The use of GRDC gauging stations for calibrating large-scale hydrological models

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Abstract. The Global Runoff Data Centre provides time series of observed discharges and information on hydrometric stations that are valuable for calibrating and validating the results of hydrological models. We address a common issue in large-scale hydrology that has not been satisfactorily solved, though investigated several times. To compare simulated and observed discharge, grid-based hydrological models must fit reported station locations to the resolution-dependent gridded river

10   network. We introduce an Intersection over Union ratio approach to selected station locations on a coarser grid-scale, reducing the errors in assigning stations to the correct upstream basin. We update the 10-year-old database of watershed boundaries with additional stations based on a high-resolution (3 arc seconds) river network and provide source codes and high- and low-resolution watershed boundaries to easily select stations for calibration/validation of hydrological models. The dataset is stored on Zenodo with the associated DOI https://doi.org/ 10.5281/zenodo.6906577.

1 Introduction

River discharge is one of the most important variables in hydrological modeling because all basin processes are integrated into this variable. Discharge spatially and temporally integrates the range of meteorological variables and basin characteristics. Spatially and temporally distributed properties of river and lake morphology, soil, groundwater, snow, glaciers, climate, land cover, and human interaction influence discharge at the outlet of a basin. Although discharge is a useful indicator, for semi-

20   arid and arid regions, its value declines as evapotranspiration becomes the most significant basin outflow, as it then represents relatively less of the water cycle outflows (e.g., Norwegian basins have a discharge/actual evaporation ratio of 80/20, and African basins can have a ratio of 20/80). Discharge is extremely useful for calibrating and validating hydrological models using different objective functions, such as Nash-Sutcliffe (Nash and Sutcliffe, 1970) and Kling-Gupta (Kling et al., 2012) for calibrating global hydrological models (Müller Schmied et al., 2021; Sutanudjaja et al., 2014; Hanasaki et al., 2008). It is also

25   useful for tasks like estimating flood hazards (Alfieri et al., 2015), inland navigation (Nilson et al., 2013; Christodoulou et al., 2020), energy power production (Hunt et al., 2020; Van Vliet et al., 2016), and water scarcity (Hoekstra et al., 2012; Van Beek et al., 2011).

Since the establishment of the Global Runoff Data Centre (GRDC) database (Vorosmarty et al., 1998; Fekete and Vörösmarty, 1999), the number of stations has increased, and the number of publications using the GRDC dataset is also growing - the GRDC publication database of 2021 (GRDC, 2020) references 118 publications using the discharge time series. The Generic Statistical Information Model (GSIM) database (Do et al., 2018) provides a good overview of several river discharge databases worldwide. Although there are several public databases of river discharge at a basin-scale (e.g., Mekong basin, Mekong River Commission (2020)), the GRDC database offers the richest source of global river discharge data, as follows:

> "A global hydrological database is essential for research and application-oriented hydrological and climatological studies at global, regional, and basin scales. The Global Runoff Database is a unique collection of river discharge data on a global scale. It contains time series of daily and monthly river discharge data of well over 10,000 stations worldwide. This adds up to around 470,000 station-years with an average record length of 45 years" (GRDC, 2020).

The GRDC database of river discharge comes which information about the stations from the data providers, like the location of the station, name of the station and the river, upstream area, elevation, mean discharge, and more. Especially the location and the upstream area are very important to compare model results from hydrological models with station discharge data.

Quality checking of station attributes and spatial redistribution of station locations for different gridded river networks for hydrological models have been carried out since the beginning of GRDC data collection (Fekete and Vörösmarty, 1999) and for each model again and again (Sutanudjaja et al., 2018; Zhao et al., 2017; Wang et al., 2018). For example, to test the Community Water Model (CWatM) (Burek et al., 2020) global model performance on 30 arc minutes ($=0.5°$ ~ 50 km x 50 km, hereafter, 30'), we used the station data and the global drainage direction map (DDM30) network (Döll and Lehner, 2002) and corrected the locations to fit with the approach of Zhao et al. (2017). Several errors can occur when the discharge station is used for gridded hydrological modeling, as follows:

a) The station location is not at the correct location and is too far from the river.

b) The station location is at the correct location, but because of the river width and/or the grid resolution of a high-resolution river network, the station location is not in the suitable grid cell of the river network or because, even at 1090 meters, the network is not high-resolution enough to capture the station location.

c) The high-resolution network does not represent reality (e.g., the river does not flow in the deepest part of the valley because of human interventions).

d) Upscaling error. When a coarser resolution for hydrological modeling is applied (e.g., 30' for ISIMIP), using the original station location might lead to its position being wrongly assigned because, for instance, the coarser grid cell river network may include the junction with a tributary. In contrast, the station may indicate the tributary itself.

e) Mismatch error. Suppose the station location is selected only by comparing the upstream area of the upscaled network with the reported upstream area. In that case, a station could be assigned to the wrong basin because the upstream area fits slightly better.

f) Global station density is unevenly distributed. We find a high density for North America and Europe and a low
65   density for Asia and Africa. In North America or Europe, some stations are close downstream to other ones, even though no significant tributaries are entering.

This paper aims to provide a Python code to easily select stations for calibration/validation of hydrological models byThis paper addresses addressing these possible errors and giving es examples of how to correct them. Lehner (2012) has already
70   calculated explicit watershed boundaries for 7,163 basins on a high-resolution network. These watershed boundaries are freely available on the GRDC webpage (GRDC, 2020). We repeated this exercise, but using a higher-resolution network based on a more up-to-date dataset, the (3 arcseconds (3"(~10093m or exactly 92.61 m at the equator, hereafter, 3'') MERIT hydro-network (Yamazaki et al., 2019) rather than the 15 arcseconds (~500 m) HydroSHEDS (Lehner et al., 2008). Moreover, we used a greater number of GRDC stations added in the last ten years (10,701 stations as opposed to 7,532). In addition to the
75   high-resolution basins, we added a method for upscaling each station automatically to 5' (~10 km) and 30' (~50 km) using a more advanced method than simply comparing the river network upstream area with the reported upstream area. Using this method, a selection of stations can be appropriated to the resolution of the hydrological model. Furthermore, our code is available and open source in Python to change or calculate stations for individual applications.

2 Methods

80   The methods can be split up into three main groups, each group building upon the results of the previous one. The first method describes allocating a station location from the GRDC database to fit best on a high-resolution network. This method reproduces the approach from Lehner (2012). The second method describes how to upscale the station location from a high-resolution network to a low-resolution network used in standard land-surface hydrological routing models by comparing upstream area and similarity of the station upstream areas in high and low resolution. The third method describes how to select
85   the most appropriate stations for calibrating hydrological models, depending on the metadata of the stations and the chosen model grid resolution.

2.1 Procedure for station allocation on a high-resolution network

2.1.1 Automatic procedure

90   We used the MERIT hydro database of Yamazaki et al. (2019), which comes as an open-source database in chunks of 5° * 5° at 3'' arc seconds (~100 m) resolution (36 billion grid cells per 5° * 5°). We used the river network direction maps and applied

the D8 flow model convention: either each grid cell can flow into one of the eight neighboring grid cells, or it is a sink. This approach, which does not allow rivers to be split into two streams or grid cells to contribute to several basins simultaneously, is used in most Land-Surface Models and grid-based hydrological models. We obtained the upstream area of each high-resolution grid cell from the upstream area in km^2 from the MERIT dataset. For the evaluation, we used all stations with an reported upstream area greater than or equal to 10 km^2 (124 stations have an upstream area smaller than 10 km^2) or with no reported upstream area record (327 have no upstream area record in the GRDC dataset).

For the automatic station allocation, we mainly follow the protocol of Lehner (2012):

1. A rectangular search radius of 165 arcsec (~5 km) for each station was defined.
2. For each grid in this rectangle, the upstream drainage area (UPA) from the network from Yamazaki et al. (2019) was compared to the area reported in the GRDC, and the upstream area accordance is computed:

    o Upstream area error = |1 - GRDC reported area / gridded network upstream area|

    o Area accordance = minimum {GRDC reported area, gridded network upstream area} / maximum {GRDC reported area, gridded network upstream area}

    Upstream area accordance = GRDC reported UPA / gridded network UPA

    (where: GRDC reported UPA < gridded network UPA)

    Upstream area accordance = gridded network UPA / GRDC reported UPA

    (where: GRDC reported UPA ≥ gridded network UPA)

3. All cells with an upstream area accordance of less than 50% were dismissed from further evaluation.)

3.4. A first ranking scheme – area discrepancy (RA) - was calculated with values between 0 (best fit) to 50:

    RA = 100 - Upstream area accordance[%]

4.5. For the second ranking scheme – distance (RD) – the distance of the cell to the reported station location in the GRDC database was calculated and normalized to get the value 0 at the station location and 50 in 5 km distance. The distance to the original location of the station was computed.

5.6. An objective criterion (OC) for ranking was computed by OC = RA + 2 * RD. The equation and weighting were taken from Lehner (2012).(1- Area accordance) + 2 * distance

6.7. The grid cell with the lowest OC value was taken as the corresponding grid cell for the station location on a high-resolution network

7.8. If no station location was found in this step, the search radius was increased to 5'30 arc seconds (~10 km), OC was calculated as OC = RA + RD, and the lowest OC value was taken as the corresponding grid cell.

2.1.2 Manual procedure for the remaining stations

For the ~7.5% of the stations that failed both rounds of searching, we carried out the following manual inspections:

- 3% of the stations in the GRDC database (327 stations) have a reported area of -999. For these stations, we used the next
125   biggest river. We checked manually with GIS, but we did not check all station information manually (e.g., station name, river name, and altitude).
- 1.5% of stations that failed the automatic search but had a valid UPAupstream area record (169 stations), we manually checked and assigned a location in the range of up to 120 km from the original site (to address any typographical error, e.g., 51.57° instead of 52.57°)
130 - For 2.23% of the stations (228352 stations), we could not find an adequate location on the high-resolution network - due perhaps to errors in the GRDC database or insufficient network maps (e.g., missing canals, braided rivers, diversion, and confluent rivers)

2.1.3 Output: Polygons of basins

For 10,349 basins, we assigned polygons based on the reallocated station locations on the high resolution (3'' arc seconds)
135   with the Python library flwdir from Eilander et al. (2021) and the river direction mosaic maps from Yamazaki et al. (2019). Like the original from Lehner (2012), we produced two versions: a) polygons that follow the exact grid cell contours with high memory requirements, and b) a version with smoothed edges and low memory consumption. The resulting shapefiles were produced in the ESRI shapefile format and included the station information from GRDC. This process addresses errors a), b), and c) (noted above) and provides an update to the shapefiles of Lehner (2012)

140   **2.2 Upscaling station location to a coarser grid cell resolution**

The main idea of creating a new set of high-resolution watershed boundaries was not to update the work of Lehner (2012) but to use a different method of assigning station discharge time series to the correct grid cell in grid-based hydrological models. Global hydrological models use 30' arc minutes resolution in the ISIMIP3 project (Warszawski et al., 2014). The trend for global modeling is to move toward higher resolutions at 5' and hyper resolution (≤ 1km) (Bierkens, 2015). For regional studies
145   (Hanasaki et al., 2022; Guillaumot et al., 2022), the resolution is already 1 km or below. Approaches to upscaling to coarser resolutions are mainly based on comparing reported UPA and UPA calculated from the river networkupstream network areas (Fekete and Vörösmarty, 1999; Zhao et al., 2017).

With the flwdir tool from Eilander et al. (2021) and with the idea of Munier and Decharme (2021) of comparing the similarity
150   of shapes, it is possible to introduce another objective criterion - the similarity of high-resolution watershed boundaries and low-resolution boundaries. Using the method of comparing upstream areas, we can partly address error (d) upscaling error but not errors (e) and (f).

For an automatic upscaling process, we followed this protocol:

155   — We defined a minimum UPA~~upstream area~~ for the station we wanted to use in the low-resolution hydrological model (e.g., UPA ≥ 9,000 km^2 for 30' (~3~~1~~80 cells), UPA ≥ 1,000 km^2 for 5' (~12~~00~~ cells))~~.~~

-   ~~A search radius of 5 * 5 = 25 grid cells of the coarse resolution network was used with the high-resolution allocated station located in the middle.~~

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160 - To find the grid cell on the coarse resolution network which fits best to the UPA and shape of the high-resolution network, we calculated two objective criteria for all coarse grid cells with a distance <= 2 coarse cell distance (altogether 25 grid cells) to the location of the station on the high-resolution network (see figure 1)

- For each coarse grid cell, the coarse UPA ~~watershed and upstream~~ was~~ere~~ derived, and the upstream area accordance was computed as first objective criterion.

165   upstream area accordance = GRDC reported UPA / coarse UPA (GRDC reported UPA < coarse UPA)

  upstream area accordance = coarse UPA / GRDC reported UPA (GRDC reported UPA ≥ coarse UPA)

The upstream area accordance can have a value between]0,1], with 1 having GRDC and coarse UPA having the same value.

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170 - The second objective criterion was the Intersection over Union ratio (Rezatofighi et al., 2019; Munier and Decharme, 2021). Intersection over Union ratio = Area ~~of i~~Intersection / Area ~~of u~~Union

Therefore the watershed shape for the station on high-resolution and the shape for each coarse grid cell was created. The area of intersection represents the area the high-resolution and the low-resolution shape have in common. The area of union represents the area of the combined shapes of high and low resolution. The Intersection over Union ratio can have a value between [0,1]. The closer to 1 the Intersection over Union ratio value, the more similar the shapes are.

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- ~~The closer to 1 the value of Intersection over Union ratio is, then the more similar the shapes are.~~

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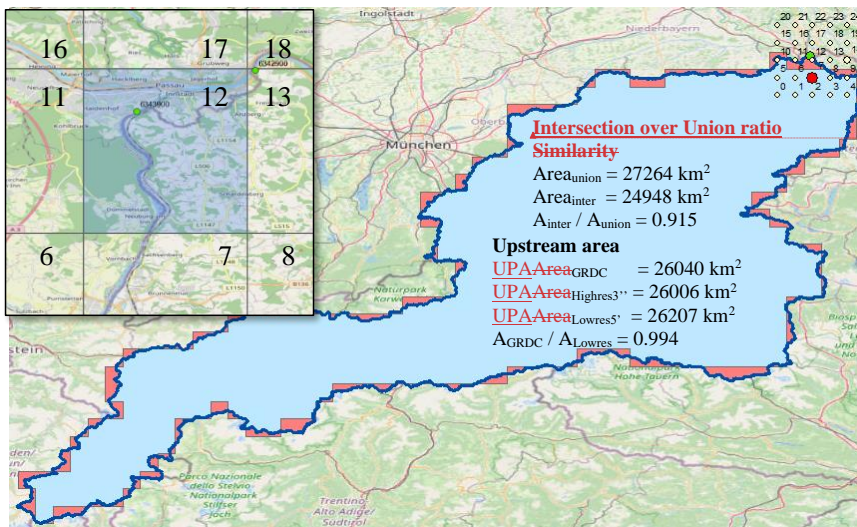
- To reduce the two objective criteria to one solution, the minimum Euclidian distance between the best possible
180 solution (at 0,0) and the two objective criteria was calculated. Both objective criteria have a range between 0 and 1. Therefore, we decided to use a weighting factor of 1 for both criteria.

$$ED = \sqrt{(1 - Upstream\ aArea\ accordance)^2 + (1 - Intersection\ over\ Union\ ratiosimilarity)^2}$$

- ~~For the example in Figure 1: Passau Inn: ED$_{min}$ = 0.085 at location No 7~~

- The coordinates on low-resolution with minimum Euclidian distance were chosen as the station coordinates for this
185 grid size resolution

Figure 1 illustrates this method for low resolution 5' and for cell location No. 7, which is one 5' cell south of the cell where the station "Passau/Inn" is located (see the zoom in the upper left part of figure 1). Even if this cell is not

representing the cell where the station is located, this cell fits the upstream area accordance and the Intersection over Union ratio best of all 25 cells around the station location.

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Intersection over Union ratio Similarity
$$Area_{union} = 27264 \text{ km}^2$$
$$Area_{inter} = 24948 \text{ km}^2$$
$$A_{inter} / A_{union} = 0.915$$
Upstream area
$$UPAArea_{GRDC} = 26040 \text{ km}^2$$
$$UPAArea_{Highres3''} = 26006 \text{ km}^2$$
$$UPAArea_{Lowres5'} = 26207 \text{ km}^2$$
$$A_{GRDC} / A_{Lowres} = 0.994$$

Figure 1: Intersection over Union ratio for the River Inn basin at Passau, Germany, GRDC 6343900. The dark blue line is the watershed of the Inn to Passau at a 3" high resolution. The light blue is the intersection between the low-resolution Inn at 5' and 3'', and red signifies the union of the 5' basin with the 3'' basin. **).** © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

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Figure 2 shows four examples of the 25 cell locations around station "Passau/Inn". Figure 2a uses the cell where the station is located. This cell represents not only the Inn, but the also the Danube and the Inn basin. Figure 2b includes only a small tributary of the Inn and figure 2c contains only the Danube basin but not the Inn basin. Figure 2d shows the best location (one grid cell south of the grid cell with the station – same as in figure 1).

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As a result, we obtain a pair of coordinates for each station on a coarser resolution. Here we chose 5' and 30'. For 5', the network from Eilander et al. (2021) was used based on the high-resolution network from Yamazaki et al. (2019), while for 30', the DDM30 network from Döll and Lehner (2002) was used, as this is the agreed network for the ISIMIP2 and ISIMIP3 (Frieler et al., 2016) hydrological modeling effort.

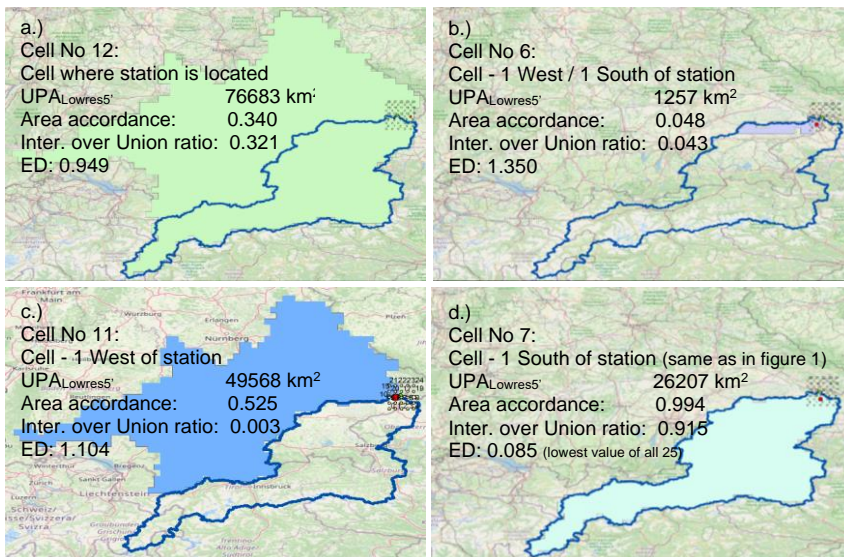



Figure 2: Concept of similarity for the station Passau, Inn, Germany - GRDC 6343900 with a high-resolution watershed map shown as a blue outline and four different watershed maps based on a 5' resolution network around the station location. © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

2.3 Selecting station for calibration of a hydrological model based on metadata

In the previous step, we selected stations based solely on location metadata. For the next selection step, we included meta information of time series like length, end date, and the number of missing values in a time series. For calibration or validation, the unsuitable stations were those with only short time series, those that ended too far in the past, and those with too many missing values. The criteria for "too short" and "too old" are subjective and can be chosen in another way, as in Alfieri et al. (2020), but if the criteria are not strong enough, a post-selection can be done. If they are too rigid, the settings part of the Python code can be changed. Fortunately, all the necessary information is included in the metadata file from GRDC.

2.3.1 Deselection and ranking criteria

We included several criteria for selecting or deselecting a station (see table 1). We derived the first two criteria from the previous analysis of the station location.

- The accordance of the UPAupstream area on the chosen resolution with the area reported from GRDC: here, we chose a relatively forgiving upstream aArea accordance. If the upstream area of the selected resolution had a criterion of more than 40%, this criterion is fulfilled. In most cases, the area was above this ratio, but we did not want to deselect stations where the GRDC record might be accurate.

- The ~~similarity index~~ Intersection over Union ratio between the high-resolution shapefiles and the shapefile of the chosen resolution: the high-resolution shapefile was built on the 3'' MERIT network data. The 30' had a different source and went through an upscaling approach. Therefore, more significant discrepancies between the high-res shapefile and the low-res 30' were possible.

We included two selection criteria from the metadata information about the time series.

- The time series should have at least five years of monthly or daily records.
- The end date of a time series should be later than 1985.

Table 1: Selection criteria based on low-resolution

Name of criterion	Selected at 30'	Selected at 5'
Intersection over Union ratio~~Similarity~~	70%	80%
Ups. a~~A~~rea accordance	40%	40%
Years in time series	5 years	5 years
End date	1985	1985

2.3.2 Division of stations

The stations may be too close to each other for it to be worth calibrating both. We checked the similarity of the low-res shapefiles. If they were equal to or more than 95% similar, we decided to calibrate only one station and keep the other for validation purposes. To choose which of the similar stations we kept for calibration, we introduced a ranking/scoring system. If a station had a higher Intersection over Union ratio or upstream area accordance than 80% it got one scoring point for every 2%. Stations earn scoring points for every five additional years of time series length and for end dates of the time series after 1985. For missing data in the time series, scoring points are subtracted (see Table 2 for the scoring criteria). The station with the higher scoring points is chosen. These criteria are subjective and can be changed in the Python code.

~~If a station had a more extended time series or a more recent end date (see Table 2 for all the ranking criteria), we chose the station with the higher score.~~

Table 2: Scoring where two stations are too similar

Name of scoring	0 points at	1 point for every	Max/Min points
Intersection over Union ratio ~~Similarity~~	80%	2%	10
Ups. a~~A~~rea accordance	80%	2%	10
Years of time series	5 years	5 years	10
End date	1985	3 years	12
Missing %	100%	Neg. point for 5%	-20

245 **2.3.3 Output: List of stations to be appropriated for calibration**

As a result of this step, we obtained two tables for 30' and 5' that distinguished the stations as useful for calibration, stations that could be used for validation, and stations that were not recommended for calibration or validation. All evaluation was solely based on the metadata file provided by GRDC.

3. Results

250 **3.1 Station allocation on high resolution**

The March 2022 GRDC station dataset has 10,701 stations in total. We used only those stations with an UPA~~upstream area~~ equal to 10 km^2 (thus discounting 124 stations), but we kept the stations without data for the UPA~~upstream area~~ (327 stations). Using automatic detection of the most appropriate high-resolution MERIT network on 3'' and with manual search (for 169 stations), we still had 228 stations we could not assign to a basin. Figure 3 shows the global distribution of GRDC stations
255 (status: March 2022), with a high concentration of stations in North America and Europe and a lower and more clustered distribution in Africa and Asia.

For further analysis, we had 10,349 stations with a counterpart in a location on the MERIT network and an assigned basin on 3'', and 49 of these basins did not have a reported area in GRDC. From the remaining 10,300 stations, we calculated the area
260 in accordance ~~between~~ with the GRDC reported UPA~~upstream area~~ and the area calculated on the high-resolution network using UPA maps from Yamazaki et al. (2019). We kept only those with an upstream area accordance ≥ 0.4 (1,0241 stations). For hydrological modeling, this accordance ~~error~~ might be too low~~big~~. Still, we assumed there ~~are~~ were some errors in the reported area of GRDC and that these stations could be deselected in a further step, if necessary.

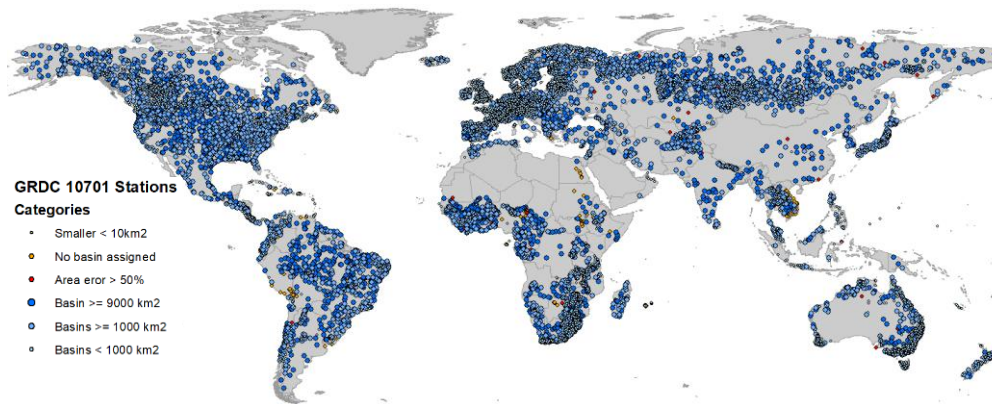



Figure 3: Location and categories of 10701 GRDC stations (World administrative boundaries by https://www.opendatasoft.com)

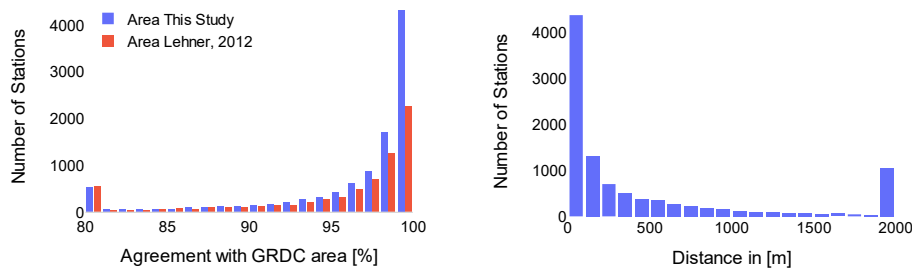



Figure 4: Histogram of (a) accordance with GRDC upstream area and (b) distance from the corrected location to the GRDC location

The histogram of upstream area accordance in Figure 4a and Table 1 shows that a high number of stations (43%) have upstream area accordance that is equal to or more than 99% (an area error of less than only 1%). Compared with the work from Lehner (2012), we obtained a slightly higher percentage of accordance in this class but almost twice as many stations (4,332 vs. 2,422). 88% (85% for Lehner (2012)) still had good accordance of 90% or more. 330 stations had an area accordance of less than 75%, 18 stations of less than 50%, while 49 stations had no area reported.

Figure 4b shows the distance in meters from the reported station coordinates in GRDC and the station location according to the high-resolution network. A necessary shift in stations might be required because a) the river network is not high-resolution enough to capture the river (see Figure 5d), or the river width is greater than 90 meters, and it would be necessary to shift the station location from the river shore into the middle of the river to match with the high-resolution network. However, we assumed that most distance errors greater than 500 meters come from the stations being wrongly allocated. Table 3 1 shows

280 that the percentage of upstream area accordance negatively correlates with the distance median. (Here, the distance is the distance in meters between the reported station location in the GRDC dataset and the location represented in the 3'' MERRIT network. The median of distance is calculated as the median of distances for all stations in each row of table 3.)

Table 3: Comparison of stations with accordance in area of high-resolution basins with area reported from GRDC

Percentage of Area Accordance	Number of Stations This Study	% This study	Median of Distance [m]	Number of Stations Lehner (2012)	% Lehner (2012)	* of 7163 station in Lehner (2012), 7025 also match with the new dataset
≥ 99	4332	42	98	2422	35	
≥ 95	7920	77	180	5043	70	
≥ 90	8980	87	203	5888	85	
≥ 85	9446	92	382	6287	90	
≥ 75	9862	96	418	6627	95	
≥ 50	10174	99	661	6922	99	
≥ 0	10300	100	1306	6976	100	
no area	10349			7025*		

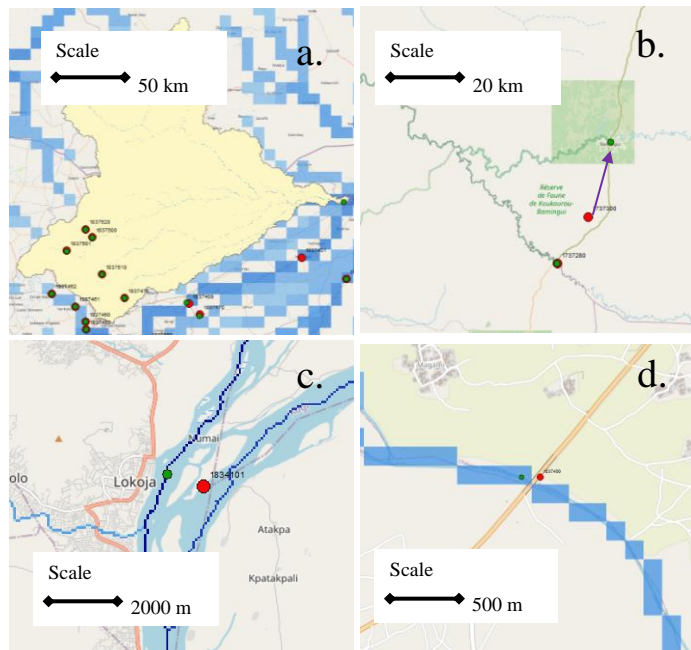



Figure 5 shows some of the possible errors as well as the need to correct station location that will be used in hydrological models:

Part a) GRDC station 1837401 Hadejia, Nigeria, has a reported UPAupstream area of 30,435 km^2. The closest river to the city of Hadejia has a high-resolution UPAupstream area of 19,500 km^2. The next location with a closer upstream area to the reported one (29,000 km^2) is 50 km to the northeast. Thus, here, either the station location or the reported area is wrong.

Part b.) GRDC station 1737300 Bamingui, Central African Republic, with a reported area of 4,380 km^2, has no river of this size at a closer distance. We thus chose the river near the city of Bamingui with a high-resolution UPAupstream area of 6,075 km^2 at a distance of 25.7 km from the GRDC station location.

Part c) shows the station location of GRDC 1834101 Lokojao, Niger. The station seems to be on the River Benué, a tributary of the Niger River. According to Udo et al. (2021), the station is located on the Niger River, upstream of the junction of the Niger and Benué. Lehner (2012) assumed the station is downstream of the junction. No area is reported as being associated with this station, but the area could be 337,000 km^2 (Benué), 1651,000 km^2 (upstream Niger), or 1990,000 km^2 (downstream Niger).

Part d) shows the GRDC station 1837450 at Challawa Bridge in Nigeria at the exact location underneath a bridge over the River Challawa. However, the high-resolution network of 90 meters shows no river on this grid cell, and the station location must thus be shifted 90 meters to the west.

Another example are is GRDC stations 1396200, 1396201, and 1396210, which have the same reported location but different river station names and UPAsupstream areas.

For GRDC station 4208919 on the Dunkirk River, Canada, we found a typographical error. Instead of 58N, it should be 56N. Station Siramakana, Mali, at the river Baoule GRDC station 1112330 is, according to Hydroscience_Montpellier (2022), around 50 km from the station location mentioned in the GRDC dataset.

The remaining 10,241 stations are not equally distributed globally. There are regions where water cannot be measured as streamflow, such as Greenland, the Sahara, the Arabic peninsula, the Kalahari, and Central Australia. In other regions, we know that streamflow is measured, but GRDC does not have the records (some parts of Italy, Indonesia), and some regions where we do not even know if there are measurements (e.g., North Korea). Some basins, especially in North America and Europe, have a dense reported discharge station network (e.g., the Danube). Figure 6 shows the number of subbasins of GRDC stations placed inside the other. For example, in the Danube, there is a station for the upper River Inn, which is inside the basin

of the lower Inn (another station), which is inside the basin of the upper Danube, which is inside the basin of the middle Danube, just like the concept of stacked dolls (Matryoshka dolls).

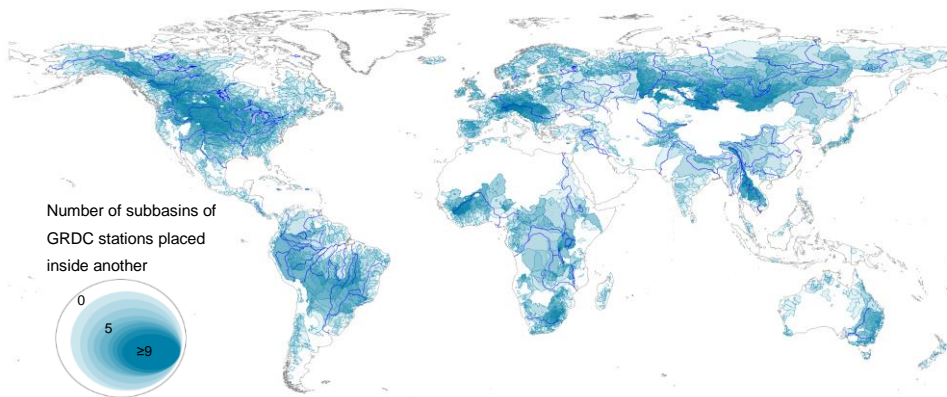



Figure 6. Watershed shapefile of 10241 station using GRDC stations and MERIT network map
(World administrative boundaries by https://www.opendatasoft.com)

3.3 Station allocation on low resolution 5' and 30'

We allocated 10,241 stations with an area $\geq$ 10km^2, and after creating shapefiles for each station, we created shapefiles and a station record for low-resolution of 30' and 5'. For the resolution of 30', we used a threshold of an UPA~~upstream basin area~~ of $\geq$9,000 km^2 (around three grid cells on 30'). For 5', we used a threshold of $\geq$1,000km^2 (~12~~1~~ grid cells on 5'). This selection was subjective, and other papers have slightly different assumptions (Alfieri et al., 2020).

With the similarity method, we can avoid a basin being allocated to a station that fits better by the UPA~~upstream area~~ but is not very similar to the basin shapefile at high resolution. Figure 7 shows this for two examples. The South Platte River GRDC No. 4122130 joins the North Platte River GRDC No. 4122150 at the city of North Platte, Nebraska, USA, and before the junction, they run in parallel. If we take the location of the station GRDC No. 4122130 on 30', we obtain the North and South Platte River basin together (Platte River). We must therefore move the station to allocate it to the correct basin. The reported UPA~~upstream area~~ of the station is 61,901 km^2. If we had selected only by upstream area, we would have chosen the North Platte River (UPA~~upstream area~~ of 30': 66,815 km^2) in preference to the South Platte River (UPA~~upstream area~~ of 30': 49,745 km^2). Figure 7a shows that the selected 30' basin in darker blue (South Platte River) with the lower UPA~~upstream area~~ fits better with the high-resolution basin.

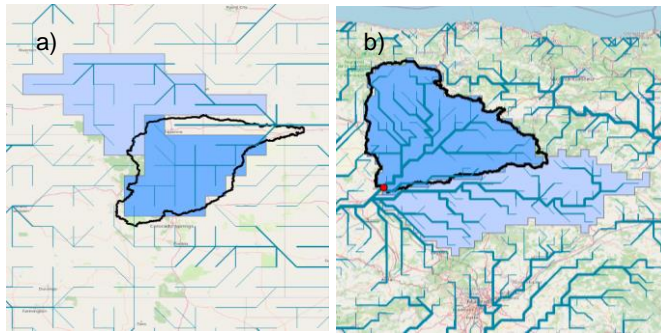
Figure 7̲4b shows a station mismatch selected by the U̶P̶A̲upstream area at 5'. The river Pisuerga in Spain, GRDC No. 6212740, has a reported U̶P̶A̲upstream area of 15,638 km^2. Again, we must move the station, as the river network at 5' does not match the station location. If we select by U̶P̶A̲upstream area, the Douro River, with an U̶P̶A̲upstream area on 5' of 15,448 km^2, fits better than the Pisuerga River, with an U̶P̶A̲upstream area on 5'of 15,908 km^2. Selecting by area and shape similarity points

to the correct basin, shown in dark blue in Figure 4b.

Figure 7: Mismatch of basin allocation because of selection from upstream area only. a) shows the South Platte River, USA at 30'
resolution b) shows the river Pisuerga, Spain at 5' resolution. © OpenStreetMap contributors 2022. Distributed under the Open
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Database License (ODbL) v1.0.

For the coarser resolution of 5', we selected 6,414 stations with a basin area ≥ 1,000 km^2. For the resolution of 30', we selected 2,741 stations with a basin area ≥ 9,000 km^2. We assigned polygons based on the upscaled river network for those two resolutions. We provided the list of stations with adjusted station locations and the 5' and 30' watershed boundaries as shapefiles.

3.4 Selecting stations for calibration on low resolution 5' and 30'

Based on the selection criteria of tables 1 and 2, we included meta information of the station time series (length and end date of the time series, number of missing values, daily or monthly values). As mentioned in the method section, the selection criteria were subjective, but the Python code for changing the criteria tables is available on GitHub.

For the low resolution of 30', from the 2,724 stations (with an U̶P̶A̲upstream area of ≥ 9000 km^2), we selected 953 stations for calibration. Another 105 stations could be used for validation purposes. The latter stations are not in the first calibration category because they are equal to or more than 95%, similar to a station chosen for calibration. We dismissed 1,666 stations

395 from the calibration because they do not fulfill the necessary criteria given in Table 1. For the low-resolution of 5', we selected 3,917 out of 6,415 stations. Another 175 stations were available for validation, and we dismissed 2,323 stations.

Figure 8 and the histograms in Figure 9 show the global distribution. North America, Brazil, Europe, Russia, and Australia are well covered, but Asia and Africa only partly. On 5' resolution, 441 stations are in Africa, and 1,270 and 746 are in North America or Europe.

400
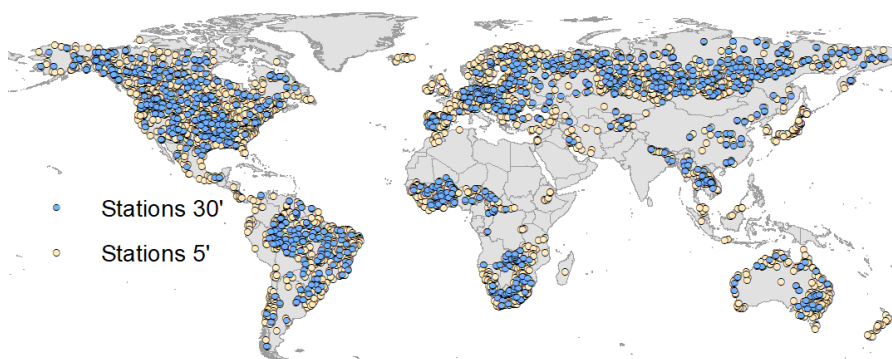
Figure 8: Selected station for calibration on 30' (949 stations) and 5' (3,917 stations)
(World administrative boundaries by https://www.opendatasoft.com)

405
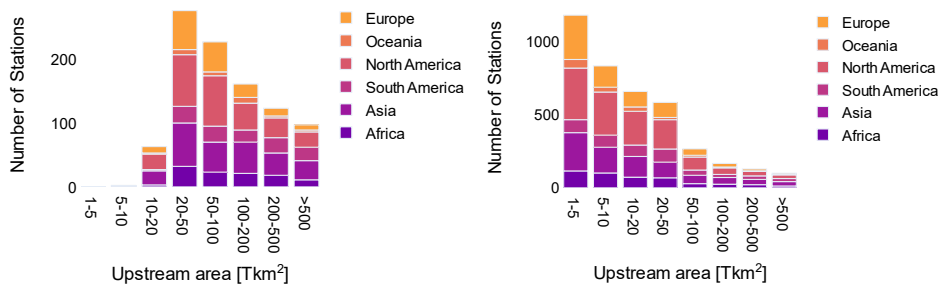
Figure 9: Histogram of selected calibration stations (a) 949 stations for 30' (b) 3,917 stations for 5', classified by upstream area and continent

4. Conclusion

This paper describes the procedure used to generate a dataset of station locations of observed discharge to be used at different resolutions for calibrating large-scale hydrological models. It is based on the metadata of GRDC stations and MERIT Hydro. The Python source code and dataset produced are freely available for download through a GitHub and Zenodo repository.

The first step toward generating a high-resolution collection of watershed shapefiles was to update the work of Lehner (2012) to include more basins (10,241 stations vs. 7,163) based on a higher resolution river network database (3'' MERIT Hydro from Yamazaki et al. (2019) vs. 15'' the HydroSHEDS from Lehner et al. (2008), including the changed GRDC IDs from September 2021. The second step, of generating a lower-resolution collection of watershed shapefiles based on the Intersection over Union ratio, was inspired by the ideas of Rezatofighi et al. (2019) and Munier and Decharme (2021). It is a better approach than selecting a station location on low-resolution river network systems based only on the UPA~~upstream area~~ and distance to the original location. Here, we provide the low-resolution watershed boundaries on 30' and 5' and the source code to produce results for different resolutions and projection systems. The third step, selecting suitable stations for calibration and validation, was also based on the Intersection over Union ratio. This selection of stations can now be used more effectively to calibrate grid-based hydrological models at different resolutions.

We are very grateful for the work of GRDC in collecting and making available a considerable number of stations. Around 8,000 of the 10,701 stations fit very well and have less than a 5% UPA~~upstream area~~ difference between the reported UPA~~upstream area~~ and the MERIT Hydro calculated UPA~~upstream area~~. 10,000 stations have less than 30% UPA~~upstream area~~ difference. For 228 stations, however, we could not find a suitable location, and for another 437 stations, the reported area and calculated area are very different (25% error). Most stations (8544) could be located on the high-resolution MERIT network within a 1 km range. However, 843 stations have a corrected station location more than 5 km distance to the original position. We propose a quality check for these stations; otherwise, the time series cannot be used for any application.

5. Code and data availability

The MERIT Hydro - global hydrography dataset is available for download at http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_Hydro (Yamazaki et al., 2019) and was last updated on 17 May 2019. The metadata information on 10,701 was provided by the Global Runoff Data Centre (GRDC, https://www.bafg. de/GRDC) (04/04/2022). The watershed boundaries based on Lehner et al. (2011) can be downloaded from GRDC.
The source code, tables, and shapefile datasets for high-resolution 3'' and low-resolution 5' and 30' are stored on Zenodo with the associated DOI https://doi.org/ 10.5281/zenodo.6906577. In addition, we provide the source code on a GitHub repository https://github.com/iiasa/CWATM_grdc_calibration_stations as release version 1.0. Please keep in mind that the Zenodo repository is the location where users can retrieve exactly the data that have been used for this study.

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CRediT authorship contribution statement

Peter Burek: Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review and editing.
Mikhail Smilovic: Writing - review and editing.

Competing interests

The contact author has declared that neither they nor their co-authors have any competing interests.

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