EStreams: An Integrated Dataset and Catalogue of Streamflow, Hydro-Climatic Variables and Landscape Descriptors for Europe

Authors

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Abstract

Global hydrology datasets have become increasingly available, contributing to important scientific advances. However, in Europe, only a few such datasets were published and they only capture a fraction of the wealth of information national data providers have. We present "EStreams", an extensive catalogue of openly available stream records and a dataset of hydro-climatic variables and landscape descriptors for 15,047 European catchments. The dataset spans up to 120 years of records, including catchment-aggregated hydro-climatic indices as well as landscape attributes (terrain, soils, lithology, vegetation and landcover). The catalogue includes detailed descriptions to allow users to directly access the sources of streamflow used, which overcomes data redistribution policies, different languages and structures of data portals. Furthermore, EStreams provides Python scripts for data retrieval, aggregation and processing. This approach enables users to readily and directly update their data as new records become available. Our goal is to extend current large-sample datasets and make a further step towards the integration of hydro-climatic and landscape data over Europe.

Background & Summary

Large-sample datasets are crucial for hydrological analysis, in particular with the growing demand for data-intensive machine learning models[1]. Yet, the data compilation and pre-processing phase can be notably time-consuming and challenging. In this study, we primarily focus on streamflow, the main objective of hydrological predictions. Most countries collect streamflow data on a daily or even shorter time scale at many river gauging stations. However, despite them being, in principle, publicly available, access to these data can be challenging. Identifying where to find and how to retrieve this information can be particularly daunting. Some countries offer this data on the official websites of government agencies or associated data providers, while others provide it upon request only. Official government websites are frequently available only in national languages, adding an extra layer of complexity. Gaining access can be intricate, involving navigation to a selection of stations and periods, which need to be downloaded individually. Furthermore, the data may require substantial formatting and pre-processing before it can be effectively utilized. This poses a critical challenge when conducting hydrological analyses of catchments in large-sample investigations, particularly given the short time horizons of typical research projects.

Following the publication of the MOPEX dataset in the early 2000s, there has recently been a broad and increasing movement to making large-sample hydrology (LSH) datasets available. Many of those were developed inspired by the Catchment Attributes and MEteorology for Large-sample Studies (CAMELS) initiative that compiled and made available full datasets for the contiguous United States[2]. Many countries and regions have embraced these or similar initiatives, including Australia[3], Brazil[4], Chile[5], Great Britain[6], Switzerland[7], Central-Europe[8], North America[9], China[10] and Central Asia[11].

At the global scale, there are already some collection efforts for hydro-meteorological data. The Global Streamflow Indices and Metadata Archive (GSIM)[12,13] provides streamflow indices for 35,000+ locations around the globe, but no extensive set of catchment landscape and meteorological attributes. Recently another global streamflow indices time series initiative took place enlarging the analysis to 41,000+ river branches worldwide and using different streamflow signatures to enrich the flow regime analysis[14]. Considering stream records, the Global Runoff Data Centre (GRDC)[15] provides daily records for 10,000+ stations, but similar to the previous datasets, no catchment attributes and meteorological forcing time series are available. In addition, the GRDC data is only updated episodically, while the others do, to our knowledge, not provide any updates. More recently the Caravan[1] dataset compilation was published as a global initiative for standardizing already open-source published streamflow time series datasets of initially 6,930+ catchments, where catchment attributes and meteorological forcing were derived from gridded global products.

These global datasets, while easy to access, have the limitation that they still represent a fraction of what is currently available from national providers worldwide. The Caravan dataset, for example, originally covered Europe for only Great Britain, Austria and the Danube catchment as far downstream as the city of Bratislava (Slovakia). By now, there are multiple extensions for Denmark, Israel, Switzerland, Spain, Iceland and, most recently, a GRDC extension[16] adding another 25 countries globally. Yet, for eastern and southern Europe publicly available data is still lacking.

The republishing of country-specific data is not always possible due to redistribution restrictions. Another limitation of the currently available large sample hydrology datasets, including all CAMELS databases, is their limited extensibility, making the accommodation of newly available data challenging.

Here, we present "EStreams", an extensive streamflow catalogue and dataset of weekly, monthly, seasonal and annual indices, hydro-climatic signatures, meteorological time-series and landscape descriptors for 15,047 catchments across 38 countries over pan-European territory. Currently, the dataset covers the period from 1900-2022 of varying catchment sizes.

While the focus of EStreams is on streamflow, it also contains catchment aggregated meteorological forcing and landscape descriptors, typically necessary for hydrological analyses. These indices and descriptors were derived from various open sources and include climate[17,18], lithology[19,20], catchment characteristics[21–23], land use and land cover[24–26], soil types [27,28] and vegetation characteristics[29,30]. Similarly to streamflow, national providers often have more accurate information for such auxiliary data. Here we limit ourselves to note that the accuracy of such auxiliary data may vary spatially and may not be the best possible option in some regions, where alternative data may be available but not easily accessible.

Hence, our main contribution with this work is to increase currently available catchment datasets for Europe by about an order of magnitude, to overcome the redistribution limitation and to speed up the data collection process by:

i. The introduction of the currently most extensive and extensible integrated collection of weekly, monthly, seasonal and annual indices of streamflow for Europe. As well as catchment aggregated meteorological and landscape time series and attributes variables for Europe.

ii. Providing detailed streamflow gauge metadata information, catchment boundaries, and data providers.

iii. Finally, making available all codes used to retrieve the source data and aggregate them per catchment in an easy-to-use workflow. This allows both the replicability of the entire results or the extension of it to new datasets by the users.

Methods

This section describes the step-by-step procedure of how the source data were processed to obtain the current dataset.

Streamflow data

Available stations

Daily streamflow data from 15,047 European river catchments with varying sizes and characteristics were aggregated from 38 countries and regions and more than 50 different data providers. Sometimes one single country may have several data providers used in this dataset, as is the case for Italy and Germany. **Figure 1a** shows the distribution of the gauges with their respective catchment boundaries in the background. As can be seen in the figure there is a significant variability in terms of station density which is the highest in central Europe and the lowest in the South and the East. The time series records fall within the period 1900–2022 and vary in length for each catchment as shown in **Figure 1b**. Central Europe is the area with both the longest time series and higher station density, with a considerable concentration of stations reaching more than 80 years of records. Additionally, **Figure 1c** shows the evolution of the number of stations with measurements over the years accounting for the discontinuity of stations over time. The plot shows an increasing trend of gauging stations.

The current streamflow datasets were selected because (i) they were available from official authorities from their respective country or a recent open-access dataset, and (ii) they were open-source and easily accessible either via the internet or under e-mail request. The latter point emphasizes that no dataset where the users need to buy access to data was included. It is important to remark that data that are freely available do not necessarily come with a free redistribution license. Therefore, we cannot and do not make obtained raw daily streamflow data directly available. Instead, we provide descriptive statistics of these data, along with a catalogue of data sources for data download from the original repositories.

This approach has two main advantages:

i. The users can check for temporal and spatial availability, regime characteristics and catchment properties before using the time series optimizing the download phase.

ii. The users can access the most up to date information directly from the data sources.

Finally, **Table 1** shows an overview of the different data providers and their references. France is the country with the highest number of gauges (3,155), followed by Germany (2,093) and Spain (1,440). In contrast, Serbia (6 gauges) Moldova (2) and North Macedonia (1) have only limited numbers of gauges, while several more countries have not readily available, open streamflow data at all. The various data retrieval instructions are described in the detailed catalogue available in the Zenodo repository with all the necessary guidance for data retrieval.

Streamflow gauges labelling

After the collection of the streamflow data and gauge information from each provider, the individual datasets were collated into a single dataset. In this process, each gauge was labelled with a unique 8-digit code. Consequently, each catchment was also renamed according to their respective streamflow gauge. The 8-digit codes were generated with the following logic: the first two digits represent the country/region, two optional ones refer to specifications about the data provider within the countries that had more than one official provider, and the last four digits refer to the gauge counter for each country/region. For example, the gauge GB000045: GB = Great Britain, 00 = only one provider, 0045 = gauge number; ITIS0001: IT = Italy, IS = ISPRA as the data provider, 0001 = gauge counter. The gauges with records obtained from GRDC have the second two digits as "GR" (e.g., LVGR0001) to facilitate identification. With that, all gauges have a code that is standardized for the entire dataset and that offers a direct indication for the user about the source and the number of records.

Duplicated gauges identification

This study introduces a methodology for labelling streamflow gauges based on the possibility of duplication within the dataset. For that, we used a similar approach as used by the GSIM[12], where we identify potential duplicate gauges by examining similarities in gauge and river names. The similarity was explored employing the Jaro-Winkler distance metric to quantify alphanumeric similarity, as discussed by Christen, 2012[31] with a threshold set at 0.75. At the same time, we considered spatial proximity, constraining to pairs of gauges within 1 km of each other, while also verifying that these duplicates originate from distinct data providers. This latter criterion emphasizes the improbability of a single provider providing duplicated gauges within its database. Hence, gauges that followed the four abovementioned criteria were assigned to at least one potential duplicated candidate. Notably, in the interest of presenting a comprehensive catalogue of available data, we retain all potential duplicates in our final dataset.

Basin delineation

Since catchment boundaries were rarely available, this work introduced a semi-automatic delineation of the catchment boundaries for all streamflow gauges using Python scripts and QGIS software. We used the *delineator.py*[32], a Python package for catchment boundary delineation using hybrid vector and raster-based methods. This module requires as input the latitude and longitude coordinates of the streamflow gauges and uses the MERIT-Hydro dataset[21] to derive the boundaries. After the delineation, the catchments were split into two categories: (i) catchments with a reported area from the primary sources and (ii) catchments where this information was not available.

For the gauges where the official catchment area was available, the following workflow to appraise the accuracy of the delineated area was adopted:

i. First the reported area was compared to the calculated area. If the difference was below 10% regardless of catchment size, the delineation was accepted, and the catchment was labelled with a quality flag of "0".
ii. However, if the difference was above 10% the catchment delineation was visually inspected.
iii. After the visual inspection, the catchments were assigned to a specific quality flag as described in **Table 2**, where an overview of the flags used, and the final number of gauges within each flag is shown.

The visual inspection was made using the MERIT-Hydro jointly with the EU-Hydro River network[33], Google Maps satellite imagery and nearby catchments delineated and labelled with a quality flag of "0". The three data sources were used as they tend to represent independent sources and may provide a good trade-off about the catchment delineation usability. During the visual inspection, it was observed for some catchment delineations that the boundary delineation difference to the reported source could be corrected with an adjustment in the streamflow gauge location. We assumed that potential uncertainties brought by the georeferenced system or even the presence of river branches could cause this to happen. For those catchments, we moved the gauge location (snapped) to the closest point within the

MERIT-Hydro River network following the gauge's river and location names which could allow the delineation of a feasible catchment boundary. These catchments were labelled with the quality flag "1" which indicates acceptable delineation after the snap. Because of that, besides the column "lat" and "lon", we also present the "lat_snap" and "lon_snap" which indicates either a repetition of "lat" and "lon" when no snap was done or the new location of the catchment outlet.

In particular for small catchments large relative area deviations might occur. Therefore, apart from the quality flags we also present the attribute "area_perc" for each streamflow gauge. This variable indicates the difference between the calculated area and the one obtained from original data providers. It is important to note that for some situations where human-influence such as canalization, water exports and additionally specific lithologies such as karstic systems, the actual catchment boundary delineation remains challenging. Hence, for such areas, we assigned the code "888" in the quality flag to provide initial guidance to the users that might decide to use or not the current delineation.

From the total of 15,047 stations, 13,899 had a reported catchment area in their primary sources. **Figure 2a** shows the distribution of these streamflow gauges divided into two classes. In red there are the gauges with an absolute difference to the reported area above 50%, and in blue the ones with an absolute difference below 50%. Generally, gauges with high area discrepancies are located in regions with a high gauge density (Denmark), within the presence of many lakes (Denmark and Sweden), small catchments (Ireland) and karstic regions (Croatia).

Figure 2b shows a plot of the exceedance percentage (in %) of the absolute area differences of the 13,899 catchments with any reported area. The plot is limited in the y-axis from 0 to 100 to improve the visualization. Additionally, it also incorporates the dashed red line as the exceedance percentage for catchments with an absolute area difference above 50% as only 8% (1,135 catchments). Moreover, from the plot is also possible to infer that less than 19% of the catchments (2,503) presented an absolute area difference above 10%. Moreover, **Figure 2c** improves the visualization of the catchment area distribution for the subset of catchments with an absolute area difference above 50% (1,135 catchments). The plot reinforces that most of the catchments with high area differences are rather small catchments, with areas below 100 km^2.

Finally, for all the gauges without information about the catchment area (1,115 gauges, 7% of the data) the delineation provided was visually inspected and a label was assigned to indicate the accuracy of the delineation (**Table 2**). The visual inspection was again made using the river name, the MERIT-Hydro and the EU-Hydro River network[33], Google Maps satellite imagery and catchments delineated and labelled with a quality flag of "0".

Catchment aggregated data

The aggregated data provided in EStreams comprises streamflow, meteorological and landscape variables. For streamflow the attributes are divided into streamflow indices, and hydro-climatic signatures. For simplicity, we refer to meteorology as one unique group and divided the landscape into six groups (Terrain, Soils, Lithology, Hydrology, Vegetation and Land cover). The final aggregated data is organized in records of indices (Streamflow), time series (Meteorology, Vegetation and Landcover), and static (Terrain, Soils, Lithology, Hydrology, Vegetation, Hydro-Climatic signatures) categories.

The aggregation of the data at catchment level scripts and the final datasets are available respectively at the current GitHub and Zenodo repositories. The scripts are clustered based on their groups, which allows the users to follow some logical sequence during the use of the codes. All the scripts for data processing are written in Python, but some data retrieval is made with JavaScript written for the Google Earth Engine (GEE) platform. Instructions referring to the version used, where to retrieve and any pre-processing of the original data are well-described in their respective script.

Streamflow indices

This work used the same approach for publishing streamflow indices instead of raw unprocessed daily values adopted by the GSIM dataset[12,13]. We refer as indices the statistics of the records such as mean streamflow, maximum, minimum, percentiles and coefficient of variation, aggregated at the annual, seasonal, monthly and weekly resolution. This approach was previously adapted from the CCl/WCRP/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) (https://www.wcrp-climate.org/data-etccdi), which has developed this method to make relevant climate information publicly available in cases where access to raw daily values is restricted. In this sense, **Supplementary Table 1** shows the Streamflow indices computed and made available in the present database, alongside to their respective description, units and resolution. It is interesting to note that all indices were derived using the gauges specific discharge (in mm/day), which was computed using the calculated catchment area.

As discussed by GSIM, the chosen set of streamflow indices are of high relevance and have been widely used in many hydrological studies. Additionally, they can facilitate the analysis of trends and changes in the regional water balance and the seasonal cycle. All the indices were computed for time-steps where at least 95% of the data was available, e.g., at annual time-step, the indices were computed for years where at least 347 days of data were available.

Hydro-climatic signatures

In addition to the streamflow indices, we computed the same set of meteorological indices and hydrological signatures provided in the original CAMELS[2]. Our motivation is that the used set of hydro-climatic descriptors alongside the other attributes provided will deliver an efficient and detailed overview of the catchments for future users and will enhance the decision process of catchment selection for hydrological analysis. Here we refer to these indices and signatures as hydro-climatic signatures (e.g., streamflow & precipitation mean, seasonality & aridity index, and runoff coefficient). For meteorology, we used precipitation and temperature derived from the Ensembles Observation (E-OBS) product[18]. This work used the hydroanalysis python package[34] for the computation of these signatures.

The full list of signatures used is available at **Supplementary Table 2**. Similarly to the streamflow indices, we used the specific discharge derived using the calculated catchment areas for the signatures' computation. We considered only catchments with more than one year of continuous measurements within the period of 1950-2022. Finally, we also provide the fields regarding the number of years used for the signature's computation ("num_years"), and the start ("start_date") and the end ("end_date") of the measurements between 1950-2022 to give a further overview of the period the signature refers to, considering separately the hydrological ("hydro") and the climatic ("climatic") signatures.

Meteorological records

EStreams uses E-OBS for meteorological forcing data records. E-OBS provides a pan-European observational dataset of surface climate variables, that is derived by statistical interpolation of in-situ measurements, collected from national data archives. It is an open-access database with daily records ranging from 1950-present. The product has been widely used in hydrological works over Europe[35–38] and offers a regional database which may standardize regional studies. Additionally, we used the temperature records from E-OBS to derive potential evapotranspiration (PET) using the Hargreaves formulation[39] and the *pyet.py*[40] Python module for computation. Each catchment therefore has 9 meterological time series associated with it (**Table 3**). Furthermore, the accuracy of E-OBS may be dependent on station density[38], which varies significantly by country. Hence, this work also included information regarding the number of weather stations and density aggregated to a buffer of 10 km within each catchment boundary.

Landscape attributes

A full overview of the landscape attributes derived in EStreams, and respective groups is shown in **Table 4** and **Table 5**, with a short description, their units, and main source. Regarding coverage, except for the landcover & land use and soil types that have pan-European coverage, all the remaining products are global. **Table 4** covers solely the fully static attributes, which refers to the ones that are considered time invariable such as elevation, soil types, main lithology and mean vegetation indices. Conversely, **Table 5** encompasses a group of attributes reported in time series in either monthly and yearly resolution (normalized difference vegetation index (NDVI), leaf-area index (LAI) and snow cover) or a specific number of years (irrigation and landcover).

Terrain attributes were based on MERIT-Hydro[21], which is a digital elevation model (DEM) developed to remove multiple error components from the existing spaceborne DEMs (SRTM3 v2.1 and AW3D-30m v1) and was also used in the catchment delineation. Lithology made use of the widely used Global Lithological Map Database (GLiM)[19] and a gridded product for the estimation of the depth to bedrock[20], which have been used in several applications databases[2,8,41]. For the number of dams and of total upstream volume grouped at hydrology we used the Georeferenced global dams and reservoirs dataset[22]. A similar aggregation was performed for lakes using the HydroLakes dataset[42]. Vegetation indices and snow cover percentage made use of three MODIS products[26,29,30] and were aggregated considering both temporal and static attributes. For irrigation, we decided to use the global dataset of the extent of irrigated land[25], which ranges from 1900 to 2005, and has been already used in other studies[12,13,41]. The soil attributes were based on the European Soil Database Derived data (ESDD)[20,28] and the land cover on the CORINE land cover dataset[24]. Both are widely used products which have been used in previous LSH datasets covering Europe[8,43]. For further description of the catchment landscape attributes adopted in EStreams, users are referred to the respective official sources.

Data Records

The current version of the dataset and catalogue (15,047 catchments) is available at https://doi.org/10.5281/zenodo.10733142. The Zenodo repository is organized into the following subfolders:

- The ***streamflow_gauges*** folder contains two csv-files. One comprises all the metadata associated with each of the 15,047 streamflow gauging stations such as location, river, area, and elevation; another file provides all the data provider information, the streamflow catalogue.
- The ***shapefiles*** folder contains one shapefile with the calculated catchment boundaries associated with each streamflow gauge; and another shapefile with the location of the streamflow gauges. Both files are referenced in WGS 84.
- The ***streamflow_indices*** folder contains one sub-folder per time resolution adopted (weekly, monthly, seasonal and yearly) where there is one csv-file per computed indices. The rows of each csv-file represent the date, and the columns the catchment.
- The ***meteorology*** folder has one csv-file per catchment (15,047 in total) which contains all the daily aggregated meteorological forcing records for that catchment (**Table 3**). The rows of each csv-file represent the date, and the columns each of the 9 derived variables.
- The ***attributes*** folder contains two sub folders. The ***static_attributes*** contain one csv-file per attribute group (i.e., terrain, soils, lithology, hydrology, vegetation and landcover) and encompasses all the attributes shown in **Table 4**. The rows of the csv-file represent the unique gauging stations, and the columns the attribute variable. The ***temporal_attributes*** encompass all the monthly or annual landscape attributes shown in **Table 5**. For the

temporal_attributes*, the* csv-files are either organized where each row represents the unique gauging stations, and the columns the attribute variable, or in the form of a time series where each column represents one gauging station and each row one date.

- The ***hydroclimatic_signatures*** folder contains one csv-file with all the computed hydro-climatic signatures for all catchments. The rows of each csv-file represent the streamflow gauging station, and the columns each of the 25 derived signatures.

Streamflow data catalogue

The main product of EStreams is the European streamflow catalogue, which provides complete guidance about how to retrieve the currently included streamflow data in this publication. **Table 6** shows a full overview and description of the attribute fields included in the catalogue. The "provider_id" field presents the unique code used for each provider. The "code_basins" is used to indicate the first two-four digits in the 8-digit "basin_id" to which each provider is connected. The "provider_country" and "country_code" refer to the country where the provider is located. The "provider_name" shows the official name of the provider.

Additionally, the "license_redistribution" attribute specifies, when available, the data redistribution policy of the data provider. In specific cases, when we cannot secure any information, the user is advised to proceed with caution regarding any redistribution or specific intended use of these data. In these cases, we advise one to directly contact the data provider. The "platform" describes if the data source provides the data on a website or via contact-form/emails. The number of streamflow gauges available at the data source is present in the "num_stations" field, with information regarding the date of the first ("start_date") and last ("end_date") available streamflow measurement made available at the time of download/request of the data at the providers.

The providers links are available for their official website ("website"), license information ("source_license"), streamflow time series ("source_streamflow") and the streamflow gauges metadata ("source_gauges_infos"). Up to four different links are available because the website where the time series is available for download is sometimes not the same as where the gauge metadata is available. The "references" give the formal reference of the data provider, and "observations" are seldom used to give the user additional information about the data retrieval.

Since we intend to provide an extensible and updatable catalogue, we reiterate that users should always refer to the latest version of the Zenodo repository. To enable maintenance, the repository is linked to a GitHub page, which allows users to keep track of potential changes in the data providers, websites, and propose updates, which can lead to new releases of the current catalogue. Therefore, we expect to maintain an updated and dynamic repository for EStreams.

Gauges layer

A full overview of the gauges' attributes and metadata included in this dataset is shown in **Table 7**. We expect that these attributes may offer complete guidance about data availability for users before download, which may optimize the data collection process.

The attribute "basin_id" specifies the 8-digit unique identifier provided for each streamflow gauge while "gauge_id" provides the original code available by the data provider. The "gauge_id" can be useful when future users want to download the original data from their respective sources. The attributes "lon", "lat", "lon_snap" and "lat_snap" provide information about gauge location in the WGS84 projection (EPSG:4326). The "gauge_name" (official name), "gauge_country" (country where the gauge is located) and "river" (river draining to the gauge) attributes include further information about the location of the gauge. The "gauge_provider" provides the data source unique-id, which is also shown in the catalogue

(**Table 6**), and may be used to directly redirect the user to the platform where to retrieve the streamflow data. The attributes "area" and "elevation" provide official information from the official source, while "area_calc", "area_perc" and "area_flag" provide respectively the calculated catchment area, the difference to the area reported by the data provider (when available) and the flag attributed to the respective catchment area delineation.

The fields "start_date" and "end_date" provide respectively the first and last date with streamflow data available and extracted at the publication time from the official data provider. The attributes also provide information about the number of years ("num_years"), months ("num_months") and days ("num_days") with available data for each gauge records. The attribute "num_days_gaps" offers an overview of the number of gaps between "start_date" and "end_date" and "num_continuous_days" specifies the maximum number of days between the "start_date" and "end_date" with no gaps between. The field "duplicated_suspect" provides a qualitative flag derived in this work which shows a potential candidate for duplication for the given gauge.

Finally, regarding nested catchments, the field "watershed_group" assigns a number to the main watershed group the gauge belongs to, e.g., all gauges within the Rhine watershed have the "watershed_group" equals to 1. The "gauges_upstream" gives an indication to the order of the flow gauge by attributing the number of streamflow gauges upstream the given outlet. The smallest "gauges_upstream" in EStreams is 0, which refers to catchments with no gauge upstream besides itself, and the highest is 1,523 (ROGR0012) at the outlet of the Danube watershed.

Catchments layer

The delineated boundary of each catchment is stored in the catchment layer. As expected, this layer also has the same field "basin_id" which was used for the gauges and allows the link between the two datasets. Additionally, the catchments layer also has the fields "gauge_id", "gauge_country", "area", "area_calc", "area_flag", "area_perc", "start_date", "end_date", "watershed_group" and "gauges_upstream", which were already described in **Table 7**.

Technical Validation

Duplicated stations

This work provides alongside the gauges metadata the potential candidates for duplication. This information is useful for users that aim to have a consistent dataset to start their hydrological analysis. The results showed that a total of 156 gauges present a duplicated suspect. This value is only about 1% of the total database, and it means that at least 14,968 gauges in the dataset are unique gauging stations. Additionally, these duplicates represent mainly gauging stations maintained in the boundaries between two countries, and are present in Austria (33), Switzerland (35), Czech Republic (51), Germany (2), Hungary (10), Italy (20), Luxemburg (1) and Poland (3). Notably, as all potential duplicates are maintained in EStreams, users are free for selecting their preferred data provider for the given station.

Basin delineation validation

In this part, we used the dataset provided by the LamaH-CE[8] for Austria, which provides both catchment boundaries and their respective official areas reported to compare to the boundaries delineated by the methodology adopted in this work. **Figure 3a** shows a scatter plot with the comparison between the areas reported at LamaH-CE and those derived in this work. As expected, the main source of scatter between the computed and reported areas is concentrated in smaller catchments. Additionally, **Figure 3b** shows a histogram with the distribution of the percentage of the difference between the two areas (in %). From the 599 catchments provided for Austria at the LamaH-CE dataset, 539 were initially delineated in this work with a percentage area difference to the reported area below 10%. It represents that roughly 90% of the catchments were very well delineated during the automatic part of the delineation.

However, if we consider only catchments with areas above 100 km^2 the number of catchments with delineation discrepancies above the 10% threshold drops from 60 to only 21. After a visual inspection, we concluded that the main source of these discrepancies in the catchment's delineations was either associated to catchments with areas below 100 km^2, and potential difficulties in delineating such catchments or due to small discrepancies between the streamflow gauge location in terms of the MERIT-Hydro network. **Figure 3c-d** shows one example of the catchment delineation workflow for catchment AT000009. The catchment has an officially reported area of 1281.0 km^2, but initially, our delineation derived an area of 4680.0 km^2, a difference of +265.0%. After the visual inspection, it was found that the inconsistency was due to the inaccurate location of the streamflow gauge regarding the MERIT-Hydro River network (**Figure 3c**). As the outlet was not within the river network, the used Python module moved it to the closest river network intersection with the highest drainage area. Hence, we manually adjusted the streamflow gauge location, which provided a delineation of 1,300.0 km^2, a difference of only +1.5% to the reported one provided in LamaH-CE (**Figure 3d**).

E-OBS coverage

EStreams used E-OBS to derive the catchment aggregated time series of meteorological variables. However, the number of stations used to produce the gridded dataset varies significantly from country to country. Here we provide a brief overview of the station densities used to derive precipitation provided in E-OBS within each catchment. We present this analysis only for precipitation since it is considered the most important forcing input in hydrological studies and gives already a significant overview of the E-OBS network. To make a fair comparison, we considered a buffer of 10 km for the catchment boundaries and considered any station within this range to compute the number of stations.

Figure 4a shows the spatial distribution of the stations, and from there, it is possible to spot the major spatial variability. Central and North Europe presents the highest coverage, with Germany and Poland taking the lead in station coverage, while the density decreases significantly towards South and East. Portugal and Spain are the countries with the lowest coverage.

The World Meteorological Organisation (WMO)[44] recommends a threshold of one station per 575 km^2 for the interior plane and undulating areas. **Figure 4b** shows the histogram of the stations' density per catchment included in EStreams. The plot presents the x-axis resampled to stations per 575 km^2 to facilitate the visualization and presents the WMO threshold as a red bin. A total of 11,962 catchments (80% of the total included in EStreams) presented a density above this threshold. Additionally, as observed in **Figure 4b** the catchments presented a median of 8 stations per 575 km^2 (1.3 stations per 100 km^2). With that, we encourage the users to use the E-OBS as a meteorological forcing benchmark for the first hydrological analysis. However, a deeper look at its limitations concerning station density should be taken into consideration mostly when working with data-scarce regions such as the South and East of Europe.

Validation of meteorological forcing

At this step, we further validated the aggregated precipitation forcing derived from E-OBS comparing it to the reported time series available at CAMELS-CH[7] and CAMELS-GB[6]. As the aggregation of the forcing variables used E-OBS gridded data with 0.25 degrees of resolution, we decided to use in the comparison only catchments with areas above 100 km^2. **Figure 5a** shows a scatter plot with the mean daily precipitation available of the E-OBS and CAMELS for comparison. CAMELS-GB is represented in blue and CAMELS-CH in orange. From there it is possible to observe a broad correspondence between the two sources, with a correlation coefficient of 0.89 for GB and 0.94 for CH. Generally, the scatter was more concentrated in catchments with higher daily mean precipitation and the recurrent behaviour was of underestimation from E-OBS when compared to the two sources.

Additionally, **Figure 5b** shows the distribution of the correlation coefficients between each daily time series of E-OBS and CAMELS. Again, it is possible to observe that most of the catchments presented a correlation above 0.8, which reinforces the high agreement between the two precipitation-forcing sources. CAMELS-CH presented overall higher correlation coefficients than CAMELS-GB. This comparison, although only encompasses two different regions over a large span which EStreams covers, was made using two independent sources. Hence, this analysis suggests that E-OBS provides a broadly consistent starting point for representing precipitation time series.

Usage Notes

The current version of the dataset (15,047 streamflow gauges) is available at https://doi.org/10.5281/zenodo.10733142 the data records and at https://doi.org/10.5281/zenodo.10740405 for the code. Moreover, we believe that the EStreams has the potential to be further expanded. Hence, we invite the users to keep track of updates and news at the GitHub repository (https://github.com/thiagovmdon/EStreams/) and to actively collaborate with pull requests and feedback.

Original data: Since all the source data used to aggregate the variables available in EStreams are open source, we do not store any of them in the repository. The users can access and retrieve the original data from their respective sources.

Streamflow data: All the original daily streamflow data has been processed to daily specific discharge prior to any analysis present in EStreams. Due to redistribution reasons, the current dataset does not provide any original daily streamflow time series.

Streamflow catalogue: We recognize that the potential retrospective check and updates of streamflow time series by the data providers may alter the information of the gauges metadata provided here. We also acknowledge that potential changes in the data providers' platforms may alter the available links in the catalogue. Therefore, we invite the users to access the latest version of the catalogue on the project GitHub page for potential updates.

Instructions for Python: We kindly request that future users of the EStreams' codes read and follow carefully the instructions provided in the scripts. In particular, (i) to use the specified version of the Python modules (requirements.txt); (ii) to clone the repository locally and keep all the original folders' names; (iii) to place the original data at their specified folder and with their expected filename and version; (iv) to follow the pre-defined specified order of run for the available scripts (when necessary). Be aware that the potential main source of problems when running the scripts might be caused by not paying attention to these points.

Code Availability

The code used to produce the EStreams dataset at the moment of this submission is available at https://doi.org/10.5281/zenodo.10740405. For the latest version of the code, the users are invited to visit the project GitHub repository at https://github.com/thiagovmdon/EStreams.

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Author contributions

The co-authors T.N., J.R., R.E., M.H., J.S. M.Hr. and F.F. were involved in the development of the concept of this paper. T.N. and J.R. collected and pre-processed the data. M.C. provided guidance to some data providers in Eastern Europe. T.N. wrote the data aggregation and processing codes in Python and Google Earth Engine. T.N. and J.R. processed the catchment boundaries. T.N. wrote the first draft. M.Hr and F.F. retrieved the funding for the project. All co-authors participated in reviewing the manuscript.

Competing interests

The authors declare no competing interests.

Figures & Tables

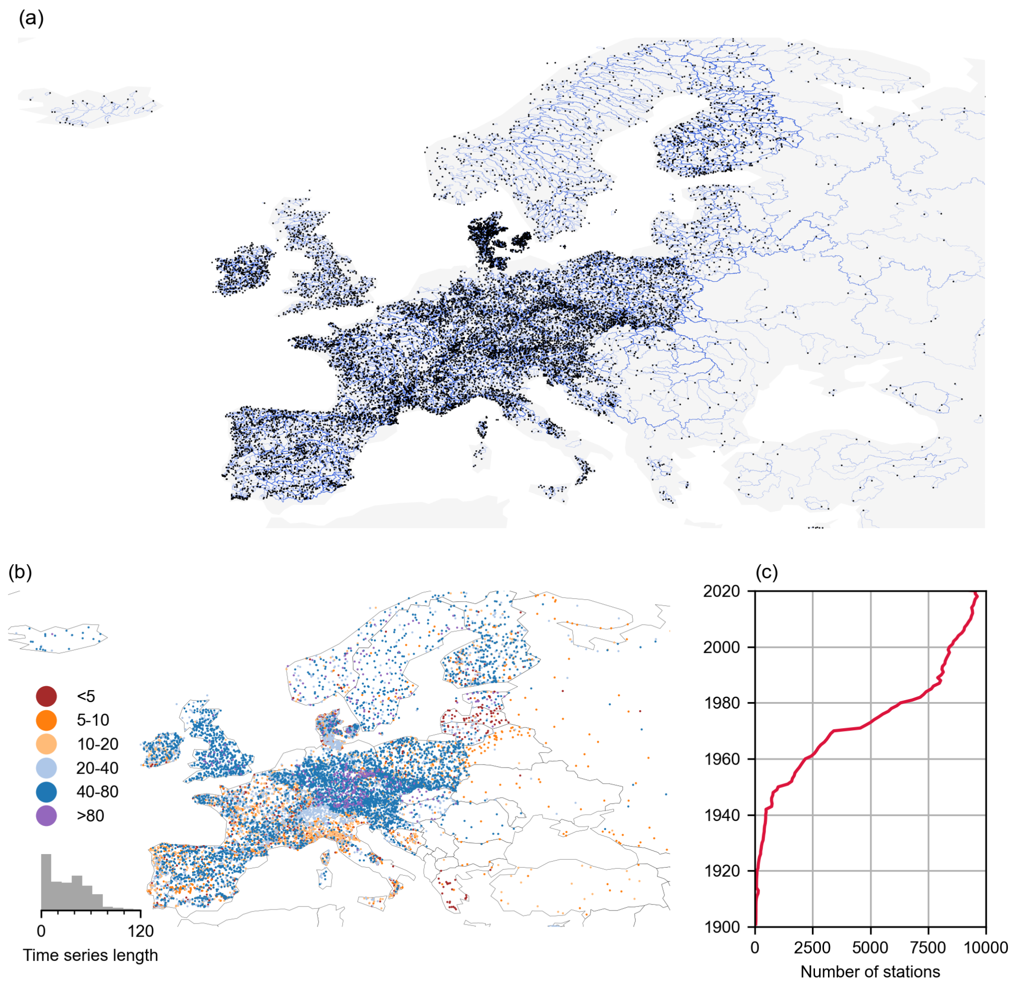

Figure 1. (a) Spatial distribution of the 15,047 streamflow gauges currently included in EStreams (in black dots) with their catchment boundaries in background (in blue) over Europe. (b) Spatial distribution of the streamflow with the colors representing the time series length in years. (c) Temporal evolution of station coverage. The plot shows the number of stations with measurements over the years. Although the curve accounts for dismissed stations, it still shows an increasing trend.

Country/region	Code	Stations	References
Austria	AT	582	BML[45]
Bosnia and H.	BA	91	GDRC[15]; FHMZBIH[46]
Belgium	BE	230	VW[47]; SPW[48]
Bulgaria	BG	8	GRDC[15]
Belarus	BY	51	GRDC[15]
Switzerland	CH	298	BAFU[7,49]
Cyprus	CY	14	GRDC[15]
Czechia	CZ	566	CHMI[50]
Germany	DE	2093	LHW[51]; ASOEAG[52]; Umweltportal[53]; ELWAS-WEB[54]; NLWKN[55]; HLNUG[56]; GKD[57]; LUBW[58]; WB[59]; LBAW[60]; MKUEM[61]; LUBN[62]; BFG[63]
Denmark	DK	1000	ODA[64]
Estonia	EE	54	GRDC[15]
Spain	ES	1440	CEDEX[65]
Finland	FI	669	FEI[66]
France	FR	3155	BanqueHydro[67]
Great Britain	GB	671	NRFA[68]

Country/region	Code	Stations	References
Greece	GR	31	GRDC[15]; OHIN[69]; HCRM[70]
Croatia	HR	158	DHZ[71]
Hungary	HU	98	GRDC[15]; OVF[72]
Ireland	IE	464	EPA[73]; OPW[74]
Iceland	IS	25	GRDC[15]
Italy	IT	767	GRDC[15]; ISPRA[75]; APC Abruzzo[76]; CFRA Valle d'Aosta[77]; ARPAE Emilia-Romagna[78]; ARPA: Umbria[79], Sardegna[80], Lombardia[81,82], Toscana[83], Piemonte[84]; ARPAL Liguria[85]; ARPAV Veneto[86]; SPRUD Trentino[87]
Lithuania	LT	76	GRDC[15]
Luxembourg	LU	19	NGGL[88]
Latvia	LV	61	GRDC[15]
Moldova	MD	2	GRDC[15]
Macedonia	MK	1	GRDC[15]
N. Ireland	NI	51	NRFI[68]
Netherlands	NL	17	RWS[89]
Norway	NO	189	NVE[90]
Poland	PL	1287	IMGW-PIB[91]
Portugal	PT	280	SNIRH[92]
Romania	RO	18	GRDC[15]
Serbia	RS	6	RHSS[93]
Russia	RU	98	GRDC[15]
Sweden	SE	290	SMHI[94]
Slovenia	SI	117	ARSO[95]
Slovakia	SK	21	GRDC[15]
Turkey	TR	28	GRDC[15]
Ukraine	UA	21	GRDC[15]

Table 1. Overview of the different streamflow time series data available per country/region, with some general information regarding number of stations and data providers.

Quality flag	Number of gauges	Description
0	11,168	Difference to the reported area below 10%
1	122	Difference to the reported area below 10% after moving the gauge location
2	835	Difference above 10% or no reported area available, but delineation visually compared to other delineations from down and upstream gauges labelled "1", Google Maps satellite imagery and to the EU-Copernicus River network.
3	297	Difference above 10% or no reported area available, but delineation visually compared to Google Maps satellite imagery and to the EU-Copernicus River network.
4	248	High discrepancy to reported area or no reported area available, but delineation compared to EU-Copernicus River network.
5	69	Delineation manually adjusted using EU-Copernicus in addition to MERIT-Hydro.
6	13	Similar to "5", but still with high discrepancies to the reported area.
888	62	Difference above 10% to the reported area or no reported area available, but location in areas under canalization or karstic.
999	2,200	High discrepancies to the reported area.

Table 2. Description of the quality flags adopted for the current catchment delineations and overview of the number of catchments per group.

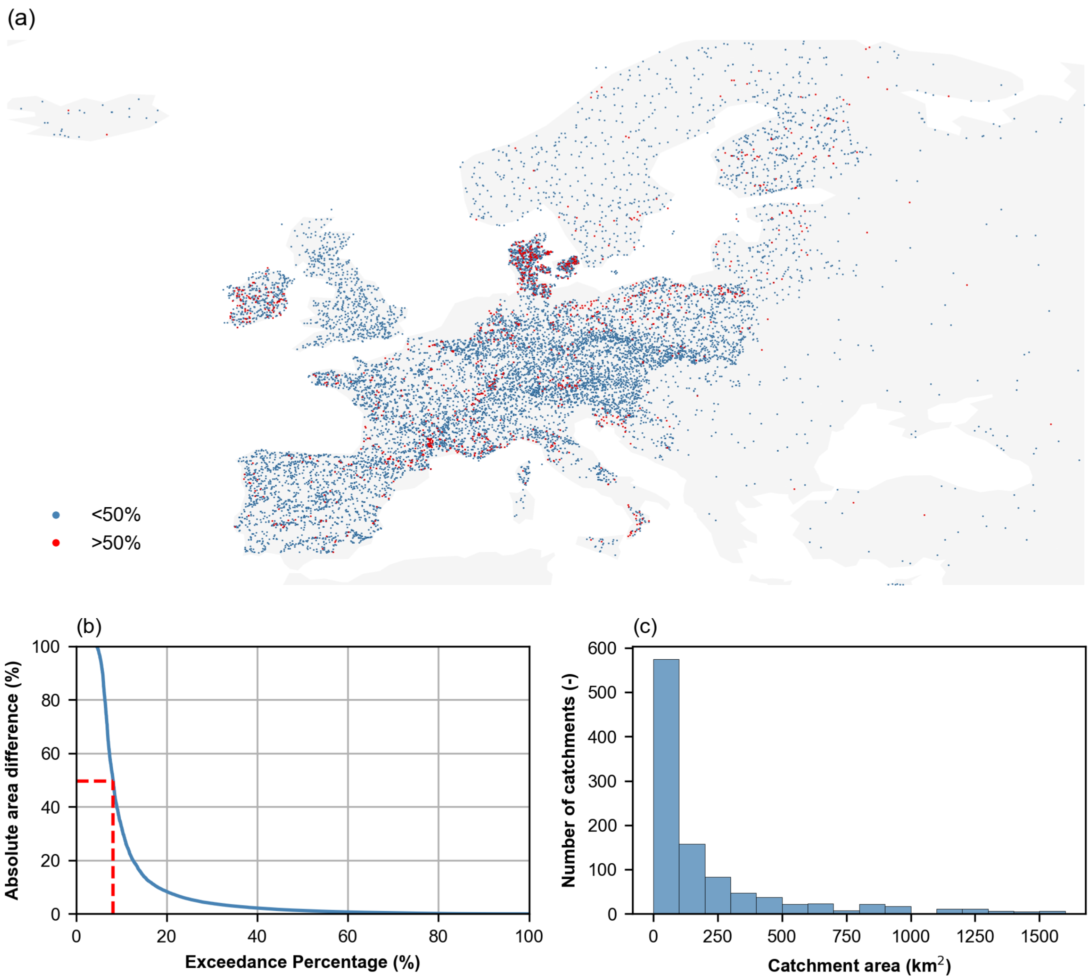

Figure 2. (a) Spatial distribution of the streamflow gauges difference to the reported area classified in above 50% (in red) and below 50% (in blue). (b) Exceedance percentage of the absolute area differences. Notice that there is also a red line highlighting the exceedance probability of areas with a difference above 50%. (c) Histogram of the distribution of the catchment areas considering only catchments with an absolute area difference above 50%.

Group	Attribute	Description	Unit	Source
Meteorology	p_mean	Total mean daily precipitation measured as the height of the equivalent liquid water in a square meter	mm/d	E-OBS[18]
	t_{mean, min, max}	Daily mean, minimum and maximum air temperature measured near the surface	°C	
	sp_mean	Mean air pressure at sea level.	hPa	
	rh_mean	Daily mean relative humidity measured near the surface	%	
	ws_mean	Daily mean wind speed at 10-meter height.	ms^{-1}	
	swr_mean	The flux of shortwave radiation (also known as solar radiation) measured at the Earth's surface.	Wm^{-2}	
	pet_mean	Potential evapotranspiration was estimated using the Hargreaves equation[39].	mm/d	derived
	stations_num_{p,t,sp,rh, ws, swr}	Number of weather stations measuring the given variable	-	E-OBS[18]

Group	Attribute	Description	Unit	Source
		within the catchment boundary assuming a 10 km buffer.		
	stations_dens_{p,t,sp,rh, ws, swr}	Weather stations density for the given variable within the catchment boundary.	stations/km^2	

Table 3. Set of meteorological catchment attributes included in the database available at daily resolution from 1950-2022 and aggregated over each catchment boundary. The table presents both the time series variables and the information regarding the number of stations and density.

Group	Attribute	Description	Unit	Source
Terrain	ele_mt_{mean, min, max}	Mean, minimum and maximum elevation	m	MERIT-Hydro[21,96]
	slp_dg_mean	Mean terrain slope	°	
	flat_area_fra	Percentage of area with slope <3°	%	
	steep_area_fra	Percentage of area with slope >15°	%	
	elon_ratio	Derived elongation ratio[97]	-	
	strm_dens	Stream density, ratio of lengths of streams and the catchment area	$1000 Kmkm^{-2}$	
Soils*	root_dep	Depth available for roots	cm	European Soil Database Derived data (ESDD)[27,28]
	soil_tawc	Total available water content	mm	
	soil_fra_{sand, silt, clay, grav}	Sand, silt, clay and gravel fraction of soil material	%	
	soil_bd	Bulk density	gcm^{-3}	
	oc_fra	Fraction of organic material	%	
Lithology	lit_fra_{class}	Percentage of each lithological class aggregated over the catchment	%	Global Lithological Map Database (GLiM)[19]
	lit_dom	Lithological dominant class	Classes (n=16)	
	tot_area	Percentage of the catchment area covered by GLiM.	%	
	bedrk_dep	Depth to bedrock.	m	Pelletier, 2016[20]
Hydrology	dam_num	Number of dams upstream	-	Georeferenced global Dams and Reservoirs[22]
	res_num	Number of reservoirs upstream		
	res_tot_sto	Total upstream storage volume	$10^6 m^3$	
	dam_yr{first, last}	First and last years of dam's construction	-	
	lakes_num	Number of lakes upstream	-	HydroLakes[42]
	lakes_tot_area	Total area covered by lakes upstream	Km^2	
	lakes_tot_vol	Total upstream volume	$10^6 m^3$	
Vegetation	ndvi_{mean}**	Mean NDVI	-	MODIS[29]
	lai_{mean}**	Mean LAI	-	MODIS[30]
Landcover	sno_cov_{mean}**	Mean snow cover percentage over the catchment area	%	MODIS[26]

Table 4. Set of static catchment attributes included in the present database.
* All soil attributes were aggregated by mean, max, min, P05, P25, med, P75 and P90, which sums to a total of 64 variables.
** NDVI, LAI and snow cover attributes were aggregated considering the total mean and the month of the year (January-December) mean from the period between 01.01.2001 to 31.12.2022, which means that each attribute has 13 variables here referred as static since not shown in a time series format.

Group	Attribute	Description	Unit	Source
Vegetation	ndvi_mean	Monthly and yearly NDVI	-	MODIS[29]

Group	Attribute	Description	Unit	Source
	lai_mean	Monthly and yearly LAI	-	MODIS[30]
Landcover	sno_cov_mean	Monthly and yearly snow cover percentage time series	%	MODIS[26]
	irrig_area_{yr}	10/5-year resolution total area equipped for irrigation	km^2	AEI_EARTHSTAT_IR product from HID[25]
	tot_area_{year}	Percentage of the catchment area covered by the Corine product	%	CORINE[24]
	lulc_dom_{year}	Land cover majority class for 1990, 2000, 2006, 2012 and 2018	Classes (n=44)	
	lulc_{year}_{class}	Percentage of each landcover class aggregated over the catchment for 1990, 2000, 2006, 2012 and 2018	%	

Table 5. Set of the temporal catchment landscape attributes. Vegetation and snow cover attributes have a monthly and yearly resolution from 2001-2022. The irrigation has a variable window resolution of 10-5-years from 1900-2005.

Attribute name	Description
provider_id	Unique code used to refer the basin_id to their respective data provider
code_basins	Code shown in the first two-four digits of the basin_id of their respective catchments
provider_country	Country of the data provided.
country_code	Country code of the data provided.
provider_name	Name of the data provider.
license_redistribution	Type of license when it comes to redistribution.
platform	Platform where the dataset is available. Either a website, or via contact request.
num_stations	Total number of streamflow stations available at the platform by the day the catalogue data was accessed.
start_date	Date of the first available streamflow measurement at the date of request/download.
end_date	Date of the last available streamflow measurement at the date of request/download.
website	Link to the official website of provider.
source_license	Link where the users can get further information regarding license and terms of use (when available)
source_streamflow	Link to the streamflow data provider website.
source_gauges_infos	Link to the official source where the gauges information is available (location, river and name)
references	Formal reference for citing the streamflow data.
observations	Extra information when needed to provide further guidance to the users

Table 6. Attribute fields included in the European Streamflow Catalogue provided.

Attribute name	Description
basin_id	An 8-digit code defined by this work.
gauge_id	The official code available by the data source.
gauge_name	The official name of the station provided by the data source*.
gauge_country	Country where the gauge is located.
gauge_provider	Data source code aligned with the catalogue.
river	The name of the river provided by the data source*.
lon_snap	Longitude of the gauge in WGS84 original or moved.
lat_snap	Latitude of the gauge in WGS84 original or moved.
lon	Longitude of the gauge in WGS84 provided by the data source.
lat	Latitude of the gauge in WGS84 provided by the data source.
elevation	The official gauge elevation reported by the data provider*.
area	The official area reported by the data provider*.
area_calc	The area (km^2) derived from the current delineation methodology.
area_perc	The percentual (%) difference between the reported and the derived area.
area_flag	A quality flag for the current area computation.

Attribute name	Description
start_date	First date with observations.
end_date	Last date with observations.
num_years	Number of years with data.
num_months	Number of months with data.
num_days	Number of days with data.
num_days_gaps	Number of days with gaps between the start_date and end_date.
num_continuous_days	Maximum number of days between the start_date and end_date with no gaps.
duplicate_suspect	If it is the case, basin_id of the gauge suspect of being a duplicate with this gauge.
watershed_group	A number assigning to which main watershed is the gauge belongs to.
gauges_upstream	The number of gauging stations upstream the given gauge.

Table 7. Description of the attributes of the streamflow gauges' layer.
*These are information seldom not available from the official sources.

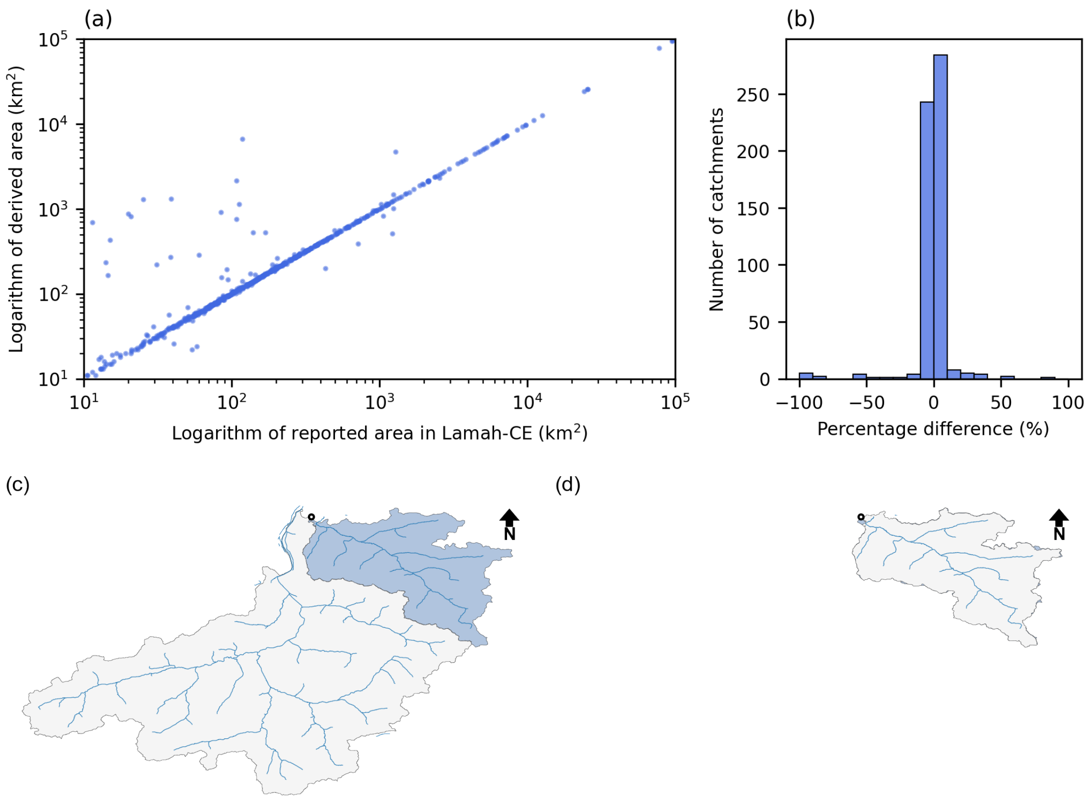

Figure 3. (a) Comparison between the catchments boundaries areas from the reported source into the delineation approach used in this work. Note that the two axes are in the logarithm scale for improving the visualization. (b) Histogram of the percentage difference between the two area sources, where it is possible to notice most of the catchments presenting differences below 10%. Finally, the figure also shows a visual comparison of the catchment boundary delineation generated by this work (light blue) to the equivalent one available at LamaH-CE (light grey) with the rivers within the catchments in background shown in blue. Catchment AT00009 (EStreams) delineations are shown (c) before the manual adjust of the outlet location and (d) after the manual adjust.

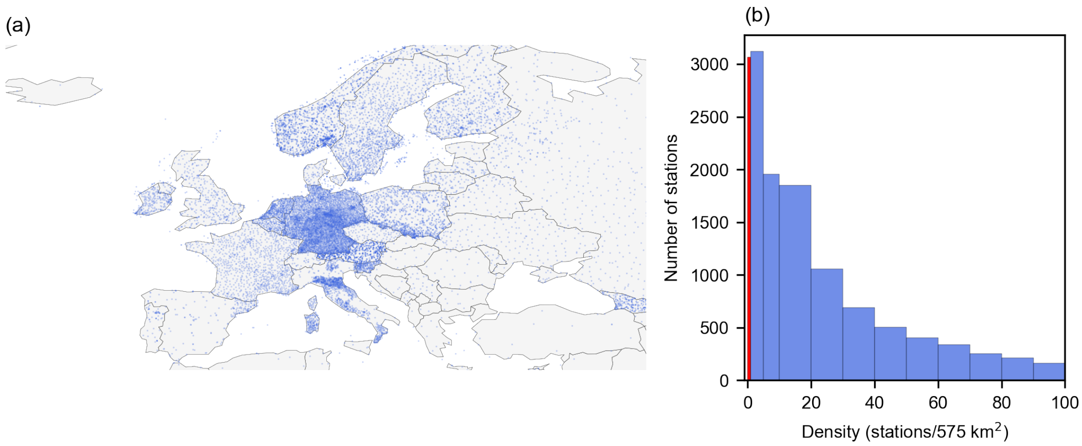

Figure 4. (a) Overview of the spatial distribution of the stations used to derive the precipitation time series grided data available at E-OBS. (b) Histogram of the station's density per catchment. Due to the high distribution of densities the bins are not evenly spaced, and the first bin (in red) corresponds to the WMO recommended minimum threshold of one station per 575 km^2.

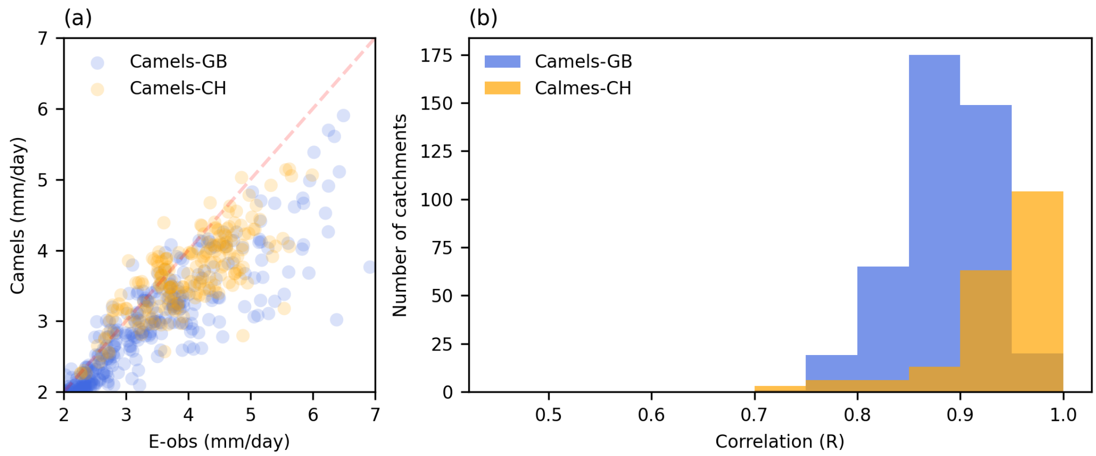

Figure 5. (a) Scatter plot of the long-term mean daily precipitation (1950-2022) considering the precipitation forcing time series derived from E-OBS and the provided in CAMELS-CH and CAMELS-GB and (b) Histogram of the correlation coefficient between the two data sources. The plots only show catchments with estimated areas above 100 km^2.

Supplementary material

Variable	Description	Units	Resolution
mean	Mean daily streamflow	$m^3 s^{-1}$	W, M, S and Y
std	Standard deviation of the daily streamflow	$m^3 s^{-1}$	W, M, S and Y
cv	Coefficient of the variation of the daily streamflow	-	W, M, S and Y
min	Minimum daily streamflow	$m^3 s^{-1}$	W, M, S and Y
max	Maximum daily streamflow	$m^3 s^{-1}$	W, M, S and Y
min7	Minimum 7-day streamflow	$m^3 s^{-1}$	W, M, S and Y
max7	Maximum 7-day streamflow	$m^3 s^{-1}$	W, M, S and Y
p_{5, 10, 25, 50, 75, 90, 95, 99}	Percentile values of the daily streamflow.	$m^3 s^{-1}$	M, S and Y
iqr	Interquartile range of the daily streamflow (P75 minus P25)	$m^3 s^{-1}$	W, M, S and Y

Variable	Description	Units	Resolution
ct	Centre timing, which corresponds to the day of the year (doy) at which 50 % of the annual flow is reached.	day	Y
doymin	The day of the year (doy) at which the minimum streamflow occurred.	day	Y
doymax	The day of the year (doy) at which the minimum streamflow occurred.	day	Y
doymin7	The day of the year (doy) at which the minimum 7-day streamflow occurred.	day	Y
doymax7	The day of the year (doy) at which the maximum 7-day streamflow occurred.	day	Y
gini	Gini coefficient	-	Y

Supplementary Table 1. Streamflow time series indices computed and made available at the present database.

Signature	Unit	Description
q_mean	mm day^{-1}	Mean daily discharge.
runoff_ratio	-	Ratio o of mean daily discharge to mean daily precipitation.
q_elas_Sankarasubramanian	-	Streamflow precipitation elasticity. It represents the sensitivity of streamflow to changes in precipitation at the annual timescale computed using Eq. (7) in Sankarasubramanian et al. (2001), the last element being P/Q not Q/P
slope_sawicz	-	Slope of the flow duration curve computed using Eq. (3) in Sawicz et al. (2011)
baseflow_index		Ratio of mean daily baseflow to mean daily discharge, hydrograph separation performed using the Ladson et al. (2013) digital filter.
hfd_mean	day of year	Mean half-flow date. It represents the date on which the cumulative discharge reaches half of the annual discharge.
hfd_std	day of year	Standard deviation of the mean half-flow dates.
q_5	mm day^{-1}	5 % flow quantile, which represents low flows.
q_95	mm day^{-1}	95 % flow quantile, which represents high flows.
high_q_freq	days yr^{-1}	Frequency of Q > 9 times the median daily flow.
high_q_dur	days	Average duration of flow events of consecutive days > 9 times the median daily flow.
low_q_freq	days yr^{-1}	Frequency of Q < 0.2 times the median daily flow.
low_q_dur	days	Average duration of flow events of consecutive days < 0.2 times the median daily flow.
zero_q_freq	-	Frequency of days with Q = 0
p_mean	mm day^{-1}	Mean daily precipitation.
pet_mean	mm day^{-1}	Mean daily potential evapotranspiration (PET).
aridity	-	Ratio between PET and precipitation.
p_seasonality	-	Seasonality and timing of precipitation, which was estimated using the precipitation and temperature time series.
frac_snow	-	Fraction of precipitation falling as on days colder than 0 $^{\circ}$C.
high_prec_freq	days yr^{-1}	Frequency of P > 5 times the median daily precipitation (high precipitation).

high_prec_dur	days	Average duration of periods with consecutive high precipitation events.
high_prec_timing	season	Season during most high precipitation events occur.
low_prec_freq	days yr^{-1}	Frequency of P events < 1 mm day^{-1} (dry days).
low_prec_dur	days	Average duration of periods with consecutive dry days.
low_prec_timing	season	Season during most dry days occur.
num_years_{hydro, climatic}	-	Number of years with hydrological or meteorological observations used for the signatures' computation.
start_date_{hydro, climatic }	Date	First date with with hydrological or meteorological observations used for the signatures' computation.
end_date_{hydro, climatic }	Date	Last date with hydrological or meteorological used for the signatures' computation.

Supplementary Table 2. Set of hydro-climatic signatures derived in the present dataset. The hydrological year considered in this study starts at 1st of October and goes until the 30 of September. The hydrological time series used are the ones presented at EStreams, and all the meteorology used the aggregated data from E-OBS derived for this work.

* References: Ladson, A., Brown, R., Neal, B., and Nathan, R.: A standard approach to baseflow separation using the Lyne and Hollick filter, Aust. J. Water Resour., 17, 25–34 (2013);
Sankarasubramanian, A., Vogel, R. M., and Limbrunner, J. F.: Climate elasticity of streamflow in the United States, Water Resour. Res., 37, 1771–1781 (2001).
Sawicz, K., Wagener, T., Sivapalan, M., Troch, P. A., and Carrillo, G.: Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA, Hydrol. Earth Syst. Sci., 15, 2895–2911, https://doi.org/10.5194/hess-15-2895-2011, (2011).