Strahler Stream Order and Strahler Calculator Values in NHDPlus

Suzanne M. Pierson, Barbara J. Rosenbaum, Lucinda D. McKay, and Thomas G. Dewald

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Abstract

For several years, numerous federal and state agencies have collaborated to produce the National Hydrography Dataset Plus (NHDPlus). NHDPlus is a continually evolving, fully-attributed national database which encompasses surface water features in the contiguous United States and Hawaii. Each stream trace, with a known flow direction in NHDPlus, is attributed with several variables including Strahler order. Strahler stream ordering was first developed by Arthur Strahler and is used to characterize the relative size of streams. The original NHDPlus algorithm used to calculate Strahler order produced values that were high and frequently not in agreement with published sources. A new algorithm was developed and implemented to correct Strahler order values throughout NHDPlus. In addition to Strahler order (SO), the new algorithm also incorporates an innovative secondary variable called Strahler calculator (SC), which assists in properly incrementing Strahler order in complex drainage systems. Removing divergences using Strahler calculator simplifies the identification of mainstem streams in all networks. This has practical implications for many hydrologic modeling applications, which have historically used manual methods to locate stream mainstems in the National Hydrography Dataset (NHD). The new Strahler Order/Strahler Calculator (SOSC) algorithm is described in this paper. NHDPlus is available to the public via ftp download from http://www.epa.gov/waters/ (NHDPlus quick link on the right side of webpage).

The SOSC approach was developed by Suzanne M. Pierson (CSC) and Barbara J. Rosenbaum (Excel Management Systems, Inc.) while under contract to the US Environmental Protection Agency’s Office of Research and Development National Health and Environmental Effects Research Laboratory – Western Ecology Division (US EPA ORD/NHEERL/WED) in Corvallis, Oregon. Anthony R. Olsen, Branch Chief WED - Freshwater Ecology Branch, was the project lead. Lucinda D. McKay (Horizon Systems Corporation) implemented the SOSC algorithm in NHDPlus. This document was prepared by Suzanne M. Pierson and Barbara J. Rosenbaum under contract to the US EPA Office of Water. Thomas G. Dewald was the EPA project lead.

NHDPlus Background

The National Hydrography Dataset (NHD) is a geographic database that interconnects and uniquely identifies the stream segments or “reaches” comprising the nation’s surface water drainage system. The initial NHD was based on US Geological Survey (USGS) 1:100,000-scale Digital Line Graph (DLG) hydrography data integrated with reach-related information from the US Environmental Protection Agency (US EPA) Reach File Version 3.0 (RF3) and was developed collaboratively by the USGS, EPA, and state cooperators.

The NHD provides a national framework for assigning reach addresses to water-related entities, such as industrial dischargers, drinking water supplies, fish habitat areas, and wild and scenic rivers. Reach addresses establish the locations of these entities relative to one another within the NHD surface water drainage network in a manner similar to street addresses. Once linked to the NHD by reach addresses, the upstream/downstream relationships of water-related entities and any associated information can be analyzed using software tools ranging from spreadsheets to Geographic Information Systems (GIS). GIS can also be used to combine NHD-based network analysis with other data layers, such as soils, land use, and population, to better understand and display respective effects on one another in support of the Clean Water Act and the Safe Drinking Water Act. Furthermore, since the NHD provides a nationally consistent framework for addressing and analysis, water-related information linked to reach addresses by one organization (national, state, local) can be shared with other organizations and easily integrated into many types of applications. For additional information, navigate to the NHD website, http://nhd.usgs.gov.

NHDPlus is an integrated suite of application-ready geospatial data products that incorporate many of the best features of the National Hydrography Dataset (NHD), National Elevation Dataset (NED), and National Watershed Boundary Dataset (WBD). NHDPlus includes a stream network, based on medium resolution NHD (1:100,000-scale), improved networking, feature naming, and “value-added attributes” (VAAs). NHDPlus also includes elevation-derived catchments produced using a drainage enforcement technique. The VAAs include greatly enhanced capabilities for upstream and downstream navigation, analysis, and modeling. VAA-based routing techniques were used to produce NHDPlus cumulative drainage areas and associated land cover, temperature, and precipitation distributions. The cumulative attributes are used to estimate mean annual flow and velocity attributes included with the NHDPlus data. The VAAs also provide Strahler stream order values.

NHDPlus can be downloaded by USGS hydrologic region as a suite of related datasets (text files, dBase files, and ESRI-formatted shapefiles and grids) and optional tools, which allow users to access additional information about NHD medium resolution data (Figure 1). NHD stream features (referred to as flowlines in the NHD) are provided as
shapefiles. Individual flowlines within each shapefile are coded with several attributes. Additional flowline attributes are included in the Value Added Attribute (VAA) table. The NHD COMID is the common linking attribute between flowline topology in shapefiles, attributes in VAA tables, and other NHDPlus datasets. There are over 2.9 million flowline features in NHDPlus, of which, 2.6 million have a known flow direction. Flow direction information is contained in an attribute called FLOWDIR in the NHDFlowline shapefile attribute table. FLOWDIR is either coded as “With Digitized” (known flow direction) or “Uninitialized” (unknown flow direction). Only flowlines with a defined flow direction [FLOWDIR = With Digitized] are attributed within the NHDPlus VAA tables.

The VAA tables contain numerous attributes which assist in tracing up and down each stream network. The VAAs are calculated through an automated process for complete hydrologic drainage basins. Although the data is processed by USGS hydrologic region, most of the VAAs link information from headwater streams to the terminus of the water course. For example, all flowlines within the Mississippi River drainage basin (hydrologic regions 5, 6, 7, 8, 10, and 11), are linked so attribute values at the mouth of the Mississippi River include cumulative flowline and catchment information within the entire drainage basin (Figure 1). To obtain additional information about NHDPlus and attributes stored in the VAA tables, please refer to the NHDPlus User Guide available at [http://www.horizon-systems.com/nhdplus/documentation.php](http://www.horizon-systems.com/nhdplus/documentation.php).

Figure 1. USGS hydrologic regions. Hatched area shows regions (5, 6, 7, 8, 10, and 11) in the Mississippi River drainage basin that have linked VAA tables. Regions 14 and 15 (the Colorado River drainage basin) also have linked VAA tables.
Original Strahler Order Calculations and Values in NHDPlus

Strahler stream ordering is a method for assessing river size and complexity based on the number and hierarchical relationship of tributaries (Strahler 1957). When determining Strahler order, perennial and intermittent streams are included. The headwater stream (a stream with no tributaries) is considered a 1st order stream. When two 1st order streams join, a 2nd order stream is formed. When two 2nd order streams join, a 3rd order stream is formed, and so on. The ordering continues downstream within a drainage network. Smaller or lower order streams entering the network will not change the Strahler order of larger or higher order streams. For example, a 3rd order stream entering a 4th order stream will not change the Strahler order of the 4th order stream (Figure 2). The Amazon River is a 12th order river – the largest Strahler order designation in the world.

To effectively calculate Strahler stream order, the features comprising a stream network (whether represented on paper maps or in Geographic Information System databases) must be topologically connected. In the NHD, waterbody features such as wide rivers, lakes, and reservoirs add complexity to the drainage network and create breaks in stream segments. Where waterbodies intersect stream features, the NHD provides linear features (known as artificial paths), which are generated using a least cost path algorithm for each waterbody, thereby connecting each inflow and outflow point (Figure 3). The artificial paths allow the stream network to flow through the waterbodies and maintain connectivity with other stream features.

The NHDPlus development team designed an algorithm to calculate Strahler order (stored as “STREAMORDE” in the NHDFlowlineVAA database) for every flowline in NHDPlus with a known flow direction (FLOWDIR = With Digitized). The algorithm assigned all headwater features (coded as “start” features in the NHD) as Strahler order “1”. The NHDPlus algorithm followed the basic premise of Strahler order assignment except when a stream divergence was reached. The NHD stream network contains numerous braided channels, secondary channels, and major stream splits which are coded as divergences. The divergence variable (DIVERGENCE in the NHDPlus VAA table)
is assigned “1” to the downstream main path of the divergence and “2” to the downstream minor path. If the downstream flowline is not a divergence, the divergence value is 0 (Figure 4). In an effort to properly calculate the Strahler order value for the main path of the stream, the original NHDPPlus algorithm decremented the Strahler value by one for minor path divergences. The purpose was to prevent the artificial increase of Strahler order values as divergences rejoin the main path.

Issues with the original algorithm to determine Strahler order became apparent after values were calculated for each stream segment. For example, in NHDPPlus, Strahler order (variable STREAMORDE) equals 47 at the mouth of the Mississippi River, when, in fact, the Mississippi is classified as a 10th order river (Benke and Cushing, 2005). The inflated Strahler order values can be primarily attributed to the numerous stream network divergences that exist in the NHD. Multiple divergences, with decremented Strahler order values, combined to increase the Strahler order of the divergences. Consequently, the Strahler order values for the main path of the stream were incorrectly increased when the divergence rejoined the main path (Figure 5).

In addition to inordinately large Strahler order assignments, another problem with Strahler order values in the initial release of NHDPPlus was the inability to remove minor path divergences and easily select the main path of streams or rivers. Strahler order values varied widely along a connected stream network, sometimes changing as minor path divergences re-entered the main path of a stream. Often, minor path divergences are coded with the same (or higher) Strahler order as the main path of the stream and cannot be easily removed from the network to create a simplified hydrologic network. Additional variables in the VAA table may provide a limited ability to select a simplified hydrologic network. However, each method is time-consuming and does not yield satisfactory results.

Improved Strahler Order Calculations and Values in NHDPPlus

For many years, the US EPA’s Aquatic Resource Monitoring Program (ARM) has relied on different versions of RF3, the NHD, and NHDPPlus to create surface water sampling frames and designs (http://www.epa.gov/nheerl/arm). The sampling designs are used by federal, state, and local agencies to assist in reporting the condition of surface waters by sampling a statistical subset of the aquatic resource and creating general population estimates based on the findings. The ARM probability-based sampling designs use Strahler order to help balance the disproportionate amount of stream length associated with lower order streams compared to higher order streams. Also important for some ARM sampling designs, is the ability to remove minor path divergences from the stream network, especially for large order rivers (i.e., Strahler order 5 and higher).

The continued development of surface water sampling frames and designs for the US EPA’s Aquatic Resource Monitoring Program (ARM) led to the need for accurate Strahler order values for all flowlines in NHD and the ability to easily locate the main path of every stream or river. A new method for calculating Strahler order
has been developed which addresses these requirements. The new method relies on the improved stream networking capabilities and variables available in NHDPlus.

Unlike the original NHDPlus premise of decrementing the Strahler order of minor path divergences, the improved methodology maintains the same Strahler order value for all divergences from the main path. A new variable is calculated to correctly assign or increment the Strahler order (SO) value for main paths and minor path divergences. The new variable is named “Strahler calculator” (SC). Strahler calculator values differentiate main path Strahler order values from minor path Strahler order values. Strahler calculator is assigned a value of “0” for minor paths and a value equal to Strahler order for main paths.

For example, all headwater or “start” reaches are assigned a Strahler order of “1”. Strahler calculator is assigned the same value as SO for all headwater flowlines. If there are no divergences, SO and SC have the same value – both values are increased in the defined manner for calculating Strahler order. Using the new Strahler order algorithm, when a main path divergence is reached, the defined main path (DIVERGENCE = 1) is assigned the same value for SO and SC. The defined minor path divergence (DIVERGENCE = 2) is assigned the same SO value as the flowline directly upstream, but SC is assigned the value “0”. As the minor path divergence continues downstream, the SC value remains “0” and the SO value cannot increase until the flowline is combined with another flowline having a SC value greater than “0”. This allows multiple minor path divergences to intertwine without increasing the Strahler order of the minor path. When two minor path flowlines with SC values of “0” and different SO values join, the larger SO value is maintained and SC remains 0. Also, because SO cannot increase if SC is equal to 0, when a minor path rejoins the main path, the main path Strahler order value is maintained. Figure 6 demonstrates the new NHDPlus Strahler order algorithm. For comparative purposes, Figure 6 shows the same stream network schematic used in Figure 5, but is attributed with the new Strahler order algorithm values (SOSC) instead of the original STREAMORDE values. Note the variations in Strahler order assignments between the two methodologies.

Because the new Strahler order/Strahler calculator algorithm was created after the first release of NHDPlus, the SO and SC variables are stored in separate data tables. The tables are linked through the COMID in NHDPlus and are available through the NHDPlus data extensions website http://www.horizon-systems.com/nhdplus/StrahlerList.php.

Comparison of Original and New Strahler Order Values

The new Strahler order algorithm addresses many issues discovered in the original NHDPlus calculation of Strahler order. The assignment of values for the new Strahler order (SO), matches published Strahler order values more often than does the original STREAMORDE attribute. In the new SOSC NHDPlus data tables, none of the Strahler order values are larger than 10 which is the accepted value for the Mississippi River - the highest Strahler order river in the contiguous US. The original Strahler order algorithm assigned the Mississippi River a stream order of 47 (Figure 7).

When using the new algorithm, Strahler order is higher than published values (e.g., Rio Grande River) in arid or highly channelized regions. Table 1 shows a list of select large rivers with unusually high STREAMORDE values and Strahler order assignments from other sources. The book, Rivers of North America (Benke and Cushing, 2005), was referenced for published Strahler order values.
A comparison of original Strahler order values (STREAMORDE) and the new values (SO) was completed for each USGS hydrologic region. Table 2 shows a matrix of the frequency for the original Strahler order (STREAMORDE) values plotted against the new Strahler order (SO) values for all NHDPlus flowlines with a flow direction. Table 3 displays the stream length totals for NHDPlus by Strahler order for the two methodologies – SOSC and the initial NHDPlus algorithm. Because the largest SO value is 10, STREAMORDE values greater than or equal to 10 were included in the values for 10th order in Table 3. The greatest variation in values between the two methods occur predominately in higher order streams (4th order and larger) as shown in Tables 2 and 3. Also, the two tables show that many flowlines originally assigned Strahler order values greater than 10, are corrected with the new Strahler order algorithm.
Table 2. Comparison of the number of flowlines coded through the initial Strahler order calculations in NHDPlus (STREAMORDE in the rows) to the improved calculations (SO in the columns). The highlighted SO column demonstrates how SO values equal to 10 were previously coded using the original STREAMORDE variable. For example, 370 flowlines had STREAMORDE values of 47, but are coded as 10th order flowlines using the SOSC algorithm.
Conclusions

• An exciting and extremely useful benefit of the new Strahler order and Strahler calculator variables is the ability to derive a simplified national network of mainstem (main path) streams with braided segments and divergences removed. Not only does Strahler calculator identify minor path divergences (SC = 0), but SC also denotes main paths (SO = SC) for all or any given Strahler order. For example, by using the query, SC > 0, the entire mainstem network is easily extracted and minor path divergences are removed (Figure 8). Additionally, Strahler calculator can be used to create a very simple query for selecting main path flowlines (with minor path divergences removed) for a specific Strahler order (e.g., SC = 4) or range of Strahler order streams (e.g., SC > 4). The resulting simplified networks can assist in calculating and estimating flow volumes and velocities, selecting sampling locations on major river networks, and hydrologic modeling.

• The re-assignment of 1\textsuperscript{st}, 2\textsuperscript{nd}, and 3\textsuperscript{rd} order values was relatively uncommon between the original and new Strahler order algorithms. However, the new algorithm provided a more accurate assessment of larger order flowlines than the original method (Figure 9).

<table>
<thead>
<tr>
<th>Strahler Order</th>
<th>Total Length SO (km)</th>
<th>Total Length STREAMORDE (km)</th>
<th>Length Difference (km) SO - STREAMORDE</th>
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<tr>
<td>1</td>
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<td>3,070,361</td>
<td>7833</td>
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<td>514,469</td>
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<td>38,155</td>
<td>-36,139</td>
</tr>
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*All STREAMORDE values greater than or equal to 10 were combined for this comparison.

Table 3. Summary of flowline lengths (km) by order for initial Strahler values (STREAMORDE) and new values (SO). Length differences are new SO values minus original STREAMORDE values.

Figure 8. Schematic demonstrating the ability to easily select the main path of streams (solid lines) using SOSC values. Removal of minor path divergences is accomplished by selecting flowlines with a SC greater than zero (solid lines). Dashed lines show divergences which are removed. Arrows indicate direction of flow.
Figure 9. Example of Strahler order assignments for a portion of the Red Rock River in Montana using (A) the original STREAMORDE values and (B) the new SO values. Note the original STREAMORDE values range from 1\textsuperscript{st} to 9\textsuperscript{th} order, whereas, SO values range from 1\textsuperscript{st} to 4\textsuperscript{th} order. SO provides the correct values for this portion of the river. Also demonstrated (C), is the ability to remove side channels by selecting SC > 0. The ability to select the mainstem of streams greatly simplifies the hydrologic network.
When summarizing the total length of NHDPPlus flowlines by Strahler order (SO), approximately 90% of total flowline length is represented by 1st through 3rd order flowlines (approximately 60% of the length is 1st order, 20% is 2nd order, and 10% is 3rd order). Although 1st through 3rd order flowlines represent a significant proportion of stream resources, many federal, state, and local agencies rely on larger order streams for their research and monitoring activities. For example, over 22,000 USGS gaging station locations (active and inactive) have been associated with NHDP flowlines. The USGS visually inspected and reviewed over 90% of the stations for locational accuracy. Table 4 is a summary of the percent of gaging stations by Strahler order (SO) groupings (1st – 3rd, 4th – 10th) for each USGS hydrologic region in NHDPPlus. Table 4 shows 55% of all gages are located on streams coded 4th order and higher (using the new Strahler order values), whereas only 10% of NHDPPlus total flowline length is assigned with a SO value of 4th order or higher.

The US EPA’s Aquatic Resource Monitoring Program has implemented the new Strahler order (SO) and Strahler calculator (SC) values to develop more representative stream sampling frames than were previously available. This may decrease the need for oversampling of the stream population and lead to more streamlined field efforts.

The new NHDPPlus variables, SO and SC, will allow cartographers and geospatial analysts to easily control the magnitude and complexity of streams portrayed in spatial displays (Figure 10) and used in analysis.

NHD features and NHDPPlus attributes are continually corrected and updated through federal and state stewardship programs and during database refreshes. Plans for the next release of NHDPPlus include the ability to weight stream flows through divergences based on estimated or known flow values. Where multiple divergences occur, SO and SC values may be helpful to determine the downstream flowpath for braided channels because the SO value is consistent for all divergences from the main stream path.

References and Links
Information about US EPA surface water probability-based sample designs. [http://www.epa.gov/nheerl/arm](http://www.epa.gov/nheerl/arm)