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The Hydrogeological Conditions in Islamabad in the Context of Groundwater Footprint
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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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Case study

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ABSTRACT

In Islamabad (Pakistan), surface water and groundwater extract water from shallow alluvial sediments are the sources of water supply. The direct research on hydrogeological conditions in Islamabad, carried out in 2020, included chosen hydrogeological field studies, physicochemical analyses of groundwater, surface water, precipitation and the investigation of and sediments permeability. The purpose of the hydrogeological research was to join the discussion on groundwater hazards and to recommend actions to overcome problems related to water supply. The study results indicate lithological heterogeneity of shallow aquifer, vertically and spatially variable, good chemical status of groundwater and groundwater recharge constituting 10 to 20% of annual precipitation. The groundwater is characterized by a high groundwater footprint, from 5747.8 to 11495.6 km^2 depending on recharge variant, documenting the threat to the water. The research results made possible to present recommendations to protect groundwater and water management in Islamabad.

Keywords: Islamabad; Pakistan; groundwater; groundwater circulation system; groundwater footprint.

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1. INTRODUCTION

Given the international standards for safe drinking water [1], it is available to only 25.61% of Pakistan's population [2-3]. It is estimated that about 10% of Pakistan's population does not have access to safe drinking water at all. The water demand in Pakistan is estimated to increase annually at a rate of 10%, which is projected to reach 338 billion cubic metres by 2025 [4-5].

In Pakistan, groundwater (GW) is of strategic importance due to the constantly growing demand for water: in agriculture, households and industry [6-8]. Groundwater accounts for 97% in the drinking water supply [3]. Agriculture, the main branch of the state economy, requires constant access to groundwater [9], also due to the bacteriological contamination of surface water; the groundwater abstraction is increasing [10]. The private tubewell density per 1,000 hectares in Punjab has increased from 3 to 46 since 1965, with a significant increase in the number of wells over the past decade [6, 8-9, 11].

The purpose of the hydrogeological research was to join the discussion on groundwater hazards and to recommend actions to overcome problems related to water supply for residents of a large agglomeration in Pakistan. Studying lithology of surface sediments, as well as hydrogeological conditions, allowed indicating groundwater circulation systems against the background of a broader context of hydrogeological conditions. Groundwater resources is convenient availability close to where water is required, the natural quality of groundwater is usually better than that of surface water, and the possibility of developing for their protection development, is usually more easily for ground-water than for surface water. This is particularly important in Islamabad, the capital of Pakistan, which is struggling with the problem of protecting and managing water resources, including groundwater resources. The research results also made possible to present recommendations along with a proposal for further research to protect waters in Islamabad.

Problems related to the groundwater protection in Pakistan are undertaken in many projects and programs, which result from the geopolitical, economic and social situation of Pakistan [3, 12-15] although the water management is limited by financial and technical considerations. The scope of direct hydrogeological research in Islamabad, including field and laboratory tests, is limited and hence analyses of results are scarce and the groundwater database (also on the monitoring) is modest, including information on the volume of groundwater abstraction.

2.2. Islamabad, Water Supply to the City

Islamabad, the capital of Pakistan, is a modern large city that plays an important political and economic role. It is a new city, planned and built in the 1960s, being the capital city and the seat of country's political authorities since 1966. The city is located at the foot of the Margala Hills north of the "neighbour" Rawalpindi - a city with a long tradition, founded in the late 18th century. Rawalpindi is an industrial, commercial and military centre. Islamabad and Rawalpindi form a metropolitan area in the Punjab province, the most densely populated Pakistan's province. According to the Pakistan Bureau of Statistics, the population of Islamabad has risen from 0.8 million in 1998 to 2 million in 2017, with the current population density of over 2000 persons/km^2 [16]. In Rawalpindi, the number of inhabitants is 2 098 231 with a population density of 8101 persons/km^2 [16-18]. A characteristic element of the entire metropolitan area, especially in Islamabad, is the land development diversity, from densely inhabited areas, to villa districts in the suburbs of the vast city covering an area of 905 km^2 (Fig. 1, Photo 1). The land development and water distribution affect the conditions of protection and contamination of groundwater. The present water demand for Islamabad is estimated to be more than 475 million litres per day (ML/D); however, only 250-280 ML/D is being supplied [19-21].

Groundwater currently accounts for more than 40% of water used for irrigation, especially in Punjab [22-23]. In some regions of Pakistan, there are significant restrictions on access to fresh water, especially in desert areas and those of low precipitation, where brackish water is used for irrigation and to supply residents [7, 13].

In Islamabad, surface water and groundwater are the sources of water supply. Wells that supply the agglomeration extract water from Quaternary alluvial sediments. Only part of the water is treated before it is used for water supply. In 2005, there were five water treatment (filtration) plants in Islamabad, and 26 in Rawalpindi, selected water quality proxies are tested [23]. The Clean Drinking Water Program [24], introduced in Pakistan, has improved the water quality in the metropolitan area by building purification stations and by regular testing of some water quality proxies.

According to reports by the Capital Development Authority (CDA), Islamabad is divided into water supply zones. Simli Dam and Khanpur Dam are major water resources for the capital city of Islamabad. Khanpur Dam also supplies water to the city of Rawalpindi along with the Rawal Dam. The average demand for water in Islamabad and Rawalpindi is about 250,000 m^3/24 h and over 660,000 m^3/24 h, respectively [19]. The amount of groundwater supply to the population is over 100,000 m^3/24 h from approximately 180 public wells in Islamabad, and over 120,000 m^3/24 h from approximately 260 wells in Rawalpindi, pumped for approximately 18-22 hours a day throughout the year [25].

2. CHARACTERISTIC OF RESEARCH AREA

2.1 Climate: Precipitation, Evapotranspiration

The amount of precipitation and its distribution is of basic importance for the assessment of the capacity and intensity of groundwater infiltration recharge and water supply to rivers and reservoirs. Islamabad is located in the monsoon climate zone characterized by intense rains in warm summers and a dry and cool winter period. The rains start in June; the highest intensity is recorded in August, and the rainfall practically ends in September. Much lower monsoon precipitation occurs in March.

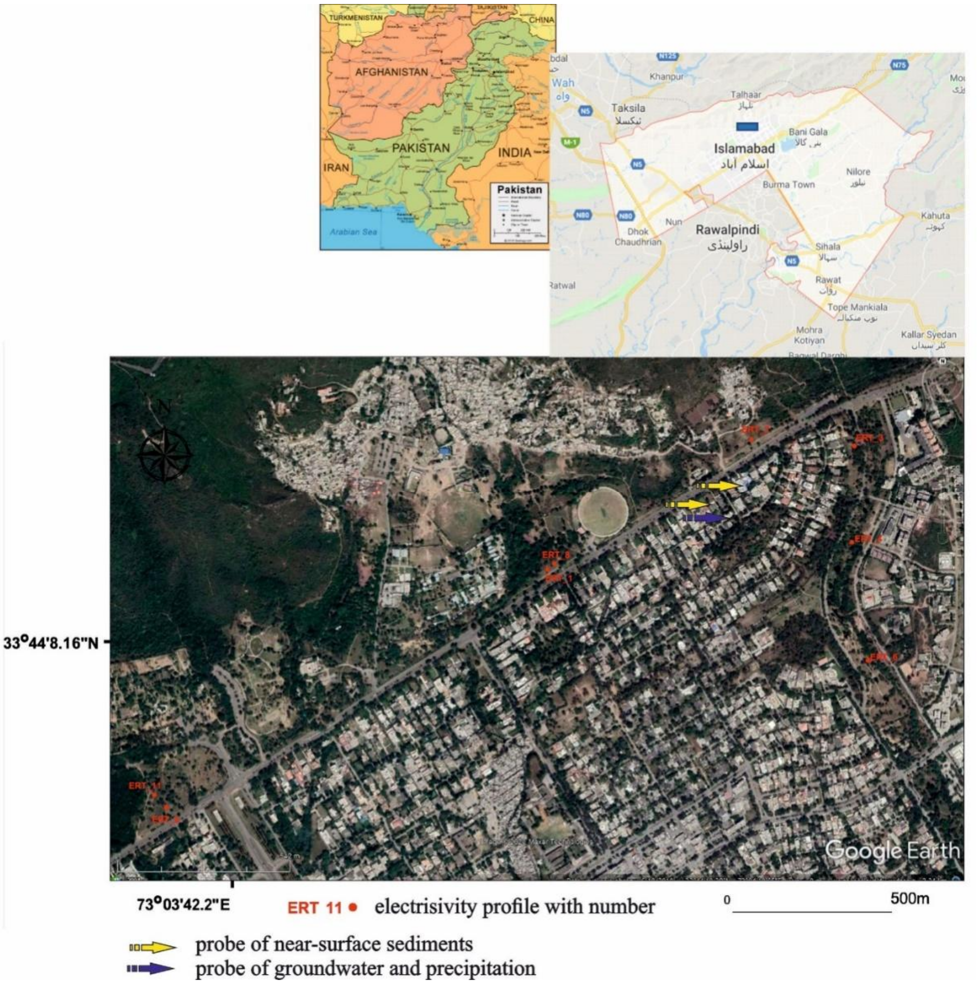

Fig. 1. Location of Islamabad; research location

Photograph 1. Landscaping in Islamabad. A & C – north part of city, B & D – center of city (commercial district) (by E. Krogulec)

The lowest annual precipitation value of 249 mm in 1982, and the maximum rainfall of 1952 mm in 2013. The average annual rainfall in Islamabad for the long-term period 1959 - 2017 is 1175 mm [19, 26-27] (Table 1).

The amplitude of average monthly precipitation amounts to almost 300 mm. The average monthly precipitation is 95.18 mm, ranging from 17.8 mm in November to 309.9 mm in August (Table 1). The highest amount of rainfall is recorded in the July-September period.

Evapotranspiration plays an important role in terms of groundwater loss. According to PMD data, the average evapotranspiration value in the period 2006 - 2015 was between 0.9 mm and 6.8 mm per day, which corresponds to the average annual evapotranspiration of 1283 mm [25, 29-30]. The amount of evapotranspiration varies between individual months. The highest value is recorded in the May-July period - about 140 mm/month. The highest evapotranspiration value was recorded in May - 147.87 mm, while the lowest value was in February - 65.52 mm.

2.2 Outline of Hydrogeological Conditions in the Islamabad Region

The Islamabad area is divided into three geomorphologic/physiogeographic/structural units, showing different terrain reliefs: Margala Hills, foothill area (Piedmont), and river valleys. The geological structure is of fundamental significance for determining hydrogeological conditions especially in the field of infiltration and groundwater circulation systems. The Margala Hills are composed of Jurassic and Miocene limestones and clay shales, bounded by the Hazara fault zone. To the south of the Margala Hills, there is a foothill area made up of rocks of the Rawalpindi Group, covered with alluvial sediments: sands, gravels, loess and clay [31-32]. The geological structure of near-surface deposits is very diverse [27,33]. On the terrain surface, there is the Lei Conglomerate (Middle Pleistocene) consisting of 93% limestones, muds, sands and loams [34-35]. The Lei Conglomerate covers the rocks of the Sivalik and Rawalpindi groups [31]. Locally, there is a layer of the Potwar Clay on the surface [36]. The Potwar Clay (Pleistocene and Holocene) contains an admixture of silt and a small amount of gravel [37] and ranges in thickness from 1 to 35 m, depending on the terrain relief [31]. The foothill area is crossed by several valleys of large river, up to 1.5 km wide, e.g. the Soan River [31-32]. Repeated episodes of changes in rainfall and erosion have resulted in the formation of terraces in the river valleys at several levels. The oldest over-flood terraces (Pleistocene) occur 5 m above the flood terrace level. These are discontinuous covers composed of gravels and sands covering terrain's ridges and peaks. Their maximum thickness is 3 m [31]. The younger terraces (upper Pleistocene and Holocene) are composed of gravels, clays and muds, locally cemented with calcium carbonate. The terraces occur along the present-day river valleys. The thickness of the alluvial sediments is small and amounts to about 3 m; their surface is located about 5 m above the level of current floods. The floodplain (Holocene) is composed of sand and gravel sediments covered with a thin layer of sandy mud and loam originating from periodic flooding and runoff from river banks and slopes. The maximum thickness of the floodplain sediments is about 6 m. The watercourse channels are filled with modern (Holocene) unconsolidated gravels, sands and muds, which are subject to stream transport [31].

The knowledge of hydrogeological conditions of the Islamabad region needs to be completed [38]. There is usually a single usable aquifer characterized by lithological variability, reaching locally a thickness of about 100 m [38]. In the foothill area (Plain), the aquifer is represented by the non-cemented Lei Conglomerate: gravel and sands embedded in finer sediments derived from sandstones and shales of the Rawalpindi Group [31, 34-35,39]. The deposit thickness is 106 m, although there are significantly thick (up to 14 m) loam layers in the section [31, 39], and therefore it is possible to interpret two aquifers. Locally on the surface, there is a layer of the Potwar Clay [36] ranging in thickness from 1 to 35 m, depending on the terrain relief [31]. The mud and loam layers are very prone to erosion, and therefore there deep and extensive are gorges. The aquifer within the river valleys is represented either by alluvial sediments: variously grained and fine-grained sand, mud, loam, and gravelly loam, or locally by gravel layers, 1–20 m thick [40]. The thickness of the aquifer ranges from 2 to 20 m [39]. It is in places subdivided into two water-bearing strata by a layer of poorly permeable sediments [36]. The upper terraces are covered with gravel, fine-grained sand, mud, and locally by a loess cover.

In general, the aquifers of the study area are unconfined [8,39] like other aquifers in Punjab, but locally they may be confined. In Islamabad, 21 hydrogeological wells [39] have been drilled to determine the water table level. The depth to the groundwater table is very variable, which is related to the geological structure. The average depth to the groundwater table is over 8.5 m, although the maximum can be more than 19.5 m. In flood terraces, the depth is small, averaging 2 m [39].

2.3 Groundwater Quality and Qualitative Assessment

The factors determining the quantity and quality of groundwater in Islamabad can be categorized into anthropogenic and natural. Land use directly affects the groundwater recharge rate, including rainwater infiltration, evapotranspiration and other elements of the groundwater balance [29, 30, 40-45]. Natural factors include, predominantly lithology of the saturation and vadose zones, water residence time in the aquifer, infiltration conditions, climatic conditions, and extreme phenomena such as floods and earthquakes.

Table 1. The amount of precipitation and evapotranspiration [28]

Precipitation	Value [mm]	Remarks
Annual total	1175	Period 1957-2017
Monthly average	95.18	Based on data from period 1957-2017
Monthly maximum	309.9	August
Monthly minimum	17.8	November
Monthly amplitude	292.1	August - November
Jun-Oct (average)	826	Six months
Nov-May (average)	350	Six months
Evapotranspiration	**Value [mm]**	**Remarks**
Annual total	1283	Period 2000-2015
Monthly average	95.18	Based on data from period 1957-2017
Monthly maximum	147.87	May
Monthly minimum	65.52	February
Monthly amplitude	292.1	May-February
Jun-Oct (average)	826	Six months
Nov-May (average)	350	Six months

There is virtually no quantitative groundwater monitoring system in Pakistan, except for some data (number of wells) collected by the Pakistan Bureau of Statistics (PBS) [46]. In large cities of Pakistan, such as Rawalpindi, Islamabad, Lahore, etc., water distribution takes place through the Sanitation Agencies called WASA, which is obliged to provide drinking water of appropriate standard, and manages sewage drainage and rainwater discharge systems in the cities [17, 30, 32, 47-48]. Pakistan Council of Research in Water Resources (PCRWR) has been conducting a wide range of research on surface waters since 1964, published in annual reports [49-52]. Some of the tests are conducted as part of monitoring research related to water supply, and concern mainly the bacteriological status of water. The quality assessment of groundwater for drinking water supply was carried out in the city at several sites in 2017.

The improper disposal of industrial and agricultural sewage has led to contamination of the Lake Rawal water that is used by residents around the lake [17, 53]. In Rawalpindi, fecal and total coliforms have been found in water samples from distribution networks and water treatment plants [54-55]. Research revealed that the water of Rawal Lake in Islamabad is also contaminated with fecal and total coliforms [3]. The PCRWR [3, 49, 51] monitored the groundwater quality of Islamabad; 74% of the samples were contaminated with coliforms and 41% of all samples collected were contaminated with Escherichia coli. The analysis showed that 56.1% of drinking water samples in the Islamabad-Rawalpindi metropolitan area were microbiologically contaminated, 32 samples taken from different areas in Islamabad were contaminated with coliform bacteria [24, 56-57].

Extreme factors also cause groundwater contamination, which is associated with surface runoff and infiltration along with microbial contamination [58-61]. There are two industrial settlements in Islamabad, which release sewage and waste to the Sawan River [62]. In addition, the concentrations of some chemical indicators exceeded the applicable standard levels. In Islamabad, the maximum limits for Ca^{+2} [49, 63], toxic substances, pesticides, nitrogen compounds, arsenic and fluorine [24, 64] were exceeded in 73% of groundwater samples, and high levels of iron and chlorides were found in Punjab [55].

Another problem is the limited amount of groundwater resources, which may be related to the lack of groundwater balance studies in Pakistan. The main element of quantitative estimates is the assessment of the amount of groundwater recharge. The amount of groundwater recharge in urban areas depends on many overlapping factors, including climatic conditions and the dynamics of their changes [65-66], lithology of near-surface sediments [67-70], land relief [71-72], land use/land cover [66, 73-76] and the thickness of the vadose zone [70, 77]. It is very often difficult, especially in urban areas, to indicate the most important factor determining the amount of infiltration; it is usually a cumulative impact of factors.

A lowering of groundwater table is reported in Islamabad; the water table has dropped from 12 m in 1986 to 35 m in 2015, and a further drop of 11 m is anticipated by 2025 [25,78]. This is associated with unsustainable water consumption, increased groundwater extraction, and reduced infiltration resulting from changes in spatial development due to urban expansion and growing population. The water table has been depleting at a staggering rate of 1.7 m/year due to excessive and unauthorized withdrawal of groundwater [79-81]. Certainly, the changes in the groundwater table drop in Islamabad are significant, but the values presented are only estimates due to the lack of a dedicated network of groundwater monitoring in the city.

3. METHODS

Studying lithology of subsurface sediments by assessing filtration parameters and electric resistivity allowed indicating groundwater circulation systems against the background of a broader context of hydrogeological conditions. The chemical properties of subsurface sediments were determined on the basis of sampling performed at three depths. Shallow probing was performed to collect subsurface sediment samples and determine physical properties of sediments, and to collect sediments for gran-size analysis and petrographic assessment of rocks. The hydraulic conductivity value was determined on the basis of granulometric analysis as the average of three samples at each depth.

Geophysical investigations were performed using the electrical resistivity tomography (ERT) method. This method allows for recognition of the distribution of electric resistivity in the soils, in the 2D system. The Terrameter LS, produced by ABEM from Sweden, was utilized for investigations of the electric resistivity performed for the study. Field data was processed using the Res2Dinv software package [82]. Electrical resistivity tomography (ERT) is a technique that has been successfully used in various lithological settings (e.g. [83-90].

Eight electrical resistivity profiles were acquired, each 200 m long, with the interpretation of results to a maximum depth of 40 m. Interpretation of results allows assessing the geological structure to determining the aquifer location. The scope of the studies was limited for technical and organizational reasons related mainly to both the transfer of equipment from Poland and the fieldwork. For technical reasons, detailed sampling in the river valleys was not possible.

The aim of the direct hydrogeochemical analyses was to determine the type of groundwater at the sampling site, to determine the water quality, and to compare it with the composition of precipitation and subsurface sediment in the aeration zone. The chemical analyses of over a dozen microelements and basic ions were made on 40 soils probe (8 places on different depth), 8 water samples from a domestic water supply system (groundwater – personal communication) in Islamabad (district F6) and from 4 rainwater samples (Fig. 1).

The limited scope of research, especially in the field of water quality research was due to the technical possibilities of in-situ sampling and transporting to the laboratory; therefore, among others, no bacteriological sampling was made. Chemical composition of four sediment samples, taken from different depths during geological soundings, was determined. Sample analyses were carried out in the ACME laboratory in Canada [80].

4. RESULTS

4.1 Hydraulic conductivity of Sediments and Groundwater Recharge

On the surface, there are loams, silty loams, cohesive loams, sands, and locally silty sands. The hydraulic conductivity value, determined at each depth to 1,5 m depth as the average of three tests, ranges from $2.86E^{-7}$ to $5.71E^{-6}$ m/s (Fig. 2). The subsurface sediments are characterized by low hydraulic conductivity values, typical for both alluvial deposits and the Potwar Clay. The grains that are smaller in diameter than 0.001 mm account for about 20% of the subsurface sediments.

Based on the distribution of resistivity values, by analysing subsurface sediments and comparing with a few borehole profiles, lithological categories of rocks were distinguished within individual depth intervals. The aquifer consists of alluvial sediments: silt, silty loam, loam, variously grained sand, and gravel. To a depth of 10 m, the resistivity variation indicates highly variable lithology. Beneath, there are sediments with resistivity typical of sands, muddy sands, and gravelly sands. The groundwater table, interpreted on the basis of electrical resistivity measurements, occurs at a depth ranging from 4 to more than 10 m b.g.l. (below ground level).

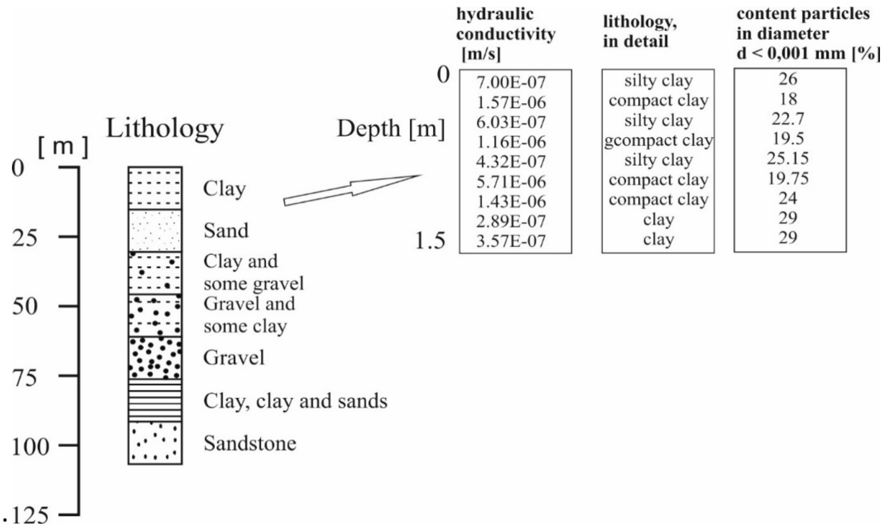

Fig. 2. Schematic lithological profile and parameters of aquifer

The amount of infiltration during various precipitation periods and the assumed values of the infiltration index ω were estimated on the basis of knowledge of subsurface lithology. Steady-state natural infiltration recharge was determined from precipitation data. The amount of recharge for the whole year was determined on the basis of average annual precipitation from the period 1957-2017 (Table 1). It is a theoretical value because the evapotranspiration level is almost equal to precipitation, was calculated for three months (July-September), during which the precipitation level is very high. The amount of recharge was also determined by reducing the amount of precipitation by evapotranspiration during high precipitation periods.

The value of infiltration recharge was estimated by the empirical method (as the product of infiltration rate ω and annual average precipitation - *P*) [91]. In Pazdro's classification [92], the infiltration rate ω ranging from 0.05 to 0.3 was agreed on the strength of the infiltration capability of lithology, a similar approach was adopted in Zaluski [93] and Wright et al. [94]. The amount of recharge (*P* x ω) was calculated for three values of the infiltration index ω: 0.1; 0.15; 0.2, assumed with respect to the lithology of subsurface sediments (Table 2).

The recharge values range from 120.1 mm/year to 240.2 mm/year at the annual precipitation level for different variants of the recharge index value. For high precipitation periods with low evapotranspiration (, it varies from 82.6 to 165.2 mm/3months, depending on the assumed infiltration index. When evapotranspiration is involved, the recharge value ranges from 35.9 to 71.9 mm/3months.

4.2 Groundwater Footprint

In the study area of Islamabad, two groundwater circulation systems can be distinguished (Fig. 3): a local one related to the drainage nature of minor, periodically dry watercourses, and a deeper-seated one, in which major watercourses and groundwater extraction from deeper wells are the dominant drainage elements. The identification of the circulation systems should be helpful in planning water management in the city and analysing the causes of groundwater level changes. The research made possible to calculate the groundwater footprint (GF), and to quantify groundwater demand by both man and the environment. Groundwater footprint was defined as GF = A [C/(R-E)], where A, C, R and E were defined as surface area, groundwater abstraction, infiltration recharge rate and outflow, respectively [95]. The groundwater footprint GF for Islamabad was calculated at 906 km^2 for three different variants of recharge (Table 3). The calculations are only estimating due to the lack of accurate information on the amount of groundwater abstraction in Islamabad. Outflow is practically insignificant because the groundwater inflow is simply the same as groundwater outflow (Fig. 3). The aquifer in Islamabad is characterized by high GF, which is documented by the quantitative impoverishment of the groundwater. The groundwater footprint index GF/A, determining the pressure on groundwater, is 1-3.8, lower than classifying the aquifer for Upper Ganges [95].

Table 2. Groundwater recharge (infiltration) in Islamabad

Date	Infiltration recharge [mm/year]		
	ω = 0.1 Variant 1	ω = 0.15 Variant 2	ω = 0.2 Variant 3
Precipitation (annual average from period 1957-2017) [mm]	120.1	180.2	240.2
Precipitation-evapotranspiration (annual average 1957-2017 and 2000-2015, respectively) [mm]	-4.1	-6.2	-8.2
Precipitation in July-September [mm]	82.6	123.9	165.2
Precipitation-evapotranspiration (in July-September) [mm]	35.9	53.9	71.9

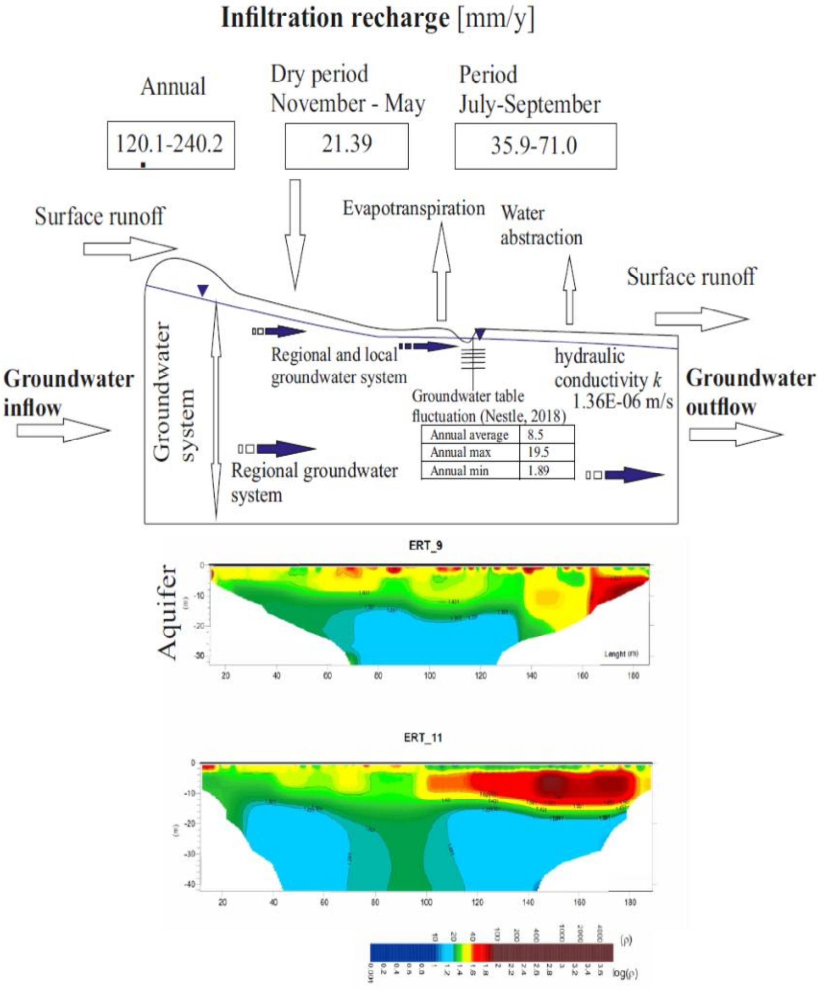

Fig. 3. Schematic model of groundwater systems in Islamabad on the background of selected (9 and 11) electrisivity profiles

4.3 Hydrochemical Groundwater Research

The tested tap water was of good quality (Table 4). The concentrations of selected proxies were compared with permissible values for good quality water status according to the EU Water Framework Directive [81] and for quality standards according to the National Environmental Quality Standards (NEQS). None of the examined proxies exceeded the permissible values. These are typical bicarbonate-calcium and bicarbonate-calcium-magnesium waters (Table 4; Supplementary Table 5). The dominant HCO_3 ion represents from about 77% to over 90% of the total anions. Among cations, the Ca^{2+} ion dominates definitely, and its percentage ranges from about 60 to 70% of the total cations.

The sediments do not show characteristics of permanent contamination (Supplementary, Table 6). Low concentrations of the studied indicators (more than 20 parameters) are typical of urban area. In the study area of Islamabad, the subsurface sediments are not contaminated, although the reconnaissance carried out in various parts of the city indicates numerous outbreaks from unsecured waste that cause soil (Supplementary Table 6) and water contamination.

Table 3. Groundwater footprint, groundwater stress in variants 1-3 of infiltration

Data	**Groundwater footprint [km^2]**			**GF/A**		
Abstraction [m^3/day]	46990					
Recharge [m^3/day]	Variant 1	Variant 2	Variant 3	Variant 1	Variant 2	Variant 3
Precipitation; average in period	5747.8	8621.7	11495.6	6.3	9.5	12.7
Precipitation July-September	3953.1	5929.7	7906.2	4.4	6.5	8.7
Precipitation-evapotranspiration July-September	1720.4	2580.5	3440.7	1.9	2.8	3.8
Data	Groundwater footprint [km^2]			GF/A		
Abstraction [m^3/day]	87100					
Recharge [m^3/day]	Variant 1	Variant 2	Variant 3	Variant 1	Variant 2	Variant 3
Precipitation; average in period	3100.9	8621.7	11495.6	3.4	9.5	12.7
Precipitation July-September	2132.7	5929.7	7906.2	2.4	6.5	8.7
Precipitation-evapotranspiration July-September	928.1	2580.5	3440.7	1.0	2.8	3.8

Table 4. Hydrochemical type of the groundwater

Anions A/ Cations C [%]	**Sample No**							
	1	2	3	4	5	6	7	8
HCO_3	78.30	88.45	82.01	79.71	90.92	77.63	76.89	77.49
SO_4	12.95	0.00	10.19	12.39	0.00	12.89	11.22	12.22
Cl	8.21	11.15	7.32	7.34	8.45	9.01	11.51	9.78
NO_3	0.55	0.39	0.49	0.56	0.63	0.48	0.38	0.50
$\sum A$	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Na	9.69	4.94	5.51	6.69	6.95	6.59	6.53	9.84
K	1.35	1.65	1.40	3.01	2.66	2.85	2.91	2.55
Ca	66.67	74.58	72.91	70.44	71.08	69.47	70.16	66.51
Mg	22.29	18.84	20.18	19.86	19.30	21.09	20.41	21.10
$\sum C$	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Hydrochemical type	HCO_3-Ca-Mg	HCO_3—Ca	HCO_3-Ca-Mg	HCO_3-Ca	HCO_3-Ca	HCO_3-Ca-Mg	HCO_3-Ca-Mg	HCO_3-Ca-Mg

5. DISCUSSION

In Islamabad, there are different water supply and sewerage systems in different regions of the city. Although a modern sewage treatment plant operates in the city, from which part of the sewage is discharged to a waste recycling plant, but the sewage and waste from some parts of the city are discharged directly into the river [3, 62; 95 - 100] (Photo 1).

The study results indicate significant lithological heterogeneity of the near-surface zone and the aquifer, both vertically and spatially. The subsurface sediments, down to a depth of 1.5 m, are characterized by low hydraulic conductivity values, ranging from $2.86E^{-7}$ to $5.71E^{-6}$ m/s, classifying these sediments as poorly permeable [92]. The hydraulic conductivity value was compared with other research results conducted in the Punjab province [60, 101]. The hydraulic conductivity value, determined during test pumping in seven wells located in Khanewal, Lower Bari Doab, is supported by the varying values of aquifer's hydraulic conductivity, which range from $1.84E^{-4}$ to $7.04E^{-4}$ m/s [101]. The values were much higher than those determined for subsurface sediments in Islamabad, but they also confirm their lithological variability documented by electrical resistivity profiling. The lower value of hydraulic conductivity of subsurface sediment in Islamabad is related to the local presence of both the Potwar Clay on the ground surface and wind-blown fine-grained sediments. subsurface sediments in the Rechna Doab (Punjab) are characterized by good, moderate and poor hydraulic properties. The hydraulic conductivity identified for the first layer of the hydrodynamic model ranges from $1.85E^{-3}$ to $1E^{-5}$ m/s [8]. These values are much higher than those obtained from direct research, which is associated with the regionalization of results during modelling and their approximate value obtained during the model calibration.

The identification of lithology from resistivity data was based on studies from other areas and available borehole sections [39]. Electrical resistivity profiling confirmed the heterogeneity of the aquifer, and its lithological diversity. The profiling carried out along a watercourse valley (profiles 3, 4 and 6) presents an aquifer that is more diverse lithological. Alluvial sediments in the valleys are several metres thick. Subsurface sediments in the watercourse valley are represented by fine-grained sands, muddy sands, and gravelly sands, characterized by higher values of permeability parameters than in the plateau area. In the valleys, the precipitation infiltration rate is greater, but there is also the possibility of groundwater inflow in the local circulation system. Profiles 1, 7, 8, 9 and 11 (Fig. 1) show lower variability in resistivity values. The aquifer is more homogeneous in terms of lithology. On profiles 1 and 8, urban infrastructure has been interpreted: probably a water outflow from the water supply network or the sewerage system, or another urban infrastructure.

The groundwater footprint can be used to assess the impact of transferring groundwater consumption between regions. The Upper Ganges aquifer in northwestern India and Pakistan has the largest groundwater footprint and a large GF/A ratio [95], but the Lower Ganges aquifer has a GF/A ratio of less than one owing to low groundwater consumption and high recharge rates. The groundwater footprint index GF/A in Islamabad region is 1-3.8, lower than classifying the aquifer for Upper Ganges. Index GF/A ratio remains greater than one, indicate that the groundwater consumption in the region cannot be made sustainable by groundwater consumption.

The groundwater recharge estimated as a result of hydrodynamic modelling in the Rechna Doab region (Punjab) was considered from 20% to 22% of total precipitation [102] and about 20% in the Upper Chaj Doab (Punjab) [101]. The recharge value as a parameter for assessing groundwater vulnerability to contamination by the DRASTIC method in the Lahore region, was assumed as 40 mm/year [17, 28, 58], i.e. 3.4% of annual precipitation. The recharge calculated for the Islamabad area ranges from 2 to 6% of precipitation, depending on the calculation variant. Assuming the annual precipitation level, the amount of recharge is 10 - 20% of the level, although this value is overestimated due to evapotranspiration.

6. CONCLUSIONS

1. The study results indicate significant lithological heterogeneity of both the near-surface zone and the aquifer, vertically and spatially variable. The knowledge of subsurface sediments in northern Islamabad points to a variable thickness of the aquifer. The groundwater is characterized by a high GF/A index up to 3.8, depending on the calculation variant, documenting the quantitative threat to the water. At the same time, hydrogeological conditions are indicative of water infiltration ranging from 82.6 to 165.2 mm/3months in the period of high precipitation, constituting 10 to 20% of precipitation in an annual cycle. The amount of infiltration, knowledge of the lithological conditions in the aquifer, and the occurrence of at least two groundwater circulation systems, considered against the background of a broader context of hydrogeological conditions, point to the possibility of a wider use of groundwater for water supply to Islamabad.
2. The aquifer in Islamabad is characterized by high groundwater footprint, which is documented by the quantitative impoverishment of the groundwater. Identification of hydrogeological conditions and groundwater footprint can be helpful in planning sustainable water management, identifying groundwater hazards, predicting the effects of irrational water management, and limiting the inappropriate direction of urban infrastructure development.
3. The direct research on hydrogeological conditions in Islamabad, carried out in 2020 in selected area of Islamabad did not show any signs of chemical contamination during the study period. Groundwater

quality assessment requires the design of regular monitoring studies. Hydrogeological conditions in Islamabad indicate local and periodic groundwater contamination resulting from human impact and extreme situations associated with floods and earthquakes.

4. Analysis of the study results indicates the need for further investigation of hydrogeological conditions for the assessment of groundwater balance elements. An important part of the studies is the variant testing and simulations, e.g. of hazard indexes related to seasonal changes in groundwater recharge conditions, which results from different short- and long-term climatic conditions.

SUPPLEMENTARY MATARIALS

Supplementary table 5 and 6 is available in this following link.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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