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Climate Change and Human-Induced Factor Impacts on Quetta Valley Aquifer, Baluchistan, Pakistan

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Abstract

The study aims to analyze the impact of climate change and human-induced factors on the Quetta Valley aquifer, Pakistan. The geological and hydrogeological studies revealed that the exposed geological formations are of sedimentary origin that ranges in age from Triassic to Recent. The precipitation recharges to the aquifer are negligible as compared to groundwater withdrawal. The drought of 1997-2004 reduced the precipitation up to 67% of average values which declined the groundwater table by 8m. From 2005-2020, the cumulative yearly average temperature increased from 23.8-27.3 ^{o}C, and the potential evapotranspiration augmented from 1,468-1,669 mm. The valley population increased from 1.02-1.8 million, yearly water demand exceeds 93-139 Mm^3, and the number of tubewells boosted up to 56%. Statistical analysis and regression trend correlations signify a combined positive influence of climate change and human-induced factors with the declination of the groundwater table. The yearly recharge to the aquifer varies from 61-89 Mm^3, abstraction from 72-101 Mm^3, and the annual deficit ranges from 1-37 Mm^3. The groundwater table was depleted from 28-36m and land subsidence ranges from 0.5-12cm/yr. The demand and supply of aquifer waters are at risk due to continuous groundwater depletion. The significant threat is the scarcity and security of freshwater resources that would eventually upshoot a predictable turmoil of urban disaster.

Keywords: Climate Change, Human-Induced Factors, Aquifer, Quetta Valley.

1. Introduction

Despite worldwide groundwater (GW) scarcity and significance, little research work has been commenced to ascertain the collective potential impacts of climatic change and human-induced factors on GW. Simultaneously, no specific climatic change and human-driven factors impact studies on GW resources have been conducted in the proposed study area and elsewhere in the country. However, many researchers studied the supply shortages and depletion of GW resources locally and globally, (Steenbergen et al., 2015; Li et al., 2014; Rahman & Mahbub 2012; Hao et al., 2007; Chen et al., 2004). In most cases, these studies are typically related to economic assessments and vulnerability that link to GW depletion.

Climate change and human-induced factors are global problems, which have a dynamic impact and uncertainties on the operation and management of water resources. It has been estimated that the global mean surface temperature has raised 0.6 ± 0.2 °C since 1861, and an increase of 2-4°C has been predicted for the next century, (Gellens, & Roulin, 1998). The hydrologic cycle impacted by the continuous increase in temperature caused excessive potential evapotranspiration (PET). The precipitations amount, timings, duration, and intensity rates change, and finally impact the surface and GW resources (Durrani et al., 2017). Climate change and GW variabilities are complex and less understood phenomena. The variability in rainfall and reduction in snowfall has reduced the surface flow which means more dependence and extraction of GW resources. Similarly, more population means more agricultural and industrial activities and more pumping of GW. A slight change in average global temperature may cause severe changes in climatic and weather conditions. The climatic change may cause intense rain, heat and cold waves, extreme temperatures, storm surges, extensive flooding, and prolonged droughts. Reduction in snowfall, soil moisture, similarly high evaporation, and PET rates are relevant consequences. All these climatic factors are visible, and their impact is apparent on the surface and GW resources Durrani et al., 2021).

The human-induced factors include mismanagement, scarce monitoring, inadequate quality, and quantity of collected data. The rapid increase in population and unplanned settlement patterns put an extra burden on GW resources. The over-pumping for irrigation purposes, subsidy on agricultural tubewells, and availability of economic solar water pumps increased the rate of pumping, resulting in GW depletion (Khair et al., 2010). The non-political determination to implement water laws, registration, and licensing of tubewells worsened the GW conditions.

2. Study Area

Balochistan Plateau is comprised of small to large18 rivers divided into three groups; rivers part of the Indus River System, closed rivers (Hamun), and Markan Coastal Rivers that drain directly into the Arabian Sea. Area wise Pishin River is the seventh biggest river basin with 9 subbasins, named Pishin, Kuchlagh, Quetta, Kolpur, Mastung, Mangochar, Kalat, Shirinab, and Patki Shahnawaz, location map of the study area is presented in Figure 1. Quetta subbasin is situated in an arid zone where GW is the sole source for all purposes. Quetta Valley is part of the Quetta Subbasin which is spread over a geographical area of 1,794 Km^2. For the last five decades, the GW table is declining in all parts of Quetta Valley (Khan and Mian, 2000). The large-scale decline of the GW table raised questions about GW security, quality deterioration, contamination, local economy, and urban land subsidence.

Quetta Subbasin has diverse topography, characterized by elongated mountain ridges, depressions, and small plains including NS widespread Quetta Valley. The valley floor is flat and gently sloping southwards along the drainage pattern. The subbasin height increase toward the northeast bounded by Zarghoon Range at 3,519m, Takatu at 3,401m, Chiltan at 3,261m, and Murder Range at 3,134m above sea level (masl). Between steep shoulders of ranges, the topographic height of the valley floor ranges from 1,570 in the northern to 1,780 masl in the southern parts, the average topographic index is 1,650 masl. Many ephemeral streams emerging from the adjacent mountain ranges join and merge in the Sariab River, the same called Balelli River in the northern region before leaving the subbasin. The subbasin is divided into Mountain High Land, Piedmont High Lands, and Valley Floor, (I&PD, 2010). The basin's major part is covered by mountain highlands, where piedmonts serve as GW recharge areas to infiltrate rainfalls readily to the water table.

Fig. 1. Location map of Balochistan showing 18 River Basins. The enlarged map in brown color of Pishin River Basin with nine subbasins including Quetta Subbasin and location of Quetta Meteorological Station.

3. Methodology and data processing

The research methodology was devised to evaluate and establish a correlation between climate change factors including temperature, precipitation, humidity, and PET with depletion of the GW table. To associate the impact of human-induced factors including population growth, mechanized pumping for domestic supply, urban development, irrigation, mining, and industrial utilization with depletion of the GW table. And to quantify the total decline of GW level in different regions of Quetta Valley. Climate change impact studies are typically based on numerical modeling of hydrologic processes; the present study is based on physical methodology. The study was initiated with field geological, hydrogeological mapping, and GW monitoring. The geological map of the area was updated, and the hydrogeological properties of the exposed lithological formations were reassessed. The geometry of the aquifer was conceptualized, and the hydrogeological model of the subbasin was created with the help of geophysical survey data and deep borehole lithological logs. To compute the hydraulic gradient, GW flow, movement, and water table decline, GW elevation maps displaying GW-level altitudes above sea levels during 2005 and 2020 and 15-year GW level change maps were prepared.

Climate changes may change regional and local hydrologic cycles and significantly affect water soil moisture and PET, surface water quantity, and GW resources recharge. The climate change and human-induced factors' influence on streamflow intensities are assessed by basinal topography. Metrics of surface topography in hydrologic analyses may be reduced to a single topographic index (TI), (Beven & Kirkby, 1979). TI = In (α / tan β) α = specific contributing area of site β = local slope angle. The TI increases as the area increase and the slope angle decreases. Weather and climatological parameters including air temperature, humidity, PET, wind speed, and daily sunshine hours data presented by graphs, correlated with precipitation, and analyzed. The PET values were calculated with the Hargreaves method for the Quetta Station, (Hargreaves, 1994). Human-induced factors including population increase, settlement pattern, urban planning, GW governance, agricultural land, forest cover, industry, and mining impacts were correlated with GW depletion and analyzed statistically. The climatic and human-induced factors are presented in graphs and analyzed in their temporal behavior, linear trends, anomalies, and correlation among each other, with precipitation and an average decline in the GW table. All said factors were statistically computed and regression analysis was performed. The descriptive statistics utilized for analyzing mean, standard deviation (SD), correlation of variation (CV%), correlation coefficients (R^2), change, and % change were evaluated for the entire study period of 15 years from 2005-2020.

From short to long-term, two types of data sets with different duration were utilized for the present study. The yearly GW monitoring data set of short duration from 2018-2020 was physically collected year after year and verified by real field monitoring to observe the GW decline. Precipitation, air temperature, humidity, and PET data span from 2005-2020 for 15 years. The long-term meteorological parameter data were acquired from Pakistan Meteorological Department (PMD) for Quetta Station located at latitude 30^o-05' N, longitude 66^o-58' E, and altitude 1,719m, Figure 1, (PMD, 2021[a,b]). The datasets were screened for missing values and the missing values were filled through the last-observation carried-forward approach. The imputed and observed values were evaluated precisely to fill out missing data. To minimize the variations and uncertainties for intrinsic correlation between the time series of different climate variables, human-induced factors, and GW decline data were used for the same period from 2005-2020. The 15 years data set long duration from 2005-2020 was related to human-induced factors including population census, agricultural land, forest cover, water supply schemes, livestock, number of tubewells, industry, and mining data collected from relevant government agencies. The details of the data sets, units, and time periods acquired from different agencies presented in Table 1.

4. Hydroclimatology

Quetta Subbasin is situated in the upper highlands climatical zone with semi-arid climatic features (Umar et al., 2014). The mild to hot summers and harsh winters are classified as "sub-tropical continental highland" climates. Winter span from October to March, having a mean temperature of 3-5ºC. Spring is from April-May having a 15ºC temperature. May-September is Summer having temperatures from 24-27ºC, and September-November is autumn having 12ºC (Climate and geography of Quetta, 2010). From 1980-2020, the cumulative yearly average temperature of Quetta increased from 24.2-25.8ºC. Arid to semi-arid climatic characteristics of Quetta have an extreme difference between summer and winter temperatures that made it inhospitable, as shown in Figure 2. As per rainfall, November-May are the wet months and 80% of precipitation falls in the wet season. The yearly average rainfall of 213 mm and snowfall is 15% of it. Quetta received 950 mm of record precipitation during 1982-1983, (Pakistan Meteorological Department, 2021[a]). Quetta Valley was devastated by drought from 1997-2004, the yearly precipitation was 40-70% below average. In 2009 and 2011 there was the heaviest annual rainfall of 317 and 437 mm (Pakistan Meteorological Department, 2021[b]). Rainfall of 55 mm decreased in the last 35 years from 1975-2009, (Khan, et al., 2013).

Table 1. Data types, units, and periods were collected from different agencies.

#	Agency	Data Type	Units	Period
1	Agricultural & Cooperatives	Agriculture land	Km^2	2005-2020
2	CLIMATE-DATA.ORG	Sunshine Wind speed	Hours Km/day	2005-2020 2005-2020
3	Field monitoring data	GW monitoring	mbgs	2018-2020
4	Forest and Wildlife	Forest land	Km^2	2005-2020
5	Irrigation	GW monitoring Tubewells	mbgs Nos.	2005-2017 2005-2020
6	Livestock and Dairy Development	Livestock census	Nos.	2005-2020
7	Mines and Minerals	Mining areas	Km^2	2005-2020
8	Pakistan Meteorological Dept.	Temperature Precipitation Humidity PET	ºC mm % mm	2005-2020 2005-2020 2005-2020 2005-2020
9	Population Welfare	Population census	Nos.	2005-2020
10	Public Health Engineering Dept.	Water supply schemes Tubewells	Nos. Nos.	2005-2020 2005-2020
11	Quetta-Water & Sanitation Auth.	Water supply & demand GW monitoring	m^3 mbgs	2005-2020 2003-2017

January-February and October are the most to least humid months of the year in the subbasin. The winter humidity ranges from 50-60% whereas in the dry season, it ranges from 28-40%. The maximum and minimum humidity in January-February and in May-June when the temperature is minimum and maximum. The maximum PET in the dry season varies from 280-300 mm, and during summer it varies from 75-90mm. The statistical analysis specifies PET values increased with temperature increase. The daily average PET ranges from 2.4 to 10.8 mm/day from January to June. The monthly mean PET from 1975-2020 augmented from 1550-1575mm/yr. The monthly mean wind speed from 1961 to 2004 ranges from 302-573 Km/day, whereas the mean annual wind speed is 436 Km/day, (Ashraf and Majeed, 2006). The monthly low to high sunshine hours range from 8 hours in January-February to 12 hours in May-July, whereas the average is 8.6 hours. The mean annual sunshine hours and temperature are at their peak in the summer. The maximum values of wind speed were observed in June and July. In the subbasin, the natural ecosystem is complex and influenced by many climatical variables, that collectively impact GW recharge, flow, occurrence, movement, and fluctuations. For this study 6 meteorological variables including precipitation, temperatures, sunshine hours, wind speed, humidity, and PET correlated with each other and their influence on GW depletion. The average long-term meteorological parameter for a quick assessment in graphical form is presented in Figure 2, the data set utilized is based on Ashraf & Majeed, (2006); Imad, (2018); PMD, (2021); and CLIMATE-DATA.ORG, Dec. (2021).

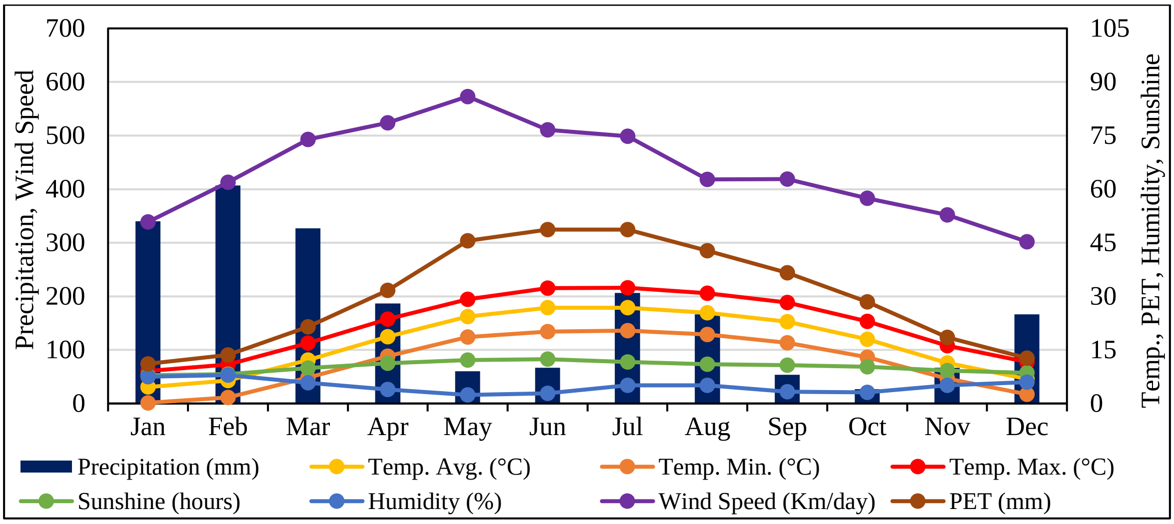

Fig. 2. Average monthly graphs of precipitation, temperatures, sunshine hours, wind speed, humidity, and PET.

5. Geology

The field geological mapping of the study area was conducted to verify the major geological boundaries on already available geological maps of the Hunting Survey Corporation, (1961) at a scale of 1:5000, as shown in Figure 3. The Quetta Subbasin developed as a part of a major north-south striking anticline/syncline structure. The Himalayan orogeny is responsible for geologic structures in the study area. The complex geological structures consist of Murdar Ghar, and Chiltan Anticlinoriums in the east and west, and the Takatu Anticlinorium in the north and southern area. The carbonate aquifer is cropping out at Mian Ghundi and Landi Hills in the center of the Quetta Valley. The mountain ranges at the shoulders of the subbasin are Jurassic comprised of Shirinab and Chiltan Formations. The tectonically active north-south trending Chaman Fault has influenced the geology and structural features of the subbasin. The Chaman Fault is of strike-slip that occurred during the compressional movement of Indian and Eurasian plates. The complex geology of the subbasin is influenced by slip faulting and convergence. Quetta Valley developed as a synclinal valley filled with Quaternary deposits underlying hard-rock formations of the Middle to Lower Jurassic. Due to the tectonic movements of the Chaman Fault, several folding, faulting, fractures, and joint systems developed in limestone formations exposed in the area, as shown in Figure 3. These faults, fractures, and joints form prominent zones of secondary porosity and permeability for the occurrence and movement of GW. The limestone, conglomerates, and sandstones are exposed in wide areas of the subbasin. The Chiltan Limestone formation of the Middle Jurassic is exposed at the rims of the subbasin and forms the drainage boundary in most of the valley. The Chiltan Limestone covers the entire Murdar Range, while the Dungan limestone of the Paleocene is exposed along Chiltan Range in the west. The massive conglomerates of the Pleistocene are exposed all along Zarghoon Range in the north.

5.1. Stratigraphy

In the study area, the exposed rock units are dominantly comprised of sedimentary sequences belonging to the Shirinab Formation of the Middle-Late Jurassic to Recent ages. The mountain ranges at the flanks of the valley are composed of Jurassic rocks of the Shirinab and Chiltan Formations. In the Quetta region, the exposed Jurassic rocks have a maximum thickness of 3,000m, which consists of thick-bedded limestones and shales (Kazmi & Jan, 1997). The description of all exposed geological formations is reported in the following paragraphs and graphically presented in Figure 4, (Sagintayev, 2010).

The Shirinab Formation is comprised of limestones, shales, and sandstones. These rock units are exposed in the southwestern part having a thickness of 1,500m. Limestone is dark in color, thin to medium bedded interlayered with grey color shale beds. The Shirinab Formation has been divided into three members namely Anjira, Spingwar, and Loralai (Kazmi & Jan, 1997). Chiltan Formation is comprised of Middle-Jurassic limestone having a thickness of 1,800m. The rock units are thick-bedded, and color varies from light grey to dark, and brownish to blueish. The formation is extensively fractured and jointed, forming important Karstic aquifers (Hunting Survey Corporation, 1961). The Sembar formation contains lower Cretaceous black silty shale interbedding of argillaceous limestone. Sembar Formation's lower contact with the Chiltan Formation in the eastern part is disconformable with a thickness of 135m (Hunting Survey Corporation, 1961). Fort Munro Formation of the Upper Cretaceous comprised of dark gray to black limestone having lower contact with the Parh Limestone Formation is unconformable in the Quetta Region, (Sagintayev, 2010). Goru Formation is comprised of Upper-Lower Cretaceous grey, thin-bedded limestones interlayered with maroon siltstone and shale. Its lower contact with beliminate shale is conformable and its thickness is 70 m (Kazmi & Jan, 1997). Brewery Limestone of Upper-Cretaceous exposed at Chiltan Range towards the southwest, where its thickness ranges from 25 to 60 m (Hunting Survey Corporation, 1961).

The Dungan Formation comprised of the Paleocene age. The medium to thick-bedded marley limestone beds is exposed in the north. In the study area, the Dungan Limestone is unconformably overlying Cretaceous and Jurassic rocks (Hunting Survey Corporation, 1961). Ghazij Formation of Early Eocene overlies conformably on Dungan Formation. It's predominantly composed of shale interbedded with mudstone, claystone, limestone, sandstone, and conglomerates. It has olive-colored with abundant foraminifera, 590 m thick, and the type-section exposed in Spintangi at NE of Quetta (Kazmi & Jan, 1997). The Urak Formation is predominantly composed of poor to well-sorted conglomerates. The conglomerates are interlayered with sandstone, siltstone, and claystone. The lower contact is gradational with the Shinmithai Formation of Miocene, with thickness ranging from 470-940 m. The Shinmithai Formation is Miocene in age. The formation is composed of light grey, brown-greenish, fine to coarse sandstone, calcareous claystone, and conglomerate. The thickness of the Shinmithai Formation ranges from 120-300 m (Hunting Survey Corporation, 1961).

The Quaternary loose sediments are mainly composed of recent deposits such as coarse alluvial material found in stream beds including gravels, sand, silt, and admixtures. The alluvial fans are comprised of scree, talus, silt, sand, and gravel in addition to silty clay. The loess and aeolian sediments are found in the center of the valley. The alluvial fans formed at the piedmont plains of the valley along the mouths of all major streams. These sequences are formed by the erosion of the surrounding mountains. The thickness of the alluvial ranges from a few meters to about 1500m in the central part of the valley. The detailed stratigraphy of each formation is summarized in Figure 4.

6. Hydrogeology

The karstic aquifer is comprised of the Shirinab and Chiltan Formations of the Jurassic and the Urak Formation of the Miocene age. These hard-rock formations of limestone and conglomerates are highly jointed and fractured having well-developed secondary porosity and permeability due to the active tectonism of the Chaman Fault System. The karstic aquifers are recharged directly from precipitation and surface runoff along mountain slopes through exposed limestone formations. The second aquifer is of unconsolidated alluvial of Quaternary, comprised of gravel, sand, and silt deposits. The alluvial aquifer's thickness gradually increases from the valley shoulders to the center and from the southern to the northern part of the valley. The aquifer developed in the form of loose valley-fill sediments deposited at depths ranging from 210 to 1,058 m (Alam & Ahmad, 2014). The Quaternary aquifer is of primary importance from a GW depletion point of view. The studies of Quaternary Aquifers are based on inadequate geological data that deliver a typical account of these systems. These analyses are based on subsurface data to illustrate rock geometry, permeability, boundary conditions, and other hydrogeological features. The lateral stratigraphy, lithostratigraphic changes, and basement and boundary characteristics of these formations may affect GW flow quantity and quality. The aquifer is recharged directly from the infiltration of rainfall, runoff, and also inflow from the karstic aquifers.

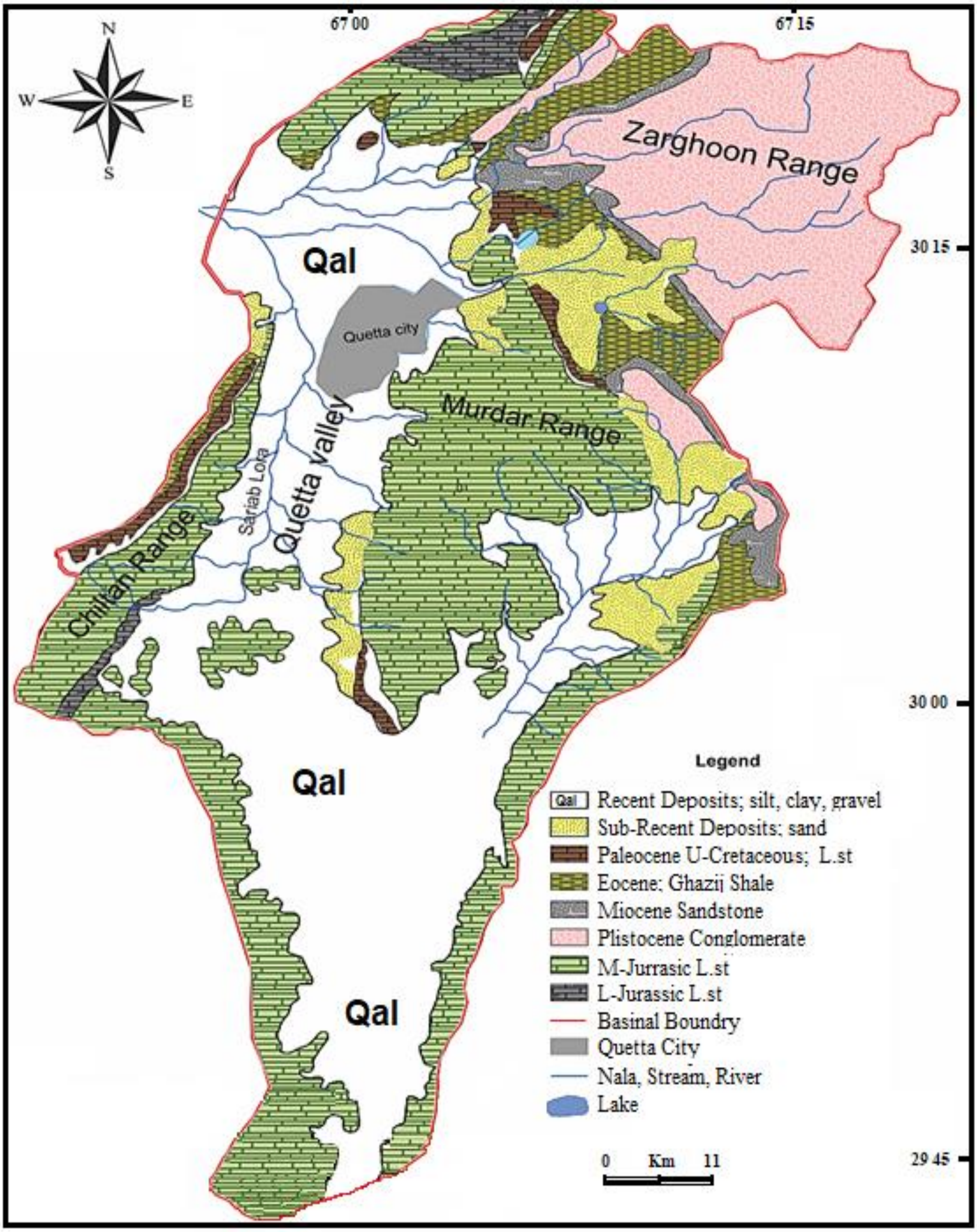

Fig. 3. Geological map of Quetta Subbasin, modified after Hunting Survey Corporation (961), & Imad (2018).

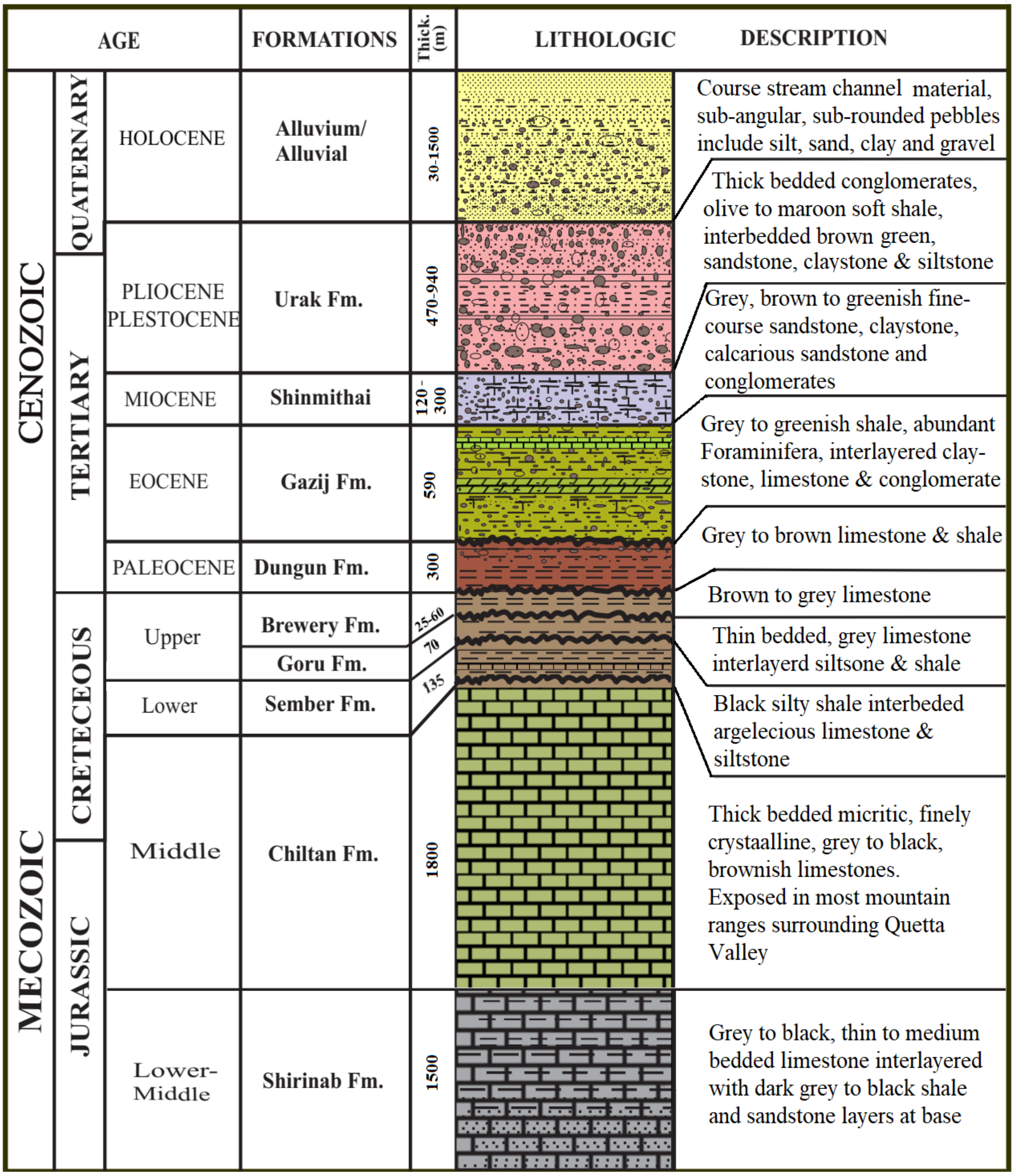

Fig. 4. Lithostratigraphic Column of Quetta Subbasin, modified after Sagintayev, (2010) and Imad, (2018).

The valley has been divided into six distinct zones based on morphology, surface topography, and associated landforms. The subbasin's half of the area is comprised of dry landmass and mountains which are 30 and 24% of the total land area, respectively, (Halcrow Pakistan and Cameos, 2008). Hydrogeologically the subbasin can be divided into high, medium, and low potential GW recharge zones. The high potential zone is composed of carbonate formations, foothills, alluvial fans, and piedmont plains bordering all mountain ranges. The medium potential recharge zones are comprised of basin plains where gravel and sandy deposits are present. The existing and dormant stream channels and routes are among the important sources of GW recharges. The low potential recharge zones are composed of impermeable geological formations like shale, clay, and silty formations. Most of the uncultivated lands and valley plains are comprised of low-potential recharge zones. The recharge to the aquifer through precipitation is negligible as compared to GW withdrawal. The drought of 1997-2004 reduced the precipitation from 40-70% and considerably declined the GW table. The study area's TI is varied considerably based on part of the watershed, terrain relief, ruggedness of basin, and variation in slope. the Increase in the drainage area, increase in GW contributions, and reduced slope angle also reduce GW transmission rate, and surface topography estimates the hydraulic gradient for shallow GW system. Subbasin has diverse topography, characterized by elongated mountain ridges, depressions, and small plains including NS widespread Quetta Valley. The impact of low to high periods of precipitation is directly related to the recharge amounts and fluctuations in the GW table. The impacted area lies in the central part of the valley near the foothills of the Chiltan and Murdar Ranges. These mountain ranges are the prominent recharging zones of the Quaternary Aquifer. The class-wise land area and corresponding major recharge zones are presented in Table 2, (GKW 2000, and Imad 2018). The seven annual GW budget estimations from 2000-2015 represent that the subbasin aquifer is recharged 61-89 Mm^3, discharges 72-102 Mm^3, and the water deficit ranges from 1-37 Mm^3. The total water demand for the study area was 134 Mm^3 in 2020. About 65 Mm^3/yr was extracted from the Quaternary Aquifer, whereas 7.0 Mm^3/yr was extracted from Karstic Aquifer, Spin Karez Dam and Kuchnai Dam, etc. The 24.8 Mm^3/yr was planned to obtain from treated wastewater for irrigation, and the remaining deficit from additional water resources, (GKW, 2000).

Table 2. Land utilization in Quetta Subbasin and corresponding recharge zones.

#	Class Name	Area (Km^2)	(Area (%)	Recharge Zones
1	Forest / Agriculture Land	176.25	9.8	High Potential
2	Sparse Vegetation	305.55	17.0	Medium Potential
3	Cultivable Land	58.15	3.2	Medium Potential
4	Flood Plains	292.67	16.3	Low potential
5	Mountains	427.92	23.9	High potential
6	Desert / Dry Plains	533.2	29.7	Low potential
Total		**1793.74**	**100**	**-**

6.1. Aquifer Geometry

The geophysical survey techniques including gravity, electrical resistivity, and seismic surveys were conducted by Alam & Ahmad, 2014 in Quetta Valley. The major purpose of these surveys was to explore the subsurface structure and depth of bedrock to determine the geometry of the Quaternary aquifer. The location map of electric resistivity sounding points and other geophysical surveys are presented in Figure 5. The deep electric resistivity survey was conducted at 13 locations in the center of the valley, the depth of bedrock ranges from 210-511m below ground surface (mbgs). The gravity survey was conducted to estimate the depth-to-bedrock at a regular grid pattern, modeling was conducted along 43 gridlines at a space of 1 Km. The density of 2.35 and 2.67 g/cm^3 were utilized for alluvium and bedrock. In the said area the depth of bedrock ranges more than 1350 m. The depth-to-bedrock towards the north side of the valley reaches a maximum of 1500 mbgs, (Alam & Ahmad, 2014). A seismic survey in Dasht Plain of Quetta Subbasin was conducted, where the reflector of bedrocks comprised of Chiltan Limestone, shown on the seismic sections utilizing normal move-out velocities. Depth-to-bedrock was evaluated at every shot point at the L1 seismic line. The bedrock topography undulates along the line where the depth of bedrock fluctuates from 211-1058 m (Alam & Ahmad, 2014). The geophysical survey results along with geological investigations and borehole lithological logs were utilized to draw the conceptual hydrogeological model of the aquifer, along the W-E cross-section, as shown in Figure 6. The top layer of the valley fills alluvium comprised of sand, silt, and gravel with a thickness of 200 to 800 m. Underneath, the top layer of gravel and admixture is present in the middle part of the valley. In reality, the said both layers are part of the same layer, it might be due to the disparate explanations of different onsite drilling Hydrogeologists. This zone is promising from a GW point of view and all potential tubewells are pumping GW from this zone. In the central region of the valley, a clay layer of Bostan separated the illuvial aquifer from the limestone aquifer. A proven minimum thickness of about 6m of sandy clay in the Killi Abdul Nabi area of about 4 Km north of Mian Ghundi is separating the alluvial aquifer from the limestone aquifer. In the valley's northern part, the clay layer's thickness increases to more than 150 m. The lithological cross-section represents that the top zone in the valley is comprised of gravel and admixture and below that zone is silty-clay and silty-sandy-clay. The second zone is making a barrier between bedrock and alluvium aquifer. Deep drilling investigation wells and further detailed studies are required to estimate the hydraulic relationship between alluvium to silty and sandy clay layers and bedrock formations. The drawn aquifer geometry is based on sketchy data, that may be improved with additional data and deep drillings.The historic GW data of the subbasin represents that before 1970 several springs and artesian wells were present, whereas many running karezes were used for irrigation. The GW recharge and discharge were in equilibrium, and GW quality was promising. Before large-scale pumping of GW, the general GW flow direction is from valley peripheries towards the Sariab River. Thereafter a continuous decline in GW level was observed, and a generalized comparison in the decline of GW level before 1970 and present-day is shown in Figure 6. To quantify the GW level fluctuations in the Quaternary aquifer, data of 20 monitoring wells were analyzed. The location points of the monitoring wells are presented in Figure 5.

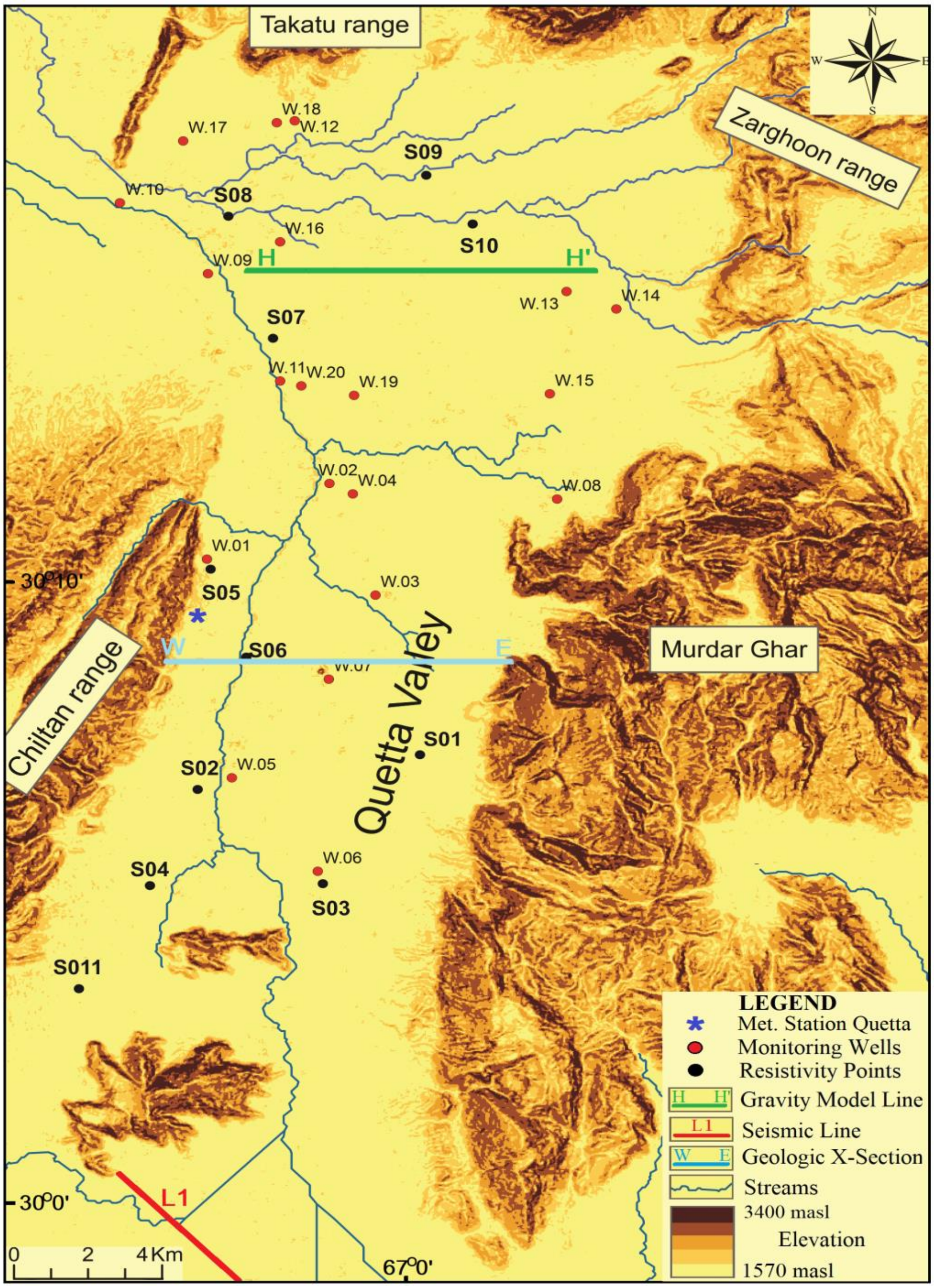

Fig. 5. Location map of monitoring wells, electrical resistivity soundings points, gravity model, seismic survey, geologic cross-section line, and meteorological station Quetta.

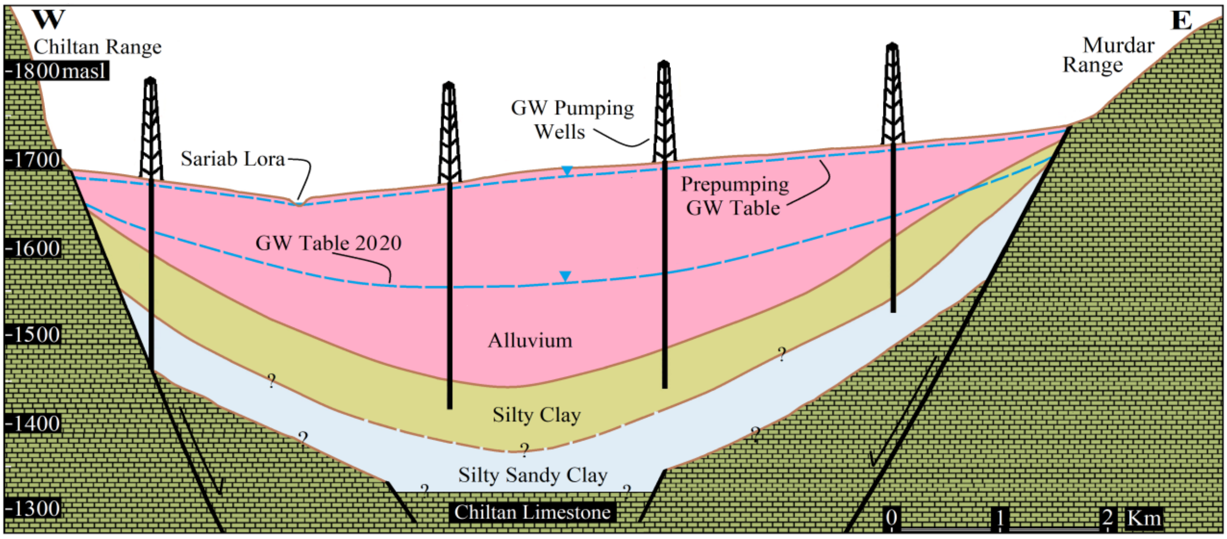

Fig. 6. The conceptual hydrogeological model of Quetta Valley aquifer along the W-E cross-section line, based on geophysical surveys, geological data, and driller logs, see Figure 4 for legend.

6.2. GW-Level Change Maps

The monthly wells monitoring data of Quetta-WASA from 2003-2015 and the P&M Wing of Irrigation Department's annual monitoring data from 2005-2016 have been analyzed. The primary data were collected from all measuring points and piezometers to correlate and obtained an updated trend of GW level fluctuations from 2017-2020. In the valley GW-level altitude varies from region to region. The GW-level altitudes across the Quetta Valley ranged from 1,480-1,660 meters above sea level (masl) during winter 2018. In the northern region of the valley, the GW level ranges from 1,480-1,600 masl, and in the central region from 1,610-1,660 masl. While in the southern region GW level ranges from 1,640-1,650 masl. Simplified GW elevation contour maps of the valley are prepared for the years 2005 and 2020. The maps were prepared to estimate and correlate the past and present average GW elevation, flow direction, and movement. The GW contours were plotted on the map for 2005 with an interval of 10m. The GW flows from high GW potential to low potential as we can see in the map from contours 1,640-1,580 masl. In the valley, the prominent GW flow direction is from southeast to northwest direction i.e., from the foothills of Murdar Range towards Balelli Gap. The hydraulic gradient in 2005 of the Quaternary Aquifer in the central part of the valley is about 0.01. The hydraulic gradient during the same period is about 0.005 in the southern part of the valley and gradually further decreases towards the south. Despite all localized changes, the major GW flow direction is from southeast to northwest in the central part of the valley. The hydraulic gradient in 2020 varies from 0.012-0.011 in the central region. The prominent GW flow direction in a major part of the valley is like 2005, from southeast to northwest. The GW elevation contour maps are presented in Figures 7 and 8. GW level-change map of the year 2005 and 2020 was prepared to see the areas and amount of GW table decline during the last 13 years. The contour maps of the GW level display an overall minimum to maximum decline of 8-36m in different regions.

7. Climate Change Factor Impacts on GW

Quetta subbasin is susceptible to climate variability and change, the variation in climatic parameters is a recurring phenomenon. In the arid environment of Quetta, the ecosystem is complex, temperature and precipitation are the most important climatic factors that have a significant influence that closely correlates to GW recharge and decline of the water table. Statistical analyses were employed to demonstrate the relationship between climatic variables with GW depletion. The long-term climatologic parameters from 2005-2020 for the last 15 years were evaluated to estimate the increasing and decreasing trends. The average minimum and maximum temperature values for long-term ranges between 23.8-27.3°C whereas the yearly average value is 25.4°C, the increase in temperature is 3.5°C and the change is 13.8%. The temperature trend, in the long run, is somewhat stable but during the study period, most of the values are above the average of 25.4°C.

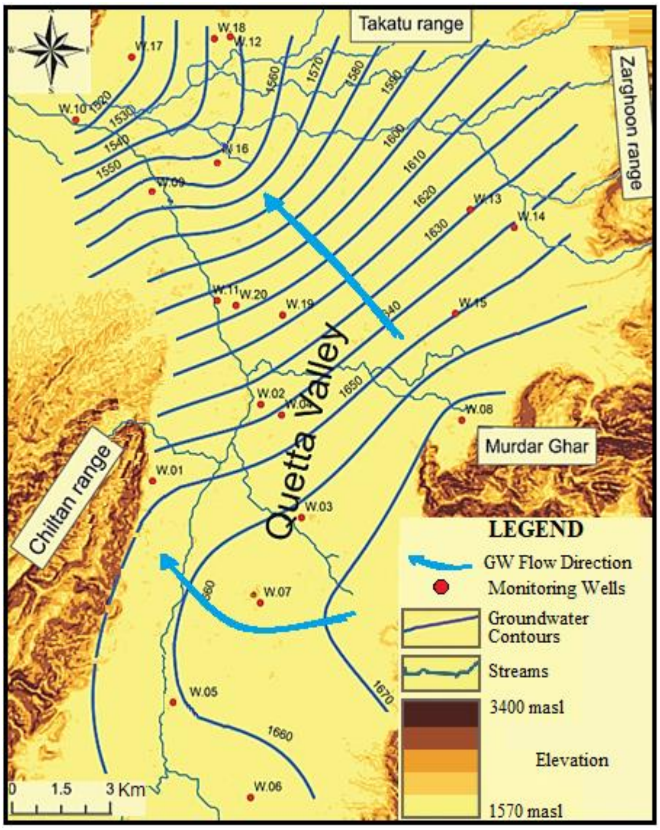

Fig. 7. Simplified GW elevation map showing GW-level altitude masl for 2005, Quetta Valley.

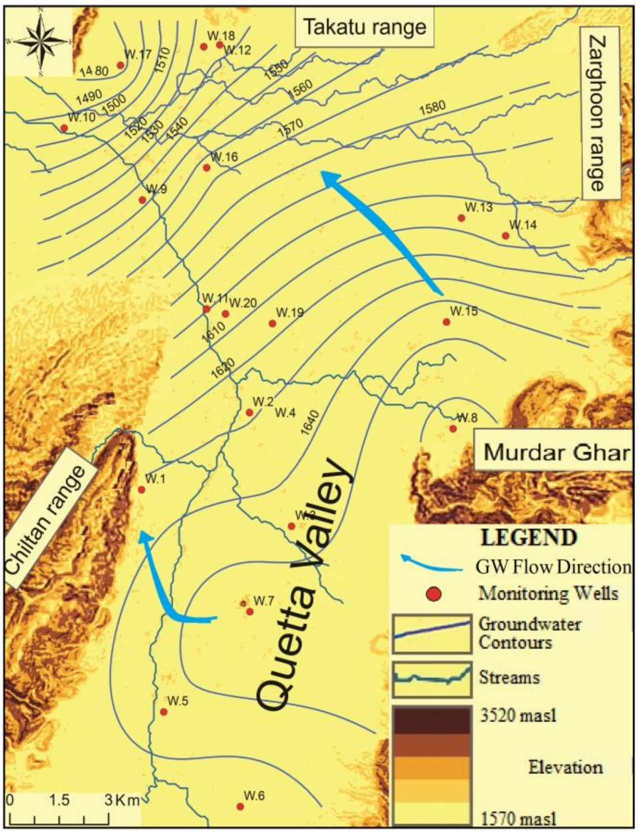

Fig. 8. Simplified GW elevation map showing GW-level altitude masl for 2020, Quetta Valley

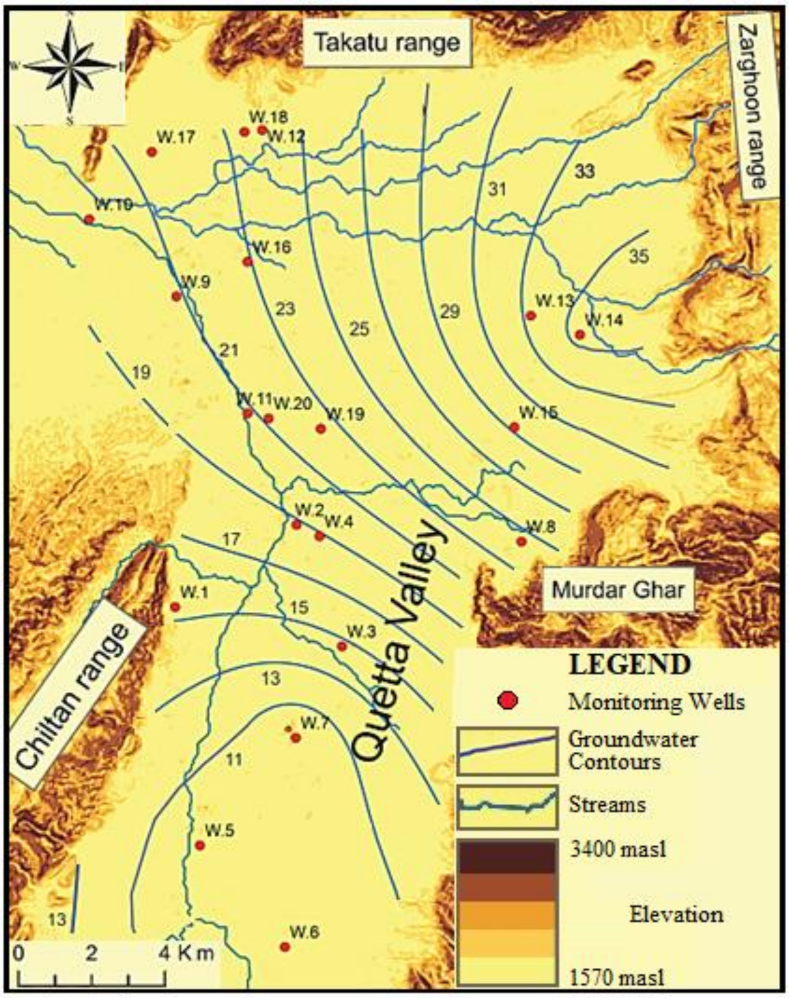

Fig. 9. Simplified 15-year GW level change map in meters from 2005-2020 for Quetta Valley.

The long-term minimum and maximum precipitation values range from 119.4-459 mm, the average is 234.2 mm and the change is 339.6 which is a 145% decrease. The precipitation evaluation represents a continuous decreasing trend in the long run because, during the evaluation period, the average precipitation values are below average. The precipitation represents a significant decreasing trend. The long-term annual rainfall is 265 mm, whereas during 2011-2012 a peak anomaly of rainfall occurred when the maximum precipitation reached 459 and 313 mm, respectively. During last the 15 years, the rainfall amounts have been below-average anomalies. The increasing trend of temperature with a decreased trend of rainfall is autocorrelated during the entire analysis period.

The long-term minimum and maximum humidity values range between 21.1-30.8%, respectively. The yearly average value is 24.3%, and change is 9.6% which counts as 39.6% of change. During the evaluated period most of the humidity values are below averages representing a continuous decreasing trend in the long run. The minimum and maximum yearly average PET values for the long term are 1,468-1,669 mm, change in minimum to maximum is 201 mm which is 12.9%. During the evaluated period the overall PET values are above average with a slightly decreasing trend. The humidity rates signify a significant decreasing trend, and the last 15 year's values are incessantly below average. The humidity graph represents only two above-average anomalies up to 40% while low average anomalies up to 20%, Figure 10.

The PET graph represents a somewhat stable trend which highly increased during 2015-16 and decreased thereafter. The yearly PET values represent uninterrupted above and low-average anomalies. Humidity and PET associations were at a minimum during the complete analysis, a reasonably higher and better correlation is challenging. On one hand, increasing temperature and PET; on the other hand, the decreasing rainfall and humidity values directly influence on recharge to GW. The substantial increase in temperature and decrease in precipitation rate prompt the high PET rate in the valley, which exerts extra pressure on the water demand in all sectors. The computed R^2 represents the variance of the dependent variable against the independent variable ranging from 0.0062-0.0398. The patterns didn't represent any consistent and significant relationship. The equations of the trend lines and values of R^2 are presented on each graph Linear regression trends and correlation between cumulative yearly average temperature, precipitation, humidity, and PET data from 2005-2020 are presented in Figure 10.

For the study area, all meteorological parameters are also not supported of natural recharge of GW as the average GW graphs from 2005-2020 represent a consistent decline in the GW table, Figure 13. The low recharge and continuous decline of the water table is a net impact of persistent increase in temperature and PET trends as R^2 values estimation are 0.0062 and 0.0032, whereas a sharp decrease in precipitation and humidity trend as R^2 valuation are 0.0398 and 0.0245.

The linear regression analysis was performed to investigate interactions and patterns in rainfall, temperature, humidity, and PET as dependent variables (Y), and (X) years as the independent variables. The long-term yearly means precipitation of 265.3 mm, and change of 856 mm, with a reduction of 333% indicate a high degree of inconsistency and variability. The 55.3 mm coefficient of variation associated with yearly precipitation denotes high reliability and dependability of rainfall for the recharging of GW. For comparison, the descriptive statistical summary comprised of mean, SD, CV, change, and % change in climatic parameters from 1975-2020, linear regression equations, and R^2 of all climatic parameters is presented in Table 3.

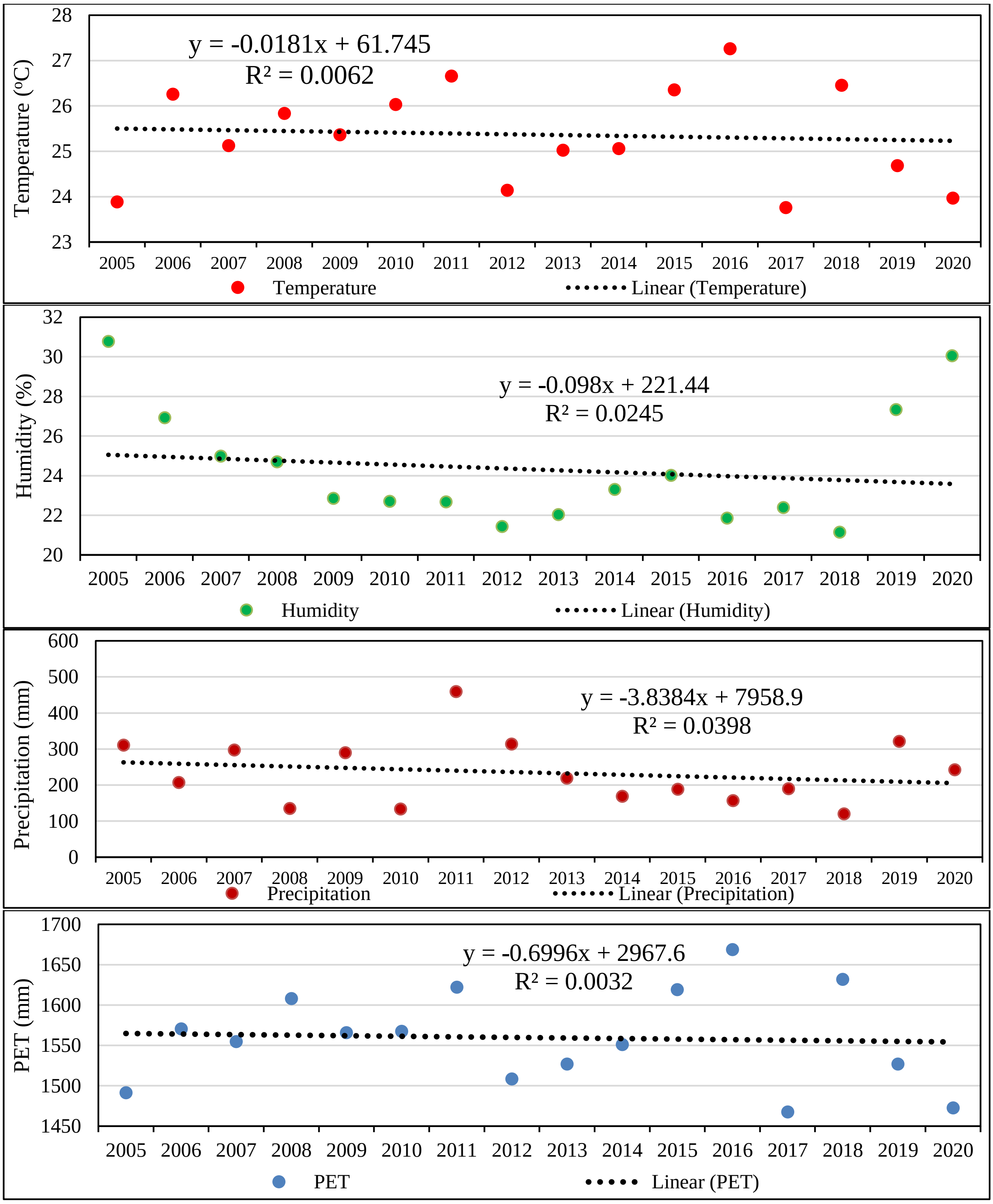

Fig. 10. Linear regression trends and correlation between cumulative yearly average temperature, precipitation, humidity, and PET data from 2005-2020.

Table 3. Statistical summary, linear regression equations, change, and % change in climatic parameters from 1975-2020.

Parameters	Mean	SD	CV %	Change	%	Regression equations	R^2
Temperature (ºC)	25.0	1.0	4.0	3.5	14	Y= -0.0181x + 61.745	0.0062
Precipitation (mm)	265.3	146.6	55.3	856	333	Y= -3.8384x + 7958.9	0.0398
Humidity (%)	27.4	3.9	14.2	13.9	50	Y= -0.098x + 221.44	0.0245
PET (mm/yr)	1562.9	47.9	3.1	157	10	Y= -0.6996x + 2967.6	0.0032

8. Human-Induced Factor Impacts on GW

Human socioeconomic activities are the major driver of human society development which includes spatial and social development. Human activities had a strong impact on GW resources since the early Holocene 90-4,200 years. Human activities affect the aquifer vulnerability, circulation system, depletion, distribution, quantity, and quality of GW. The apparent impact of some activities is short to long-term ranging from years to decades. The impact of some activities is at a local scale, while others are from a few kilometers square to a regional scale. In Quetta Valley, the urban population, urbanization rate, built-up area, and all other variables statistically show an upward trend, which impacts specifically on the quantity and extraction of GW.

8.1. Population Growth, and Water Demand

Pakistan had 6 population censuses in 1951, 1961, 1972, 1981, 1998, and 2017. In Balochistan, the yearly intercensal growth rate from 1998-2017 was 3.4% and for Quetta 5.8%. The growth levels of Balochistan were high among all provinces and Quetta was highest among all provincial capitals (Pakistan Bureau of Statistics, 2017). The population of the Quetta district was 0.142 million in 1951, which quickly increased in the 70s, and 80s, because of the migration of Afghan refugees. The census of 2017 represents that the total population of the district was 1.7 million with an annual growth rate of 4.13% (Pakistan Bureau of Statistics, 2017). The estimated subbasin population reached 1.8 million in 2020. Linear regression trend of population growth showing an increase based on official census reports from 1951-2017, the number of water supply schemes, and the increase in water demand is presented in Figure 11. Whereas for comparison the descriptive statistical summary comprised of mean, SD, CV, change, and % change from 1975-2020, linear regression equations and R^2 of population growth, increase in water supply schemes, and water demand is given in Table 4.

Quetta Water and Sanitation Authority (Q-WASA) is managing water supply and delivery systems for all the urban centers of the subbasin. Quetta water supply scheme (WSS) was devised in 1999 for 130 liters per capita per day (lpcd) or 0.13 m^3/day), by 2020 it has been projected up to 180 lpcd (0.18 m^3/day) and remains constant thereafter. In 2005 water demand for domestic and yard connections, public taps, and industrial connections were 93 million cubic meters per year (Mm^3/yr). Afterward, the water demand enhanced from 117-139 Mm^3 from 2015-2020, (Irrigation & Power Dept. GOB, 2021). The Quetta WSS is managed by Q-WASA with 430 tubewells. The present water supply data of Q-WASA and the Public Health Engineering Department (PHED, 2021) represent that the daily water demand of Quetta urban supply is about 190,000 m^3/day, while Q-WASA is capable to supply 110,000 m^3/day, the gap in supply and demand is 80,000 m^3/day, (Q-WASA, 2021). PHED is responsible for the rural WSS in the valley. PHED is managing 162 rural WSS in the valley. The PHED's latest record represents that the daily water demand of Quetta rural supply is about 45,000 m^3/day, while PHED can supply 22,000 m^3/day, the gap in supply and demand is 23,000 m^3/day, PHED GOB, 2021. Population growth intensified eventually demand for supply water put extra pressure on the aquifers. The resulting R^2 values of 0.99 to 0.97 for population and water demand are closely correlated with significant determination coefficients. The water stress analysis was utilized as an indicator to merge the effects of climate change, population increase, and GW demand. The linear regression trend of population growth, increase in water supply schemes, and water demand for Quetta Water Supply is presented in Figure 11, whereas a statistical summary is presented in Table 4.

8.2. Settlement Pattern and Urban Planning

In the 2017 census, the population was 2.28 million with 277 thousand housing units. The rural housing units were 148 thousand and the urban housing units were 129 thousand. From 1998 to 2017, the population density increased from 286 persons/Km^2 to 858 persons/Km^2. Quetta Development Authority (QDA) developed about 10 housing schemes in and around the city from 1976-2006 with a few housing units, (QDA, 2021). The remaining urban and rural housing units are without any plan constructed all along the valley. The majority of the rural housing units were established outside city limits on foothills and piedmont areas.

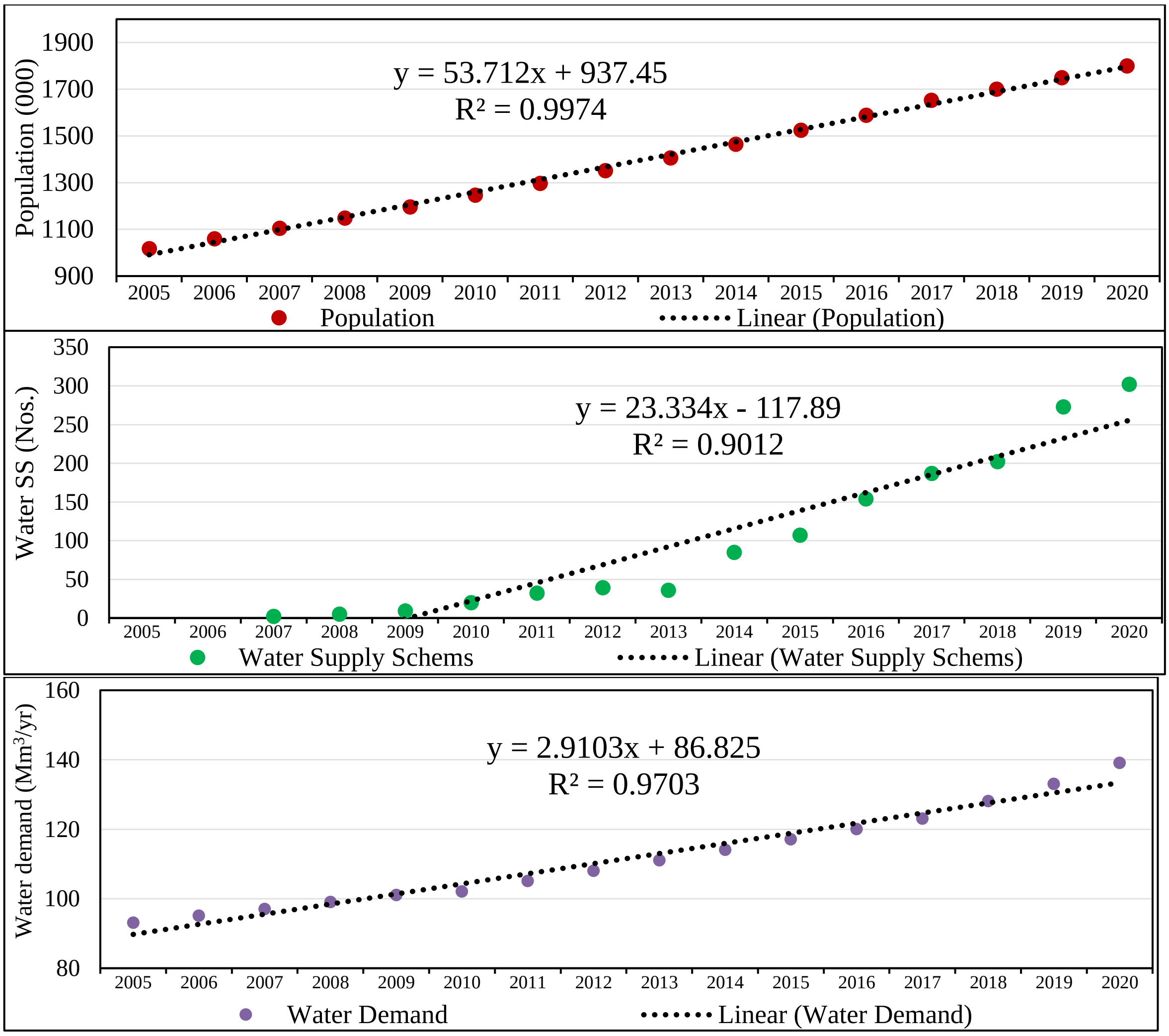

Fig. 11. Linear regression trend of population growth showing an increase from 2005-2020; increase in water supply schemes; and water demand for Quetta WSS.

The housing schemes of QDA have proper water supply systems but the suburban communities have no appropriate arrangements for water supply. The Piedmont area is important from the GW recharging point of view. Many of the city dwellers or Kachi Abadees have established permanent housing all around the city. Most of these settlements are constructed on the foothill and piedmont slopes of the Murdar Range and to some extent at the foothills of the Chiltan Range.

The foothill and piedmont slopes are geographically highlands that gradually increase in elevation at the base of mountain ranges. These are transition zones between plains and adjacent topographically higher mountains. The thicknesses of these sedimentary zones range from a few meters to hundreds of meters. Foothill and piedmont slopes are comprised of unconsolidated younger sedimentary deposits and alluvium, which consists of gravel, sand, and silt. These sedimentary deposits and piedmont areas are very important for GW recharge. The accumulated sediments are highly porous and permeable and unconfined aquifers developed in said zones. The Chiltan and Murdar Ranges are comprised primarily of karstified limestone formations. The limestone aquifer is hydraulically connected to the Quaternary aquifer of Quetta Valley through the piedmont areas. The permanent unplanned settlement in piedmont areas is a major hurdle to replenishing the Quaternary aquifer through natural recharge by precipitation.

Proper planning is required for settlements around Quetta City to avoid more construction on the foothill and piedmont slopes. The geographical areas on the eastern side of the Eastern Bypass and the western side of the Western Bypass should completely be banned from all sorts of construction. Similarly, no more construction activities should be allowed from Kansi Graveyard onwards to the Eastern Bypass at the foothills of

Murdar Range. This ban is imperative for safety, and security to maintain quality, and enhance the natural recharge of the GW resources of Quetta Valley. By protecting the 491.4 Km^2 piedmont area of the subbasin, the GW recharge amount was considerably enhanced.

8.3. Agriculture, Forestry, Livestock, Industry, and Mining

The six decennial agricultural censuses have been organized in Pakistan in 1960, 1972, 1980, 1990, 2000, and 2010. The 2015-16 statistics represent that the agricultural land in Quetta Subbasin irrigated for Rabbi and Kharif Crops is 33.5-57.8 Km^2 respectively. The cropped area irrigated by numerous sources is about 91.3 Km^2. Previously the land was irrigated by utilizing dug wells, tubewells, springs, and Karezes (underground water channels), no canal system exists in the valley. At present only deep tubewells are the sole source of agriculture because declining of GW level all springs, dug wells, and Karez systems completely dried. The drilling of deep tubewells increased the drilling and pumping costs that worsen the social and economic conditions of communities in the water supply and agriculture sectors. The minimum and maximum agricultural land irrigated with GW from 2005-2020 was 6.95-9.5 Km^2. The average was 8.08, SD 0.77, CV% 9.55, change in 15 years 2.55 Km^2, which is 32%, R^2 0.9413, and regression equation $y = 0.1572x + 6.7423$. The linear regression trends and graphical correlation showing analogous increasing patterns among agricultural land, forest cover, livestock, and tubewells are presented in Figure 12. The descriptive statistical summary comprised of mean, SD, CV, change, and % change from 1975-2020, linear regression equations, and R^2 of agriculture land, forest cover, livestock, and tubewells are shown in Table 4. The agriculture sector is the most prominent among all GW utilization, other sectors are domestic supply, industry, mining, and livestock.

In the subbasin small natural forests at Urak, Spin Karez, Karkhasa, Takatu, Zarghun, and Hazargunji areas are designated as state forests. Year-wise a small increase in forest cover area has been reported by the BOS, GOB Quetta. An increase in forestry is a good sign for surface water retention and GW recharge. These areas are important for meeting the local needs for timber, and fuel wood. These forests are degrading due to overexploitation. The coniferous and scrub forests are important verities. The Chiltan and Karkhasa forests are designated as national parks and protected areas for wildlife. Protection of natural forests, planting and maintenance, and nursery-raising of the Forest and Wildlife Departments have not been active due to a lack of funds, and weak law enforcement. Government agencies are not engaged in watershed management and range-management activities.

The livestock census of 2006 represents that there are 0.326 million domestic animals present in district Quetta. For livestock in rural areas, water is stored in earthen ponds for domestic and public use and livestock. In the subbasin, the livestock water requirement is met mainly through water supply systems. The daily water consumption of livestock is depending on some physiological and environmental factors. The actual quantities are hard to determine as appropriate farming units are not existing in the valley. The linear regression trends and graphical correlation showing analogous increasing patterns among the increase in forest cover area, and livestock are presented in Figure 12. The correlation and increasing patterns represent a consistent and significant relationship with an increase in water demand, ultimately more pumping and declining of the water table, shown in Table 4.

The industrial and mining sector's development pace and of small industrial units is very slow in the province. As per Directorate General Industries and Commerce, GOB, (2021) there is only one Industrial Estate at Sirki Road Quetta. The industrial estate was established during 1961-62 and has 55 functional units. The small industrial unit owners and mining companies have little concern with the water accessibility, source, demand, and consumption problems. The actual and enumerated industrial water demand for Quetta was calculated by GKW, (2000). For the industrial requirements of Quetta, it has been estimated that about 5.4 Mm^3 was utilized during 1993. The industrial requirement would increase to 5.6 Mm^3 in 2000 and ultimately 6.21 Mm^3 by 2015. As an average for the design of water supply schemes, 10% of domestic supply is assumed for industrial and 10% for mining sector utilization.

9. Declination of GW Table

From 1985-2020 the minimum to maximum level of the GW table was 80-115 mbgs. The cumulative yearly average GW level was 98 mbgs, change in level was 35 mbgs which is about 70%. The statistical parameters as 12.2m SD, 12.4 CV%, 0.9728 R^2, and the regression equation y=2.312x + 80.472, Table 4. Regression analysis was performed to correlate the correlation between GW level decline to temperature and precipitation. The GW monitoring graphs signify a maximum decline in the water table in some monitoring wells from 2005-2011. Subsequently, in 2010-2011, the decline in GW table was the least steady. The GW monitoring results represent that the water table at Haji Saadullah, Chashma Achozai area declined from 24.9 to 29.5m from 2003-2018. GW decline around GOR Colony was 4 to 42m.

The declinations in Labor Colony and Killi Nasiran range from 10 to 38m. Rapid declination is recorded in Killi Shabak in the Sra Khula area, which shows a decline of 70.5m. Whereas 102m was recorded up to 2005 and 140m was recorded up to 2018. The decline at Sariab and Sabzal Roads reveals a decline of 5 to 9m. Police Training Center, Military Dairy Farm, and Killi Barazai show a decline of 9m, 10m, and 13m, respectively.

The GW level decline at Killi Kirani and Killi Shahozai at Brewery Road is 15.4m and 30m, respectively. The difference in the magnitude of long-term GW declines in almost all the wells reflected conditions that despite all up and downs uninterrupted decline of water level is evident. The minor and major fluctuations in rates of GW-level change highlight the value of ongoing water-level monitoring to differentiate short and long-term fluctuations associated with climatic variability. The average GW level graphs from 2005-2020 represent a consistent decline in the GW table. The continuous decline of the water table is a net impact of all climatic and human-induced factors. The correlation of precipitation with seasonal and long-term GW level fluctuations, at individual wells, is presented in Figure 13. The precipitation impact is reflected in almost all monitoring wells in the subbasin. The effect of minimum and maximum precipitations can be observed as a minimum and maximum decline of the GW table in almost all the wells located in the central parts of Quetta Valley. The GW decline figures represent that the maximum GW table declined during the year 2010 and the minimum declined during 2011.

The maximum and minimum decline of the GW table is due to maximum and minimum precipitation during the same periods. In Quetta and Balochistan, there was a severe drought from 1997-2004, the precipitation amount was reduced up to 67% of average values that declined the GW table up to 8m. To compare the GW monitoring results and to correlate the GW fluctuations of different wells, the GW level hydrographs of some observation wells are presented in Figure 13. The water level fluctuation trends of just a few wells resemble each other and show a parallel trend. In most cases, the fluctuation in hydrographs is dissimilar to each other. The major reason for this difference is the locations and hydrogeological characteristics of the Quaternary aquifer sediments. A well located near or away from the GW recharge or discharge area will have a different pattern of fluctuations.

The historical long-term GW decline from 1969 to 2020 represents a continuous decline of GW in Quetta Valley, (Nguyen, et. al., 2007, Ashraf & Ashfaq, 2017, Imad 2018). The average minimum GW decline was 4m during 2005-2009. A cautious estimate represents that GW declined in the central part of Quetta Valley from 1969-2020 is around 40-45m. The latest figures show that the average maximum GW decline is around 15m during 2015-2020. The history of long-term GW level decline meter above sea level (masl) in Quetta is presented in Table 5.

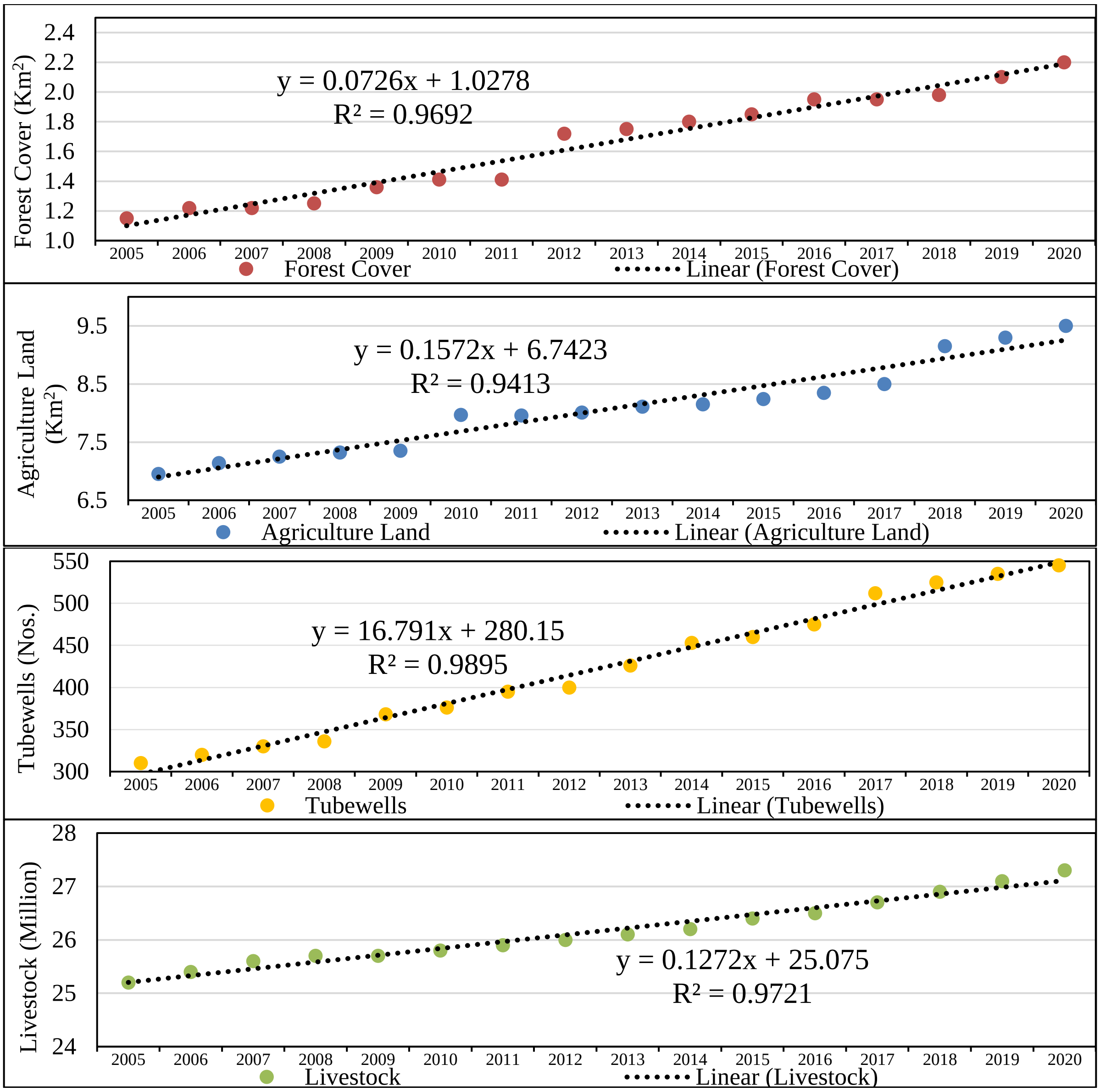

Fig. 12. Linear regression trends and graphical correlation showing analogous increasing patterns among agricultural land, forest cover, livestock, and tubewells.

Table 4. Statistical summary and linear regression equations of Human Induced Factors, change, and % change along with GW decline from 2005-2020.

Factors	Mean	SD	CV %	Change	%	Regression	R^2
Population (000)	1394	256.1	18.37	783	56.2	y= 53.712x + 937.45	0.9974
Water Supply S (Nos.)	104.0	103.0	99.07	300	289	y= 23.334x – 117.89	0.9012
Water Demand (Mm^3/yr)	111.6	14.07	12.61	46	41.2	y= 2.9103x + 86.825	0.9703
Agriculture land (Km^2)	8.08	0.77	9.55	2.55	31.57	y= 0.1572x + 6.7423	0.9413
Forest cover (Km^2)	1.65	0.35	21.35	1.05	63.83	y= 0.0726x + 1.0278	0.9692
Livestock (million)	26.16	0.61	2.35	2.1	8.03	y= 0.1272x + 25.075	0.9721
Tubewells (Nos.)	432	80.0	19.00	235	55.6	y= 16.791x + 280.15	0.9895
GW decline (m)	98.0	12.2	12.4	34.4	70.0	y=2.312x + 80.472	0.9728

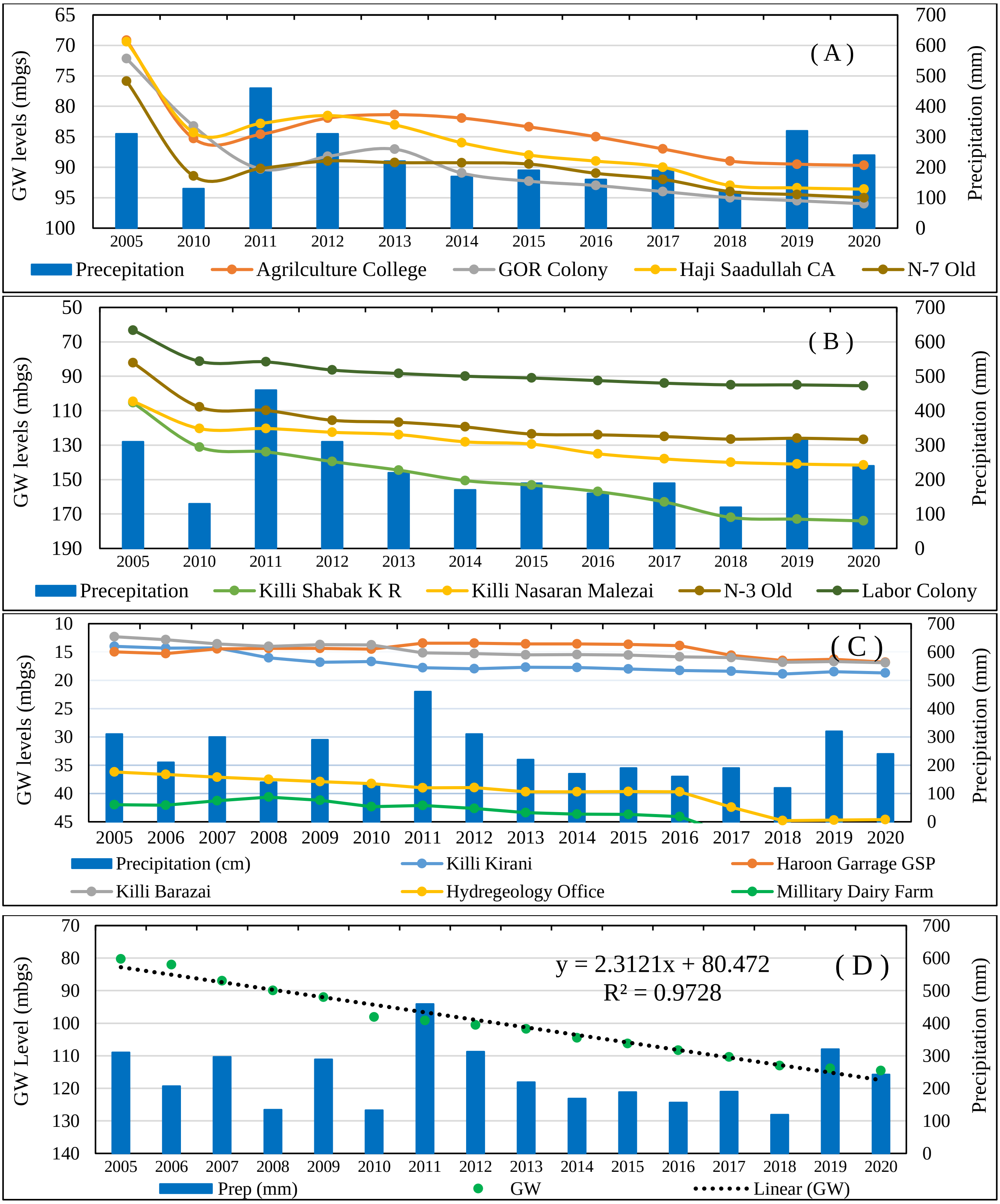

Fig. 13. Correlation between precipitation and long-term yearly relative changes in GW level hydrographs along with linear regression trend of cumulative average GW level decline from 2005-2020. A, B, and C graphs represent a group of monitoring wells with similar data sets and trends of GW decline, and D is the linear regression trend of yearly average GW decline.

10. Groundwater Governance

The GW governance comprises the government's rules, regulations, policies, and actions to control, protect, and sustainable the utilization of aquifer systems for communities and ecosystems. From 1992-2015 different federal and provincial governments and private sector organizations developed 20 different strategies and policies to keep the ecosystem, protect biodiversity, and secure natural resources in their respective domains of Balochistan, (Aftab et. al., 2018). The strategies comprise protecting and conserving the environment, agriculture, rangelands, forests, watershed management, river basins, surface, and GW resource management, and dealing with the influence of climate change. The protection and management of surface and GW resources is a major component of each policy and strategy. Not a single strategy or policy has ever been implemented in letter and spirit in the province. The mismanagement of GW resources resulted in a worsening of water quality, and quantity, water-stressed, a decline in the water table, and ultimately land subsidence started at an alarming rate.

In Balochistan, systematic GW investigations were started by the Hydrogeology Directorate of WAPDA in 1970. Thereafter the GW was easily accessible in large quantities and from greater depths through enhanced drilling techniques. The suction pumps are converted into deep submersible pumps for irrigation in a very short period. Rural electrification started in 1971 and a subsidized power supply was initiated in 1973. The subsidized electric-powered and thereafter solar water pumps put extra pressure on all GW resources. The ban on new tubewells in Quetta Subbasin was imposed in 1995, which was never been implemented. Some important milestones of the provincial government related to GW governance are presented in Table 6.

Table 5. Historical declination of GW levels in Quetta Valley.

#	Period	GW level declination		
		Ave. (m)	**Mini. (masl)**	**Maxi. (masl)**
1	1969-1989	4.6	-	-
2	1989-1996	4.3	-	-
3	1997-2000	4.4	-	-
4	2001-2004	4.3	-	-
5	2005-2009	4.0	1,670.0	1,520.0
6	2010-2014	7.0	-	-
7	2015-2020	15.0	1,650.0	1,480.0
Total	**1969-2020**	**43.6**	**20.0**	**40.0**

Table 6. Year-wise GW governance milestones.

#	Governance issues	Years
1	Rural electrification initiated	1971
2	GW investigation started	1972
3	Subsidized power supply	1973
4	Interest-free pumping loans to farmers	1974
5	GW Ordinance	1980
6	Flat rate on electricity bills	1981
7	WASA Quetta Act	1984
8	Subsidized tubewells	1988
9	Private drilling intensified	1992
10	Ban on new tubewells in Quetta Subbasin	1995
11	90% subsidy on electricity bills	1997
12	Electric supply was reduced by 50%	2004
13	Drought rehabilitation program	2006
14	Rehabilitation of WSS affected by floods	2012

The government incentives encourage communities to pump as many quantities of GW as possible. There was no restriction on the number of tubewells, the quantity of GW abstraction, management, and conservation. The number of tubewells in Quetta District increased from 1,500 in 1996 to 1,766 in 2000, (GKW, 2000). The tubewells installed from 2000-2020 increased from 1,766 to more than 3600 in numbers, increasing about 50% in 20 years, including irrigation and water supply. The number of tubewells for water supply in the subbasin area increased from 310 to 545 in numbers from 2005-2020, respectively. The statistical mean of tubewells is 432 Nos, SD 80, CV 19%, which increased 235 in 15 years which is a 56% increase. Statistically, the installation of tubewells directly correlates to all human-induced factors associated with an increase in proportion. Due to over-pumping, a continuous decline in the GW table was observed in all parts of the valley. The linear regression trends and analogous increasing patterns of tubewells in comparison to human-induced factors are shown in Figure 13.

The distinctive features of GW governance are specific to the nature of surface and GW resources and their active integrated management. Despite the provincial government having a well-functioning institutional, administrative, and technical infrastructure for GW governance, it completely failed for sustainable GW management. It has been observed that governing departments lack the political will to imply responsible resource use as per environmental and economic sustainability with stakeholder participation. The GW resources of the subbasin are a common property of all the residents and it requires a universally applicable and measurable plan, policy, and strategy for GW governance. To sustain GW use in already stressed subbasinal aquifers serious interventions are required to minimize scarcity by establishing enforcement of an appropriate Sustainable GW Management Act.

The GW mining over the last four decades caused a continuous decline in GW levels that aggravate land subsidence specifically in the central region of Quetta Valley. The impact of land subsidence instigated damage to housing, commercial buildings, roads, and other urban infrastructures. A few similar studies based on global positioning systems (GPS) have been conducted to estimate the intensity and amount of land subsidence in the valley. Khan et al. (2013) studied “land subsidence and declining water resources in Quetta Valley” with GPS data and assessment of spatial and temporal differences in GW levels. GPS data of two stations from 2006-2009 represent land subsidence occurred at 10 cm\year.

Ahmad, et al, 2017, studied land subsidence in Quetta affected by the exploitation of GW-based analysis of the European Space Agency’s Sentinel satellite data. Interferometric Synthetic Aperture Radar (InSAR) data were analyzed using twenty-nine Sentinel-1 SAR images to obtain twenty-eight interferograms of land subsidence from October 2014 to October 2016. The land subsidence associated with land cover is derived from Sentinel-2 multispectral images. The study represents that the valley had uneven land subsidence with a magnitude of 5-28 cm within two years, from 0.5-14 cm/yr. Figure 14 represents Sentinel-1 SLC satellite images of sub-swath IW1 and IW2, the city center with GPS stations, pumping well locations, and maximum land subsidence in the valley center, Ahmad W. et al. 2017. Najeebullah et. al., (2020), studied land subsidence data from five GPS stations located in Quetta. The GW decline data from 41 monitoring wells during 2010-2015 were correlated with land deformation data. The analysis represents that the land subsided from 3-12 cm/yr from the flanks to the central part of the valley.

The overall result of the above-mentioned studies illustrates a land subsidence rate of 10 cm/yr from 2006-2009, 0.5-14 cm/yr from 2014-2016, and 3-12 cm/yr from 2014-2019. Collectively, the estimated land subsided at an average rate of 12cm/yr in the central part of the valley from 2006-2019. Accordingly, the central region of the valley has subsided by more than 1.56 m in 13 years. These figures are on the very higher side, but the land subsidence is tangible and continuously subsidizing because of the continuous depletion of the GW table over the last four decades.

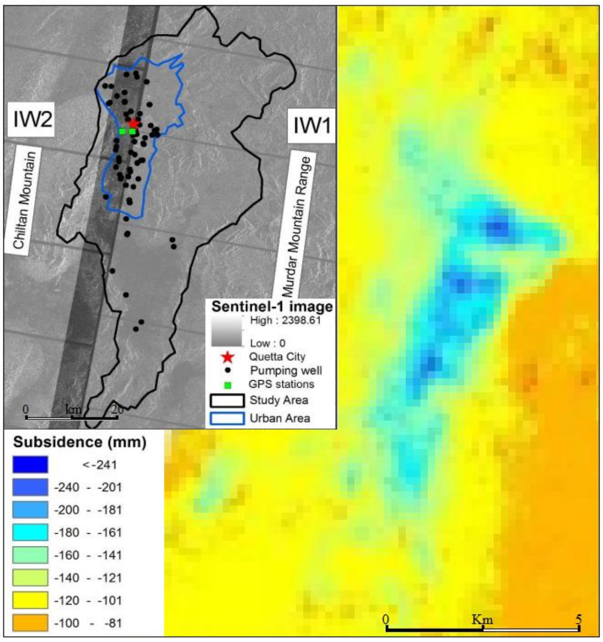

Fig. 14. Sentinel-1 SLC satellite images of sub swath IW1 and IW2, the city center with GPS stations, pumping well locations, and in color land subsidence in the central valley from 2014-16, modified after Ahmad et al., (2017).

11. Conclusions

Temperature and precipitation are the most determinant climatic parameters that influence the recharge of the valley aquifers. The low to high periods of precipitation is directly related to recharge amounts and fluctuations in the GW table. The impacted area for recharge lies in the central part of the valley near the foothills of the mainly Murdar and Chiltan Ranges. These mountain ranges are the paramount recharging zones of the aquifer. The aquifer geometry reveals that the maximum thickness of Quaternary sediments is about 1,500m in the central part of the valley. In the same region, the maximum thickness of the gravel zone is about 120m from the ground surface. Due to the bad governance and mismanagement of GW resources, the land subsided at a rate of about 12cm/yr in the central part of the valley.

The statistical analysis and regression trend correlations represent that reduction in rainfall and rise in temperature prompt the high PET values and decline in recharge to the aquifer, resulting in depletion of the GW table. The other climate extreme variabilities and human-induced factors simultaneously impact the recharge that aggravates and worsens the social and economic conditions of communities in the water supply and agriculture sectors. The foremost reason associated with the human-induced factors and continuous depletion of the GW table is the increased abstraction due to the increased population. Census analysis represents that in 2005 the population was 1.02 million which increased to 1.8 million up to 2020 an increase of 56%, which caused a big gap in supply versus demand of GW. In 2005 domestic water demand was 93 Mm^3 which increased to 139 Mm^3 in 2020, a 46% increase. The tubewells installed for water supply from 2005-2020 increased from 310-545 Nos. during the same period, the number of rural water supply schemes increased from 2 to 302 Nos. Similarly, the demand for GW increased many folds in agriculture, industry, mining, and all other sectors.

The minimum and maximum decline of GW level vary from 28-36m during the last 15 years. The average GW level was 80 mbgs in 2005, which further declined to 115 mbgs during 2020, an average decline of 35m. The maximum decline is observed in the NE of the valley where it ranges from 32-36m. The statistical analysis validates the continuous decline of the GW table is due to the combined impact of climatic and human-induced factors collectively. It has been realized that the security of freshwater resources cannot be managed with short-term climate change adaptation strategies. To avoid predictable urban turmoil, a "Sustainable GW Management Act" is mandatory to protect the water resources of the valley.

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Author's Contribution

Imad Ali: The study is part of Eng. Imad Ali's MS thesis was submitted to the Department of Civil Engineering, BUITEMS Quetta, Pakistan. Mr. Imad conducted fieldwork, data collected, performed analysis, interpretation, and report preparation.

Syed Mobasher Aftab: Conceptualized, supervised, reviewed methodology, editing, and article publishing.

References

Aftab, S. M., Rehanul, H. S., and Muhammad, A. F., (2018). Strategies to Manage Aquifer Recharge in Balochistan, Pakistan: An Overview. *IOP Conf. Ser.: Mater. Sci. Eng.* **414** 012023

Ahmad, W., Choi, M., Kim, S., and Kim, D. (2017). Detection of Land Subsidence due to Excessive GW Use Varying with Different Land Cover Types in Quetta valley, Pakistan Using ESA-Sentinel Satellite Data. Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-234,2017.

Alam, K., & Ahmad, N. (2014). Determination of Aquifer Geometry through Geophysical Methods: A Case Study from Quetta Valley, Pakistan. Acta Geophysica, 62, 142-163. doi: 10.2478/s11600-013-0171-8.

Ashraf M., and Ashfaq A. Sheikh, (2017). Sustainable Groundwater Management in Balochistan. Pakistan Council of Research in Water Resources (PCRWR), pp. 34.

Ashraf M., and Majeed A., (2006). Water requirements of major crops for different agro-climatic zones of Balochistan.

Beven, K. and Kirkby, M. J.: A physically based variable contributing area model of basin hydrology, Hydrol. Sci. Bull., 24, 43–69, 1979.

Chen, Z., Grasby, S., & Osadetz, K. G. (2004). Relation between climate variability and GW levels in the upper carbonate aquifer, southern Manitoba, Canada. Journal of Hydrology, 43–62.

Climate and geography of Quetta. (2021). www.servinghistory.com.

CLIMATE-DATA.ORG., (2021). https://en.climate-data.org/ Dec.2021.

Directorate General Industries and Commerce, (2021). Data related to mining and industries. GOB, Quetta, Balochistan.

Durrani, I. H., Adnan, S., Aftab, S. M., (2021). *Daily Climate Extremes of Temperature and Precipitation Over Quetta Valley, Pakistan During 1961-2019*. https://www.researchgate.net/publication/353426442.

Durrani, I. H., Adnan, S., Ahmed, M., Khair, S. M., & Kakar, E. (2017). Observed Long-Term Climatic Variability and Its Impacts on the Ground Water Level of Quetta Alluvial. Iran J Sci. Technol. Trans. Sci. doi: 10.1007/s40995-017-0235-8

Gellens, D., and Roulin, E., (1998). Streamflow response of Belgian catchments to IPCC climate change scenarios. Journal of Hydrology, 210 (1998) 242–258.

GKW, (2000). Quetta waters supply and environmental improvement project, Quetta, Pakistan.

Halcrow Pakistan and Cameos, (2008). Pishin Lora Basin Management Plan. Asian Development Bank: Supporting Public Resource Management in Balochistan.

Hao, X., Chen, Y., Xu, C., & Li, W. (2007). Impacts of Climate Change and Human Activities on the Surface Runoff in the Tarim River Basin over the Last Fifty Years. Water Resour Manage, 22, 1159–1171. doi: 10.1007/s11269-007-9218-4.

Hargreaves, G.H., (1994). Defining and using reference evapotranspiration. J. Irrig. Drain. Eng. 1994, 120, 1132–1139.

Hunting Survey Corporation Ltd., (1961). Reconnaissance Geology of Part of West Pakistan: Toronto, ON Canada.

Imad Ali, (2018). Impact of Climate change and Human Induced factors on the Quaternary aquifer of Quetta Subbasin, Pakistan. MS thesis (unpublished), Dept. of Civil Engineering, BUITEMS Quetta, Pakistan.

Irrigation & Power Dept. GOB, (2021). Groundwater monitoring data and number of tubewells BOG, Quetta, Pakistan.

Irrigation & Power Dept. GOB, (2000). Present and Future Water Demand of Quetta Water Supply. Quetta, Pakistan

Irrigation & Power Dept. GOB, (2010). *Ground Water Management Action Plan for Pishin Lora Basin & Implementation of Pilot Program in Quetta Sub-basin*.

Kazmi, A. H., and Jan, M., Q. (1997). Geology and tectonics of Pakistan: Graphic Publishers.

Khair, S. M., Culas, R. J., & Hafeez, M. (2010). The causes of GW decline in upland Balochistan region of Pakistan: Implication for water management policies. Paper presented at the Australian Conference of Economists, Sydney, Australia.

Khan A.S., Mian, B.A (2000). Groundwater development Issues of Pakistan. Proceedings of the Global Water Partnership Seminar on Regional Groundwater Management, Islamabad.

Khan, A. S., Khan, S. D., & Kakar, D. M. (2013). Land subsidence and declining water resources in Quetta Valley, Pakistan. Environmental Earth Sci., 70(6), 2719-2727.

Li, X., Li, G., & Zhang, Y. (2014). Identifying Major Factors Affecting Groundwater Change in the North China Plain with Grey Relational Analysis. *Water*, *6*, 1581-1600. doi: 10.3390/w6061581.

Najeebullah Kakar, Din Muhammad Kakar, and Sadia Barrech, (2020). Land subsidence caused by GW exploitation in Quetta and surrounding region, Pakistan. Proc. IAHS, 382, 595–607, 2020. https://doi.org/10.5194/piahs-382-595-2020. © Author(s) 2020.

Nguyen L, Khan S D, Sultan M, (2007). Finding causes of groundwater fluctuations in Quetta basin, Pakistan. Geol. Soc. Am. Abstr. Progr. 39(6):323

Pakistan Bureau of Statistics, (2017). District wise census results 2017, Government of Pakistan.

Pakistan Meteorological Department[a], (2021). Climate of Quetta. www.wikipedia.com.

Pakistan Meteorological Department[b], (2021). Climate data sets of Quetta, Islamabad.

Public Health Engineering Department, (2021). Data related to rural water supply schemes and number of tubewells. GOB, Quetta, Balochistan.

Quetta Development Authority, (2021). Data related to different housing schemes and water supply systems. GOB, Quetta, Balochistan.

Quetta Water and Sanitation Authority, (2021). Groundwater monitoring data and number of operational tubewells. GOB, Quetta, Balochistan.

Rahman, M., & Mahbub, A. Q. M. (2012). GW Depletion with Expansion of Irrigation in Barind Tract: A Case Study of Tanore Upazila. Journal of Water Resource and Protection, 4, 567-575.

Sagintayev, Z. J. S. (2010). Integrated approach for the assessment and development of groundwater resources in arid lands: Applications in the Quetta Valley, Pakistan. Western Michigan University.

Steenbergen, F. V., Kaisarani, A. B., Khan, N., & Gohar, M. S. (2015). A case of GW depletion in Balochistan, Pakistan: Enter into the void. Journal of Hydrology: Regional Studies, 4, 36–47.

The 2017 Census of Pakistan, (2018). Analysis of Results – Volume 1. Research Report No. 101. Social Policy and Development Centre, Karachi, Islamabad, Pakistan, www.spdc.org.pk.

Umar, M., Waseem, A., Kassi, A. M., Farooq, M., Sabir, M. A., & F. (2014). Surface and subsurface water quality assessment in semi-arid region: a case study from Quetta and Sorange Intermontane Valleys, Pakistan. *Global NEST Journal*, *16*, 938-954.