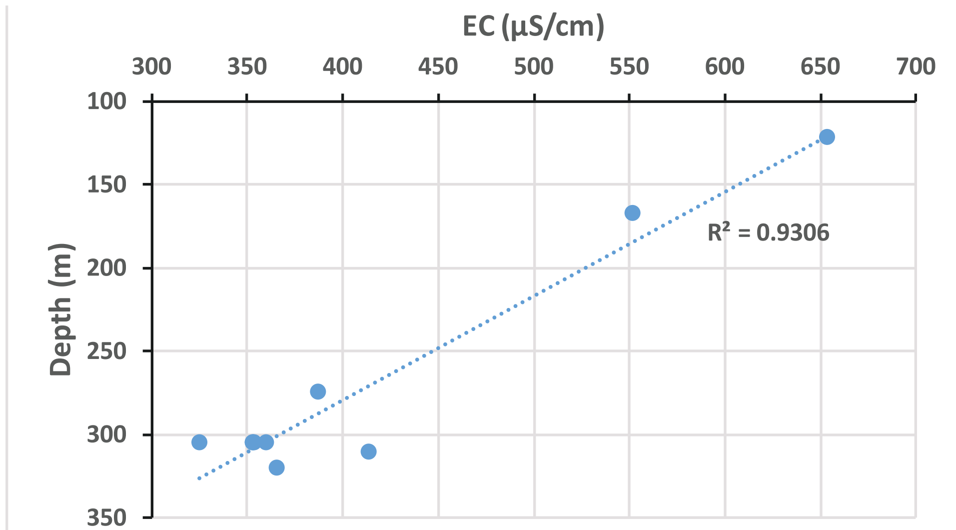

Figure 5: A Plot of Depth vs EC Showing a Linear Relationship

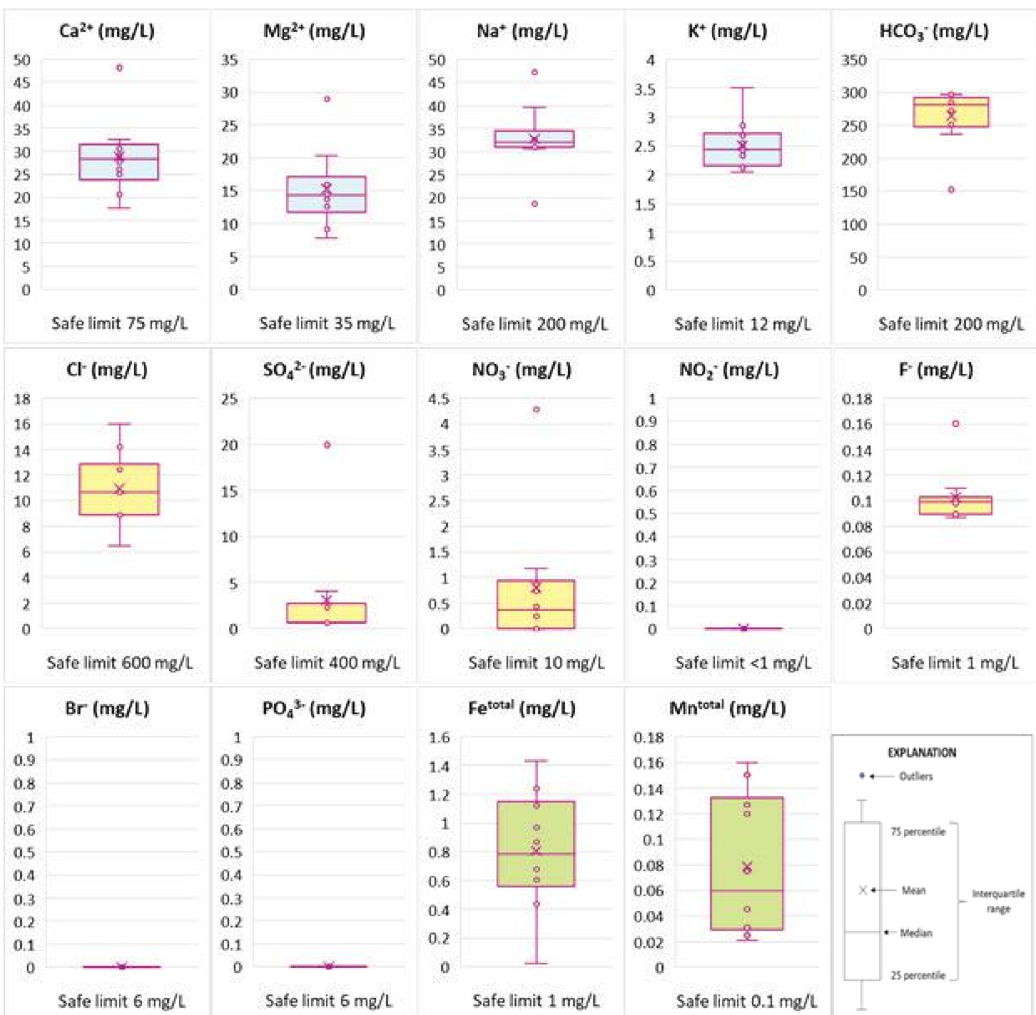

Figure 6: Box and Whisker Plots of the Concentrations of Chemical Parameters of the Water Samples (Blues are Cations and Yellows are Anions) along with Their Safe Limits (DPHE; WHO, 2017)

Chemical Parameters of Groundwater

In the studied groundwater, cation concentrations are as follows: Ca^{2+} ranges from 17.70 to 48.14 mg/l; Na^{+} ranges from 18.65 to 47.19 mg/l; Mg^{2+} ranges from 7.74 to 28.97 mg/l, and K^{+} concentration varies from 2.04 to 3.51 mg/l. For anions in the groundwater, the HCO_3^- concentration varies between 152.50 and 297.37 mg/l; Cl^- concentrations range from 6.50 to 15.97 mg/l; SO_4^{2-} concentration ranges from 0.61 to 19.94 mg/l and NO_3^- concentration ranges between 0 and 4.2826 mg/l. Regarding trace metals, Iron (Fe^{total}) concentration ranges from 0.03 to 1.43 mg/l, and (Mn^{total}) concentration ranges from 0.021 to 0.16 mg/l (Fig. 6). It's worth noting that while three samples exceed the safe limit of Fe, this is primarily an aesthetic concern and not associated with severe health issues.

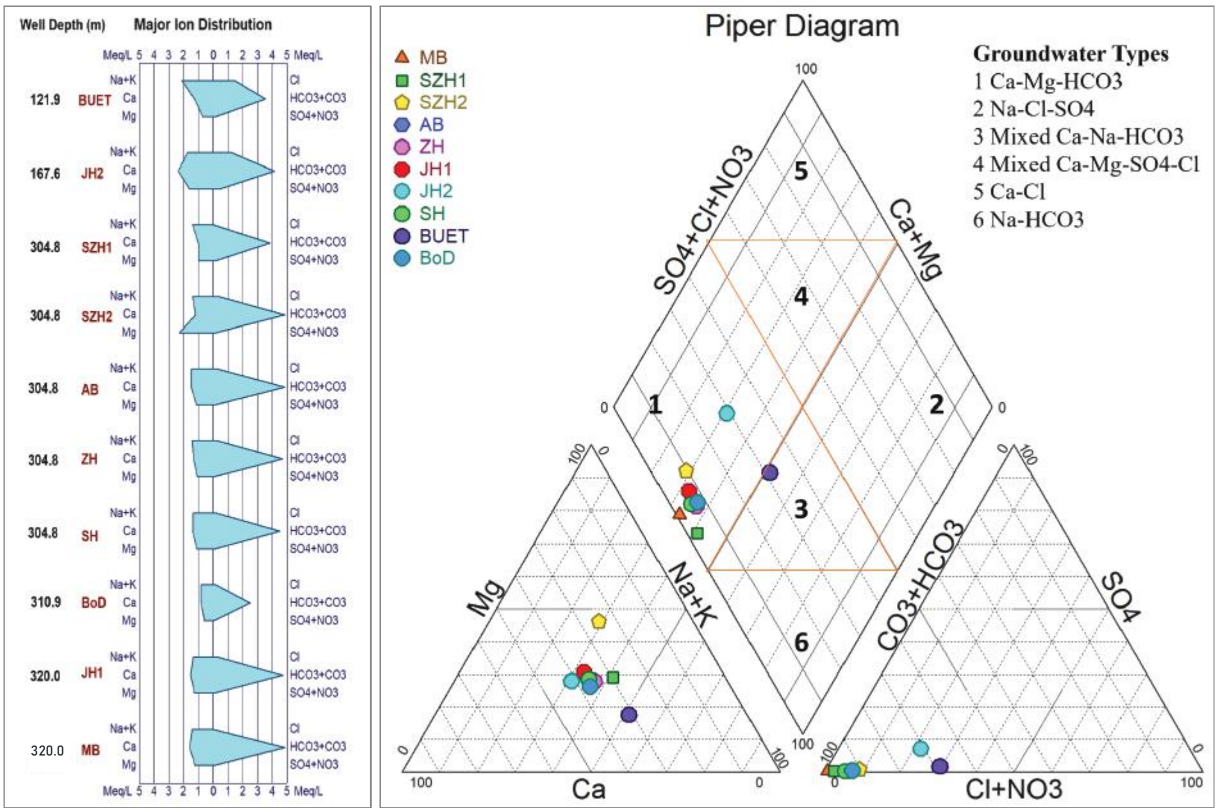

Figure 7: Stiff Diagram Showing the Concentrations of Major Cations and Anions and Their Well Depth (Left). Piper Diagram Showing the Groundwater Types (Right)

In the Stiff diagram (Fig. 7 left), the concentrations of major ions create polygons for a quick visual comparison between high and low ion concentrations. Most water samples show similar shapes with relatively lower to moderate concentrations of cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-}) in meq/L; no significant variation was observed with the increase of the depth of wells, except BUET, SZH2 and the new production well BoD BUET well shows slightly high concentrations of Na^{+} and K^{+} compared to Ca^{2+} and Mg^{2+}, resulting in a distinct polygonal shape. SZH2 also shows a different shape with high Mg content (nearly 29 mg/L).

HCO_3 concentrations are notably higher than other ions, as the wells draw water from Dupi Tila aquifers, where water interacts with carbonate and silicate minerals, resulting in increased HCO_3^- concentrations (Foster, 1950). Also, the sample BoD showed comparatively lower concentrations of both cations and anions despite being located at a deeper depth (310.9 m). Note that this sample was collected during the onset of the wet season, and the reason for its smaller shape in stiff pattern compared to other deeper wells is puzzling and merits attention. The BUET sample, which shows a different stiff pattern than other samples, might be influenced by its relatively shallow well depth of about 120m, drawing water from a different layer (yellowish brown sandy upper aquifer) compared to the other wells. It is worth mentioning that the EC value (654 µS/cm) is the highest for this well.

Hydrochemical Facies and Groundwater Types

In the Piper diagram (Fig. 7 right), nine out of the ten water samples are classified as Ca-Mg-HCO3 type, labeled as 1 in the diamond of the Piper plot. Only one sample (BUET) fell within diamond 3, indicating a mixed Ca-Na-HCO_3 type of groundwater showing different stiff patterns (Fig. 6 left). The prevalence of Ca-Mg-HCO3-type groundwater suggests carbonate weathering in the aquifer system. When groundwater percolates through the CO_2-enriched sediments, carbonate ($CaCO_3$) dissolution occurs quite readily and releases Ca^{2+} and HCO_3^- into groundwater (Foster, 1950; Hem, 1985).

Geochemical Modeling

The saturation indices of some minerals calculated from the water chemistry data presented in Table 6 imply that the groundwater samples are marginally under-saturated for calcite, dolomite, gypsum, and rhodochrosite across all locations. Therefore, these minerals possess the potential for dissolution at all sites.

Table 6: Saturation Indices of Minerals of the Analyzed Groundwater Samples

Sample ID	Calcite	Dolomite	Gypsum	Siderite	Rhodochrosite	logpP_CO_2(g)
MB	-0.22	-0.38	-4.04	0.35	-0.86	-1.72
SZH1	-0.79	-1.44	-4.18	0.22	-0.82	-1.51
SZH2	-0.78	-1.15	-3.64	-0.38	-1.44	-1.33
AB	-0.32	-0.61	-4.02	0.16	-0.93	-1.62
ZH	-0.31	-0.57	-4.08	0.49	-0.75	-1.75
JH1	-0.35	-0.63	-4.04	0.08	-0.37	-1.63
JH2	-1.15	-2.32	-2.44	-2.21	-1.97	-0.80
SH	-1.09	-2.12	-4.10	-0.34	-0.97	-0.94
BUET	-1.44	-2.98	-3.33	-0.85	-1.24	-0.64
BoD	-1.23	-2.47	-4.16	-0.29	-0.95	-1.50

Furthermore, Table 6 underscores that the water samples are slightly under saturated for siderite at SZH2, JH2, SH, BUET, and BoD locations, suggesting the likelihood of siderite dissolution at these points. However, water samples collected from MB, SZH1, AB, ZH, and JH1 locations are saturated for siderite, indicating that siderite may precipitate at these sites.

Water Quality Index (WQI) for Drinking

The WQI values were calculated (Table 7). 100% of water samples collected for this study fell in the excellent quality category for drinking.

Table 7: Categories of Water Quality for Drinking Uses Based on the WQI Values (Adimalla and Taloor, 2020; El Baba et al., 2020; Nawrin et al., 2022)

WQI value	Type of water	Number of samples	% of samples
<50	Excellent	10	100.0
50-100	Good	0	0.0
101-200	Poor	0	0.0
201-300	Very poor	0	0.0
>300	Unsuitable for drinking	0	0.0

Hydraulic Conductivity (K) and Aquifer Transmissivity (T)

The hydraulic conductivity (K) values within the fine to medium sand layer (depth of 850 to 950 ft) at the Botany Department site range from 20.912 to 89.915 m/day, indicating varying levels of permeability within the aquifer. These values also indicate the ability of the sandy aquifer to transmit water. Higher K values signifying better permeability. The K values varied due to differences in the sand's porosity and size of the grain. Understanding hydraulic conductivity is crucial for managing groundwater resources, as it helps assess the potential for water flow.

Transmissivity is a crucial parameter as aquifer property, indicating how easily groundwater can flow through the formation. In this study, transmissivity values range from approximately 637 m^2/day to 2740 m^2/day. The highest transmissivity value occurs around 930-940 ft (283.5 – 286.5 m), suggesting that the formation at that depth has higher permeability, facilitating more efficient groundwater flow. Understanding the vertical distribution of transmissivity helps manage groundwater resources, design wells, and assess the potential for groundwater contamination and movement.

CONCLUSION

A comprehensive hydrogeochemical investigation and estimation of aquifer properties have been carried out at Dhaka University Campus, focusing on physicochemical parameters, water quality parameters, water type (hydrochemical facies), geochemical modelling and hydraulic conductivity and transmissivity estimation. The major contributions, achievements, new observations, interpretations, and broader implications of the research are outlined in those above, corresponding to the specific aims of the study. The investigation revealed a complex interplay of factors affecting water quality, including pH, EC, TH, and Eh. The results indicated that 30% of the water samples in Dhaka University's production wells contain moderately hard water, while 50% displayed hard water, with the remaining 20% categorized as very hard water. None (0%) of the sample shows soft water. The hydrochemical analysis revealed that groundwater samples are of the Ca-Mg-HCO3 type, except for one of the Ca-Na-HCO_3 type. The saturation indices imply that the water samples are (under) saturated for calcite, dolomite, gypsum, and rhodochrosite across all locations. An evaluation of the WQI suggested that the groundwater of the University campus is excellent for drinking uses. This comprehensive analysis offers insights into the hydrochemical dynamics of the aquifer system. The hourly groundwater level data analysis shows that the current groundwater level in July 2023 is 72 m below the ground level with a declination rate of 2.8 m/year. The estimated hydraulic conductivity values of 20 to 90 m/day and transmissivity values of 650 to 2750 m²/day suggest better permeability of the lower aquifer and its ability to transmit substantial amounts of water. These hydraulic conductivity and aquifer transmissivity findings will contribute significantly to developing hydrogeological models and future groundwater exploration efforts. This study contributes to the scientific understanding of the hydrogeochemistry, water quality assessment, and aquifer characteristics at Dhaka University Campus. However, further investigations are recommended, encompassing arsenic and microbiological assessments, continuous monitoring of water quality parameters, and long-term groundwater observation.

REFERENCES

Adimalla, N., Taloor, A.K., 2020. Hydrogeochemical investigation of groundwater quality in the hard rock terrain of South India using Geographic Information System (GIS) and groundwater quality index (GWQI) techniques. Groundwater for Sustainable Development 10, 100-288. https://doi.org/10.1016/j.gsd.2019.100288.

Afroz, M., Islam, M. S., Hassan, M. Q., 2010. Assessment of water quality and supply management system of Dhaka University Campus area. Dhaka University Journal of Earth and Environmental Sciences 1, 35-41.

Ahmed, K.M., Hasan, M.A., Sharif, S.U., Hossain, K.S., 1998. Effect of urbanization on groundwater regime, Dhaka City, Bangladesh. Journal Geological Society of India 52, 229-238.

Ahmed, E., 2004. Water management in Dhaka City. Water Resources Management and Development in Dhaka City 33.

Ahmed, K.M., Bhattacharya, P., Hasan, M.A., Akhter, S.H., Alam, S.M.M., Bhuyian, M.A.H., Imam, M.B., Khan, A.A., Sracek, O., 2004. Arsenic enrichment in groundwater of the alluvial aquifers in Bangladesh: An overview. Appl. Geochem 19, 181-200.

Ahmed, K M., Islam, M. S., Sultana, S., 2010. Changes in the groundwater regime of Dhaka City: a historical perspective, in (S U Ahmed and G Rabbani eds) celebration of 400 years of Capital Dhaka: Plants, wildlife, gardens and environment of Capital Dhaka. Asiatic Society of Bangladesh, Dhaka 383-400, ISBN 978-984-33-1558-8.

El Baba, M., Kayastha, P., Huysmans, M., Smedt, F.D., 2020. Evaluation of the groundwater quality using the water quality index and geostatistical analysis in the Dier al-Balah Governorate, Gaza Strip, Palestine. Water 12, 262. https://doi.org/10.3390/w12010262.

Burgess, W. G., Hasan, M. K., Rihani, E., Ahmed, K. M., Hoque, M. A., Darling, W. G., 2011. Groundwater quality trends in the Dupi Tila aquifer of Dhaka, Bangladesh: sources of contamination evaluated using modelling and environmental isotopes. International Journal of Urban Sustainable Development 3, 56-76.

Charles, K.J., Ong, L.A., Achi, N.E., Ahmed, K.M., Khan, M.R., Hoque, S., Nowicki, S., 2021. Bangladesh MICS 2019: water quality thematic report, Bangladesh bureau of statistics, Ministry of Planning, Government of the People's Republic of Bangladesh and UNICEF Bangladesh, Dhaka, Bangladesh 106.

Cheng, C., Chen, X., 2007. Evaluation of methods for determination of hydraulic properties in an aquifer-aquitard system hydrologically connected to river. Hydrogeology Journal 15, 669-678.

Domenico, P.A., and Schwartz, F.W., 1997. Physical and chemical hydrogeology. John wiley & sons.

DPHE. Water Quality Parameters Bangladesh Standards & WHO Guidelines, DPHE Laboratories, Department of Public Health, Kakrail, Dhaka, Bangladesh. http://old.dphe.gov.bd/index.php?option=com_content&view=article&id=125&Itemid=133.

Al-Mamoon, H., 2006. Water utility services in Dhaka City: Present and future. In Capacity Building Workshop on Partnerships for Improving the Performance of Water Utilities in the Asia and Pacific Region 25-27, Bangkok, Thailand.

Folk, R.L.,1974. Petrology of sedimentary rocks. Hemphill Publishing Co., Austin. Texus, USA.

Facey, R.M., Smith, D.W., 1995. Soft, low-temperature water-distribution corrosion: Yellowknife, NWT. Journal of Cold Regions Engineering 9 (1). https://doi.org/10.1061/(ASCE)0887-381X(1995)9:1(23)

Foster, M.D., 1950. The origin of high sodium bicarbonate waters in the Atlantic and Gulf Coastal Plains. Geochim. Et Cosmochim 1, 33–48.

Hem, J.D., 1985. Study and nterpretation of the Chemical Characteristics of Natural Water, 3rd ed.; U.S. Geological Survey Water Supply Paper 2254. US Government Printing Office: Washington, DC, USA, 272.

Hoque, A.M., 2004. Hydrostratigraphy and aquifer piezometry of Dhaka City, (Unpubl.), Institute of Water and Flood Management, BUET, Dhaka.

Hoque, M. A., Hoque, M.M., Ahmed, K.M., 2007. Declining groundwater level and aquifer dewatering in Dhaka Metropolitan Area, Bangladesh: causes and quantification, hydrogeology journal, Springer-Verlag, DOI. 1007/s10040-007-0226-5.

Hoque, M. A., McArthur, J. M., Sikdar, P. K., Ball, J. D., Molla, T. N., 2014. Tracing recharge to aquifers beneath an Asian megacity with Cl/Br and stable isotopes: the example of Dhaka, Bangladesh. Hydrogeology Journal 22, 1549-1560.

Hossain, M. S., Rahman, M., Rahman, S.M.M., Serazuddin, M., 2007. Development of ground water resource-a case study for Dhaka City, Abstracts, xii Geological Conference (March 19-20) Bangladesh Geological Society.

Islam, M. B., Firoz, A., Fogila, L., Marandi, A., Khan, A. R., Schuth, C., Ribbe, L., 2017. A regional groundwater-flow model for sustainable groundwater-resource management in the south Asian megacity of Dhaka, Bangladesh. Hydrogeology Journal 25, 617-637.

Islam, M., Van Camp, M., Hossain, D., Sarker, M. M. R., Khatun, S., Walraevens, K., 2021. Impacts of large-scale groundwater exploitation based on long-term evolution of hydraulic heads in Dhaka City, Bangladesh. Water 13, 1357.

Khan, S.I., Hassan, M.Q., 2004. Microbiological quality of groundwater at site of abstraction in Dhaka City water resources management and development in Dhaka City, 83.

Miah, M. M., Bazlee, B. L., 1968. Some aspects of geomorphology of the Madhupur Tract. Oriental Geographers 12, 39-48.

Morris, B.L., Seddique, A.A., Ahmed, K.M., 2003. Response of the dupi tila aquifer to intensive pumping in Dhaka, Bangladesh, Hydro Geology Journal 11, 496-503.

Moshfika, M., Biswas, S., Mondal, M. S., 2022. Assessing groundwater level declination in Dhaka City and identifying adaptation options for sustainable water supply. Sustainability 14, 1518.

Nahar, N. K., 2009. Characterization of aquifer condition and assessment of water management system of Dhaka University Campus. Unpub. MS thesis, Department of Geology, University of Dhaka.

Nawrin, N., Junayed, T.R., Khan, M.R., Alam, M.J., Mia, M.B., Ahmed, K.M., 2022. A hydrogeochemical characterization and quality assessment of groundwater from the Sadar Upazila, Khagrachhari District, Bangladesh for Irrigation and Drinking Uses. Water 14, 3052. https://doi.org/10.3390/w14193052.

Parkhurst, D. L., Appelo, C., 1999. User's guide to PHREEQC (Version 2): a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. Water-Resources Investigations Report 99(4259), 312.

Rainwater, F. H., Thatcher, L. L., 1960. Methods for collection and analysis of water samples. USGS WSP. 1454, Washington, 39-301.

Sharif, M.S.U., 1996. Urban and Industrial Pollution to Ground Water of the Southern part of Dhaka City. M.S. Thesis (Unpub), University of Dhaka.

Sultana, S., 2009. Prospects of Artificial Recharge and Other Options for Augmentation of the Upper Dupi Tila Aquifer in Dhaka City, Bangladesh, unpublished MS Thesis, Department of Geology, University of Dhaka.

Todd, D.K., 1980. Groundwater Hydrology, 2nd ed. John Wiley and Sons, Inc.: New York, NY, USA.

Vukovic, M., Soro, A., 1992. Determination of Hydraulic Conductivity of Porous Media from Grain-Size Composition. Water Resources Publications, Littleton, Colorado.

World Health Organization (WHO), 2017. Guidelines for Drinking-Water Quality, 4th ed.; Incorporating the First Addendum; World Health Organization: Geneva, Switzerland, 541.

World Health Organization (WHO), 2010. Hardness in drinking-water, background document for preparation of WHO guidelines for drinking-water quality, World Health Organization: Geneva, Switzerland, 11.