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The African Database of Hydrometric Indices (ADHI)

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Abstract

The African continent is probably the one with the lowest density of hydrometric stations currently measuring river discharge, despite the fact that the number of operating stations was quite important until the 70s. This new African Database of Hydrometric Indices (ADHI) is compiling data from different sources carefully checked for quality control. It includes about 1500 stations with at least 10 years of daily discharge data over the period 1950-2018. The average record length is 19 years and for over 100 stations complete records are available over 50 years. With this new dataset spanning most regions of the African continent, several hydrometric indices have been computed, representing mean flow characteristics and extremes (low flows and floods), and are made accessible to the scientific community. The database will be updated on a regular basis to include more hydrometric stations and longer time series of river discharge. The ADHI database is available for download at: https://doi.org/10.23708/LXGXQ9 (Tramblay and Rouché, 2020).

1. Introduction

There is a growing need for large-scale streamflow archives (Addor et al., 2020; Hannah et al., 2011), that are extremely useful to evaluate continental land-surface simulations (Newman et al., 2015; Ghiggi et al., 2019; Do et al., 2020), remote sensing data products (Beck et al., 2017; Brocca et al., 2019; Forootan et al., 2019; Satgé et al., 2020), develop operational flood or drought monitoring systems (Alfieri et al., 2020; Harrigan et al., 2020; Lavers et al., 2019; Thiemig et al., 2011), or evaluate aquifers outflows and characteristics (Dewandel et al., 2003, 2004). In Africa, the density of active monitoring networks is lower compared to other continents and there are challenges in the exchange of hydrometric data across countries (Mahé and Olivry, 1999; Viglione et al., 2010; Mahe et al., 2013; Stewart, 2015; Dixon et al., 2020).

African countries are largely under-represented in large-scale databases such as the Global Runoff Data Center (GRDC) or the recent GSIM initiative (Do et al., 2018; Gudmundsson et al., 2018), and/or the time series are mostly not updated. At the African scale, there is still a lack of coordination for hydrological data collection and dissemination, despite the launch in 1975 of the UNESCO Intergovernmental Hydrological Program (IHP) dedicated to water research, water resources management, as well as education and capacity building. This programme enhanced the set up and management of international rainfall and runoff databases at the regional scale of the FRIEND programs (Van Lanen et al., 2014), but these are still largely not updated.

There is still not enough partnership between the national hydrological services and in many countries licensing issues prevent the distribution of the data collected.

The density of monitoring networks in Africa has been declining over time; a serious concern for hydrologists since data acquisition and experimental data analysis remain central to understand hydrological processes and their spatio-temporal variability (Hannah et al., 2011; Roudier et al., 2014; Blume et al., 2016; Beven et al., 2020). There are mainly two reasons for this decline: the budgetary austerity measures imposed by the international financial institutions, the lack of permanent funding of national hydrological services, and the typically low number of well-trained technical staff in these departments (Bodian et al., 2016, 2020; Hannah et al., 2011). As a result, hydrological monitoring is now often dependent on research projects that cannot support long term observations. Studies focusing on regional river discharge variability are rare at the scale of Africa due to the lack of data. For instance, Conway et al. (2009) could only present a study of a reduced number of representative regional basins in their study of African rivers variability during the XXth century, and Roudier et al. (2014) compared only published anomaly results rather than direct measurements in their review of climate change impacts on the hydrology of West Africa.

Since in many cases, there are strict conditions related to the redistribution of un-processed data (Do et al., 2018), it is very often not possible to provide the complete time series of discharge data. Nevertheless, hydrological indices or hydrological signatures are useful to characterize the behavior of different components of river discharge, from low flows, annual runoff to floods (Addor et al., 2018; McMillan et al., 2017), and to assess the potential impact of climate change and human activities on river regimes (Mahe et al., 2013; Gnann et al., 2020). They can be used for various purposes, including basin classifications, aquifer properties characterization, hydrological predictions in ungauged catchments (Westerberg et al., 2016) and to investigate long term trends for different hydrological processes (Do et al., 2017; Nka et al., 2015). We introduce here the African Dataset of Hydrometric Indices (ADHI) that aims at giving access to an ensemble of hydrometric indices computed from an unprecedented large ensemble of stations with daily discharge data (Tramblay et al., 2020, Tramblay and Rouché, 2020). Thus, a minimum of useful information regarding the African rivers variability over the last 68 years can be shared with the international community, while respecting the confidentiality of the original records when these are not allowed to be publicly shared by the national authorities.

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2. Data sources and processing

2.1 Data collection

The database used in the present work is based on the collection of stations from the Global Runoff Data Center (GRDC) and the SIEREM database (Boyer et al., 2006; Dieulin et al., 2019). The hydro-climatological data contained in SIEREM is the legacy from the former *Laboratoire d'Hydrologie* of the *Office de la recherche scientifique et technique outre-mer* (ORSTOM, now *Institut de Recherche pour le Développement*, IRD, France). It must be noted that in addition to the daily data, the SIEREM database also contains instantaneous rainfall and discharge for hundreds of experimental small catchments mostly established in the 1950s and 1960s. The criterion to include a station in the ADHI database is to have a minimum of 10 full years of daily discharge data between 1950 and 2018. Most of the hydrological stations in French-speaking countries have been set up and managed for decades by the ORSTOM Institute (Mahe and Olivry, 1999). At the time the data were processed, the SIEREM database included a total of 1046 series, with several of them being duplicates of the same monitoring station but for different time periods. There are a total of 101 stations with 2 times series, 42 stations with 3 time series, 24 stations with 4 time series and 7 stations with 5 time series. In most cases, one time series includes the longest record and that one was kept for the analysis in the present paper. For some stations, the different time series were differing substantially during the same period, due to different rating curves. A careful inspection of these series led to the elimination of erroneous or doubtful data. Only for 17 stations the time series were concatenated, after making sure the rating curve(s) applied on the different time periods to compute river discharge were adequate, by comparing daily runoff on a common period. Additionally, to these 1046 series, 933 stations have been retrieved from the GRDC database. For 106 of these stations, there was a duplicate station in the SIEREM database with longer time series and the latter were selected. After this data quality processing step, 673 stations were kept for SIEREM and 800 for the GRDC database for a total of 1473 stations (Figure 1). Figure 2 depicts the number of stations available per year, showing a sharp decline at the end of the 1980s, and shows the number of stations having from 10 to 69 years of record. It can be seen that, for about 100 stations, complete records are available over 50 years.

2.2 Data quality

Since the data collected are sometimes from manual records, they are subject to possible errors in the reporting of discharge values. About outlier detection, no single

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method can outperform visual inspection and local expert knowledge (Crochemore et al., 2020). Indeed, in rivers with a strong variability in the annual regime and extremes, the most important flood peaks may be wrongly reported as outliers. Consequently, we carried out a visual inspection of the data when the maximum value was exceeding 5 times the median discharge. For only a few data points obvious errors were detected, with discharge exceeding by several orders of magnitude the median flow, and for these cases the data has been reported as missing data in an absence of an objective criterion to correct the record. In addition, through visual inspection it was possible to identify stations where some gap filling methods have been applied (13 stations) or where the data are suspicious (28 stations). A flag has been added in the metadata to identify these stations. It is worth noting that, for the stations of the SIEREM database, most of the data were analyzed and criticized prior to the inclusion in the database by the former ORSTOM hydrology laboratory, with therefore a much reduced level of error in the archived data.

In addition, to detect possible shifts in the data due to non-natural influences, such as an artificial drift in the monitoring devices, changing instrumentation, recalibration of the rating curve, or river regulation by dams or reservoirs, the Pettitt test (Pettitt, 1979) was applied to mean annual runoff series. We reported the cases when the null hypothesis of homogeneity was rejected, at the 5% significance level. 14 stations are reported with homogeneity breaks in the metadata and this result was consistent with a visual inspection. Since the possible causes of these changes in flow regime could be many folds and should be investigated with a more detailed case-by-case analysis, we choose to keep these stations in the database, but to flag them accordingly.

2.3 Climate characteristics

This data collection results in the largest ever built database of daily discharge data in Africa. These stations belong to different climate zones, according to the Köppen-Geiger climate classification (Peel et al., 2007). The main climate zone represented is Savannah (class Aw) for 687 stations corresponding to west and central Africa basins. The second most represented climate zone is Steppe-hot (Bsh) for 207 stations located in the Sahel region and south Africa (Botswana, Namibia). The temperate with dry winter classes (Cwa and Cwb) includes 187 and 125 stations, respectively located in south Africa (Zambia, Angola, Rwanda, Mozambique, South Africa and Zimbabwe). The 98 stations belonging to the Desert-hot class (Bwh) are mostly located in the northern and southern boundaries of the Sahara Desert. 87 Stations under a temperate climate with dry hot summer, corresponding to Mediterranean climate (Csa) are found in North Africa and the southwestern part of South Africa. Thus, the selected river basins are representative of most of the climate zones in Africa. It must be noted that for large

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basins, such as the Congo, Niger or even the Orange rivers, the climate type at the outlet may not be representative of the whole catchment, that may span over diverse climate zones.

2.4 Catchment delineation and information about river regulation

Station catchments areas have been delineated with the Hydroshed Digital Elevation Model (DEM) at 15 sec resolution using the TopoToolbox2 algorithm (Schwanghart and Scherler, 2014). The map of the catchments is shown in Figure 3. Despite a careful check of the geographic coordinates of the stations, this type of automatic catchment delineation procedure is prone to some errors, in particular in regions with low elevation and flat terrain properties. For several hundred of catchments it is possible to compare the results of the automatic delineation procedure with the catchment boundaries available in the SIEREM database, which have been most often individually delineated and carefully checked from ground knowledge over the years (Dieulin and Boyer, 2005). From the catchment delineated, the mean, maximum and minimum altitude have been extracted and included in the metadata.

Dams and reservoirs have also been extracted and added in the metadata of the stations. The Global Reservoir and Dam Database (GRanD) v1.3 (Lehner et al., 2011) has also been considered to identify regulated basins. The number of dams included in each river basin has been extracted using the catchment boundaries. As shown in the metadata of GRanD, most of the dams in Africa basins have been constructed around the 1970s (Figure 4). The rivers could be considered regulated if at least one dam exists in the catchment area, otherwise the river is considered natural (Figure 1). However, the influence of dams and reservoirs on the flow regime are linked to the location of the regulation structure, the portion of the basin controlled, and the management strategies. For instance, in a large basin with only one dam located on a small headwater catchment, its influence may not be distinguishable at the river outlet. On the other hand, a station located immediately downstream a dam outlet may have its flow regime strongly impacted by dam operations. It should be also noted that other regulation structures like small dams or water diversion channels that may not be included in the GRanD database could be present in the catchments considered natural (Lehner et al., 2011; Pekel et al., 2016). This is particularly the case in semi-arid areas where earthen-made channels, often informal, draw their water supply from the river itself, by building small diverting structures (Underhill, 1984; Kimmage, 1991). They can represent a large number of structures, but a variable amount of water withdrawal at the basin scale (Barbier et al., 2009; Bouimouass et al., 2020). Similarly, no data is available yet on the importance and impact of groundwater abstraction, if any, on the flow regime measured at the stations.

3. Hydrometric indices

Here is presented the list of indices computed from daily discharge data. It includes absolute indices, for example annual maximum daily discharge but also relative indices computed with a base period as reference, such as standardized drought indices. The indices are computed for a given year only if there is less than 5% missing data.

3.1 Indices computed on the whole record

These indices have been computed using the whole time series available for each station. Consequently, they are computed on different base periods depending on the stations, with the period of record for each station being made available in the metadata. These indices include:

1. Mean daily streamflow, the arithmetic mean of daily data
2. Standard deviation of daily streamflow
3. Minimum daily streamflow
4. Maximum daily streamflow
5. Mean monthly streamflow (12 values from January to December)
6. 5th, 10th, 25th, 50th, 75th, 90th, 95th and 99th percentiles of daily streamflow

3.2 Indices computed on an annual basis

These indices have been computed for each calendar year. This choice was motivated by the fact that hydrological years have different definitions across the different regions of Africa. For example, in North Africa and most of southern Africa the hydrological year starts in September, after the dry summer season, while in West Africa the hydrological year starts between January and March, depending on the latitude, with the annual maximum runoff occurring during the summer months. The use of calendar years has been also selected for consistency with other databases such as GSIM (Do et al., 2018; Gudmundsson et al., 2018). These indexes have been computed for the years with less than 5% missing data:

1. Mean annual runoff
2. Minimum of 7-days consecutive streamflow, per year, and corresponding date
3. Annual maximum runoff, and the corresponding date

This database includes a wide range of catchment sizes and rivers with different hydrological regimes, as shown on figure 5 displaying mean daily runoff against catchment areas. From the supplied indices, other useful indicators could be derived. For example, for hydrogeology applications it would be interesting to compute the low stage specific discharge that is the ratio between the low-stage discharge and the area of the watershed. This can be an indicator of aquifers' contribution to river discharge. The main issue is related to the definition of the low-stage discharge. From the indices proposed in the present database, it could be 5th percentiles of daily streamflow or the minimum of 7-days consecutive streamflow, per year. Similarly, the low-flow index could be computed from the ratio of the 90th and 50th percentiles of daily streamflow (Smakhtin, 2001).

4. Data availability

The ADHI database is available for download at: https://doi.org/10.23708/LXGXQ9 (Tramblay and Rouché, 2020). These different files are supplied in the AHDI database:

The stations.txt file contains:
- Unique identifier for each station
- Station code (native code from the original datasource)
- Data Source
- Catchment Area (km²)
- Mean Altitude (m)
- Maximum Altitude (m)
- Minimum Altitude (m)
- Station Name
- Starting year of the records
- Ending year of the records
- Longitude (WGS84)
- Latitude (WGS84)
- Number of dams from the GrandDam database
- Country
- Flag, 0: no identified data issue, 1: some gap filling detected, 2: suspicious data, 3: regime break

The sumary.txt file contains for each station (lines) the following variables (columns):
- Mean daily streamflow (m^3/s)
- Standard deviation of daily streamflow
- Minimum daily streamflow
- Maximum daily streamflow
- Mean monthly streamflow (12 values from January to December)

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- 5th, 10th, 25th, 50th, 75th, 90th, 95th and 99th percentiles of daily streamflow

The compressed folders AnnualMean.zip, AnnualMax.zip, Annual7DayMin.zip, contains time series and corresponding dates for mean annual runoff, annual maximum runoff and annual minimum of 7-day discharge. There is one file per station.

The compressed folder Plots.zip contains for each station a plot of the daily discharge data available.

5. Conclusions and perspectives

This new hydrological database brings together the largest number of African river flow measurement stations, in comparison with other previously published datasets. It results from a pooling of the GRDC and SIEREM databases, built from contributions of several agencies in African countries in charge of the management of hydrological measurement networks. This database will be regularly updated with data from SIEREM and GRDC. The dataset provides a series of indices that describes mean and extreme runoff, allowing the characterization of the hydrological regime and applications linked to the management of water resources and hydrological risks. Since most of the pre-processing steps have been automated, it would be possible to increase the number of stations considered or the length of the data series, if more data would become available. The data from the SIEREM database is regularly updated from contributions of different organisms. In the future, individual contributions from researchers or institutes will be welcome to increase the spatio-temporal coverage of the data. The FRIEND programme (UNESCO/IHP) will also contribute to increase the number of stations through coordinated efforts at the regional level.

More broadly, this ADHI database could contribute to a better knowledge on African hydrology. For instance, the impacts of dams on river discharge remains largely unquantified at the scale of Africa (Biemans et al., 2011). From these indices, various applications can be sought. For example, the percentiles of the daily streamflow could be useful to calibrate hydrological models using the flow duration curve (McMillan et al., 2017) and to constrain model outputs (Tumbo and Hughes, 2015; Ndzabandzaba and Hughes, 2017). Flow duration curves are also useful for catchment classification according to their rainfall-runoff response (Cheng et al., 2012). In the recent years, global runoff simulations have been provided by the Global Flow Awareness System, with land surface or global hydrological model driven by reanalysis data (Alfieri et al., 2020; Harrigan et al., 2020). Yet, due to the small number of stations representing African basins in the currently available databases preventing a robust calibration of the models, the hydrological simulations have a poor performance (Harrigan et al., 2020).

More generally, this new ADHI database could open perspectives to apply hydrological models in African basins, in particular combined with recent remote sensing data products (Brocca et al., 2019; Satgé et al., 2020). Beside deterministic hydrological modelling approaches, several statistical methods to estimate the return levels of floods have been proposed, in order to safely design dams, reservoirs, sewers or other water regulation structures. Regional frequency analysis methods have been applied to estimate floods in ungauged basins in several African countries such as Morocco (Zkhiri et al., 2017), Tunisia (Ellouze and Abida, 2008), South Africa (Nathanael et al., 2018; Smakhtin et al., 1997), or the Volta basin (Komi et al., 2016). However studies at a larger regional scale remain very scarce (Farquharson et al., 1992; Padi et al., 2011) while there is a strong need to improve the knowledge on hydrological hazards in African countries (Di Baldassarre et al., 2010). With this recent database becoming available, it could be possible to develop regional frequency analysis techniques for floods or low flows tailored for the African context, taking also into account the impacts of global changes.

Acknowledgements

River runoff has been obtained from The Global Runoff Data Centre, 56068 Koblenz, Germany and included in the database with their authorization. We would like to thank the GRDC for granting access to their data. A large part of the data processed in the present study comes from the SIEREM database, and the authors wish to express their gratitude to all the persons who contributed to this database over the years.

The database is available from the online repository: https://doi.org/10.23708/LXGXQ9
Additional indices could be computed upon reasonable request to the corresponding author.

This work is dedicated to the memory of Claudine Dieulin who passed away in January 2020 during the course of this project

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Figures

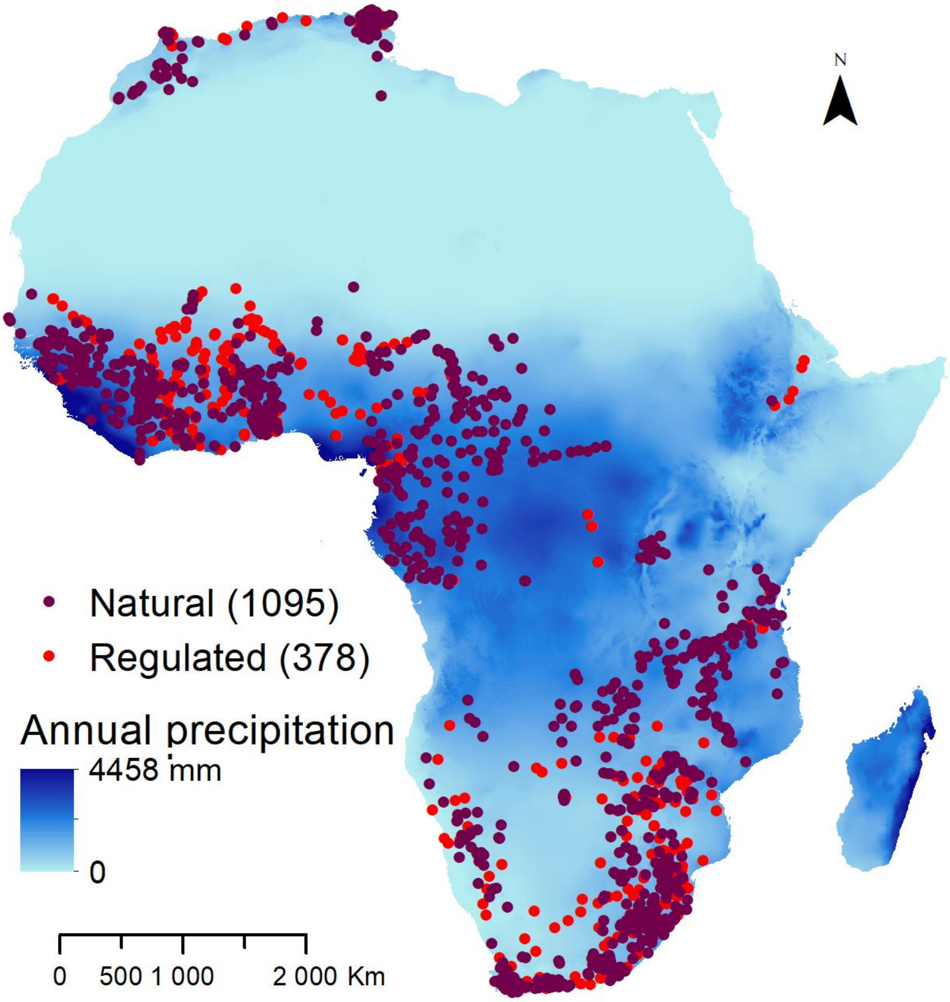

Figure 1: Map of available stations, regulated basins refer to basins with at least one dam in the catchment. Mean annual precipitation between 1970 and 2000 is provided from the WorldClim database (Fick and Hijmans, 2017). Basins are considered regulated if they contain at least one dam or reservoir from the GRanD database (Lehner et al., 2011)

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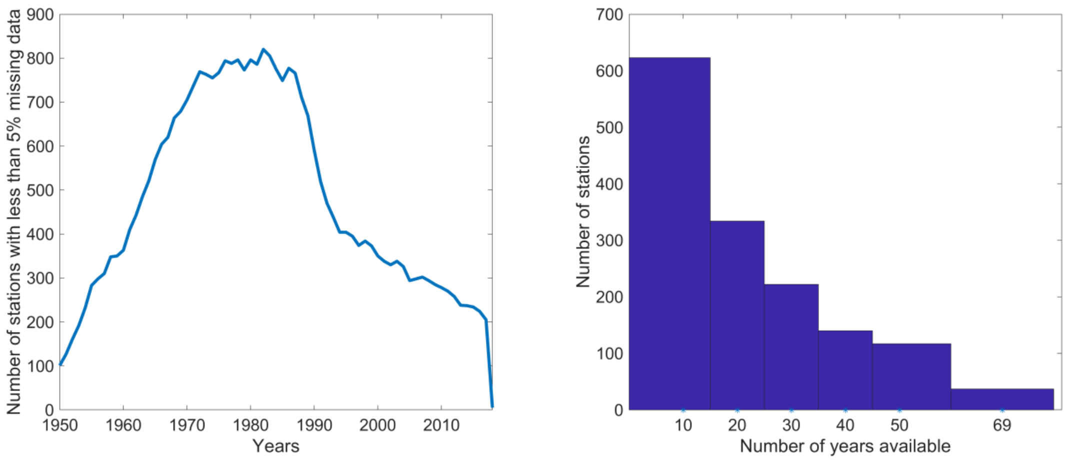

Figure 2: Number of available stations per year with less than 5% missing data (left) and number of stations available for different record lengths (right)

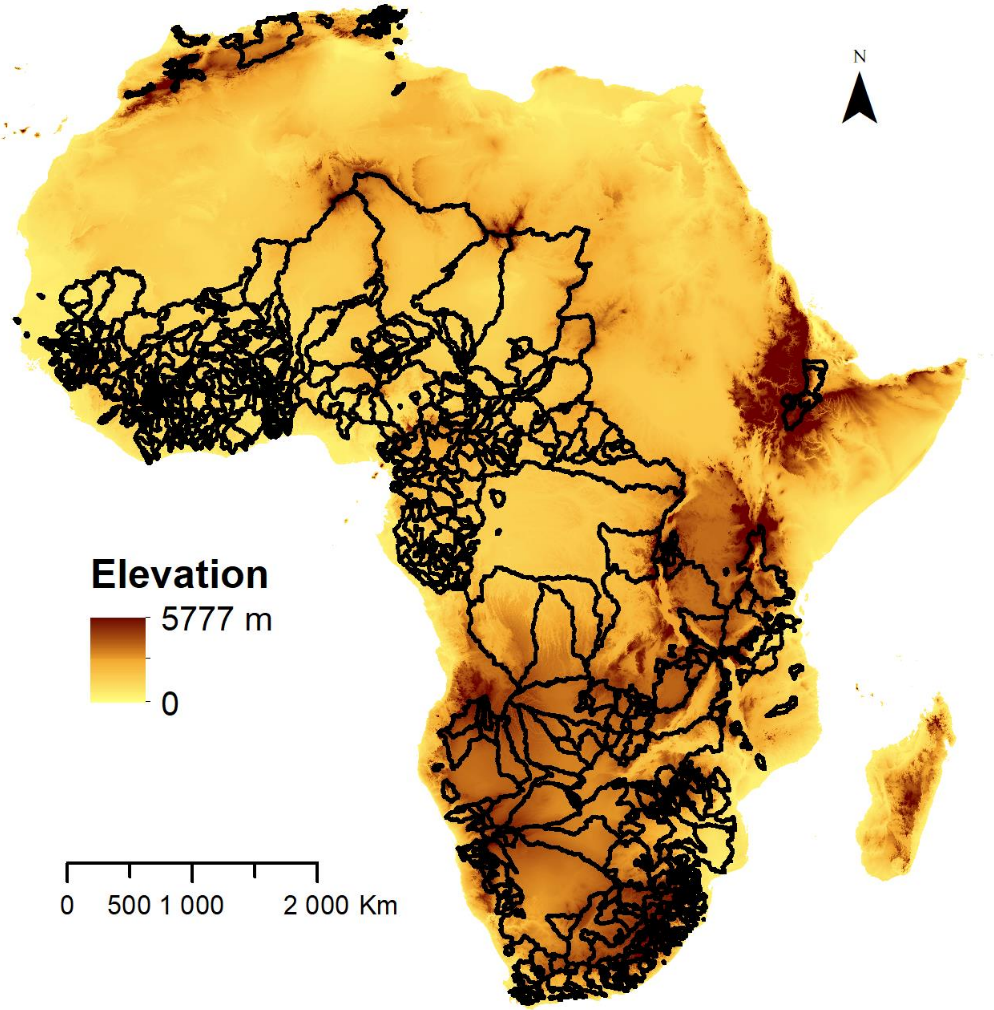

Figure 3: Map of the delineated catchment boundaries in black, with elevation from HydroSheds digital elevation model (https://www.hydrosheds.org/).

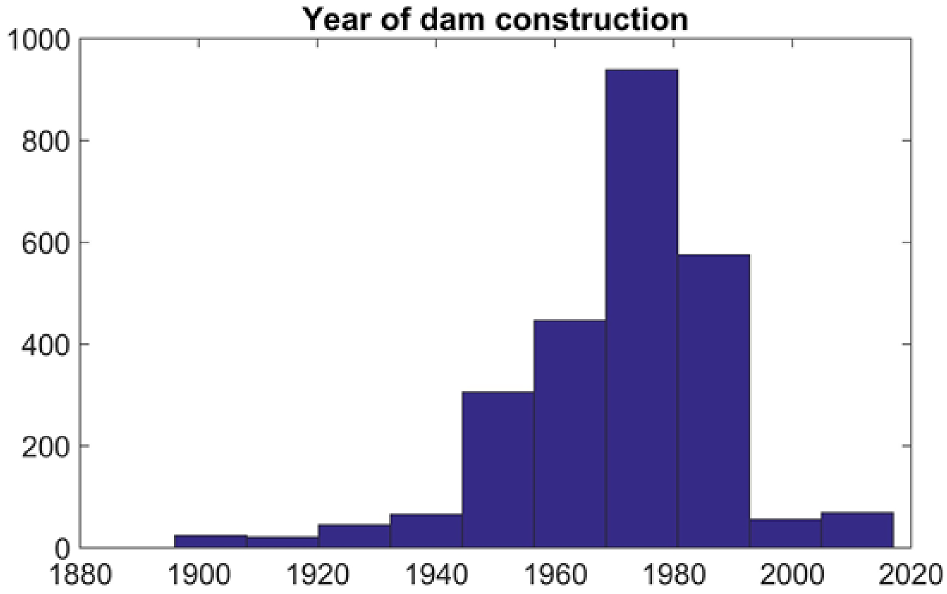

Figure 4: Years of building date for dams located in the catchment database (data from the Global Reservoir and Dam Database v1.3)

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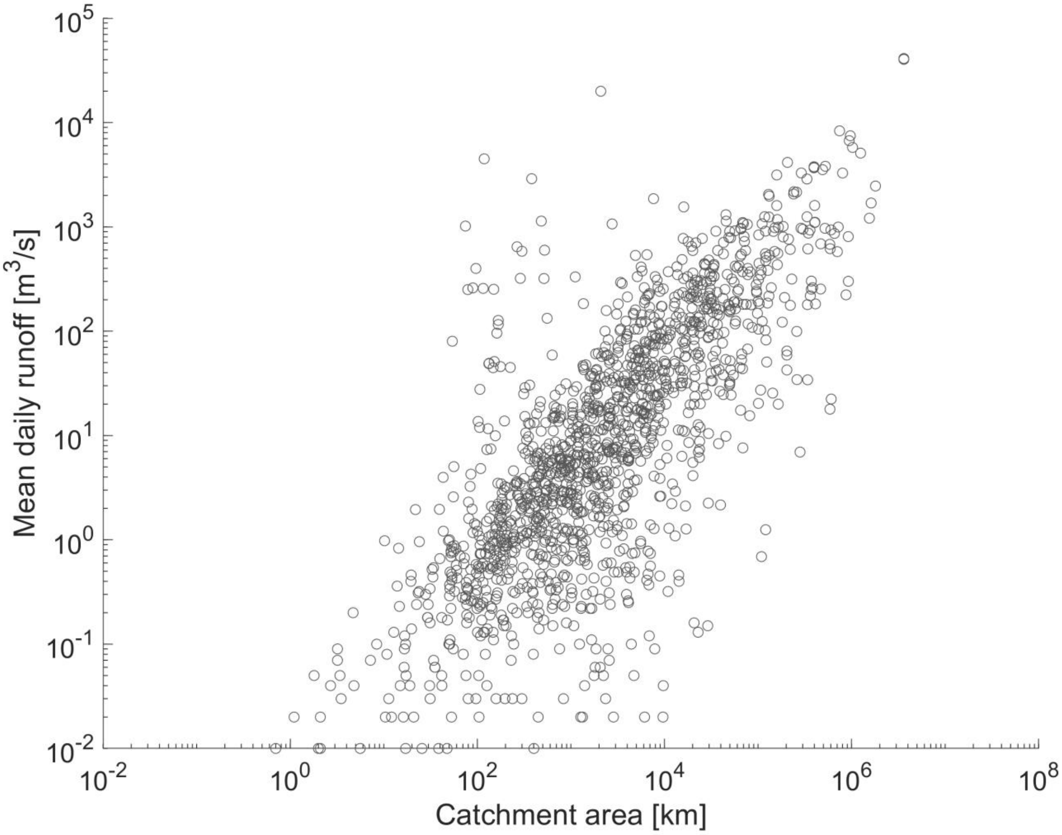

Figure 5: Relationship between mean daily river discharge and catchment area (in log scale)

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