Lahore's Groundwater Depletion-A Review of the Aquifer Susceptibility to Degradation and its Consequences

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Abstract-Lahore is provincial capital of Punjab and 2nd largest city of Pakistan. Long history of groundwater over abstraction with reduced aquifer recharge has led to groundwater level recession substantially. This paper reviews the hydrology of Lahore and summarizes the results of various hydrological researches conducted for Lahore. Moreover in this paper, susceptibility of Lahore aquifer resulting due to pollution coming into and reduction in recharge resources and its consequences have been addressed. Among the main recharge sources of the Lahore aquifer, average precipitation is not adequate enough to arrest the decline in groundwater levels and River Ravi remains almost dry except in monsoon season. Peizometric levels recession, land subsidence and salt water intrusion has also contributed to its degradation. Developments like rapid increase in population, urban migration and industrialization has increased the reliance on groundwater supply manifold. On the other hand, the urbanization, industrialization and increased land impermeability have reduced the aquifer recharge significantly. Due to less consideration paid towards aquifer protection in Lahore, these impacts have been diagnosed long after their occurrence. Therefore susceptibility of Lahore aquifer to degradation has become a cornerstone of its protection policies. With the current extraction rate, increasing demographic growth and land development rates; it is more likely in future that this declining trend will end up in exhausted aquifer. If this situation remains persistent, groundwater conditions both in terms of quantity and quality are likely to worsen. Critical review concludes that energy crisis does not only mean load shedding it may be water shedding which is knocking at the doors of Lahore. Therefore there is an urgent and emergent need to solve the wicked water issues in Lahore.

Keywords-Aquifer, Lahore, Tube Wells, Depletion, Depression Cone, Ravi, City Growth

I. INTRODUCTION

Water is absolutely essential not only to human life but all the life. Indeed it is life blood. It is used for various purposes including drinking, washing, bathing, air conditioning, agriculture, industrial processes, power generation, fire protection and so many others. Almost all fresh water is groundwater which is held in underground reservoirs. Groundwater plays a very important but often an unappreciable role in social and economic well-being of urban areas. Today industrialization and urbanization has resulted in overexploitation and excessive abstraction of groundwater by pumping more and more water out. This is what is happening in Lahore where the main issue of public concern is water level recession mainly due to over pumpage compared to lesser recharge [i-vi]. Since water demands are entirely met by groundwater supply [vii], therefore the study of aquifer depletion vis-a-vis its low recharge and increasing water demands are very important.

Groundwater depletion in heavily populated and industrial city of Lahore is pushing it back to the wall. The city is also a victim of power imbalance created by India. Therefore its importance has increased all the more. Karachi which is the economic hub of Pakistan, its peace has been ravaged by ethnicity and target killing. The stability of Lahore city is important because after Karachi it is the center of economic activity. Its water crisis microcosm of the water crisis of Pakistan is likely to encounter increased use rather misuse of water resulting in swiftly declining water table. Apparently it's an issue concerning water but taking a broader view the very subsistence of is attached to it.

A. Groundwater surpassing the surface water in importance

Earth is a watery place as almost 70% of its surface is covered with water [viii]. Despite the fact that there is lot of water on the planet Earth, only about 2.5 % of the total is fresh [ix-x]. For human consumption, only about one-third of this 2.5 % is available [xi]. About 50% of the available freshwater supplies are already being used [xii]. Underground aquifers contains approximately 99% of all the liquid fresh

water [iii],[xiii] and at least one-fourth of the world's population fulfills its water needs from its supply [xiv]. In last 50 years (1950-2000), the total amount of water abstracted for human consumption has almost tripled from 1382 km^3/year to 3973 km^3/year and it is predicted that annual consumption will further increase to 5235 km^3 by 2025 [xv].

Groundwater is held in aquifers which is defined as a rock unit that yields water in usable quantities to wells or springs. The term "groundwater" is reserved for subsurface water occurring beneath the water table, in the depth of saturated soils. Precipitation which seeps down through the soil and reaches the impervious soil/rock material, saturated with water becomes part of groundwater. Groundwater is a natural source of fresh water and is an indispensable substance. The low permeability of saturation zone reduces further peracolation of water. In this way, rate of downward movement of water becomes smaller than the rate of replenishment from above. In this way, a zone of saturation is formed. The water contained in this zone is called groundwater and the top of the zone is known as water table.

Groundwater's importance is more than surface water in almost every region of the world [xvi]. Reference [xvii] estimated that about 60-70% inhabitants of Pakistan directly or indirectly dependent on groundwater for its livelihood. About 80% of the domestic water supply in rural areas is met through groundwater supply [ii],[xviii] as well as more than 50 % of drinking water supply needs. About 8.2% of renewable groundwater is annually withdrawn for human consumption [xviii]. Water crisis and challenges have different facets appearing in the form of problems concerning health, environment, poverty, scarcity, sanitation, industry, food and many others [xiii]. Following problems have been reported in arising due to groundwater over-abstraction and degradation [ii], [xix-xxvi]: (i) Lowering water tables; (ii) Wells running dry seasonally; (iii) Rising pumping costs; (iv) Competitive well deepening; (v) Land subsidence; (vi) Loss of wetlands and water bodies; (vii) Salt water intrusion and other related salinity issues; (viii) Groundwater degradation resulting from natural toxins (e.g. fluoride, arsenic); (ix) Food scarcity (critically related to water groundwater availability in developing countries including Pakistan and India); and (x) Changes in hydrological cycle.

II. Study Area

Lahore is the provincial metropolis of the Punjab province and 2nd largest city of Pakistan characterized with hot semi-arid climate. Geographically it lies between 31°15'-31°45' N latitude and 74°01'-74°39' E longitude, as shown in Fig. 1. It is bounded on the north and west by the Sheikhupura District, on the east by Wagah, and on the south by Kasur District. The Ravi River flows on the north-western side of district Lahore.

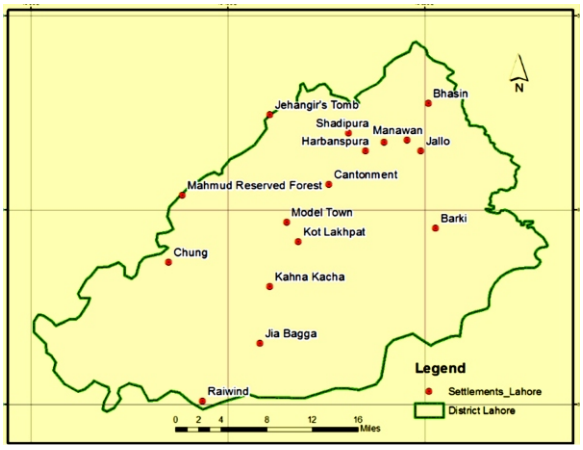


Fig. 1. Map of Study Area

Population of this already densely populated city is still growing quickly [xxvii] due to urbanization trends and migration of people to Lahore. It is entirely groundwater dependent city [xxviii]. The crux of the matter is this that exploitation of groundwater and uneven distribution of surface waters have resulted in imbalances in the demand and supply of water in the region thereby making water management the matter of utmost important concern. If the over exploitation of groundwater could be minimized, it will not only add to the natural resource in the region, it will relieve the ever increasing cost of pumping in Lahore.

III. Groundwater Problems in Lahore

In the last decade, rate of water use, in the industrial city of Lahore, has grown more than the rate of population growth. Water stress coupled with urbanization and industrialization is posing a serious threat to Lahore aquifer. The situation of water shortage is further aggravated by discharge of untreated sewage into rivers and leakage to underlying aquifer thereby causing water pollution [iv]. Another aggravating factor is water scarcity coupled with probable decrease in groundwater.

Reference [xxix] described four possible types of blue water (water in rivers and aquifers) scarcity;

1. Climate driven: due to limited run-off generation
2. Pollution driven: resulting in water quality degradation
3. Population driven: in terms of high population pressure on available water resources resulting in water shortage [xxx]
4. Demand driven: in terms of high water demand compared to water availability resulting in water stress in an area [xxx]

Presently, Lahore is facing all types of water

scarcity. It's just a game of demand and supply. To address water scarcity problems and achieve a balance between supply and demand of water, it needs improved water governance and demand management. There are two major threats to groundwater degradation; contamination and over pumping.

IV. Hydrological Setup of Lahore

Administratively Pakistan consists of four provinces, the Federal Capital Territory (FCT) of Islamabad, two disputed territories, and a group of federally administrated tribal areas. Punjab is most populous of all the provinces and have a number of locations reported to be contaminated by industrial waste water discharge [xxxi], experiencing escalating rates of aquifer depletion. Lahore, the provincial capital, is no exception to the rule. Studies report that groundwater, the main source supplying water, is vulnerable to depletion because of its excessive abstraction compared to poor recharge. This situation has arrived due to lack of property rights over water usage and either absence or no control of regulation authority [xxxii].

The book entitled "Groundwater Resources of Pakistan" by Dr. Nazir Ahmad, published in 1974, provides some useful historical insights into Lahore's hydrogeology [xxxiii-xxxiv]. Alluvial deposits of Quaternary age are underlain in this area [xxxv]. This unconfined aquifer is composed of alluvial sands and unconsolidated alluvial complex of about 400m (1300 ft) thickness [iv], [xxvii]. Despite its heterogeneity in nature due to these alluvial sediments, it behaves as homogenous and highly transmissive aquifer on large scale [iv].

Hydrogeologically, it is part of the large inter-fluvial Bari Doab which is bounded by the River Ravi to the north-west and the Sutlej and Beas River to the south-east [xxxv], as shown in Fig. 2. Due to the extension of city across the River Ravi, the Lahore aquifer now constitutes a part of the Rechana Doab (land between the River Ravi and River Chenab) [ii],[xxxvi]. The Bari Doab and the Rechana Doab are itself a part of vast alluvial plain thwarted by the River Indus and its tributaries.

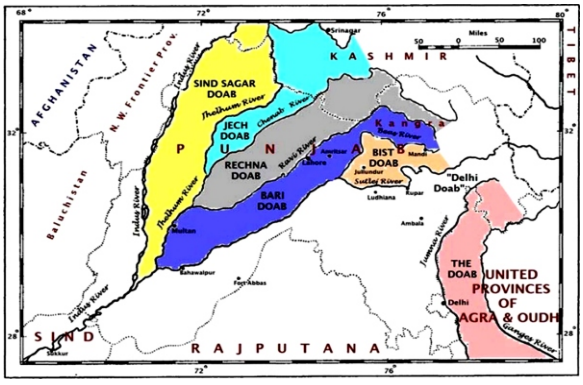


Fig. 2. Doabs of Punjab Province [lxvi]

No systematic study about underground formation was carried out till 1950. In 1954, Punjab Irrigation Department in cooperation with U. S. Geological Survey (USGS) started a study on soil and groundwater resources [xxxiii], [xxxviii]. This hydrogeological investigation included drilling of test bores, construction of test tube wells, carrying out pumping test and analyzing the data [xxxv], [xxxiii]. Test sites were drilled upto 600 ft. and each bore was 4-5 miles apart. During this regional investigation, several deep test holes were drilled in Bari Doab to determine the thickness of Alluvium, the depth to bedrock and water quality at deeper zones [xxxiv]. At a few sites bores were drilled upto bed rock and in some cases upto 1500 ft and analysis of samples collected during drilling revealed that Punjab Indus Plain consists of deposits of sand, silt and claywith appreciable amounts of kanker and other concretionary material [xxxv],[xxxviii]. The thickness of sand which is principally grey or greyish-brown colored and fine to medium grained [xxxviii] is comparatively more than silt and clay [xxxiii]. Gravels of hard rock are absent from the alluvium and coarse or very coarse sands are not common [xxxv], [xxxviii]. The unconsolidated alluvial plains of Punjab forms an extensive, highly permeable aquifer in which groundwater is generally unconfined [iii], [xxxiii]. References [xxxviii] summarized the geohydrological conditions of the Punjab plains including study area, based on the data collected during investigation study by WASID. WASID issued two reports based on its investigation; one on the geology and the other on the regional hydrology.This is the only study found providing an extensive insight into lithology of Bari Doab deposits [xxxv].

V. Aquifer Recharge and Discharge

The process by which the groundwater is replenished is called aquifer recharge. Estimation of aquifer recharge is important for following reasons [xxxv];

- The relationship between the amount of recharge and the amount of abstraction is very helpful in defining the aquifer susceptibility to the effects of excessive pumping.
- The relationship between the recharge amount and abstraction amount helps to define the area subjected to or receiving amount of recharge and needs to be protected.
- The locations as well as processes of recharge and its relationship to potential sources of pollution help in determining the pollutant loads.

The possible sources of recharge of the aquifer of Lahore are; Rainfall, River Ravi and irrigation branch canals passing through the area [iii],[xxvii],[vi]. Only two major sources will be discussed here; the rainfall and River Ravi in recharge perspective.

Reference [xxxv] presented the overview of hydrology of the Lahore region and reported a great

imbalance between the groundwater withdrawal and recharge along with absence of any regulation w.r.t water pumps installation and any groundwater model running currently.

A. Aquifer Recharge Components and factors affecting these components

i) Rainfall

Lahore lies in sub-tropical, semi-arid region. The average monthly precipitation is low and varies from month to month, as shown in Figure 3. Monsoon period in July and August months comes with highest rainfall which makes about 40% contribution to annual groundwater recharge. The average annual rainfall is of the order of 575mm, varying from 300-1200 mm. The annual potential evapotranspiration is about 1750 mm which exceeds the rainfall, thus making irrigation essential to supplement the rainfall [iii],[v-vii].

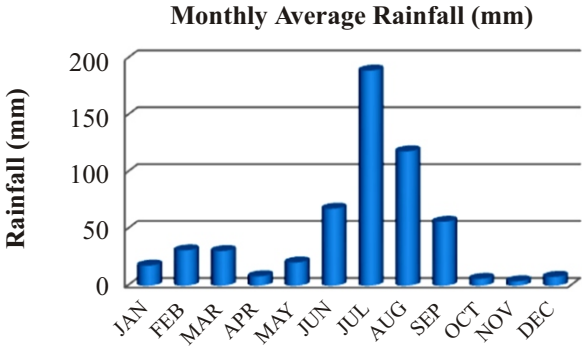


Fig. 3. Lahore Monthly Average Rainfall [xiv]

Fig. 4 shows that average annual precipitation is low and varies from and varies from year to year.

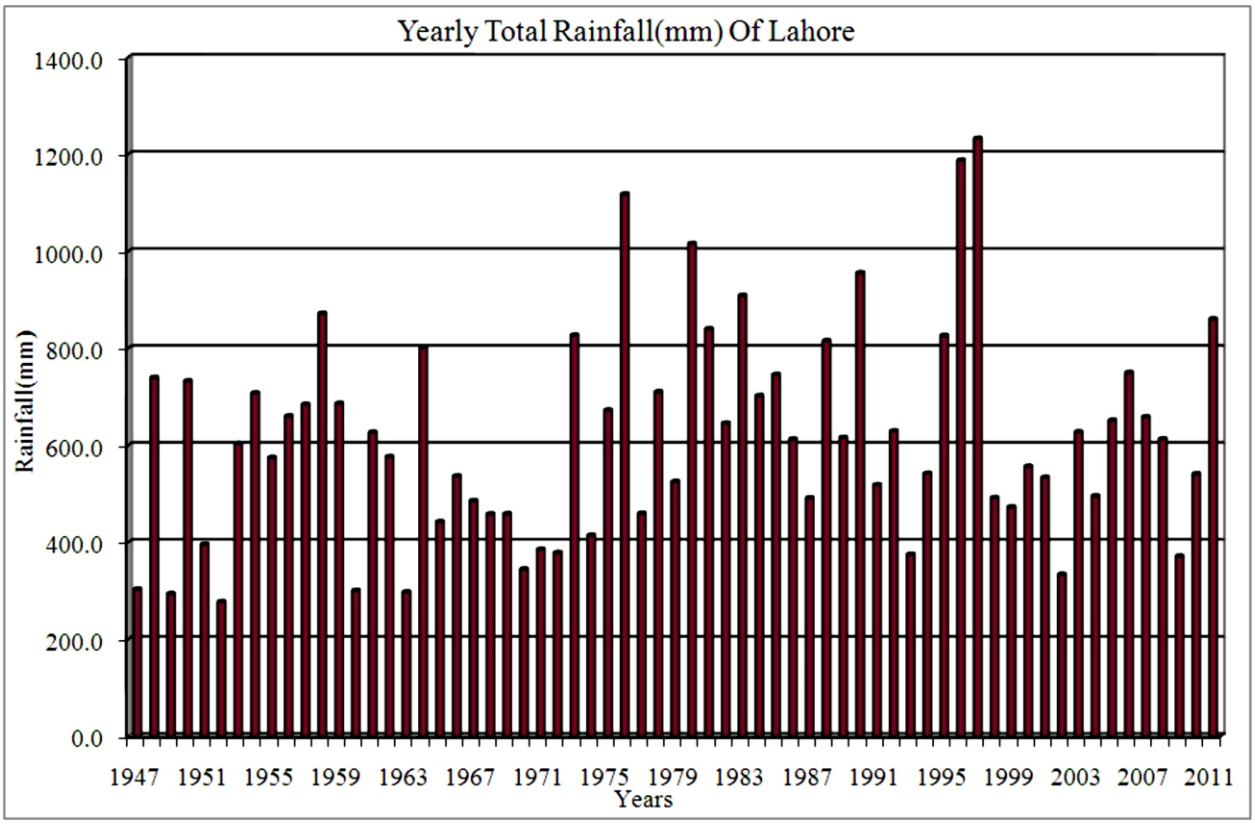


Fig. 4. Total annual rainfall of Lahore [xiv]

ii) River Ravi

The major of all sources of recharge to Lahore aquifer systems is the River Ravi originating from the neighbor country India. It is really a stumbling block that River Ravi come in Pakistan from India. This is the reason that surface flows of the river started reducing immediately after independence in 1947 ending to almost zero by 2000 when Thein Dam was constructed upstream of Madhopur head works in India [ii-iii],[xxvii],[xxxv]. It resulted in substantial lowering in water table in river adjoining areas of Lahore city. The river remains dry except monsoon season [iii]. Researches made to analyze the effect of construction of Thein dam have confirmed the lowing of aquifer recharge resulting in water table recession due to reduction in inflow of river Ravi. Study for the water

supply, sewerage and drainage of Lahore produced by Camp, Dresser and McKee (CDM) Ltd. (1976) predicted that drawdown over large parts of Lahore city after construction of Thein Dam was between 40m and 82m (also known as Ranjit Sagar Dam) and 30m to 55m before Thein Dam was constructed. However, the actual decline in water table has been less than the predictions made by Messers CDM [ii]. NESPAK conducted a research study entitled "Groundwater Resources Evaluation and Study of Aquifer under Lahore" in collaboration with Binnie & Partners Consulting Engineers, London, UK in 1988. The computer model developed by them was also being used to test the effect of construction of Thein Dam on the flow of River Ravi [vi]. Unfortunately, the River Ravi once a river that could endure life and livelihoods for thousands of people has now become dead.

Graphs in Fig. 5 shows that inflow of River Ravi has reduced substantially with the passing years thereby its contribution to underlying aquifer recharge has reduced as well and hence, endangering the aquifer sustainability.

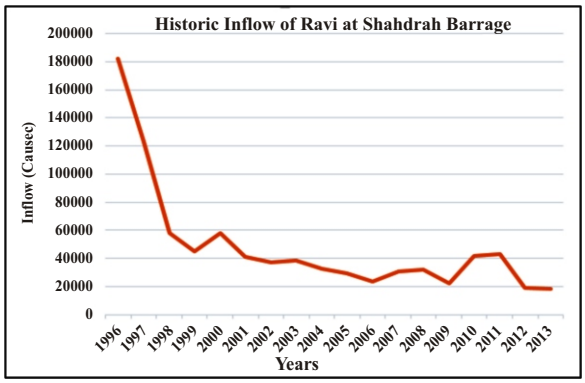


Fig. 5: River Ravi Inflow at Shahdrah Barrage

Moreover, pollution content in Ravi is much higher compared to other rivers in Pakistan. It receives a good amount of untreated urban and industrial waste waters of Lahore as well other urban and industrial waste on its way to Pakistan from the Indian catchment [iii-iv],[xxvii]. Lahore city produces 240 million gallons per day of wet sewerage [xii]. This untreated effluent is then carried into River Ravi as such where it pollutes the aquifer as it seeps down the surface. The Hudiara Drain is a major source of pollution for River Ravi. It carries agricultural and industrial waste from both India and Pakistan and discharges it into River Ravi [ii],[xxvii]. Detail of wastewater intake by River Ravi is given in Table I.

TABLE I
DETAILS OF INDUSTRIAL AND MUNICIPALITIES DISCHARGE FROM DISTRICT LAHORE [10]

No. of Industries	151
Effluent from Industries (cusec)	120
Effluent from Municipalities (cusec)	3126
Total Effluent (cusec)	3246
Treated	2
Untreated	149

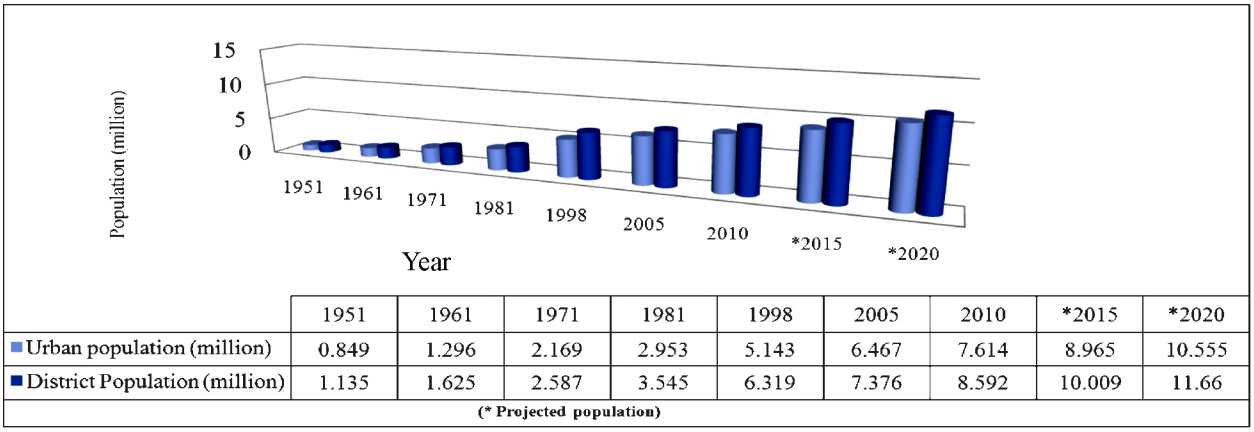
As Lahore groundwater recharge is highly dependent on river recharge [ii]; therefore a better understanding of the surface-ground water interactions is extremely important to maintain both the quality and quantity of the urban groundwater supplies. Reference [vii] proposed various types of method to recharge the depleting groundwater in Lahore artificially.These proposals include river bed modification, percolation basins, ditches and furrows, flooding, injection wells, induced recharge and modification of canal bed.

iii) Other factors affecting aquifer recharge

Lahore has been experiencing growth in various forms which is adding to aquifer stress and its susceptibility to degradation, as discussed hereunder:

1. Population growth

Lahore's population was more than 6,310,000 in 2006. It is about to become a 'mega city' with more than 10 million inhabitants, as shown in Fig. 6. Rapidly increasing population of this already densely populated urban city is adding to its water stress because the city is solely dependent upon groundwater resources for it water needs.



	1951	1961	1971	1981	1998	2005	2010	*2015	*2020
Urban population (million)	0.849	1.296	2.169	2.953	5.143	6.467	7.614	8.965	10.555
District Population (million)	1.135	1.625	2.587	3.545	6.319	7.376	8.592	10.009	11.66

(* Projected population)

Fig. 6: Lahore's Demographic Profile [xxxviii]

Table II shows how the no. of tube wells are increasing yearly because every year more tube wells are installed to meet the citizen's demands for water.

TABLE II
LAHORE'S POPULATION AND TUBE WELLS GROWTH
[xvii],[xli],[lxiii],[lxvi]

Year	Population	No. of Tube wells
1977	2602277	127
1978	2698561	133
1979	2798561	136
1980	2901949	142
1981	2952689	142
1982	3061938	142
1983	3175230	149
1984	3292714	153
1985	3414544	154
1986	3540882	181
1987	3671895	188
1988	3807755	206
1989	3948642	-
2001	7041839*	320
2010	8,592,000*	467
2011	10,000,000*	476
2012	12,500,000*	480
2013	13,200,000*	483

*Projected Values

2. Peripheral growth

Apart from population growth within city, growth along periphery is also going on in the form of haphazard subdivision of the land. Many areas lack basic infrastructure and amenities. The small communities in the city are growing like mushrooms with no proper water supply. It is a common observation that they are installing their own tube wells to fulfill their water needs without registration and any consideration of rules and regulations. With the increase in number of tube wells, the groundwater level, which used to exist at about 4.5 m below surface, has gone down to 40m. Proliferation of such unplanned urban settlements which is adding to the pressure on the groundwater resources has become a major source of concern.

3. Land Development

Lahore has practically no infiltration due to extensive industrialization and increasing heavy construction trends. Consequently, number of irrigation fields has been reduced. This factor is playing an indirect but a significant role in aquifer depletion and its susceptibility because a large part of the land has become impermeable. Urbanization affects the quality as well as quantity of the groundwater by;

- Rapid change in aquifer recharge patterns and rates
- Establishing new abstraction regimes

B. Discharge Component

i) Tube well Pumping

Before 1876, water extraction from open wells was the most common source of water [xl]. Now a days, the major source of water supply to the public is groundwater supply system of WASA/LDA tube wells, installed in different parts of the city. Total WASA abstraction of groundwater from the aquifer is 280 to 290 million gallons per day [ii]. Private Sector is also pumping a substantial amount of water, which is estimated at 150 million gallons per day. Increasing pumping rates means increasing water drawdown. Heavy groundwater abstraction in the study area has been resulted in an irregular shaped depression-cone in the central part of the city, as shown in Fig. 7.

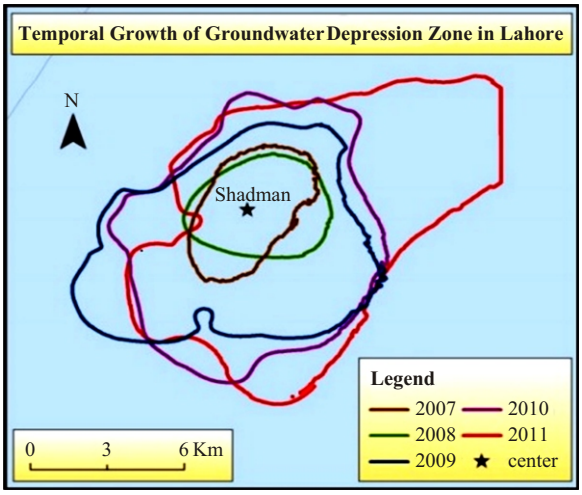


Fig. 7. Expansion of Depression Zone Contour of 38m from 2007

Moreover, it shows that the area of this depression cone has been increasing over the past few years. Depression has expanded from 16 to approximately 103 km^2 just over the span of 5 years.

Attempts have been made from time to time by various organizations to estimate the groundwater resources of the Lahore based on status of available data. The importance of groundwater for domestic, industrial and agricultural uses and its characteristics of being readily and locally available have led to overexploitation of this precious natural blessing. Technological improvement in construction of deep tube wells and pumping methods have also added to excessive abstraction from underlying aquifer, the one and only source of water for Lahore. And it has been going on since immemorial time [iii-iv].

Groundwater abstraction is the process of taking water from an aquifer, either temporarily or permanently and over abstraction may lead to

groundwater levels reduction substantially. In Lahore City, groundwater pumpage through tube wells was started in 1930, when the water table was within the suction limit (10-20 feet) of centrifugal pumps [xl]. A few small capacity (1 cusec) tube wells were installed in public sector to meet the water requirements. As the population went on increasing, more and more tube wells were of varying capacity were installed to meet water demands, as shown in Table II. Large scale exploitation started after 1960. In 1960, the number of tube wells increased to 52 and in 1988, this figure increased to 205 with total installed capacity of 670 cusecs and annual abstraction of 420 mcm. In 2000, there were 320 water supply tube wells and this figure has now reached up to 483 tube wells of varying capacity. These tube wells are operated in WASA's jurisdiction whereas there are hundreds low to medium capacity (1-2 cusecs) tube wells owned by individual citizens and private co-operative housing schemes sprouting across the city whose exact figure is not known yet. Figure 8 shows the distribution of tubewells including WASA and others in district Lahore. Due to absence of any proper legislation and compliance of the available legislation, no of un-registered tube wells are increasing expeditiously.

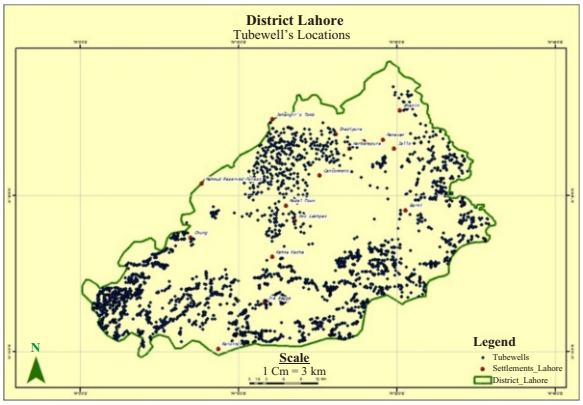


Fig. 8. Spatial distribution of thousands of tubwells installed in territory of District Lahore

VI. History of Water Table Depletion

In the study area, the groundwater level is receding due to unwise use of water for drinking, washing, bathing and other purposes. The WASA authorities are now installing more tube wells to meet public water demands. These tube-wells are being installed from 600 to 700 feet depth resulting in further more decline in falling ground water levels. This is not only threatening groundwater levels of underlying aquifer of Lahore but affecting its quality and taste as well. Rate of ground water abstraction is about 1.45 million cubic meters per day [iv]. According to the WASA report, the water table since 1961 has gone down to 61 feet on an average. Reference [iii] reported that the water table depleted by 17 feet in the Ravi Road area, 10 feet in Ichhra, 9 feet in Industrial Area KotLakhpat and Misri Shah, 29 feet in Mustafabad, 7.3 feet in Gulberg, five feet in Green Town and Baghbanpura, 2.3 feet in Data Nagar, 2 feet in Islampura and Iqbal Town, 4 feet in Samanabad, 0.6 feet in Mughalpura subdivisions, 7 feet in Shahdara and Shimla Hill, 6.4 feet in Mozang, 6 feet in Garden Town, and 4.2 feet in Township. Average decline in ground water level in Lahore is found to be 2.03 feet per year [xxxv]. Currently water level is receding at the rate of about 3 ft/yr [xli], given in Table III.

The magnitude of response of the aquifer, however, varied in different localities of the Metropolis depending upon density of wells, volume of pumping and coefficient of storage (specific yield) of water bearing formations.

TABLE III
Average Annual Rate of Groundwater Decline [lxviii]

Period	Rate of Decline	
	ft/year	m/year
1960 - 1967	0.984	0.30
1967 - 1973	1.804	0.55
1973 - 1980	1.969	0.60
1980 - 2000	2.133	0.65
2007 - 2011	2.6	0.792
2011 - 2013	3	0.9144

VII. Groundwater Management

Lahore Development Authority (LDA) is responsible for planning and land development in the Lahore Metropolitan area. The Water and Sanitation Agency (WASA) is provides water supply, sewerage and drainage collection and disposal services. Presently, WASA's monitoring network includes over 476 WASA tube wells located within study area. Water level measurements at these tube well locations are made on monthly basis. Discharge measurements are made on 100 selected water supply wells every month and about 25 water samples are collected and analyzed chemically at WASA Laboratory every day [vii]. Municipal services in the urban area are provided by the Lahore Metropolitan Corporation and the Cantonment Board.

VIII. Need of Groundwater Monitoring

Large scale taping of groundwater and over exploitation is equivalent to non-renewable water mining. Studies show that Lahore water supply is not based on groundwater but exploitation of groundwater.

This is becoming such an unprecedented case for which no other experience is found in its history. This is why study of Lahore aquifer vulnerability to degradation has become a cornerstone of groundwater sustainable management. For the sustainability of groundwater levels and quality, it is very important to be aware of the groundwater levels, quality and quality trends. Reference [xliv] stated in their report that if the world's water crisis is "mainly a crisis of governance" groundwater situation represents the merciless side of this crisis in Asia. Lahore is a very significant example of such a kind of crisis in Pakistan. There is no strict law made to limit the exploitation of groundwater in Lahore district like many other cities of Pakistan. Anyone who want and need can install his own tube well and extract water from the underlying aquifer as much as he wants. Therefore groundwater levels monitoring is needed for planning and management for sustainability of this precious resource.

Reference [xlv] described a number of objectives of groundwater level monitoring: (i) Detect impact of groundwater recharge and abstractions; (ii) Monitor the groundwater level changes; (iii) Assess depth to water level; (iv) Detect long term trends; (v) Compute the groundwater resource availability; (vi) Assess the stage of development; and (vii) Design management strategies at regional level.

IX. Impacts of Groudwater Degredation

A. Groundwater quality degradation

The region west to the Lake Michigan in the United States, includes major cities of Chicago and Milwaukee with over 12 million people is an illustration of the connection between groundwater quantity and quality management [xxxv]. Pumping from the aquifer there has caused a depression cone extending throughout large portion of the region, with groundwater level declined upto 300m at some locations. This depression cone is among the largest in the United States. High levels of arsenic are present in the upper part of the aquifer which is attributed to the mineral oxidation in newly unsaturated deposits at the top of the aquifer. Likewise, artificial recharge options to store the water in Lake Michigan aquifer have been hampered by the presence of arsenic in recovered water. Drawdown in the sandstone aquifer has also coincided with increases in the concentration of total dissolved solids (TDS) from upcoming of saline water.

Likewise urban water supply in Lahore is prone to water pollution resulting from heavy aquifer pumping in the region [xxxv], [xxviii]. Radiation and Isotope Application, a division of PINSTECH (Pakistan Institute of Nuclear Science and Technology) carried out hydrological investigation of Lahore aquifer using chemical, isotopic and numerical methods, sponsored by IAEA (International Atomic Energy Agency) and classified Lahore groundwater into four categories Hydro-chemically: (i) Calcium bicarbonate; (ii) Magnesium bicarbonate; (iii) Sodium bicarbonate; and (iv) Chloride type. Chloride type of ground-waters emerges directly from industrial activity in the area. Reference [xxviii] reported that the study showed that waters of shallow and deep aquifers are not mixing efficiently in the south east and north east areas, while in the center of the city (Gowal Mandi, Mozang, Governor House) both shallow and deep groundwater are mixing in substantial amounts. Overlapping of areas having apex of the depression-cone and peak of Cl ions in the center of the city further supports the occurrence of shallow aquifer waters mixing with the deep aquifer in the center of the city, causing deterioration in the quality of water.

In 2001, Pakistan Council of Research in Water Resources (PCRWR) conducted first national water quality monitoring program [x]. In this 5 years program, water quality analyses from different areas of the country were documented and reported in 2007. The in-depth report analyzed quality of 357 water samples collected from 23 major cities, 8 rivers, 6 dams, 4 lakes, 2 canals and one reservoir from across the country. Drinking water in every major city was found and reported unsafe including Lahore. The results of water quality analysis carried out in Lahore during 2005-2006 are given in Table IV.

TABLE IV
Results of Water Quality Analysis Carried Out During 2005-2006 [xlvii]

Sr. No.	Water Quality Parameter	Unit	Total No. of Samples Analyzed	No. of Contaminated Samples	%age of Contaminated Samples
1	As	(ppb)	16	16	100
2	Fe	(mg/l)	16	9	56
3	TI	(ppb)	16	2	13
4	Coli Forms	(MPN/100 ml)	16	8	50
5	E.Coli	(MPN/100 ml)	16	7	44

Irrigation and Power Department, Lahore publishes reports on groundwater quality and quantity monitoring for different cities of Punjab including Lahore [xv]. In their groundwater monitoring report published in 2009, water level and water quality trends in different cities of Punjab and status of groundwater monitoring has been described in volume-I while volume-II contains relevant basic details on groundwater levels and quality. For Lahore zone, groundwater quality data was collected from 389 monitoring points and water level data for 169 points. Groundwater level trends for the period 2003-2008 based on the continuous data available for 28 monitoring points for Lahore district were mapped. Perusal of groundwater data for Lahore district showed declining trends both in terms of water table and quality.

X. Other Impacts of Aquifer Depletion

A. Formation of depression zone

Due to heavy abstraction of water, water table has already gone down very deep in Lahore. Reference [xlvi] reported a continuous decrease in water table of Lahore based on the groundwater level's historical record (1993-2003). PEPA [xlvii] also reported a decline of 4m in water table in the Punjab Province capital-Lahore between 1993 and 2003. Over abstraction has resulted in cone shaped depression in Lahore aquifer as shown in Fig. 7 and groundwater researches made for Lahore region has confirmed the formation of a depression cone in the center of the city [ii-iii], [xxx], [xlviii], [xxviii], [vii], [xl]. The deepest point of the depression was located around Mozang [xii] which is now located at Shadman [xlii-xliii].

Radiation and Isotope Application, a division of Pakistan Institute of Nuclear Science and Technology (PINSTECH) carried out hydrological investigation of aquifer under Lahore using chemical, isotopic and numerical techniques, sponsored by International Atomic Energy Agency (IAEA) and a conceptual flow model was developed for Lahore aquifer which confirmed the formation of irregular shape depression cone in central part of the city [xxviii]. They predicted that if abstraction continues with the same rate, depression cone will extend south toward Raiwind and Kasur areas where polluted saline waters will likely intrude into underlying fresh aquifer. Moreover results showed that Lahore aquifer is highly vulnerable to pollution as a rapid mixing of shallow groundwater (at location near the River Ravi) and deep groundwater (at locations away from river, in the center of the city) is occurring [xxviii].

Reference [xlii] has also confirmed the formation of depression zone in aquifer under Lahore [xliv]. They also identified an eastward shifting in the depression cone, indicating higher groundwater abstraction and less aquifer recharge in the area [xlii-xliii]. This is mainly due to the recent land developments in eastern parts of Lahore city changing agricultural land into concrete structures.

B. Rise in pumping cost

The water tables lowering increases pumping cost too, thus make it uneconomical to obtain water from depths of aquifer.

C. Saline water intrusion

As already discussed, heavy abstraction in the study area has resulted in irregular shape depression cone in central part of the city [xlii],[xv],[xxviii],[xliv] and activated saline water movement from adjacent areas and from depth of aquifer thus resulting in upper aquifer's salinization [xxviii],[xliv]. Lahore aquifer being unconfined is highly vulnerable to pollution as a rapid mixing of shallow groundwater (at location near the River Ravi) and deep groundwater (at locations away from river, in the center of the city) is occurring. Few years ago, there was only a single depression zone under the city. Now not only this depression zone has expanded over even larger area, few other small depression zones have appeared due to the stress on the aquifer in those regions [xliii].

D. Danger of Land subsidence

Land subsidence occurs when a large amount of groundwater has been drawn from certain type of rocks and soils. These soils and rocks may collapse when heavy abstraction of groundwater s made because water is partially responsible for holding ground up. Increasing development of land, construction of new and high buildings, and exploitation of groundwater may result in and exacerbate land subsidence. But still Lahore is saved from land subsidence just because there is a hard-pan of clay under the city [vii] which is supporting the buildings but it may eventually collapse if the over-pumping of groundwater continues without any curative measures for recharging the aquifer.

XI. Epilogue

It is more likely that aquifer of Lahore will become non useful in future in view of present groundwater conditions because present state of groundwater levels and quality in Lahore is miserable. Therefore there is a dire need for understanding the dynamics and factors responsible for this wretched situation. Making a close critical analysis based on previous studies regarding groundwater problems in the study area, key messages are:

1. Over exploitation and degradation of groundwater is going on.
2. Installation of new tube wells cannot be stopped.
3. There is a great need of having regular watch on continuously lowering water table in the study

Area.

4. In Lahore, rapidly increasing trends of urbanization and industrialization coupled with dependence of city solely on groundwater is deteriorating both the quality and quantity of underlying aquifer.
5. Heavy groundwater pumping is the sole cause of reduced water table which has already gone down below 43m in many areas.
6. Besides, tube well's close spacing is another factor accelerating the aquifer depletion.
7. Groundwater lowering if not arrested in time may result in land subsidence in Lahore.
8. Saline water intrusion is occurring due to uncontrolled groundwater pumping.
9. The central part of the city is likely to undergo the highest decline in water levels, making groundwater pumpage very expensive in these areas.
10. Installation of more tube wells without taking proper regulation into consideration will pollute area's remaining groundwater resources in near future.

XII. RECOMMENDATIONS

Apparently the issue of water abstraction is likely to perpetuate rather exacerbate in coming years. Natural recharge to underlying aquifer has been reduced considerably and flow of River Ravi is almost zero. So there is a great need to recharge the aquifer artificially and stop installation of new tube wells at least in the boundary of Lahore city. Groundwater is valuable but vulnerable resource that requires management which should aim at protecting the quality and quantity of groundwater [li-lii]. If due attention will not be paid, Lahore will have to face the situation similar like Quetta and Karachi. Following recommendations can be followed to avoid worse situations likely to occur in years to come:

1. Groundwater levels monitoring is needed for sustainable management of this precious resource [liii-liv].
2. There is great need of taking steps for public awareness about the dwindling status of groundwater [lv] in order to reduce the un-wise water usage.
3. Well spacing is a major factor which can help to arrest the groundwater draw downs and keep it at a minimum level. Concentration of tube wells in an area is generally not recommended. In 1976 , it was recommended to keep 4000 ft. well spacing in order to keep utilizing groundwater as a water source for Lahore for the very long term [xlix].
4. To make small ponds or water reservoir either in or near River Ravi for water storage during flooding. This may serve as an alternative option for aquifer recharge and contribute to save it from exhausting.
5. To develop an early warning system for Lahore to forecast groundwater quality and quantity trends [iii].

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