Impact of Hydrological Infrastructure Projects on Land Use/Cover and Socioeconomic Development in Arid Regions—Evidence from the Upper Atbara and Setit Dam Complex, Kassala, Eastern Sudan

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Abstract: In recent years, Africa has seen much construction of large-scale hydrological infrastructures in the arid and semi-arid regions of numerous countries. This paper aims to quantify the effects of this form of hydrological infrastructure, especially the Upper Atbara and Setit Dam Complex (UASDC) in Eastern Sudan, on the land use/cover (LUC) and socioeconomic domains. This paper attempts to advance our understanding of this phenomenon by using multiple approaches. A framework using the integration of 3S technologies and a logical approach for quantifying the significance of the results to society has been developed. The method used Landsat5 TM in 2002, Sentinel2A in 2018, and statistical data to create the LUC map. The final map included seven classes; the overall accuracy of changes in LUC patterns was 94.9% in 2002 and 93% in the results reveal that significant changes occurred in terms of LUC, having a considerable effect on socio-economic development. The results were analyzed with the logical approach for overall objectives, where 85% represents S1, 3.3% represents S2, and 11.7% represents S3, respectively. This study provides an insight into further investigations of the dam’s effect on climate and groundwater, and offers a new perspective on land use prediction, simulation, and environmental sustainability.

Keywords: arid and semi-arid regions; spatial dynamics; sustainability; change detection; social responsibility; land use and land cover change

1. Introduction

Water is not only critical to human survival but also influences socioeconomic, agricultural, technological, and industrial development [1]. Therefore, ensuring water security has been considered as one of the sustainable development goals (SDG) (Goal 6) of the United Nations [2,3]. In this regard, the construction of dams has played an overarching role in the processes of agricultural activities, environmental use, industrialization, and urban development [4]. Dams provide access to fresh water, control floods, and generate electricity, thereby leading to economic and agricultural development. In semi-arid and arid countries, dams have an important role to play in maintaining agricultural activities and livelihoods during the dry seasons [5,6]. At present, nearly 160 countries in the world use hydroelectric plants for generating electricity [7]. Large dams can promote clean energy, agricultural sustainability, and considerable socioeconomic developments, particularly for developing countries in Latin America, Africa, and the Middle East [8]. In this context, the construction of a large dam can also be considered as a symbol of advanced technology,
science, and poverty reduction in such countries. This is because fresh water and electricity are major deriving forces of socioeconomic growth [9]. Hence, the coming decades are likely to witness unprecedented rates of large dam construction in such countries [10].

Dams were believed to magically transform barren wastelands into fertile acreage, elevating the nation, and, through irrigation and electrification, integrating the domestic political economy [11]. Nehru saw dams as the “modern temples of India”, lifting hundreds of millions out of poverty through spectacular multiplier effects in industry and irrigated agriculture [12]. The Grand Ethiopian Renaissance Dam in Ethiopia increases the economic benefits of electricity generation [13]. Gamal Abdel Nasser also advanced his revolutionary “second Egyptian independence” through the Aswan Dam, Africa’s biggest infrastructure project, which controlled the Nile floods for the first time in history [14].

Lack of access to water and electricity in semi-arid and arid developing countries, such as most African countries, is a key challenge for economic development [15]. Hence, the construction of dams in these regions has an important role to play in ensuring the supply of water for agriculture and daily life. For instance, the construction of dams in Africa, such as, but not limited to, the Aswan High Dam in Egypt, the Sinnar Dam in Sudan, and the Kandadji Dam in Niger, have led to a range of advantages, such as controlling flooding, generating hydropower, providing irrigation, providing access to drinking water and establishing economic development [16]. Given the advantages of dams in semi-arid and arid regions, many countries in North Africa and the Middle East have witnessed the rapid construction of dams [17].

Water scarcity is a major challenge in the arid climate of Sudan, and people struggle to manage this difficulty in the contexts of electricity, agriculture, drinking water, the economy, and so forth [18]. The construction of dams is one sustainable way to improve the socio-economic climate of the region [19]. The Roseires Dam, which spans the Blue Nile 630 km upstream of Khartoum, is used for the supply of irrigation water and hydroelectric power [20]. The Merowe Dam is used for hydroelectric power and is located on the River Nile, about midway between Khartoum and the Egyptian border [21]. One of the recently constructed dams is the Upper Atbara and Setit Dam Complex (UASDC), which is the focus point of this study. Prior to constructing the UASDC, the nearby regions of the dam had experienced serious challenges, such as the shortage of water due to climate change, intensive land-use pressure due to the negative impacts of drought in the agricultural sector, a shortage of drinking water and domestic water, and land tenure disputes, while the construction of this dam offered a range of benefits, such as irrigation. Hydroelectric power, flood prevention, and the improvement of the socioeconomic conditions of the region [22].

Although the construction of a dam can mitigate many problems, these hydrological systems can lead to an array of environmental problems, such as the submergence of urban and horticultural land and archeological features, the imbalance of water resources between the upstream and downstream inhabitants, and also the disturbance of regional and international political conditions, especially when dams are constructed on rivers shared by several different countries [23]. Moreover, the construction of dams also has adverse impacts on society, such as the displacement of tens of thousands of people, devastating ecological and environmental damage to unique ecosystems, and the undemocratic decision-making surrounding dams has triggered a rethink [24].

There has been a wealth of literature published that analyzes the merit and demerit of dams on the environment. Numerous studies have utilized remotely sensed data and geographic information technology (GIS) to analyze the impacts of dams. The environmental impacts of LULC have been investigated by various means, including the remote sensing assessment of surface changes using, for example, the leaf area index (LAI), land surface temperature (LST), the normalized difference vegetation index (NDVI), and the normalized difference water index (NDWI). LST is often utilized in studies on global temperature change, as well as in hydrological, geo-biophysical, and LULC investigations [25]. Recent research in this area has mostly focused on improving the econometric techniques.
of estimation using limited dependent-variable models. This study uses intervention logic and the relative ratio method to develop a dynamic model to estimate the determinants of land-use changes, using data derived from satellite images [26]. Two modeling techniques characterize the literature. The first group of studies, from [27], uses a multinomial logic specification to compute the probabilities of observing each land-use choice at each location. The second group of more recent studies has experimented with survival models in order to overcome some of the limitations and shortcomings of the multinomial logic approach. Most of the economic literature that uses spatially explicit data to investigate the determinants of land-use choices and land-use change is limited to static models and uses cross-sectional datasets [28].

Some previous studies employed a 3S technology synthesis method to monitor and predict the LUCC process comprehensively and systematically. With the increased availability of open-access historical and current satellite sensor imagery, it is now also possible to monitor the effects of human activities, such as the construction of dams and Landuse Land Cover Change LULCC in a timely, accurate, and cost-effective way [29]. A number of investigations have quantified the impacts of dams on LUC via remotely sensed imagery, with a combination of geographic information systems (GIS) and landscape metrics of drones and aerial photography [30,31]. However, few studies have explored the application of 3S technologies, intervention logic, and relative ratios for quantifying the impacts of hydrological infrastructure on LUCC, particularly in developing countries [32].

The aim of this research is to understand more clearly the potential merits and drawbacks of constructing dams on the surrounding environment in the context of arid and semi-arid areas in the developing countries of Africa. To do so, this research contributes in three important directions. First, we propose a multifaceted approach that consists of remote sensing and GIS to quantify LULCC. Second, we systematically link the objectives of the dam to the socio-economic conditions of the study area [33]. Third, the study scrutinizes the challenges of drought and climate change, at the same time analyzing the role of the water control structure in reducing such negative effects. To address these contributions, the UASDC was selected as a typical example of a major advanced dam infrastructure in Sudan. Moreover, this case study provided a framework and comprehensive results to guide more detailed assessments of the impacts of dams on the surrounding regions in African developing countries with an arid and semi-arid climate.

2. Materials and Methods

2.1. Study Area

This study focused on the eastern part of Sudan in the southeast of Kassala and Gadaref State, located along the borders of Eritrea and Ethiopia. The Setit region covers an area of approximately 42,282 km², with a semi-arid climate. The average annual rainfall is 578 mm, which mostly falls during the rainy season from June to October, with an average annual temperature of 29 °C. The main environments within this region are the plains and stretches of savannah forest, and the soil is of dark, cracking Montimorillonitic clays with low permeability [34]. The major cities in this region include Kassala, Gadaref, Halfa, Aroma, Girba, and Shwak, in addition to the villages around the region of the Setit Dam.

2.2. The Importance of the Dam to Society

Since the 1990s, with the increasingly intensified conflicting demands among populations, resources, and the environment, the sustainable use of land resources has been at the core of the 21st-century agenda, making land resources research part of a development period for the sustainable use of land [35]. This dam was constructed for multiple purposes, such as socioeconomic development, public services, and the boosting of ecosystems. These objectives were developed from the point of view of the provision of irrigation water to the Halfa Agricultural Scheme and Setit Agricultural Scheme, where the irrigated area after the construction of the dam has increased from 1400 to 1580 km²). The dam also made it possible to increase the accessibility of adequate and sufficient drinking water to the city.
of Gaderf and the development of the fishery sector, which increased the production of fish up to 1700 tons/year). Moreover, the increase of forested land affected the habitat and ecosystem of that area. The dam also generated jobs in the production sector, such as agriculture, value chains, agricultural services, and the fishing sector.

Before the construction of the dam, the villages in the region had poor infrastructure and public services, such as drinking water supply and roads; however, the construction of the dam as a social responsibility led to improvements in housing standards and in the infrastructure, the construction of new roads and bridges for transportation purposes and the improvement of public services. Such outcomes were revealed to the authors during field visits, in discussions with a majority of local people, who narrated that the construction of the dam not only improved the supply of irrigation water but also resulted in the development of new agricultural schemes in the area [36].

The study revealed that the dam is utilized increasingly for power generation for the national electricity network. Accordingly, the local villages and houses could then be linked with the national electricity network, and the resettlement villages could be modernized. The dam has also improved the drinking water quality, due to institutional support for water control and the quality testing of water, ensuring potable water for the people around the dam area and resettlement villages and for those who live a distance from the dam. The availability of irrigation water throughout the year will encourage the local farmers to increase crop production and encourage multi-seasonal cropping, e.g., cereals, vegetables, and fruit trees. Accordingly, the cropping system is designed to reduce soil exhaustion and maintain the soil conservation process. The existence of a continental road and two airports in the region will further facilitate local business and support the translocation of agricultural products.

2.3. Data Collection

The primary data were collected during the field trip observation, to gather first-hand evidence of the dam’s effects, such as the hydrological conditions and infrastructure (site of the dam before and after dam construction and the Gadaref drinking-water supply lines) and its socioeconomic effects, such as the sorghum crop in the Halfa Agricultural Scheme (HAS) and Sitit Agricultural Scheme (SAS), resettlement villages, the hydroelectric power structure, and fish production. Secondary data were collected to build rich information resources prior to land use/cover classification [37], these consist of socioeconomic, resettlement and livelihood data before and after the dam construction. These statistical data were collected during visits to the corresponding institutions that have participated in the construction of the dam.

The most prominent feature of the study area is the Atbara River and its tributaries of Settit and Upper Atbara, crossing the region from the southeast to the north, with a total annual discharge of 12 BmThis river is perennial and comprises the main surface water flow in the region, and it is one of the River Nile's tributaries [30]. According to the 2008 national census, the population of the states of Kassala and Gadaref was approximately 3million people, with an annual population growth rate of 2.65%. The major livelihoods are from agriculture and grazing [31]. The main agricultural product in the region is cereal crops, like sesame, sorghum, groundnuts, beans, millet, and fodder.

The Upper Atbara and Sitit Dam Complex (UASDC) dates back to 1946 and was developed to deal with the effects of arid climate conditions of the region; consequently, due to the provision of abundant arable plains in the area, referred to as arid soils, the Ministry of Irrigation in Sudan established a basic survey to secure water for irrigation, drinking water supply and limited hydropower generation [38], (Figure 1).
The Kassala State Administration initiated the updating of the UASDC study in 2006 for water provision to irrigate 400,000 hectares of arable land in Kassala State, and for drinking-water supply availability to the irrigated agricultural land. The Sudan government restored the plan again under the supervision of the Dam Implementation Unit (DIU) during the period of 2007–2009 [39]. The Dam Implementation Unit updated the feasibility studies and commissioned the planning, design, and preparation for construction by multiple international contracting companies. The dam study plan concluded with establishing twin dams in the Al-Bardana area on the Setit river, and a second dam in the Rumaila area on the Atbara River. This resulted in a backwater of 2.7 Bm³, the dam construction operation lasted for three years from 2013 and was completed by the end of The dam was built for multipurpose use including the provision of irrigation water for the HAS and Setit Agricultural Scheme (SAS), drinking water for the city of Gadaref, generating 320 MW of hydroelectric power, and improving livelihood [35].

2.4. Datasets

The LUCC study initially focused on manual surveys and the classification and mapping of land use and land cover types. Therefore, this study used Landsat5 TM data, Sentinel2A data, Google Earth, statistics, and socioeconomic data at two different time points of 2002 and 2018 for the land-use classification system and planning and determination. Satellite sensor data were downloaded from the United States Geological Survey (USGS) website (http://earthexplorer.usgs.gov/) (accessed on 16 March 2021) from the same dates of 2002 and 2018, to minimize the effects of seasonal differences on LUC during the classification process. Bands 1–7, excluding band 6, were used for Landsat5 TM, and bands 1–12 of Sentinel2A were used for classification procedures. The reason behind using Sentinel2A and Landsat5 was that the Sentinel2A series was launched in 2013, and Landsat5 data were available in 2002, while Landsat7 was not yet launched at that time. This will also achieve a better image resolution of 10 m and 12 bands. In addition, this study used the digitizing function in Google Earth to detect the fine features, the produced Shapefile being consolidated with the data projection of Landsat5 and Sentinel2A (Table 1).
Statistical data were collected from the Ministry of Agriculture in Kassala and related institutions, including the Dam Implementation Unit (DIU), the Ministry of Water Resources, Irrigation and Electricity, the HAS administration, and the Gadaref Drinking Water Administration. The static and remote sensing data were consolidated in a concise land use/cover change matrix table that includes changes in socioeconomic, LUC, and public services, derived using the logical concept of land use impact phase classification (LIPC) beside data validation for analyzing land use indices in 2002 and 2018.

2.5. Satellite Data and Pre-Processing

The evaluation of regional land ecological change is implemented through a series of models, with the use of remote sensing and GIS technologies. ENVI5.1 and ArcGIS10.2 software were used for the image processing of Landsat5 and Sentinel2A data, while the SNAP platform was used for image data re-sampling through Raster and the geometric operation tool of Sentinel2A. The quick atmospheric correction model in ENVI was employed to perform atmospheric correction of the Landsat5 TM images [40], at the same time, the atmospheric correction module in SNAP was applied to the Sentinel2A images. To match the pixel size of the Landsat5 image to Sentinel2A, the pixel size of the Landsat5 image was resampled to 10 m by resizing with the data tool in ENVI. Both images were then subjected to layer stacking, mosaic, image clip, and enhancement processes. Finally, the area of interest zoning and test-sample pixels of the land-cover classes were extracted from the Landsat and Sentinel imagery.

2.6. Methodology

The study of land use classification systems is the basis of land use research [41]. The definition and standardization of land use types have important scientific value for the research and practice activities related to land attributes, such as land resource quality evaluation, land use structure adjustment, and land use planning determination. The optimization class model includes a bio-intelligence-based optimization model. For the optimization of the multi-objective, non-line, and multi-constraints of land use structure, solution models based on the bio-intelligence optimization algorithm have been developed, which are the Support Vector Machine (SVM) and other bio-intelligence algorithm models [42]. The SVM classifier has been used successfully for mapping LULC from remotely sensed imagery, due to its non-parametric characteristics. In this study, the SVM classifier was applied to Landsat and Sentinel imagery. The classification parameters of SVM were the radial basic function, gamma in the kernel: 0.007, penalty parameter: 120.00, pyramid level: 0.00, classification probability threshold: 0.05 [40].

It is important to bear in mind that Sentinel2A and Landsat5 TM data may not provide fine-scale details, such as a change in resettlement villages, urban expansion, affected villages, horticultural land, and roads. Therefore, we used the manual digitizing of the Google Earth engine [43] in data from 2002 and The extracted information was then consolidated with classified images in Arc Map (Table 2). In addition to that, we used a forest buffer zone for quantifying the change in forest class areas [44]. The forest buffer zones were established in three zoning regions around water class areas, with 1 km spatial distance.
Table 2. The observed land use/cover feature was affected by UASDC.

| Land Use Class Key      | Description                                                                 | Classification Method |
|-------------------------|------------------------------------------------------------------------------|-----------------------|
| Water                   | Water class, including the lake, the Atbara River, and water bonds (Hafir)   | SVM                   |
| Forest                  | The vegetation of acacia trees used for Gum Arabic production and firewood   | SVM                   |
| Cropped land            | Irrigated agricultural land in HAS and SAS                                   | SVM                   |
| Resettlement village    | New villages built for people affected by the dam construction               | Digitizing            |
| Roads                   | New paved and improved roads, constructed to link the resettlement villages  | Digitizing            |
| Horticulture            | Farms on the riverbank used for fruit trees, vegetables, and fodder production. | SVM                   |
| Built-up area, airport  | City areas delineated in Google Earth                                        | Digitizing            |

2.7. Accuracy Assessment

Assessing the accuracy of classified land used and land cover (LULC) maps based on remotely sensed imagery is a crucial step to ensuring the quality and quantity of generated maps for the subsequent procedures, such as change detection, planning, and conservation programs [45]. In effect, accuracy assessment should be performed using ground reference data or fine-scale remotely sensed imagery. Ideally, an accuracy assessment based on the field campaign using GPS should be conducted for the entire region and for each classified image [46]. However, it often happens that daunting challenges exist in obtaining ground reference data and fine-scale remotely sensed imagery, particularly in developing countries such as the African countries, due to conflict, security, a lack of appropriate archives, and so forth. To mitigate these problems, this research utilized fine-scale remotely sensed imagery using the Google Earth software [47]. The accuracy assessment was divided into three steps:

1. Generating random reference points.
   Seven hundred random points for each classified map from Landsat5 in 2002 and Sentinel2A in 2018 were generated using the random point tools in ArcGIS 9. These points were converted from a shapefile into KLM format, in order to be imported to the Google Earth map interface. Then, we carefully scrutinized each point from the 2002 and 2018 classified maps for comparison with the corresponding point on Google Earth images in 2002 and our careful evaluation showed that 105 points were not appropriate for accuracy assessment due to their bring on blurred images (i.e., some Google Earth imagery, particularly prior to 2010, may not be of high quality); thus, these points were removed. A total of 592 points remained to assess the accuracy of LULC in 2002 and 2018.

2. Comparison between LULC maps and Google Earth images.
   We made a table in Excel with two columns: we classified LULC based on our framework and observed LULC on Google Earth. To accurately and reliably evaluate the classified LULC maps’ performance, this step was conducted blindly, whereby the reference points and Google Earth images were distributed among three experts in remote sensing, without revealing the name of the location and details of the procedure. They compared each point in the class with an actual feature in Google Earth and checked whether this point referred to the class of interest or to another class. The observed results were recorded in an Excel.

3. Calculating accuracy assessment metrics.
   The obtained results were subjected to three accuracy assessment metrics: producer accuracy percentage, the measurement of commission error, and the overall accuracy percentage. These metrics were calculated using the following formulas [48]:

   \[
   a = \frac{c}{\sum (p1 : p\Delta) \times 100}
   \]

   \[
   e = 100 - a
   \]

   \[
   o = \frac{\sum (c1 : c\Delta)}{(p1 : p\Delta)}
   \]
where $a$ is the producer accuracy percentage; $c$ is the pure class point; $p$ is the total raw point; $e$ is the measure of the commission error, and $o$ is the overall accuracy percentage (Figure 2).

![Figure 2](image-url)

Figure 2. Random points for the overall accuracy assessment of the water class in 2018.

2.8. Logical Framework

In this research, the qualitative analysis of land use status, as well as mathematical statistics, are employed. Mathematical analysis is used as a reasoning framework to achieve prediction; the commonly used instruments are the relative ratio and regression analysis prediction model [49]. The framework includes the 3S of LUC classified data, as a major method for identifying LUC patterns. Firstly, intervention logic analysis is used for linking the objectives that need to be pursued, or the problems that need to be tackled. In order to generate data on land use impact change, the intervention logic proceeded the impact structure, which includes output [50]. This study used the relative ratio model to quantify the sequence effects [51]. Eventually, the impacts of these data were classified as very high (S1), high (S2), moderate (S3), and weak (N1) (Table 3), according to the importance of the dam to society [52,53].
Table 3. Reference table codes of change phases in land use/cover change impact.

| Codes of Change Phases                                      |
|-------------------------------------------------------------|
| S1 | S2 | S3 | N1 | N2 |
|---------------------------------|
| Relative Ratio is higher than (100%) with high Change in services received by the end users. |
| Relative Ratio between (100–70) % with Sufficient change in services received by the end users. |
| Relative Ratio between (70–30) % with insufficient change in services received by the end users. |
| Relative Ratio between (30–1) % with weak change in services received by the end users. |
| Relative Ratio is less than 1% with decreasing in services received by the end users. |

The selection of evaluation reference standards is one of the key links in land-based ecological change [54]. There is no unified reference standard used for evaluation in Sudan. The evaluation reference standards that can be selected in this study mainly developed from the background value of the land ecological environment in the study area, taking this as the evaluation reference standard, for example, regional vegetation coverage, regional soil, and water loss background values, and so on (Figure 3).

Figure 3. Illustration of the methodological workflow scheme, including the logical framework adopted for this study.

2.9. Land-Use Change Analysis and the Spatial Dynamic

The study used the relative ratio of land use indices in the area in 2002 and 2018 to quantify the change trends before and after the construction of UASDC. This is illustrated by the amplitude of difference, area difference ratio, speed of spatial change, change trend index of regions, etc. The amplitude of variation is also known as the area of LUC.
types, which showed changes in the total number of different types; this is depicted mathematically as:

$$Rd = \frac{(Ua - Ub)}{Ua \times 100}$$  \hspace{1cm} (1)$$

where $Rd$ represents the spatial dynamic change (calculated amplitude of variation), $Ua$ and $Ub$ are the values of the area of single indices at the reference year and at the ending of the study periods [55]. The effects on LUC may be divided into two types of change: the first is the change of a single LUC and the second is the overall dynamics of LUCC. The first dynamics change reflects the spatial and temporal differences of a single LUC feature change; the second dynamics change is in LUCC for the overall study area. In the current study, we used the dynamics of single land-use change in order to generate the UASD’s effects on land use [56] (Figure 4).

![Figure 4. LUC output indices by the dam in (a) 2002 and 2018. (b) Optimal LUC map, illustrating the change detection in 2002 and 2018.](image-url)
3. Results and Discussion

3.1. Accuracy Assessment

The accuracy assessment was calculated using the methods of overall accuracy and producer’s accuracy; the overall accuracy was 94.9% and 93% for the classified images for the years 2002 and 2018, respectively.

The combination of remote sensing images and field survey data is used to improve the accuracy of the analysis of land-use change status [57]. Ideally, an accuracy assessment based on the field work and using GPS should be performed for the entire region and for each classified image [46]. However, such a procedure may be costly and difficult to acquire, particularly in the early period of change detection research. The advantage of this method consists of the utilization of remotely sensed data from other sources instead of in the field, which is costly and time-consuming. This method is an indicator of the reliability of RS image classification.

Understanding what causes the benchmark reference and map classification data to differ reveals more powerful uses for the map, as well as enabling the formation of better maps in the future [58]. The differences between the map and benchmark reference data will be as a consequence of one of the four following error sources:
1. Errors in the reference data.
2. Sensitivity of the classification scheme to observer variability.
3. Inappropriateness of the RS technology for mapping a specific LUC class.
4. Mapping error.

Errors 1 and 2 are the most easily addressed, whereas errors 3 and 4 are more difficult to correct.

By using remote sensing methods, including an accuracy assessment, four classes were analyzed. The number of random points (row total) in each class differs from the others due to variations in density and class area; a greater class area includes more random points. The study used Google Earth software, as well as ArcGIS, for making an accuracy check due to its higher resolution than in the study image data, in addition to the fact that familiarity in the area was reinforced to an identified purest pixel in the classification process (Table 4).

Table 4. Overall accuracy assessment data, 2002 and 2018.

| Year | Classification     | Class | Non-Class | Row Total | Producer Accuracy (%) | Measure of Commission Error (%) |
|------|-------------------|-------|-----------|-----------|-----------------------|---------------------------------|
| 2018 | Water             | 67    | 3         | 70        | 95.7                  | 4.3                             |
|      | Forest            | 84    | 6         | 90        | 93.3                  | 6.67                            |
|      | Crop land—HAS    | 74    | 6         | 80        | 92.5                  | 7.5                             |
|      | Crop land—SAS    | 82    | 8         | 90        | 91.1                  | 8.9                             |
|      | Column Total      | 307   | 23        | 330       |                       |                                 |
|      | Overall accuracy  | 93    |           |           |                       |                                 |
| 2002 | Water             | 55    | 5         | 60        | 91.7                  | 8.3                             |
|      | Forest            | 74    | 6         | 80        | 92.5                  | 7.5                             |
|      | Crop land—HAS    | 69    | 6         | 75        | 92                    | 8                               |
|      | Crop land—SAS    | 45    | 5         | 50        | 90                    | 10                              |
|      | Column Total      | 243   | 22        | 265       |                       |                                 |
|      | Overall accuracy  | 94.9  |           |           |                       |                                 |

3.2. Spatiotemporal Change Analysis of the Regional Situation in 2002 and 2018

In recent years, there has been an extensive theoretical discussion regarding improving the concept of land-use change and impact. Driving factors for ecological changes in this region include climate change, vegetation succession, soil processes, hydrothermal conditions, natural disasters, and socioeconomic factors [59]. Decades prior to the dam’s construction, the study area experienced severe drought and water scarcity problems, due
to the arid climate of the region, global climate change, and the weak management of water resources. After the dam’s construction, there were considerable changes that resulted with regard to the LUC and the socioeconomic domain.

The main water source in the region is the River Atbara and its tributaries of Setit and Upper Atbara, with an annual total discharge of 12 BmIt over other main sources is the monsoon, seasonal rainfall with normal average precipitation for the region of 578 mm, occurring from July to October, and with an intensity graded south- to northward, within a semi-arid climate zone [60]. As far as the temperature of the region is concerned, a high temperature with a low atmospheric moisture percentage prevails for most of the year; moreover, most of the land comprises plains, with limited obstacles for agricultural use and scattered acacia vegetation. The majority of the population live in the lands adjacent to the River Atbara, in 93 villages, where they have access to water for drinking purposes and other domestic needs. In the dry season, which spans 8 months of the year, the inhabitants also have access to limited fishing activities and family farming in small-scale horticulture. The main socioeconomic factors and the livelihoods of the majority of the locals depend on rain-fed agriculture and pastoral farming.

Land-use structure optimization is the core content of overall land use planning and is an important means to achieving the sustainable use of land resources [61]. The increasing pressure on limited agricultural lands and pastures and the decline in natural vegetation prior to dam construction are due to the increasing population and expanding urban areas (for example, the city of Kassala’s population increased by 81% from 2003 to 2018) and the arrival of thousands of refugees from the neighboring African countries. These were hit with a drought in the early 1980s, which resulted in the severe degradation of land coverage. Therefore, the demand for food, drinking water, power services, and environmental rehabilitation has increased several fold, especially in the area that has a long border with Ethiopia and Eritrea [62]. Due to the construction of the dam in 2015, the availability of water in the study area has increased severalfold; the water is utilized for municipal purposes, agriculture, fishing, and hydroelectric power generation (Figure 5).

![Figure 5. (a) Dam site. Prior construction, (b) completion of the water infrastructure, 2013–2015.](image)

3.3. The Quantification of the Impact of Dam through Observation and Statistical Data Analysis

Land use structure optimization includes quantitative structure and spatial structure. The land use’s spatial layout should be the spatial implementation of the quantitative structure, which together reflect the regional land use’s structure regulation [63]. Several advantages have been observed in the region after the construction of the dam, like improvements in the socio-economic domain and significant changes in the LUC indices, particularly in the water and forest classes.

In this respect, the water body increased by 244.6% in the forest area increased by 338.3 km², with a forest buffer distance of 1, 2 and 3 km, respectively. The study used the buffer method in ArcGIS to detect the forest land distribution around the water class. Accordingly, an increase in the amount of water in the dam lake induced changes in the other land use indices. Moreover, a change in the cropped area from 1341 km² to 3013.5 km² in HAS and from 81 km² to 2564.7 km² in SAS, between 2002 and 2018, respectively, is also
observed. Instead of using the wells for drinking water, the study result indicated that the dam ensured the provision of adequate and safe drinking water of up to 75,000 m³/day to the city of Gadaref through 70 km of pipeline from the dam area. In addition, 11 modernized resettlement villages were constructed to replace those old villages that were affected totally or partially by dam construction. The urban area of Kassala increased by 81% after the dam was constructed, followed by 17% for the city of Gadaref, 34% for Girba, and 18% for the city of New Halfa (Table 5) (Figure 6).

Table 5. The logical chain of the dam’s impact on land cover.

| Intervention Logic | Output | Specific Objectives | Impact |
|--------------------|--------|---------------------|--------|
| Index/sub index    | Indicators | 2002 | 2018 | Alteration (km²) and (Relative Ratio (%)) | LIPC | Validity |
| Dam region         | Water class Area (km²) | 179 | 437.6 | 258.60 (>100) | S1 |
|                    | Forest land (km²) | 7861 | 10,584 | 2723 (34.64) | |
| Downstream         | Irrigated land (HAS) km² | 1340.77 | 3013.5 | 2672.58 (>100) | S1 |
| Effects on land cover | Irrigated Land (SAS) km² | 81.25 | 2564.78 | 2483.53 (>100) | S1 |
| Kassala            | Canals (SAS) km | 0 | 70 | 70 (>100) | S1 |
| Gadaref            | | 66.51 | 78 | 54.01 (81.73) | S2 |
| Shwak              | | 18.48 | 21.79 | 3.31 (18) | S3 |
| Girba              | | 3.77 | 4.98 | 1.21 (32.1) | S3 |

Figure 6. (a) Output and outcome of the dam. (b) Water class change, change in crop area.

3.4. Detailed Case Study of Land Use/Land Cover Change and the Impact of the Dam Up/Downstream

The basic function of the land is to support human beings and maintain the ecosystem [64]. The land also has the means to store wealth, produce biomass, balance the storage and flow of surface water, preserve history, provide or restrict biological migration, and other functions. The output of this can be translated into a significant change in water class and the increase of vegetated lands after the construction of this dam, which represents a key advantage [65] (Table 6).
Table 6. The dam’s impact on public infrastructure.

| Intervention Logic | Output                          | Specific Objectives | Impact            |
|--------------------|---------------------------------|---------------------|-------------------|
| Index/sub index    | Indicators                      | 2002 | 2018 | Alteration and (Relative Ratio (%)) | LIPC | Validity |
|                    |                                 |        |      |                                 |      |
| **Dam region**     | Hydroelectric power (MW)        | 0     | 320  | 320 (>100%)                      |      | Statistics data |
|                    | Resettlement modernistic        | 28,394 | 30,000 | 1606 (5.66)                      | S1   | Statistics data/Google Earth |
|                    | Roads (km)                      | 0     | 183  | 183 (>100)                       |      | Statistics data |
|                    | Bridges                         | 0     | 2    | 2 (>100)                         |      | Statistics data |
|                    | Airport                         | 0     | 1    | 1 (>100)                         |      | Statistics data |
|                    | Gadaref Drinking water          | 0     | 70   | 70 (>100)                        |      | S1 |
| **Downstream**     | pipeline (km)                   |        |      |                                 |      |
|                    | Gadaref Drinking water          | 0     | 75,000 | 75,000 (>100)                  |      | Statistics data |
|                    | discharge (m³/day)              |        |      |                                 |      |
|                    | Upper water tank in Girba Dam   | 0     | 10,000 | 10,000 (>100)                  |      | Statistics data |
|                    | Storage Capacity                | 0.6   | 1.3  | 0.7 (>100)                       |      | Statistics data |

The outcome stage showed that multiple services were received by the end-users in the region, including prospective effects on land cover, basic infrastructure improvements, and other services. The transition of the forest class area refers to the increasing vegetation area in the region, especially after creating a second and third forest buffer zone around the water body (Table 7) (Figures 7 and 8).

Table 7. Forest buffer zone around the water class, 2002 and 2018.

| Zone km | Vegetation (km²) 2018 | Buffer Change % | Alteration km² | Vegetation (km²) 2002 | Vegetation Change (%) |
|---------|-----------------------|------------------|----------------|-----------------------|-----------------------|
| 1       | 1503.491              | 0                | 330            | 1164.24               | 0                     |
| 2       | 2188.88               | 45.59            | 391            | 1797.90               | 54.43                 |
| 3       | 2089.35               | 38.97            | 393            | 1796.18               | 54.28                 |

Figure 7. Forest buffer zone and water class. (the buffer in 2002 and the buffer in 2018).
Ecological compensation refers to the sensitivity and resilience of natural ecosystems to disturbances [66]. Later, this gradually evolved into socioeconomic means and mechanisms to promote societies and ecological environmental protection. The government also performed its social responsibility to mitigate the adverse effects of the dam [67]. For instance, 30,000 new housing units were constructed concurrently with the construction of the dam and were distributed to 11 resettlement villages, accommodating 28,000 families who were affected by the construction of the dam and who were also provided with safe, adequate, and accessible drinking water and electricity services.

In addition, in order to save the history of the area, a team working on heritage studies has published 5 books that narrate the history of the community whose villages were submerged by the dam’s reservoir. The construction of the dam also increased clean power generation by 320 MW of electricity to the national network for use inside and outside the study area region. Moreover, the construction of the dam provided safe, adequate, and accessible drinking water to the Gadaref inhabitants and to all villages lying along the banks of the River Atbara. After the construction of the dam, new roads were constructed with a length of 175 km, which connect the 11 resettlement villages with the continental highway of the Port of Sudan, which goes to different parts of Sudan. Social services, in the form of two bridges and one airport, were also constructed near UASDC on the Atbara and Setit river as one of the dam’s aims to facilitate people’s movement. These services mitigated the dam’s side effects from a socioeconomic aspect and strengthened the social stability in the region.

The land use balance should be based on the rational and sustainable development, utilization, governance, protection, and management of land resources under specific circumstances and regional conditions, to achieve the balanced development of regional society, the economy, resources, and environment [68]. Dams change the hydrological behavior up- and downstream due to changes in water velocity, water depth, and canal bed width, in addition to changes in water quality. This dam retains backwater to a distance of 75 km, submerging some indices of ancient villages, horticultural land, and riverbank ecology.

During the construction of the dam, the study found that almost 36 villages and 580 Hectare of horticultural farmland around the riverbanks have totally or partially disappeared. The extent of such floods includes the loss of the historical heritage of the societies who live beside the riverbank and the loss of their income-generation source via farming activities. One of the goals of realizing land ecosystem security is to protect the human living environment by maintaining and improving the land ecosystem service functions [69]. Maintaining ecosystem service functions is the most basic guarantee of sustainable ecosystem security [70]. Consequently, the horticultural land downstream depended on pumping irrigation water at a specific level before the dam’s construction in 2015, which changed after the construction of the dam; in addition, the water was reduced in the lake of the ancient Girba Dam, downstream.
In the downstream area, the water flow decreased due to retaining the river discharge as dam backwater. This increased the pumping cost due to changing to higher capacity pumps, in addition to needing an additional power supply. This change increased the total production cost. The fishing and farming activity increased in the upstream area, especially around the dam lake in the recession and dry seasons. These changes in environmental features will take a long time to become evident after the construction of the dam, especially for groundwater and near aquifers up- and downstream, as well as changes in ecosystem types [71].

3.4.1. Overall Objective of the Dam

Land-use planning is an important regulation and control measure for implementing sustainable land use strategies, and the core content of land-use planning is the optimal adjustment of land-use structure [72]. The optimization of land use structure is intended to achieve certain optimal economic, social, and ecological goals. According to the evaluation of the characteristics and suitability of land resources, the land use types in the region are more rationally and spatially arranged, to improve the land. Using efficiency to maintain the relative balance of land ecosystems and achieve the sustainable use of land resources, the core of land use planning is the adjustment of quantitative structures and spatial layout. Logically, the dam’s impact differs from the output and outcome; however, the overall impact can be attributed to the dam’s construction [73].

Accordingly, the increase in food production, income source, and food security improved by up to >100% by increasing the irrigated agricultural land in the region, especially in the Sitit Agricultural Scheme (SAS) and Halfa Agricultural Scheme (HAS), where the correlation increased between farmers’ associations and other agricultural entities. The housing standard has been improved by the accessibility of adequate and sufficient electricity in the resettlement villages. All these advantages highlight the importance and significance of hydroelectric power to a modernized life, the economic boom, national prestige, and technological advancement [74].

The increase in the water body led to an increase in fisheries activity and food security improvement. Fish is a rich source of proteins and a food source that is essential for the dietary needs of humans in the area and for daily supplies to the local and external markets. This change is considered to be very significant, according to the LIPC reference table.

Before the construction of the dam, the people of the city of Gadaref were experiencing a shortage of accessible drinking water; however, after the construction of the dam, the inhabitants of Gadaref have been given access to clean, adequate, and sufficient water (>100% of water provision). The total water supply per year to the city of Gadaref is 75,000 m³, and the average water consumption standard for safe and drinking water in Sudan per appliance is 86.4 L/person/day [75]; the daily consumption reached 38,880 L/day, which represents 52% of the total water supply for the 450,000 inhabitants of the city of Gadaref, while the remaining 48% is used for other municipal purposes and future expansion. In addition to that, drinking water has become accessible and safe for the inhabitants of Gadaref, Kassala, and the villages along the River Atbara area. Consequently, due to the provision of drinking water, public health, water prices, and the quality of water were improved (Figure 9).
According to the technical specifications of the evaluation method, when using satellite remote sensing image interpretation data and regional environmental statistics, the weighting of the ecological environment assessment is determined by five aspects, i.e., biology, vegetation, water network, land, and environmental pollution. Despite this, environmental changes take a long time; the forest features have moderately increased, which is an indicator of a change in the annual rainfall rate. In addition, such an increase reduces gas emissions and reactivates the ecological function relating to vegetation coverage [76]. Consequently, harvesting Gum Arabic from Hashab and Taleh acacia trees increased as a part of the livelihood activities of the local community. The evaporation and evapo-transpiration rates have increased due to the greater water surface area and increase in forested land in a region with an arid and semi-arid climate [77], which could be influencing the precipitation patterns in the region [78].

Since 1996, urban land use planning research has received considerable attention. The new land management law clearly states that overall urban planning should be linked to overall land use planning [79]. The urban zone in the region has experienced expansion since 2018 due to improvements in basic services and infrastructure. This change has been categorized as very high, according to the LIPC reference table. However, the overall impact of the dam was analyzed by LIPC as a new assessment framework, and the result showed 51 indicators that were classified as S1, 2 indicators classified as S2, and 7 indicators classified as S3 (Table 8) (Figure 10). Eventually, these changes in settlements led to changes in social affairs, the writing of novels, interest in the history of the affected area, and the collecting of heritage and artifacts, including folklore and popular culture in the area.
Figure 10. The overall impact of UADC on land use/cover.

3.4.2. Dam-Related Livelihoods and Enabling Community Resilience

Rationally, using the scarce land resources to meet the area’s productivity, safety, protection, feasibility, and social affordability needs is still a problem. Social responsibility has almost always been accompanied by the support of livelihood assets as an outcome of this dam [80]. However, as a social responsibility, the government supports those who have lost their homes and income sources by the provision of tools for subsistence, which include fishing facilities tools, agricultural tools, public sanitation equipment, and boats for transport across the rivers (Table 9).

Table 9. Development of community assets from the dam construction, through social responsibility.

| Intervention Logic | Output                  | Outcome   | Specific Objectives | Impact                   |
|--------------------|-------------------------|-----------|---------------------|--------------------------|
| Social responsibility | Livelihood              | Indicators | 2002 | 2018 | Alteration/(Relative Ratio %) | LIPC | Validity |
| Tractors           | 0                       | 96        | 96 (>100)           | S1                        |
| Disc plough        | 0                       | 96        | 96 (>100)           |                           |
| Fuel tanker        | 0                       | 24        | 24 (>100)           |                           |
| Drinking water tanker | 0                | 34        | 34 (>100)           |                           |
| Trolley for sanitation | 0               | 24        | 24 (>100)           |                           |
| Fishing Boat       | 0                       | 50        | 50 (>100)           | S1                        |
| Fish production    | 2                       | 1700      | 1698 (>100)         |                           |
| Ton/year           |                         |           | Statistics data     |                           |
| Loader             | 0                       | 2         | 2 (>100)            | S1                        |
| Furry              | 0                       | 3         | 3 (>100)            |                           |
| Bantoon            | 0                       | 1         | 1 (>100)            | Overall Accuracy assessment |
| Drinking water supply/day within 20 years | 0 | 346.7 m³/day | 346.7 m³/day (>100) |

The improvement of social services can be witnessed in educational institutions, security centers, and hospitals; this change led to an increase in the population around the area served by the well. Paved roads were constructed, which increased the transportation links even in the rainy season, thus increasing the social and economic movement from the area.
neighboring region (Table 10). Negative effects were observed for the dam construction, which included the submerging of villages due to dam backwater and the loss of archeological features. Moreover, the water-pumping cost increased for the horticultural land that was upstream, due to flow reduction from the dam construction, causing an imbalance of water flow between upstream and downstream areas.

Table 10. The effects of the Dam on public services through Social responsibility in UASDC.

| Social responsibility | Infrastructure and facilities | Index/subindex | Indicators | 2002 | 2018 | Alteration/(Relative Ratio %) | LIPC | Validity |
|-----------------------|-----------------------------|----------------|------------|------|------|-------------------------------|------|----------|
|                       |                             | Houses         | 28,394     | 30,000| 1606 (5.7) |                               |      |          |
|                       |                             | Drinking Water pipes line m³/day | 0 | 342 | 342 (>100) |                               |      |          |
|                       |                             | Electricity (subscriber) | 0 | 30,000 | 30,000 (>100) |                               |      |          |
|                       |                             | Primary schools | 18 | 100 | 82 (>100) |                               |      |          |
|                       |                             | Higher secondary school | 3 | 56 | 53 (>100) | S1 |          |
|                       |                             | Hospital/health center | 2 | 11 | 9 (>100) |  |          |
|                       |                             | Mosques        | 7 | 23 | 16 (>100) | Statistics data | |
|                       |                             | Social services center | 6 | 14 | 8 (>100) |  |          |
|                       |                             | Police office/station | 5 | 11 | 6 (>100) |  |          |
|                       |                             | Courts         | 1 | 2 | 1 (100) |  |          |
|                       |                             | Attorney General | 1 | 3 | 2 (>100) | S2 |          |
|                       |                             | School teachers’ houses | 21 | 22 | 1 (4.8) | S2 |          |
|                       |                             | Doctors’ rest house | 0 | 11 | 11 (>100) | S1 |          |
|                       |                             | Security office | 2 | 2 | 0 (<1) | S3 |          |
|                       |                             | Drinking water services | 0 | 4 | 4 (100) | S1 |          |
|                       |                             | Administrative unit | 1 | 2 | 1 (100) |  |          |

4. Conclusions and Recommendation

Overall, this study concludes that the dam is an auxiliary of the decision-making of planning schemes to improve the level of land use planning, through the stimulation of agricultural production, manufacturing, and the provision of basic services. The basic goal of the LUCC study is to improve human understanding and the prediction of the dynamic processes of the region. The multipurpose dam construction generated impacts in multiple aspects, which include environmental, economic, social, and public services. Consequently, the LUC indices have different values of impacts according to the spatiotemporal change results; generally, the UASDC has had a very high impact according to the results and LIPC reference table. The environmental effects are exemplified by the increasing forest area, which reduces air pollution. This change can be attributed to the influence of the dam on climate factors, especially on the rainfall rate and the evaporation of water from the lake. In addition, the local population can utilize forest resources and products as income sources, including charcoal-making, firewood, and wood for house building. Limited adverse environmental effects were observed from the construction of the dam, such as damage to villages and farms, due to the water rising and submerging large areas around the dam.

Increasing the irrigated land in HAS and SAS has led to an increase in agricultural production, which will further encourage agriculture, livestock-rearing, and the manufacturing, for example, of wheat flour, cooking oil, and milk products. This will further increase peripheral agricultural services activity, including veterinary services, fertilizers, pesticides, agricultural mechanization equipment, and consultancy; also, job opportunities would be created in the manufacturing and agricultural sectors. On the other hand, clean energy is characterized as having a low cost of operation and is environmentally friendly and sustainable. The overall impact of the power of its provision would support the manufacturing sector, not only for domestic use but also in the production process, as well as the provision of water for municipal use. Finally, this research innovates by employing a new
method for impact assessment and evaluation, as seen with regard to the importance of the hydrological infrastructure to the society and environment in the arid region examined in this study.

Future research directions might focus on the impact of the reservoir on the climate indicators in the region, groundwater level, and water management. However, the dam’s water surface is exposed to high temperatures in the dry season that can reach up to 44 °C with a northeast wind in the summer season. Therefore, the evaporation as well as the humidity would be increased, which may influence climate factors. Other changes may happen due to the reservoir’s impact on groundwater, which suggests prospective research topics about the influence of the dam on groundwater. Future research may also be undertaken on climate change and changes in the ground aquifers throughout the region.

This study recommends increasing support for the various agricultural production institutions and encouraging producers by adding value to their products, facilitating, and supporting farmers. In addition to the use of agricultural mechanization at various cropping stages, the provision of training for post-harvest processing in order to maximize production is also recommended. Finally, the authors recommend future research into water management to coordinate the resulting socioeconomic trends and manage the efficient use of water without compromising the sustainability of a vital ecosystem.

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