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A topological system for delineation and codification of the Earth's river basins

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Abstract

A comprehensive reference system for the Earth's river basins is proposed as a support to river basin management, global change research, and the pursuit of sustainable development. A natural system for delineation and codification of basins is presented which is based upon topographic control and the topology of the river network. These characteristics make the system well suited for implementation and use with digital elevation models (DEMs) and geographic information systems. A demonstration of these traits is made with the 30-arcsecond GTOPO30 DEM for North America. The system has additional appeal owing to its economy of digits and the topological information that they carry. This is illustrated through presentation of comparisons with USGS hydrologic unit codes and demonstration of the use of code numbers to reveal dependence or independence of water use activities within a basin. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The river basin has seen a renewed interest in recent years as a fundamental landscape unit for development planning and management. The 1992 Dublin Conference on Water and the Environment and the 1992 UN Conference on Environment and Development in Rio de Janeiro have formally focused their attention on this topic. Growing practical concerns have encouraged this emphasis in more immediate and compelling ways. Increasing human populations steadily raise demand for fresh water while often adversely affecting the quality of the available supply. Meanwhile, global climate changes threaten to alter the spatial and temporal patterns of precipitation and evapo-transpiration, further challenging the human capacity for adaptation.

River basin management is the intellectual basis for responding to these challenges (Newson, 1992). Among the problems that have impeded its successful application, Barrow (1998) cites the lack of baseline data and improved simulation modeling that they can support. Goulter and Forrest (1987) and Burton (1995) note the positive contribution that geographical information systems (GIS) can have in this regard. GIS can assemble available data and facilitate the visualization, modeling, and analysis needed to avoid planning decisions based on false assumptions.

Delineation of river basins is an indispensable step if GIS technology is to be used to support river basin planning. We feel that there is a need for a simple and globally applicable reference system that at once

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uniquely identifies and indicates the spatial nature of a hydrographic basin. To meet this need, we present a system for delineation and codification of basins on the basis of topography and the topology of the resulting drainage network.

2. Description of existing systems

Several codification systems for basins and stream gauges have been developed over the years by organizations with a need to organize hydrologic data. Basin codification schemes directly address the need for numbering natural landscape units that are the focus of river basin management. Stream gauge numbering systems implicitly identify upstream areas but they do not necessarily correspond to resource management units. Stream gauge locations are often dictated by logistical considerations, such as easy access at highway-river crossing sites or operational needs, such as gauges installed at points of diversion.

The Water Resources Division of the US Geological Survey (USGS) has its Hydrologic Unit System (Seaber et al., 1987) which divides U.S. territory into 21 major regions composed of 222 subregions. The subregions of the system are broken into successively smaller accounting units and cataloging units. The boundaries of these units are defined in terms of topographic river basin divides and subbasins. A hydrologic unit code (HUC) is an eight-digit number that has two digits each to indicate region, subregion, accounting unit, and cataloging unit. The hydrologic units delineate all river basins with a drainage area of at least 700 mi^2 (1800 km^2), except in Alaska where a much larger minimum drainage area has been used. In some cases, units smaller than this predefined limit are delineated. Approximate mean areas of regions, subregions, accounting units, and cataloging units are, respectively, 500 000, 50 000, 25 000 and 4000 km^2. The Hydrologic Unit System is used by the USGS and other federal and state government agencies as the basis for reporting and planning water use and development. The system has not been extended to areas beyond US borders.

Systems that implicitly code basins have arisen from the need to develop identification numbers for stream gauging stations. A gauging station's location, of course, corresponds to a unique upstream basin and its measurements record runoff integrated over that surface area. The National Water Information System (NWIS) is the repository for USGS surface water records (Wahl, 1995). NWIS includes a system of stream gauge station identification numbers. These are 8-digit numbers whose ordinal values increase in a downstream sense. In station listings, position of a station on a tributary is indicated by an indentation, and there is successive indentation to indicate tributary rank. The numbers themselves, however, offer no distinction between tributary and main stem, nor do they convey information on drainage network topology. The first two digits are referred to as the Part Number and designate the major river basin. Thereafter, the remaining six digits increase in downstream order. Values are not consecutive because gaps are left in the series to permit addition of future stations.

The French research organization, ORSTOM, employs a nine-digit system for the stations for which it has data in Africa, South America, Europe, and Oceania (Roche, 1968). The first digit identifies the continent, the second and third identify the country, and the fourth and fifth a continental river basin, with a maximum of 99 major river basins per continent selected by ORSTOM. The rivers that give their names to the basins and their alphabetical order determine the numerical value of a basin's code. The sixth and seventh digits used in the system identify the river on which the gauging station is found, and the eighth and ninth digits uniquely specify the station, given the information carried by the preceding digits. In these latter two cases, the alphabetical order of river and station names is used, once again, to assign numerical values for the digits of the identification number. This system has been defined only for those regions for which ORSTOM has data. It is very practical and well suited to sorting tabular station data by continent, country, basin, and river, provided these items have been defined a priori. Addition of a new station and associated basin or river, not previously recognized, would presumably require a request to ORSTOM for modification of its code tables, and alphabetical order would be lost. Changes in country names or territories as a result of political events can present complications as well.

In Brazil, the hydroelectric power agency, Departamento Nacional de Aguas e Energia Eletrica

Table 1
Summary of several basin and stream gauge codification schemes that have been applied over wide areas

Organization/system	Country	Basis	Extent	No. digits
USGS/HUCS	USA	Basin	National	8
USGS/NWIS	USA	Gauge	National	8
ORSTOM	France	Gauge	Continental	9
DNAEE	Brazil	Gauge	National	8
GRDC	United Nations	Gauge	Global	7

(DNAEE), has defined a codification scheme for gauging stations that somewhat resembles the NWIS system. It uses the leading two digits to represent basins and subbasins (Fernandes, 1987). There are nine basins (1–9) for the country, and each is subdivided into 10 subbasins (0–9). Thereafter, digits three, four, and five are used for station numbers, with values increasing from upstream to downstream. Digits six, seven, and eight are provided to accommodate stations added in the future, though ordinarily they are shown as zeroes (000). There is no capability to further subdivide the basins beyond the 10 subbasins. The DNAEE system is defined only for Brazilian territory.

The Global Runoff Data Center (GRDC) of the World Meteorological Organization is operated by the Federal Institute of Hydrology in Koblenz, Germany. It publishes a variety of data reports and analyses (Global Runoff Data Center, 1996). Inspection of a GRDC stream gauge index list reveals that it uses a system with seven-digit identification numbers for the thousands of stations around the world for which it archives and disseminates streamflow data. The first digit indicates continent, the second country, the third and fourth together identify a continental basin, and digits five, six, and seven are for the station itself. When there are more than nine countries on a continent, values 1–9 are used over again for the second digit, and digits three and four, indicating basin, are depended upon to prevent confusion.

Table 1 summarizes the codifications discussed previously. There are undoubtedly other schemes in existence for coding basins and stream gauging stations, because there are several organizations around the world with responsibility for archiving and cataloging the hydrologic data for these units. However, we are not aware of any system currently in use that comprehensively provides for basin delineation and codification according to the topology of the Earth's natural drainage patterns.

3. Topological characteristics of the proposed system

The system proposed here for the delineation and codification of the Earth's river basins is founded upon concepts first articulated by the late Otto Pfafstetter, an engineer with the Departamento Nacional de Obras de Saneamento (DNOS), a civil works agency of the federal government of Brazil (Pfafstetter, 1989). It is a natural system based upon topographic control of areas drained on the Earth's surface and the topology of the resulting hydrographic network.

At the heart of a basin's identity are the size and shape of the catchment area and channel configuration that produce flow at the outlet. All channel reaches have unique direction, and therefore order, and they are arranged in a bifurcated network. The Pfafstetter system is designed to exploit features of the base-10 numbering system that mirror these basin characteristics: the ordinal nature of digit values from one through nine, and their binary trait of being alternately odd or even. The ordinal value of a digit indicates relative upstream/downstream position, while a digit's parity indicates network position on or off the main channel. The objective is the definition of basin identification numbers whose digits can be used in and of themselves to perform basin topological analyses. One important outcome of this strategy is the efficient use of digits. Compared to the systems described in the previous section, the Pfafstetter system uses significantly fewer digits to uniquely code a population of basins.

As the Pfafstetter system definition stems directly

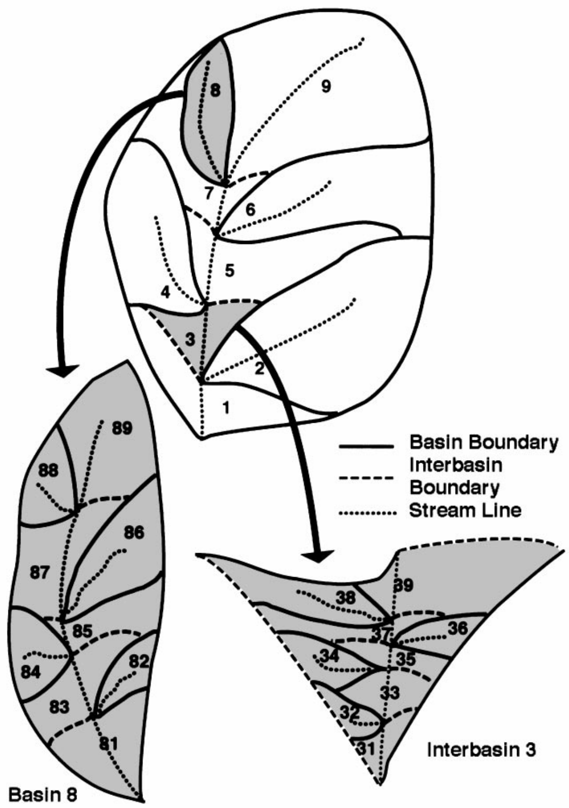


Fig. 1. Sample subdivisions of a basin and an interbasin obtained by applying the rules of Pfafstetter codification.

from topography and consequent drainage network topology, it lends itself to implementation through manipulation of digital elevation models (DEMs) and to subsequent exploitation with data base management and geographic information system (GIS) software. The appeal of the approach stems from its economy of digits, the topological information that the digits carry, and its global applicability. In order to explain the system, it is first necessary to cover basic definitions.

Consider the exercise of tracing a river on a map from its mouth to its source. As confluences are encountered, it is necessary to distinguish between the main stem and the tributary. By the Pfafstetter method, the main stem is always taken as the watercourse that drains the greater area; the tributary drains the lesser of the two areas. At times this is inconsistent with local custom or map notation, but the drainage area rule is nonetheless strictly applied.

The area drained by a tributary is called a basin. Continuing upstream to a second confluence, one once again applies the drainage area rule to distinguish between the main stem and the tributary. A second basin is associated with the newly encountered tributary. The area directly drained by the reach of the main stem lying between the two tributaries is called an interbasin. Boundaries between interbasins are found by beginning at a point on the bank of the main stem immediately opposite the outlet of a basin and tracing uphill, orthogonal to the topographic gradient, until encountering a basin boundary.

Subdivision of the area drained by a major river into coded basins and interbasins involves assignment of digits in a way that takes advantage of their ordinal values and parity. The Pfafstetter convention is to increase ordinal values from downstream to upstream, and to assign odd digits to interbasins and even digits to basins. A zero digit is reserved for areas of internal, closed drainage. For the initial subdivision of a parent basin, one therefore has five available values (1,3,5,7,9) for interbasins, and four values (2,4,6,8) for basins. This conforms to the topological fact that there will always be one more interbasin than basin, regardless of the manner in which they are labeled. There will be a large number of candidate tributary basins to be delineated, but only four digital values available. To ensure that subdivision occurs in a balanced way, the four tributaries with the greatest drainage areas take the available values. However, the ordinal even value assigned to a basin depends on its topological position among the four, not its area.

Application of the system proceeds, then, with identification of the four tributaries with the greatest area drained. These are assigned the numbers 2, 4, 6, and 8, in the order in which they are encountered as one traces the main stem from outlet to source. Next, the interbasins are numbered 1, 3, 5, 7, and 9, again moving upstream from the mouth of the main stem. Interbasin 1 is the area drained by the main stem between the outlet of basin 2 and the mouth of the main stem. Interbasin 3 is the area drained by the main stem between the outlets of basins 2 and 4. Interbasin 5 is the area drained by the main stem between basins 4 and 6, and interbasin 7 lies between basins 6 and 8. Interbasin 9 always consists of the headwaters area of the main stem, and it always drains a larger area than basin 8, by definition. If closed basins are encountered, the largest one is assigned the number zero. An idealized river basin showing subdivision into coded basins and interbasins is shown in Fig. 1.

Any basin or interbasin can be further subdivided by simply applying the same rules to its internal area. Within each basin or interbasin, the four tributaries with the greatest drainage area are identified. These are numbered 2, 4, 6, and 8 from downstream to upstream. Thus, basin 8 of our example is subdivided into basins 82, 84, 86, and 88, and interbasins 81, 83, 85, 87, and 89, and interbasin 3 is further subdivided into basins 32, 34, 36, and 38 and interbasins 31, 33, 35, 37, and 39. Again, refer to Fig. 1.

Depending on the scale and density of the mapped stream network, any basin or interbasin can be further subdivided until four tributaries can no longer be found.

4. Implementation of the method for a continent

The USGS has developed a consistent set of DEMs with 30-arcsecond (approximately 1 km) postings for the land masses of the Earth (Gesch et al., 1999). They have been given the name GTOPO30 and are available to the public on the World Wide Web at `http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html`. Procedures for continental basin delineation and codification were developed using these data sets as input. The North American continent was chosen as the first for implementation of the Pfafstetter basin numbering scheme. This was due, in part, to the abundance of digital data (streams and basins) available for verification from the US, Mexican, and Canadian organizations.

It is necessary to use standard GIS drainage analysis software (Jenson and Domingue, 1988) to refine a continental DEM prior to basin analysis. This involves identifying and filling spurious sinks and preserving representations of natural sinks in the landscape (Verdin and Jenson, 1996). After transforming the DEM to a cartographic projection that supports area calculations, such as the Lambert Azimuthal Equal Area coordinate system, and selecting a 1-km spacing for elevations, the drainage software is applied to the properly filled DEM to solve for flow direction at each posting location. An algorithm is used that finds the path of steepest descent between a posting and its eight adjacent neighbors. Next, a flow accumulation value (a count of the number of tributary postings) is computed for each position, and a 1000 km^2 threshold applied to obtain a drainage network in raster format. This drainage network is vectorized, and each arc in the network is given an attribute with the maximum flow accumulation value from the set of raster elements used to derive it. In this way, each arc in the resulting vector drainage network is prepared for application of the Pfafstetter rule for distinguishing between the main stem and its tributaries by the criterion of area drained.

To begin the continental subdivision, the stream arcs examined initially are those draining directly to the sea. First, the four with the greatest area drained

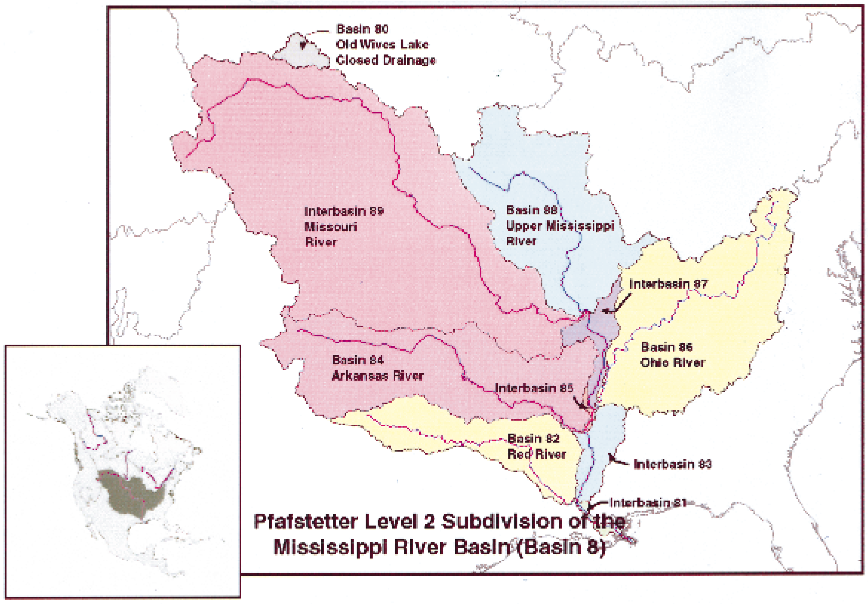
Fig. 2. Subdivision of the North American continent into Pfafstetter basins using the GTOPO30 DEM from USGS.

are identified. They are assigned Pfafstetter codes 2, 4, 6, and 8, following a clockwise order around the continent, starting with the basin closest to due north.

Returning to the raster DEM and its associated flow direction grid, the surface areas drained by basins 2, 4, 6, and 8 are determined from the flow direction grid, vectorized and the polygons are each given their appropriate Pfafstetter code as an attribute. Basin 0 is identified as the largest closed basin, obvious at the continental scale. The remaining continental area is assigned to polygons corresponding to coastal interbasins 1, 3, 5, 7, and 9, so that interbasin 3 lies between basins 2 and 4, interbasin 5 lies between basins 4 and 6, and interbasin 7 lies between basins 6 and 8. The area between basins 2 and 8 is divided between interbasins 1 and 9. Choosing a divide that connects basin 0 with the coast can be a convenient way to do this. Fig. 2 illustrates how this was done for North America.

The result of the preceding steps is a vector coverage of the continental land mass composed of 10 polygons numbered 0 through 9. This coverage is intersected with the vector coverage of the continental drainage network in order to pass a Level 1 Pfafstetter code to each arc of the drainage network, defining the basin or interbasin in which it lies. This completes the Level 1 subdivision of a continent. As shown in Fig. 2, the Level 1 subdivision of the North American continent delineates the four largest river systems of the continent: the Mackenzie, Nelson, St. Lawrence, and Mississippi Rivers.

Further subdivision is carried out to obtain a Level 2 set of Pfafstetter units for the continent. All stream segments within any basin or interbasin are again



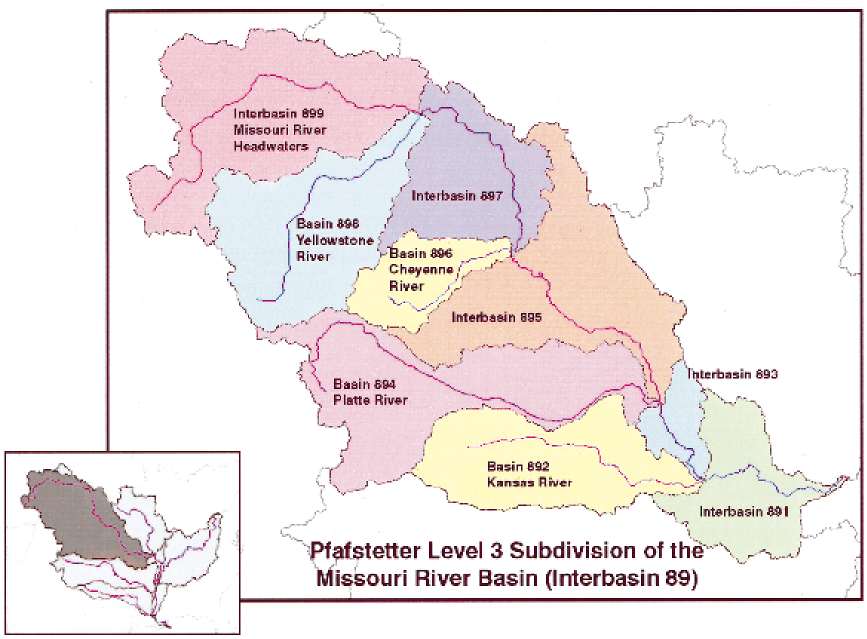


Fig. 3. The upper diagram shows subdivision of the Mississippi River basin (basin 8 of Fig. 2) and in the lower diagram, subdivision of its headwaters interbasin (the Missouri River basin, interbasin 89).

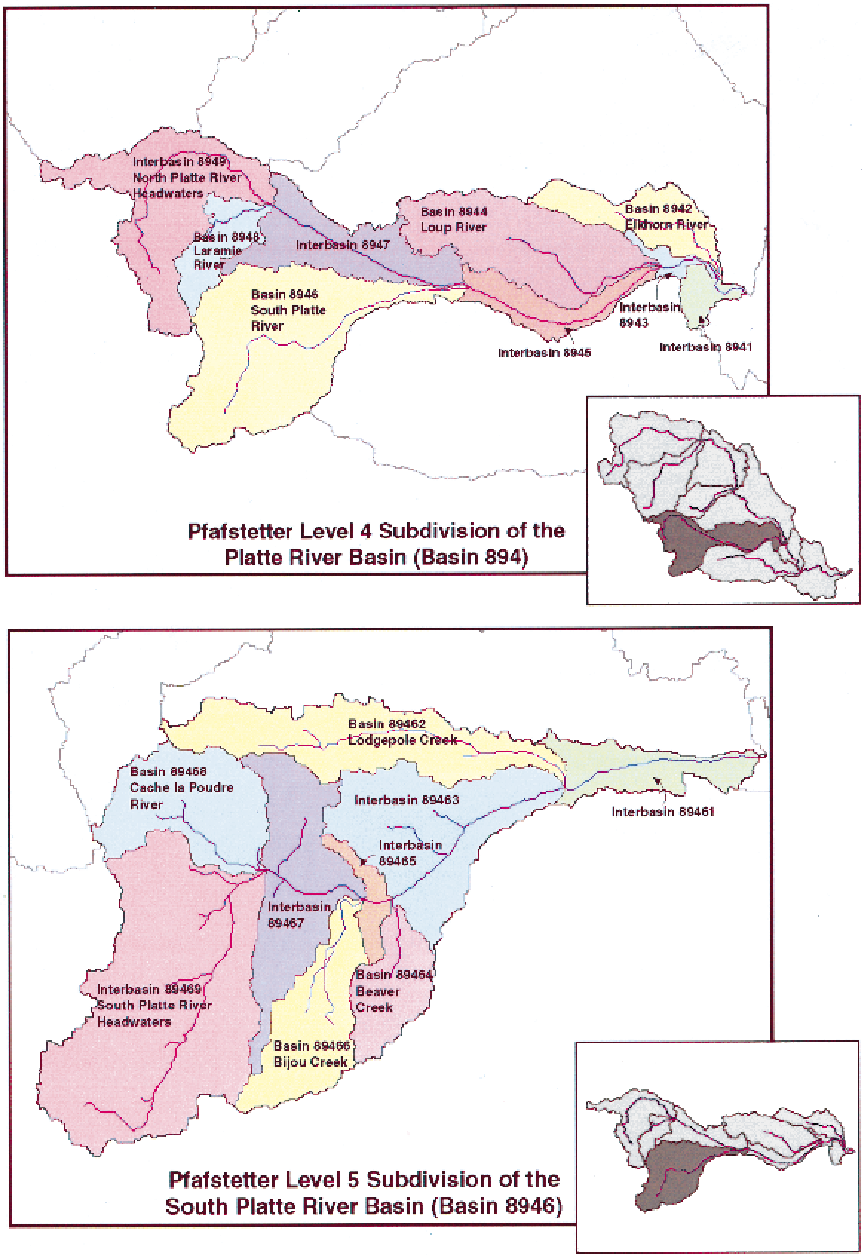


Fig. 4. The upper diagram shows subdivision of the Platte River basin (basin 894) and in the lower diagram, subdivision of its tributary, the South Platte River (basin 8946).

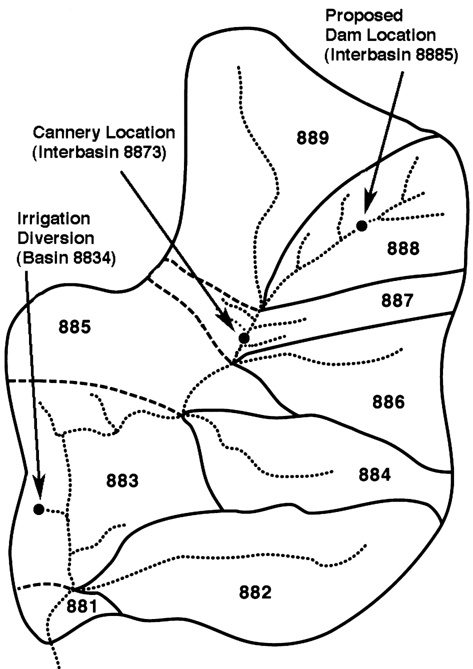


Fig. 5. A hypothetical basin illustrating the use of the topological information carried by Pfafstetter codes to infer dependence or independence of water resource development activities.

identified as main stem or tributary according to the criterion of area drained. The tributary arcs within each basin or interbasin are sorted by area drained, and the four largest numbered 2, 4, 6, and 8, from downstream to upstream along the main stem, or in the case of a coastal interbasin, in a clockwise fashion. The corresponding polygons are derived using the flow direction grid, and all arcs are given the second Pfafstetter digit as an attribute.

It can be seen that this process can be repeated over and over to obtain successively finer subdivisions of basins and interbasins. The process is ultimately limited by the spatial resolution of the DEM used. This limit becomes evident when it is no longer possible to identify four tributaries within a basin or interbasin. Switching to a higher resolution DEM for an area of special interest would, however, permit the process to continue.

The procedures described earlier were coded in Arc Macro Language (AML) for automatic implementation within the commercial GIS package ARC/INFO. In the case of the 30-arcsecond North American DEM, Level 5 Pfafstetter units were extracted. This produced 5020 Level 5 Pfafstetter basins and interbasins for North America with an average surface area of 3300 km^2. Overall, the resolution of the DEM did not merit finer extraction of basins.

As an example of the level of basin subdivision that can be achieved with the 30-arcsecond DEM, Figs. 3 and 4 show the repetitive subdivision of the Mississippi River basin (Basin 8 for the North American continent) down to Level 5. Shown in the upper diagram of Fig. 3 is the Level 2 subdivision. The Red, Arkansas, Ohio, and Upper Mississippi River basins are extracted at this level. Note that the Pfafstetter rule for designation of tributary versus mainstem on the basis of area drained yields Basin 8 headwaters that are, in fact, what we know as the Missouri River basin. Subdivision of these headwaters (Interbasin 89) is shown in the lower diagram of Fig. 3. This level 3 subdivision extracts the Kansas, Platte, Cheyenne, and Yellowstone River basins. Further subdivision of the Platte River basin (Basin 894) is shown in the upper diagram of Fig. 4. At this level, smaller basins such as the Elkhorn, Loup, South Platte, and Laramie River basins are delineated and numbered at the 4-digit level. Taking the subdivision one level further, the South Platte River basin (Basin 8946) is subdivided to Level 5 in the lower diagram of Fig. 4. Here Lodgepole Creek, Beaver Creek, Bijou Creek, and the Cache la Poudre River basins are extracted. As can be seen, basins of relatively small surface areas are extracted at Level 5 of the Pfafstetter basin numbering scheme. Notice in the lower diagram of Fig. 4 that the South Platte Headwaters interbasin still shows four tributaries flowing into it, and could therefore be subdivided one more time using the 30 arc-second DEM.

5. Characteristics of the numbering scheme

Identification numbers that end with an even digit represent basins, and numbers that end with an odd value represent interbasins. Upstream-downstream dependency between locations can be inferred by examining and comparing the topological information

Table 2
Surface area of USGS hydrologic units (HUCs)

Region	Area (km^2)	Subregion average area (km^2)	Accounting unit average area (km^2)	Cataloging unit average area (km^2)
1	165 966	15 088	13 831	3131
2	290 199	36 275	20 728	3055
3	716 159	39 787	33 280	3635
4	450 601	30 040	16 689	4059
5	421 441	30 103	20 069	3512
6	105 865	26 467	21 173	3308
7	490 856	35 061	28 874	3747
8	271 683	30 187	12 349	3313
9	153 550	51 183	30 710	3656
10	1320 782	44 026	30 018	4261
11	642 031	45 859	25 681	3711
12	471 235	42 839	21 420	3863
13	343 603	38 178	26 431	4909
14	293 658	36 707	29 366	4736
15	362 829	45 354	24 189	4269
16	366 781	61 130	30 565	5166
17	716 753	59 730	32 580	3288
18	417 199	41 720	26 075	3137
19	1508 547	251 425	45 714	11 092
Average	500 513	50 587	25 776	4203

carried by the identification numbers. This is perhaps best explained by means of a few examples.

Fig. 5 provides a schematic representation of the relationships between a proposed dam, a cannery, and an irrigation diversion. Consider the cannery situated on the main stem of a river in interbasin 8873. Will a new dam at a location in 8885 affect flows to the cannery? Yes, because the dam site is upstream of the cannery. The identification numbers reveal this, without the need to refer to a map or an engineering straight line diagram. The match of the leading digits, 88, tells us that the two locations are in the same basin. Beyond the matching digits, 85 is greater than 73, and the dam lies upstream of the cannery. As both numbers end with an odd digit, they both are on the main stem and therefore the dam will affect flows to the cannery.

Will the dam affect the irrigation diversion of a farmer at 8834? No, it will not. The leading digits, 88, match and 85 is greater than 34, however, the trailing 4 indicates a tributary off the main stem. Consequently, the irrigation diversion is upstream of any flows influenced by the dam. Thus, river reaches affected by the dam will have a match of leading digits, 88, and trailing odd digits less than 85. These are: 8883, 8881, 8879, 8877, 8875, 8873, 8871, 8859, 8857, 8855, 8853, 8851, 8839, 8837, 8835, 8833, 8831, 8819, 8817, 8815, 8813, and 8811. The first two are downstream interbasins in basin 888. The rest are downstream interbasins on the main stem. Basins 886, 884, and 882 (and all of their interbasins and basins) belong to tributaries that enter the main stem downstream of the dam and are therefore unaffected. Areas that are tributary to the dam in interbasin 8885 are those that are upstream: 8886, 8887, 8888, and 8889.

It can be seen from these examples that simple rules to check digits with tests of “odd” or “even”, and “less than” or “greater than”, can quickly isolate areas of interest for a particular investigation. Such tests are easily implemented in data base management and GIS software packages.

6. Economy of digits

The Pfafstetter system is attractive not only because it is natural and topological, but also because of its economy of digits. Continents can be subdivided into small units of practical size without the need to carry lengthy identification numbers. A comparison with USGS hydrologic unit codes bears this out.

Consider a comparison of the fineness of a subbasin areal breakout and the number of digits in the corresponding identification numbers for two cases: the Pfafstetter subdivision of North America and the USGS HUCs. Although the Pfafstetter approach is at an initial disadvantage because the surface area of North America is almost 2.5 times that of the United States, this handicap is soon overcome in the course of successive subdivisions. This occurs because all 10 potential values of each digit are used in the Pfafstetter method. Table 2 presents the mean surface areas associated with regions (two-digit HUCs), subregions (four-digit HUCs), accounting units (six-digit HUCs) and cataloging units (eight-digit HUCs). Table 3 presents mean surface areas of basins and interbasins carrying one-, two-, three-, four-, or five-digit Pfafstetter identification numbers. We see that the mean area of a region (two-digit HUC) is on the order of 500 000 km^2, compared with 230 000 km^2 for

Table 3
Surface area of North American Pfafstetter units

Level	Level 1 area (km^2)	Level 2 average area (km^2)	Level 3 average area (km^2)	Level 4 average area (km^2)	Level 5 average area (km^2)
0	368 758	46 095	10 947	2669	2669[a]
1	3232 005	323 200	37 149	7652	3045
2	1749 654	194 406	21 871	4268	1827
3	3032 711	336 968	41 874	9761	7276
4	1109 407	110 941	15 175	4334	2354
5	2383 428	264 825	29 793	6719	3083
6	1055 209	117 245	13 190	2890	755
7	1536 468	170 719	18 969	6180	4434
8	3239 411	323 941	50 503	9508	3178
9	4385 016	438 502	47 663	8418	3925
Average	2209 207	232 684	28 713	6240	3255

[a] Subdivision of the Great Basin was limited to four digits.

two-digit Pfafstetter subbasins. The mean area of a subregion (four-digit HUC) is about 50 000 km^2, while four digits in the Pfafstetter system yield a breakout with subbasins averaging 6200 km^2, an order of magnitude finer. Accounting units, which carry six-digit identification numbers, average about 25 000 km^2, while five digit Pfafstetter units average around 3300 km^2. This latter figure is not even matched by the USGS's HUC system when going to eight-digit cataloging units. Table 4 summarizes the preceding comparison.

Table 4
Relationship between mean surface area (km^2) and number of ID digits for USGS hydrologic unit codes for the United States and Pfafstetter subdivisions of North America

Number of digits	Average area USGS HUC (km^2)	Average area North American Pfafstetter subbasins (km^2)	Average area global Pfafstetter subbasins (km^2)
1		2200 000	
2	500 000	230 000	2200 000
3		29 000	230 000
4	50 000	6200	29 000
5		3300	6200
6	25 000		3300
7			
8	4200		

Although North America is the first continent to have been subdivided according to the Pfafstetter numbering scheme, the technique will be applied by the USGS to all seven continents, except Antarctica. This will require the introduction of a leading digit for continental identification. A continental numbering scheme for this purpose, based on relative surface areas, has been devised and is presented in Table 5.

Even with the introduction of a leading digit, the Pfafstetter scheme still retains an advantage thanks to its efficient use of digits. With six digits, it achieves a subdivision of all the land masses of the globe into subbasins of a size that the HUC system, with its eight-digit cataloging units, can only match for the limited case of the United States.

While we have made a point of the Pfafstetter system's economy of digits, it is not its only favorable attribute. If it were, the system might be improved by using a larger-base number system, like hexadecimal, to reduce the number of digits even further. However, we feel this would detract from its ease of use. Comparisons of base-10 numbers to check 'greater than' and 'odd/even' relationships between numbers are readily coded in common GIS, data base, and spreadsheet software, and are easy to make by visual inspection as well. Use of a hexadecimal or other number base would forfeit this convenience without providing a commensurate benefit.

Table 5
Continental identification digits

Leading digit for continental identification	Continental area
1	Asia
2	Africa
3	North America
4	Europe and the Middle East
5	South America
6	Australasia

7. Conclusion

We have presented a system for delineation and codification of the Earth's river basins that we believe is unique in its global extent and applicability. It is a natural system, defined by topographic control of drainage and the topology of the resulting network of rivers. It has been implemented by the USGS through application of GIS techniques to the North American portions of the GTOPO30 global DEMs. The identification numbers that are generated carry valuable topological information that can be easily exploited by standard data base management software operations. This characteristic facilitates analyses of natural systems and of human activities that affect or depend on surface water resources. The topological information of the identification numbers makes full and efficient use of all digits, and for this reason the system compares favorably with existing national and continental numbering schemes. A series of single six-digit codes is sufficient to uniquely identify subbasins smaller than 5000 km^2 in mean surface area for all the land masses of the globe. We propose this system as a fundamental spatial framework that can be used to reconcile data and information from a variety of scales, from global circulation models to irrigation projects. We anticipate that it will find usefulness as river basin management addresses the interplay of human activities and natural systems with increasing reliance on geospatial methods.

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