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Improvements on the Pfafstetter basin coding system proposal

Melhorias na proposta do sistema de codificação de bacias hidrográfica de Pfafstetter

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ABSTRACT

The coding basin system proposed by Pfafstetter (1989) is an important reference point and adopted by the principal water resources management system in the world. This adoption is due to the method's simplicity and the topological relationship between the river stretches built-into the codes. Otherwise, the Pfafstetter basin coding system can only be applied in a hydrographic vector represented by an anti-arborescence binary graph. This type of representation causes loss of hydrographic information due to the simplification of regions where there are anabranching, braided or delta areas that implies multiple confluences, cycles or disruptions of the network. This paper proposes improvements to the Pfafstetter basin coding system, maintaining it simple, while keeping the topological relationship between the stretches and including the possibility to represent the hydrography with multiple confluences, cycles, delta mouths, sinks, water masses and disruptions to drainage.

Keywords: Pfafstetter basin coding system; Drainage network; Hydrography; Graph theory.

RESUMO

O sistema de codificação de bacias hidrográficas proposto por Pfafstetter (1989) é um importante ponto de referência e adotado pelos principais sistemas de gestão de recursos hídricos do mundo. Essa adoção se deve à simplicidade do método e à relação topológica entre os trechos de drenagem embutidos nos códigos. Porém, o sistema de codificação da bacia de Pfafstetter só pode ser aplicado em hidrografia vetorial representada por um gráfico binário anti-arborescência. Este tipo de representação causa perda de informação hidrográfica devido à simplificação de regiões onde existem áreas anastomosadas, reticuladas, em delta ou que apresentem confluências múltiplas, enlaces ou drenagens desconectadas. Este trabalho propõe melhorias no sistema de codificação da bacias hidrográficas de Pfafstetter, mantendo-o simples, assegurando a relação topológica entre os trechos de drenagem, incluindo a representação da hidrografia com múltiplas confluências, ciclos, deltas, sumidouros, massas de água e drenagens desconectadas.

Palavras-chave: Sistema de codificação de bacias hidrográficas de Pfafstetter; Rede de drenagem; Hidrografia; Teoria dos grafos.

INTRODUCTION

The ordering or numbering of drainage system channels aims to contribute to water resources management based on a hierarchical classification of basins. For example, drainage lines with a lower hierarchical classification in the so-called Horton-Strahler ordering (Horton, 1945; Strahler, 1952, 1957) are typically located in the head of a basin. These drainage lines have minor importance in a regional or national water quantity analysis because they have, theoretically, less surface water. On the other hand, the vegetation around these drainage lines must be protected to avoid river siltation and is very important for quality analysis, for example.

Various proposals use different criteria and approaches for the codification of basin areas that have been formulated so far, both in Brazil (Pfafstetter, 1989) and abroad (Jackson, 1834; Gravelius, 1914; Horton, 1945; Strahler, 1952, 1957; Shreve, 1966). The advantage of these approaches is that each one of them has a specific logic that can be used for a particular goal. The user must understand the logic of each proposal to maximize its use.

Peckham (1999) indicates more sophisticated uses of the Horton-Strahler ordering in empirical studies (Jarvis & Woldenberg, 1984), analytical theories (Shreve, 1967; Tokunaga, 1966) and evolution models (Rodriguez-Iturbe & Rinaldo, 1997), illustrating that Hortonian relationships generally hold for drainage networks. In his paper, Peckham presented a theoretical formulation of statistical self-similarity using Horton-Strahler ordering derived variables to calculate the geometry of river basins, the hydraulic-geometry and the topological or branching structure of river networks in terms of the statistical distribution of side tributaries.

Another application for water resources management is the Horton-Strahler ordering as geomorphologic parameters of a basin to calculate the structure of the hydrologic response (Rodríguez-Iturbe & Valdés, 1979).

Noticeable among these diverse proposals for basin coding systems is Pfafstetter's (1989) suggested numbering system, whose digit-codes present the topological relationship between the drainage network stretches. In other words, given two different Pfafstetter coding numbers calculated for two different drainage lines, it is possible to compare them and infer which drainage line is downstream or upstream or if they belong to other basins. Using the Pfafstetter coding system calculated for a geospatial drainage line layer in a Geographic Information System (GIS), it is possible to select the drainage line features located upstream a given Pfafstetter coding number using SQL query. Another way to do this task is extracting the drainage network arc-node relation and run a recursive algorithm, which is much more complex than a simple SQL query in GIS software.

Despite the Pfafstetter system being widely used to develop various information systems on water resources (Verdin, 1997; Verdin & Verdin, 1999; Silva, 1999; Furnans, 2001; Furnans & Olivera, 2001; Vogt, 2002; Brasil, 2003; Vogt et al., 2007; Lehner et al., 2008; Silva et al., 2008; Jager & Vogt, 2010), it places inherent limitations on representing river systems through a binary anti-arborescence graph-type, that is precisely two drainage lines converging to one, with the vector direction going towards the basin mouth. When the drainage network representation is simplified to fit this model, drainage lines that cause divergent behaviour in river multi-channelled streams like anabranching, delta, anastomosing, or braided regions with high gradient must be eliminated. This drainage network representation simplification led to the loss of hydrographic information.

Given such framework, this research paper intends to conduct a comprehensive literature review of existing basin coding systems and current improvements on basin coding systems based on Pfafstetter's proposal to maintain the simplicity of the Pfafstetter basin coding system while preventing the loss of any hydrographic representation.

BASIN CODING SYSTEMS

First basin coding systems

Beckinsale & Chorley (1991) state that one of the first studies undertaken to order and hierarchize branches within a drainage basin goes back to Jackson (1834). In his work, Jackson proposes a classification scheme in which the stream that flows into the sea is classified as a first-order stream, while the junction of two first-order streams forms the second-order stream, and so on. The analysis is performed downstream to upstream, and the sea is the initial reference.

Eighty years later, Gravelius (1914) proposed a new method by which drainage systems could be ordered based on Jackson's rationale. Gravelius proposed that all the segments that form the main stem flowing into the sea should be designated as being of Order 1, while that all stream segments that drain into this stream as of Order 2, and so on. Zhang et al. (2007) claimed that the proposed codification scheme had some limits because, although drainage basins have the same stream order, there would still be a remarkable difference in their sizes.

Horton (1945) proposed that drainage channels that have no tributaries should be considered first-order streams in his methodology. Second-order channels are those which have as tributaries only first-order streams. Third-order channels receive second-order or first-order tributaries, and so forth, from the source to the basin mouth.

The method of stream order classification proposed by Strahler (1952, 1957) was based on the first part of Horton's proposed stream-ordering. According to Strahler, first-order streams have no tributaries. Second-order streams are formed when two first-order streams come together downstream and so forth to the basin mouth. When streams of unequal order join each other, the junction stream downstream has the same order as the higher-order stream.

Tucci (1993) states that the main difference between Horton and Strahler stream-coding is that the Strahler system considers that the mainstream and tributaries do not maintain the order number in all of its extensions, which is the case with the Horton system (1945). Another difference is that Strahler's stream-coding considers that all channels with no tributaries are first order, including major rivers and 'tributaries' headwaters. This coding is contrary to the subjective Horton criterion as regards to determining the source.

Shreve (1966) presents a coding system whereby the order of a particular drainage system segment is equal to the number of sources, i.e., the graph leaves situated upstream of that segment.

Among some efforts made abroad for the determination of basin coding systems, Verdin & Verdin (1999) highlighted the work of the United States Geological Survey (USGS) (Seaber et al., 1987), the US National Water Information System (NWIS) (Wahl et al., 1995), ORSTOM (Roche, 1968) the French ORSTOM and the Global Runoff Data Centre (1996) to the World Meteorological Organization coordinated by the Federal Institute of Hydrology in Koblenz, Germany. However, none of the codification systems proposed by these organizations has employed digits that carry topological information on the stream 'segments' links.

The USGS Division of Water Resources has proposed the division of US territory into 21 river basin regions composed of 222 subregions. In this proposal, hydrologic unit boundaries for drainage basins greater than 700 square miles (1,800 square kilometres) are depicted, except for Alaska. Each hydrologic unit is identified by a hydrologic unit code consisting of an eight-digit number with two digits indicating the region, subregion, accounting unit and cataloguing unit (code 04030203, for example). For each classification level, there is an estimated association of catchment area of approximately 500,000 km^2 for regions, 50,000 km^2 for the subregions, 25,000 km^2 for the accounting units and 4,000 km^2 for cataloguing units (Seaber et al., 1987).

The US National Water Information System (NWIS) is the repository for stream gauge stations of the USGS surface water. It employs a system based on the drainage system for the numbering of these stream gauge stations. The identification number of stream gauging stations consists of eight-digit numbers whose ordinal values increase downstream. Station code 07167500 is upstream of station code 07169500, for example. An indentation of the number indicates a station position on a tributary, and there is a successive indentation to indicate the tributary rank. Numbers themselves do not offer any distinction between the tributary and the mainstream, nor do they indicate the drainage system topology (Wahl et al., 1995).

The Global Runoff Data Centre (GRDC) of the World Meteorological Organization, operated by the Federal Institute of Hydrology in Koblenz, Germany, proposes a system with seven-digit identification numbers for the stations. The first digit indicates the continent, the second the country, the third and fourth a continental basin, digits five, six, and seven for the station itself (Global Runoff Data Centre, 1996). Thus, for example, the code station 4 2 14 670 is located in North America (code 4), in Canada (code 2) at the Broadback river basin (code 14) and rank code number 670.

The French research organization ORSTOM presents another example of classification applied to the drainage system to identify stations based on an eight-digit system. The first and second digits identify the country. The third and fourth digits identify the basin of the main river where the station is located. To this end, the ORSTOM selects and sorts the 99 major rivers of the continent in alphabetical order. The fifth and the sixth digits are used to identify the stream where the gauging station is positioned. The seventh and eighth digits are the numerical order of the station itself. For example, the ORSTOM station code 07 05 01 01 is referenced to the country of Congo (07), Congo river basin (05), Kouilou river(01), and 01 is the number of the station (Roche, 1968).

Brazilian basin coding system

In 1972, the former National Hydroelectric Water and Power Agency of Brazil, DNAEE, proposed the first coding system to identify gauging stations that formed the Hydrological Information System (Ibiapina et al., 1999). This system is very similar to the one proposed by NWIS (Wahl et al., 1995).

The DNAEE codification scheme uses two digits to represent basins and sub-basins and six digits to identify the station number. The first digit represents one of the eight basins in which the country was divided into, reserving number 9, which is used to determine any basin in South America with no network interference in Brazil (Galvão & Meneses, 2005). Each of these basins is divided into ten major subbasins numbered from 0 to 9. Digits from three to eight are used to identify station numbers, with values increasing from upstream to downstream (Fernandes, 1987). For example, gauge station code 1 0 200000 refers to station Palmeiras do Javari, where digit 1 represents the Amazon river basin. The digit 0 represents the Solimões/Javari/Itacuai river sub-basin, and the digit 200000 represents the number of this station (Brasil, 2012). Late, Otto Pfafstetter (1989), an engineer with the former National Bureau of Sanitation Works (DNOS), proposed a new codification system for basin classification, which was later employed by the National Irrigation Register (Rubert & Figueiredo, 2001) of the former National Irrigation Department. This system used the ten digits of the base-10 numbering system and was devised to exploit the catchment area features, its topology or connectivity and drainage system position. Compared to other codification systems, Pfafstetter coding system has several advantages since it is a natural, hierarchical method based on the drained area topography and the drainage system's topology. Besides, the codes convey topological information (Galvão & Meneses, 2005).

In compliance with Law 9,433 (Brasil, 1997), in 1998, the Water Resources Secretariat (SRH) of the Brazilian Ministry of Environment (MMA) launched a plan for a codification of all river basins in Brazil to be georeferenced at a scale of 1:1,000,000 of the Brazilian systematic mapping. This project had participation from the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA). The codification was based on the system devised by Pfafstetter and was detailed up to level 5 of the river system (Silva, 1999).

Following the review and modifications to Silva (1999) approach through an agreement with the Development Company of the Sao Francisco Valley (Codevasf), it was possible to detail Level 1 regions delineated by the Pfafstetter coding system (Rubert & Figueiredo, 2001). In this paper, Rubert & Figueiredo (2001) state that the resulting Level 1 codification differs from that one proposed by Pfafstetter. The difference is due to three main factors: the digital and most accurate nature of the river system, the basemap at a scale of 1:1,000,000 and the change of the boundary between number one and number nine basins.

Parallel to this effort, in 2000, the Brazilian Institute of Geography and Statistics (IBGE) presented a general classification for Brazilian river basins that divided them into ten basins and 57 sub-basins based on the cartographic mapping at a scale of 1:1,000,000.

In 2002, the Brazil National Council of Water Resources (CNRH) approved Resolution nº 30 (Brasil, 2003), establishing the Pfafstetter basin coding system as a reference tool to be used in the National Water Resources Policy (Silva, 1999).

In 2003, the CNRH established the National Water Division, composed of twelve Level 1 hydrographic regions and thirty Level 2 regions through Resolution nº 32 (Brasil, 2003). However, the delineation of these regions is not limited to their hydrographic features to guide water resources planning and management. Instead, they are characterized by the Brazilian territorial space within a basin, a group of an adjacent basin or sub-basins with homogeneous or similar natural, social and economic characteristics.

The Brazillian National Water and Sanitation Agency (ANA), established in 2000 by Law 9,984 (Brasil, 2000) for the management of Brazil hydro-meteorological network, has employed the DNAEE coding system (Fernandes, 1987) to identify gauging stations to date. However, in 2006, ANA introduced a hydrological dataset for the Brazilian territory based on the Pfafstetter basin coding system at the scale of 1:1,000,000 (Brasil, 2006; Teixeira et al., 2007a, 2007b) to be composed of hydrography network and catchment areas.

The ANA Pfafstetter System Dataset was developed to meet the National Water Resources Information System (SNIRH), specifically concerning modelling and geospatial processing data of the river system that forms the system dataset. Therefore, unlike previous works, this dataset is not limited to numbering basins up to Pfafstetter Level 5. Instead, considering that the development process of this dataset was carried out in a computing environment and using Geographic Information System (GIS), the catchment areas of all stream segments have been numbered, with 96.38 percent of Pfafstetter basins being of at least Pfafstetter Level 6 (Teixeira et al., 2007a).

More recently, in 2021, IBGE (Instituto Brasileiro de Geografia e Estatística, 2021) published a new hydrography dataset based on the twelve CNRH (Brasil, 2003) National Water Divisions split into two more detailed levels. These new delineations were based on the ottocodified hydrography dataset on a scale of 1:250.000 (Brasil, 2021) that was created using the PgHydro extension for PostgreSQL/PostGIS spatial database system (PgHydro, 2021).

Pfafstetter basin coding system abroad

The Pfafstetter basin coding system has been implemented abroad since 1997, including by Verdin (1997) for the numbering of the North American continent and by Verdin & Verdin (1999) for the numbering of the seven continents in the world, except Antarctica, using GIS techniques based on the GTOPO30, an elevation model produced by the US Geological Survey.

The Norwegian National Catchment Dataset (Norwegian Water Resources and Energy Directorate, 2009) was established and maintained by the Directorate of Norwegian Water Resources and Energy (NVE). Norway's coding system of hydrographic units proposed to REGINE form a hierarchy, each level being more detailed than the last. This hierarchical classification comprises the following nine categories: 1) Water system area, 2) River basin, 3) Sub-unit in the river basin, 4) Central catchment, 5) Sub-unit in the central catchment, 6) Edge area, 7) Sub-unit in the edge area, 8) Coastal area, 9) Subunit in the coastal region.

The REGINE coding system is composed of several levels and criteria for codification. It is very complex compared to other existing coding systems (Flavin et al., 1988). 015.C810 is an example of a hydrographic unit coding system located in the region of Lagen (Norwegian Water Resources and Energy Directorate, 2012). The basin coding system proposed by the German Working Group on Water (Länder-Wasser-Arbeitsgemeinschaft, 1993) in 1993 (Flavin et al., 1988) is very similar to Pfafstetter's proposed coding system, the significant difference being that the codification in the former starts from the source towards the mouth of the river and not from the mouth as in the latter. Besides, in the LAWA proposal, the greater the code number, the more significant the increase in the drainage area. Another feature of the LAWA system (Länder-Wasser-Arbeitsgemeinschaft, 1993) is that it does not provide digit numbers for coastal basins, only for continental basins (Flavin et al., 1988).

In 1998, the UK Institute of Hydrology, the Denmark National Environmental Research Institute and the University of Freiburg launched the European Rivers and Catchment 1:1M (ERICA) dataset (Flavin et al., 1988). In addition to geographic data on rivers and catchment areas, this project also proposes integrating those datasets into the EEA member 'states' monitoring program through a coding system using indirect spatial reference (Flavin et al., 1988).

The ERICA codification system consists of four parts: (1) two-digit code for sea basins where the river flows into, (2) three-digit code for the shoreline code, (3) digit code for basin and inter-basin areas, (4) and a basin-area-indicator.

Still, the ERICA system proposes that the codification of basins and interbasins is carried out for each coding cycle within a catchment area. First, the 49 largest tributaries of the main river within that area are identified numbered using even numbers from 2 to 98. After that, interbasins located between major tributaries shall be assigned odd numbers between 1 and 99. The code 99 020 06 02 is an example of the ERICA basin codification system. The development of the ERICA codification system followed an evaluation of the European systems REGINE and LAWA, which had been deemed unclear or inconsistent when dealing with shorelines, respectively (Flavin et al., 1988). According to Néry et al. (2001), the ERICA system most challenging point was identifying the 49 major tributaries of each of the European rivers, especially in treating smaller catchment areas.

The European Union Members, Norway and the European Commission have jointly developed a common strategy for supporting Directive 2000/60/CE, or the Water Framework Directive (WFD), establishing a Community action plan in water policy. This strategy's main objective was to enable a coherent and appropriate implementation of Directive 2000/60/CE while focusing on methodological issues related to a common understanding of its technical and scientific implications. Therefore, implementing the Water Framework Directive GIS elements proposed a basin coding system based on the Pfafstetter system, including a pair of two-digit codes each to be assigned before Pfafstetter digit codes. Both codes are composed of the Member State 2-character Member State's identifier responsible for code assignment and the Marine Waters identifier code under the International Hydrographic Organization (Vogt, 2002). The code takes the following form: MS MW N1 N2 N3...NN.

The Pfafstetter basin coding system was also applied by Vogt et al. (2007) for the numbering of pan-European basins using digital elevation models from the Space Shuttle Radar Topographic Mission (SRTM) at 100-m grid-cell resolution and USGS GTOPO30 data at 1,000-m grid-cell resolution. Later, Jager & Vogt (2010) proposed extending this system, providing a unique identifier for any drained hydrological objects of the European continent based on the seas and oceans' delineations and river basins in continental landmasses and islands.

In 2009, Fürst & Hörhan (2009) applied the LAWA coding system for Austria's rivers and basins (the Danube, the Rhine and the Elbe), a modified version of the Pfafstetter system. The significant difference here is that the order of numbering is downstream from the source to the outlet instead of upstream, as initially proposed by Pfafstetter. Another feature of the coding system proposed by Fürst & Hörhan (2009) is that the criterion for defining the main stem within a basin would be first by name and second by the main stem being defined as having the longest flow path, i.e. drainage area upstream.

Furnans (2001) developed a computing algorithm that is based on the Pfafstetter basin coding system for defining stretches of drainage system downstream of the mouth of a particular point and applied for the Yangtze River Basin, China (Furnans & Olivera, 2001).

Silva et al. (2008) proposed a modified version of the Pfafstetter basin coding system (1989), whose primary reference is based on the size of the stretch of drainage system instead of the size of the catchment area as proposed initially by Pfafstetter (1989). Silva et al. (2008) also suggest adopting this method if no catchment area within a basin is available.

Another proposal for basin numbering system was put forward by Figueiredo (1999), who suggested the numbering of all streams of the drainage system through the systematic mapping of Minas Gerais state at a scale of 1:1,000,000. This proposal was based on the DNAEE system regarding the stream name, the order, and the tributary bank. The codification consists of numbers and letters, where the first two digits identify streams within the basin and sub-basin based on the codification proposed by DNAEE. The remaining digits indicate, from downstream to upstream, the main tributary order and the left (L) and right (R) banks. This procedure is performed until the last body of water upstream has been numbered. Although the adopted criterion is based on the river name and does not consider the discharge or the catchment area upstream, this scheme enables the identification of all streams downstream of a particular river that has already been labelled. The code 60 40L 172R 87R 2R is an example of the basin coding system of the Rebolo River.

More recently, the Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales project, or HydroSHEDS, (Lehner et al., 2008) presents a hydrographic spatial database for regional and global-scale applications using the Pfafstetter basin coding system. This project subdivides the world into nine regions using an algorism for each.

PFAFSTETTER BASIN CODING SYSTEMS

The coding system devised by Pfafstetter (1989) employs ten digits of the base-10 numbering system, in which each code digit identifies a stream within a basin. In this proposal, even numbers, except for zero, are for the main river basins and odd numbers are for inter-basins. The zero number is for basins draining into the sea or endorheic basins.

Pfafstetter defines mainstem of the basin as the group of stretches of connected stems with the highest annual runoff. As the general yearly runoffs are approximately proportional to the areas of their basins, this variable is used as a criterion for numbering. However, Pfafstetter states that this criterion should be employed with discretion, mainly in regions with high climate variability.

Thus, it is possible to delineate the four tributaries with the largest drainage areas discharging to the main stem from downstream to upstream at any classification level. At each bifurcation point, the tributary is defined as the smaller drainage area, and the main stem is defined as the one with the largest area. Each branch level main stem four major tributaries are assigned even numbers 2, 4, 6 or 8 from downstream to upstream. The four major tributaries are once again delineated for each one of these tributaries by simply assigning a value to the end of the Pfafstetter digit code of the next lowest level and so forth until all the streams within the drainage system have been numbered. All other tributaries within the main river are grouped into five areas designated by Pfafstetter as inter-basins assigned the odd numbers 1, 3, 5, 7 and 9, again moving from downstream to upstream (Figure 1).

Although Pfafstetter claims that the partial basins of the headwaters of each river are inter-basins because they are assigned, in effect, the final digit code 9, there are cases where this code could be 3, 5 or 7, such as when there are only 1, 2 or 3 tributaries of the main stem, respectively. Apart from that, Pfafstetter stressed that the area of partial basins of each headwater would be larger than the last tributary area.

Among the potential disadvantages or difficulties of this approach pointed out by Pfafstetter is that a simple analysis of the code can conclude as such: if a basin has the first number, or the number farther to the left, and is an odd number, then the stream is part of one of the four coastal basins under evaluation. On the other hand, if this code farther to the left is an even number, the stream is part of one of the four major tributaries of the basin under evaluation. Besides, any simple analysis of the digit code helps to identify which stream is upstream or downstream of any particular point.

The Pfafstetter basin coding system is based on a discrete model of vector and geospatial data represented by drainage areas. Each area is associated with a river stretch defined as a drainage segment beginning or ending with a confluence. It may or may not characterize the source or the mouth of the stream, respectively.

By making an analogy of the drainage system studied by Pfafstetter and graph theory, the river system can be described as an anti-root connected graph without oriented cycles, known as anti-arborescence (Boaventura Netto, 2006). Such a statement

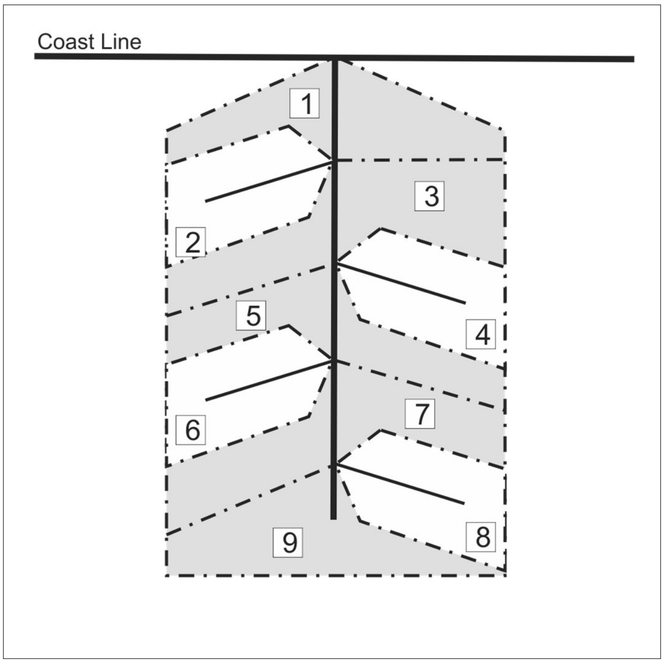

Figure 1. Example of Pfafstetter (1989) basin coding system.

is based on the fact that the streamflow is oriented from the leaves towards the anti-root, i.e. from the source to the mouth. Netto also notes that the arborescence (tree) is associated with the idea of hierarchy or classification, and therefore is of order relation, ruled by a single element. Netto indicates these features are crucial to help decision-making procedures related to water resources because their management is carried out at different levels. The drainage system cannot be considered a tree in graph theory because a tree is a connected graph with no cycles and no orientation.

Therefore, using the Pfafstetter basin coding system, defining the hierarchy classification and topological relationship of catchment areas and related river stretches is possible.

In 2006, the Brazilian National Water and Sanitation Agency (ANA) presented the first computer-based Brazilian Hydrography Dataset based on the Pfafstetter basin coding system to the community at a scale of 1:1,000,000 (Brasil, 2006; Teixeira et al., 2007a, 2007b). This dataset comprises a hydrography network and catchment areas calculated using a geographic information system (GIS).

This method primary purpose is to provide the community with a mechanism that other water resources managers can use to standardize the current reference hydrographic dataset. The standardization of this hydrographic dataset was proposed to meet the Brazilian National Water Resource Information System (SNIRH), specifically regarding the treatment of geospatial data on the drainage system to provide information for the system as a whole.

Based on the Pfafstetter System Dataset, it is possible to identify the relationship between the different river stretches and deal with issues related to the position of elements along the drainage system, such as which river is downstream or upstream of any particular reference point.

The methodology for developing a Pfafstetter Hydrography Dataset (Brasil, 2006) adds a new concept to the Pfafstetter basin coding system: the Pfafstetter watercourse code. Initially, the Pfafstetter basin coding system is focused on basin codification, but the association of basin codification to the related watercourse is inherent in the development process. What is remarkable in the very description of Pfafstetter codification methodology is when it defines the main basin watercourse and four major tributaries.

Thus, according to developing the Pfafstetter System Dataset methodology, the watercourse code stems from the basin code itself. At the same time, all odd numbers are set aside, from right to left, until the first even number has been reached. This procedure leads to the deletion of the inter-basin code number, i.e. it presents the basin digit code of the main watercourse where the inter-basin is in-between.

PFAFSTETTER BASIN CODING SYSTEM LIMITATIONS

Jackson (1834) stated that the drainage network system resembles a tree with the leaves converging to the branches and the branches converging to the trunk or to the basin's mouth. However, Jackson did not ignore the several bifurcations and channels that form the deltas of many rivers and compare them to the tree roots. On the other hand, Jackson stated that the root-like appearance in deltas does not always exist and could be simplified to the convergent model, ignoring the bifurcations for basin coding systems general purposes. In the following years, other authors (Gravelius, 1914; Horton, 1945; Strahler, 1957; Shreve, 1966) also proposed basin coding systems using this same approach, ignoring the drainage bifurcation. This was also the Pfafstetter basin coding system (1989) approach that brings limitations to the total drainage line representation.

The Pfafstetter basin coding system offers several advantages over other coding systems, mainly for its simplicity and digit codes, which convey information on the topological relationship between stretches of watercourses that form the drainage system. Galvão & Meneses (2005) state that the main advantages of the Pfafstetter system involve the use of a natural and hierarchical method, based on the topography of the drained area, in which the drainage system topology can be identified through the digits code, and is easily implemented by a computer program, as well as in a Geographic Information System (GIS).

These advantages allowed the spread of the Pfafstetter system (1989) through the international community and its adoption by, for example, the USGS for the numbering of basins worldwide (Verdin & Verdin, 1999), and more recently by the European Commission for the implementation of the elements that form the Geographic Information System of the Water Framework Directive (WFD).

Despite the Pfafstetter basin coding system's (1989) advantages, this coding system's main limitation is related to the river system representation using an anti-arborescence binary graph (Boaventura Netto, 2006). This type of model is characterized by the direction of the arc from the leaves towards the root, i.e. from upstream to downstream, with the convergence of two arcs on a node, except the node that represents the mouth or the anti-root of the arborescence structure, where a single arc converges on a single node. The anti-arborescence structure also requires that all arcs are connected and do not present cycles nor loops (Boaventura Netto, 2006).

The representation of the river system using an anti-arborescence structure has been the traditional method of a spatial model of the drainage system within the scientific community since Gravelius (1914), Horton (1945), Strahler (1952, 1957), Shreve (1966), Pfafstetter (1989), among others. However, such representation methods are appropriate only for drainage systems composed of single channels because the representation of a river system using an anti-arborescence structure would not be possible in regions where you have flood-dominated regimes involving multi-channelled stream like anabranching (Figure 2), delta (Figure 3), anastomosing (Figure 4) or braided in regions with high gradient.

According to Twidale (2004), anabranch channels can be found in alluvial or hard rock settings, or a mixture of both, where there is a river branch that goes back to the main bed, forming an island. The best-known case in Brazil is the Araguaia River, whose branching leads to Bananal Island, the 'world's largest river island (Figure 2).

According to Twidale (2004), deltas are located in plains areas where rivers flow into an ocean or a lake. Depending on the relative density of river and sea/lake water, there are three different delta forms. Long comparatively narrow delta forms where the incoming flood flow is heavier than the ocean/lake water. Arcuate or fan-shaped structures form where the density water of both are the same. An elongated and distributary delta forms where the river water is less dense than the ocean/lake water.

Thus, the spatial representation of the Pfafstetter drainage system and all other proposed drainage coding systems is limited in areas where the drainage system has multiple junctions or branched with cycles in the delta mouth, anastomosing, branched and braided channels.

Another problem related to the representation of the river system is the presence of sinks and water masses. Currently, these limitations are overcome by simplifying the drainage system where these phenomena occur. However, the procedures for such simplification are subjective, and even in situations where

Figure 3. Example of a deltaic channel according to IBGE 1:1,000,000 basemap (Instituto Brasileiro de Geografia e Estatística, 2000).

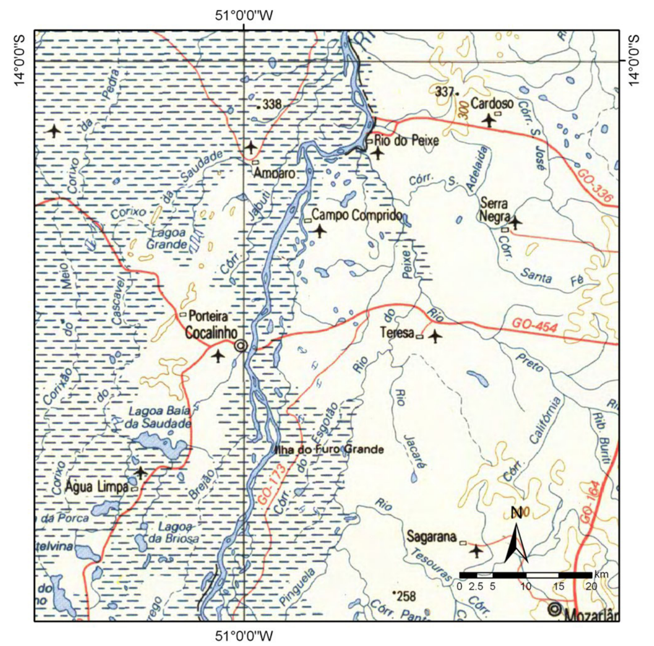

Figure 2. Example of anabranches channel according to IBGE 1:1,000,000 basemap (Instituto Brasileiro de Geografia e Estatística, 2000).

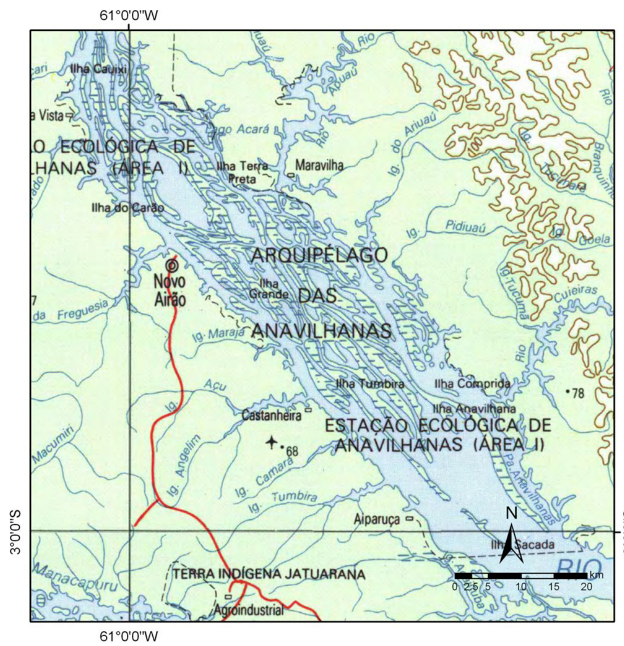

Figure 4. Example of the anastomosing channel according to IBGE 1:1,000,000 basemap (Instituto Brasileiro de Geografia e Estatística, 2000).

systematized and computational processes are used (McAllister, 1999), too much hydrographic information is lost.

Moreover, although uncommon in nature, there are situations where three or more drainage channels converge to a single point. This phenomenon is known as multi-confluences, the most typical example of which is the double confluence. The problem with this type of phenomenon under the Pfafstetter system coding is that when numbering the four major tributaries downstream to upstream, the double confluences shall theoretically be at the same level after odd numbers are assigned. This problem has been solved by inserting a small drainage stretch in-between both confluences, moving the stretch downstream or upstream. However, while resolving the ambiguity of the codification, this attitude does not represent the drainage system real nature.

In regions with a delta (Twidale, 2004), the mouth region is usually simplified into a single drainage channel that empties to the sea. Even significant islands within river water masses make the hydrography network representation without cycles or loops more difficult. The simplification of the drainage system in these regions as an anti-arborescence structure is problematic, if not impossible. Any solution to make the codification drainage system simpler involves a considerable distortion of the hydrographic area actual features.

The representation of the river system in a karst region poses a problem inherent in this type of region, specifically sinks and the resulting interruption of the drainage system. The representation of the river system through the Pfafstetter basin coding system in an anti-arborescence structure does not allow the drainage system to be disrupted.

The Pfafstetter basin coding system does not include water masses, such as dams, lakes, ponds, and wide rivers. Therefore, the solution to this type of situation represents the river natural channel before the emergence of that water mass or the representation of a central line over a wide river (Figure 5).

McAllister (1999) proposes a series of computational geometric algorithms within geographic information systems to define the centerline of water or 'rivers' centerline that match the representation of the river system under the Pfafstetter basin coding system in an anti-arborescence format. Although this representation is systematized and does not resort to manual and subjective process errors, there is still the loss of hydrographic information.

IMPROVEMENTS ON PFAFSTETTER BASIN CODING SYSTEM

The basin coding system improvement shown here is based on the Pfafstetter basin coding system. It aims to keep the coding system simple, as various countries have adopted the Pfafstetter basin coding system. Thus, the proposed approach is designed to address the limitations inherent in representing the river system as an anti-arborescence structure. The new coding system was designed to be applied in natural settings where there are multiple confluences, cycles or loops, delta mouth, sinks, water masses and segmentation of the drainage stretch between two basins of up to 5 parts.

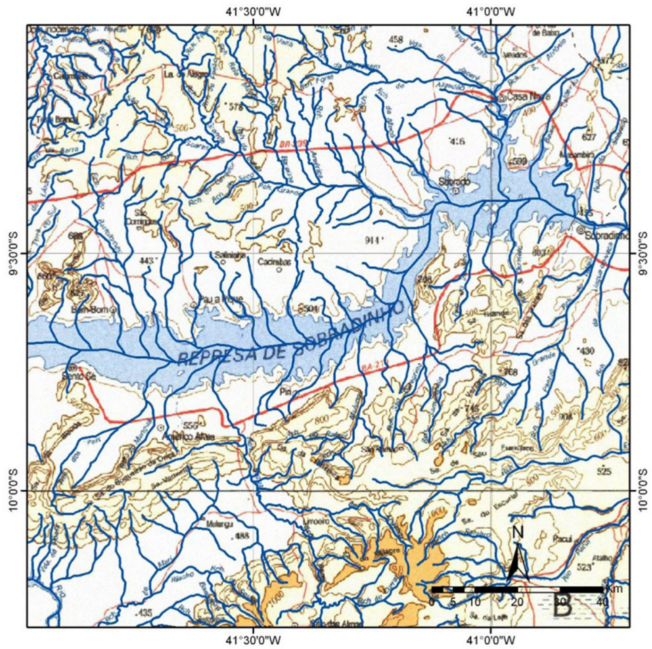

Figure 5. Example of classification of natural channels of a Dam according to IBGE 1:1,000,000 basemap (Instituto Brasileiro de Geografia e Estatística, 2000).

The Pfafstetter basin coding system can be summarized as follows:

a) the mainstream of the basin is defined from the mouth to the source of the mainstream, where the only criterion looked at is the largest area upstream at each point of bifurcation in the river system;

b) the four largest tributaries stemming from the mainstream are identified;

c) the four largest tributaries are assigned the numbers 2, 4, 6 and 8 from downstream to upstream;

d) inter-basins, which are found in between coded basins, receive the odd digits 1, 3, 5, 7 and 9 from downstream to upstream;

e) steps from (a) to (d) are repeated for each of the mainstream tributaries, and a new digit is added to the end of the codification. This procedure is applied recursively until all stream segments have been coded.

The improvements on the Pfafstetter basin coding system (1989) consists of the following steps:

a) the flow direction shall be defined from the source of the drainage system to the mouth, using as criterion the shortest distance to the mouth;

b) based on the flow direction, the main streams are defined between the source of the drainage system and the basin mouth. There shall be a stream at each source of drainage;

c) the mainstream of the basin is defined between the mouth and the source of the mainstream, using as criterion the direction of the flow and the largest drainage area in the upstream direction at each point of bifurcation;

d) the four major tributaries are defined based on the mainstream;

e) the four major tributaries are assigned even numbers 2, 4, 6 and 8 from downstream to upstream;

f) the remaining inter-basins, positioned in between the coded basins or resulting from the segment of the drainage system, are assigned the odd numbers 1, 3, 5, 7 and 9 from downstream to upstream;

g) steps (c) to (f) are repeated for each of the main stem tributaries, adding the new code at the end of the codification. This procedure can be repeated over and over until all stream segments have been coded.

h) the four major tributaries of remaining secondary streams are assigned even numbers 2, 4, 6 and 8 from downstream to upstream;

i) the remaining secondary inter-basins, positioned between coded basins or basins resulting from the segment of the drainage system, are assigned odd numbers 1, 3, 5, 7 and 9 from downstream to upstream;

j) steps (g) to (i) are repeated for each of the secondary stream tributaries, adding the new digit code at the end of the codification. This process is repeated until all the remaining secondary streams have been coded.

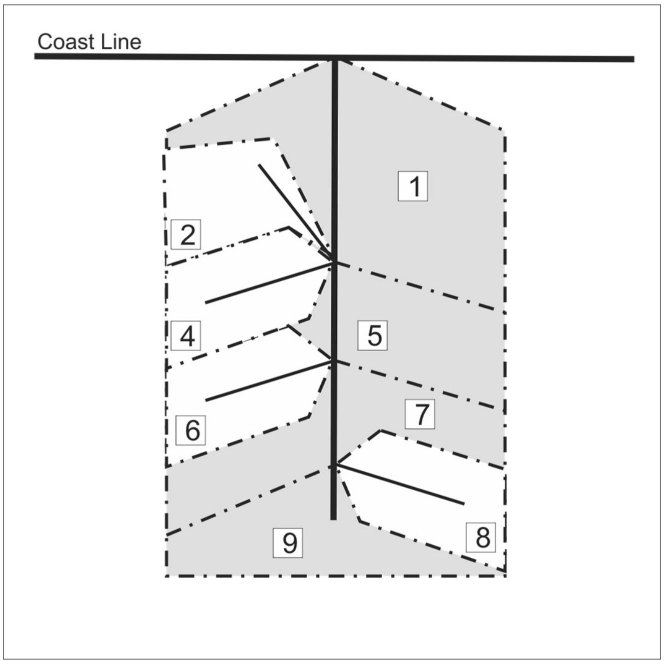

Figure 6. Example numbering a basin with the double confluence in which both tributaries are located on the same bank of the main stem.

Multiple confluences

In situations where the river system has multiple confluences (Figures 6 to 11), the inter-basin inserted into the drainage system is deleted from the network to adapt it to an anti-arborescence structure. For example, in places where the double confluences are two of the four major tributaries of the basin and are further downstream with the other two, major tributaries are numbered 2 and 4. In that case, two locations are possible: (a) both tributaries are located on the same bank of the main stem, or (b) each of the tributaries is situated on one of the mainstream banks.

In the first case (Figure 6), the codification order is according to the tributary position with the mainstream, i.e. the tributary lying in-between the stream downstream of the multiple confluence and the other tributary is numbered 2. In contrast, the tributary in-between the stream segment upstream of the confluence and the other tributary is numbered 4. Therefore, the mainstream segment downstream of the double is numbered 1, and the segment of the main double confluence upstream is numbered 5, since number 3 is omitted in these cases.

In the second case (Figure 7), in which the tributaries are located on each bank of the mainstream, uncertainty over these 'tributaries' position with the main stem requires a different criterion, preferably geometric, to determine which tributary shall receive numbers 2 and 4. Examples of criteria are the mainstream bank where the tributary flows together or even the drainage area upstream of each confluent tributary. In this proposed scheme, the right river bank shall be considered, from upstream to downstream, as a criterion to define which tributary is further downstream. Thus, in that case, the tributary located at the right bank is given number 2, while the tributary on the left bank is given number 4.

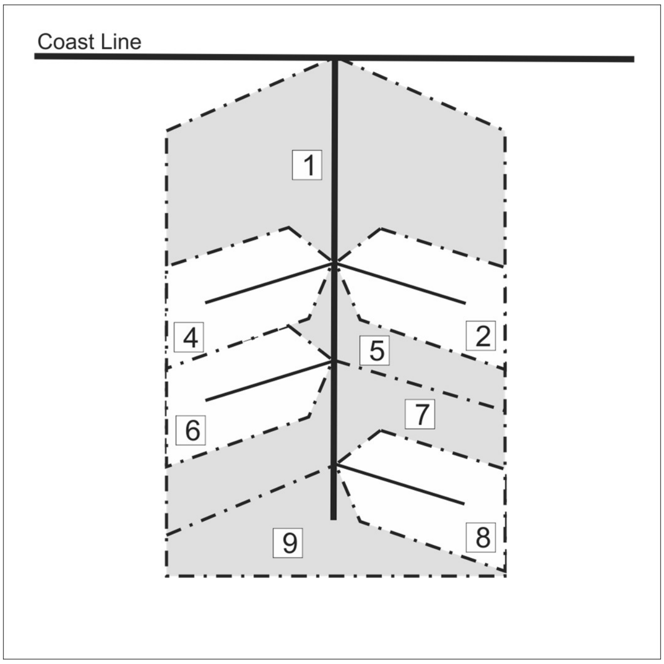

Figure 7. Example of numbering a basin with double confluence in which tributaries are located on different banks of the main stem.

In double confluence, where only one of the tributaries is one of the four major tributaries within that basin (Figure 8), then that tributary shall be assigned the corresponding digit code. Simultaneously, the smaller tributary shall receive a digit code according to its position with the main stem and the other larger tributary within the double confluence. Thus, if both tributaries

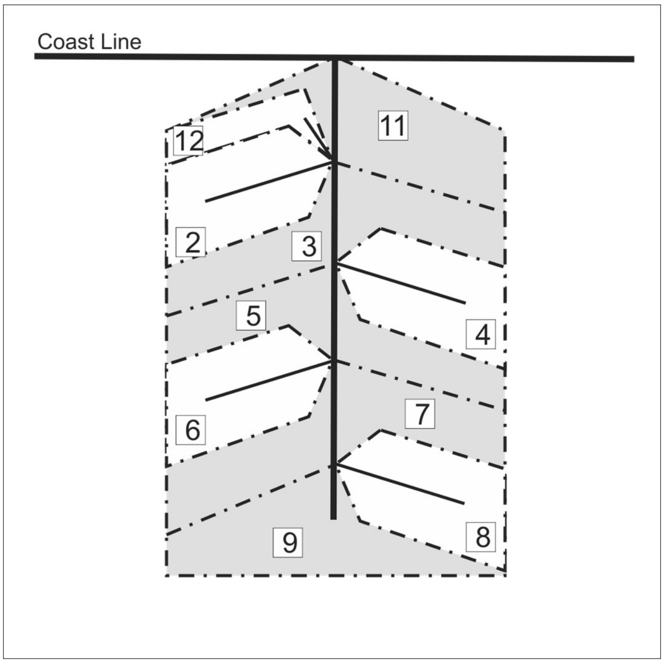

Figure 8. Example of the numbering of a basin with the double confluence in which both tributaries are located on the same bank of the main stem.

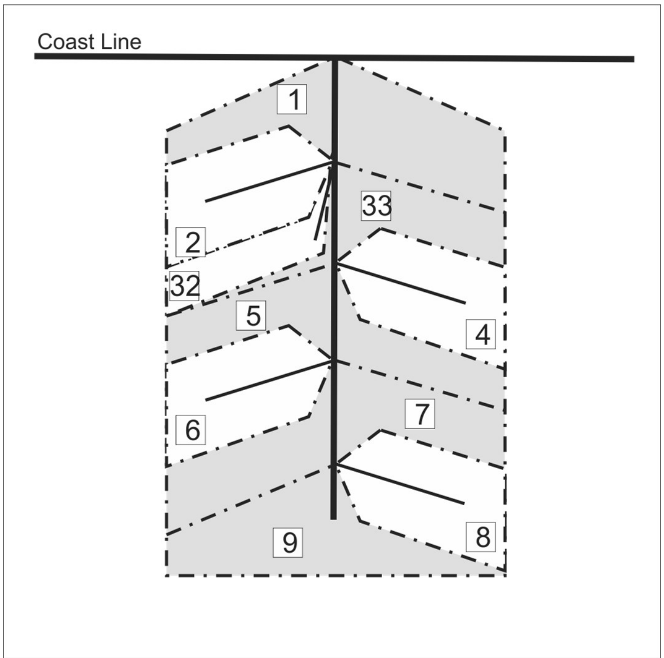

Figure 9. Example of numbering a basin with the double confluence in which both tributaries are located on the same bank of the main stem.

are located on the same bank of the mainstream, and the smaller tributary is positioned between the stream segment downstream of the double confluence and the larger tributary, it shall be given the digit code 12, and basin 13 is omitted.

Suppose the smaller tributary is located between the stream segment upstream of the double confluence and the larger

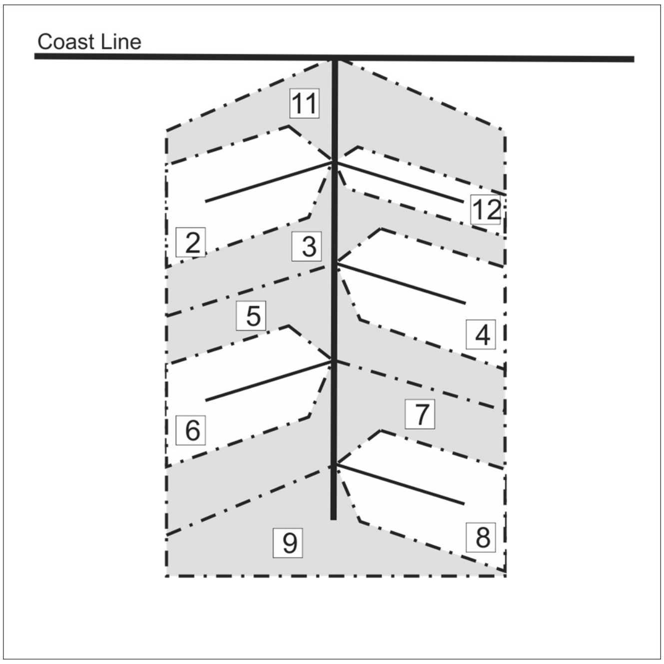

Figure 10. Example of numbering a basin with double confluences in which tributaries are located on opposite banks of the main stem.

tributary (Figure 9). In that case, this tributary shall be given digit code 32, while basin 31 is omitted. Thus, the mainstream segment downstream of the double confluence is given number 1, and the mainstream segment upstream of the double confluence is given number 33.

Suppose both tributaries of the double confluence are located on opposite banks. In that case, the largest branch shall be given a typical digit code. Still, according to the tributary criterion at the right bank further downstream, the smaller tributary located at the right bank shall be given digit code 12 (Figure 10) or digit code 32 (Figure 11) if it is located on the left bank.

The procedure for numbering double confluences also applies for confluences of three and four streams. Still, it should be noted that the greater the number of streams merging into a single stream, the rarer its occurrence in nature. However, this type of circumstance is common in river systems defined using reliable hydrological digital elevation models. In that case, concerning local flow obtained using the D8 (eight flow directions) method, it is possible to describe up to six streams flowing together. However, if over five streams join at a single point, the numbering shall no longer follow the homogeneous order. A solution to this problem would be implementing a coding system based on Pfafstetter's proposed system, providing the numbers based on the base 16-number system.

Cycles or loops

Cycles or loops of stream segments are found at the multiple channels of the drainage system and in regions that depend on the topography of the drainage area or the amount of sediments in the discharge of a river (Figure 12). The simplification in those cycles or loops representing a river system as an anti-arborescence structure leads to the loss of hydrographic information that, depending on the degree of simplification, puts at risk the quality of data to help the water decision-maker.

Thus, the basin coding system proposed in this paper considers the stream segments that form the cycles or loops, such as secondary streams. The main stem is composed of the source and the mouth. Cycles or loops include secondary streams whose main feature is the absence of the source.

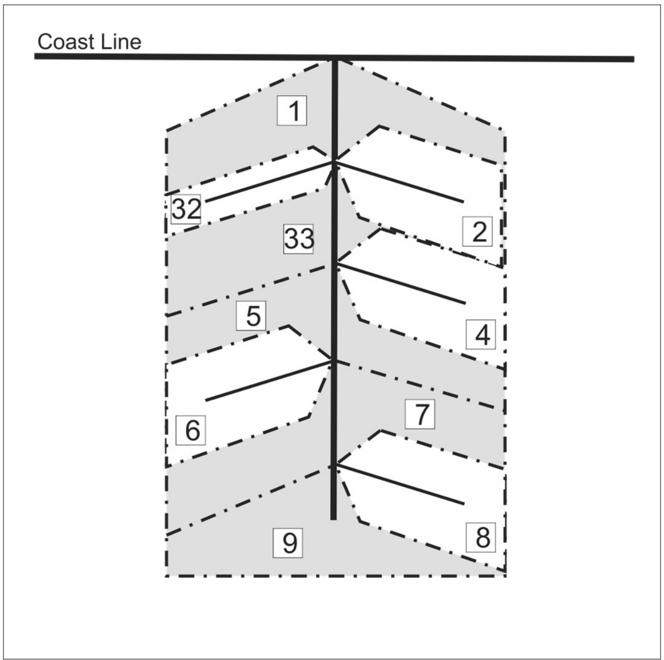

Figure 11. Another example of numbering a basin with double confluences in which tributaries are located on opposite banks of the main stem.

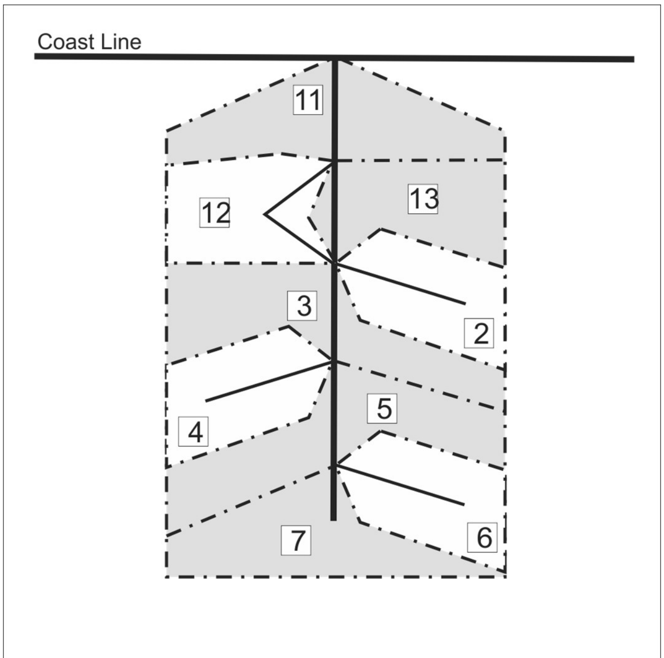

Figure 12. Example of numbering basins with multiple channels.

One challenge in structuring the drainage system by any coding system is integrating coastal and continental basins. One solution proposed by Teixeira et al. (2007a), developed using the Brazil Pfafstetter System Dataset, is integrating coastal basins with continental basins by using the shoreline reference as the integrating element of the drainage system. This solution ensures that the whole drainage system in different coastal or continental basins is connected. However, the coastline definition is beyond the limit established by the cartographic mapping developed by relevant bodies because this line does not depend on physical and chemical features, such as salinity, administrative or political issues. Furthermore, this line represents the boundaries of the hydrography units and therefore interferes directly in determining the code of the basin.

The codification of the drainage system in delta areas (Figure 13) is similar to the process used for the numbering of drainage systems with cycles or loops in continental basins. The main difference with delta rivers is that loops occur in stretches of the drainage system in coastal and continental basins. At the same time, the latter takes place exclusively in stretches of continental drainage basins. Thus, only one of the stretches connecting to the coastline is part of the main stem.

Sink/spillway

In karst regions (Figure 14), the representation of the river system in the form of an anti-arborescence structure is not appropriate because of the disruption of hydrography. The underground stream segment must be described and included in the river system to ensure that this representation does not interfere with the river system analysis. However, each underground stream segment shall be received a digit code that is different from the segments of surface water upstream and downstream. Although

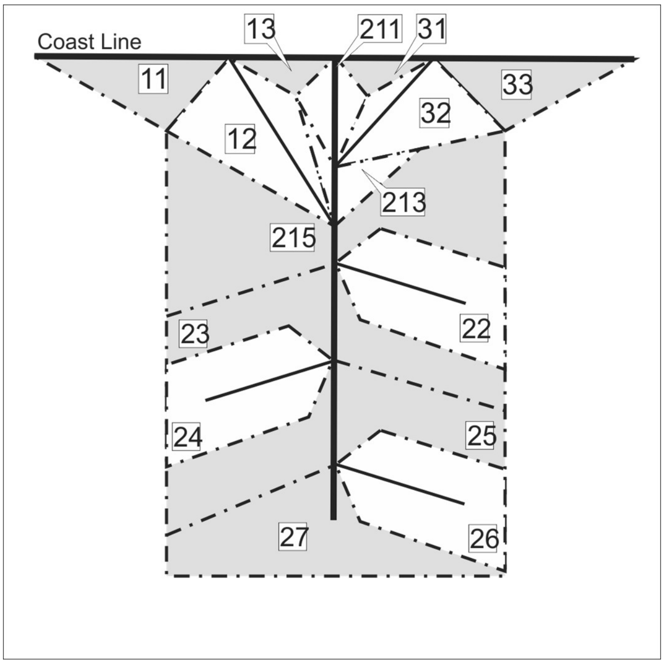

Figure 13. Example of numbering basins with a river delta.

no tributaries are dividing the inter-basins, these stretches are assigned digit codes as if they were inter-basins.

Water bodies

For water bodies, there is an individual stream segment or an inter-basin within the water mass. Thus, each stream segment within the water body is associated with an inter-basin, which is not necessarily positioned in-between two tributaries (Figure 15). This situation can be observed in water bodies such as a lake, pond, dam, river, channel and lagoon.

Logical work-flow

The logical work-flow presented in the Figure 16 shows a general view of the coding process where it is possible to identify the arrangements needed to improve the original Pfafstetter basin coding system, mainly the primary and secondary flow direction identification steps.

CONCLUSIONS AND RECOMMENDATIONS

The Pfastetter basin coding system improvements proposed in this paper paper maintain its simplicity, considering that such a feature was primarily responsible for disseminating the method worldwide. Furthermore, the new approach outlined here aims to prevent the loss of information due to the simplification of the hydrography network when describing the river system traditional representation based on an anti-arborescence graph-type.

Notice, however, that the advantage of implementing the Pfafstetter basin coding system goes far beyond the numbering scheme based upon the topology of the hydrography network. Instead, it provides the hierarchy needed to help decision-

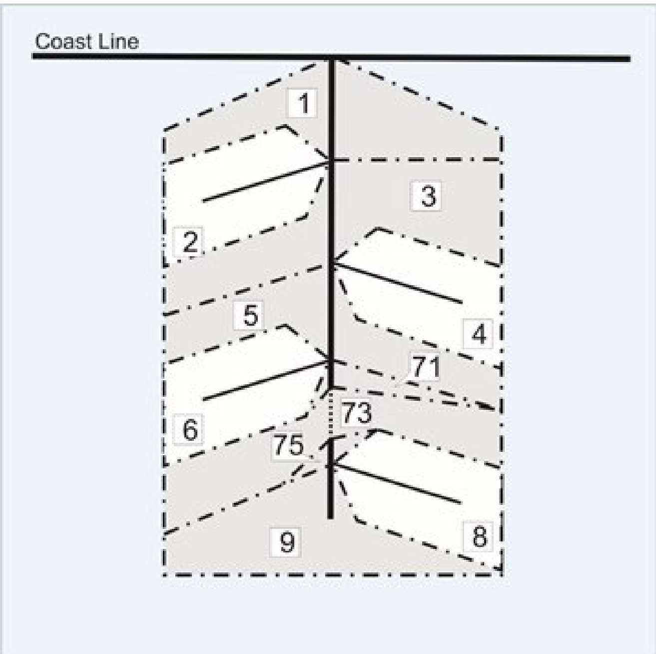

Figure 14. Example of coding basin of a sink/spillway.

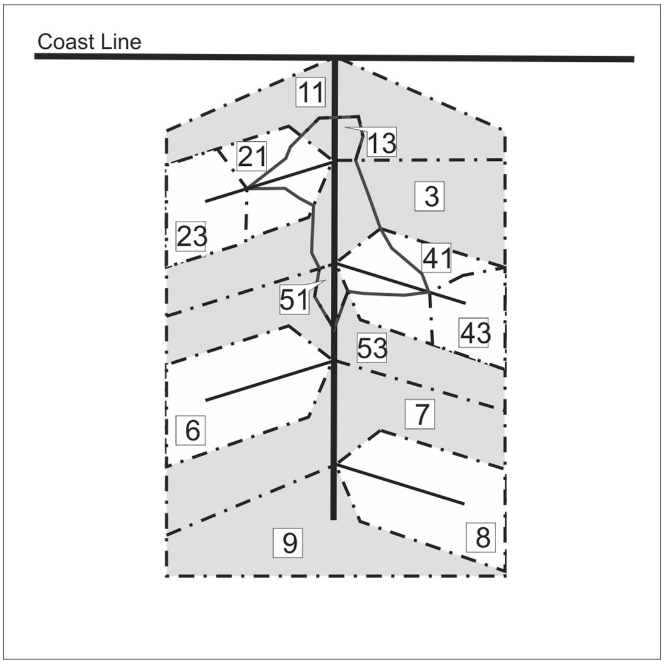

Figure 15. Example of numbering basins with water mass.

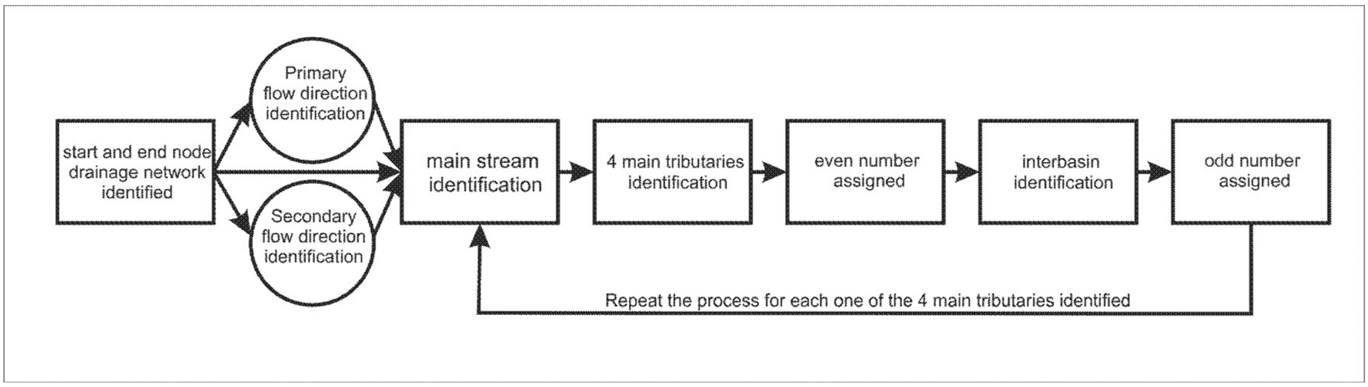

Figure 16. Pfafstetter basin coding system improvements logical scheme. Rectangles represent the original Pfsfstetter basin coding system algorithm, and the circles represent the additional steps needed to code the remaining or secondary basins.

making processes regarding water resources management that require information such as river basin levels or stream orders. The most interesting aspect is that hierarchy is independent of the representation of the river system and is directly related to catchment areas upstream of the drainage network stretches.

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