Groundwater budgeting of Nari and Gaj formations and groundwater mapping of Karachi, Pakistan

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Received: 23 January 2022 / Accepted: 17 October 2022 / Published online: 2 November 2022
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Abstract
Groundwater depletion is an emerging problem worldwide due to changes in climate and an increase in urbanization. Two significant water-bearing formations, the Oligocene-aged Nari and the Miocene-aged Gaj, were utilized as a case study exposed near Karachi, Pakistan. Groundwater budgeting was performed through a classical equation. The inflow of groundwater in the formations was calculated by thermo-pluviometric data and water loss of Hub Dam. The potential of evapotranspiration (PET) was calculated by the Thornthwaite method. The groundwater inflow from Hub Dam was estimated by using 20 years of annual water loss data by removing PET. The total mean annual inflow of groundwater in the formations was 2414.12 US Gallons per Second (gps). The annual mean outflow was estimated by calculation of groundwater usage for industries and domestic purposes and the mean annual groundwater outflow was 5562.61 US gps and an annual deficit of groundwater was 3148.5 US gps. The research is composed of validating the groundwater budget. Direct Current Electrical Resistivity (DCER) and static water level data from existing industrial wells were used for groundwater maps. The DCER data indicates A-Type and K-Type sub-surface with high resistivity in the three-layer model. The average water table of residential areas in 2019 was 60 m and in industrial areas was 130 m. The oscillation of the groundwater table over the last 20 years and the deficit of the groundwater budget shows an alarming condition for the future. If the same scenario persists, then by 2025, the water table will decline up to 140 m.

Keywords Groundwater budgeting · Groundwater mapping · Inflow · Outflow · Direct current electrical resistivity

Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| C.I.P.       | Coefficient of infiltration potential |
| C.I.P.S      | Coefficient of infiltration potential weighted with the slope |
| DCER         | Direct current electrical resistivity |
| EGL          | Existing ground level |
| ERS          | Electrical resistivity survey |
| gps          | Gallons per Second |
| KWSB         | Karachi water and sewerage board |
| PET          | Potential evapotranspiration |
| SITE         | Sindh industrial trending estate |
| SPI          | Standard precipitation index |
| VES          | Vertical electrical sounding |
| WAPDA        | Water and power development authorities |
Introduction

Groundwater is an essential source for the sustenance of life and ecosystem but an ever-growing population with increased anthropogenic activities induces overexploitation and contamination of groundwater globally. The groundwater footprint studies highlight flawed approaches to calculating the area and size of the aquifers, where 80% of the aquifers do not cover enough surface area. Thus, unsustainable depletion renders an extreme threat to 1.7 billion people out of 2.5 billion people dependent on groundwater, specifically in Central and South Asia (Fig. 1). Moreover, environment and climate change, agricultural development, Land use land cover (LULC) change etc. exert severe pressure on freshwater demand with a projected freshwater deficit to rise 40% till 2030. Thus, scientific management becomes imperative to sustain the groundwater source quality and quantity regionally and globally because of its significant contribution, 30% of the global freshwater supply, to the ecosystem (Connor 2015; Gleeson et al. 2012; UNESCO 2012; Otto and Maddocks 2015; Cotterman et al. 2018; Achu et al. 2020a).

According to UN-Habitat, the South-Asian subcontinent, especially Pakistan, is one of the most densely populated regions with a high urbanization rate globally (UNDP 2019; UN-Habitat 2012). According to Wada et al. (2010), there are various hotspots of groundwater depletion throughout the World, the highest rates of groundwater depletion were observed in North-East Pakistan and North-West India. Several recent studies which are largely using the Gravity Recovery and Climate Experiment satellites data set identified groundwater depletion in Pakistan (Ahmed et al. 2019; MacAllister et al. 2022). Pakistan is one of the 36 countries under severe water stress, with a projected decrease of 500 cubic meters in water availability per capita. Here, the abstraction rate exceeds the annual recharge, which may cause a deficit of 102.37 km$^2$ per annum till 2025. As the demand for water is increasing by 10% annually, the surface water supply is becoming insufficient and non-viable because the Indus water basin is considered the most depleted river basin globally, exerting pressure on groundwater sources. Currently, 50% of water requirements are fulfilled by groundwater abstraction, which ascertains the need for systematic groundwater budgeting and mapping (Sharma et al. 2013; Qureshi et al. 2010; Reig et al. 2013;)

Fig. 1 Baseline water stress satellite map of the world (Otto and Maddocks 2015)
et al. 2020a, b). Thus, this study undertakes the area of Karachi, Pakistan as a case study that faces an extreme shortage of groundwater and performs groundwater budgeting and mapping.

In recent years, Pakistan has been facing the most severe issue of water. Nowadays, the availability of water in Pakistan is reduced from 5600 m$^3$ per capita to 1100 m$^3$ per capita over the previous 50 years. It is expected to further reduce to 700 m$^3$ per capita in 2025 (Kahlown and Majeed 2003; Dawood et al. 2021). According to a report by JICA and KWSB (2008), Karachi city will continue to face severe water shortages over the planning horizon of 2025. It was also determined that there is no realistic hope of producing new groundwater resources to meet Karachi’s future freshwater demand. According to a recent study, surface water from the Indus River can be used to meet Karachi’s freshwater needs and reduce water stress (Tayyab 2021; Jica and KW&SB 2008).

Karachi is famous with the name “city of lights” with a population of approximately 16 million with growth rates of 4–5% per annum and inhabitants accompanied around 60% of industries. These industries have a significant impact on the economy by contributing 12–15% to the GDP of Pakistan. Export-based enterprises must adhere to strict environmental standards to meet the demands of overseas clients. As a result, the country’s socio-economic progress becomes more sustainable. Policy statements outlining precise laws, thorough implementation, and stakeholder input are required to achieve this. Water and its management are one of the most important aspects of environmental compliance, hence data on it is essential for successful policymaking. This analysis of Karachi’s water status is based on data gathered from a variety of sources (Jica and KW&SB 2008; Qureshi 2010; WWF 2019; Dawood et al. 2021).

Human reliance on groundwater has increased exponentially in recent decades all around the world, resulting in depletion of the water table and instability of the aquifer system (Akhtar et al. 2016; Ahmad et al. 2019). Because only 30% of total freshwater is present in aquifers (Achu et al. 2020a, b). Most of the research is conducted worldwide to assess and quantify freshwater resources (Ahmad et al. 2022). There are two sources of water supply for Karachi, i.e., surface water (includes Lake Haleji, Lake Keenjhar and Hub Dam) and groundwater (source includes Dumloot-tee well-fields). However, there is a very low water supply from the mentioned wells and also water quality is very saline (WWF 2019). Groundwater is a significant source of freshwater that caters to domestic water. The demand for freshwater is rising due to the escalating population and agricultural and industrial practices in many developing countries. Groundwater is generated through a large number of borewells, tube wells and dug wells, which are spread in the agricultural fields, residential areas, and industrial areas. The massive withdrawal of groundwater has resulted in the lowering of groundwater levels (Senthilkumar et al. 2015).

Recent research forecasted that by the period 2017–2030, the population of Karachi city will grow by 30%. This growth will increase the demand for water by putting pressure on scarce supply resources of water availability. Furthermore, water supply and sewerage tubes are deteriorated and frequently run parallel to one another, resulting in cross-contamination. As a result, the majority of Karachi does not have access to safe, clean water (WWF 2019). Climate change also poses a threat to Karachi’s water security in the form of unpredictable river flows caused by changes in rainfall patterns and increasing sea levels. Reduced water availability is also expected to have a significant impact on the industrial and agricultural sectors. In the arid climate, the groundwater resource is disbalance due to over-evapotranspiration (Lubczynski 2000). The scarcity of sweet and saline groundwater is a significant problem in Karachi city due to the arid conditions of the region and the high exploitation of groundwater resources as well as a decrease in surface water for domestic and industrial purposes (Mashiatullah et al. 2002).

The groundwater quality of Karachi is deteriorating as compared to other major cities in Pakistan (Khattak and Khattak 2013). In Karachi, freshwater resources are limited; the available shallow and deep groundwater are exploited because of specific domestic and industrial purposes. Protracted over-pumping of groundwater from the coastal hydrogeological system can lead to encroachment of the interface between seawater and freshwater, through intrusion. Contamination by salty seawater can further increase the deterioration of groundwater quality in the coastal aquifer. The two to three percent mixing of coastal aquifer water with seawater makes freshwater unsuitable for human consumption. A five percent mixing makes it unusable for irrigation (Mashiatullah et al. 2002). In the coastal areas of Karachi, based on geochemical analysis of deep wells water suggested that there was seawater intrusion (Khan and Eghbal Bakhtiari 2017).

This work was carried out by measuring the difference between water inflow and outflow in Gaj and Nari formations. The inflow will be measured from thermo-pluviometric data, and Hub Dam, and the outflow will estimate by gathering water usage data from industries. The groundwater level map will be prepared with the help of electrical resistivity surveys and direct measuring of water levels from wells. The work aims to find out the impact of rainfall and surface water reservoirs on the water table by using meteorological data and ArcGIS software applications. The research objectives are to find out the recharge values of groundwater from rainfall and surface water resources, calculate outflow values from Nari and Gaj formations, and develop groundwater maps of the study area. This work will be helpful for
further research and urban management to overcome the current groundwater issue in Karachi, Pakistan.

Study area description

Karachi is the capital city of the Sindh Province. It is the most populous city in Pakistan and the fifth-most populous city in the world. Karachi is a beta-global city as per world ranking and Pakistani’s primer city of industries and financial center. The history of Karachi starts millions of years ago, this city is found as a heartened village of Kolachi in 1729. Geographically in East to South boundary of Karachi consists of the long Shoreline of the Arabian Sea and the west and north side is bounded by seasonal water channels (Hasan 2009). In the south of Karachi, Sona Pas and Lal Bakhar Ridges, and in the west, Pir Mango Ridges are present (Niamatullah and Imran 2012).

Administratively Karachi city was divided into six districts: (i) District West, (ii) District East, (iii) District South, (iv) District Central, (v) Malir, (vi) Korangi. District west is an administrative unit of Karachi City Government and is found at the west of Karachi and attach to Baluchistan province. This is a tectonically disturbed and structurally elevated district of Karachi City. It has further divided into seven sub-divisions as Manghopir sub-division, Orangi sub-division, Mominabad sub-division, Baldia sub-division, SITE sub-division, Mauripur sub-division and Harbour sub-division (GOP 2017).

District west is present in the west of Karachi, Sindh (Fig. 2), and in District West SITE sub-division is situated on the eastern side of district west. SITE sub-division shares its boundary with sub-division Nazimabad in North, Mauripur sub-division in the south, Lyari sub-division and Mominabad sub-division in the west. The study area has seven union councils (Fig. 2) (GOP 2017). SITE sub-division is about 5–55 m elevated from the mean sea level.

The study area is less populated but has dense industries. The SITE sub-division is situated between 24°56’84″ N 67°00’24.1″ E and 24°52’08.83″ N 66°58’06.45″ E. In the SITE area, 2800 multiple industries are present at 23 km² area in which 60% is the textile industry and 40% are multiple industries, including Pharmaceutical, Engineering Companies, Plastic Industries, Beverages, Wood, Steel, Food, etc. (Mansoor and Mirza 2007). The population of the SITE sub-division is 404,757 persons (GOP 2017).

Fig. 2 Location of SITE sub-division study area (GOP 2017, Geological Survey of Pakistan 2001)
The Gaj and Nari formations are exposed in the west of Karachi city (Fig. 3). The exposure of these formations is extending toward the north of Karachi, the Nari Formation extends approx. 230 km and the Gaj Formation is exposed from Karachi city to 100 km in the north toward the Pab Range (Geological Survey of Pakistan 2001).

The Gaj and Nari formations belong to the Miocene and Oligocene age, respectively. The type locality of Gaj and Nari is Kirthar of Pab ranges (Fig. 3). The thickness of these formations is 350–400 m in the Karachi trough. The Gaj Formation consists of limestone and subordinate Shale and Nari Formation is comprised of limestone and sandstone with interbedding shale or clay (Table 1).

### Neighboring Meteorological Stations and Location of Nari and Gaj Formations Exposure

![Map of Sindh with Nari and Gaj formations and meteorological stations](image)

**Legend**
- Lastbella
- Moen-Jo-Daro
- Khuzdar
- NawabShah
- Dadu
- Karachi Air Port
- Gaj Formation
- Nari Formation
- Main Grid Box
- Sub Grid
- Sindh
- Pakistan

**Fig. 3** Location of Nari and Gaj formations in Sindh with the meteorological station (Geological Survey of Pakistan 2001; PMD 2019)

### Table 1 Stratigraphic column of Lower Indus Basin, Pakistan (Niamatullah and Imran 2012)

| Period      | Epoch       | Age       | Formation         | Member according to new literature | Member according to the current study          |
|-------------|-------------|-----------|-------------------|-----------------------------------|-----------------------------------------------|
| Tertiary    | Pliest-pliocene | Miocene   | Manchar Formation | Manchar Formation                 | Manchar Formation                             |
|             |             |           | Gaj               | Mol                               | Talawa (Limestone)                            |
|             |             |           |                   | M undo                           | Jhil (Limestone)                              |
|             |             |           |                   | Orangi                           | Metan (Claystone)                             |
|             |             |           |                   | Pir Mango                        | Orangi (Sandstone)                            |
|             |             | Oligocene | Nari              | Pir Mango                        | Ghora Lakhi (Limestone)                       |
|             |             |           |                   | Hub                              | Halkani (Sandstone)                           |
|             |             |           |                   |                                  | Pir Mango (Limestone)                         |
|             |             |           |                   |                                  | Hub (Shale)                                   |
Nari and Gaj’s formations belong to the shallow marine environment and form in the earlier Karachi trough. In the Jhill limestone of Gaj Formation and Ghora Lakhi of Nari Formation, the presence of reefal and in Orangi and Halkani sandstone of Nari Formation, presence of ripple marks and crossbedding are evidence of shallow marine environment. The Metan Clay of Gaj Formation and Tobo shale of Nari Formation act as a detachment for thrust faults (Niamatullah and Imran 2012; Ehsan et al. 2018; Aziz et al. 2020). Tectonically the study area is part of the Karachi Arc, which is part of the Kirthar Fold Belt (Kazmi and Rana 1982). This is an eastward acute structural feature bounded by east–west oriented sinistral and dextral faults near Mancher Lake in North and near Karachi in south, respectively. The east-verging structures in the Karachi Arc indicate an eastward tectonic transport in a thin-skinned fashion as a result of India–Arabia convergence (Niamatullah 1998).

The geology of a region has a significant impact on the presence and flow of groundwater (Aju et al. 2021). Geological structures play a significant role in groundwater flow and quality-related problems. The geologic structures like dikes, lineaments, and fractures act as both carriers as well as barriers for groundwater flow. There have been many studies/technical reports indicating the role of dikes in controlling the groundwater flow in an area. Several researchers have used the spatial distribution of geology, geomorphology, land use, drainage, and lineaments to identify potential groundwater zones (Umar et al. 2013).

Climate of the study area

Karachi has an arid climate and experiences two major seasons, Summer and Winter, while Spring and Autumn are very short (Alam et al. 2014). The annual meteorological report of the Pakistan meteorological department shows west to the southwest border of the Sindh Province, especially Karachi city been suffering from extreme drought to mid drought regarding other areas of Pakistan for the last 20 (period 1999–2018) years (CDPC 2020).

The annual rainfall is divided into two ranges based on the mean potential evapotranspiration in the last 20 years. The first range is less than 200, and the other is equal to and greater than 200 mm. From 1999 to 2002, 2004, 2005, 2009, and 2012 to 2018 the annual rainfall was bellowed 20 mm, and only six remaining years (2003, 2006, 2007, 2008, 2010, and 2011) in the last 20 years the annual rainfall was greater than 200 mm (Fig. 4) (CDPC 2020).

Due to a mild climate, Karachi city had moderate temperatures in the last 20 years. The maximum monthly temperature of Karachi in the past 20 years was 32 °C, and the minimum temperature was 19 °C. Furthermore, the mean annual temperature of Karachi ranges from 28 to 26.5 °C (Fig. 5) (CDPC 2020).

Materials and methods

The Meteorological Department of Pakistan, the Statistical Bureau of Pakistan (SBP), the Geological Survey of Pakistan (GSP), and BNB Enterprises provided data for the research. The water discharge data of the study area gather through interviews as well as published reports. Moreover, the different methods used for calculation and interpretation. Research work had divided into three parts based on output and methodology: Groundwater Budgeting, Groundwater Mapping, and Climate Trend Index.
Groundwater budgeting

The classical groundwater budget equation states that the total groundwater recharge is equal to total discharge with the plus-minus change in the storage coefficient. In this research work, a change in the storage coefficient was neglected because of considerable formations exposure and the time period neglected (Viaroli et al. 2018).

The neighboring meteorological stations were marked by plotting Nari and Gaj formations polygons and meteorological stations on ArcGIS from the geological map of Sindh and the website of the Meteorological Department of Pakistan. Dadu, Karachi, Khuzdar, Lasbella, Monjo-Daro, and Nawab-Shah as shown in (Fig. 3).

The meteorological department provides 15 years of data from the Khuzdar meteorological station because this station was established in 2004. From the other five meteorological stations, PMD provides 20 years of data. The given data show many spells of mild drought and mild wet periods. The graphical representation of thermo-pluviometric data is shown in Figs. 6 and 7. The groundwater inflow was calculated from two water sources, rainfall, and surface water (Hub Dam).

To calculate the amount of groundwater percolation, multiply the surplus amount of precipitation with the coefficient of infiltration potential weighted with the slope (C.I.P.S). The values of infiltration potential coefficients (C.I.P) based on the physical properties of the soil or rock as shown in
Nari and Gaj’s formations comprise of limestone, sandstone, and some part of shale (Ehsan et al. 2018). To remove the impact of the dip on the percolation, the value of C.I.P was multiplied by the slope (%). The general dip angle of the Gaj and Nari formations as per the Geological map of Sindh is $\partial = 50$. The slope is 8.7% and C.I.P.S = 41%.

The surplus water was calculated by:

$$ \text{Water Surplus} = P - E_p $$

where $P$ is Annual Precipitation, $E_p$ is Potential Actual Evapotranspiration.

Annual precipitation on the exposure of Nari and Gaj formations will be taken by the GIS integration method.

The potential evapotranspiration (PET) of neighboring meteorological stations was calculated by the Thornthwaite method (Thornthwaite 1957). Further, the PET of formations exposure will be taken from the GIS integration method. The total water percolates in the formation, called effective rainfall. For the calculation of effective rainfall, multiply water surplus with the C.I.P.S (Viaroli et al. 2018).

$$ \text{Effective Rainfall} = \text{Water Surplus} \times \text{C.I.P.S} $$

The total amount of groundwater recharge will calculate by multiplying effective rainfall by the total exposed area of formations (Cianflone et al. 2015).

$$ \text{Total groundwater recharge by rainfall} = \text{Effective recharge} \times \text{total exposed area} $$

The Hub Dam is the surface water source for groundwater recharge in Nari and Gaj formations. Hub Dam is situated on the southwest end of Karachi city and is geologically situated in the Nari Formation. For recharge calculation, WAPDA provides 20 years’ average water loss data from the Hub Dam by evapotranspiration and seepage. The Hub Dam is an earth-fill dam. Therefore, the seepage is in the sub-surface as well as from the embankment. The potential evapotranspiration of the Hub Dam will also calculate by the Thornthwaite method. The annual recharge from Hub Dam will calculate by subtracting evapotranspiration and embankment seepage from annual water loss.

The groundwater outflow from a hydrogeological system can be divided into a natural discharge and anthropogenic withdrawal (Kresic 2006). Natural discharge in underlying formations is not possible from Nari and Gaj formations because of the confining layer of the Tobo member at the bottom of Nari Formation (Niamatullah and Imran 2012).

### Table 2: C.I.P values (Celico 1988)

| Hydrogeological complexes | C.I.P (%) |
|---------------------------|-----------|
| Fine-grained              | 45        |
| Coarse-grained            | 50        |
| Limestone                 | 95        |

![Fig. 7 Mean annual temperature (°C) of neighboring meteorological stations (period 1999–2018)](image-url)
Anthropogenic discharge of groundwater is for different uses like withdrawal for irrigation, domestic and industrial purposes (Kresic 2006).

The quantification of the agricultural withdrawals is one of the most essential and complicated terms of the water budget to be quantified (Tsanis and Apostolaki 2009). In the study area, only 3,638.00 m² of agriculture fields are present. They were using the water of the Layri River and Karachi Water and Sewerage Board (KWSB) for irrigation.

For domestic purposes also use groundwater from these formations in the SITE sub-division, North Karachi sub-division, Orangi sub-division, and Pir-Mango sub-division and the population of these sub-divisions is 404,757.00, 871,232.00, 520,609.00 and 713,753.00 persons, respectively (GOP 2017).

For domestic purposes, in southwest England, 113 Gallons per person of water was used (Hall et al. 1988), 45,173 gallons per day of water was used in America (Mayer et al. 1999). It is assumed that 90 Gallons of water were used by each person in a day to calculate average water consumption in the study area. KWSB is providing 5,606,484,363.67 gallons per day of water was used in America (Mayer et al. 1999).

Groundwater mapping

For the exploration of groundwater use Vertical Electrical Sounding (VES) as a geophysical exploration method. The configuration of the Schlumberger electrode array was widely used for VES (Alile et al. 2010). The Schlumberger array is a linear type. The low-frequency direct current was produced on the field by helping of energizers or storage batteries and the current was introduced into the sub-surface with the help of two metal electrodes. With the help of the other two metal electrodes receive the current and also measure voltage difference. The voltage difference uses to calculate the resistivity of the sub-surface. Rock has a wide range of resistivity; the sub-surface electrical resistivity is depending upon the material of rock and the presence of liquid (Fetter 2018).

The PASI 16GL-N electrical resistivity tool was used for Electrical Resistivity Survey (ERS). The maximum spacing between AB electrodes is 300 m, and a minimum of 100 m, spacing was selected based on the available area. Thirty probes of ERS were taken in the survey. For inverse models of apparent direct current resistivity surveys with depth and variation of resistance with depth are developed by IPI2WIN software (Siddalingamurthy et al. 2014).

The static groundwater level was noted by inserting an electric probe in the well. When the circuit had been completed, the buzzer responded and then note the length of the probe that shows the depth of water level from the existing ground level.

Climate trend index

The Standard Precipitation Index (SPI) is a widely used index to characterize meteorological drought on a range of timescales. On short timescales, the SPI is closely related to soil moisture, while at longer timescales, the SPI can be related to groundwater and reservoir storage. The SPI can be compared across regions with markedly different climates (Guttman 1999). Hence, for analysis of the drought period, SPI is used. SPI is described in Eq. 7. The SPI was intended to quantify the deficit of precipitation for different timescales according to the water resource sub-tleties (He et al. 2015).

SPI was written as:

$$\text{SPI} = \frac{\text{Monthly amount of rainfall} - \text{Arithmetic Mean of Rainfall}}{\text{Standard Deviation}}$$

(7)

Results and discussions

According to the Pakistan Council for Research in Water Resources (PCRWR), 86% of water sources (surface and groundwater) are polluted with Coliform and are dangerous to consume. The Karachi Water and Sewerage Board (KWSB) provides roughly 665 million gallons per day (MGD) of water against a demand of 820–1200 MGD, resulting in a 155–535 MGD shortage. Unfortunately, approximately 35% (232 MGD) of the provided water is lost during transmission, reducing the available water to only 433 MGD (WWF 2019). To overcome water storage in Karachi the viable solution is to use additional Indus River water. River Indus is Karachi’s primary source of fresh water, and its availability varies annually; during the dry period, the overall system is under stress, whereas sufficient flows are available during the wet season.

For inflow calculation thermos-pluviometric data will use because groundwater in the terrain underlain by crystalline rocks is governed by several geo-environmental factors, viz., rainfall, topography, geomorphology, lithology, structure, soil, organization of drainage network, land use/land cover as well as the aquifer parameters (Achu et al. 2020b). The groundwater inflow zones in the basin are delineated by using remote sensing and GIS (Achu et al. 2020a). Groundwater level maps of the SITE sub-division will be prepared by the Direct Current Resistivity method and water level measurements by water wells and the climate trend values are estimated. Rainfall and annual potential evapotranspiration data of respective meteorological stations compute the total annual precipitation and annual potential evapotranspiration from the exposure of Nari and Gaj formations. The
total annual rainfall on the formation in the last 20 years ranged from 28.15 mm in 2018 to 335.00 mm in 2011 (Fig. 8). At the exposure of Nari and Gaj formations, the annual average PET is ranging between 274 and 178 mm in the last 20 years (Fig. 9).

The surplus water is only in 2003, 2006, 2007, 2008, 2010 & 2011 and the maximum value was 155.23 mm in 2011 and the minimum value is 10.15 mm in 2007. The water deficit is marked in other years as shown in Fig. 10.

The effective rainfall was marked only in 6 years, having surplus water. The minimum effective rainfall was 4.16 mm in 2007, and the maximum was 63.64 mm in 2011 as shown in Fig. 11.

The total exposed area of formations is 6287.94 km². The maximum groundwater recharge encountered in 2011 is 3352.341 US Gallons per Second, and the minimum groundwater recharge in 2007 is 219.281 US Gallons per Second (Fig. 12). The groundwater recharge by rainfall occurred in the 6 years (2003, 2006, 2007, 2008, 2010 & 2011). In the other 14 years (1999, 2000, 2001, 2002, 2004, 2005, 2009, 2012 to 2018), groundwater recharge considers zero due to the water deficit (Scanlon et al. 2002). The total groundwater recharge value by rainfall is below 500 US Gallons per Second in 2007, 2006, 2007, and 2008, while in 2003 is 1578 US Gallons per Second and in 2011 is 3352 US Gallons per Second.

**Surface water (Hub Dam)**

Surface water losses occur due to a variety of anthropogenic processes, such as increasing water abstraction, groundwater exploitation, land drainage, and increased evaporation, which could occur in urban areas like Karachi and damages freshwater ecosystems (Rodell et al. 2018; Palazzoli et al. 2022). The Hub Dam has been loosed 2235.2 US Gallons of water per year due to seepage and evapotranspiration.
Fig. 10 Annual rainwater surplus/rainwater deficit (period 1999–2018)

Fig. 11 Effective rainfall (period 1999–2018)

Fig. 12 Groundwater recharge in Nari and Gaj formations by rainfall (period 1999–2018)
The average monthly temperature of Hub Dam in the last 20 years was ranging from 33 to 19 °C. Thus, the average annual potential of evapotranspiration had been ranging between 19.71 and 16.08 cm. Meanwhile, the water seepage from the embankment of Hub Dam was 0.672 US Gallons per Second (Arshad and Babar 2014). Due to a little amount of water seeping out from the embankment; therefore, the seepage from the embankment is neglected. So, the maximum annual recharge of water in formations from Hub Dam is 2102.67 US Gallons per Second in 2002 and the minimum recharge is 2077.95 US Gallons per Second in 2018 (Fig. 13). Annual groundwater recharge and potential evapotranspiration from Hub Dam (period 1999–2018) are shown in Fig. 13.

In the case of the Nari and Gaj formations, the total groundwater inflow is the sum of recharge from rainfall and Hub Dam. The groundwater inflow was ranging from 2076.17 US Gallons per Second in 2009 to 5446.57 Gallons per Second in 2011. The annual groundwater recharge in 2003, 2006, 2007, 2008, 2010 & 2011 is respectively higher than the other years (1999, 2000, 2001, 2002, 2004, 2005, 2009, 2012 to 2018) due to the recharge of groundwater from rainfall as shown in Fig. 14.

Outflow

The outflow of groundwater from Nari and Gaj formations is mainly in Karachi city. In Karachi city, four subdivisions (SITE, Orangi, Pir-Mango, and North Karachi) are located on them. Moreover, three large industrial areas (SITE Industrial Zone, Pir-Mango, and North Karachi) exploit groundwater from these formations. The total population in these areas is 2,510,351 persons and industries are 5800. All the mentioned populations and industries use 5,740.39 US Gallons per Second as mentioned in Table 3 (GOP 2017).

The total amount of water used for domestic and industrial purposes was 5740.39 Gallons per Second. The total amount of water provided by KWSB and other sources as mentioned in Table 4 was 177.78 Gallons per Second. The amount of groundwater exploitation from Nari and Gaj formations is 5562.61 Gallons per Second.
In 2018 inflow of water in Nari and Gaj formations was 2070.41 US Gallons per Second and the outflow was 5562.64 US gps. These values show −3492.23 US gallons per second inflow.

**Groundwater mapping**

The study area contains 58% A-Type, 36.4% K-Type, and 5.6% H-Type sub-surface class (Table 5). The A-type curves are present in five Union Councils that show the absence of water in deep aquifers. So, there is a possibility of the water in shallow wells. In the other two Union Councils, the sub-surface is classified as K-Type. The K-Type shows that deep aquifers have good potential for water with concerns of shallow aquifers (Siddalingamurthy et al. 2014).

**First layer resistivity, thickness, and depth**

In the first layer of the sub-surface based on apparent resistivity, the minimum value of resistivity is 1.0 Ω-m and the maximum value is 10,000 Ω-m. The thickness and depth of this layer vary from 0.47 to 6.03 m. In six Union Councils, the resistivity value ranges from 100 to 10,000 Ω-m, and only in the Allama Iqbal Colony, the resistivity value ranges between 1.0 and 10,000 Ω-m. The thickness and depth of this layer in the five Union Councils are between 0.466 and 2.23 m and in the other Jahanabad and Golimar Union Councils, the thickness and depth are 0.466–6.02 m and 0.0466–4.17 m respectively.

**Second layer resistivity, thickness, and depth**

In the second layer of the sub-surface based on apparent resistivity, the minimum value of resistivity is 1000 Ω-m and the maximum value is 100,000 Ω-m. The thickness of this layer varies from 0.16 to 170.0 m and its depth 1.83–176.0 m. In five Union Councils, the apparent resistivity value ranges between 10,000 and 100,000 Ω-m in three Union Councils and in other Union Councils 1000–100,000 Ω-m. The thickness of this layer in five Union Councils is between 0.165 and 56.8 m. In Metrovile Union Council, its range is 0.165–170.0 m and in Old Golimar, it is 0.75–113.0 m. Furthermore, the depth of this layer in the three Union Councils ranges from 1.83 to 59.9 m, in another two Union Councils (Pak-Colony, and Frontier Colony) depth is 1.83–118.0 m and in Metrovile and Old Golimar Union Councils the range of second layer depth is 1.83–176.0 m.
The third layer of the sub-surface has resisted from 1000 to 100,000.0 Ω-m. In six Union Councils, it ranges between 1000 and 100,000 Ω-m. While in Allama Iqbal Colony, it was 10,000–100,000 Ω-m.

**Measurements by water wells**

The static water table was measured from 30 water wells. Groundwater table or static water table in industrial and domestic wells having a depth of 150–300 m was measured with respect to existing ground level (EGL). These wells were located near electric probes. The static water level in the study area ranges between 30 and 130 m from the existing ground level (Fig. 15).

In the south (Allama Iqbal Union Council) of the study area having a groundwater table 70 m deep from the existing ground level. Towards the Southeast, in Jahanabad Union Council the groundwater table is at 80 m. In the Northeast of the study area, in Old Golimar and Pak-Colony Union Council groundwater table was at 70 m and 80 m respectively. Furthermore, in the North direction, in Frontier Colony Union Council the water table was at 60 m and the same as in the Metrovile and Bawani Chali Union Council the water table was at 100 m. While in the center of the sub-division to the western side is marked as a major industrial zone having a water level of 130–90 m (Table 6).
Climatic trend analysis

The computed standardized precipitation index (SPI) value (Fig. 16) shows the spells of drought and wet periods of precipitation as per the classification (Tigkas et al. 2015). SPI is considered an indicator that eliminates the temporal and spatial variation in rainfall during a specific period through easy calculation and stability in a certain region (Liu et al. 2021). In the last 20 years, from 1999 to 2018, only 2002, 2003, 2005, 2006, 2007, 2008, 2010, 2011, 2013, and 2018 are mild wet and the other 10 years are classified as a mild drought climate (Table 7).

Groundwater depletion trend

In the study area, the groundwater depletion trend shows that the water table in 1999 was 6 m, and in 2018 it was 130 m. These values show the groundwater table going down continuously (Fig. 17). The data were collected by taking short interviews with drillers and other relative persons.

A brief review of the groundwater level and groundwater table maps was prepared with the help of a direct current electrical resistivity survey and the commercial and domestic wells, respectively. The current study finding validates the research with the help of climate trend analysis and the groundwater depletion trend.

This study uses low-quality data set of thermo-pluviometric data along with the annual groundwater level for the last 20 years. The reason for selecting low-quality data is the research gap and the absence of Government or private department those monitors the groundwater level.

Table 6 Static water level in union councils of the study area

| Union council   | Existing ground level (EGL) (m) |
|-----------------|----------------------------------|
| Frontier Colony | 60                               |
| Bawani Chali    | 100                              |
| Metroville      | 100                              |
| Pak Colony      | 80                               |
| Old Golimar     | 70                               |
| Jahanabad       | 80                               |
| Allama Iqbal    | 70                               |

Table 7 Climatic trend analysis table (Tigkas et al. 2015)

| S. no | Classification     | SPI value |
|-------|--------------------|-----------|
| 1     | Extremely wet      | 2.0 <     |
| 2     | Very wet           | 1.46 < 2  |
| 3     | Moderately wet     | 1. < 1.46 |
| 4     | Mild wet           | 1 < 0     |
| 5     | Mild drought       | 0 < − 1   |
| 6     | Moderately drought | − 1.5 < − 1|
| 7     | Severe drought     | − 0.2 < − 1.5|
| 8     | Extremely drought  | < − 0.2   |

Fig. 16 SPI values of Nari and Gaj formations exposure (period 1999–2018)
Groundwater budgeting

The groundwater budget is considered a preliminary tool for studying water deficit and its socio-economic impact (Zhou 2009). In this study, by calculating the inflow and outflow of groundwater from respective formations, make a conceptual groundwater budget as a preliminary tool. Like in Italy, groundwater budgeting is applied as a preliminary tool for water management. Thus, the groundwater budget is not ever a reliable source for groundwater management, but it is necessary for processed research work and developing a hypothesis (Viaroli et al. 2018). The groundwater budget is examined with the help of every possible inflow and outflow source. Furthermore, validate the results with the help of the groundwater level trend and the climate trend index.

Inflow of groundwater

Scanlon et al. (2002) explain two basic sources of groundwater recharge. The first source of recharge is the surface water, which includes rainwater, streams, channels, etc. and the other source is from adjacent aquifers. In this study, the groundwater recharge was estimated by rainfall and from Hub Dam. It is considered that no lateral inflow in the formations from adjoining hydrogeological systems due to the unconfining nature of formations that provide detachment for all surrounding thrust faults. Like, one of the major thrust faults in Nari and Gaj formations is the Pir-Mango fault and in this fault, a thick layer of Tobo Formation and Metan clay provides detachment (Niamatullah and Imran 2012).

There are different techniques of recharge explained based on the saturated and unsaturated zone. While in arid and semi-arid regions for groundwater recharge, the most suggested technique is unsaturated zone-based techniques (Scanlon et al. 2002). The under-study formations are exposed to arid to the semi-arid climate. That is why unsaturated zone-based techniques were selected for recharge estimation.

Rainfall

In the Swash groundwater budget, the inflow is measured by rainfall (Peterson 2014). The groundwater recharge from rainfall depends upon the amount of precipitation, evapotranspiration, slope, type of soil cover, or exposed rock type and type of vegetation (Al Kuisi and El-Naqa 2013). In the study area, due to the high annual temperature and exposure to rock, the vegetation cover is very low. Therefore, the vegetation was neglected.

The (Viaroli et al. 2018; Celico 1988) show in their research papers, the annual evapotranspiration is changing with the change in climate trend as well as the total annual precipitation was also affected by it. According to them, in Italy, there are many spells of surplus and deficit water in their respective basins based on evapotranspiration and precipitation. In the area of investigation, also the annual potential evapotranspiration and annual total precipitation have oscillated with the change in climate trend. The average annual potential evapotranspiration in the last 9 years (2002, 2003, 2005, 2008, 2010, 2011, 2012, 2014 and 2017) equaled to or less than 200 mm and in the remaining 11 years out of 20 years (1999–2018) have evapotranspiration greater than 200 mm. As well as the annual rainfall in 2003, 2006, 2007, 2008, 2010 and 2011 had equal to and higher than 200 mm and the other remaining years out of the past 20 years (1999–2018) annual rainfall was less than 200 mm.

The annual evapotranspiration and total annual precipitation are affected by climate change. Furthermore, they are reasons for the water surplus and deficit (Tilahun and Merkel 2009). In the present work, the water surplus was found only in 6 years (2003, 2006, 2007, 2008, 2010, and 2011) out of 20 years. In 4 years (2006, 2007, 2008 and 2010) water surplus was less than 50 mm per annum and in 2003, the surplus water was 73 mm, and the maximum surplus water was 2011, 155 mm. To verify the values of surplus and deficit make a comparison curve (Fig. 18) that shows with a decrease in precipitation rate, the deficit was increased and with an increase in precipitation, the surplus water was increased. The annual potential of
evapotranspiration also oscillates but its oscillation does not trigger the water surplus and deficit values.

The Swash basin’s groundwater budget shows that there are alternate spans of groundwater recharge and drought periods (Peterson 2014). In this research work also the spans of groundwater recharge and drought periods were encountered in 14 years (1999, 2000, 2001, 2002, 2004, 2005, 2009, 2012 to 2018) groundwater recharge was zero due to water deficit. While in the remaining 6 years (2003, 2006, 2007, 2008, 2010, and 2011) the groundwater was recharged. In 2007, 2006, 2010, and 2008, the recharge value is 219.18, 260.48, 458.49 and 539.89 US Gallons per Second, respectively. Moreover, in 2003 it was 1578.16 US Gallons per Second and the maximum recharge was encountered in 2011 was 3352.34 Gallons per Second. In 2003 and 2011, the climate was mild wet, but high evapotranspiration is the reason for low recharge in 2003 with respect to 2011 (Fig. 18).

In southern Spain, the rainfall was recharged by only 3% of total groundwater withdrawal (Martín-Rosales et al. 2007). In the area of investigation, the rainfall provides 5.58% of the total amount of groundwater extraction from the reservoirs.

**Hub Dam**

Surface water sources play an essential role in groundwater inflow. In the Jefferson Basin of Montana, the groundwater level oscillation follows the inflow of water from running streams and ponds (Brancheau 2015). In the study area, only the Hub Dam exists as a surface water recharge source. The water storage capacity of Hub Dam is 2.137 e + 11 Gallons of water.

As the location Hub Dam is in between the metrologic station of Karachi and Lasbella. The potential of evapotranspiration of the Hub Dam was computed by using the ArcGIS integration method and it was 255.37 US Gallons per Second. The other remaining water was seeping into the sub-surface 1979.8 US Gallons per Second water was percolated into the sub-surface.

Al-Khud dam in Oman is the major source of groundwater in nearby areas. It provided 40–50% of groundwater discharge from nearby areas (Abdalla and Al-Rawahi 2013). In southern Spain, 107 Dams provide more than 50% of the total amount of water usage (Martín-Rosales et al. 2007). While in the investigation area, the Hub Dam provides only 37.4% of groundwater.
By comparing both values of inflow parameters average annual percolation from rainfall (325 US Gallons per Second in 20 years) and average annual recharge by Hub Dam (1979.8 US Gallons per Second). Furthermore, the total average annual recharge is 2,304.8 US Gallons per Second.

In this research work, 87% of total groundwater recharge is done by Hub Dam, and the other 13% is by average rainfall in the last 20 years (Fig. 19a). These values show that there is groundwater recharge by Hub Dam much higher than the rainfall. Thus, the Hub Dam is the major source of groundwater recharge.

Outflow of groundwater

The outflow of groundwater should be divided into two categories, anthropogenic and geogenic outflow. The anthropogenic outflow included domestic, industrial, and agricultural use. While the geogenic outflow includes spring and into attached or underline formations (Viaroli et al. 2018; Akhtar et al. 2016). In the present study, the geogenic outflow has been neglected. This neglect is due to unconfining layers at the top and bottom of Nari and Gaj formations. As well as the major faults bound these formations were detached from the unconfining layers or thick clay beds (Niamatullah and Imran 2012).

The groundwater budget has been majorly affected by anthropogenic outflow. The over-exploitation of water was the reason for groundwater level depletion and caused a shortage of water storage in the aquifer (Cao 2011). In this study, the anthropogenic outflow had been encountered as the major component and reason for the water level deficit.

The groundwater of Nari and Gaj formations is being used for domestic and industrial purposes in Karachi city. KWSB also supplies tap water all over the city through pipelines. The KWSB provides only 50% of the city water demand. Illegal sources also supply water in Karachi. All of these activities do not fulfill the requirement of water for domestic and industrial purposes. To fulfill the water needs for domestic and industrial purposes uses groundwater in Karachi. In the under-study areas, those situated in the Nari and Gaj formations the industries use 52% of total groundwater withdrawal while the domestic purpose uses 48% of total groundwater usage (Fig. 19b).

Water budget

Based on the difference between inflow and outflow, the groundwater budget is classified into three classes: the first class is a positive budget in which the inflow is higher than the outflow, the second class is a normal or zero budget in this condition the inflow is equaled to outflow, and last or third class of groundwater budgeting is negative budgeting here the inflow is less than the outflow. In the third-class condition, the groundwater table will deplete (Zhou 2009).

The groundwater planning of Riardo Basin Italy shows a 40% of water shortfall (Viaroli et al. 2018). Same as in this study, groundwater release was assessed uniquely in 2018 from the modern and household regions established

![Fig. 19 a Comparison of groundwater recharge by Rainfall and Hub Dam. b Groundwater usage percentage for industrial and domestic purposes from understudy formations. c Water provided by KWSB and total groundwater use in SITE sub-division. d Groundwater usage percentage for industrial and domestic purposes from Nari and Gaj formations](image-url)
on the hydrogeological arrangement of Nari and Gaj formations. The groundwater discharge had been 5,562.61 US Gallons per Second. While for groundwater recharge estimation use thermo-pluviometric information for the most recent 20 years from 1999 to 2018. In this way, the mean yearly groundwater recharge over the most recent 20 years was 2414.1183 US Gallons every Second. These amounts of Gallons per Second water inflow and surge the ordinary yearly groundwater lack was 3148.5 US Gallons consistently. Therefore, the inflow of water is about 56% of the total outflow.

**Groundwater maps**

The groundwater level is the uppermost layer containing water. This layer in the unsaturated zone is influenced by anthropogenic and geogenic activities. In the summer season, at the seashore or coastal areas and water channels toward the coastal side, seawater surge in and disturb water quality and rises water level (Mohal et al. 2006). Moreover, drain channels, and sewerage water percolated into the upper unsaturated zone and disturbed water quality. In the study area, on the eastern side from north to south by the Lyari River, which is flowing down and fluid in the sea Southeast of the study area and in the South of the study area sea is present, the alluvium of these two portions was affected. In summer high tides, the water level of alluvium in the South was nearer to the surface while in winter, the level was going down. However, it was not affecting groundwater due to the impermeable layer of Manchar Formation (clay) and on the Eastern side, also upper unsaturated zone was disturbed by the Lyari River. While in some other parts, the unsaturated zone is disturbed due to anthropogenic activity by leakage of industrial and domestic drainage lines, underground water tanks, etc. The saturated zone of water influences the groundwater table. In the SITE sub-division, it was encountered in confined aquifers. For making a groundwater level map, a direct current electrical resistivity method was used, and static water levels were prepared the groundwater table in industrial and domestic wells.

**Groundwater level map**

Considering of apparent resistivity between each spacing of electrodes, the quantitative interpretation of ERS was done. Unpack the distinct topographical layers into three segments, based on the model curve. The apparent electrical resistivity of geological layers obtains from the model curve. In the case of three geological layers, there were four possible classes based on apparent resistivity (Devi et al. 2001).

- A-Type = \((\rho_1 < \rho_2 < \rho_3)\)
- K-Type = \((\rho_1 < \rho_2 > \rho_3)\)
- H-Type = \((\rho_1 > \rho_2 < \rho_3)\)
- Q-Type = \((\rho_1 > \rho_2 > \rho_3)\)

The A-Type of values shows that the top layer is conductive soil while below the soft layered hard rock is present. K-Type representing the top and bottom layers are conductive while the central portion is highly resistive. H-type values indicate the first layer is dry or high resistive soil while the second layer is low resistive, and the third layer is a hard rock. Furthermore, the last Q-Type curves show the values of the coastal region (Siddalingamurthy et al. 2014).

Based on the classification of the sub-surface, the study area can be divided into two wide parts. One has top low resistive soil of unsaturated zone, the second and third layer is relatively high resistive due to dry or compacted rocks, and this part is classified as A-Type. The second part is K-Type, first and the third layer is highly resistive and has hard rock, while the central or second layer was marked as low resistive relative to other layers. The straight-line curves show A-type sub-surface with hard bedrock (Devi et al. 2001) and the high resistivity in K-Type curves is due to top dry soil and third layer hard bedrock (Gnanachandrasamy et al. 2016). In A-type, the first layer and K-Type, the second layer is consisting of alluvium or sandstone and other layers having high resistivity consist of hard rock.

Before discussing the apparent resistivity values and their depth, is needed a short review of the impact of urbanization on the unsaturated zone. In urban areas for water supply and drainage systems, pipelines were used. These pipelines have some leakage of water into the upper layer of the unsaturated zone, but the depth and amount of percolation are very low (Yang et al. 1999). In this research work, the average depth of the first sub-surface layer is 1.35 m. While in residential areas low apparent resistivity was measured in industrial areas. Although, this layer was marked as urban water system leakage in the unsaturated zone, and it is not a part of the groundwater system.

The apparent resistivity of the second and third layers the resistivity has two ranges 1000–10,000 Ω-m and other ranges 10,000 Ω-m and 100,000 Ω-m. The first range shows dry sandstone, dolomite, and limestone, and the second range represents dry dolomite and limestone (Goldman and Neubauer 1994). These values show that there is not any water-bearing zone till the investigation depth (250 m).

**Groundwater table map**

Based on the water table and type of zone, the study area was divided into two major portions residential and industrial zones. The residential zones are Frontier Colony, Pak-Colony, Old Golimar, and Allama Iqbal and the industrial zones are Bawani Chali, Metroville and Jahanabad Union Councils. In these zones. The average water table in residential areas is
In a hydrogeological system, the overexploitation of groundwater is encountered in industries and urbanization. Another reason for groundwater depletion is a low groundwater recharge rate in the arid climate. To fulfill water needs in arid climate areas mainly groundwater is used. Like in Iran’s arid climate areas, 80% of water need is fulfilled by groundwater and this groundwater withdrawal scenario is approximately the same in developed countries (Ahmadi and Sedghamiz 2007). The study area is part of the arid climate and there is 96% of the total water need is fulfilled by groundwater, and KWSB provides the remaining 4%. Of this 96% of groundwater, 77% of the groundwater is used by industries and 23% for domestic purposes (Fig. 19c, d). This high rate of groundwater withdrawal by industries causes dewatering impacts on the hydrogeological system. Therefore, it causes groundwater depletion in industrial areas as well as in surrounding residential areas and disturbs the flow network.

**Accuracy assessment**

**Climate trend analysis**

The groundwater infiltration and its effect are the direct evidence by making a relationship between SPI calculated by rainfall and groundwater recharge values (Viaroli et al. 2018). In this research, the groundwater recharge is validated by making a relationship between total groundwater recharge and climate index trend (SPI). From 2002, 2003, 2005, 2006, 2007, 2008, 2010, 2011, 2013, and 2018 the values show mild wet and the other 10 years mild drought season. Finally, the values of groundwater recharge and climate change index define the increase in groundwater recharge by increasing the SPI value in the mild, wet season (Fig. 20).

**Groundwater depletion trend**

Groundwater depletion is the most reliable indicator of negative budgeting (Viaroli et al. 2018; Mazza et al. 2014). In the study area, for the last 20 years, groundwater depletion is going on, and it started at 6 m depth and nowadays, it is at 130 m (Fig. 21). These values show there is a difference between inflow and outflow which leads the groundwater table depletion as the indicator of the negative groundwater budget.

The groundwater depletion trend is followed by rainfall and evapotranspiration. Therefore, it is tightly linked with groundwater recharge by rainfall and oscillates along with dry and wet seasonal cycles (Marandi 2012). Here, in 2002, 2005, and 2007 the groundwater level was raised and in 2009 and 2011, the groundwater level remained stable with the increase in the recharge rate. In other years the groundwater level was going down due to the absence of groundwater recharge by rainfall. While the recharge by Hub Dam is remained constant at approx. 2000 US Gallons per Year. In this study also the oscillation of the groundwater table follows the annual recharge by rainfall, rather than the surface water source adding a major role in the groundwater.

For the groundwater budgeting, the aquifer properties of Nari and Gaj formations remain constant throughout assume. Due to formations exposure, there are hard rocks, so the vegetation on these types of rocks is negligible. Therefore, the impact of vegetation was neglected throughout the study. In outflow, the calculation assumes that no village exists on it.
Conclusions

In Karachi, especially, the SITE sub-division is facing a serious issue of groundwater due to unplanned industrialization, urbanization, and high groundwater exploitation. The groundwater budget analysis shows negative budgeting because of the high discharge rate and low recharge rate of the groundwater. The Nari and Gaj formations groundwater budgeting highlights the deficit of groundwater recharge by rainfall ranging up to ~25% as compared to potential evapotranspiration. Therefore, groundwater recharge was approximately zero. Furthermore, the total annual deficit is ~64%. In contrast, in 2008, due to the mild wet season, the total groundwater deficit reduced to 47% because of 14% surplus water in the rainfall after subtracting by evapotranspiration. In the study area, 36% of groundwater contributed by Hub Dam acted as a key factor in groundwater recharge.

In a broad spectrum of 20 years, the groundwater table of the study area shows annual oscillation according to the variability of groundwater recharge by rainfall. Furthermore, the quantitative comparison of the total discharge rate with the groundwater levels seems to depict a direct relationship (in 2009 and 2010, the groundwater level remains stable). Finally, although the aquifer outflow is greater than the total recharge. The rainfall still triggers the depletion of the water table in the aquifer, despite the surface water source contributing a major part of groundwater inflow.

The direct current resistivity values have shown that in the SITE sub-division till 250 m, no water-bearing formation or water potential zone exists. The groundwater table map shows the water level in industrial areas is between 130 and 100 m, while in residential areas it was starting from 30 to 60 m. The trend of groundwater depletion from the last 20 years shows that in 1999, the water level was 6 m and with time it was going down in 2004 it was 40 m; in 2009 it was 99 m and now in industrial areas, it was 130 m if the recharge rate of groundwater will not exceed, and discharge also remains constant in 2030 the water table will be approx. imitated at 150 m.

Recommendations

I. To make a more realistic model, further investigation for flow direction is needed to study nearer hydrogeological structures.

II. To understand recharge, stable isotope analysis is needed.

III. Adoption of modern groundwater artificial recharge methods like the construction of surface water reservoirs, recharge wells, and injection of treated industrial fluid.

IV. To overcome the groundwater problem, legislation is required for maintaining groundwater exploitation. It is recommended that the concerned departments like Karachi Development Authority, Karachi Water and Sewerage Board, the Karachi Municipal Corporation, and Ministry of Municipality must take concrete steps to solve the issues by strong coordination and sharing information and proper future planning for Karachi City.
Acknowledgements The authors would like to thank Mr. Faizan Ahmed (CEO BNB Enterprises) for his guidance, advice, motivation and especially for providing survey instruments and relevant data sets. We are also extending thanks to PBS, PMD, KWSB, WWF, and the SITE association for their facilitation and data providing. Without their continued support and interest, this work would not have been the same as presented here. The work is also submitted to HEC, Pakistan repository.

Funding Open access funding provided by Lulea University of Technology.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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