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Research article

Hydrological and ecological impacts of run off river scheme; a case study of Ghazi Barotha hydropower project on Indus River, Pakistan

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ABSTRACT

Run off river schemes are getting widespread importance as they are considered environmentally safe. However, number of studies and the consequent information regarding impacts of run off river schemes is very limited worldwide. Present study attempted to analyze impacts of Ghazi Barotha Hydropower Plant, which is a run off river scheme situated in Khyber Pakhtunkhwa province of Pakistan. This study attempted to analyze impacts of this run off river scheme on hydrological and ecological conditions of downstream areas. Data on river discharge, groundwater levels, agriculture area, vegetation and bare soil was utilized for this study. All data sets between the year 1990 till 2020 were analyzed. Hydrological impacts were analyzed through secondary data analysis, whereas ecological impacts were studied through remote sensing technique. Statistical methods were applied to further draw conclusions between hydrological and ecological interrelationships. Results showed that after functioning of Ghazi Barotha, there was 47% and 91% reduction of river discharge, in summer and winter seasons respectively. Groundwater level dropped by 50%. Agriculture area reduced by 1.69% and 9.11% during summer and winter respectively, whereas land under bare soil increased. River water diversion was considered to be responsible for groundwater reduction, as strong correlation was found between both. Agriculture land recovery, in post Ghazi Barotha period, was premised at intense groundwater mining, as groundwater level and agriculture area were significantly related ($p < 0.05$). Governments' groundwater development schemes, and a shift into motorized groundwater mining were major factors behind further groundwater exploitation in study area. This study came to the conclusion that Ghazi Barotha Hydropower Plant had impacted flow regime of Indus River, as well as groundwater levels and land use of downstream area along the river. These

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effects were triggered by inappropriate compensatory measures and uncontrolled water resource exploitation.

1. Introduction

With increasing world population, there is a constant demand for infrastructural and technological developments, especially in the energy sector [1]. Among all sources of energy, hydropower is considered one of the most cost-effective technologies, and contributes to the global electricity requirement by 17% [2]. According to Qin et al., 2020 [3], the demand of hydropower is expected to grow in future also due to its safe characteristics and GHG emission reduction During 20th century, the development of hydroelectric power involved building of large dams through creating huge artificial lakes by placing massive barriers of concrete, rock and earth across river valleys [4]. These dams were beneficial for major reliable power supply and provided additional irrigation water but resulted in massive environmental issues [2]. Water impoundment on a large area, water logging and salinity, displacement of people, shrinkage of fertile lands, river flood alteration etc. are some of the most prominent manifestations in this regard, which have also led into political conflicts [5]. In addition, alterations in reservoir releases, demanded for biological improvement of biodiversity is becoming a major debate confronting environmental experts and scheme managers [6]. More attention, hence, is towards small hydropower schemes especially run off river schemes, which are considered environmentally safer [7]. Run off river schemes operate through utilizing natural flow of river and requires no storage reservoir, whereas channel diversion is typically done through conventional weirs that divert water into a secondary channel for power production [5]. Therefore, the development of such schemes is speeding up internationally due to their perceived safe characteristics [8]. Number of run off river schemes doubled from 2001 to 2011, and the same rate of increase would be expected in future [9]. In Europe, since most of the sites for large hydropower plants have been development, it is expected that run off rive schemes will constitute about 75% of future projects. In developing countries especially, run off river hydropower plants are proving to be the most affordable renewable energy sources due to low construction and maintenance costs and shorter construction times, and hence receive considerable funding and subsidies [10]. As with all forms of hydropower schemes, following the environmental and biodiversity requirements is always mandatory, both for the river systems as well as biodiversity conservation [2]. In many countries, well established legislation (for example in EU, water framework directive 2000/60/EC, convention on biological diversity, and national environmental policy of Pakistan (section 6), does exist, and calls for requisite planning, design and execution of hydropower schemes to guarantee “good” ecological status of rivers and regions [2]. However, in many transition countries, these requirements are often compromised owing to corruption, weak or non-transparent environmental impact assessment studies, as well as inappropriate tools to assess their impacts [2,5]. This is especially true about run off river schemes, as their perceived safe characteristics have always led into inappropriate and incomplete assessment of their impacts [5,11]. Also, a few studies previously carried out on run off river schemes mostly focused on only regional or basin wise impacts on ecology, invertebrates or public perception. but seldom on downstream hydrology and local ecology [2]. Therefore, there is an acute paucity of information regarding the impacts of these schemes, mainly due to the lack of direct studies in the subject matter [5].

Surprisingly, numerous studies, some indirectly related to the subject, and some preliminary review studies have pointed towards possible negative impacts of even the run off river schemes. For example, Gibeau et al., 2017 [12], conducted a hydrological study based upon 31 run off river projects and concluded that river flow reduction may potentially affect downstream hydrology and ecosystem. Similarly, Anderson et al., 2015 [5], also conducted a wider review study and considered run off river schemes to be potentially affecting physical and ecological conditions of streams, land use and the resultant economic dynamics. Also, a study conducted by Lata et al., 2013 [13], carried out an analysis of existing run off river plants in Himachal Pradesh and highlighted their potential negative impacts on local land use and groundwater depths. Another study was also conducted by Kucukali et al., 2009 [14], that analyzed the renewable hydropower potential of Turkey through small hydropower and run off river schemes. This study revealed that Turkish government has taken precautions for environmental issues resulted from renewable energy utilization, but these are not adequate. Yet another study carried out on hydrological and ecological impacts of small hydropower by Biggs et al., 2005 [15], reviewed alteration of river flow along by-passed river reach and concluded possible impacts on river discharge, groundwater, and the resultant land use. More importantly, all these studies recommended in depth analysis of run off river schemes on the surrounding areas, as most of the mentioned studies were carried out at a wider level. There is hence immediate need of studies which can summarize the cumulative impacts of these schemes on downstream hydrology and local ecological changes. Also, as development of such schemes is on the rise in developing countries (due to the reasons discussed above), in-depth studies targeting sustainability of these schemes is highly desirable.

In order to conduct this study, an important run off river scheme, Ghazi Barotha Hydropower Project (GBHP), which is constructed on Indus River in Pakistan, was selected. It diverts water for power production through infrastructural facility that generates 1450 MW (MW) power. Construction of the project initiated in the year 1999 and water diversion took place during 2002 [16]. According to ADB, 2005 [16], impacts of GBHP on the land use of surrounding areas were identified in the Environmental Impact Assessment carried out prior to project execution. A minimum flow of 28 m^3/s was sanctioned for downstream Indus River, which was anticipated to cause no ecosystem alteration. However, credibility of environmental impact assessments, especially carried out in developing countries are always unrealistic and merely licenses to be obtained [17]. Also, as most projects are often linked with positive impacts, findings of initial assessment may be highly unreliable [18]. Preliminary studies about GBHP’s impacts were also carried out, but none of them focused on its detailed impacts. These studies mostly aimed at finding the impacts of GBHP only on groundwater levels [19, 20]. Limited number of studies on the downstream impacts of GBHP and unreliable impact assessment therefore prompted a need for current study. This study hence was thus designed to evaluate the temporal impacts of this project on selected important variables, like river discharge, groundwater level, agriculture, vegetation and bare soil, in pre and post project regimes. Main objectives of this study are to 1) Identify the hydrological and ecological impacts of GBHP, and 2) To understand the hydrologic-ecologic system as transformed by the scheme in study area. This novel study is expected to aid better policy and decision making through in depth understanding of such projects in future.

2. Materials and methods

2.1. Study area

Geographically, the study area falls in Pakistan's Khyber Pakhtunkhwa province and partly in Punjab province. It extends between 33.7800° North latitude to 72.2597° East longitude. Study area has a warm and temperate climate with hot, humid summers and mild winters, with average temperature of 22.2 °C, and average annual precipitation of 639 mm [21]. Agriculture and other natural resources are the most prominent sources of income. Study area comprises irrigated and rainfed lands during both the winter and summer cropping seasons [22,23]. Winter cropping in the study area starts from November and ends in April whereas summer cropping starts from May and ends in October [24]. Most irrigated lands are irrigated through water drawn from unconfined aquifers, operated manually or through Persian wheels [20]. According to Ahmad et al., 2019 [20], most of the right bank of the river's land is used for agriculture (Sugarcane, wheat, maize, lentils and tobacco being major crops), however there are a few scattered plants and trees. As for the left bank of the river, the main land uses are grasses, crops, trees, and bushes. Ghazi Barotha Hydropower Project is constructed in the Indus River and located about 10 km west of district Attock (Punjab province) and east of Swabi and Haripur (Khyber Pakhtunkhwa province), as shown in Fig. 1. The project diverts water through Ghazi barrage, which is located 7 kms downstream of Tarbela dam, which is also built on Indus River. A concrete power channel convey water from Ghazi Barrage to power complex, which is in Barotha (Punjab province) near the confluence of Indus and Kabul rivers. Area along Indus River downstream of Ghazi barrage, up to the river's confluence with Kabul River is selected for this study. Villages on both sides of river were focused by this study. Right bank of the river downstream of GBHP comprises villages of district Swabi, whereas left bank comprises villages of districts Haripur and Attock.

2.2. Hydrological dataset acquisition and analysis

Hydrological variables for this study included river discharge, groundwater levels, precipitation and temperature. All datasets from 1987 till 2020 was acquired for further analysis. Datasets were acquired from concerned institutions as mentioned in Table 1. Groundwater data was taken from 8 monitoring wells (Fig. 1) and provided by concerned institution. Time period till 2002 is considered pre GBHP regime whereas 2003 onwards is considered post GBHP regime. Data sets were aggregated for summer and winter seasons and mean values were calculated for further analysis. Numerous other studies have used mean seasonal values for

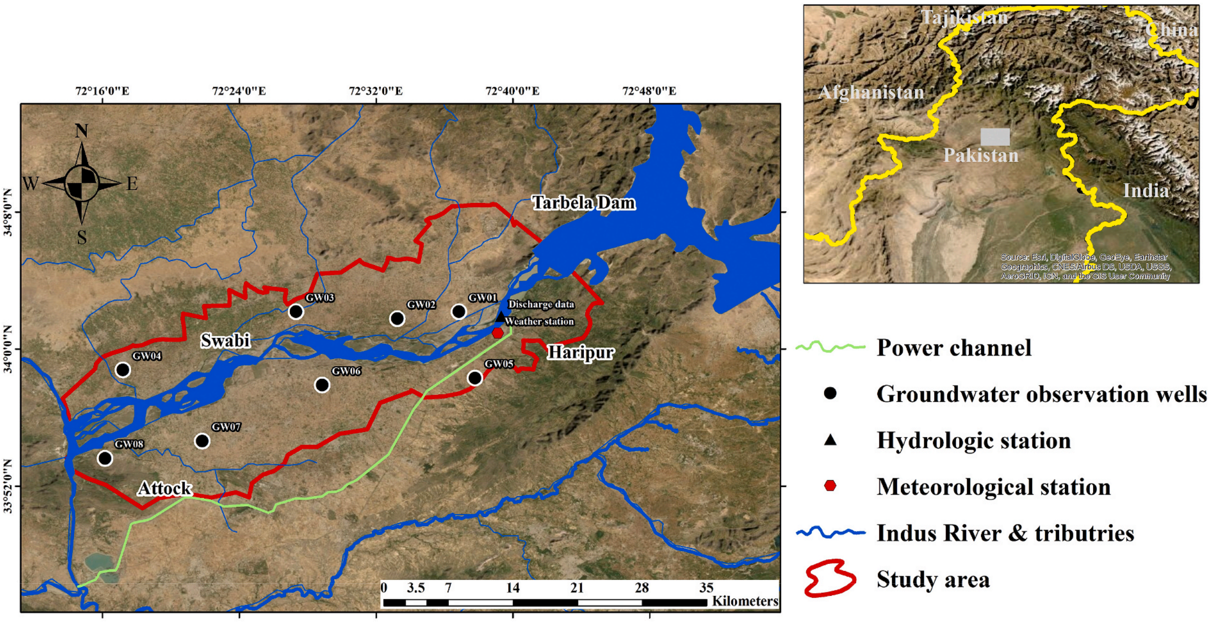

Fig. 1. Study area (Source: USGS).

Table 1

Variable description, data range and sources.

Indicator	Type	Data Range	Source
Discharge (m^3/sec)	Hydrological	1987–2020	Water and Power Development Authority
Groundwater level depth (Feet)	Hydrological	1987–2020	Public Health Engineering Department Swabi
Mean seasonal rainfall (mm)	Meteorological	1987–2020	Pakistan Meteorological Department Islamabad
Mean seasonal temperature (^{o}C)	Meteorological	1987–2020	Pakistan Meteorological Department Islamabad

calculating flow and groundwater depth variation [25,26].

2.3. *Ecological data acquisition through satellite imagery*

Ecological impacts of GBHP were determined through land use classification of the study area. This was carried out through big data analytics using Google Earth Engine (GEE). GEE is considered a very efficient tool to access pre-processed satellite imagery [27]. Satellite Imagery of Landsat 30 m resolution of surface reflectance was utilized for this purpose. LANDSAT 5 and LANDSAT 8 imagery data with eight bands was used for Landuse/Landcover indices analysis. LANDSAT 5 data is used from time period of 1990–2000, whereas LANDSAT 8 data was used for time period of 2001–2020. The datasets available in GEE platform of each successive year, starting from 1990 were selected. First part of the analysis required pre-processing of the datasets. Images with less than 10% cloud cover were selected by applying filter. Second step was the terrain correction of the datasets which was done by Shuttle Radar Topography Mission (SRTM) with 30 m resolution of Digital Elevation Model (DEM) data. The mean of pixel values of satellite images was utilized in order to have a better and unbiased representation of study area for both seasons of the years. All the raster calculations for different indices (NDVI, NDWI, and NDBI) was done using Raster calculator tool in ArcGIS. These indices were further used to create composite maps of different times periods (two seasons with ten-year intervals). The data was processed from 1990 to 2020, for all the eight available bands in the electro-magnetic spectrum [28]. Study area was classified into the following major classes: Agriculture (including summer and winter crops), bare soil, vegetation (including grasses, shrubs and trees), and water. These classes were selected as ecological parameters for this study.

2.4. *Statistical analysis*

Descriptive and inferential statistics was in this study to analyze the data and further draw conclusions. Variables were analyzed to get complete picture of the pre and post GBHP scenarios on temporal basis.

Linear regression analysis was applied on all study variables both within hydrological and ecological components, whereas multiple regression analysis used in this study quantified the interrelationships between ecological and hydrological effects. The coefficient of determination R^2 explains the percentage variability of the dependent variable explained by the model. In other words, it is a measure of the model's goodness-of-fit. Following form of model was used:

$$Y = \beta o + \beta 1\ X1 + \beta 2\ X2 + \beta\ k\ Xk + E \tag{1}$$

Where:

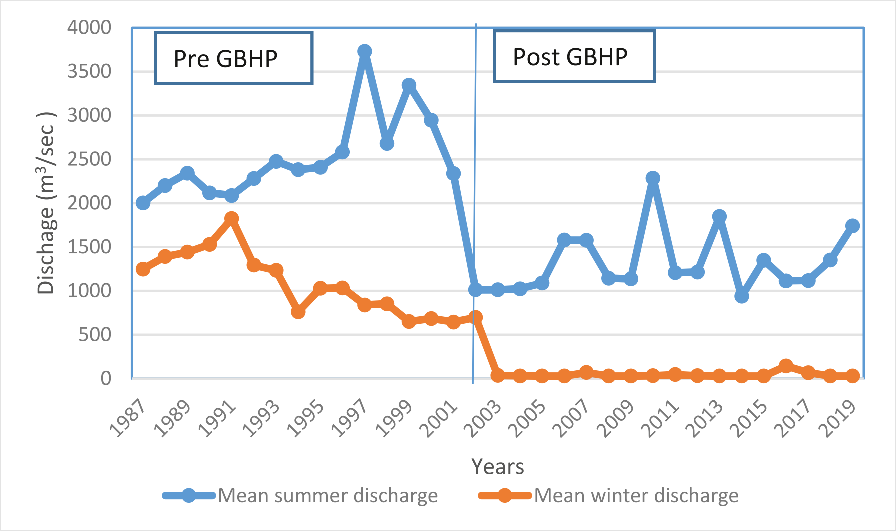

Fig. 2. Mean seasonal discharges.

Y—dependent variable (explained variable),
X1, X2… Xk—independent variables (explanatory variable),
βo, β1, β2… βk—equation parameters,
E—random component (rest of the model).

Agriculture area in sq. kms. was taken as dependant variable (Y), whereas discharge in m^3/sec, groundwater level in feet, rainfall in mm and temperature in °C were taken as independent variables (X1, X2, X3 and X4, respectively), along with a dummy variable, where $1 =$ Post GBHP regime, while $0 =$ Pre GBHP. Numerous other studies [26,29] used similar approach by taking agriculture area as dependant ecological variable, which was correlated with multiple hydrological and agronomic variables. Trend was considered statistically significant at $p < 0.05$, whereas R^2 denoted strength of relationships (positive and negative).

3. Results

3.1. Hydrological regime shift

Indus river discharge is largely regulated by Tarbela dam, upstream of GBHP [30]. River discharge reduction, through Tarbela dam, happens both in winter and summer seasons, with lesser reduction is experienced in summer season due to summer floods [31]. However, the river discharge downstream of Tarbela dam had a regular increasing and decreasing trend in summer season before GBHP (Fig. 2), whereas in winter season, discharge followed a similar regular trend with slight reduction between 1998 and 2001. However, water diversion after construction of GBHP led to significant reduction in river discharge both in summer and winter seasons. Discharge reduced by 47% during summer season, and by about 91% during winter season after GBHP. Before GBHP, peak summer discharge of 3730 m^3/s was observed (during 1997), whereas after GBHP, peak summer discharge was 2284 m^3/s, (observed during 2010). Similarly, peak winter discharge of 1822 m^3/s was observed (during 1991), before GBHP, whereas it was observed to be only 142 m^3/s (during 2016).

3.2. Groundwater level variation

Results of the study found visible variation in groundwater levels before and after construction of GBHP, as apparent from Fig. 3. GBHP induced about 50% drop in groundwater levels, both during summer and winter seasons. Before GBHP, mean groundwater level lied at 15.35 feet during summer, with deepest level of 17.60 feet observed during 2001. However, after GBHP, mean groundwater level dropped to 23.21 feet in summer, with deepest level of 30.6 feet during 2019. Similarly, in winter, before GBHP, mean groundwater level lied at 18.25 feet, with deepest level of 21.35 feet during 2001, whereas, after GBHP, mean groundwater level dropped to 27.38 feet, with deepest level of 35.4 feet observed during 2019.

3.3. Land use/Land cover changes

Land use/land cover of the study area prevailing in pre and post GBHP regimes is shown in Fig. 4. According to the Figure, before GBHP, agriculture occupied 28.66% of the study area in summer, and 32.98% in winter. Likewise, vegetation occupied 45.41% of the study area in summer, and 49.78%. in winter. Similarly, bare soil covered 20.05% of the study area in summer, and 12.92% in winter.

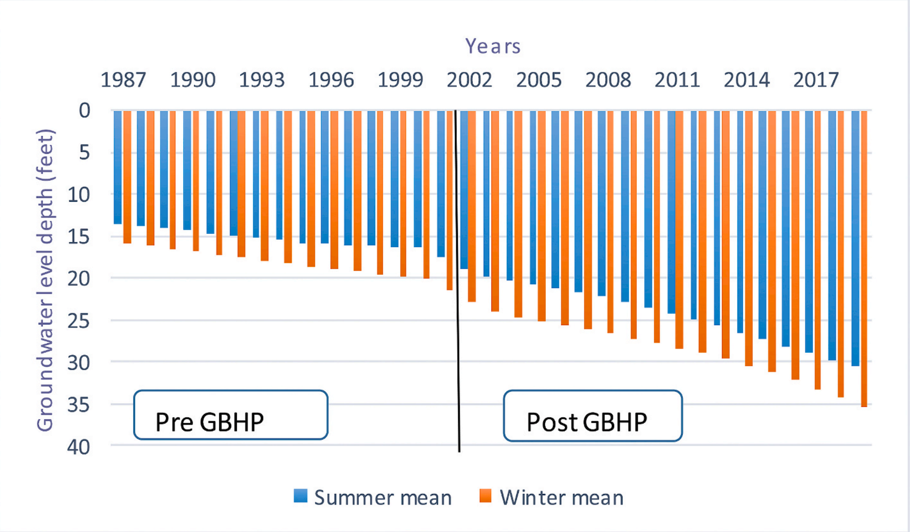

Fig. 3. Mean Groundwater level depths.

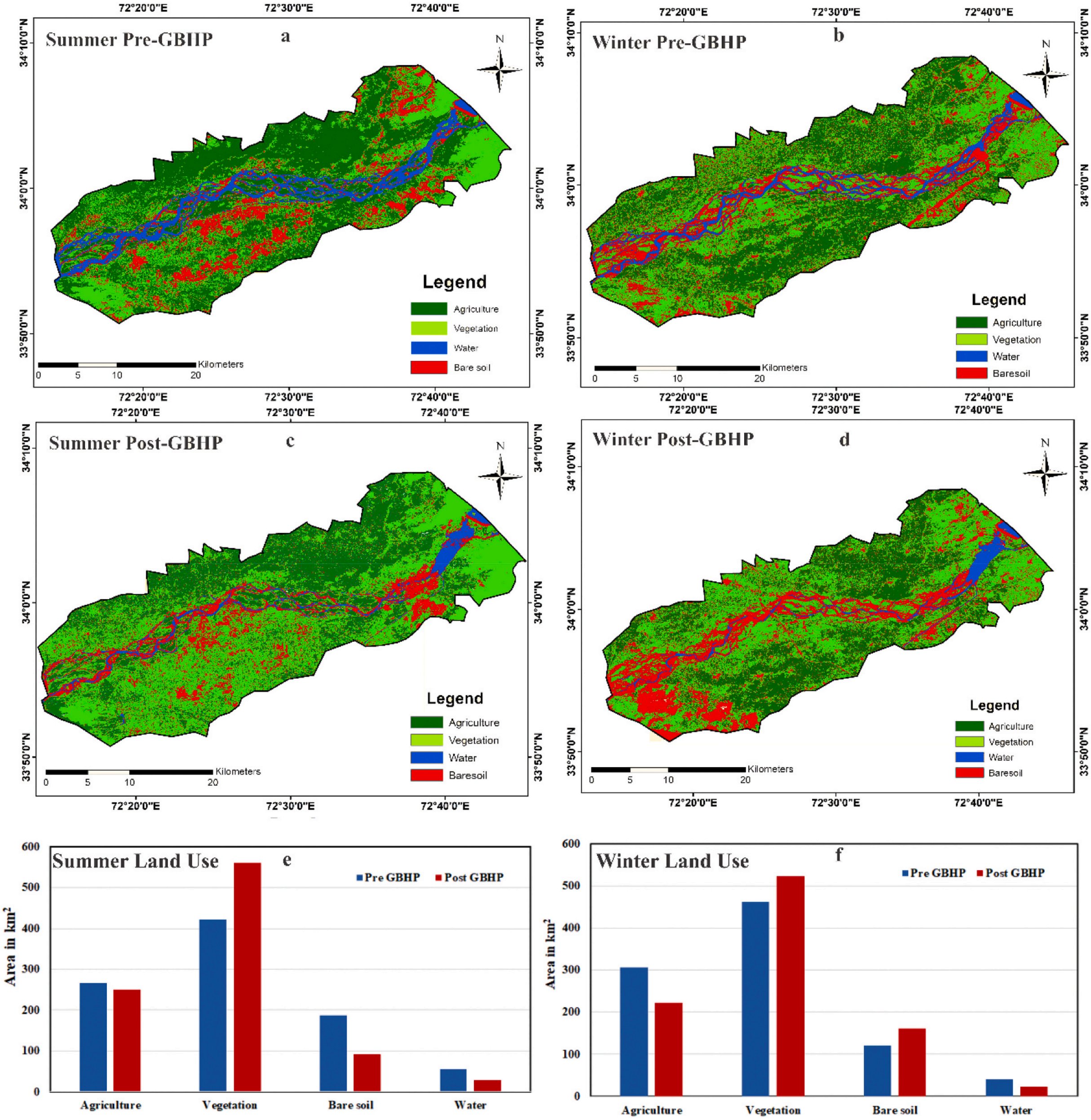

Fig. 4. a) summer land use distribution of Pre GHBP, b) winter land use distribution of Pre GBHP, c) summer land use distribution of Post GBHP, d) winter land use distribution of Post GBHP, e) area occupied by different land use classes in summer during Pre and Post GBHP and f) area occupied by different land use classes in winter during Pre and Post GBHP.

Also, water covered 5.88% of area in summer, whereas occupied 4.32% in winter. After GBHP, however, agriculture area reduced to 26.96% (reduction of 1.69%) in summer, and to 23.87% in winter (reduction of 9.11%). Also, area under vegetation increased to 60.24% in summer (increase of 14.83%), and to 56.25% in winter (increase of 6.47%). Moreover, bare soil followed a reducing trend in summer, reducing to 9.82% (reduction of 10.23%), but increased to 17.40% in winter (increase of 4.48%). Also, area under water reduced to 2.97% in summer (reduction of 2.91%), and to 2.48% in winter (reduction of 1.84%).

More interestingly, this study revealed different trends of land use change occurring after functioning of GBHP. First trend was observed between 2003 and 2010, and the second trend between 2011 and 2020. According to Fig. 5, first significant change in land use can be witnessed between 2003 and 2010. As evident from Fig. 5, agriculture area reduced by 8.59% in summer, and its highest reduction was observed in winter i.e., 18.62%. Vegetation increased by 9.62% and 14.66% in summer and winter respectively. Bare soil also increased by 0.96% and 6.48% in summer and winter respectively. Water reduced by 2% in summer and an even higher reduction of 2.5% was observed in winter.

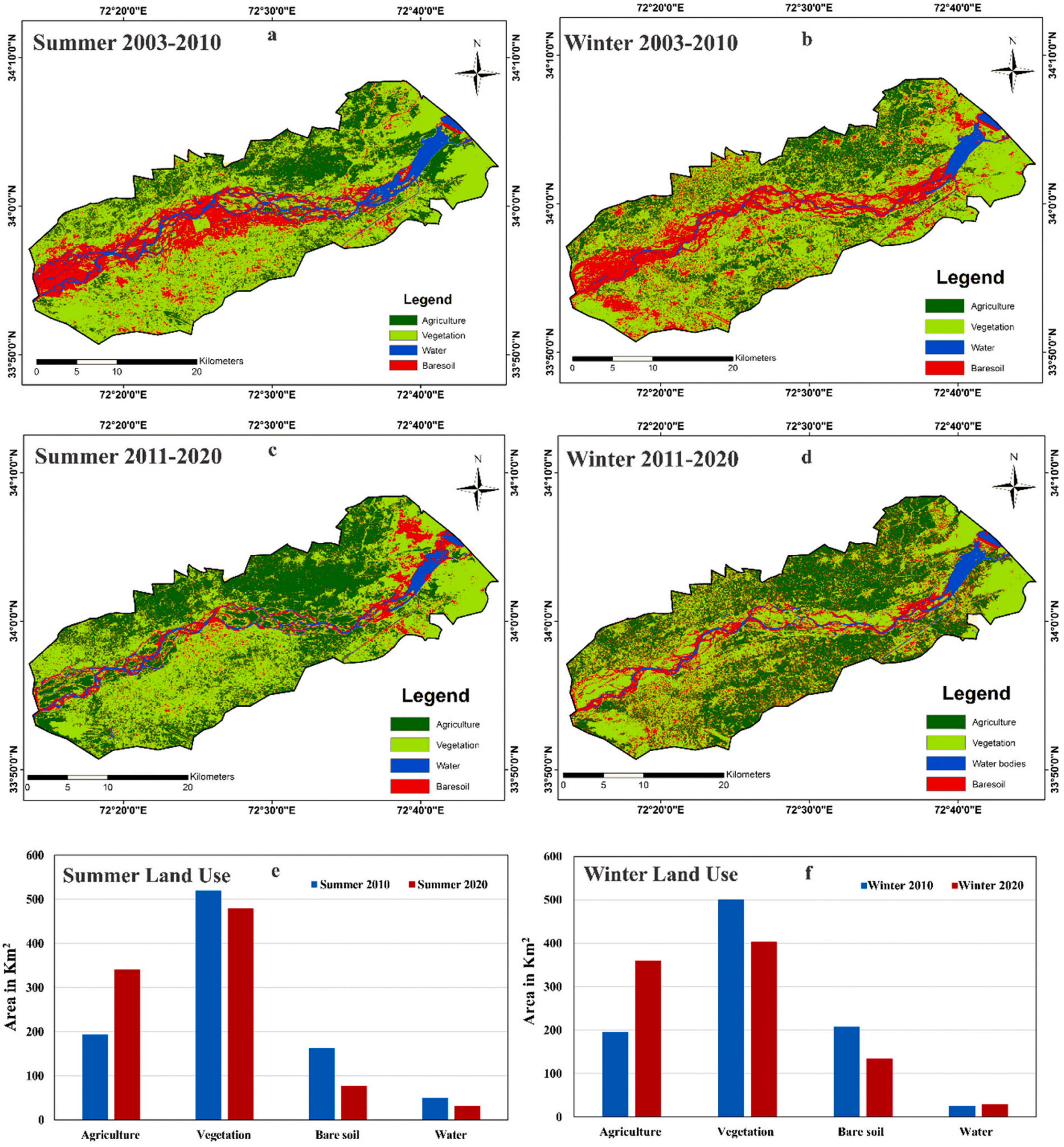

Fig. 5. a and c) decadal land use changes in summer during Post GBHP, b and d) decadal land use changes in winter during Post GBHP, e) area wise distribution of land use classes in summer during Post GBHP and f)) area wise distribution of land use classes in winter during Post GBHP.

Second trend in land use/land cover between 2011 and 2020 was characterized by a visible increase in share of agriculture to study area during this period, as it increased by 15.83% and 17.75% during summer and winter respectively. However, vegetation and bare soil reduced considerably during this period. Vegetation reduced by 4.46% and 10.46% during summer and winter respectively, whereas bare soil reduced by 9.27% and 7.84% during summer and winter respectively. Water was further reduced by 2.1% during summer but increased by 0.51% during winter.

3.4. Interactions between hydrological and ecological effects

Descriptive analysis of the study variables shows significant differences in discharge, groundwater level and agriculture area before and after GBHP (Table 2). Mean discharge reduced from 2778.5 to 1552.28 m^3/s in summer, and from 1004.68 to 82.2 m^3/s in winter.

Mean groundwater level dropped from 14.27 to 19.2 feet in summer, and from 15.53 to 29.13 feet in winter. Agriculture area reduced from 294.56 to 230.95 sq kms. in summer, whereas from 350.35 to 276.84 sq kms in winter. Moreover, mean rainfall increased from 31.62 to 32.14 mm in summer, and from 53.89 to 58.15 mm in winter. However, mean temperature remained unchanged at 25.3 °C, but increased from 16.52 to 17.23 °C in winter.

The relationship between discharge and groundwater level is shown in Figs. 6 and 7. As evident, a strong negative correlation exists between discharge and groundwater level ($R^2 = 0.57$ and $p = 0.0115$ in summer, whereas $R^2 = 0.80$ and $p = 0.000$ in winter). This implies increase in groundwater level depths with reduction in river discharge as significantly explained by p-values ($p < 0.05$ in summer and $p < 0.01$ in winter). Moreover, as per Table 3, groundwater is the only independent variable (X2) that shows significant relation with agriculture area (Y). Both these variables are positively correlated before and after GBHP ($p < 0.05$ in summer and winter). None of the remaining independent variables show any significant relation with agriculture area.

4. Discussion

4.1. Hydrological regime

This study found visible shift in hydrological regime after functioning of GBHP. There was major reduction in discharge of Indus River downstream of Ghazi barrage. This reduction in discharge caused water scarcity in the study area as it led into major hydrological changes. It could be linked with diversion of river water into power channel. Also, these results are in line with numerous other studies carried out on similar subjects. For example, a study was conducted by Borgohain, 2019 [25] on downstream impacts of Rangadi hydel project in India. It was concluded that water diversion for electricity generation deprived Rangadi river by 63% annual discharge that caused major alteration in downstream ecology. Another study was conducted by Monirul, 1998 [32] on diversion of Ganges River at Farruka and its effects on salinity in Bangladesh. Findings of this study also established that significant reduction of dry season discharges occurred in Ganges and Gorai rivers in Bangladesh. Present study hence safely suggests that run off river schemes may also reduce river discharge similar to water diversion projects.

4.2. Groundwater level

The study also found obvious lowering of groundwater level after functioning of GBHP. This could possibly be linked with reduction in discharge, as well as other water abstraction means (e.g., excessive groundwater mining) in the study area. Due to the fact that the study area's primary source of agriculture was groundwater, significant water scarcity resulted from the groundwater level reduction. A series of related studies also revealed similar results and could support this study's findings. For example, Zulfiqar Ali et al., 2011 [33] concluded that diversion of water from Indus River, due to GBHP, resulted in 40% lowering of groundwater level. Also, Ahmad et al., 2019 [20] studied fluctuation in groundwater levels due to GBHP and concluded certain areas downstream Ghazi barrage to have been negatively affected due to drop in groundwater levels after construction of this scheme. Present study, however, calculated higher reduction in groundwater level occurring over time. Similar results could also be retrieved from related studies carried in other countries. For example, a water diversion project in Heihe river basin in China caused a significant groundwater level drop of about 19 feet in Heihe river basin [26] due to reduced river discharge. Another study conducted by Wahyuni et al., 2009 [34], in Uzbekistan established a strong positive correlation between increase in surface water and lowering of groundwater levels. Run off river schemes, hence, may potentially affect groundwater level in the surrounding area. This may also negatively impact downstream ecology.

4.3. Land use

This study assessed changing trends of land use occurring after functioning of GBHP. The study discovered a noticeable decrease in agriculture area and water after functioning of GBHP in the study area. The amount of bare soil also increased. This study therefore linked these alterations to water scarcity that resulted from falling groundwater levels.. Ground water reduction is hence considered the most important reason for this changed land use trend, as numerous other studies also revealed similar results. Ali et al., 2011 [20],

Table 2
Descriptive presentation of Pre and Post GBHP variables.

Season	Indicator	Pre GBHP average	Std Deviation	Post GBHP average	Std Deviation
Summer	Groundwater level (feet)	14.27	2.84	19.2	7.04
	Discharge (m^3/sec)	2778.5	1718.13	1552.28	1937.04
	Rain (mm)	31.62	39.41	32.14	39.86
	Temperature (^{o}C)	25.3	5.29	25.36	5.31
	Agriculture area (sq. kms.)	294.56	21.14	230.95	41.36
Winter	Groundwater level (feet)	15.53	2.38	29.13	5.64
	Discharge (m^3/sec)	1004.68	573.98	82.2	169.05
	Rain (mm)	53.89	42.49	58.15	45.85
	Temperature (^{o}C)	16.52	4.91	17.23	5.18
	Agriculture area (sq. kms.)	350.35	12.83	276.84	53.08

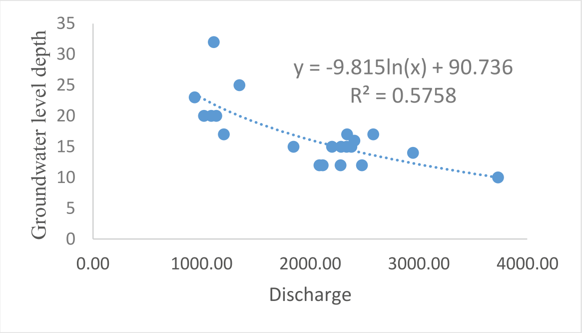

Fig. 6. Relationship between discharge and groundwater (summer).

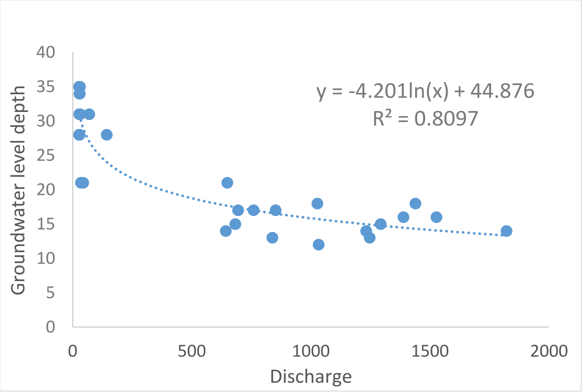

Fig. 7. Relationship between discharge and groundwater (winter).

Table 3
Multiple regression of selected variables.

Season	Indicator	Coefficients	Standard Error	t-Stat	P-value
Summer	Intercept	112.876	305.267	0.370	0.715
	Groundwater level	5.889	2.581	2.281	0.032
	Discharge	−0.020	0.012	−1.623	0.118
	Rain	−0.166	0.284	−0.586	0.563
	Temperature	5.984	12.092	0.495	0.625
	Dummy	−133.575	27.280	−4.896	0.000
Winter	Intercept	−104.283	194.133	−0.537	0.596
	Groundwater level	8.903	3.600	2.473	0.021
	Discharge	0.037	0.029	1.292	0.209
	Rain	0.419	0.286	1.467	0.155
	Temperature	13.839	9.200	1.504	0.146
	Dummy	−129.467	33.532	−3.861	0.000

$R^2 = 0.63$, Adjusted $R^2 = 0.55$ (Summer), $R^2 = 0.62$, Adjusted $R^2 = 0.54$ (Winter).

concluded that depletion of ground water lead into major loss of natural resources along downstream river after functioning of GBHP. These results also support findings of Anderson et al., 2015 [5], which concluded that run off river schemes may alter flow of a river and may affect downstream ecology and physical habitat. Another study conducted by Butt et al., 2015 [11], analyzed changes in land use of Simly watershed. Pakistan, between 1992 and 2012. The study concluded that there was major loss of agriculture area due to surface and ground water depletion, and 748 ha of agriculture land was converted to bare soil and vegetation. Yet another study conducted to analyze Impact of Karakoram Highway on Land use and Agriculture Development of Gilgit Baltistan, Pakistan [35] can also be related to the present study's findings. This study analyzed Land use/Land cover images to determine the total agriculture, vegetation, bare soil, water bodies and snow cover before and after the construction of highway and revealed a decline of 18.43% agriculture area between 1996 and 2016. However, vegetation increased by 617.86% during the same period. Post GBHP regime, hence, may be attributed to reduction in agriculture area. Increase of vegetation and bare soil further elucidate the findings.

An abrupt shift, however, occurring between 2011 and 2020, has also been assessed by this study. This was marked by an increase agriculture area. This abrupt shift in changing land use/land cover may be attributed to the government's groundwater development schemes, as environmental impact assessment identified lowering of groundwater level as a possible implication of GBHP [36]. The government, therefore, planned extensive groundwater development schemes for the affected area [36]. According to local farmers (through author's survey), most of these schemes initiated in post 2010. Same survey also revealed that the schemes replaced traditional Persian-wheels operated shallow wells, and also led into a shift from rain fed to irrigated agriculture. These groundwater abstraction means helped in recovery of agriculture, but possibly led into further drop of groundwater level. These results, however, show contradiction with numerous other studies, which have highlighted sustainable options for agriculture development in affected areas. Certain studies, in this regard advocated for alternate surface water irrigation schemes as sustainable means for agriculture development, with no pressure on groundwater. For example, a study carried out by Matlhodi, 2019 [37] focused on the effects of newly introduced surface water irrigation schemes in Bostawa, which increased agriculture area by 1.3%, whereas there was 22.2% increase in water bodies. Another study conducted by Atta-ur-Rahman et al., 2012 [38], considered construction of Chashma Right Bank Canal to increase agriculture area by 32% in Dera Ismail Khan, Pakistan. Similarly, another study conducted by Anwar et al., 2019 [35], found farmers' capacity building coupled with indigenous small scale irrigation systems as the key to agriculture improvement after construction of Karakoram Highway in Gilgit Baltistan, Pakistan. From the present study's viewpoint, therefore, uplift of agriculture in case of GBHP was premised upon groundwater exploitation only, which shows possible unsustainable planning in comparison with the aforementioned studies. Certain other reasons for reduction in agriculture area in this study could also be related to population dynamics, demand for more food, and need for more income etc. [35,39,40]. However, research has shown that groundwater has always been a crucial component of agriculture in our study area [20] Our findings thus support the conclusion that GBHP is the major driving force causing changes in agricultural land use.

4.4. *Statistical analysis*

Results of the statistical analysis performed in this study also confirm the impacts of GBHP on hydrological regime. Strong negative correlation between discharge and groundwater level attributed reduced Indus River discharge to major groundwater level drop in study area. Also, as agriculture area showed significant result only with groundwater level, the study, hence, further elucidates that agriculture was highly dependent upon groundwater. Decline in agriculture area between 2003 and 2010 was due to drop in groundwater levels. Recovery of agriculture in post 2011 occurred at the expense of further groundwater exploitation. Governments' compensatory schemes as well as uncontrolled groundwater mining though motorized means both contributed towards it. Results of this study show conformity to numerous other studies conducted on similar subjects. According to Ali et al., 2011 [19], Ghazi Barotha Hydropower Project lead into significant reduction in groundwater, that lead into downstream ecological changes. Zhang, 2018 [26] conducted a study on ecological effects and potential risks of water diversion project in Heihe river basin, China' and revealed river diversion to have caused significant ecological losses. According to his findings, water diversion from course of Heihe river lead into reduction of groundwater, which was further triggered with the excessive groundwater abstraction for agricultural enhancement purpose. The study thus considered groundwater exploitation as a serious potential problem associated with water diversion. Our results are also comparable to another study conducted by Monirul, 1998 [32], which found strong correlation among discharge, groundwater and salinity. He concluded reduction in river discharge to be strongly affecting groundwater levels, those in turn have highly affected salinity levels in study area. Also, Borgohain, 2019 [25] conducted study on Ranganadi hydel project in India and concluded a changed hydrological regime to have significantly impacted downstream ecology.

5. Conclusion

Results of this study indicate that GBHP caused major variations in hydrological and ecological conditions of area along Indus River. River discharge has considerably reduced both in summer and winter seasons due to water diversion. Major groundwater level drop was also analyzed after functioning of GBHP due to a decrease in river discharge. Ecology of the study area was impacted by this change in hydrological regime. Agriculture area in summer decreased from 28.66% to 26.99%, while in winter, it decreased from 32.98% to 23.87%. This was followed by an increase in vegetation and bare soil. In addition, the government's groundwater development schemes are also contributing to groundwater scarcity. This study finds a strong correlation of reduction in river discharge with increase in groundwater level drop ($R^2 = 0.57$, and $R^2 = 0.80$ in summer and winter respectively, with a groundwater level drop of 50%). A strong positive correlation has been found between groundwater level and agriculture area ($R^2 = 0.63$, and $R^2 = 0.62$ in summer and winter respectively). Water diversion of GBHP is thus considered the major reason behind water scarcity and leading to the change in ecological regime of the study area. GBPH as a run off river scheme, hence, pose a serious threat to local hydrological and ecological conditions. Appropriate planning, design and impact assessment of such schemes is very crucial for local hydrological and ecological sustainability. Transparent EIA procedures need to be carried out prior to the execution of these schemes. There is also a need to carry out similar studies of other run off river schemes those may be helpful in impact comparison.

Declarations

Author contribution statement

Ehsan Inam Ullah; Shakil Ahmad; Muhammad Fahim Khokhar: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper. Mohammad Azmat; Umer Khayyam: Contributed reagents, materials, analysis tools or data. Faizan ur

Rehman Qaiser: Analyzing and interpreting the data.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no competing interests.

Additional information

No additional information is available for this paper.

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