ENVIRONMENTAL RESEARCH
COMMUNICATIONS

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To cite this article: Ehsan Inam Ullah *et al* 2024 *Environ. Res. Commun.* **6** 035002

IOP Publishing Environ. Res. Commun. **6** (2024) 035002 https://doi.org/10.1088/2515-7620/ad2bb5

Environmental Research Communications

OPEN ACCESS

RECEIVED
19 October 2023

REVISED
10 January 2024

ACCEPTED FOR PUBLICATION
21 February 2024

PUBLISHED
1 March 2024

PAPER

Analyzing land use land cover (LULC) changes induced by the run-of river project and respondent survey: a case of Ghazi Barotha Hydropower Project on Indus River, Pakistan

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Keywords: Indus River, LULC, supervised classification, groundwater development schemes, run-of-the-river projects

Supplementary material for this article is available online

Abstract

Land use land cover (LULC) change determination caused by development projects is always mandatory as land is the major source of local livelihoods and regional economy. Worldwide, very limited studies have been conducted to determine LULC changes caused by run-of-the-river projects, which are generally considered safe due to their design. Present study used Google Earth Engine (GEE) to examine the LULC changes caused by Ghazi Barotha Hydropower Project (GBHP), which is a run-of-the-river project, built in 2002 on Indus River in Pakistan. The project diverts river water from Ghazi barrage, for a 6,600 GWh annual power production, through an open concrete power channel of 100 m width and 9 m depth. Field surveys were carried out to assess respondents' opinions about LULC changes and their major causes. LULC determination was carried out from 1990–2020 through processing Landsat images in GEE, and Random Forest (RF) machine learning technique was used for supervised classification of the study area. 384 respondents were consulted during the field survey and their responses were collected using semi-structured self-administered proformas. Results showed that after functioning, GBHP caused major LULC changes in project downstream areas from 2002–2010, as there was a significant decrease in area under agriculture by 29.10% and 47%, during summer and winter seasons respectively. The trend was concurrent with a decrease in area under water and was also followed by a marked increase in area under vegetation and baresoil. However, from 2010–2020, agriculture area again increased by 75.61% and 84.53% in summer and winter seasons respectively, as compared to 2002–2010. Respondents during the field survey revealed that agriculture reduction from 2002–2010 was due to water scarcity caused by GBHP; also leading to vegetation and baresoil increase. Recovery of agriculture from 2010–2020 was attributed to groundwater development intervention, better seeds, and farmers' capacity building.

1. Introduction

Changes in LULC (Land use/ Land cover) are often associated with the transformation in infrastructure, human behavior, technological advent, or their interaction [1]. These changes are frequently responsible for altering watershed characteristics and lead to biodiversity transformation [2]. Also, as natural resources like water, vegetation, land, and ecosystems provide people with means of livelihoods, it becomes imperative to study the impacts of technological and infrastructural development on their characteristics [3]. Additionally, as the world's population grows, and as there is an increasing demand for electrification due to climate change through renewable resources, there is a continuing need for such technological and infrastructure advancements, particularly in the energy sector [4]. Worldwide, there are various means of energy production, still, hydropower is a widely recognized renewable source of energy [5, 6]. There is an increase of 73% demand predicted for hydropower over the next 20–30 years, despite that many conventional hydropower projects are deemed environmentally unsafe and may spark political unrest [6, 7]. There is also a lot of debate among environmental professionals and managers on the need to modify reservoir discharges in order to biologically enhance biodiversity [8]. Also, as the Sustainable Development Goals (SDG.7) require clean energy to be provided to all by 2030, and a need to invest more in safer energy projects is arising, planners are in a constant quest to explore better and safer energy production alternatives. Resultantly, energy planners are now more likely to favor small hydropower plants since they are thought to be environmentally safe, especially run-of-the-river projects [9]. Run-of-the-river projects utilize a part of river water from its natural course and convey it to a powerhouse for power generation, often through specially designed secondary channels [7]. These projects operate without storage reservoirs/dams, and diversion of river water into channels is achieved through diversion weirs, sometimes called barrages. Since run-of-the-river projects operate without sizeable dams, they are generally considered safe, and their development therefore is fast growing [10]. However, there is very limited information about their impacts, and a very few studies, only at regional levels, have been conducted to gauge their ecological and economic sustainability [11]. Still, a majority of these studies led to unfavorable discussions regarding their viability and concluded a possible likelihood that these projects could be harmful to the hydrology, ecology, and associated socio-economic dynamics of the surrounding communities [7]. For instance, a study conducted on 31 run-of-the-river projects concluded that these projects reduce the flow of downstream river and thus severely impact the environment downstream [12]. Similarly, a review study carried out in Europe asserted that run-of-the-river projects are extremely likely to affect the physical and ecological properties of streams, which may change the LULC and result in economic upsets of surrounding areas [7]. A study carried out on run-of-the-river plants in Himachal Pradesh, India, also determined that because of land use change potential of run-of-the-river projects, they might negatively impact the socio-economic structure of the area [3]. Another study carried out in Turkey stated that the Turkish government's adoption of environmental protection measures before the development of run-of-the-river projects [13], still needs to be strengthened more due to their potential impacts. Conclusively, majority of these studies emphasized the importance of having a thorough understanding of run-of-the-river projects and recommended that in-depth research be done, particularly locally, to determine the precise implications of these projects. These studies also identified the need to utilize technological options to determine the magnitude of impacts caused by run-of-the-river projects on a temporal and spatial basis. Current study is hence conducted to identify the impacts of a run-of-the-river project on LULC of areas downstream of the Indus River and attempts to fill the paucity of information regarding run-of-the-river projects using a technological and social approach.

Ghazi Barotha Hydropower Project (GBHP) is a run-of-the-river project installed on the Indus River in Pakistan, which is situated 7 kms downstream of Tarbela Dam. As per the state regulation, Tarbela Dam releases 70% of the reservoir discharge in downstream Indus River [14]. A portion of the Indus River is then diverted through GBHP at a rate of about 1,600 m^3/sec near the town of Ghazi, Khyber Pakhtunkhwa. It then travels 52 km down to the village of Barotha, where the power complex is situated, via an open power channel that is 100 m wide and 9 m deep and made entirely of concrete. Total power production capacity of GBHP is 1,450 MW, with an average annual capacity of 6,600 GWh. Plant capacity factor is 51.96%. GBHP contributes 7% to the country's total annual energy output of 94,121 GWh [15]. GBHP's construction began in 1999, and the river water diversion process began in 2002. Since functioning of GBHP, there has only been a small number of research studies carried out, particularly outlining its effects on river downstream areas. For example, Zulfiqar *et al* 2011 [16], studied groundwater levels in surrounding areas of GBHP, and considered that their lowering may have disrupted the prevalence of natural resources which may lead to livelihood losses and socio-economic changes. Similarly, another study used social appraisal methods to determine GBHP post-project impacts on affected households [17], and concluded possible economic losses in the region, according to individual perceptions. There is hence an acute paucity of detailed information regarding the specific impacts of this project on LULC and resultant social and economic dynamics. It is also worth mentioning that according to Asian Development Bank [14], a thorough environmental impact assessment (EIA), which was carried out prior to project construction, anticipated no significant changes in areas downstream of the river. However, validity of EIA is sometimes questioned in developing nations [18], as its results tend to focus on good outcomes due to rapid development requirements, while the negative consequences are either ignored or concealed [19]. Acquisition of pre and post-project data with respect to project impacts on land use is hence always required in order to get a clear understanding of such interventions [20].

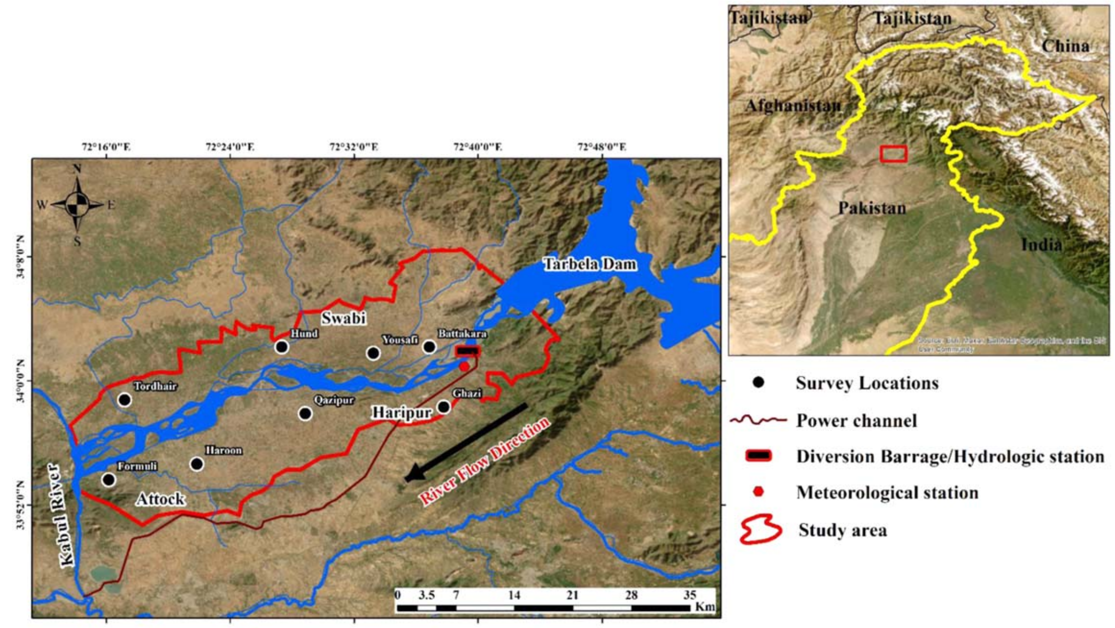


Figure 1. Selected study area (downstream Tarbela dam to confluence of Indus River with Kabul River).

Present study, therefore, was designed to analyze LULC changes and assess the reasons behind these changes, using an integrated approach. The study combined remote sensing and respondent perception datasets to establish a technological and social basis for achieving its objectives. This technique is widely used in research, as it generates a sound basis for making bias-free results [21, 22]. Based on this approach, the study outlined two major objectives to reach its anticipated outcome; (1) To determine LULC changes prevailing in downstream areas before and after GBHP, and (2) To evaluate respondents' perceptions for determining major reasons behind these changes. Findings of this study will not only validate the results obtained from both sources but will also establish a strong basis for evaluating the impacts of GBHP. Moreover, results of this study will play a pivotal role in future planning of similar projects, make a foundation for devising better compensatory strategies, and will also aid in sustainable planning of run-of-the-river projects.

2. Materials and methods

2.1. Study area

The selected area for present study is located along the Indus River and also falls in the vicinity of GBHP. Geographically, the study area is in Khyber Pakhtunkhwa (KP) and Punjab provinces. It stretches from 33.7800° North latitude to 72.2597° East longitude. Summer and winter crops are both abundantly grown, making agriculture the most noticeable land feature of the study area [23]. Along with agriculture, grasses, trees, and bushes are also in abundance [24]. The primary means of livelihood in the study region is agriculture (mostly sugarcane, maize, wheat, millet, lentils, and vegetables) and other natural resources (livestock and trees). The traditional source of irrigation in the study area was groundwater, mined through Persian wheels [23]. Water diversion by the project is performed by Ghazi barrage, which is a diversion structure that abstracts water from the main course of Indus River (figure 1). Further downstream, Indus River forms a confluence with Kabul River. Ghazi barrage is situated about 7 km downstream of the Tarbela dam, also a multi-purpose dam built on Indus River. A water conveyance concrete channel, about 52 kms in length, offtakes from Ghazi barrage and transports water to a power plant, situated in Barotha, Punjab province. Water from the power plant is eventually released into the Indus River at Barotha. This study focused on assessing LULC of the region along both embankments of Indus River, downstream of the Ghazi barrage, and up to its confluence with Kabul River. This covered villages on the right bank of the river (falling in district of Swabi KP), and on the left bank of river (falling in district of Haripur KP, and district Attock, Punjab). Location identification and delineation targeted all the communities living on both sides of Indus River downstream of GBHP, as declared as affectees by the Water and Power Development Authority (WAPDA) and considered beneficiaries of groundwater development schemes. Delineation accompanied selection of the said communities' respective village boundaries along the river.

2.2. LULC data acquisition and analysis through google earth engine

2.2.1. Data collection

The present study acquired Landsat data (Landsat-5 and Landsat-8) from the United States Geological Survey (USGS, https://www.usgs.gov/) using Earth Explorer. The datasets were made accessible using Google Earth Engine (GEE) platform [25]. GEE is regarded as a very effective technique for accessing satellite imagery that has already been processed [26]. JavaScript application (API) programming interface was used for the collection, preprocessing, mosaicking, and processing of all Landsat images (detailed information regarding GEE processing for LULC and RF classification is provided in the supplementary information file). This study utilized top-of-atmosphere (TOA) reflectance products from Landsat TM and OLI Collection 1, Tier 1, which were accessible for GBHP. TOA reflectance products were selected mainly because at different times of the year, variations in spectral band differences, solar zenith angles and Earth-to-Sun distances can cause exoplanetary effects to be removed from variable solar irradiance [27]. The study also used a digital elevation model (DEM), with 30 meters spatial resolution, for extraction of parameters like slope, aspect, and height. DEM and each of these images were created using GEE.

2.2.2. Satellite imagery and pre-processing

Present study used Landsat series (of 1990, 2002, 2010, 2020) for the analysis, as it acquires older data (as old as 1974). Landsat-5 data included the time period from 1990–2010, whereas Landsat-8 included the time period of 2020. The following procedures were applied to construct the bulk of images processing [28]. (1) For each research year, TOA reflectance data was picked for entire winter and summer seasons, to adjust for the issue of hazy/cloud cover optical images of study area. In some cases, images from before and after the years were utilized to create the most accessible composite pixel images (for replacement/ augmentation of cloud/ fog obscured photos). (2) Cloud cover from the study area images was removed from Landsat photos (cloud cover was less than 10%). (3) A single image was generated using median ee. Reducer function, from the image collection. (4) Normalized difference vegetation index (NDVI) and normalized difference water index (NDWI) were calculated for each composite image. (5) For enhancement of classification performance, DEM data's slope and aspect were utilized. This resultantly generated the best cloud-free picture combination integrating NDVI and NDWI. NDVI and NDWI indices were also computed using the accessible bands in the electromagnetic spectrum [29]. NDVI is based on visible and near-infrared (NIR) wavelengths and is used to quantify green live vegetation and baresoil. NDVI is calculated as:

$$NDVI = \frac{(NIR - \mathrm{Re}\,d)}{(NIR + \mathrm{Re}\,d)} \tag{1}$$

NDVI gives standardized values ranging between −1 and 1. Values near 0 represent baresoil. Values above 0.20 represent areas with vegetative cover. Within vegetative cover, values between 0.20 to 0.30 represent areas with grass, shrub lands, and sparse bushy trees, whereas values of 0.30 or above represent agriculture land cover.

NDWI uses near-infrared (NIR) wavelengths and is used for water analysis. Calculating NDWI takes into account the following formula:

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)} \tag{2}$$

The resultant values of NDWI are normalized between ranges of −1 to 1. Values above 0 represent areas of water presence, whereas values above 0.30 represent water surface (e.g., water bodies).

2.2.3. Training and validation samples

Present study divided the area into four major LULC classes: '**Agriculture**' which includes all the agriculture crops, '**Vegetation**' which includes all grasses/weeds, shrubs, and sparsely located trees, '**Baresoil**' which is land not covered by any crop or vegetation, and '**Water**' which includes water bodies and correspond to land under river water [30]. As the study employed supervised classification techniques, it required training and validation samples of high quality. Visual interpretations and field observations were employed to gather training samples for the classification model [31]. To reduce geographical uniformity, sampling points located more than 1000 meters apart, selected at random places, were ascertained for the year 2020 through ground truthing [31]. Handheld laser spectrometer was used in field to analyze light spectrometry in different band grading (from visible to all infrared spectrums). Additional reference for the years 1990, 2002 and 2010, samples were created based on each year's high-resolution GEE images. More than 1000 reference points altogether, corresponding to all four LULC classes (All summer and winter crops, grasses, trees, baresoil and water surface) were created for the study time periods. At least 40 samples per LULC type were gathered, of which 70% served as training samples for LULC classification and the remaining 30% served as validation samples to validate the classification outcomes [32].

2.2.4. LULC classification and accuracy assessment

A composite image with no cloud cover was produced on the GEE platform. The image creation was based on a dense time stack of multi-temporal Landsat images with no cloud cover. LULC classification was implemented using the Random Forest (RF) machine learning technique since it often has more processing capacity for data noise and overfitting and is more accurate than other conventional algorithms like maximum likelihood and solitary decision tree methods [33]. For classification of a dataset, RF uses a prediction method through an ensemble learning technique and constructs many decision trees by creating random features [34]. Due to its superior classification outcomes, the RF classifier is frequently used to categorize LULC. It could readily quantify the relative relevance of every target variable class [35]. The GEE platform's ee. Classifier.smileRandomForest function was used to produce LULC classification maps for each selected year based on the collected samples. As only two parameters must be identified by the RF classifier (desired number of classification trees and the number of prediction variables utilized in each node to increase the size of the tree), 500 trees were used in this study, and four random variables were chosen at random from the best split as each tree grew [36]. The developer's manual for the RF classifier in GEE is available at https://developers.google.com/earth-engine/classification. In order to implement the random forest classification, the four classes (agriculture, vegetation, baresoil and water) were identified and validated. Moreover, an accuracy evaluation was carried out for LULC classification to explain the interrelationship between classification findings and ground truth data. The confusion matrix, which gives the relationship between the LULC classification outcomes and verification data, was created for assessing the accuracy of image classification using remote sensing data. Overall accuracy, kappa coefficient, producer's accuracy, and user's accuracy were all calculated to verify categorization accuracy [37]. Change in each LULC type in the study area was then analyzed. Overall efficiency is the ratio of correctly classified samples to the entire number of validation samples, which indicates the algorithm's overall efficacy, and is calculated as:

$$POA = \frac{1}{N}\sum_{t=1}^{n} p_{ti} \tag{3}$$

where POA denotes the overall accuracy; N denotes the total number of samples used for accuracy evaluation; n denotes the total number of categories; and P_{ii} denotes the number of correct classifications of the ith sample in the confusion matrix.

Kappa coefficient is the degree of agreement between the predicted values and the ground truth data and is calculated as:

$$K = \frac{N\sum_{k=1}^{n} p_{kk} - \sum_{k=1}^{n}\left(\sum_{i=1}^{n} p_{ki}\sum_{j=1}^{n} p_{kj}\right)}{N^2 - \sum_{k=1}^{n}\left(\sum_{i=1}^{n} p_{ki}\sum_{j=1}^{n} p_{kj}\right)} \tag{4}$$

Where K denotes the Kappa coefficient, n denotes the total number of categories, P_{kk} denotes the number of correct classifications of the kth sample in the confusion matrix, and $\sum_{i=1}^{n} Pki$ and $\sum_{j=1}^{n} Pkj$ denote the sample size on the ith and jth columns respectively. N denotes the total number of samples used for accuracy evaluation.

Producer's accuracy is the likelihood that the ground truth reference data (validation sample) for the category is accurately identified is indicated by the mapping accuracy, and is calculated as:

$$PAA = \frac{p_{kk}}{\sum_{j=1}^{n} p_{kj}} \tag{5}$$

where PAA denotes the mapping accuracy; n denotes the total number of categories; P_{kk} denotes the number of correct classifications of the kth sample in the confusion matrix; and $\sum_{j=1}^{n} Pkj$ denotes the sample size on the jth column.

User's accuracy is the ratio of correctly identified pixels in a category to the total number of pixels in that category in the subcategory and is calculated as:

$$PUA = \frac{p_{kk}}{\sum_{i-1}^{n} p_{ki}} \tag{6}$$

where PUA denotes user accuracy; n denotes the total number of categories; P_{kk} denotes the number of correct classifications of the kth sample in the confusion matrix; and $\sum_{i=1}^{n} Pki$ which denotes the sample size on the ith row. The changes occurring in LULC, before and after GBHP, were analysed using the following formula [38]:

$$\%Change = \frac{Final_{area} - Initial_{area}}{Initial_{area}} \times 100 \quad (7)$$

These changes were calculated for both seasons to get a clear picture of the temporal variation in all the selected parameters as impacted by GBHP.

2.3. Respondents' data collection through field survey and analysis

In order to develop a dataset based on respondent perceptions about the reasons behind LULC, a comprehensive field survey mechanism was deployed between December 2019 and November 2021. Purpose of the survey was to acquire primary data based on case study design. Numerous other studies have used similar technique(s) to validate and reinforce technical datasets with perception analysis [39, 40]. Data for the present study was collected from household heads more than 40 years of age, mainly related to farming (to be able to report pre GBHP information). Data collection was done through a multi-stage sampling technique. In the first stage, clusters of villages were selected from both embankments of the river; a total of 16 clusters/ villages were selected from both embankments. This included 4 villages from Swabi, 2 from Haripur and 2 from Attock (figure 1). In the second stage, a total of 384 respondents were selected from all 16 villages on a random basis. Based on a 95% confidence interval (CI) and 5% margins of error, this sample size was calculated [22, 41]. Data was collected through a self-administered questionnaire proforma constituted by closed and open-ended questions about LULC changes and their reasons (S6). All the respondents were asked to select the given options with respect to each LULC change (increase, decrease or no-change). Further they were also asked to give their opinions on possible causes of these changes. Multiple opinions were therefore generated about the reasons of LULC change (occurring during all study periods) by all the respondents. The most prevalent opinions were aggregated and expressed in terms of the percentage of respondents who reported them. Responses given by lesser than 50% respondents were not included in the discussion. Moreover, throughout the survey, prior consent was taken from each respondent of this study regarding acquisition and publication of this data.

3. Results

This study analyzed temporal changes in LULC during a defined period before and after the construction of GBHP (1990–2020). Scope of the study is limited to the delineated catchment area as was already declared an affected area by state authorities. Assessment of LULC in pre and post-development project scenarios proves a useful method of assessing the changes caused by human activities [42–44]. In the present study, analysis time period till the year 2002 is considered pre GBHP whereas after the year 2002 is considered post GBHP. The results have been further explained for LULC changes occurring during summer and winter seasons.

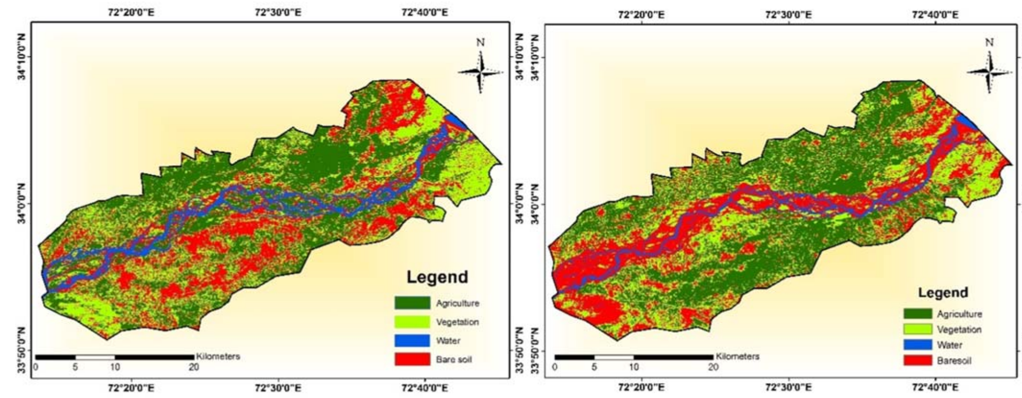
3.1. LULC analysis through GEE

3.1.1. LULC accuracy assessment

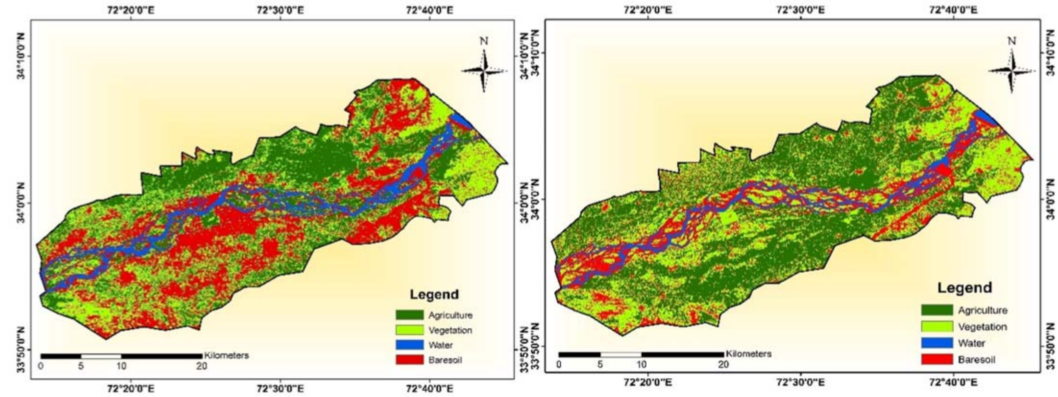
Using the LULC analysis methodology discussed in methodology section, accuracy results achieved by the present study are shown in the table 1.

Table 1. Accuracy assessment result of each LULC class.

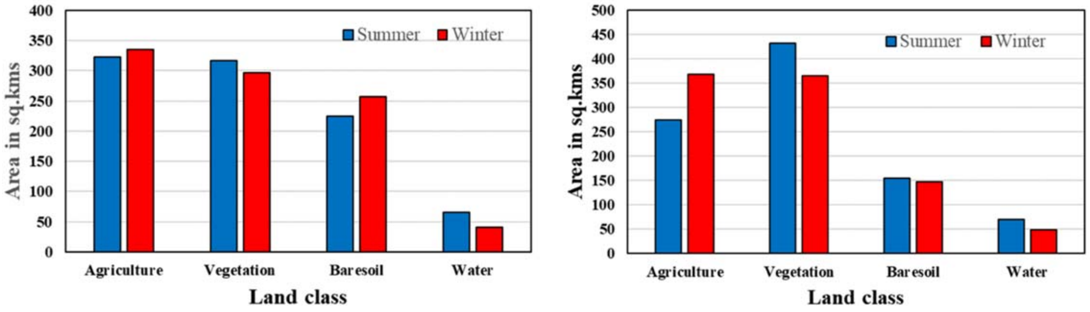
LULC types	1990			2002		2010		2020
	User's accuracy	Producer's accuracy	User's accuracy	Producer's accuracy	User's accuracy	Producer's accuracy	User's accuracy	Producer's accuracy
Agriculture	95	97	96	95	91	93	92	94
Water	92	s94	92	92	92	89	95	89
Baresoil	90	92	88	91	96	94	97	95
Vegetation	96	87	92	86	88	89	96	94
Overall accuracy	94		92		93		94	
Kappa coefficient	89		88		90		92	



(a) Land use classification of summer 1990 (b) Land use classification of winter 1990



(c)Land use classification of summer 2002 (d) Land use classification of winter 2002



(e) Area wise land class distribution (1990) (f) Area wise land class distribution (2002)

Figure 2. (a): Land use classification of summer 1990 (b): Land use classification of winter 1990, (c): Land use classification of summer 2002, (d): Land use classification of winter 2002, (e): Area wise land class distribution (1990), (f): Area wise land class distribution (2002).

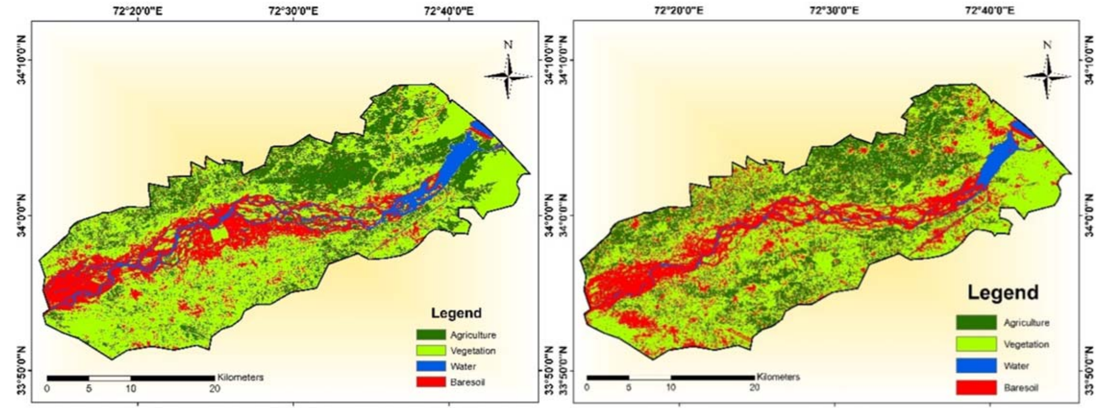
3.1.2. LULC of 1990 and 2002 (Pre GBHP)

Based on the study analysis, agriculture dominated the study area both during summer and winter seasons of 1990. It occupied 322.28 km^2 and 335.61 km^2 of area during these seasons respectively, creating a proportion of 34.67%, and 36.11% (figures 2(a), (b) and (e)). Vegetation occupied 34.04% and 31.89% of the area during summer and winter respectively. Baresoil made up 24.16% and 27.61%, whereas water occupied 7.10% and 4.37% of the area during the same seasons.

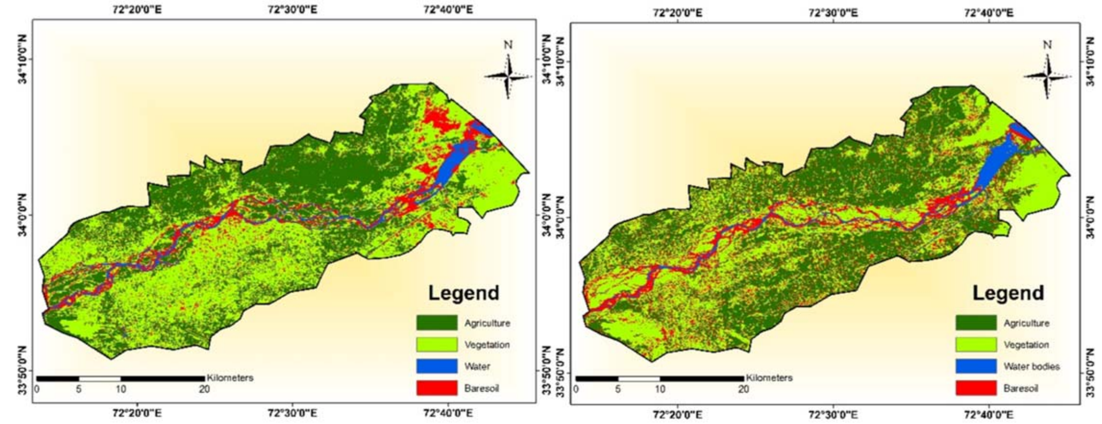
During 2002, agriculture was again dominant during winter season by occupying 39.63%, whereas during summer, occupied 29.53% of the study area (figures 2(c), (d) and (f)). Vegetation, however, dominated the largest area in summer (46.38%), whereas occupied 39.21% of the area during winter. Baresoil occupied 16.63% and 15.90%, and water occupied 7.47% and 5.25% of the area during summer and winter respectively.

3.1.3. LULC of 2010 and 2020 (Post GBHP)

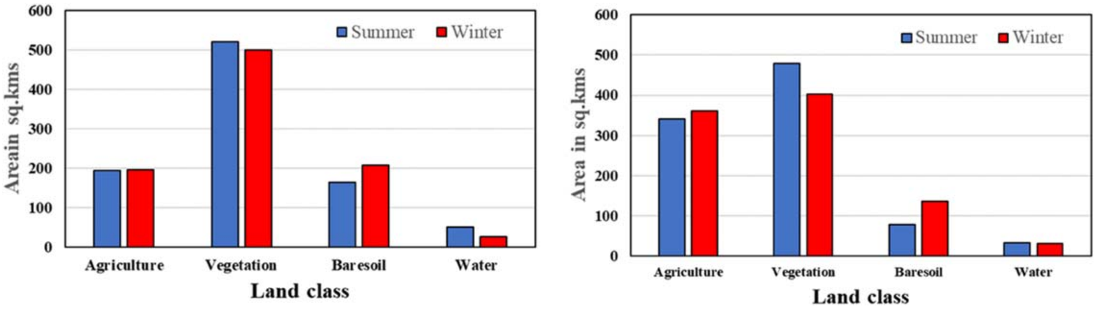
During 2010, the proportion of study area under agriculture fell to 20.93% and 21% during summer and winter seasons respectively, whereas vegetation dominated by occupying 55.99% and 53.87% of the area during the



(a) Land use classification of summer 2010 (b) Land use classification of winter 2010



(c) Land use classification of summer 2020 (d) Land use classification of winter 2020



(e) Area wise land class distribution (2010) (f) Area wise land class distribution (2020)

Figure 3. (a): Land use classification of summer 2010, (b): Land use classification of winter 2010, (c): Land use classification of summer 2020, (d): Land use classification of winter 2020, (e): Area wise land class distribution (2010), (f): Area wise land class distribution (2020).

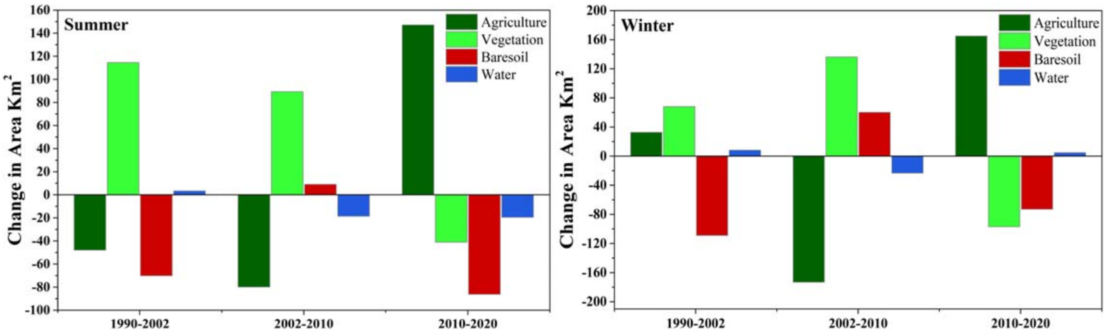


Figure 4. LULC area changes in km^2 from 1990 to 2020.

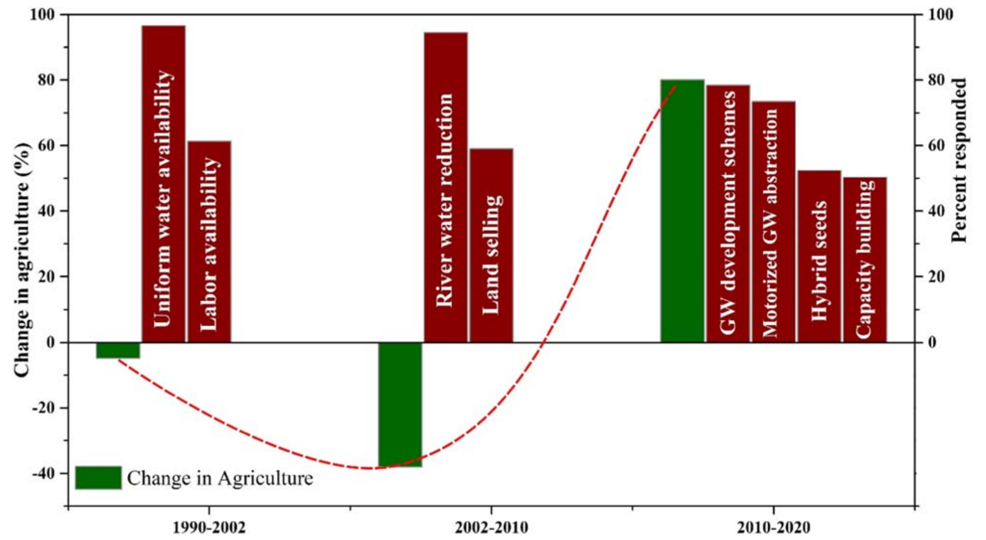


Figure 5. Agriculture change and causes.

same seasons (figures 3(a), (b) and (e)). Baresoil made up 17.59% of area in summer and 22.37% of the area in winter, making it the second-largest area in this season. Moreover, water occupied 5.46% of the area in the summer and 2.74% in winter.

During 2020, vegetation's proportion to the study area remained highest, by occupying 51.53% and 43.43% of the area during summer and winter seasons respectively (figures 3(c), (d) and (f)). The second highest land cover was attributed to agriculture, occupying 36.77% and 38.76% of the area during summer and winter respectively. Baresoil occupied only 8.32% and 14.53% of the area during summer and winter respectively. Water occupied only 3.36% and 3.26% of the area during summer and winter respectively.

3.1.4. LULC changes from 1990–2020

According to the results of current study, there have been significant changes occurring in study area's LULC trends from 1990–2020 (figure 4). From 1990–2002 (before GBHP), agriculture increased by 9.74% in winter season. Baresoil reduced by 31.21% and 42.43%, vegetation increased by 36.234% and 22.94%, and water increased by 5.06% and 20.19% in summer and winter seasons respectively (S5). However, the study explored significant changes occurring in LULC after functioning of GBHP as compared to the time period of 1990–2002. Between 2002 and 2010, agriculture experienced a reduction of 29.10% in the summer and a reduction of 47% in the winter. As a result, vegetation increased by 20.75% and 37.38% in the summer and winter, respectively, whereas baresoil increased by 5.83% and 40.73% in the same seasons. Water decreased by 26.76% in the summer and by a greater amount—47.73%—in the winter. Also, in comparison with the time period of 2002–2010, there was yet another change in LULC patterns between 2010–2020, as there was a sharp rise in the proportion of agricultural land to study area during this time. Agriculture lands increased by 75.61% in the summer and by 84.53% in the winter, respectively. Whereas there was considerable reduction in vegetation and baresoil. While baresoil had reductions of 52.69% and 35.04% during summer and winter, respectively, vegetation also experienced reductions of 7.97% and 19.37% in the same seasons. During summer, water further decreased by 38.41%, while winter witnessed a rise of 18.85%.

3.2. Causes of LULC change

Preceding section illustrates respondent perceptions regarding causes of changes that occurred in selected LULC parameters. These results correspond to the three analysis time periods. Change in LULC classes as discussed below have been calculated by using GEE, whereas opinions regarding the significant number of respondents have been grouped against each corresponding land use class and discussed in detail, in the light of information collected through field surveys.

3.2.1. Agriculture

According to the present study findings, the agriculture area from 1990–2002 underwent a minor reduction of 4% overall (figure 5). However, as per information collected through the field survey, most of the respondents (96.61%) considered agriculture area to be uniform during this period due to ample groundwater availability (as river water had a direct impact on maintaining the groundwater table in areas adjoining Indus River). Moreover,

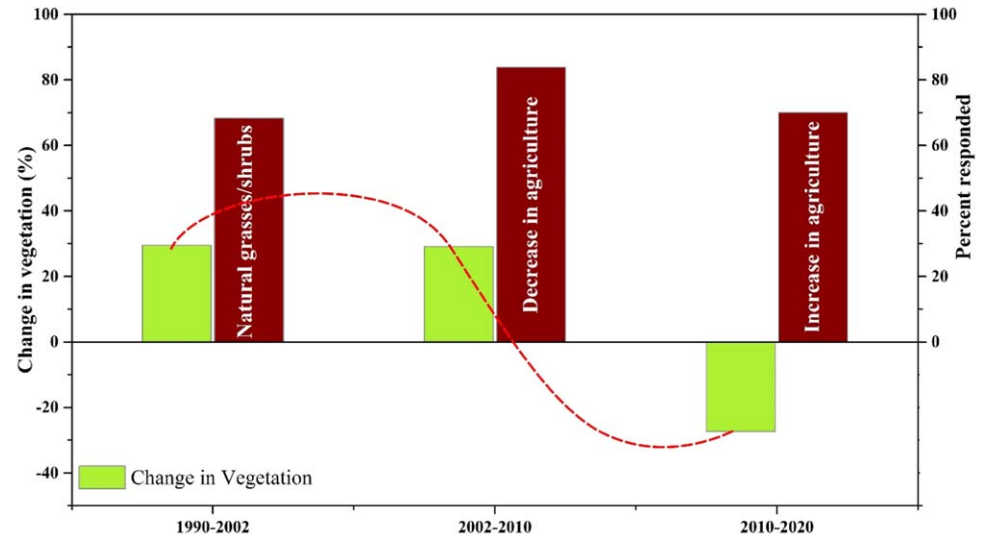


Figure 6. Vegetation change and causes.

61.30% of respondents also considered labor availability to be another reason behind the uniform agriculture area. This was due to reliable agriculture production and people's dependence on it. However, from 2002–2010, agriculture area reduced by 38.05% overall, as compared to the time period of 1990–2002, which was reported to be mainly caused by water reduction after the functioning of GBHP (by 94.53% of respondents). The second largest number of respondents (58.98%) also considered land fragmentation (mainly due to land selling) as a cause behind this reduction. Land selling became a feature of this area mainly due to water scarcity and was characterized by landowners' desperate decisions to sell their land for alternate investments. Present analysis also shows an overall agriculture increase of 80.07% occurring between 2010–2020, in comparison with the time period of 2002–2010. This increase can be attributed to numerous factors, as reported by study respondents. According to 78.39% of respondents, the Government's groundwater development projects (water mining through deep boreholes) majorly recovered lands under agriculture through ensuring reliable water supply. This aided in an abrupt improvement of the production of smaller crops like millet and other vegetable and fruit crops. Also, according to 73.44% of respondents, agriculture area increase was also due to conversion of traditional Persian wheels into motorized water abstraction methods, self-invested by farmers. This investment led to the recovery of most water-deficient agriculture land patches (mostly owned by new landowners). Yet another possible cause of agriculture area increase (reported by 52.34% of respondents) was the provision and availability of better (hybrid seeds) which helped in achieving higher production of crops. Government and private institutions ensured ample distribution of these seeds in the study area as an attempt to recover the reduced crop production and were successful in recovering a part of local livelihoods through various seed distribution schemes. Also, according to 50.28% of respondents, agriculture area increase was achieved due to farmers' capacity building through constant sensitization and regular trainings on improved agricultural practices. For this aim, the Government committed to consulting and developing regional and local bodies. In this regard, it received cooperation from multiple regional and local organizations. A cooperative body under the title of 'Ghazi Barotha Taraqiata Idara, GBTI' (Ghazi Barotha welfare organization) proved instrumental in provision of social and technical services to the farmers in study area. Its main accomplishment considered formation of farmers organizations, capacity building and trainings, and provision of necessary technical and financial resources for agriculture area improvement and recovery of lost livelihoods.

3.2.2. Vegetation

As apparent from figure 6, present study analyzed an overall vegetation increase of 29.5% from 1990–2002. The trend was validated through a response of 69.23% of respondents who considered natural production of grasses and shrubs prevailing in the area during this period. Growing some indigenous tree varieties was also a prominent feature existing in the study area, that provided additional economic benefits to farmers. From 2002–2010, vegetation remained almost unchanged (29.06%) overall. However, a significant number of respondents (83.85%) considered a slight increase in vegetation during this period, on account of the reduction in agriculture area. It was reported that all the previously cropped area was covered by natural grasses, especially in rainy seasons. From 2010–2020, however, there was a significant reduction in area under vegetation (in

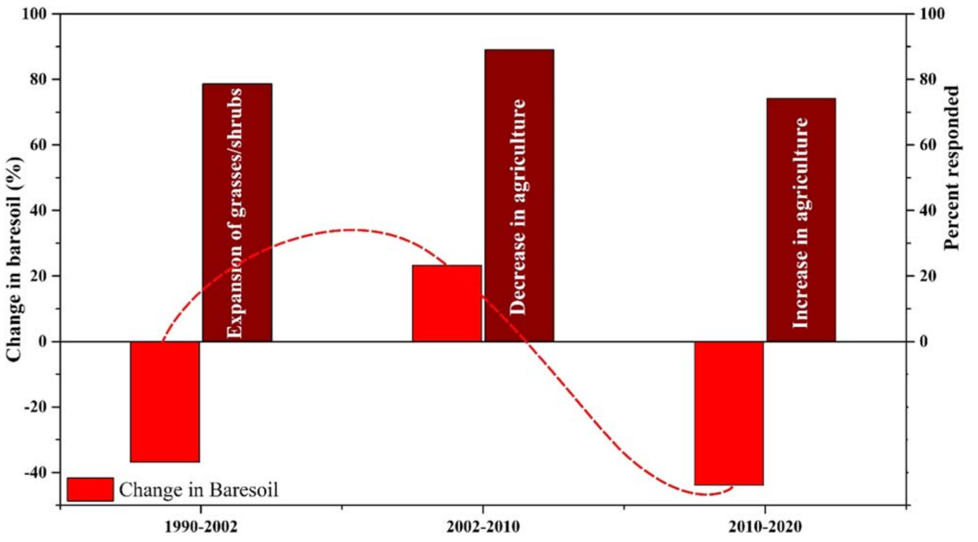


Figure 7. Baresoil change and causes.

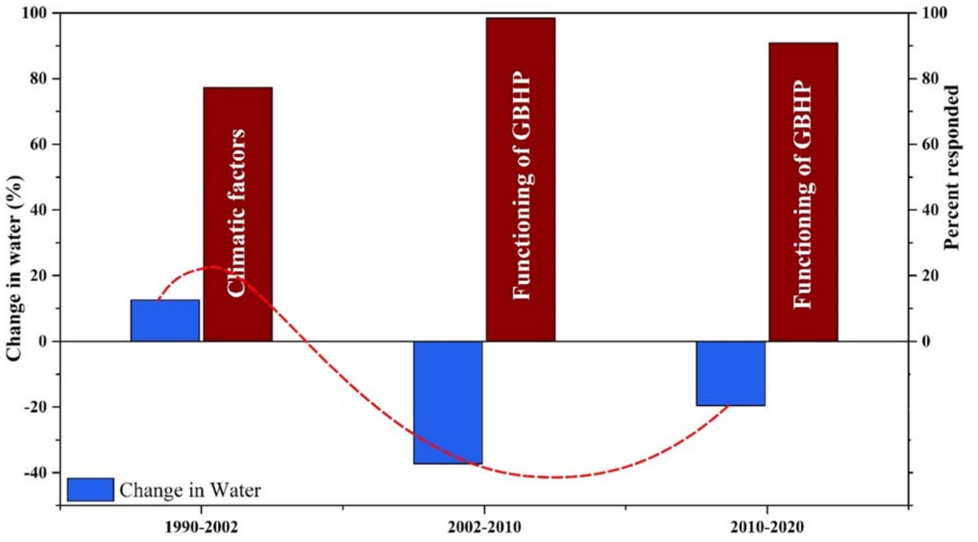


Figure 8. Water change and causes.

comparison with 2002–2010), as it decreased by 27.34% overall. About 70% of the respondents considered an increase in agriculture as the main reason behind this reduction. Recovery of agriculture during this period coupled with the expansion of agriculture lands led to a sharp decrease in lands under natural vegetation and shrubs.

3.2.3. Baresoil

Varying trends of area under baresoil was also assessed by present study during study time periods (figure 7). From 1990–2002, baresoil underwent a reduction of 36.82% overall. The trend was validated by 78.65% respondents, as they considered this decrease due to the uniform agriculture area and an increase in natural grasses and shrubs (due to better water availability) during this period. However, between the time period of 2002–2010, there was an overall increase of 23.28% in baresoil, in comparison with 1990–2002. This major increase was driven by a sharp reduction in agriculture area (as reported by 89.06% respondents), and most of previously cropped land patches converted into dry soil and overlain by stones and debris. Moreover, as compared to 2002–2010, the time period between 2010–2020 was again signified by an overall reduction of 43.86% in baresoil. This decrease was validated by a response from 74.22% respondents who considered an increase in agriculture as the main cause behind this trend. Improved water availability and increase in agriculture activities led to a major expansion in agriculture that resulted in re-conversion of baresoil into agriculture lands.

3.2.4. Water

As per findings of this study, water also went through abrupt change in pre and post GBHP time periods. According to analysis, the time period from 1990–2002 was marked by an increase in water, as it increased by 12.62% overall (figure 8). A significant number of respondents (77.34%) validated this increase and considered it to be caused by climatic factors. Further, it was informed that pre GBHP time period was also signified by controlled water releases from Tarbela dam, with cyclic variations due to natural factors. However, during post GBHP time periods, both from 2002–2010 and from 2010–2020, water mainly from Indus River, significantly reduced overall. This reduction was assessed to be 37.24%, during 2002–2010 (in comparison with 1990–2002), and 19.56% during 2010–2020 (in comparison with 2002–2010). This reduction was validated by almost all the respondents (98.44% and 90.89% corresponding to both time periods) and considered functioning of GBHP as the only cause behind this reduction. As GBHP is a run-of-the-river project, it is dependent upon water diversion for hydropower production through Ghazi barrage. This diversion created a sharp shortfall of water in the downstream river and the trend was particularly aggravated in drier months. This shortfall directly affected the groundwater table in areas located along both sides of the river and produced water scarcity for agriculture and other natural resources dependent upon it.

4. Discussion

This study highlights major LULC impacts caused by GBHP on project downstream area. The impacts were characterized by significant changes in natural resources, especially agriculture. According to literature, the study area's economy was solely dependent upon agriculture, as 60% of the population was dependent on it before the construction of GBHP [16, 23]. Agriculture also provided staple food to the local area [23]. Moreover, due to production of cash crops like sugarcane and tobacco, the need for increasing agriculture area was therefore prevalent [45, 46]. However, a significant decline in agriculture, an increase in vegetation and baresoil, and an abrupt decrease in river water was analyzed after functioning of GBHP. Water scarcity, mostly due to river water reduction, was blamed for the decline in agriculture. This decrease was brought about by the Ghazi barrage's diversion of river water, and it had an immediate effect on groundwater, the main irrigation source. Also, according to a recent study conducted by Ullah *et al* 2023, agriculture showed no major dependency on any hydrological and climatological parameter except groundwater. The study also explored a direct relation of river water quantity on groundwater table, as it reduced with the reduction of river water after GBHP [47]. Findings of current study are also consistent with another research study [16], which concluded a significant loss of natural resources along the Indus River downstream following the operation of the GBHP. Similar findings were also obtained from another study carried out in Pakistan [1], that examined alterations in the Simli watershed's land use and land cover between 1992 and 2012. According to the study, there was a drop in agricultural land in the study region due to a lack of water, with 748 hectares turning into bare soil and vegetation. Conclusively, present study supports the findings of research studies those concluded possible detrimental effects of run-of-the-river projects on the LULC, hydrology and socio-economic conditions of river downstream areas between water abstraction points and where waster returns [7, 10]. Moreover, as our results revealed another shifting LULC trend between 2010 and 2020, several reasons can be attributed to this significant increase in agriculture and reduction in baresoil. Most important reason was the government operated groundwater development projects, executed during 2010, as the main public mitigation policy to compensate for the livelihood losses. They were mainly aimed at agriculture uplift in post GBHP time period, as committed in the project EIA [48]. Present study elucidates findings of similar results that highlight the importance of government interventions for uplifting natural resources. For example, LULC changes occurring in Gaborone dam catchment in Botswana after state investment for agricultural development increased the cropland by 1.3% whereas water bodies increased by 22.2% [43]. Also, Chashma Right Bank Canal (CRBC) in Pakistan increased 32% cultivated area in Dera Ismail Khan, Pakistan [20], as a part of state investment for agriculture uplift. Other reasons for the increase in agriculture lands are population pressures, escalated food and feed demand, and a rising quest for more income [42, 44, 49]. These studies concluded that farmers' capacity building with respect to improved irrigation methods, improved water management practices, better land preparation and the use of better seeds are the main reasons behind increasing agriculture land in Pakistan. Moreover, in Pakistan, non-governmental organizations have always played their role in strengthening peoples' resources through capacity building and financial provisions [50]. Efforts of development organizations such as Ghazi Barotha Taraqiata Idara (GBTI) in the recovery of natural resources and livelihoods are also considered a basis for gradual yet constant improvement in project-affected areas [50, 51]. However, according to present study's viewpoint, as land is the primary factor sustaining natural resources and the ensuing production of food and feed, changes in the patterns of LULC (including surface water) brought about by development projects may often have a direct effect on people's livelihoods and local economy. Thus, all such projects, including run-of-the-river projects those have the potential to alter LULC need to be initiated only after being subjected to a thorough investigation. Run-of-river projects are therefore recommended, provided vigilance needs to be maintained during all the phases of project design, implementation, and monitoring. Also, if potential impacts are predicted, sustainable mitigation strategies and robust compensation measures need to be applied to prevent the affected from livelihood and economic losses.

5. Conclusions

Present study concludes that the functioning of GBHP induced major LULC changes in downstream areas, bringing a considerable reduction in agriculture. Agriculture occupied 34.67% and 36.11% of areas in summer and winter seasons before GBHP, whereas after GBHP (from 2002–2010), area under agriculture reduced by 29.10% and 47% in the same seasons as compared to 1990–2002. Concurrently, the period from 2002–2010 was also marked by an increase in vegetation (by 20.75% in summer and 37.38% in winter), and baresoil (by 5.83% and 40.73% in summer and winter seasons respectively). A major reduction of water was also observed in this period, as area under water reduced by 26.76% in summer 47.73% in winter. However, between 2010–2020, area under agriculture increased again by 75.61% in summer and 84.53% in winter, as compared to time period between 2002–2010. Also, vegetation decreased by 7.97% and 19.37% (in summer and winter), whereas baresoil also reduced by 52.69% and 35.04% (in summer and winter seasons respectively) during this period. According to responses of significant number of respondents, agriculture reduction after GBHP was a result of water scarcity which was caused due to functioning of GBHP. An increase in vegetation and baresoil was caused on account of agriculture area reduction. Moreover, another increase in agriculture (from 2010–2020) was witnessed primarily because of the Government's groundwater development projects. Conversion of traditional water abstraction practices into motorized options, provision of better seeds and farmers' capacity building through welfare organizations lead into recovery of agriculture and reduction of area under vegetation and baresoil. The study recommends development of run-of-the-river projects through sustainable planning and robust measures to counter their impacts. Moreover, establishing immediate compensatory measures directed towards affected communities is vital to prevent their subsistence as well as income losses due to similar projects.

Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

Author contribution

Ehsan Inam Ullah and Shakil Ahmad designed research and directed its implementation; Muhammad Fahim Khokhar and Umer Khayyam finished data screening, data extraction, and data analysis; Faizan ur Reman Qaiser and Muhammad Azmat made the figures and tables; Ehsan Inam Ullah, Muhammad Arshad and Faizan ur Rehman Qaiser examined the data processing; Ehsan Inam Ullah, Shakil Ahmad and Muhammad Fahim Khokhar interpreted the results and wrote the manuscript; Umer Khayyam and Muhammad Arshad reviewed and edited the writing.

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