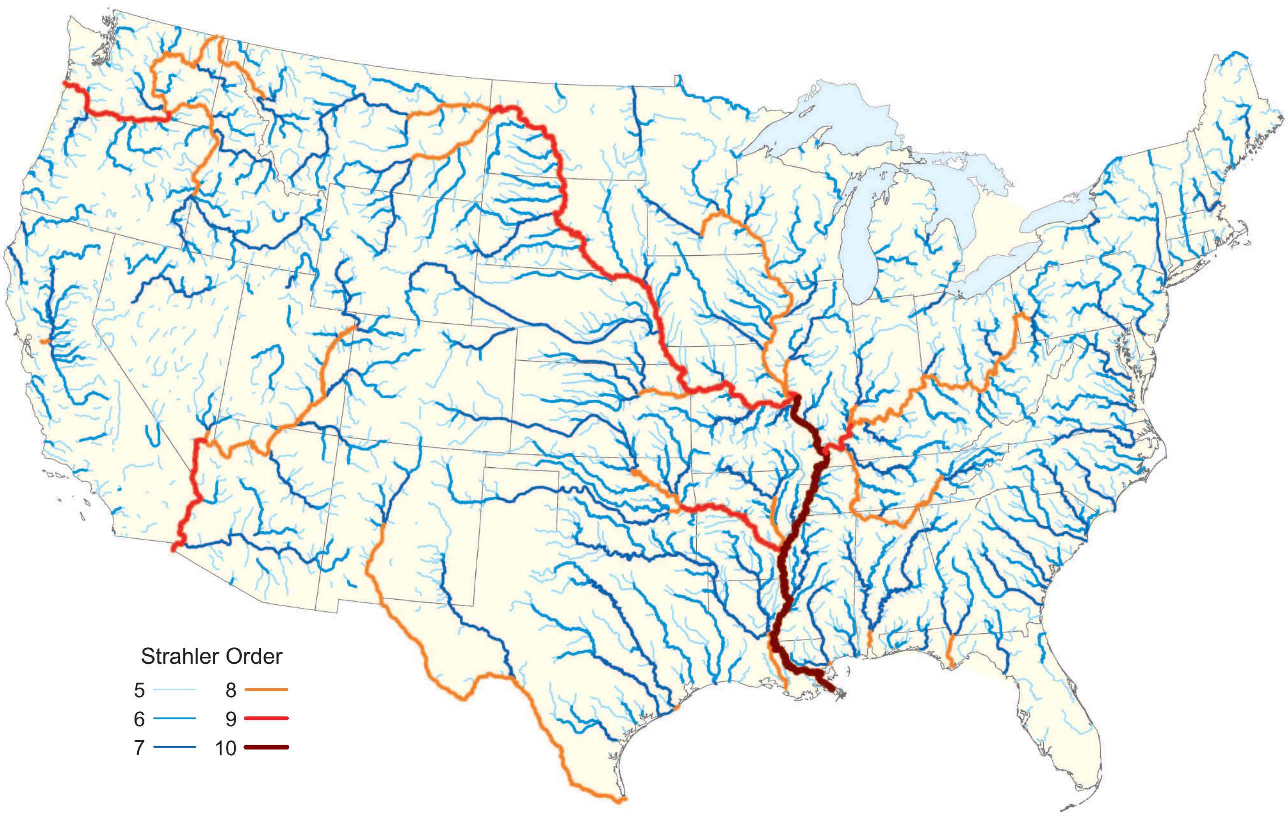
Strahler Stream Order and Strahler Calculator Values in NHD*Plus*

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

September 30, 2008



UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

NHD*Plus*

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Abstract

For several years, numerous federal and state agencies have collaborated to produce the National Hydrography Dataset *Plus* (NHD*Plus*). NHD*Plus* 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 NHD*Plus*, 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 NHD*Plus* 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 NHD*Plus*. 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. NHD*Plus* is available to the public via ftp download from http://www.epa.gov/waters/ (NHD*Plus* 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 NHD*Plus*. 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.

NHD*Plus* 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.

NHD*Plus* 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). NHD*Plus* includes a stream network, based on medium resolution NHD (1:100,000-scale), improved networking, feature naming, and "value-added attributes" (VAAs). NHD*Plus* 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 NHD*Plus* 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 NHD*Plus* data. The VAAs also provide Strahler stream order values.

NHD*Plus* 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 NHD*Plus* datasets. There are over 2.9 million flowline features in NHD*Plus*, 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 NHD*Plus* VAA tables.

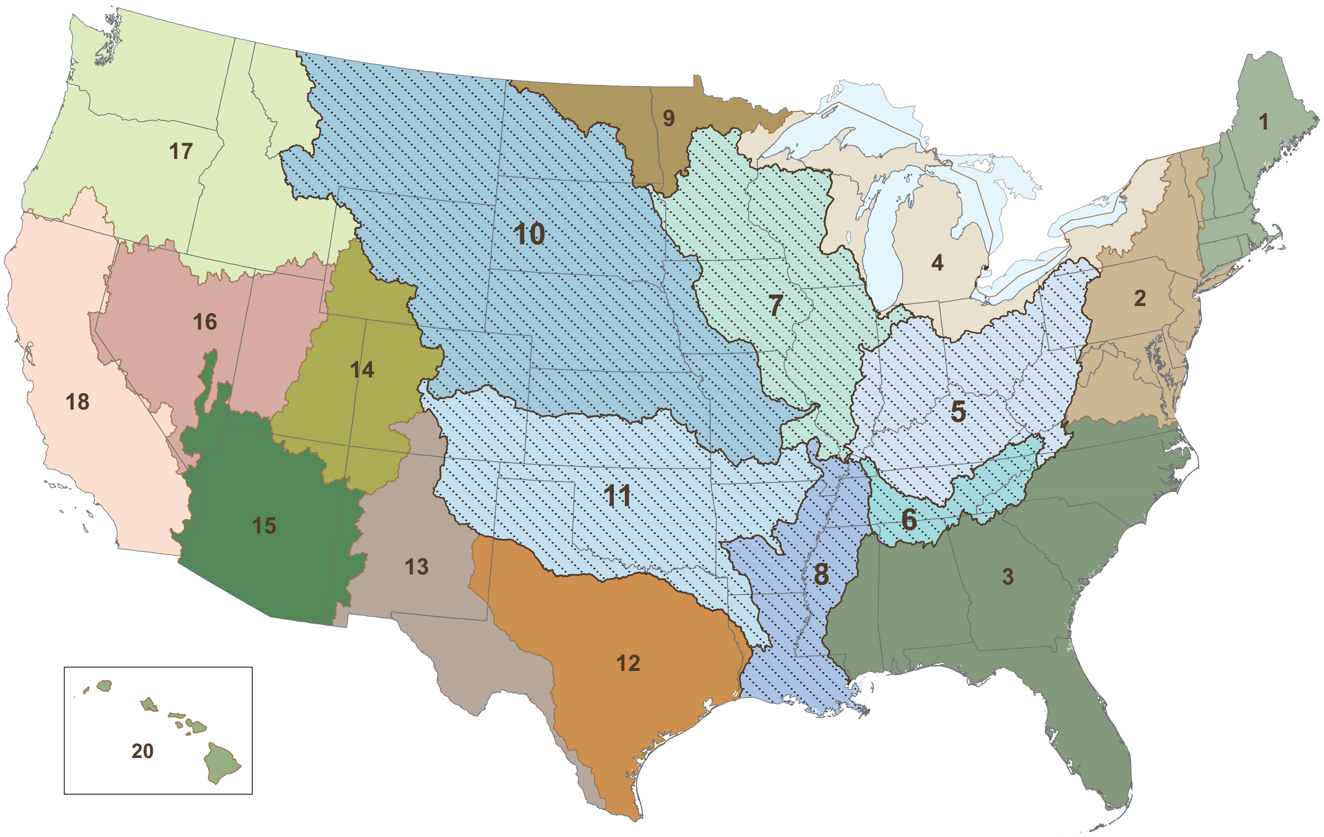

Figure 1. *USGS hydrologic regions. Hatched area shows regions (5, 6, 7, 8, 10, and 11) in the Mississippi River drainage basin that have linked VAA tables. Regions 14 and 15 (the Colorado River drainage basin) also have linked VAA tables.*

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 NHD*Plus* and attributes stored in the VAA tables, please refer to the NHD*Plus* User Guide available at http://www.horizon-systems.com/nhdplus/documentation.php.

Original Strahler Order Calculations and Values in NHD*Plus*

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.

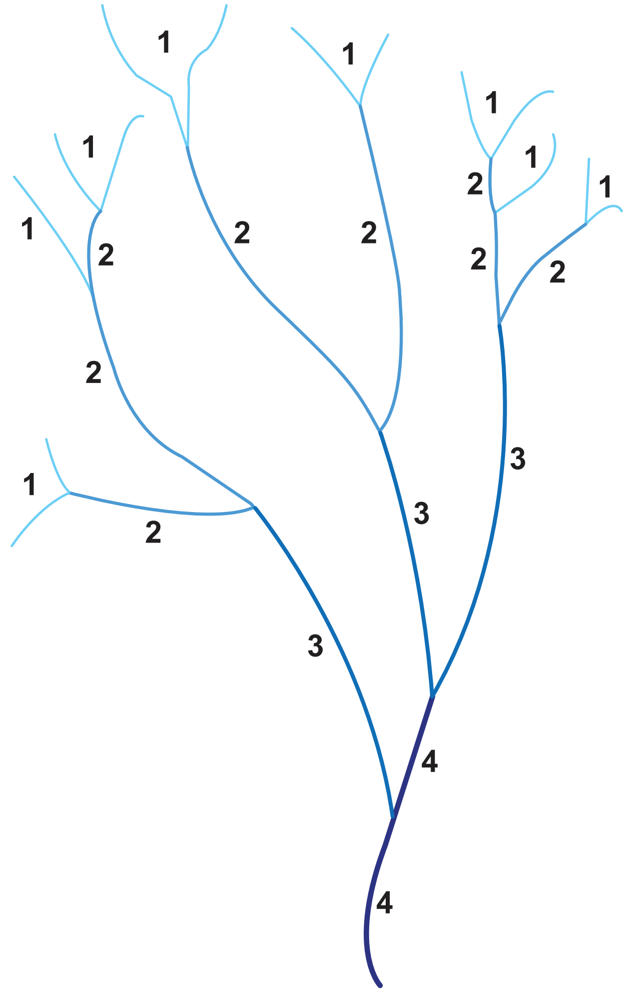

Figure 2. *Stream ordering using the Strahler stream ordering system.*

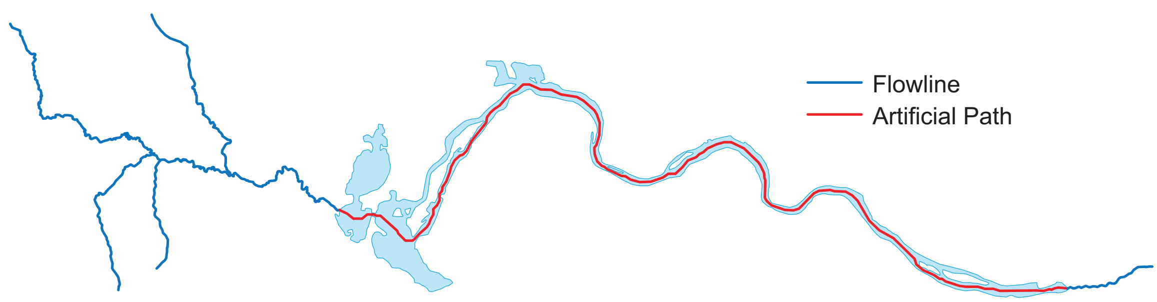

Figure 3. *Example of artificial paths through waterbodies which connect flowlines.*

The NHD*Plus* development team designed an algorithm to calculate Strahler order (stored as “STREAMORDE” in the NHDFlowlineVAA database) for every flowline in NHD*Plus* 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 NHD*Plus* 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 NHD*Plus* 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 NHD*Plus* 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 NHD*Plus*, 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 NHD*Plus* 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 NHD*Plus*

For many years, the US EPA’s Aquatic Resource Monitoring Program (ARM) has relied on different versions of RF3, the NHD, and NHD*Plus* 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

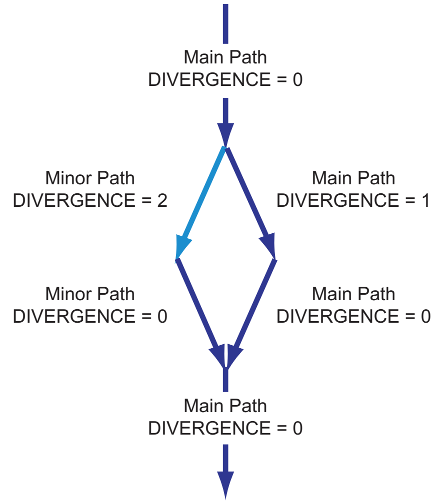

Figure 4. *Schematic of DIVERGENCE code assignments.*

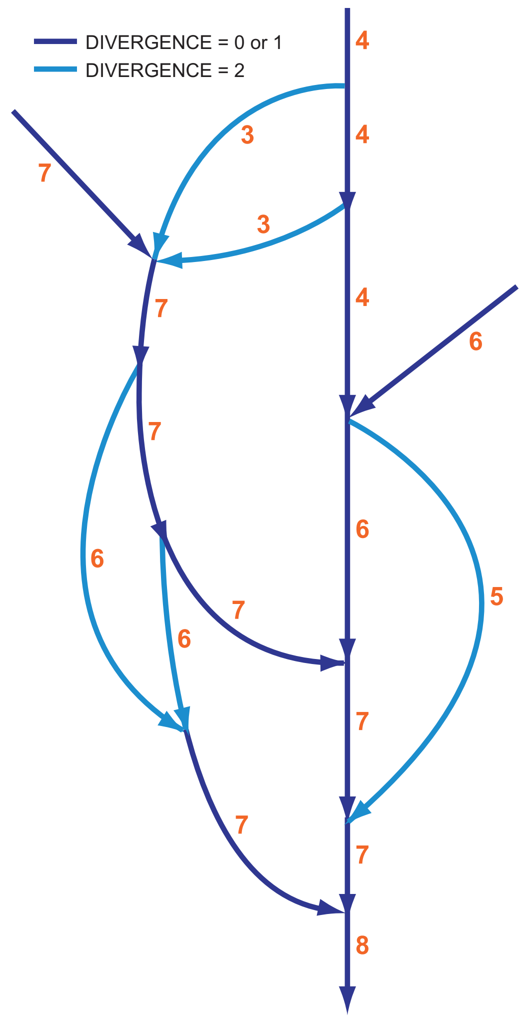

Figure 5. *Schematic of original NHDPlus Strahler order calculation methodology and associated STREAMORDE assignments (red text). Arrows indicate direction of flow.*

has been developed which addresses these requirements. The new method relies on the improved stream networking capabilities and variables available in NHD*Plus*.

Unlike the original NHD*Plus* 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 NHD*Plus* 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 NHD*Plus*, the SO and SC variables are stored in separate data tables. The tables are linked through the COMID in NHD*Plus* and are available through the NHD*Plus* data extensions website http://www.horizon-systems.com/nhdplus/StrahlerList.php.

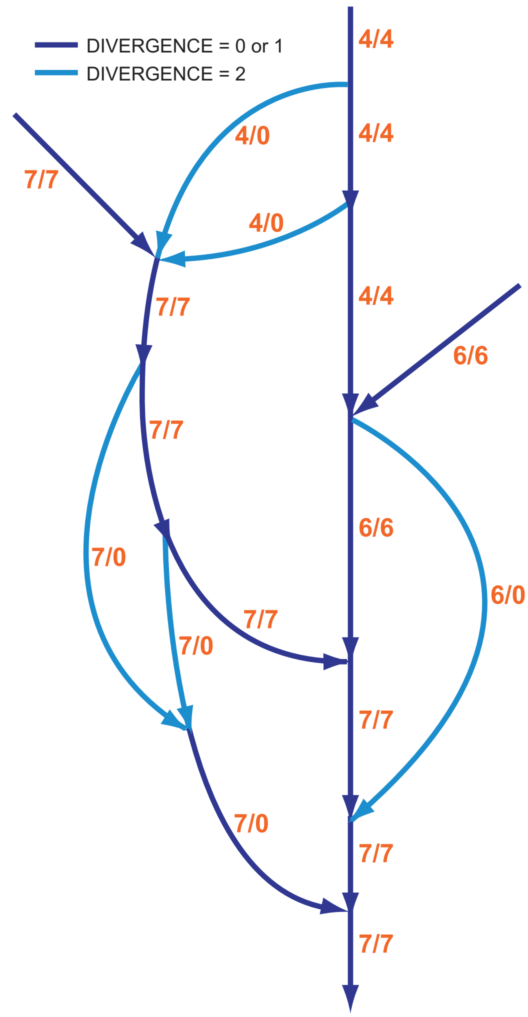

Figure 6. *Schematic of improved NHDPlus Strahler order calculation methodology and associated SO/SC assignments (red text). Arrows indicate direction of flow.*

Comparison of Original and New Strahler Order Values

The new Stahler order algorithm addresses many issues discovered in the original NHD*Plus* 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 NHD*Plus* 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.

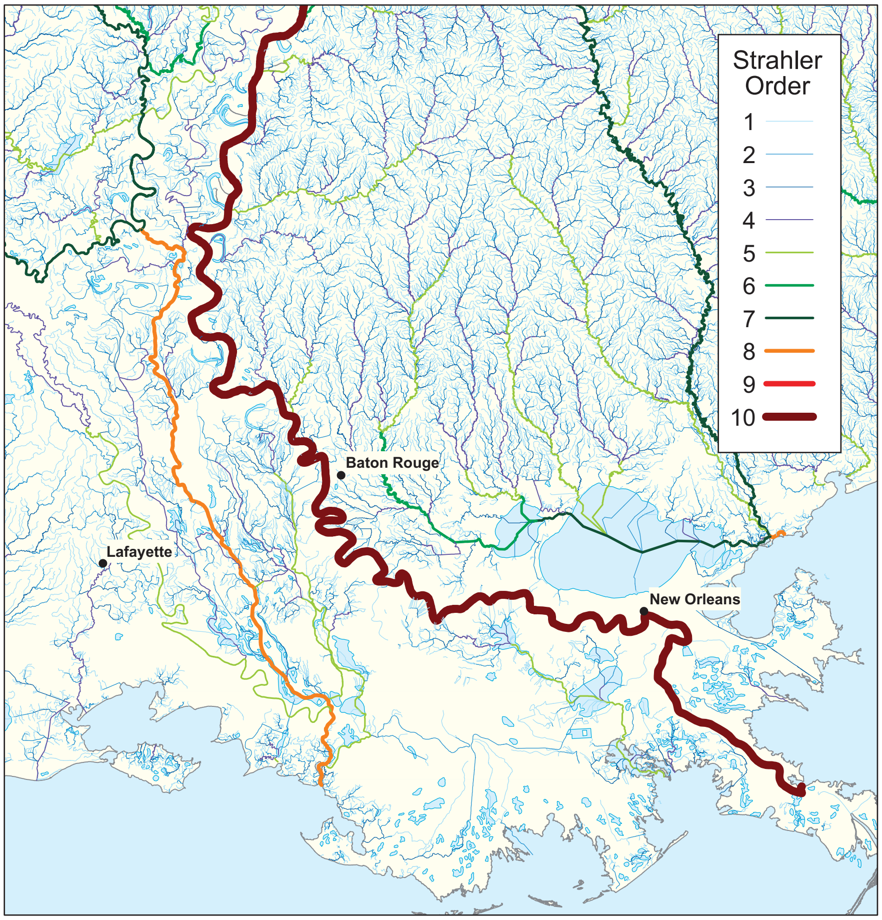

Figure 6. *Map of the lower Mississippi River as it enters the Gulf of Mexico. Strahler order assignments shown are based on the improved SOSC technique. The Mississippi River was initially classified as a 47th order stream using the original NHDPlus calculation method. The SOSC technique corrects the ordering and reclassifies the Mississippi to a 10th order stream (bold red line on map).*

River Name	Strahler Order Source		
	Rivers of North America **(Benke and Cushing, 2005)**	**NHD*Plus* NHDFlowlineVAA STREAMORDE**	**NHD*Plus* SOSC Strahler Order**
Mississippi	10	47	10
Missouri	9	45	9
Ohio	9	10	9
Columbia	9	10	9
Sacramento	8 (estimated)	13	8
Rio Grande	7	15	8
Colorado	6	22	9
Truckee	5	12	5

Table 1. *Comparison of Strahler order values for various large rivers in the US.*

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 NHD*Plus* flowlines with a flow direction. Table 3 displays the stream length totals for NHD*Plus* by Strahler order for the two methodologies – SOSC and the initial NHD*Plus* 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.

Number of NHD*Plus* Flowlines	SO										
STREAMORDE	1	2	3	4	5	6	7	8	9	10	Grand Total
1	1327407	9324	897	133	4						1337765
2	9820	567980	9473	822	60	2					588157
3	1776	7086	294454	9130	538	29					313013
4	1197	1487	6324	153310	5750	242	9				168319
5	687	1009	987	7899	74919	2920	85	1			88507
6	519	717	532	2156	8687	31241	715	7			44574
7	324	506	400	877	2599	7506	7954	46			20212
8	317	416	359	691	1678	3529	3614	1560	2		12166
9	219	283	183	391	988	1689	2809	1433	81		8076
10	150	235	160	225	644	1448	1066	631	252		4811
11	98	183	170	134	546	619	1128	264			3142
12	81	152	159	173	334	344	1379	222			2844
13	70	120	107	86	172	469	547	68			1639
14	37	27	61	50	125	757	1557	262			2876
15	26	24	25	85	53	267	410	545			1435
16	31	32	23	44	58	163	399	46			796
17	52	59	18	48	80	332	685	202			1476
18	34	68	34	33	93	123	937	941			2263
19	32	79	55	81	18	132	189	247	1		834
20	42	27	11	7	46	86	556	29	12		816
21	52	16	7	20	5	42	390	61	30		623
22	15	23	11	20	7	66	453	768	465		1828
23	7	21	5	4	11	33	159	85			325
24	14	30	13		11	26	111	69			274
25	5	26	13	5		29	139	139	36		392
26	10	6	2	1		14	13	108	270		424
27	5	7	2			20	24	28	5		91
28						21		15	32		68
29						32					32
30	1	1	2			44					48
31	2		4			36	3				45
32		1	2			33	23				59
33	1					27	203				231
34	4						25				29
35	1						24				25
36		1	6				55				62
37	1	2					85				88
38	2	2	4				40	13	3		64
39			4				22	40	19		85
40	5	8	10					75	42		140
41	19	5		2	5			298	733		1062
42	2	2	1						462		467
43		1							144		145
44	3	3	1	3					68	12	90
45	8	3		5	9				20	54	99
46	15	17	8	7	45					71	163
47	93	28	5	1	91			9		370	597
48	2	2			51			43			98
49					16			12			28
50								12			12
Grand Total	1343186	590019	314532	176443	97643	52321	25808	8279	2677	507	2611415

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.*

Strahler Order	Total Length SO (km)	Total Length STREAMORDE (km)	Length Difference (km) SO - STREAMORDE
1	3,078,194	3,070,361	7833
2	965,869	964,143	1726
3	516,606	514,469	2137
4	274,289	267,199	7090
5	143,378	134,153	9225
6	72,527	64,581	7946
7	34,813	26,091	8722
8	12,501	14,672	-2171
9	4737	11,105	-6368
10*	2016	38,155	-36,139

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.*

**All STREAMORDE values greater than or equal to 10 were combined for this comparison.*

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 1st, 2nd, and 3rd 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).

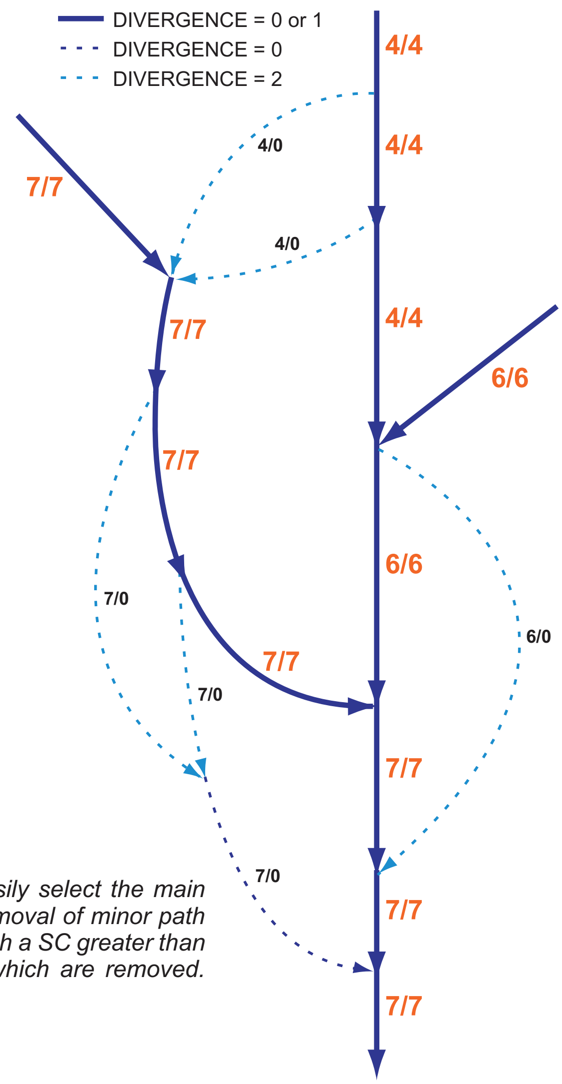

Figure 8. *Schematic demonstrating the ability to easily select the main path of streams (solid lines) using SOSC values. Removal of minor path divergences is accomplished by selecting flowlines with a SC greater than zero (solid lines). Dashed lines show divergences which are removed. Arrows indicate direction of flow.*

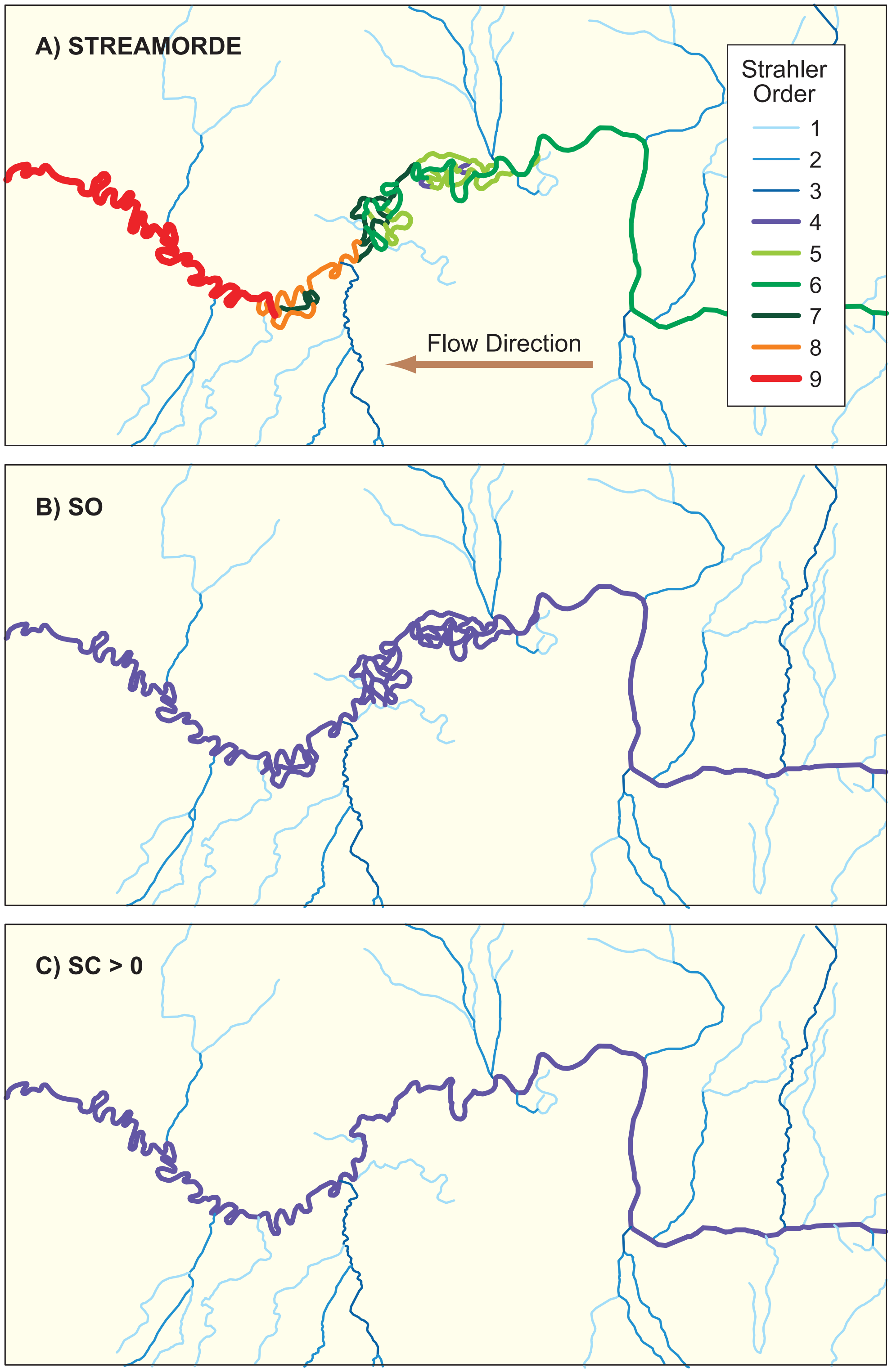

Figure 9. *Example of Strahler order assignments for a portion of the Red Rock River in Montana using (A) the original STREAMORDE values and (B) the new SO values. Note the original STREAMORDE values range from 1st to 9th order, whereas, SO values range from 1st to 4th order. SO provides the correct 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 NHD*Plus* flowlines by Strahler order (SO), approximately 90% of total flowline length is represented by 1^{st} through 3^{rd} order flowlines (approximately 60% of the length is 1^{st} order, 20% is 2^{nd} order, and 10% is 3^{rd} order). Although 1^{st} through 3^{rd} 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 NHD 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 (1^{st} – 3^{rd}, 4^{th} – 10^{th}) for each USGS hydrologic region in NHD*Plus*. Table 4 shows 55% of all gages are located on streams coded 4^{th} order and higher (using the new Strahler order values), whereas only 10% of NHD*Plus* total flowline length is assigned with a SO value of 4^{th} 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 NHD*Plus* 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 anaylsis.

Hydrologic Region	Gaging Stations by SO (%)	
	1^{st} – 3^{rd}	4^{th} – 10^{th}
1	58	42
2	60	40
3	42	58
4	50	50
5	43	57
6	42	58
7	45	55
8	38	62
9	35	65
10	36	64
11	34	66
12	45	55
13	38	62
14	55	45
15	31	69
16	50	50
17	43	57
18	51	49
20	78	22
All Regions	45	55

Table 4. *Percent of USGS gaging stations assigned to NHD flowlines by new Strahler order (SO) values, grouped by USGS hydrologic region.*

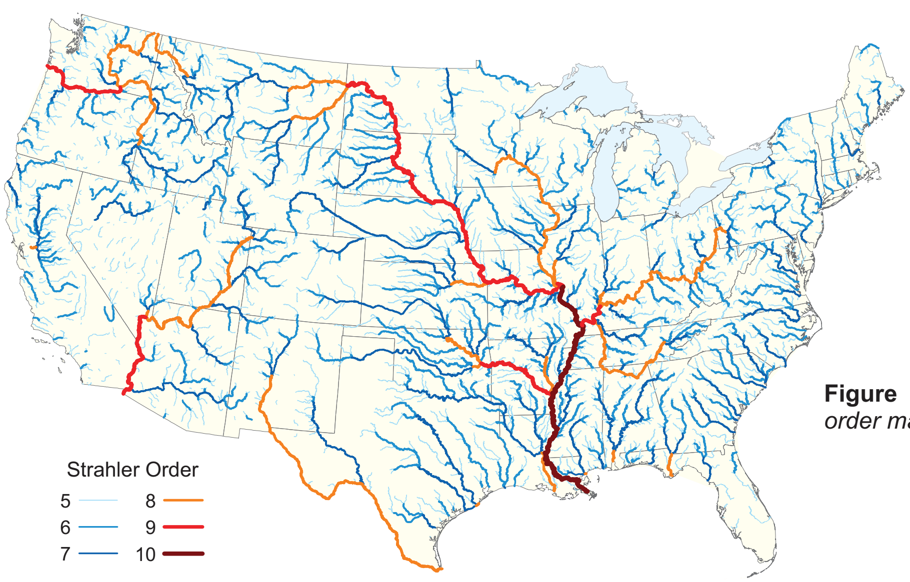

Figure 10. *NHDPlus 5^{th} through 10^{th} Strahler order main path flowlines (SC > 4).*

NHD features and NHD*Plus* attributes are continually corrected and updated through federal and state stewardship programs and during database refreshes. Plans for the next release of NHD*Plus* 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

Benke, A.C., and C.E. Cushing (eds.). 2005. *Rivers of North America*. Elsevier Inc.

NHD*Plus* User Guide. April 29^{th}, 2008. Available from http://www.horizon-systems.com/nhdplus/documentation.php.

Strahler, A.N., 1957. Quantitative Analysis of Watershed Geomorphology. American Geophysical Union Transactions 38:913-920.

Information about US EPA surface water probability-based sample designs. http://www.epa.gov/nheerl/arm.