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Estimates of Sudan's historical water withdrawals from the Nile

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ABSTRACT

Lacking reliable information on water withdrawals in the Nile Basin poses a major challenge for efficient water management. The annual amount of water withdrawn from the Nile in Sudan has been a notable research gap, with implications for various aspects. In the current research, we employed three methods to estimate the historical water withdrawals of Sudan from the Nile. These methods are based on (i) closing water balance by using river discharge and evaporation losses from surface water bodies, (ii) estimating incremental evapotranspiration through satellite information, and (iii) accounting for water needed for domestically-produced agricultural commodities. The results indicate that Sudan's water withdrawal from the Nile has increased substantially over the last decades. The highest magnitude of water withdrawal was observed during the last decade (2011–2020). Depending on the method used, this estimate ranged, on average, between 16.0 ± 2.2 km^3 and 17.8 ± 1.3 km^3. Given Sudan's ambitious plans to expand the irrigated croplands horizontally, this upward trend in water withdrawal is likely to continue. To cope with the expected limitation in water resources, Sudan should adopt a vertical development pathway in the agricultural sector that prioritizes enhancing water use efficiency and improving crop productivity. The current research findings have immediate and far-reaching implications for the mode of development in the water and agriculture sectors in the country and transboundary water management.

1. Introduction

Water is a basic resource to sustain life and development. This vital resource is increasingly becoming limited, pushing the world to enter a new era of water scarcity (Postel, 2000). Besides being a limited resource, the increasing global demands for more food production and energy generation are rising the demand for water dramatically. Moreover, external drivers such as climate change are affecting the limited water resources, endangering the lives and livelihoods of millions of people (Pardoe et al., 2018).

A river basin is a basic unit for water management (Zhang et al., 2018). There are numerous river basins of varying sizes around the world, with many crossing political boundaries. Globally, there are 310 river basins shared between two or more countries (McCracken & Wolf, 2019) and an unknown number of shared groundwater basins. Management of transboundary water is one of the greatest challenges that face future water development (Tayia, 2019). In such basins, using the shared water resources might be a major source of tension and conflict, since unilateral actions can harm other riparian countries, especially those located downstream (Kasymov, 2011). Farinosi et al. (2018) have identified the Nile, Ganges/Brahmaputra, Indus, Tigris/Euphrates, and Colorado River basins, among others, to be the future hot spots for transboundary disputes, which are more likely to occur due to future demographic and climatic changes.

This challenge is more complex under uncertainty imposed by lacking continuous records of observations of water cycle components (e.g. rainfall, evapotranspiration, and river discharge) and improper monitoring of water withdrawal. The lack of reliable estimates of water withdrawals is jeopardizing sustainable water resources (Puy et al., 2022). This is a critical issue, especially in the agriculture sector which accounts for the majority of global water depletion. It is especially pronounced in developing countries, where water withdrawal is not monitored continuously, posing serious challenges for water planning, management, and development (Hoogeveen et al., 2015). The complexity of this challenge is further amplified in transboundary settings, making water sector management and development an arduous task (Tayia, 2019).

According to literature, there are many methods for estimating water withdrawals. These methods vary according to source of water, either surface (van Eekelen et al., 2015) or groundwater (Meza-Gastelum et al., 2022; Shao et al., 2014), and the water use sector under consideration such as agricultural (Puy et al., 2022), industrial (Fujimori et al., 2017),

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and municipal (Yan & Jia, 2023). The determination of water withdrawal can be done directly through monitoring gauges as well as indirectly utilizing various variables to approximate water withdrawals. Martindill et al. (2021) provided an example of estimating agricultural groundwater withdrawals in California indirectly using energy data as a proxy for groundwater extraction. Studies on water withdrawal estimates are conducted spatially at different scales: global (Alcamo et al., 2003), transboundary river basin (van Eekelen et al., 2015), national (Nikiel & Eltahir, 2021), regional (Wei et al., 2022), and field (Filippelli et al., 2022). While some studies follow simple approaches using, for instance, river discharge data (Abdellatif, 2017) and accounting for agricultural production as a proxy for water abstraction (Nikiel & Eltahir, 2021), others adopt up-to-date technologies such as remote sensing (van Eekelen et al., 2015; Filippelli et al., 2022; Wei et al., 2022), and apply advanced artificial intelligence and machine learning algorithms (Majumdar et al., 2020; Wei et al., 2022). The choice of the method to estimate water withdrawals considers multiple issues, including data availability, scale of analysis, the complexity of the system, and other relevant considerations.

The Nile River Basin is a typical example of the aforementioned complex challenge. In the Nile, the transboundary dispute is coupled with a severe lack of monitoring of water withdrawals. The transboundary dispute in the Nile Basin has recently intensified as a result of the increasing demand for water to satisfy the riparian countries' needs for socio-economic development. Without a comprehensive and inclusive water treaty that involves all the riparian countries, unilateral actions may further escalate existing disputes. The ongoing transboundary conflict between Ethiopia, Sudan, and Egypt concerning the Grand Ethiopian Renaissance Dam (GERD) represents the most significant and recent manifestation of the Nile dilemma. This dispute has resulted in a deep mistrust between the three countries and a shortfall in proper cooperation over the Nile waters. In addition, there is a lack of operational frameworks that promote a regular and adequate exchange of data and information, including the 1959 bilateral agreement between Sudan and Egypt (Swain, 2011).

The issue of Sudan's water withdrawals from the Nile is contentious and has received little research attention, carrying significant local and transboundary implications that impede efficient management of the Nile water. This is mainly because of the lack of reliable, independent, and transparent estimates of gauged and ungagged diversions (Wheeler et al., 2020). While numerous studies have repeatedly reported estimates of Sudan's water withdrawals from the Nile (Fig. 1), none of these studies have provided information on the underline assumptions and methodologies employed to generate these figures. The annual water withdrawal by Sudan from the Nile during the last decades is reported in these studies to be between 12.5 km^3 and 19.0 km^3, depending on the timeframe (Blackmore & Whittington, 2008; Merem et al., 2020; MIWR, 1999; Mohieldeen, 2016; Multsch et al., 2017; NBI, 2016; Omer et al., 2015; Pacini & Harper, 2016; Salman, 2011; Wheeler et al., 2018; Yimer, 2015). The wide range of estimates has serious implications, especially for Sudan's ambitious plans to expand irrigated agriculture horizontally by developing new irrigated schemes along the Nile tributaries. With its large arable land resources, some researchers suggest water availability be the limiting factor for agricultural development in Sudan rather than land (Ahmed & Ribbe, 2011).

Despite the significance of this topic, this subject has received little attention from researchers. The systematic estimation of water withdrawals from the Nile, particularly in Sudan, using transparent and replicable approaches, remains a significant knowledge gap. The primary research questions in the current research revolve around quantifying water withdrawals in Sudan from the Nile, relying mostly on public-domain data and replicable and transparent approaches, as well as investigating whether different estimation methods yield similar results. Thus, the objective of the current research is twofold: (i) to provide independent and neutral estimates for the Nile withdrawals of Sudan over the past decades, and (ii) to compare water withdrawal estimates obtained by different methods. The novelty of this study lies in the utilization of three distinct methods with varying data and underlying assumptions to estimate Nile water withdrawal in Sudan. Such a comparative analysis of different estimation methods has not been conducted for Sudan or other Nile riparian countries. The findings of this research offer valuable insights to enhance transparency and facilitate improved management, planning, and development of water resources in Sudan and the wider Nile Basin.

2. Materials and methods

2.1. Sudan and the Nile Basin

The Nile Basin is one of the largest transboundary basins worldwide, covering an area of around 3.18×10^6 km^2 (Wheeler et al., 2018). This represents nearly 10% of the total area of the African continent (Barnes, 2017). The Nile river originates from two main sources: the Blue Nile and the White Nile. The Blue Nile originates from the Ethiopian

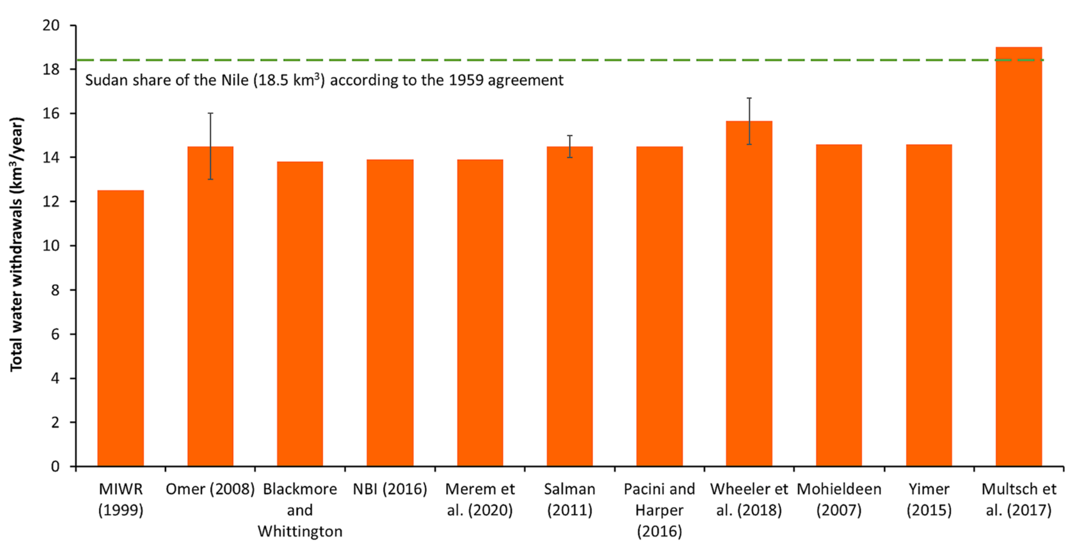

Fig. 1. Total Nile withdrawals in Sudan as reported in the literature. According to these literature, Sudan's Nile withdrawals range between 12.5 km^3/year and 19 km^3/year.

highlands, while the White Nile originates from the Equatorial Lakes region. The basin is shared by 11 countries, namely, Burundi, the Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda (Fig. 2). The upstream riparian countries enjoy significant rainfall, whereas downstream regions, i.e., most of northern Sudan and Egypt receive minimal rains. The historical annual flow of the Nile, measured at Aswan (southern Egypt) is 84 km^3 (Haynes & Whittington, 1981). However, several studies indicate an increasing trend in the average Nile flow, with flow volumes surpassing historical levels in recent decades (Abdelkader et al., 2018; Siam & Eltahir, 2017; Senay et al., 2014b).

On November 8th, 1959, Sudan and Egypt concluded and signed a bilateral agreement for the "Full Utilization of the Nile Waters". According to this agreement, Sudan and Egypt divided the entire Nile outflow reaching Aswan in southern Egypt between them. Egypt was allocated 55.5 km^3 and Sudan received 18.5 km^3, while the remaining 10 km^3 was allocated to account for evaporation losses from Lake Naser (Cascão, 2008). This agreement is not recognized by the other countries located in the Nile basin. Nikiel & Eltahir (2021) estimated Egypt's water withdrawal from the Nile exceeds the perceived share of 55.5 km^3 by 8–10 km^3, which includes a portion of Sudan's unutilized share and the increases in the Nile flow gained during the past decade (Senay et al., 2014b). There have been debates between Sudan and Egypt regarding the accurate measurement of Sudan's actual water withdrawals from the Nile. Additionally, the handling of evaporative losses from Sudan's reservoirs is another source of controversy.

As development activities in the upstream countries of the Nile basin intensify, there has been a significant surge in the demand for Nile water. The bilateral agreement reached in 1959 did not account for this substantial rise in the demand for the Nile water in upstream countries. Under the umbrella of the Nile Basin Initiative (NBI), a new Cooperative Framework Agreement (CFA) has been developed. It has already been signed and ratified by many riparian countries. However, Sudan and Egypt have expressed strong reservations towards the CFA, mainly because they believe it does not respect their historical water rights established in the 1959 bilateral agreement, as both countries argued.

Sudan is located in the central part of the Nile basin (Fig. 2), and the Nile water serves as the primary water resource for a significant portion of the population and agricultural activities in the country. The three main tributaries of the Nile, namely Blue Nile, White Nile, and Atbara meet inside the country to form the Main Nile, which then flows northward towards Egypt (Fig. 2). To satisfy the growing demand for water, energy, and food, Sudan has constructed several multi-purpose dams with varying storage capacities (Supporting information file: Table S1). They have substantially increased the storage capacity, agricultural production and hydropower generation capabilities in the country. However, these dams are facing a critical issue of declining storage capacities. It is reported that many of these dams have already lost anywhere between 8% to 60% of their storage capacities over the years due to sedimentation generated by land cover changes in the Ethiopian highlands (Adam & Suleiman, 2022; Ali et al., 2018; Omer et al., 2015). Most of the water withdrawal in Sudan (around 96%-97%) is taking place in the agricultural sector (Mahgoub, 2014; Ritchie & Roser, 2017). Cereal crops such as sorghum, millet, and wheat dominate the cultivated area in the country (Khalifa et al., 2021).

2.2. Methods

2.2.1. Calculation of water withdrawals

In the current research, three approaches were employed to estimate Sudan's water withdrawal from the Nile (Fig. 3). The first approach was based on estimating water balance by utilizing data from discharge stations and subtracting evaporation losses from open water bodies. The second approach involved using actual evapotranspiration measured by satellites as a proxy for water withdrawal. The final approach utilized the Blue Water Footprint (BWF) of domestically produced agricultural commodities to indirectly account for water withdrawal. The estimates obtained from these three methods were assessed and compared to establish correlations between them.

2.2.1.1. Determine water withdrawals using the water balance method. In this method, we utilized annual measurements of flow for the main gauged rivers and estimates of evaporative and non-evaporative losses, using equations (1) and (2). The approach focused on determining water depletions by considering the balance between inflows, outflows, losses, and withdrawals in Sudan. Sources of major losses include evaporation from open water surfaces (e.g., dam reservoirs and river channels), infiltration into groundwater, and water withdrawal. While inflows and outflows were accounted for from eight stations located at different reaches along the Nile in Sudan (see section 2.3.1), we accounted for

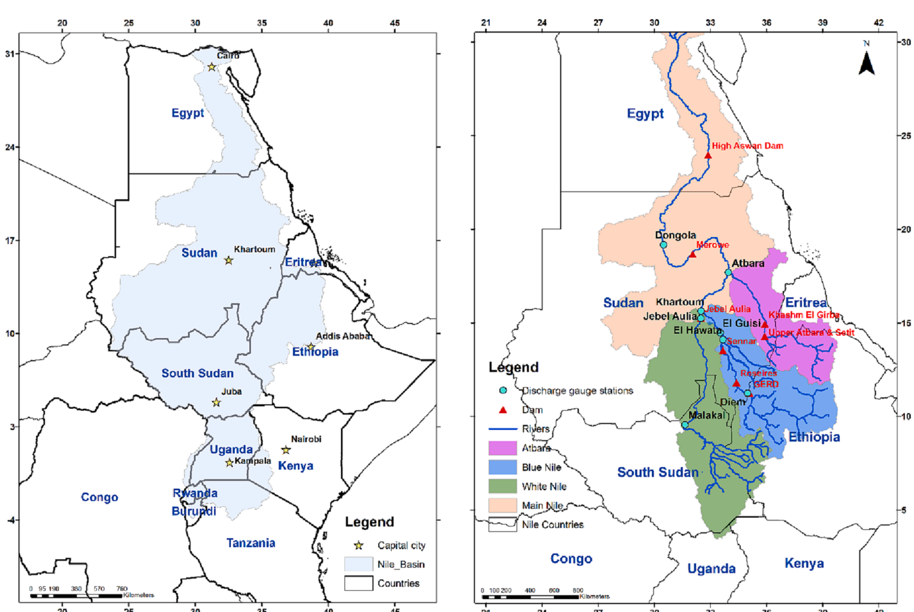

Fig. 2. Maps of the Nile Basin: boundaries of Sudan, neighboring countries and the Nile River Basin in light blue shading (left), and some of the Nile sub-basins, rivers, dams, and the discharge gauge stations that were utilized in the current study (right).

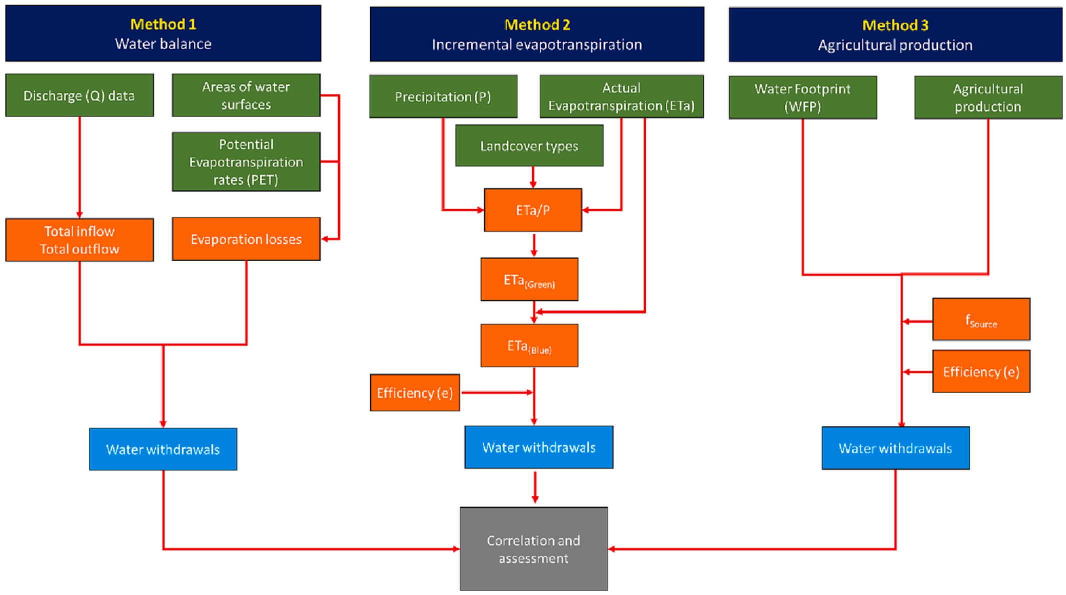

Fig. 3. Flowchart of the methodological approaches adopted in the current study. The current investigation employed three different methods using multiple datasets.

evaporation losses using the information on areas of water bodies and the corresponding Potential Evapotranspiration (PET) rates.

$$Inflow - Outflow - Losses = 0 \quad (1)$$

or, equivalently

$$\sum Q_{in} - \sum Q_{out} - ET - L - W = 0 \quad (2)$$

where Q_{in} is the inflow, Q_{out} is the outflow, ET is the evaporation losses from open water surfaces, L is all other non-evaporative losses and W is the water withdrawal. Among other assumptions we adopted for the current study (Table 1), we assumed non-evaporative losses other than groundwater recharge to be negligible. For total Sudan's withdrawal, we used equation (3), in which the river discharge estimated at the Dongola station (Fig. 2) represents the spot for Sudan's outflow, while all other stations of Atbara, Diem, and Malakal account, respectively, for the inflows from Atbara, Blue Nile, and White Nile sub-basins, the main Nile reaches in Sudan. Besides, small inflows from Rahad and Dinder streams - two small tributaries of the Blue Nile River - were incorporated into the estimated inflows.

Table 1
Underline assumptions adopted in the current study.

Method	Assumptions
Method 1	- Non-evaporative losses other than losses to groundwater are negligible - To account for inter-annual changes in evaporation losses, we used three estimates of reservoir areas (most reliable, minimum, and maximum). - Groundwater losses rnage between 1 and 4 km^3/year (FAO, 2022a; Mohamed et al., 2017). - Timeframe: 1927–2005
Method 2	- Cropping intensity = 157.3% (FAO, 2022b) - Irrigation efficiency = 0.48–0.65 (Al Zayed et al., 2015; Hamid et al., 2011; Multsch et al., 2017) - Timeframe: 2003–2020
Method 3	- Water consumption: 96–97% of Sudan's water consumption is taking place in the agricultural sector (Mahgoub, 2014; Ritchie & Roser, 2017) - Source of irrigation water: 96% from surface water (FAO, 2022a) - The irrigation efficiency range: same as method 2 - Timeframe: 1971–2020

$$W = (Q_{Malakal} + Q_{Atbara} + Q_{Diem} + Q_{Rahad} + Q_{Dinder}) - (Q_{Dongola}) - ET - L \quad (3)$$

To estimate water withdrawal in each sub-basin individually, we applied a similar approach by using the corresponding upstream and downstream discharge stations. Specifically, this involves using Diem and Khartoum stations for the Blue Nile Basin, and Malakal and Jebel Aulia stations for the White Nile. Due to data quality issues in the upstream discharge stations in Atbara and Main Nile sub-basins, we calculated water withdrawal for these two sub-basins together by closing the water balance after estimating the total water withdrawal of the country.

We used three different estimates for dam reservoir areas: most reliable, minimum, and maximum estimate to account for water evaporation. This enabled us to calculate water withdrawal as a range rather than a single value, accounting for any possible uncertainties in evaporation losses.

The estimated water withdrawal was compared to the withdrawal information reported by Deltares (2012), which is one of the few sources that provide time series of water withdrawals in Sudan from the Nile with detailed descriptions of the methods used. This comparison was carried out for the overlapping period between the two studies, i.e. 1960–2005. By comparing our estimates to the data from Deltares, we aimed to evaluate the accuracy and reliability of our withdrawal estimation during this specific time period.

2.2.1.2. Estimating water withdrawal using incremental evapotranspiration (ETa) approach. This method relies on the concept of incremental ETa. It assumes that when ET in a given area exceeds P levels (P-ET < 0), the incremental ETa that exceeds P amount can be attributed to additionally applied water (surface and/or groundwater) quantities. The approach is based on the methodology described by van Eekelen et al. (2015). In rainfed agriculture regions, the dominant component of ETa is mainly green water (ET_{green}). By utilizing information on ET_{green} in rainfed areas, we can approximate ET_{blue} over irrigated areas. As crop types cultivated under rainfed and irrigated schemes in Sudan might be different, this might induce some uncertainties in withdrawal estimates. The data available for the current research did not allow for the differentiation of crop types cultivated under each system. However, as our focus is on regional approximation rather than local estimates for individual crops, adopting this approach is deemed valid, as demonstrated by previous studies (van Eekelen et al., 2015).

To estimate ET_{blue} in irrigated areas, we followed a series of calculations. Firstly, we calculated the ETa to P ratio in rainfed areas. This fraction was then multiplied by the average P over irrigated areas to approximate ET_{green} in those areas. Subsequently, we used equation 4 to calculate ET_{blue} as a difference between the total ET and ET_{green} in the irrigated regions. To account for irrigation efficiency (*e*), we divided $ET_{incremental}$ (or ET_{blue}) by Water Use Efficiency (WUE) using equation 5. WUE in Sudan is relatively low compared to other countries (Al Zayed et al., 2015), and its value can vary spatially and temporally. To account for this variation and test the sensitivity of our results, we incorporated three WUE values of 0.48, 0.54, and 0.65 (Al Zayed et al., 2015; Hamid et al., 2011; Multsch et al., 2017), allowing us to provide a range of water withdrawal estimates. Previous studies have indicated the superiority of the incremental ETa method over other methods, such as those based on the Budyko curve and soil water balance for quantifying ET_{blue} (Msigwa et al., 2021).

To determine the areas of cultivated lands in the various Nile sub-basins in Sudan, we relied on the estimates of equipped areas for irrigation provided by NBI (2016). Refer to the Supporting Information file for this specific information (Table S2). A cropping intensity of around 157% (FAO, 2022b) was used to calculate the annual cropped area (FAO, 2022). Water withdrawal was then estimated using equation (5).

$$ET_{blue} = ET_{total} - ET_{green} \tag{4}$$

$$\text{Water withdrawal} = ET_{blue}/\text{efficiency } (e) \tag{5}$$

This analysis was conducted for the period 2003–2020, which represents the overlapping timeframe for the CHIRPS (P) and SSEBop (ETa) datasets (see Section 2.3). The advantage of this approach is that both P and ETa can be measured from satellites. By relying on satellite data, this method offers an independent and transparent means to quantifying water withdrawal, particularly in regions with limited ground data and challenges in information sharing (van Eekelen et al., 2015). To validate our withdrawal estimates, we compared them to the records of discharge from the Sennar Dam to the Gezira Irrigation Scheme, as provided by Elshaikh et al. (2018). This comparison specifically focused on the Blue Nile Basin, which is the main irrigated area in Sudan. The validation covers the period spanning from 1980 to 2005.

2.2.1.3. Estimating water withdrawal based on agricultural production. In this method, we indirectly estimated water withdrawal by considering the domestic agricultural production through the concept of Water Footprint (WFP). The WFP concept, introduced by Hoekstra, (2003), is a useful indicator that accounts for all water used in producing a certain product. It encompasses three different components: blue water, green water, and greywater (Schyns & Hoekstra, 2014). For this study, we used national estimates of the Blue Water Footprint (BWF) provided by Mekonnen & Hoekstra (2011) to quantify the water used in agricultural commodities production. Our main assumptions in this method are that most of the water withdrawals in Sudan are taking place in the agricultural sector, i.e. 96%-97% (Mahgoub, 2014; Ritchie & Roser, 2017), and surface water accounts for approximately 96% of irrigation water sources (FAO, 2022a). We introduced a dimensionless fraction (f_{source}), with a value of 0.96, representing the proportion of the BWF fulfilled by surface water in Sudan. Additionally, we accounted for irrigation efficiency (*e*), employing the same WUE values utilized in method 2. By applying equation (6), we calculated water withdrawal on a country-wide scale.

$$W_{percrop} = \frac{BWF}{e} x f_{source} \tag{6}$$

2.3. Data specification and processing

2.3.1. River flow data

For the current study, two sets of daily and monthly river discharge data from multiple discharge stations along the Nile were available. These datasets were provided by the Ministry of Irrigation and Water Resources (MIWR) of Sudan, and have previously used in other studies (Siam & Eltahir, 2017). A quality control procedure was performed before incorporating these datasets into our analysis. This involves plotting these time series and visually inspecting for any abnormalities or missing entries in their estimates and patterns. Due to concerns about data quality, data from only eight main discharge stations that represent different sub-basins of the Nile were used in the current analysis (Table 2). Discharge data of some stations for the years post-2005 in Atbara and the Main Nile exhibited unusual estimates. Furthermore, discharge data for other stations for the years after 2005 were not available for this study. As a result, these stations were excluded from the current analysis. Consequently, the analysis using discharge data was limited to the period up to 2005 (see Table 2).

Several gaps were identified in the river discharge time series. The highest percentage of missing values can be found in the discharge time series of the Diem station. The percentage of missing values in the daily dataset is nearly 14% for the period 1965–2005. This percentage is less significant in other stations. It s approximately 4% and 0.2% in Jebel Aulia and Khartoum stations. To address these missing values, three different methods were employed: (i) if data for that station was available in the daily dataset, the daily data point was replaced with $1/30^{th}$ of the monthly discharge for that month in the given year. Otherwise, approach ii was used, (ii) if the duration of the period of missing data was less than 1 month, a daily average was calculated from available data within the same month to replace missing values, (iii) finally, if an entire month's worth of data was missing in the discharge data, the average daily discharge for that month was calculated based on the data from the same month in the following five consecutive years. For instance, if no data were available for March 1973, the daily average discharge for March from 1974 to 1978 was used as a replacement. This procedure resulted in a satisfactory performance in filling the existing gaps in the time series (Supporting information file: Figs. S1 and S2).

2.3.2. Areas of surface water bodies

In the current study, we differentiated between evaporation losses from river streams and dam reservoirs. While data on data reservoirs are available form multiple sources, information on evaporation losses from river streams is not readily available for the Nile in Sudan. To calculate total evaporation losses from open water bodies, accurate estimates of open water surfaces are needed. For river streams, we used the ESA-CCI land cover dataset (Table 1). Compared to other public-domain land cover datasets, ESA-CCI provides more reliable estimates of land cover areas (Ayyad & Khalifa, 2021; Tsendbazar et al., 2015). In addition to vegetation and man-made land cover classes, this dataset provides a water bodies class. River streams within the four Nile sub-basins in Sudan were extracted in the Geographic Information System (GIS) environment using ArcGIS 10.3.1 (ESRI, 2014). For the time framework considered for this method, four dam reservoirs were included in this analysis. These dams were Khashm El Girba (Atbara Basin), Sennar and Roseries (Blue Nile Basin), and Jebel Aulia (White Nile Basin). The surface areas of reservoirs were obtained from the Global Reservoir and Dam (GRanD) Database (Version 1.3). The GRanD database provides three estimates for reservoirs, representing the most reliable, minimum, and maximum reported surface area of the reservoir in square kilometers. When missing, we relied on estimates derived from literature. Since reservoir areas can fluctuate over time, having three estimates for reservoir area enables us to account for the uncertainties associated with these fluctuation.

Table 2
Details of data used in the current research: discharge stations (a), dam reservoirs (b), river streams (c), and climatic datasets (d).

a. Discharge stations

Station name	Sub-basin	Location along river	Timeframe	
			From	To
Atbara	Atbara	Downstream	1918	2005
Diem	Blue Nile	Upstream		
Khartoum		Downstream		
El Gwisi		Downstream (Dinder)		
El Hawata		Downstream (Rahad)		
Malakal	White Nile	Upstream		
Jebel Aulia		Downstream		
Dongola	Main Nile	Downstream		

b. Areas of dam reservoir

	Spatial coverage	Sudan dams considered in the current study	Reference	Data source
GRanD Version 1.3	Global	Khashm El Girba (Atbara Basin), Sennar and Roseries (Blue Nile Basin), and Jebel Aulia (White Nile Basin).	(Lehner et al., 2011)	https://globaldamwatch.org/grand/

c. Areas of river streams

	Satellite/Senseor	Spatial coverage	Spatial reolution	Temproal resolution	Data source
ESA-CCI	MERIS FR/RR SPOT-VGT AVHRR PROBA-V	Global	300 *m*	1992–2015	https://www.esa-landcover-cci.org/?q=node/164

d. Climate data

	Spatial coverage	Spatial resolution	Temporal resolution	Reference	Data source
Climate Research Unit (CRU TS v. 4.5) - Potential Evapotranspiration	Global	$0.5^\circ \times 0.5^o$ (~50 km)	1901-present	(Harris et al., 2020)	https://crudata.uea.ac.uk/cru/data/hrg/
Climate Hazard Group InfaRed Precipitation with Station data (CHIRPS 2.0) - Precipitation	Global	$0.05^\circ \times 0.05^o$ (~5 km)	1981-present	Funk et al. (2015)	https://www.chc.ucsb.edu/data/chirps
Operational Simplified Surface Energy Balance (SSEBop) – Actual Evapotranspiration (ETa)	Global	$0.008^\circ \times 0.008^o$ (~1 km)	2003-present	Senay et al. (2013)	https://earlywarning.usgs.gov/fews/product/464

2.3.3. *Potential evapotranspiration (PET)*

Climatic Research Unit (CRU) (Harris et al., 2020) provides a long-time series of PET data at a $0.5^\circ \times 0.5^\circ$ spatial resolution. Based on Penman's equation, PET in this dataset is created using extensive networks of climate ground stations, which makes it, compared to other publicly-available datasets, a more reliable source of PET data (Kanda et al., 2020; Mutti et al., 2020). For the current study, the latest version (v. 4.5) of CRU Time Series (TS) in a NetCDF format was used. To produce annual rates of annual PET, daily rates were aggregated using the functions provided by the Climate Data Operator (CDO) (Schulzweida, 2020). We generated separate time series of PET for each Nile sub-basin. By combining the estimated areas for open water surfaces with the time series of annual areal averages of PET we estimated the total evaporation losses from these water bodies.

2.3.4. *Agricultural production*

Data on the annual production of agricultural and livestock commodities (in metric tons) that are produced domestically in Sudan were obtained from the FAOSTAT platform (FAO, 2022c). FAOSTAT is maintained by the Food and Agriculture Organization of the United Nations (FAO), and provides comprehensive time series data for various agricultural indicators, including the production of crops and livestock for the period 1961–2020. Time series of former Sudan (1961–2011) and Sudan (2012–2020) were retrieved and combined to provide complete time series of crop production. The time series of former Sudan probably includes production estimates from regions that currently belong to South Sudan. However, due to the limited agriculture production in South Sudan before 2011 (Salman, 2011), the assumed overestimation is expected to be minimal. The data obtained from FAOSTAT included production estimates (in tons) for 53 different crops and 26 livestock commodities (Supporting information file: Table S3). These datasets were downloaded and processed for the purpose of our research. Following the recommendation of Nikiel & Eltahir (2021), processed crops were excluded from this analysis to avoid double counting of feed and meat production, ensuring the accuracy of our findings.

2.3.5. *Blue water Footprint (BWF)*

For the current research, we used BWF values of the aforementioned primary crops and livestock commodities, which account for direct and indirect uses of blue water (e.g., surface and groundwater). The BWF estimates are based on reference crop evapotranspiration and the FAO Penman-Monteith equation (Hoekstra, 2003). The Sudan-specific national BWFs (in m^3 per metric ton) of all primary products were obtained from Mekonnen and Hoekstra (2011). A list of all BWF values for the selected commodities in Sudan can be found in the Supporting information (Table S3).

2.3.6. *Satellite-based climate data*

We obtained Precipitation (P) and Actual Evapotranspiration (ETa), respectively, from the Climate Hazards Group InfraRed Precipitation - with Station data (CHIRPS) and the operational Simplified Surface Energy Balance (SSEBop) model (Table 2). These satellite datasets served as inputs for the second approach (incremental evapotranspiration) adopted herein to estimate water withdrawal. CHIRPS 2.0 product is considered one of the most reliable public-domain products for P estimates in the Nile Basin (Ayehu et al., 2018; Bayissa et al., 2017; Belete et al., 2020; Koukoula et al., 2020). This is mainly because it incorporates ground measurements of P in its composition (Funk et al., 2015). The product provides long-term time series of P estimates spanning over 40 years (1981-present). The SSEBop model, on the other hand, combines ET information generated from the thermal infrared component of the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images and reference evapotranspiration and incorporates a wide spectrum of variables (e.g., elevation, land surface temperature, air temperature, albedo, and vegetation indices) for model parameterization. This product provides reliable ETa estimates (Senay et al., 2014), and it was used successfully in different water applications in different regions around the world, including the Nile Basin (Bastiaanssen et al., 2014; Msigwa et al., 2021; Senay et al., 2020; Senay et al., 2014b). Using these datasets, time series of P and ET were generated for each Nile sub-basin.

3. Results and discussion

3.1. Spatio-temporal variation in climate and river flow

The analysis of climatic variables (P, ETa, P-ETa, and PET) on an annual time scale reveals large spatial and temporal variation between the four Nile sub-basins within Sudan. Spatially, the level of P shows a decreasing trend from south to north in these sub-basins (Fig. 4.a1). The highest average P rates were found in the Blue Nile (550.7 mm) and While Nile (484.8 mm). While Atbara receives a comparatively lesser amount of P (224.2 mm) than the Blue Nile and the White Nile, the Main Nile receives negligible quantities (62.9 mm). An increasing trend is recognized in P over the period from 2003 through 2020 (Fig. 4.b1). On the other hand, the highest ETa values were found over the main irrigated areas and open surface water bodies such as Nile streams, and dams' reservoirs (Fig. 4.a2). The White Nile exhibits the lowest average ETa magnitudes (76.1 mm), whereas the Blue Nile, Atbara, and White Nile have higher average ETa values of 462.8 mm, 405.6 mm, and 484.8 mm, respectively (Fig. 4.b2). This reflects the land cover prevailing in this basin, which lacks natural vegetation and significant agricultural activities due to low rainfall levels and desert conditions.

The annual difference between P and ET (P-ETa) serves as a simple water balance (Senay et al., 2014b). Positive values of P-ETa reflect conditions where P exceeds ETa levels. These regions can be considered water producers, where runoff can be generated out of this water surplus. On the contrary, negative values of P-ETa indicate locations where ETa exceeds P, signifying water-consumption or sinks. Generally, while many regions in the Blue Nile and White Nile sub-basins within Sudan can be considered as water-producers, most regions of Atbara and Main Nile are water-consumers (Fig. 4.a3; 4.b3). The main water sinks include the large irrigated schemes in central and eastern Sudan (e.g. Gezira, Rahad, and New Halfa Schemes) and water bodies in rivers and large dams' reservoirs. It is important to note that in the analysis presented, the P-ETa values are limited to the Sudanese sides of the sub-basins. Therefore, the time series generated in Figure 4.b3 do not represent the actual water balance encompassing the entire sub-basin.

The average PET values for the four sub-basins, arranged from highest to lowest, were determined to be 2347.7 mm (Main Nile), 1988.2 mm (Atbara), 1872.7 mm (Blue Nile), and 1798.3 mm (White Nile). The relatively higher PET magnitude in the Main Nile is mainly due to the higher temperature levels experienced in the northern part of the country.

The analysis of discharge data from the main stations for the period 1918–2005 revealed significant spatial and temporal variations in river flow. The long-term river flow averages was determined to be 12.0 km^3, 48.6 km^3, 29.6 km^3, and 80.5 km^3 for Atbara, Blue Nile, White Nile, and Main Nile, respectively (Fig. 5). A notable period of reduced flow occurred from the mid-1960s to the mid-1980s, leading to an average flow of 68.2 km^3 for the Main Nile during that time (Fig. 5). Several shifts in discharge time series correspond to the implementation of dams on the Nile rivers and major drought and flood events (Supporting Information: Fig. S3).

3.2. Evaporation and groundwater losses

The use of the ESA-CCI dataset to delineate and calculate areas of river systems was a suitable choice compared to other public domain land cover datasets. Comparing our estimates of the areas and evaporation losses from the five major reservoirs in Sudan, i.e., Khashm El Girba, Roseries, Sennar, and Jebel Aulia, with corresponding areas found in other products and the literature (Ali, 2018; Khairy et al., 2019; Messager et al., 2016; Muala et al., 2014) revealed comparable figures (Supporting information: Fig. S4).

The estimated evaporation losses calculated by method 1 (water balance) were found to be consistent with the figures reported in the literature (Deltares, 2012; Khairy et al., 2019; NBI, 2016). For instance, we calculated evaporation from Jebel Aulia, Roseries, and Khashm El Girba reservoirs to be on average around 2.2, 0.5, and 0.6 km^3, respectively (Table 3). These values align with the ranges reported in the literature for the three reservoirs, which are 2.2–2.9, 0.2–0.5, and 0.2–0.4 km^2, respectively (Deltares, 2012; Khairy et al., 2019; NBI, 2016). By distinguishing between evaporation losses from river streams and those occurring in dam reservoirs, this study provides important information that is often lacking in previous studies. The evaporation losses from river streams in Sudan were found to be substantial. Sudan is located in arid and semi-arid conditions, and open surface water bodies of the river traveling through harsh desert conditions experience considerable amount of evaporative losses. Our results revealed that the amount of evaporative losses from river systems are approximately equal to the total evaporative losses from the four reservoirs combined (3.6 vs. 3.5 km^3). The total evaporative losses from the entire system (streams + reservoirs) were estimated to be around 7.1 km^3 on average (Fig. 6).

There is a lack of reliable estimates of how much water infiltrates annually to recharge the deep aquifers in Sudanese portion of the Nile. However, the most recent estimate by the UN Food and Agriculture Organization (FAO) for groundwater produced internally in Sudan is 3.0 km^3 (FAO, 2022a). An earlier estimate of recharge to the Nubian Sandstone aquifer, a large transboundary groundwater aquifer with a significant portion located inside Sudan, suggests a possible recharge range of 1.44 km^3 and 4.01 km^3 in Sudan (Mohamed et al., 2017). Additionally, other estimates propose an annual groundwater recharge in Sudan of around 2.3 km^3 (MacAlister et al., 2012). Thus, for the current investigation, we assume that groundwater losses from the Nile in Sudan lie, on average, between 1.0 and 4.0 km^3. It's important to note that these estimates provide a general understanding of groundwater recharge and losses in Sudan, but more comprehensive and accurate assessments are needed to refine these figures and improve our understanding of the groundwater dynamics in the region.

A baseline estimate of stream losses of around 3.7 $\pm$ 1.1 km^3 was derived using a 7-year average water balance from 1918 through 1924, i.e., before the construction of dams. This indicates a remaining water flux between 1.7 and 3.4 km^3, which can be attributed mainly to the amount of water that percolates into deep aquifers. These estimates support our assumption regarding the quantities of water losses to deep aquifers.

3.3. Water withdrawal estimates

3.3.1. Water withdrawal estimates using the water balance method

The analysis of water withdrawal using the three methods has revealed an increasing trend in Sudan's water withdrawal from the Nile (Fig. 7). Method 1 estimates shows that water withdrawal in Sudan from the Nile was relatively minimal in the period from the 1920s and 1950s, with a maximum of around 4.8 $\pm$ 0.1 km^3. The subsequent steep increase in withdrawal can be attributed to the construction of the Khashm El Girba and Roseries dams and the associated expansion in irrigated

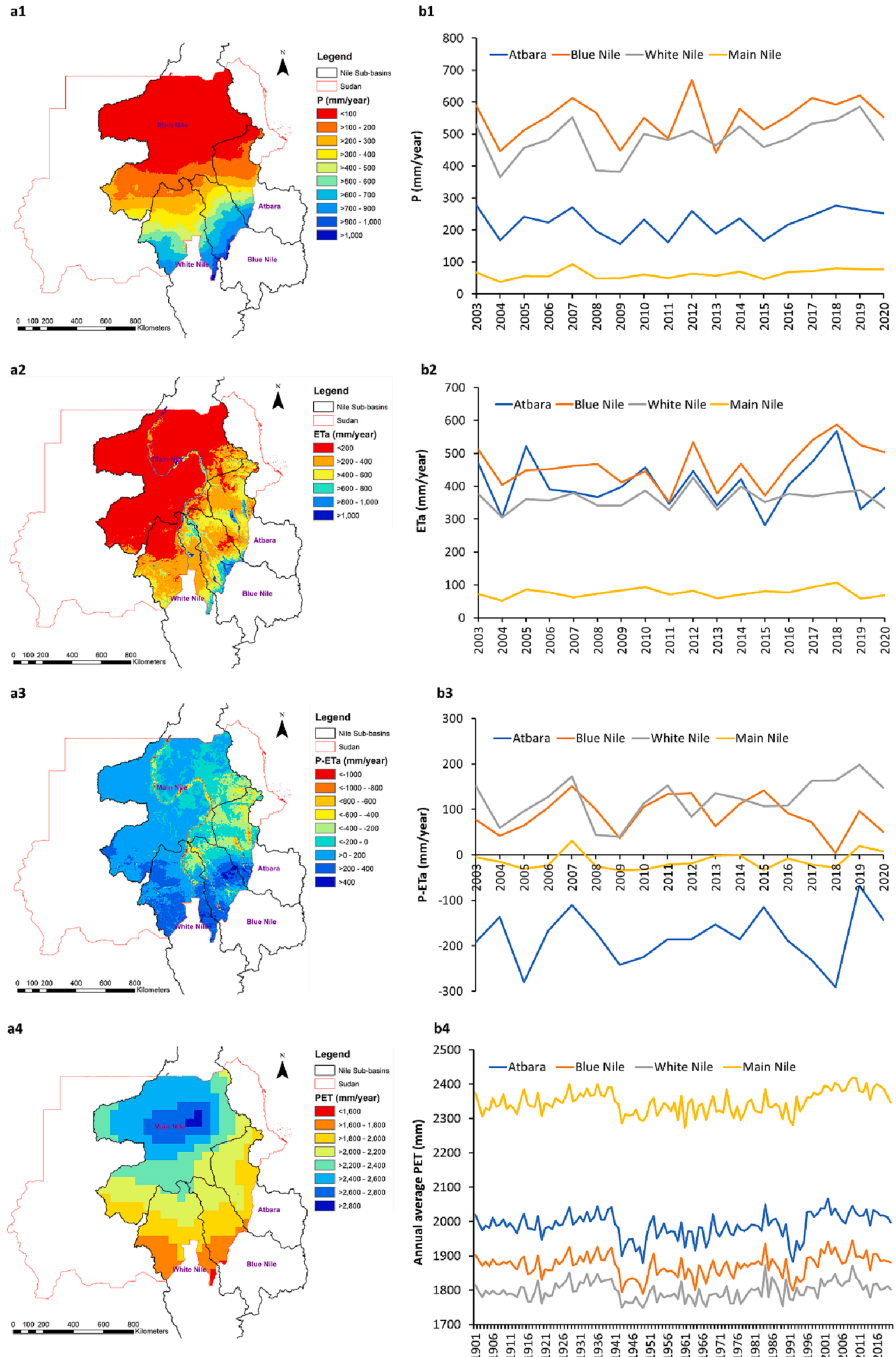

Fig. 4. Spatial and temporal variation in climate variables over the main Nile sub-basins within Sudan: annual precipitation (P) (a1, b1); actual evapotranspiration (ETa) (a2, b2); the difference between precipitation and evapotranspiration (P-ETa) (a3, b3); and potential evapotranspiration (PET) (a4, b4). The maps are based on the multi-year average for the period of 2003–2020 for P, ETa, and P-ETa, and the period 1901–2020 for PET.

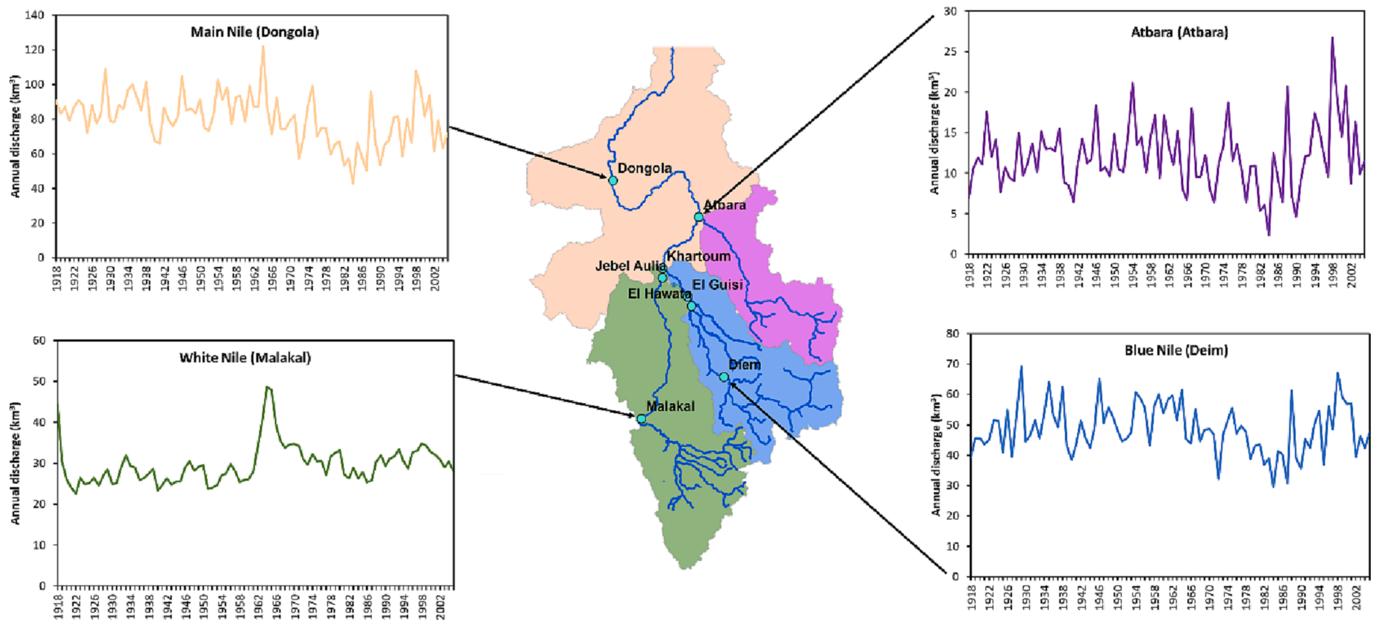

Fig. 5. Time series of measured discharge at main discharge gauges representing the four main Nile sub-basins within Sudan.

Table 3
Details of evaporation losses from open surface water bodies in the Nile basin within Sudan.

	River streams			Reservoirs			Total evaporative losses (km^3)
	Average surface area (km^2)	Average evaporation rate (mm)	Evaporation losses (km^3)	Reservoir names*	Surface area (km^2)	Evaporative losses (km^3)	
Atbara	97	1988	0.2	Khashm El Girba	315	0.6	0.8
Blue Nile	496	1872	0.9	Roseries Sennar	248.2 15.2	0.7 0.03	1.4
White Nile	124	1798	0.2	Jebel Aulia	1220	2.2	2.4
Main Nile	995	2347	2.3	-	-	-	2.3
Total	1711	-	3.6	-	1783	3.5	7.0

* Recent dams constructed after 2005 are not included. This involves Merowe in the Main Nile and Upper Atbara and Setit Complex in Atbara sub-basin.

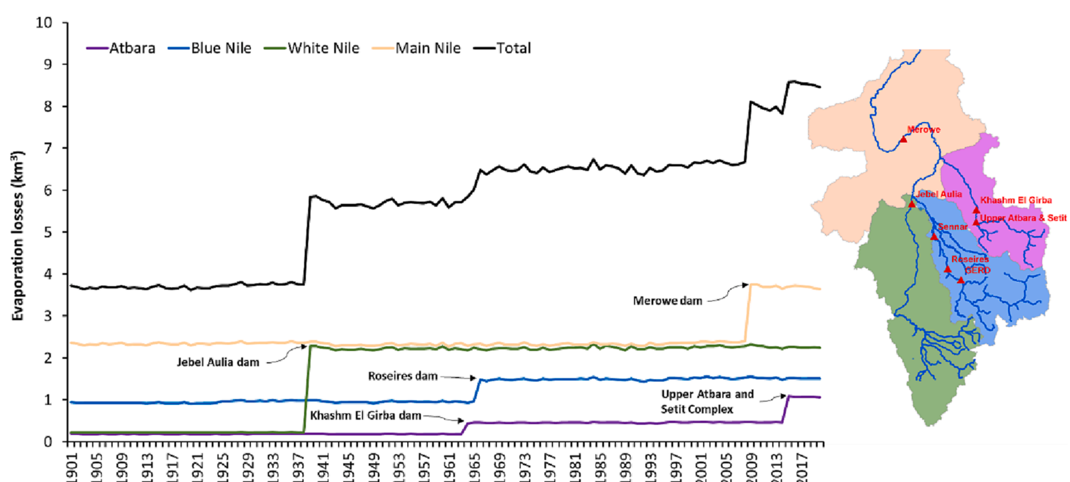

Fig. 6. Historical changes in evaporation losses from open water bodies within the Nile sub-basins in Sudan. The evaporation losses increased from 3.7 km^3 in the first three decades of the 20th century (a period with negligible water use in Sudan) to reach 8.5 km^3 in 2020. This substantial rise in evaporation losses is mainly due to reservoirs created by the built dams.

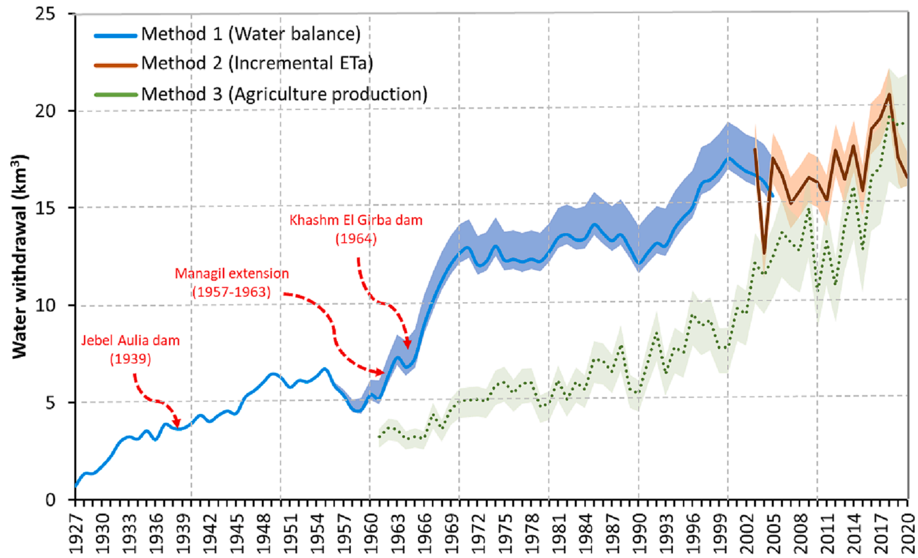

Fig. 7. Time series of water withdrawal from the Nile in Sudan using the three methods adopted in this study. These methods are based on water balance (method 1), incremental evapotranspiration (method 2), and agricultural production (method 3). The confidence intervals were calculated using minimum and maximum evaporation losses (method 1) and ranges of water use efficiency (methods 2 and 3).

areas, especially in the Blue Nile Basin. The development of the Managil extension during 1957–1963, as an expansion of the Gezira irrigation scheme, further contributed to a substantial increase in water withdrawal. Consequently, the total water withdrawal from the Nile in Sudan reached around 12.7 ± 1.0 km^3 on average during the 1970s. During the 1990s and 2000s, the average water withdrawal increased to 13.4 ± 1.2 km^3 and 14.7 ± 1.5 km^3, respectively. These findings illustrate the growing demand for the Nile water in Sudan over time.

The difference between water withdrawal calculated by method 1 and withdrawal estimates provided by Deltares (2012) equals nearly 1.0 km^3 (Fig. 8a). A comparison of water withdrawals in the Blue Nile Basin with discharge to the Gezira Scheme shows an average difference of 0.79 km^3 (Fig. 8b). This difference can be in part regarded as a discharge to other irrigation schemes in the Blue Nile Basin such as the Rahad and Suki Irrigation Schemes.

Table 4
Average estimates of the Nile water withdrawals (km^3) in Sudan as revealed by the three methods adopted in the current study.

	Method 1	Method 2	Method 3	(Deltares, 2012)
1927–1940	2.1 ± 0.8	–		–
1941–1950	4.3 ± 1.1	–		–
1951–1960	4.9 ± 1.1	–		–
1961–1970	8.1 ± 1.1	–	3.8 ± 0.6	8.7
1971–1980	11.8 ± 1.1	–	5.5 ± 0.8	12.6
1981–1990	12.7 ± 1.1	–	6.3 ± 0.9	14.1
1991–2000	14.1 ± 1.1	–	8.1 ± 1.2	14.8
2001–2010	15.7 ± 1.1	16.1 ± 1.3	12.1 ± 1.8	15.5
2011–2020	–	17.8 ± 1.3	16.0 ± 2.2	–

3.3.2. Water withdrawal using the incremental evapotranspiration method

In this method, we estimated Nile water withdrawal for the two decades spanning from 2003–2020. While the estimate shows an average of 16.1 ± 1.3 km^3 during the 2000s, there was a subsequent increase in withdrawal to an average of 17.8 ± 1.3 km^3 in the following decade (Fig. 3). The average withdrawal as estimated by this method and method 1 for some years in the overlapping period (2003–2005) seems to be comparable (See Table 4 for the multi-year averages), with an average difference between the two methods of nearly 0.4 km^3. However, this method yields higher withdrawal estimates compared to the values provided by Deltares (2012) for the same overlapping years (2003–2005), with an average difference of around 0.7 km^3. Detailed information on the estimated values of ET_{green} and ET_{blue} used in calculating water withdrawal in this method can be found in the Supporting Information (Table S4).

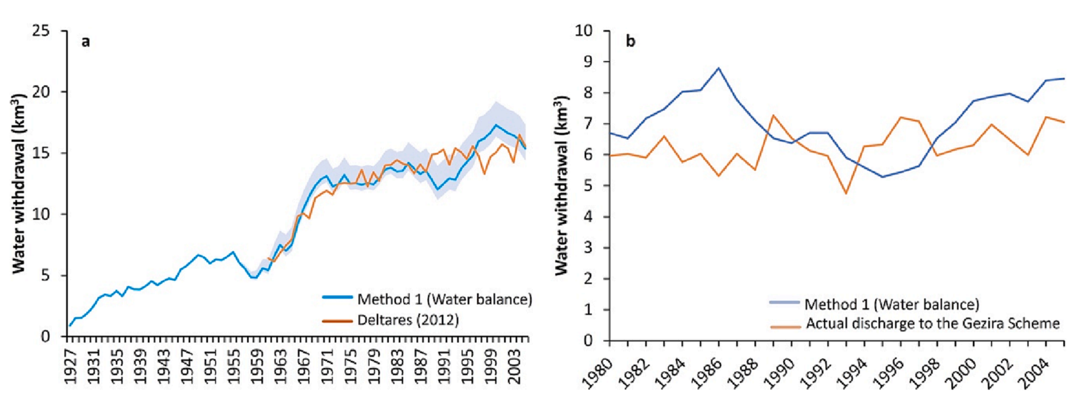

Fig. 8. Comparison of the water withdrawal as estimated by method 1 (water balance) with two independent sources: (a) Sudan's water withdrawal estimates provided by Deltares (2012), and (b) water withdrawal in the Blue Nile Basin and the actual water discharge to Gezira Irrigation scheme - the largest irrigation scheme in Sudan. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3.3. Water withdrawal estimate using the agricultural production

The agricultural production method generally exhibit lower withdrawal magnitudes compared to the previous two methods (Fig. 3). The average difference between the withdrawal estimates obtained through this method and the withdrawal estimates reported by Deltares (2012) is nearly −6.4 km^3. The underestimation in this method compared to the other two can be regarded to many reasons, including possible limitations in accounting for all agricultural commodities. The reliability and completeness of FAO's data seem to be another possible source of uncertainty. According to our analysis of the FAO data used in the current method, we found that around 66% of the data consisted of missing data, unofficial figures, and imputed values for 1961–2020 (Table 5), while only around 34% of the data were reported as official figures. Despite these challenges, the available data for agricultural production enabled us to estimate water withdrawal for the period after 2005, which was not possible with the water balance method (method 1) due to data unavailability and quality issues. The withdrawal estimate for the last decade (2011–2020) appears to be comparable to the estimate calculated using method 2, with values of 17.8 ± 1.3 km^3 and 16.0 ± 2.2 km^3, respectively. Additionally, the percentage of FAO data flagged as official data in these two decades increased to 45% and 48%, respectively (Table 5). This improvement suggests that the incompleteness of FAO's data and their quality may have contributed to the underestimation in earlier decades. Moreover, using single values of BWF, which typically tend to vary over time and space, to present the water required for each crop, might be another source for this underestimation.

4. Implications and adaptation measures

Despite showing relatively different magnitudes, the three methods captured an increasing trend in the Nile water withdrawal in Sudan. The rate of development is rapid. The ambitious plans of Sudan for expanding irrigated croplands extensively, the expected increase in water withdrawals could potentially exceed the perceived Nile share of 18.5 km^3 per year according to the 1959 agreement between Sudan and Egypt. This has multiple implications for the development of the Nile sector in the country, especially in the light of the ongoing dispute between the riparian countries of the Nile and transboundary negotiations.

As an effective adaptation measure to cope with the expected challenges of this increase, Sudan needs to prioritize improving WUE as a potential solution. Improvement of WUE can help Sudan to save substantial amounts of water. The sensitivity analysis conducted in this study on the water withdrawal estimated using method 2 (Fig. 9) highlights the significant potential of improving water use efficiency (WUE) as an effective measure to cope with water limitations in Sudan. The results demonstrate that an improvement in WUE from 0.48 to 0.70 has the potential to allow Sudan to save approximately 28% of the annual water used during 2011–2020 in Sudan's agriculture sector. Similarly, although the withdrawal estimate from method 3 (agricultural production) seems to be relatively underestimating water withdrawal for some periods, the sensitivity analysis using WUE ranges shows a comparable potential for water savings, with an estimated 26% reduction in water withdrawal estimates. These findings underscore the importance of considering variations in WUE as a crucial parameter when estimating water withdrawals (Puy et al., 2022). Improving WUE is an effective measure to cope with water limitation. This is true for Sudan and many countries with low WUE. As improvement in irrigation efficiency alone may not be sufficient to meet future water demands in the Nile Basin (Multsch et al., 2017), we emphasize the importance of integrating the policy improvement in WUE with other key elements in a wider strategy (Supporting Information file: Fig. S4). These elements include bridging the crop yield gap through the adoption of agricultural technology (e.g., fertilizers, better seeds, etc), enhancing WUE, improving climate resilience, and optimizing water allocation and water use. By integrating these strategies, Sudan can work towards a more sustainable and resilient water management system that addresses the challenges of increasing water demand and limited water resources in the Nile Basin.

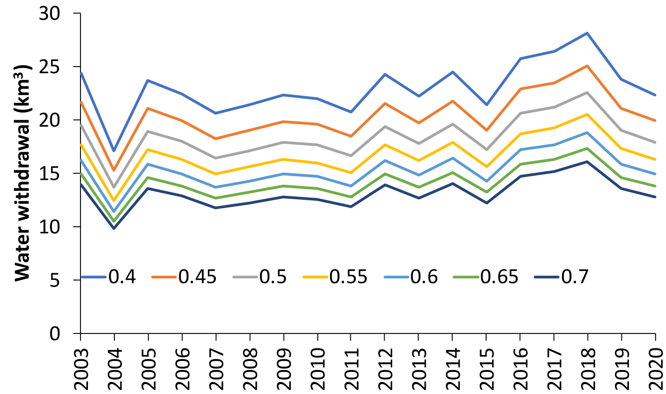

Fig. 9. Sensitivity analysis of water withdrawal calculated in method 2 (incremental evapotranspiration) as a function of varying water use efficiency (WUE). It is estimated that an improvement in WUE from 0.48 to 0.7 may potentially decrease water withdrawal by up to 28% of the current water withdrawal as estimated for 2011–2020.

Table 5
The data flags associated with the FAOSTAT dataset provide information about the quality and reliability of the data. The percentage of instances for each data flag category is calculated as a percentage of the total data used.

	Official figure	Estimated value	Missing value (data cannot exist, not applicable)	Unofficial figure	Imputed value
1961–1970	22.2	58.9	6.3	2.4	7.9
1971–1980	33.7	46.0	6.4	3.0	8.0
1981–1990	31.4	49.3	5.6	3.1	7.6
1991–2000	19.1	47.7	9.2	4.5	15.0
2001–2010	44.5	23.3	2.0	3.7	23.0
2011–2020	48.3	15.0	5.7	2.8	25.4

5. Limitations and sources of uncertainties

The current analysis highlights the strengths and limitations of the three methods applied herein to estimate Sudan's water withdrawal from the Nile. The three methods rely heavily on the availability and quality of data, as discussed above. Compared to methods 2 and 3, method 1 which is based on water balance requires relatively more ground-based data, especially river discharge. Obtaining such data can be challenging in developing countries. For the current study, it was not possible to perform the analysis beyond 2005 because of data unavailability and data quality. Moreover, calculating evaporation losses from surface water requires accurate estimates of the areas of surface water bodies. Land cover data and areas of dam reservoirs water available from public-domain sources (e.g. ESA-CCI and GRanD databases) represent a potential source for such information. However, there may be uncertainties associated with their estimates and might introduce some uncertainties in water withdrawal estimates. In the current research, we used this uncertainty to provide a confidence level in the withdrawal estimates. Quality of data, on the other hand, also affects withdrawal estimate, as demonstrated by method 3 (agriculture production) for FAOSTAT data on crop production (Section 3.3.3). There might be small inflow fluxes from ungauged streams into the Nile during the rainy season (June-October). These unaccounted water flows can not be quantified with the available data, and, therefore, neglected in the analysis. However, their contribution is relatively small compared to the gauged rivers considered in the current investigation.

In methods 2 (incremental evapotranspiration) and 3 (agriculture production), WUE is a critical parameter that significantly influences the estimated water withdrawal (Puy et al., 2022). However, due to the lack of detailed information on irrigation efficiency within Sudan's irrigation schemes and how it varies within these schemes spatially and temporally, certain assumptions had to be made based on available data. The literature report that WUE in the agriculture sector in Sudan ranges from 0.48 and 0.65 (Al Zayed et al., 2015; Hamid et al., 2011; Multsch et al., 2017). We used this uncertainty to provide a confidence level for the estimated withdrawal. A sensitivity analysis was also conducted to assess the impact of WUE variation on the estimated water withdrawal (Section 4). Some of the underestimations recognized in the withdrawal estimates of method 3 could be regarded partially to using single values for the WFP of crops, which may vary over time and space.

Although the remote sensing data, i.e., CHIRPS 2.0 for P and SSEBop for ETa used in method 3 have better performance compared to other products available from public-domain sources (Abdelmoneim et al., 2020; Alriah et al., 2022; Ayyad et al., 2019; Dinku et al., 2018; Senay et al., 2020), they have their own inherent uncertainties. Their performance tends to vary spatially and temporally, and thus, can lead to underestimations or overestimations in water withdrawal calculations, depending on the specific location and period being considered.

Lastly, our methods do not account for non-agricultural water withdrawals. These uses represent nearly 3–4% of Sudan's total water withdrawal. This can explain part of the differences between the estimated water withdrawal with those reported in the literature. Additionally, the rapid development in using groundwater for irrigation (Lanzoni et al., 2018; Omer, 2002), particularly by large companies and foreign investors (Fragaszy & Closas, 2016), might explain some of the withdrawal estimation differences. This is particularly evident in the case of the Main Nile sub-basin. The estimation of water used for irrigation from groundwater in the Main Nile was approximately 0.83 km^3 (Fragaszy & Closas, 2016), representing a substantial amount of water. It is important to acknowledge these limitations and uncertainties when interpreting the results of the study.

6. Summary and conclusion

This study quantified water withdrawal from the Nile in Sudan over the past decades by employing three different methods. Despite the differences in withdrawal magnitudes especially between methods 1 and 3, all three methods agreed on the increasing trend in water withdrawal in Sudan. Based on our estimates, the average Sudan's Nile withdrawal (2011–2020) is somewhere between 16.0 ± 2.2 km^3 and 17.8 ± 1.3 km^3, depending on the method used. With the accelerated rate of water withdrawal, water availability may become the most challenging limiting factor for the development of the irrigated agriculture sector in the country. Therefore, it is crucial for Sudan to adopt effective strategies to cope with the expected future challenges posed by this increase. Enhancing WUE in the agricultural sector is one of the effective approaches that can potentially contribute to the solution. Vertical expansion of agriculture in Sudan, rather than horizontal development, is recommended as a feasible alternative that minimizes the need for additional water resources (Ayyad & Khalifa, 2021; Eltahir et al., 2019; Khalifa et al., 2020). To conclude, prioritizing WUE and improving crop productivity is the appropriate pathway for Sudan to follow. It is important to note that the findings presented in this study are based on the assumptions adopted. Therefore, these results should be interpreted with caution, taking into account the uncertainties and assumptions highlighted throughout the research.

CRediT authorship contribution statement

Muhammad Khalifa: Methodology, Formal analysis, Data curation, Investigation, Writing – original draft, Visualization. **Natalie E. Woods:** Methodology, Formal analysis, Data curation, Investigation, Writing – review & editing. **Elfatih A.B. Eltahir:** Supervision, Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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The authors thank the Ministry of Irrigation and Water of Sudan for providing river flow data necessary for this research. We extend our gratitude to the providers of the public-domain datasets used in the current research, namely FAOSTAT, AQUASTAT, CRU TS, CHIRPS 2.0, SSEBop, ESA-CCI, and water footprint. The invaluable support and feedback provided by Dr. Yeon-Woo Choi (Eltahir Research Group, Massachusetts Institute of Technology, MIT) are highly appreciated. Special thanks are also extended the three anonymous reviewers for their critical remarks and constructive suggestions. Their contributions have helped enhance the clarity and robustness of the research findings.

Open research

Except for discharge data, all the data used in the current research are available online with public-domain policies. Discharge data can be requested from the Ministry of Irrigation and Water Resources of Sudan.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2023.129858.

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