HydroSHEDS
Technical Documentation

Data Version 1.1
Technical Documentation Version 1.4

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1. Overview

HydroSHEDS (**Hydro**logical data and maps based on **SH**uttle **E**levation **D**erivatives at multiple **S**cales) provides hydrographic information in a consistent and comprehensive format for regional and global-scale applications. HydroSHEDS offers a suite of geo-referenced datasets in raster and vector format, including stream networks, watershed boundaries, drainage directions, and ancillary data layers such as flow accumulations, distances, and river topology information.

HydroSHEDS version 1 is derived primarily from elevation data of the Shuttle Radar Topography Mission (SRTM) at 3 arc-second resolution. The original SRTM data have been hydrologically conditioned using a sequence of automated procedures. Existing methods of data improvement and newly developed algorithms have been applied, including void-filling, filtering, stream burning, and upscaling techniques. Manual corrections were made where necessary. Cursory quality assessments indicate that the accuracy of HydroSHEDS exceeds that of previous global watershed and river maps, yet important inaccuracies and inconsistencies remain, such as in braided rivers or river deltas.

The goal of developing HydroSHEDS was to generate baseline data layers to support regional and global watershed analyses, hydrological modeling, and freshwater conservation planning at a quality, resolution and extent that has previously been unachievable. Available resolutions range from 3 arc-seconds (approximately 90 meters at the equator) to 6 arc-minutes (approximately 11 km at the equator) with seamless near-global extent.

HydroSHEDS version 1 has been developed by World Wildlife Fund (WWF), in partnership or collaboration with McGill University, Montreal, Canada; the U.S. Geological Survey (USGS); the International Centre for Tropical Agriculture (CIAT); The Nature Conservancy (TNC); the Australian National University, Canberra, Australia; and the Center for Environmental Systems Research (CESR), University of Kassel, Germany. Major funding for this project was provided to WWF by Diversey Holdings, Ltd.; additional financial support was provided by The Nature Conservancy, the International Union for Conservation of Nature (IUCN), the EU BioFresh project, and McGill University.

HydroSHEDS data are free for non-commercial and commercial use. For specific restrictions and use requirements see the License Agreement provided in Appendix A.

This document describes versions 1.0 and 1.1 of HydroSHEDS, collectively referred to as HydroSHEDS version 1.

The two versions do not differ in content but only in formatting.
Some additional data layers are offered exclusively in version 1.1.

For more information, updates, and additional HydroSHEDS products please visit
https://www.hydrosheds.org

Citations and acknowledgement of the HydroSHEDS version 1 database should be made as follows:

> *Lehner, B., Verdin, K., Jarvis, A. (2008): New global hydrography derived from spaceborne elevation data. Eos, Transactions, 89(10): 93-94. Data available at https://www.hydrosheds.org.*

2. Data sources

This chapter briefly describes the main data sources that have been used in the generation of HydroSHEDS version 1. The actual processing steps are addressed in chapter 3. Please also refer to the flowchart of Figure 1.

2.1 Elevation data from the Shuttle Radar Topography Mission (SRTM)

The primary data source of HydroSHEDS version 1 is the digital elevation model (DEM) of the Shuttle Radar Topography Mission (SRTM). SRTM elevation data were obtained by a specially modified radar system that flew onboard the Space Shuttle Endeavor during an 11-day mission in February of 2000. The SRTM project has been a collaborative effort between the National Aeronautics and Space Administration (NASA), the National Geospatial-Intelligence Agency of the U.S. Department of Defense (NGA), the German Aerospace Center (DLR), and the Italian Space Agency (ASI). NASA's Jet Propulsion Laboratory (JPL) managed the mission, and the Earth Resources Observation and Science Data Center of the U.S. Geological Survey (USGS EROS Data Center) has been responsible for the hosting, distribution and archiving of the final SRTM data products. A general description of the SRTM mission can be found in Farr and Kobrick (2000).

2.1.1 SRTM elevation data, Version 1 (SRTM-1 and SRTM-3 unfinished data)

The raw SRTM data have been processed into an initial research quality DEM by JPL. No further editing has been performed, resulting in a dataset that contained numerous voids and other spurious points such as anomalously high (spike) or low (well) values. Since water surfaces produce very low radar backscatter, water bodies and their coastlines were generally not well defined and appeared quite "noisy". For areas outside of the conterminous United States (CONUS), the original 1 arc-second data (SRTM-1; cell size approximately 30 meters at the equator) were aggregated into 3 arc-second data (SRTM-3) by averaging, i.e., each 3 arc-second data point was generated by averaging the corresponding 3x3 kernel of the 1 arc-second data. For more details see NASA/JPL (2005).

2.1.2 SRTM elevation data, Version 2 (DTED-2 and DTED-1 finished data)

After JPL completed the raw processing of the SRTM-1 and SRTM-3 data, NGA performed quality assurance checks and then carried out several additional finishing steps to comply with the required data standards of the Digital Terrain Elevation Data (DTED®) format (NASA 2003). Spikes and wells in the data were detected and voided out. Small voids were filled by interpolation of surrounding elevations. Large voids, however, were left in the data. The ocean was set to an elevation of 0 meters. Lakes of 600 meters or more in length were flattened and set to a constant height. Rivers of more than 183 meters in width were delineated and monotonically stepped down in height. Islands were depicted if they had a major axis exceeding 300 meters or the relief was greater than 15 meters. All finishing steps were performed at the original 1 arc-second resolution, resulting in DTED Level 2 data products. DTED-2 was then aggregated into 3 arc-second DTED-1 data. Unlike SRTM-3, however, DTED-1 has been generated by subsampling, i.e., each 3 arc-second data point was generated by assigning the value of the center pixel of the corresponding 3x3 kernel of the 1 arc-second data. For more details see NASA/JPL (2005).

2.1.3 SRTM tiling format and data availability

SRTM elevation data have been processed in a systematic fashion and mosaicked into approximately 15,000 one-degree by one-degree tiles. Following the DTED convention, the names of the individual data tiles refer to the latitude and longitude of the lower-left (southwest) corner of the tile. For example, the coordinates of the center of the lower-left pixel of tile n40w118 are 40 degrees north latitude and 118 degrees west longitude. In the case of DTED-1 and SRTM-3 data, a single tile consists of 1201 data rows and 1201 data columns. Due to the definition via pixel centers, the four edges of a tile each exceed the assigned coordinates by half a pixel and the outermost rows and columns of adjacent tiles are overlapping. For more details see NASA/JPL (2005).

Outside of the CONUS, the 1 arc-second products (SRTM-1 and DTED-2) were originally only available upon request for scientific purposes. The 3 arc-second products (SRTM-3 and DTED-1) were in the public domain and have thus been used as the main data source for HydroSHEDS v1.

2.1.4 Void-filled SRTM data provided by CIAT

The original SRTM data were characterized by exhibiting a number of data voids, i.e., “no-data” pixels at locations where the original radar backscatter could not be interpreted properly. Small data voids can be interpolated rather easily, e.g., by applying nearest neighbor methods, but larger voids pose a problem for many applications. A team of researchers from the International Center for Tropical Agriculture (CIAT), Colombia and later from the Joint Research Center (JRC) of the European Commission have further processed the original SRTM DEMs to fill in these no-data voids (Jarvis et al., 2008). This involved the production of vector contours and points, and the re-interpolation of these derived contours back into a raster DEM. The void-filled DEM was offered as a seamless near-global coverage (up to 60 degrees north and south) in 5x5 degree tiles in geographic (lat/long) projection referenced to the WGS84 datum. For the production of HydroSHEDS, Version 2 of the CIAT void-filled SRTM data was used (CIAT 2004). The latest version of the CGIAR-CSI SRTM 90 m Database is available at https://srtm.csi.cgiar.org.

2.2 SRTM Water Body Data (SWBD)

SRTM Water Body Data files were produced as a by-product of the data editing performed by NGA to create the finished SRTM DTED-2 data. Ocean, lake and river shorelines were identified and delineated from the 1 arc-second DTED-2 data (for details see NASA 2003) and were saved as vectors in ESRI 3-D Shapefile format (ESRI 1998). The full dataset comprised approximately 12,000 SWBD files since only those SRTM tiles that contained water had a corresponding SWBD shapefile.

The guiding principle for the development of SWBD was that water was depicted as it appeared in February 2000, i.e., at the time of the Shuttle flight. In most cases, two orthorectified SRTM image mosaics were used as the primary source for water body editing. A landcover water layer and medium-scale maps and charts were used as supplemental data sources. Since the landcover water layer was derived mostly from Landsat 5 data collected a decade earlier than the Shuttle mission and the map sources had similar currency problems, there were significant seasonal and temporal differences between the depiction of water in the SRTM data and the ancillary sources. For more details see NASA/NGA (2003) and NASA (2003).

2.3 Digital Chart of the World (DCW) global vectorized river network

The Digital Chart of the World (ESRI 1993) is a global vector map at a resolution of 1:1 million that includes a layer of hydrographic features such as rivers and lakes. DCW (also known as VMAP-0) has generally been considered to provide the most comprehensive and consistent global river network data available at the time of creating HydroSHEDS. It was based on the US DMA (now NGA) Operational Navigation Charts (ONC) whose information dates from the 1970s to the 1990s (Birkett and Mason 1995). The positional accuracy of DCW varies considerably between regions, and there is no distinction between natural rivers and artificial canals.

2.4 ArcWorld global vectorized river network

The ArcWorld dataset (ESRI 1992) includes a global vector map of surface water bodies at a resolution of 1:3 million. As part of its classification scheme, it distinguishes linear rivers into natural (perennial and intermittent) or artificial (canals) waterways and provides approximately 7000 polygons of large open water bodies (including rivers and lakes). Although digitized at a coarser scale, ArcWorld includes some corrections and updates as compared to DCW and provides a consistent focus on major rivers and lakes of the world.

2.5 Global Lakes and Wetlands Database (GLWD)

The Global Lakes and Wetlands Database (Lehner and Döll 2004) combines a variety of existing global lake and wetland maps (at 1:1 to 1:3 million resolution) into one consistent coverage. It provides shoreline polygons of approximately 250,000 lakes and reservoirs worldwide, including their surface areas and other attributes. As for lakes and reservoirs, GLWD has been largely based on DCW and ArcWorld but also includes various updates and data corrections.

2.6 Various regional datasets used for reference and quality control

2.6.1 Atlas of Canada, 1:1,000,000 National Frameworks Data, Hydrology

The National Scale Frameworks Hydrology data (Natural Resources Canada, 2006) consists of area, linear and point geospatial and attribute data at a scale of 1:1 million for Canada's hydrology at a national extent. It provides a representation of Canada's surface water features, and data completeness largely reflects the original source (VMAP0, revision 4, hydrographic features) for which additional editing has been performed. The data include streamlines, lakes, and watershed boundaries.

2.6.2 National Atlas of the United States, Two-Million-Scale Streams and Waterbodies

The Two-Million-Scale Streams and Waterbodies map layer (National Atlas of the United States, 2005) shows the major water features of the United States, Puerto Rico, and the U.S. Virgin Islands that can be represented at a map scale of 1:2,000,000, including streams and rivers, canals, aqueducts, lakes, reservoirs, marshes, glaciers, waterfalls, and dams. The map layer was compiled by the National Atlas of the United States, and the U.S. Geological Survey collected information on water features to support its production.

2.6.3 Global Map Australia 1M 2001, Drainage layer (Water courses)

Global Map Australia 1M 2001 (Geoscience Australia, 2007) is a digital dataset covering the Australian landmass and island territories, at a 1:1 million scale. Vector data for Global Map Australia 1M 2001 was produced by generalizing Geoscience Australia's GEODATA TOPO 250K Series 1 data. It consists of a series of layers of information, including attributed drainage features (streamlines).

2.7 Extension to Arctic regions above 60 degrees northern latitude using HYDRO1k

SRTM elevation data do not extend above 60° northern latitude. For the 15 arc-second products of version 1 of HydroSHEDS, as well as coarser resolutions, the existing DEM of the HYDRO1k database (USGS 2000) was inserted to complete the hydrographic data framework for the derivation of drainage networks and sub-basin delineations at full global extent. The HYDRO1k DEM was originally produced at a spatial resolution of 1-km and was resampled for this project into a 15 arc-second resolution using linear interpolation based on directly neighboring pixels.

3. Database development

This chapter provides an overview of the applied processing steps for the generation of HydroSHEDS version 1 and discusses its main technical specifications. For a discussion regarding the suitability of HydroSHEDS data for specific applications, please refer to chapter 4.

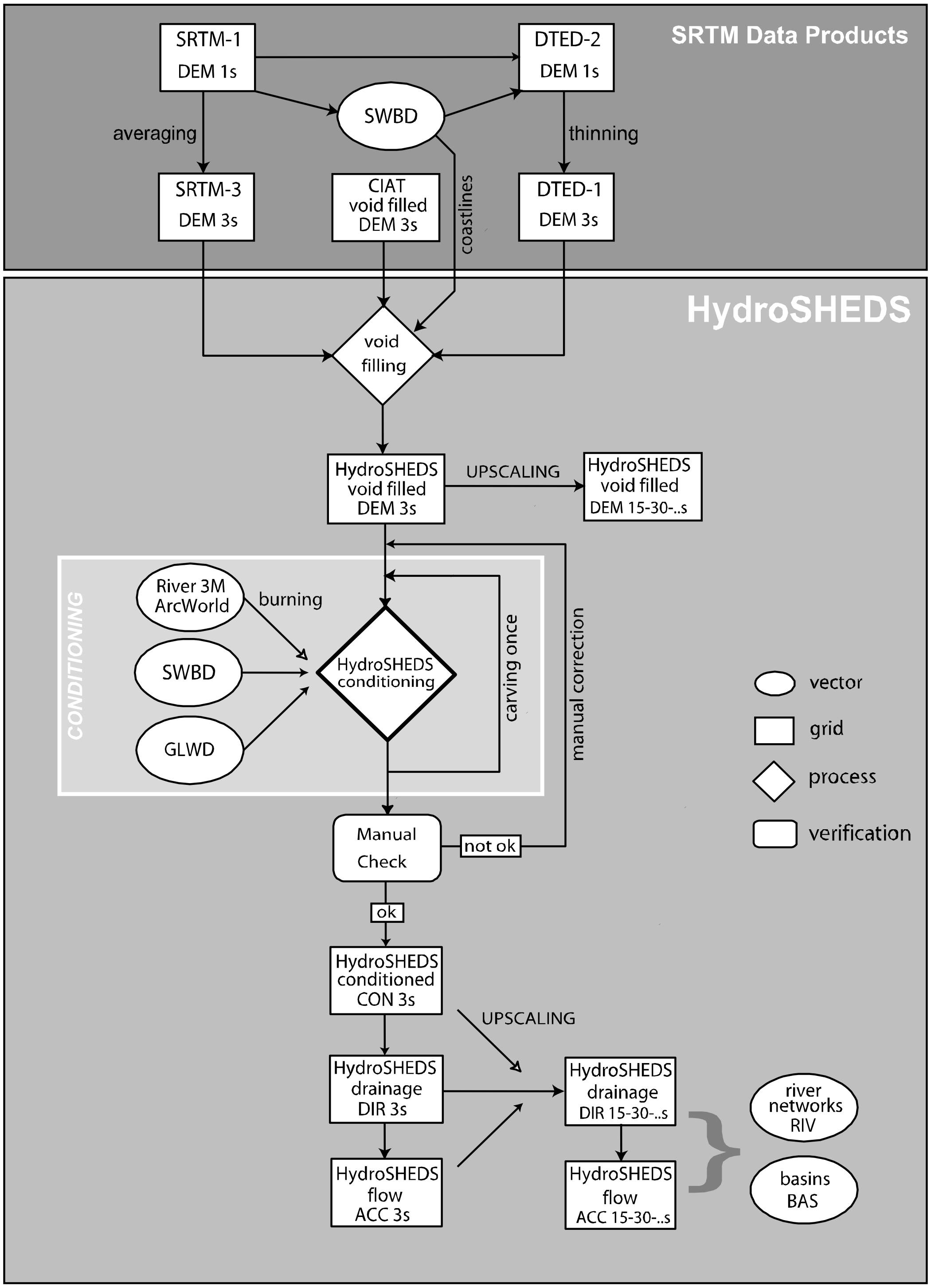


Figure 1: Flowchart of the generation of HydroSHEDS version 1; for abbreviations and further explanations see text.

3.1 Combination of unfinished SRTM-3 and finished DTED-1 data

3.1.1 Combining SRTM-3 and DTED-1 original data

For the generation of HydroSHEDS, the performance of the publicly available SRTM-3 and DTED-1 versions of SRTM at 3 arc-second resolution have been tested. Due to their specific characteristics, each dataset showed both advantages and disadvantages for hydrological applications.

As stated earlier, SRTM-3 has been derived through averaging of 1 arc-second SRTM data, as opposed to the subsampling method of DTED-1. As averaging reduces the high frequency "noise" that is characteristic of radar-derived elevation data, it is the method generally preferred by the research community (NASA/JPL 2005).

On the other hand, SRTM-3 data does not represent open water surfaces and shorelines well. DTED-1 has been specifically corrected to represent these features. However, the correction protocol introduced some critical artifacts for hydrological applications. For example, when large rivers were identified and monotonically stepped down in height towards the ocean, it was assured that the surface of each river pixel was lower than that of the directly adjacent land pixels. Yet a slightly elevated riverbank, say due to a levee or simply caused by the interpretation of riparian vegetation in the radar image, may allow for a river reach being somewhat higher than the floodplain behind the riverbank. Since the original processing was performed at 1 arc-second resolution, the elevated riverbank can disappear in the aggregated 3 arc-second version if it is only thin (one pixel wide). The resulting effect in the derived flow direction map is a possible breakout of the river course into the floodplain.

For these reasons, and after conducting a series of local tests, it was decided to apply both SRTM-3 and DTED-1 data in combination. For each pixel the minimum value found in either SRTM-3 or DTED-1 was used to generate an initial HydroSHEDS elevation model. The minimum requirement preserves the lower of both surfaces in the combined elevation data, which is considered desirable for the later identification of drainage directions.

3.1.2 Ocean shoreline

At the ocean surface, the combined data initially showed elevation values of 0 (from DTED-1) or negative (from SRTM-3). Since land close to the shoreline can also be 0 or even negative, using elevation alone as a criterion does not allow for a clean identification of the ocean shoreline. Thus to aid in the shoreline delineation, SWBD was employed as ancillary data: where SWBD indicated 'ocean', the values of the HydroSHEDS elevation model were reclassified to no-data. The resulting shoreline was then slightly generalized in order to remove small artifacts: land was first extended by a one-pixel rim into the ocean and the boundary was then smoothed using a local cell filter. All detached ocean surfaces (e.g. small estuaries entirely surrounded by land cells) were treated as land and their elevation values were retained rather than set to no-data. Some larger rivers were defined in SWBD to extend relatively far into the ocean. In these cases, the shoreline was modified based on the shoreline of DCW. Some very small islands were missing in the source data and are thus also missing in HydroSHEDS. Finally, some minor errors were detected in SWBD in visual inspections (e.g., some incomplete island boundaries) and were individually corrected. It should be noted that in all up-scaled HydroSHEDS layers, each cell that contains at least one land cell at 3 arc-second resolution is defined as land.

3.1.3 Data shift

Both SRTM-3 and DTED-1 original 1-degree by 1-degree data tiles were defined via the coordinates of the center of their lower-left pixel (see 2.4). This characteristic leads to overlapping edges of adjacent tiles and to some artifacts when aggregating a tile to coarser resolutions: either all adjacent tiles have to be included in the aggregation process or overlapping edges may have to be eliminated in the result. As the processing steps for the generation of HydroSHEDS are rather complex and aggregation (scaling) plays an important role, it was decided to shift the original SRTM data by 1.5 arc-seconds to the north and east, and to remove each tile's overlapping right column and top row. This shift leads to a 3 arc-second HydroSHEDS tile having 1200 rows and 1200 columns at an extent of exactly 1-degree by 1-degree without overlaps to adjacent tiles. All other HydroSHEDS resolutions are based on the initial 3 arc-second data and, therefore, include this shift. With respect to deriving river networks, the effect of the shift on the accuracy of the data are considered non-critical, particularly when compared to the subsequently applied data manipulations as discussed below. Note, however, that the shift may lead to significant anomalies when directly comparing HydroSHEDS elevation data and original SRTM elevation data.

3.2 Void-filling

In its original release, SRTM data contained regions of no-data (voids), specifically over large water bodies, such as lakes and rivers, and in areas where radar-specific problems prevented the production of reliable elevation data. These areas include mountainous regions where the radar shadow effect is pronounced, such as the Himalayas and Andes, as well as certain land surfaces, such as bare sand or rock conditions as found in the Sahara Desert. The existence of no-data in the DEM causes significant problems for deriving hydrological products, which require continuous flow surfaces. Therefore, a void-filling procedure has been applied to provide a void-free DEM for HydroSHEDS.

Numerous methods have been developed for void-filling of SRTM data (see e.g., Gamache 2004a), but they rarely focused on specific hydrological requirements. For HydroSHEDS, two different void-filling algorithms have been applied in combination. The first has been developed by CIAT (see Jarvis 2004; in collaboration with R. Hijmans and A. Nelson). The second has been specifically developed for HydroSHEDS. While the CIAT algorithm delivers smooth interpolation surfaces, the HydroSHEDS algorithm focuses on deepening and flattening missing water surfaces. Both methods and their combination are summarized below.

3.2.1 CIAT algorithm

The CIAT algorithm fills the no-data voids by applying an interpolation technique. The original SRTM elevation data are used to produce contours at an interval of 10 meters. The contours are interpolated using the TOPOGRID algorithm in Arc/Info. TOPOGRID, based upon the established algorithms of Hutchinson (1988, 1989), is designed to use contour and point elevation data along with mapped hydrography to produce hydrologically sound DEMs. This method produces a smooth elevation surface within the no-data regions. While micro-scale topographic variation is likely to be underrepresented, most macro-scale features are captured well in small to intermediate-sized voids. Jarvis et al. (2004) performed a detailed analysis of the accuracy of the interpolated elevation data for a region in Colombia and found little difference when compared to a cartographic DEM, particularly for hydrological applications. Gamache (2004b and personal communication) also analyzed the CIAT results and concluded that the void-filling algorithm is quite successful in representing broad scale patterns in topography. For the production of HydroSHEDS, Version 2 of the CIAT void-filled SRTM data was used (CIAT 2004).

3.2.2 HydroSHEDS algorithm

The HydroSHEDS algorithm fills the no-data voids by means of an iterative neighborhood analysis. The first step fills the outermost pixel-rim of a no-data void using a combination of a 3x3 minimum and a 5x5 mean filter (the minimum filter dominates the mean filter by a factor of 3:1). Then, the next pixel-rim is filled until the entire no-data void is processed. The no-data area is finally smoothed using a 9x9 mean filter. Particularly in the case of lakes and large river surfaces the emphasis of the minimum filter results in rather low elevation values inside the voids and a relatively flat relief as small peaks are successively filtered out.

3.2.3 Combination of void-filling algorithms

The lowering effect of the HydroSHEDS algorithm for open water surfaces is desirable for hydrological applications, as it tends to force the derived flow paths to stay within river channels and lakes. In mountainous regions, however, the CIAT results are expected to better represent the general topography. To optimize results, both algorithms were combined. For each pixel the minimum value of either the CIAT or HydroSHEDS algorithm was used. If, however, the HydroSHEDS algorithm computed values more than 30 meters lower than CIAT, CIAT values minus 30 meters were used.

In some large no-data voids entire mountains are lost using either of the two filling methods. Therefore, starting at a distance of 0.03 degrees (approximately 3 km at the equator) from the rim of large voids, elevation values were inserted from GTOPO30, a global DEM at 30 arc-second (approximately 1 km at the equator) resolution (Gesch et al. 1999). To avoid cliff effects, the inserted values were disaggregated, smoothed, as well as blended in a 0.03-degree wide transition zone.

The filled voids were then merged into the initial HydroSHEDS elevation data to provide a continuous elevation surface with no void regions. The entire process was performed for each 1-degree by 1-degree tile with a 0.25-degree overlap to the eight adjacent tiles, thus ensuring seamless transitions of topography even in areas with large voids.

The final result of steps 3.1 and 3.2 is
the HydroSHEDS void-filled digital elevation model (**DEM**) at 3 arc-second resolution.

3.3 Sink identification

Typically, an original DEM will show a large number of sinks or depressions. These are single or multiple pixels which are entirely surrounded by higher elevation pixels. Some of these sinks are naturally occurring on the landscape, representing endorheic (inland) depressions with no outlet to the ocean. In most cases, however, the sinks are considered spurious, often caused by random and mostly small deviations in the elevation surface. These anomalies occur even in high quality DEMs and high resolutions due to DEM production methods. The spurious sinks are critical problems in hydrological applications as they interrupt continuous flow across the DEM surface. Therefore, sinks are typically removed from the DEM before deriving a river network. Standard GIS procedures have been developed to remove spurious sinks, and a common approach is to raise the elevation values within the sinks until an outflow point is encountered. Natural sinks can be forced to remain in the DEM through “seeding”, e.g. by putting a no-data cell into their center.

As for HydroSHEDS, the definition of natural vs. spurious sinks has been accomplished using a GIS-assisted manual process. All sinks of the void-filled elevation model were identified in a standard GIS procedure, and their maximum depth and extent were calculated. Sinks deeper than 10 meters and larger than 10 km^2 were highlighted as ‘potential’ natural sinks. All regions of potential natural sinks were then inspected visually and were either seeded or rejected. The decision was based on information derived from DCW, ArcWorld, GLWD, and additional atlases and maps. For example, a mapped “salt lake” with no obvious river draining from it would be considered a strong indication for an endorheic basin. The visual inspections were performed at an on-screen zoom level displaying a single 1x1-degree tile at a time, and over 16,000 naturally occurring sinks were identified globally.

Obviously, the manual sink identification process is subjective, and in many cases the definition of natural sinks is difficult and ambiguous. Some depressions overflow periodically, following seasonal flooding cycles, others spill only occasionally. Some large, relatively dry areas may show numerous small depressions within a generally sloped surface, and flow paths are poorly developed if at all (e.g., in the Argentinean Pampas and many desert areas). These depressions may or may not overflow in a rain event. In some areas of no obvious drainage only some “structural” sinks were placed at strategic locations. They do not terminate the flow at individual depressions but at a final one to indicate the endorheic character of the region. In karstic areas, rivers may disappear in surface depressions, yet they can be closely connected to a larger basin via underground pathways. In cases of large karstic depressions, sinks were introduced, as it seemed easier for a user to later remove the sinks and restore connectivity than to introduce them from scratch. Artificial sinks, however, such as pits in surface mining areas, were rejected.

3.4 Hydrologic conditioning

Besides sinks, original DEMs show a series of other characteristics, artifacts and anomalies that can cause significant problems or errors in hydrological applications. Some types of problems that are specific for the SRTM elevation model are discussed in chapter 4. The most significant characteristic is likely the fact that the elevation values of SRTM, being a radar-derived product, are influenced by vegetation cover. In areas of low relief, these deviations from the true (bare-ground) surface elevation can cause significant errors in the derived river courses and flow directions.

In order to improve the performance of a DEM for hydrological applications, a series of GIS processes and procedures exist and are routinely applied. Yet due to the individual characteristics of different DEMs and, on a global scale, due to the regional variations in the type of errors, no one method exists that addresses all possible problems. For HydroSHEDS, a sequence of hydrologic conditioning procedures has been implemented, either adapted from standard GIS functionality, newly developed, or customized. The general focus was to strike a compromise between forcing the DEM to produce correct river network topology, particularly for the largest of rivers, while preserving as much original SRTM information as possible. Note that in any case the conditioning process alters the original elevation data and may render it unusable for other applications.

The following hydrologic conditioning procedures have been applied to the HydroSHEDS elevation data:

3.4.1 Deepening of open water surfaces

All rivers and lakes as identified in SWBD were deepened by 10 meters in order to force the derived flow to stay within these objects. As no-data voids in the original SRTM elevation data may also indicate open water surfaces (see 3.2), all void areas were lowered by 10 meters as well. The 10-meter threshold was chosen as it imposes a strong enough effect in flat areas (where the identification of river channels and lakes is particularly difficult), while producing only insignificant changes in areas with steeper slopes (where no-data voids are probably caused by radar shadow rather than open water).

3.4.2 Weeding of coastal zone

In the radar-derived elevation model, mangrove or coastal vegetation belts can form a low but continuous embankment blocking any direct outflow to the ocean. In the derived river network model, these barriers would therefore cause significant backwater effects. To reduce this effect, the coastal zone, i.e. a 0.02-degree wide buffer (approximately 2 km at the equator) along the ocean shoreline was "weeded" by reducing every random third cell by 5 meters. This subtle change, in combination with the follow-on filters (see below), forces occasional breakthroughs into the coastal mangrove/vegetation embankments.

3.4.3 Stream burning

The most extensive conditioning process in the generation of HydroSHEDS has been the so-called "stream burning" procedure. Stream burning is a frequently-used process to enforce known river courses into an elevation surface. The elevation values along the rivers, as depicted e.g. in an existing vector layer, are lowered by a certain value, thus "burning" deep gorges into the elevation surface. The burning can be extended to include a buffer around the river lines in order to shape a smoother transition between the original surface and the gorge. For HydroSHEDS, only large rivers and lakes were burned into the elevation surface in order to avoid excessive alterations of the SRTM surface. All perennial and intermittent rivers and lakes of ArcWorld, as well as all rivers and lakes of GLWD were used, while the higher resolution but unclassified DCW data was omitted. Since the accuracy of the existing global maps is unknown, attempts were made to minimize the impact of these datasets on the SRTM surface data. After multiple tests, the burning depth for rivers was set to 12 meters, with a buffer of 0.005 degrees (approximately 500 meters at the equator) around the river courses. The burning depth was reduced, in a stepwise manner, from 12 meters at the center to 2 meters at the edge of the buffer. Lakes were burned with a depth of 14 meters and a buffer distance of 0.0025 degrees. The parameter setting aimed for a noticeable forcing of the main rivers in flat areas, where otherwise the correct delineation of rivers is difficult. In steep regions, the small burning depth results in relatively insignificant changes of the elevation surface, hence the SRTM data remain the dominant information for deriving drainage directions.

3.4.4 Filtering

The entire elevation surface was then filtered by applying a directional 3x3 neighborhood analysis. The elevation values of all possible straight and obtuse angle flow paths in a 3x3 kernel were averaged and the minimum value was assigned to the center cell. This filter aims to remove remaining spikes and wells while preserving and enforcing linear river courses and valley bottoms. In particular, single pixels that can block a continuous flow path are removed by this approach.

3.4.5 Molding of valley courses

Next, valley courses were depicted through a neighborhood terrain analysis and were deepened by 3 meters. The valleys were identified through a 5x5 kernel median analysis combined with a grid-thinning algorithm to detect linear features. This procedure of valley "molding" has been specifically developed to improve river delineations in tropical lowland areas by removing small obstacles in shallow valleys. Due to the small deepening of 3 meters, no significant changes occur in areas with stronger relief.

3.4.6 Sink filling

In a standard process, all spurious sinks in the elevation surface were filled. Natural sinks were seeded in order to exclude them from removal (see 3.3 for more details).

3.4.7 Carving through barriers

After sink filling, a river map was produced from the conditioned elevation surface. All main river courses, defined as rivers with an upstream catchment area of more than 1000 cells (approximately 8 km^2 at the equator), were depicted. The main rivers were then projected onto the initial HydroSHEDS elevation model, and all elevation rises along the rivers when moving downstream were identified. These rising reaches in the original elevation surface, which have obviously been removed through filtering or sink-filling in the conditioning process, may represent dams, bridges, embankments of any kind, or narrow gorges that block the flow path. In many of these cases, the sink-filling effect (i.e., the lifting and implicit flattening of the dammed area) may not be desirable as any existing relief information within the filled area is lost. To minimize this effect, a second conditioning iteration was performed: first, all rising reaches along the main river courses were leveled out in the initial elevation data by appropriately lowering their respective heights, thus effectively "carving" through the barriers. After this process, all other conditioning steps (3.4.1 to 3.4.6) were repeated.

During the entire conditioning process, hard- and software limitations were reached due to the large size of the global dataset at 3 arc-second resolution. All steps have therefore been performed on a tile-by-tile basis using a default tiling of 5-degrees by 5-degrees. In order to avoid edge effects, appropriate overlaps to the adjacent tiles were added. In particular the sink-filling algorithm proved highly susceptible to tile sizes and edge effects and had to be implemented in an iterative approach. The processing was performed with an overlap of up to 5 degrees (approximately 500 km at the equator) to adjacent tiles to ensure seamless results without any edge effects.

3.5 Manual corrections

The result of section 3.4 is a hydrologically conditioned elevation surface at 3 arc-second resolution. From this elevation surface, a new river network was derived and used for error checking. Because computation of the river network at 3 arc-second resolution is very time intensive, the data were first upscaled to 15 arc-second resolution (approximately 500 meters at the equator; for the upscaling method see 3.6 below). The derived river network was then compared visually to the rivers of DCW, ArcWorld, and various atlases and paper maps.

Errors occurred particularly in flat areas with varying vegetation cover (see also chapter 4), such as floodplains and coastal zones. If the actual rivers could be visually detected in the raw elevation data, their courses were traced or adopted from the existing DCW river layer. These rivers were then added to the stream layer used in the river burning procedure of 3.4. In some areas, the given elevation values significantly misrepresented the actual flow conditions (e.g., blocked flow paths due to narrow gorges, or inadequate filling of the no-data voids of the original data). In these cases, the burning depth was individually adjusted. Some other topological problems (e.g., diversions into canals or multiple spillways of reservoirs) were treated in a similar manner through introduction and adjustment of main flow paths. Actual flow channels of braided rivers and large river deltas could not be topologically resolved due to the constraint of allowing only one drainage direction per cell (the applied D8 algorithm, see section 5.3, does not allow for river bifurcations). These zones have only been modified, if necessary, to represent the main channel properly.

After detecting the errors and preparing the corresponding correction data, all steps described in section 3.4 were repeated. In some areas, several iterations of manual corrections were performed. As with the sink identification process, the manual correction process is highly subjective. The visual inspections were performed at an on-screen zoom level displaying a single 1x1-degree tile at a time, and corrections were applied at more than 100,000 locations globally.

The final results of steps 3.4 and 3.5 are
(1) the HydroSHEDS hydrologically conditioned elevation model (**CON**), and
(2) the HydroSHEDS drainage direction map (**DIR**) at 3 arc-second resolution.

3.6 Upscaling

All procedures described in sections 3.1 to 3.5 were performed at 3 arc-second resolution. Yet for many applications, in particular continental or global assessments, coarser resolutions are desirable as they may significantly reduce calculation times while providing acceptable accuracy. HydroSHEDS therefore delivers various resolutions, from 3 arc-seconds to 6 arc-minutes. All coarser resolutions are derived from the 3 arc-second drainage direction data through a newly developed upscaling method.

Upscaling drainage directions is not a straightforward process, as typical aggregation methods, such as averaging of neighborhood kernels, are not appropriate for directional values. A frequently applied upscaling method is to first upscale the elevation data, and then derive a new drainage direction map from this coarser DEM. This method is generally fast and easy to perform, but it often delivers low-quality results with respect to river network topology, due to the loss of significant information in the aggregation process. An alternative option is to first derive the river network at high resolution, and then to upscale this network. This option preserves the network information, which is most important for hydrological applications. However, it requires complex procedures, which are difficult to realize at a global scale and for the desired high resolutions. As a compromise, a combined method has been developed and applied to create upscaled HydroSHEDS drainage directions. The main steps in the upscaling process from 3 arc-seconds to 15 or 30 arc-seconds were as follows:

1. The void-filled DEM was upscaled from the original 3 arc-second to the desired resolution. For this process, an algorithm was applied that calculates both the mean and minimum value found within the aggregation kernel and then takes the average. The minimum value is included in the calculation to emphasize valleys. Natural sinks were preserved in the upscaling process.
2. A network of main rivers was calculated at 3 arc-second resolution. Main rivers were defined as those having an upstream catchment area of more than 1000 cells (approximately 8 km^2 at the

equator). The river network was derived for 5x5-degree tiles with a one-degree overlap to adjacent tiles to avoid edge effects.

3. The main rivers were then burned into the upscaled elevation surface. The burning depth was defined as the sum of a constant (500 meters) and a value dependent on the size of the respective river reach (0-400 meters, proportional to the logarithm of upstream cells). The large and river-size-dependent burning depths assured that the river channels were preserved in the new elevation surface, and that larger rivers gain priority over smaller ones. No buffering was applied.
4. Spurious sinks were filled in the upscaled and burned elevation surface, and finally new drainage directions were calculated. Note that due to the strong burning, the elevation surface does not represent natural conditions anymore. It is appropriate only for deriving drainage directions. To avoid confusion with true DEMs, the upscaled elevation surface is not offered as a standard HydroSHEDS product.
5. To upscale to the even coarser resolution of 5 and 6 arc-minutes, a similar approach was used but with modified burning thresholds.

The described upscaling process delivered a new drainage direction map (DIR) from which a new river network can be derived. Due to the applied stream burning, all main rivers (as defined in the upscaling process) are preserved and are in good alignment with the original river network. Only if two close-by rivers drain through the same or adjacent upscaled cell, they may be incorrectly merged into one flow channel. Smaller rivers, for which no burning occurs, are based solely on the upscaled elevation surface. Their location may thus differ from the river network at 3 arc-second resolution.

The final results of step 3.6 are upscaled HydroSHEDS drainage direction maps (**DIR**) at resolutions of 15 arc-seconds and 30 arc-seconds. Also, 5 and 6 arc-minute products have been produced.

3.7 Extension to Arctic regions above 60 degrees northern latitude using HYDRO1k

For version 1 of HydroSHEDS, arctic regions above 60° northern latitude were processed using the DEM of HYDRO1k in its resampled version at 15 arc-second resolution (see section 2.7 above). Given the coarser resolution, no products at 3 arc-second resolution were produced. The DEM was merged with the SRTM DEM using blending ('feathering') techniques to ensure a smooth transition at 60°N. Some manual corrections were applied to improve the precision of larger rivers. The 15 arc-second DEM was then sink-filled and converted into a flow direction map. The resulting drainage direction map at 15 arc-second resolution was subsequently upscaled into 30 arc-second and 5 and 6 arc-minute resolutions using similar steps as outlined in section 3.6 above.

3.8 Derived products

Ancillary HydroSHEDS products were derived from the individual drainage direction maps at their respective resolutions. These products include flow accumulations, flow distances, river networks, and watershed boundaries. A list of available HydroSHEDS datasets is provided in chapter 5.

4. Quality assessment

With all digital geospatial datasets, users must be aware of certain characteristics of the data, such as resolution, accuracy, method of production, and resulting artifacts, in order to be able to judge their suitability for a specific application. A characteristic that renders the data unsuitable for one application may not be a limiting factor in a different application (NASA/JPL 2005).

While no systematic and comprehensive global data quality assessment of the HydroSHEDS version 1 data products has been performed, a multitude of regional comparisons against other hydrographic datasets support the following conclusions:

- At the time of creating HydroSHEDS, it showed significantly better accuracy than previous river network representations derived from elevation data. In particular, due to the superior quality of the underpinning SRTM elevation model, HydroSHEDS represents a clear improvement over HYDRO1k, a widely used global hydrographic dataset at 1-km resolution (USGS 2000).
- HydroSHEDS tends to show better accuracy than the 1:1 million DCW (VMAP-0) mapping product. However, the accuracy of both datasets varies by location. In some regions where HydroSHEDS is particularly susceptible to errors, such as vegetated floodplains, the quality of DCW can be superior to HydroSHEDS.
- As a global product, HydroSHEDS does not reach the accuracy of high-resolution local river networks (e.g. those depicted on national 1:50,000 hydrographic maps).

Typically, river network products derived from digital elevation surfaces are susceptible to various errors, foremost in flat regions without well-defined relief. Additionally, the quality of HydroSHEDS depends on the characteristics of the SRTM-based elevation model. Being a radar product, SRTM elevation values are influenced by vegetation and other surface effects, such as roughness, wetness, low backscatter signals at open water surfaces and radar shadow (Freeman 1996). For these reasons, known regions prone to errors in HydroSHEDS include:

- Areas with varying vegetation cover and low-relief topography, e.g., large river floodplains. The radar signal is, at least partly, reflected from atop and within the vegetation cover and the returned signal is a complex mix of land surface elevation and vegetation height.
- Low-relief coastal areas, in part due to the barrier effect of mangroves.
- Other areas of low or not well-defined relief, including lake surfaces.
- Large-scale clearings in the vegetation cover of low-relief areas, such as caused by roads. The lack of vegetation can cause artificial depressions in the elevation surface which then may be confused with river valleys.
- Rivers less than 90 m wide enclosed by riparian vegetation. The vegetation effect can cause the river channel to appear slightly elevated.
- Braided rivers and deltas. The use of the D8 single flow direction algorithm does not allow for depiction of river bifurcations.
- Narrow gorges. If a gorge is less than 90 m wide, it can appear closed on the elevation surface.
- Inland sinks, depressions, and karst features such as sinkholes. The hydrologic connections are often ambiguous or temporary in nature. In karst areas, flow paths are not necessarily terminated at sinks due to possible underground connectivity. Artificial depressions like large-scale mining pits may or may not have flow bypasses.
- Elevated "barriers" in the elevation surface that in reality have no effect on flow connectivity (e.g., bridges, high-density housing areas).
- Areas of no-data voids in the original SRTM data. Generally, the larger the void, the more prone it is to uncertainty and errors (see 3.2).

5. Data layers and availability

The HydroSHEDS database provides a suite of raster and vector datasets, covering many of the common derivative products used in hydrological analyses. The HydroSHEDS data layers exist for all landmasses of the globe from 56° South to 84° North (i.e., excluding Antarctica). **Versions 1.0 and 1.1 of the data have the same content, but are offered in different formats and with some additional layers in version 1.1.** The data are prepared in seamless mode (no edge effects) and are provided as global or regional maps, or in 5x5 degree (version 1.0) or 10x10 degree (version 1.1) tile coverage.

HydroSHEDS data have been produced in stages as follows:

Continent/region (56° South to 60° North)	*Completed*
South America	May 2006
Central America (Mexico and Caribbean)	March 2007
Asia	March 2007
Africa	October 2007
Australasia	March 2008
Europe and Middle East	October 2008
North America (USA and Canada)	January 2009
Regions north of 60°N (only available in version 1.1 and at ≥15 arc-second resolution)	
Arctic (northern Canada)	December 2015
Scandinavia and Iceland	December 2015
Siberia	December 2015
Greenland	December 2015

HydroSHEDS provides a series of gridded datasets at 3 arc-second, 15 arc-second, 30 arc-second, and 5 and 6 arc-minute resolutions, including elevation surfaces, drainage directions, and flow accumulations. River networks and watershed boundaries have been produced as stand-alone products in version 1.0 of HydroSHEDS. These were succeeded in version 1.1 by the HydroBASINS, HydroRIVERS, and HydroATLAS products (see https://www.hydrosheds.org for more information).

Note: the HydroSHEDS suite of data layers is continuously expanded with new developments. Therefore, please refer to the announcements on the HydroSHEDS website for possible updates and further information (https://www.hydrosheds.org).

At the time of this document, the following data layers and resolutions were available:

5.1 Void-filled digital elevation model

Name signature	**DEM**
Data format	Raster
Values	Elevation in meters (referenced to WGS84 EGM96 geoid)
Projection	Geographic (latitude/longitude) referenced to WGS84 horizontal datum
Available resolutions	3 arc-second, 15 arc-second, 30 arc-second

The elevation layers distributed with HydroSHEDS are based on a combination of the original SRTM-3 and DTED-1 elevation models of SRTM (for further specifications see sections 2.1 to 2.4 and 3.1). No-data voids have been filled using interpolation algorithms, and the data have been clipped at the ocean shoreline. Resolutions other than 3 arc-seconds have been derived through aggregation (averaging): each upscaled data pixel is generated by averaging the corresponding neighborhood kernel of the 3 arc-second data. Note that for technical reasons HydroSHEDS elevation data show a consistent shift of 1.5 arc-seconds to the north and east as compared to original SRTM data (see section 3.1.3 for details).

The underpinning SRTM elevation data have been provided in geographic projection (latitude/longitude) referenced to the WGS84 horizontal datum and EGM96 vertical datum. Note that most global positioning systems use the WGS84 vertical datum as default. This difference in vertical datums may result in absolute elevation differences between +106 m and -86 m. For precise comparison of GPS elevation data with SRTM elevation data, conversion of the vertical datum should be considered beforehand.

5.2 Hydrologically conditioned elevation

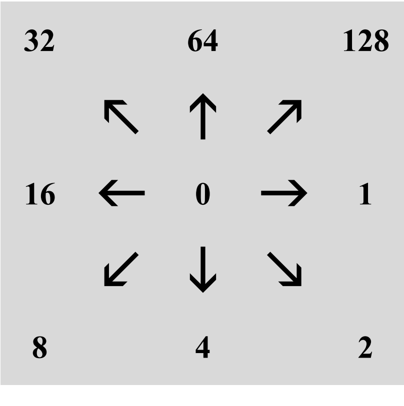
Name signature	**CON**
Data format	Raster
Values	Elevation in meters (referenced to WGS84 EGM96 geoid)
Projection	Geographic (latitude/longitude) referenced to WGS84 horizontal datum
Available resolutions	3 arc-second

The hydrologically conditioned elevation layers distributed with HydroSHEDS are the result of an iterative conditioning and correction process described in detail in section 3. For the specifics of the underlying digital elevation model see 5.1. Note that the conditioning process altered the original DEM and may render it incorrect for applications other than deriving drainage directions. Endorheic basins (inland sinks) have been “seeded” with a no-data cell at their lowest point in order to terminate the flow.

5.3 Drainage directions

Name signature	**DIR**
Data format	Raster
Values	Drainage directions in ESRI format (see below)
Projection	Geographic (latitude/longitude) referenced to WGS84 datum
Available resolutions	3 arc-second, 15 arc-second, 30 arc-second, 5 arc-minute, 6 arc-minute

The drainage direction maps distributed with HydroSHEDS define the direction of flow from each cell in the conditioned DEM to its steepest down-slope neighbor. Values of flow direction vary from 1 to 128 (see graph on right) and follow the convention adopted by ESRI's D8 single flow direction implementation. All final outlet cells to the ocean are flagged with a value of 0. In the legacy version 1.0 of HydroSHEDS, flow direction grids have the value -1 to flag cells that represent the lowest point of an endorheic basin (i.e., inland sinks). In version 1.1 of HydroSHEDS, inland sinks also have the value 0 and a complementary mask grid exists (MSK, see 5.6 below) which differentiates all inland sink pixels from coastal sink pixels.



5.4 Flow accumulation (number of cells, or upstream area)

Name signature	**ACC**, **ACA**
Data format	Raster
Values	Flow accumulation, either in number of cells (ACC) or as upstream area in hectares (ACA)
Projection	Geographic (latitude/longitude) referenced to WGS84 datum
Available resolutions	3 arc-second, 15 arc-second, 30 arc-second

The flow accumulation maps distributed with HydroSHEDS define the extent of upstream area (either in number of cells or in hectares) draining into each cell. The drainage direction layer is used to define which cells flow into the target cell. The number of accumulated cells is a proxy of the upstream catchment area. However, since the cell size of the HydroSHEDS dataset depends on latitude, the cell accumulation value cannot directly be translated into drainage areas in hectares. Thus, a flow accumulation map reflecting true catchment areas (in hectares) is available that takes the the latitudinal distortions of cells into account. The cell count starts at the river's source with 1 (rather than 0), and the largest river basin reaches about 600 million hectares for the Amazon River.

5.5 Flow length (upstream, or downstream)

Name signature	**LUP, LDN**
Data format	Raster
Values	Flow length in meters, either in upstream direction (LUP), i.e., to the furthest source of the river, or in downstream direction (LDN), i.e., to the final point of the river at the ocean or at an inland sink
Projection	Geographic (latitude/longitude) referenced to WGS84 datum
Available resolutions	15 arc-second, 30 arc-second

The flow length maps distributed with HydroSHEDS define the distance at every cell location either in upstream direction, i.e., to the furthest source of the river, or in downstream direction, i.e., to the final point of the river at the ocean or at an inland sink. Distances have been calculated using ESRI's flow length tool using a local cell weighting that takes latitudinal distortions of cell sized into account. Values were rounded to the nearest 10 meters and range from 0 to about 7 million meters (7,000 km) for the Nile River.

5.6 Mask grids (indicator values)

Name signature	**MSK**
Data format	Raster
Values	Indicator values: 1 = land, 2 = ocean sink, 3 = inland sink
Projection	Geographic (latitude/longitude) referenced to WGS84 datum
Available resolutions	3 arc-second, 15 arc-second, 30 arc-second, 5 arc-minute, 6 arc-minute

The mask grids distributed with HydroSHEDS define the extent of land (vs. ocean) as well as the type of sink (ocean vs. inland). These mask grids can be used for certain analyses, such as to identify inland basins or to clip other grids to the landmask of HydroSHEDS.

5.7 Drainage basins (watershed boundaries) – only available in the legacy version 1.0

Name signature	**BAS**
Data format	Vector (polygons)
Projection	Geographic (latitude/longitude) referenced to WGS84 datum
Resolutions	15 arc-second, 30 arc-second
Polygon attributes	ID (unique identifier) Area_skm (surface area in square kilometers)

The drainage basin layers distributed with version 1.0 of HydroSHEDS show contiguous watersheds only, i.e. without further subdivisions (and their naming syntax is amended with "beta"). Version 1.1 of HydroSHEDS does not include this data layer as it was succeeded by the HydroBASINS product (see https://www.hydrosheds.org for more information).

5.8 River network (streamlines) – only available in the legacy version 1.0

Name signature	**RIV**
Data format	Vector (lines)
Projection	Geographic (latitude/longitude) referenced to WGS84 datum
Resolutions	15 arc-second, 30 arc-second
Line attributes	ID (unique identifier) Up_cells (max. flow accumulation of stream reach in number of cells)

The river network layers distributed with version 1.0 of HydroSHEDS are directly derived from the drainage direction layers. The flow accumulation layer is used for selection and attribution. Only rivers with upstream drainage areas exceeding a certain threshold were selected: for the 15 arc-second resolution a threshold of 100 upstream cells has been used, and for the 30 arc-second resolution a threshold of 25 upstream cells has been used. The vectorized river reaches were attributed with the maximum flow accumulation (in number of cells) occurring within each river reach. Version 1.1 of HydroSHEDS does not include this data layer as it was succeeded by the HydroRIVERS product (see https://www.hydrosheds.org for more information).

6. Data formats and distribution

6.1 File name syntax

HydroSHEDS provides data in various regional extents, types, and resolutions. Information about the content of each layer is provided in the file names following the general naming convention (in vervion 1.0) of "*Extent_DataType_Resolution*", e.g., "af_dir_15s". In version 1.1, the prefix "hyd" was added, i.e., "hyd_af_dir_15s". For more information on each of the abbreviations see below:

6.1.1 Regional extent

To facilitate electronic distribution, all raster data at 3 arc-second resolution have been divided into tiles. In version 1.0 of HydroSHEDS, the tile size is 5x5 degrees; in version 1.1 of HydroSHEDS, the tile size is 10x10 degrees. The tile names are defined by a 7-digit identifier which refers to the latitude and longitude of the lower-left (southwest) corner of the tile. For example, the coordinates of the lower-left corner of tile s10w060 are 10 degrees south latitude and 60 degrees west longitude.

The regional extent of continental and global layers is defined by a two- or three-digit identifier in the file name (see table below). Note that the extent of the regions may slightly differ between version 1.0 and 1.1 (e.g., the split between Asia and Australasia has been altered).

Identifier	***Region in legacy version 1.0***	***Updated region in version 1.1***
Af	Africa	Africa
Ar	Arctic (northern Canada)	Arctic (northern Canada)
As	Asia (excl. Siberia, incl. parts of Oceania)	Asia (excl. Siberia)
Au	Australia (Australia and parts of Oceania)	Australasia (Australia and Oceania)
Ca	Central America (Mexico and Caribbean)	*n.a. (included in North America)*
Eu	Europe (excl. Scandinavia) and Middle East	Europe and Middle East
Gr	Greenland	Greenland
Na	North America (USA and Canada, excluding the Arctic)	North America (incl. Central America, excl. the Arctic)
Sa	South America	South America
Sc	Scandinavia	*n.a. (included in Europe)*
Si	Siberia	Siberia
Glo	*n.a.*	Full global extent

6.1.2 Data type

Identifier	***Type of data***
DEM	Digital elevation model (void-filled)
CON	Hydrologically conditioned elevation
DIR	Drainage directions
ACC	Flow accumulation (number of cells)
ACA	Flow accumulation (upstream area in hectares)
LUP	Flow length upstream (distance to furthest source of river in meters)
LDN	Flow length downstream (distance to final point at ocean or inland sink in meters)
MSK	Mask grid (1 = land, 2 = ocean sink, 3 = inland sink)
BAS	*Drainage basins (watershed boundaries) – only in legacy version 1.0*
RIV	*River network (streamlines) – only in legacy version 1.0*

6.1.3 Resolution

Identifier	***in sec/min***	***in degrees***	***in meters/km***
3s	3 arc-second	0.000833333333333333	approx. 90 m at the equator
15s	15 arc-second	0.00416666666666667	approx. 500 m at the equator
30s	30 arc-second	0.00833333333333333	approx. 1 km at the equator
5m	5 arc-minute	0.0833333333333333	approx. 10 km at the equator
6m	6 arc-minute	0.1	approx. 11 km at the equator

Please note that all data provided in 5x5 or 10x10 degree tiles are in 3 arc-second resolution. However, the extension “3s” is omitted in order to shorten the file names.

6.2 Data formats

6.2.1 Legacy version 1.0 (now obsolete)

Version 1.0 of HydroSHEDS, which is now obsolete but still distributed as an archived legacy version, comprises two grid formats (GRID and BIL) and one vector format (Shapefile). Version 1.0 data files are available in the HydroSHEDS archive, along with their associated documentation (Technical Documentation version 1.3) which describes these data formats in more detail.

6.2.2 Version 1.1

Version 1.1 of HydroSHEDS comprises only gridded (raster) datasets. The vector layers of drainage basins (BAS) and river networks (RIV) have been succeeded by the HydroBASINS, HydroRIVERS, and HydroATLAS products (see https://www.hydrosheds.org for details). All grids are distributed in GeoTIFF format. The GeoTIFF format ensures compatibility across nearly all Geographic Information System (GIS) platforms. All raster data are in geographic (latitude/longitude) projection, referenced to datum WGS84. The pixel depth and no-data values of each data type are listed below:

Data type	***Pixel depth (GDAL pixel type)***	***No data value***
DEM	16 bit signed (int16)	32767
CON	16 bit signed (int16)	32767
DIR	8 bit unsigned (byte)	255
ACC, ACA	32 bit unsigned (uint32)	4294967295
LUP, LDN	32 bit unsigned (uint32)	4294967295
MSK	8 bit unsigned (byte)	255

6.3 Data distribution

HydroSHEDS data are available in compressed zip file format from https://www.hydrosheds.org. [*Please note that the former data download site at the EROS Data Center of USGS at http://hydrosheds.cr.usgs.gov is now discontinued.*] To use the data, the zip files must first be decompressed. Each zip file includes a copy of the HydroSHEDS Technical Documentation. Below are coarse estimates of compressed zip file sizes (uncompressed files may be significantly larger).

Zipped file	***Estimated size range***
5x5 (version 1.0) or 10x10 (version 1.1) degree grid tiles	10 to 200 MB
Continental grids at 3s resolution	100 MB to >1 GB
Continental grids at 15s/30s resolution	10 to 300 MB (global up to ~1 GB)
Continental vector files (version 1.0 only)	10 to 100 MB

7. Disclaimer and acknowledgement

7.1 License agreement

All core data of HydroSHEDS version 1 (as described in this document and defined in Appendix A) are free for non-commercial and commercial use. For all regulations regarding license grants, copyright, redistribution restrictions, required attributions, disclaimer of warranty, indemnification, liability, waiver of damages, and a precise definition of licensed materials, please refer to the ***License Agreement*** as provided in Appendix A.

7.2 Acknowledgement and citation

We kindly ask users to cite HydroSHEDS in any published material produced using these data. If possible, online links should be provided to the HydroSHEDS website https://www.hydrosheds.org.

Scientific citations should be made as follows:

> *Lehner, B., Verdin, K., Jarvis, A. (2008): New global hydrography derived from spaceborne elevation data. Eos, Transactions, 89(10): 93-94. Data available at https://www.hydrosheds.org.*

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APPENDIX A

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EXHIBIT A

LICENSED MATERIALS

The Licensed Materials under this License include the HydroSHEDS version 1.0 and 1.1 data layers as listed in Table 1 below. Data layers are provided either in Raster or Vector format; Raster files are provided in ESRI's GRID format, in BIL format, or in GeoTIFF format; Vector files are provided in ESRI's Shapefile format. Data are provided in geographic projection (lat/long); resolutions include 3 arc-seconds (approximately 90 m at the equator), 15 arc-seconds (approximately 500 m at the equator), 30 arc-seconds (approximately 1km at the equator), and 5 and 6 arc-minutes (approximately 10 km and 11 km at the equator).

Table 1: Licensed Materials

	HydroSHEDS data layer	***Versions***	***Format***	***Resolution(s)***
1	Void-filled elevation (DEM)	1.0, 1.1	Raster	3 sec, 15 sec, 30 sec
2	Hydrologically conditioned elevation (CON)	1.0, 1.1	Raster	3 sec
3	Drainage directions (DIR)	1.0, 1.1	Raster	3 sec, 15 sec, 30 sec, 5 min, 6 min
4	Flow accumulation (ACC, ACA)	1.0, 1.1	Raster	3 sec, 15 sec, 30 sec
5	Flow length (LUP, LDN)	1.1	Raster	15 sec, 30 sec
6	Mask grids (MSK)	1.1	Raster	3 sec, 15 sec, 30 sec, 5 min, 6 min
7	River network (RIV)	1.0	Vector	15 sec, 30 sec
8	Drainage basins (BAS)	1.0	Vector	15 sec, 30 sec

The spatial extent of the Licensed Materials includes the following continents (Table 2):

Table 2: Spatial extent of Licensed Materials (as available)

	Region
1	Africa
2	Asia (incl. Siberia)
3	Australia
4	Europe and Middle East
5	North America (incl. Arctic and Central America)
6	South America
7	Greenland

Data are provided as described in the HydroSHEDS v1 Technical Documentation.

EXHIBIT B

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The scientific citation for the HydroSHEDS version 1 database is:

Lehner, B., Verdin, K., Jarvis, A. (2008): New global hydrography derived from spaceborne elevation data. Eos, Transactions, AGU, 89(10): 93-94.