Anais 7º Simpósio de Geotecnologias no Pantanal, Jardim, MS, 20 a 24 de outubro 2018
Embrapa Informática Agropecuária/INPE, p. 262-273

Topological validation of drainage network with QGIS

Leandro Luiz Silva de França [1]

[1] 3º Centro de Geoinformação (3º CGEO)
Av. Joaquim Nabuco, nº 1687,
53240-650, Olinda-PE, Brasil
franca.leandro@eb.mil.br

Resumo. A Organização Internacional para Padronização (International Organization for Standarlization - ISO), em sua série 19.100, estabelece os princípios e elementos de avaliação de qualidade de dados geoespaciais. A categoria de elementos de qualidade denominada consistência lógica busca verificar se os dados estão coerentes com regras lógicas e estruturais para modelagem do mundo real. A consistência topológica, elemento da consistência lógica, tem como objetivo averiguar a conformidade de regras topológicas no conjunto de dados em um processo conhecido como validação topológica. Nesse contexto, este trabalho se propôs a apresentar conceitos fundamentais e regras de validação topológica de linhas que compõe uma rede de drenagem em um estudo de caso aplicado as feições da classe Waterways oriundas do OpenStreetMap para a bacia hidrográfica do Alto Paraguai, no pantanal brasileiro. Para a avaliação da consistência topológica foram construídas duas ferramentas para o QGIS que identificam problemas na construção das geometrias e inconsistências na rede, além de gerar os pontos de drenagem (ponto inicial, ponto final, confluência, ramificação e ponto de mudança de atributo). Dentre as inconsistências encontradas, as linhas sem conexão tiveram maior destaque, indicando também outros problemas como o de completude, o que impede a utilização apenas de métodos automáticos para correção das inconsistências de topologia.

Palavras-chave: validação, topologia, rede de drenagem, controle de qualidade, QGIS, OpenStreetMap.

Abstract. The International Organization for Standardization (ISO), on its 19,100 series, establishes the principles and elements of quality for geospatial data assessment. Logical consistency is a category of data quality elements that verifies if the data is coherent with logical and structural rules for real-world modeling. Topological consistency, an element of the logical consistency, aims to ascertain the compliance of topological rules in the dataset in a process known as topological validation. In this context, this work was proposed to present fundamental concepts and topological rules for lines that comprise a drainage network in a case study applied to the features of the Waterways class originating from the OpenStreetMap to the watershed of the Alto Paraguai, in the Brazilian Pantanal. For the evaluation of the topological consistency, two tools were built for the QGIS that identify problems in the construction of the geometries and inconsistencies in the network, besides generating the drainage points (start point, end point, confluence, branch and attribute change point). Among the encountered inconsistencies, the unconnected lines were more prominent, also indicating other problems in the completeness, which prevents the use of only automatic methods for the correction of topological inconsistencies.

Keywords: validation, topology, drainage network, quality control, QGIS, OpenStreetMap.

1. Introduction

Several automatic methods of generating drainage network have been applied for cartographic production (Andrades Filho *et al*., 2009; Bosquilia *et al*., 2015; Cherem *et al*., 2009; Leonardi & Silva, 2007; Monteiro *et al*., 2015; Dos Santos & Shiraiwa, 2012), that happens mainly because the manual methods are more laborious and with greater subjectivity, depending on the experience of the photointerpreter (Bosquilia *et al*., 2015).

Independently of how these data are generated, they can currently be shared through voluntary geographic information (VGI), a collaborative project where volunteers collect, process and publish geographic data of various types (Goodchild, 2007; Monteiro *et al*., 2015), in this context is highlighted the *OpenStreetMap* (OSM) (Sehra *et al*., 2014), a free and editable geographic dataset of worldwide mapping that is in continuous construction in a voluntary manner with available data under Open License (Martins Junior *et al*., 2016).

Due to a large number of non-mapping specialists (Santos *et al*., 2016), more discussions are emerging about the level of quality of this data in relation to the quality categories: completeness, logical consistency, positional accuracy, temporal accuracy and thematic accuracy (França & Ferreira da Silva, 2018).

Some researches on the positional accuracy of the OSM were carried out by Brovelli *et al*. (2016), Cruz & Santos (2016) and França & Ferreira da Silva (2018), nevertheless, they have restricted to a few quality elements, that is, studies that relate the geometric properties with the topological ones are still little approached in the academic sphere (Abed-Elmdoust *et al*., 2017).

Topological consistency is an element of the data quality category called logical consistency (ISO, 2013) and refers to the geometric and topological aspects of spatial information, checking for connectivity, adjacency, containment or proximity situations (IBGE, 2017).

The term topology for Geographic Information System (GIS) is given to the arrangement that defines how point, line, and polygon features share coincident geometry, aiming accurately model geometric relationships (ESRI, 2016), that is, how places and locations relate to one another similarly the real-world situations.

Topological validation is the term given to the topological consistency inspections (IBGE, 2017), seeks to assess the adequacy of geographical data for a particular purpose (DSG, 2016). That is why, the topology validation has long been a key GIS requirement for data management and integrity (ESRI, 2016).

The drainage network, according to the specifications of the National Spatial Data Infrastructure (*Infraestrutura Nacional de Dados Espaciais* - INDE) must be modeled as a class of line features called the drainage lines corresponding to permanent or temporary water bodies, in accordance with the vector acquisition scale (CONCAR, 2010).

According to Dos Santos & Shiraiwa (2012), drainage networks are topographic features that favor the accumulation and flow of surface water. They are composed of channels organized in a characteristic pattern. Cherem *et al*. (2009) add these fluvial channels are characterized by their hierarchy, sinuosity and slope, as well as their spatial arrangement.

The drainage network is an important indicator of changes that occurred in the composition of the watershed landscape, either due to changes in its structure, shape or by loss or gain of channels (Nascimento *et al*., 2009), being a primordial element in the maintenance of the biota and in the definition of processes responsible for the relief sculpture (Cristo & Robaina, 2014). Therefore, the drainage network is a basic element of research (Andrades Filho *et al*., 2009). The watershed is considered a fundamental unit for the conservation of the environment and serves as a basis for planning and management due to the integrative character of its elements (Bosquilia *et al*., 2015; Albuquerque & Oliveira, 2015).

Andrades Filho *et al*. (2009) and Abed-Elmdoust *et al*. (2017) mention the difficulty of elaborating hydrological maps due to the high dynamics and complex topology of drainage networks. Santos Silva *et al*. (2008) and Paranhos Filho *et al*. (2017) report the scarcity of information on global application systems that uniquely and efficiently references and identifies the nature of watersheds. Therefore, there is a need for solutions based on vector structure of networks that refer, through linear addressing mechanisms, each segment of a drainage network (Santos Silva *et al*., 2008).

The consistency of the data representing a drainage network guarantees greater reliability to geographical analyses (DSG, 2016), such as the environmental analyses presented by Alther & Altermatt (2018) that analyzed the influence of fluvial network topology on Amphipod (an order of crustaceans) communities; Rudi *et al*. (2018) using geomorphological variables to predict the spatial distribution of plant species in agricultural drainage networks; and Paranhos Filho *et al*. (2017) associating the role of the drainage network as the indicator of tectonic movements.

2. Objective (Drainage Network Validation)

Topological validation has the purpose of identifying and correcting topology inconsistencies by automatic or manual processes (Passos *et al*., 2017). It can be classified into three types (IBGE, 2017):

- Intra-class topological validation: aims to identify inconsistencies in the geometry and topology between the features of a class;
- Inter-class topological validation: aims to identify topology inconsistencies between classes, based on the topological relationship rules for the classes in the data model;
- Specific topological validation: aims to check situations not explicit in the data model.

The validation rules between classes are usually described in entity-relationship diagrams (CONCAR, 2010). However, due to the complexity in the construction and validation of the Drainage Line class, this research sought to explore the main topological rules common and specific to the features of this class.

The Manual of Geospatial Data Quality Assessment (IBGE, 2017) points out the main anomalies in the construction of the geometries, being the most common for line type features:

zero-length lines; kickback/duplicate point; kink/spike; loop in line; short vector; fragmented geometry; and duplicate feature.

The Brazilian Technical Specifications for the Acquisition of Vector Geospatial Data (DSG, 2011) presents general rules for the construction of objects of the Drainage Line class, which, as regards geometry and topology, stands out: the use of line type geometry; the lines must be vectorized from upstream to downstream; the start and end points of each line must touch an object of the Drainage Point class; and the features of the Drainage Line class must represent the main flow of the water stream.

In the environment, it is possible to observe some possibilities to the drainage points. Each of them is represented in the diagram of **Figure 1** and described below:

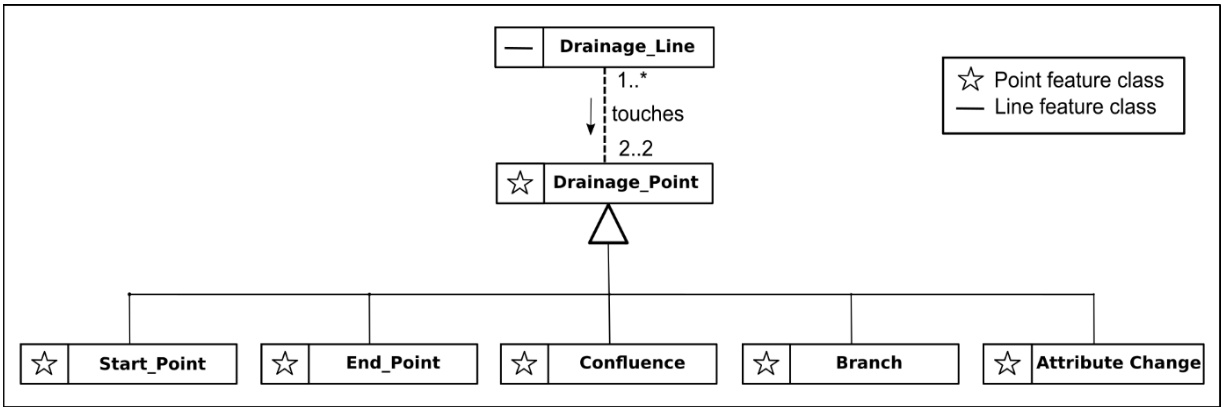

Figure 1: Entity-relationship diagram for Drainage Network.

- Start Point: point where a drainage network begins, as a water source, spillway or something similar;
- End Point: point where a drainage network ends, as a river mouth, outfall, sink or something similar;
- Confluence: point where two or more drainage lines converge, resulting in only one line;
- Branch: point where a drainage line splits into two or more lines;
- Attribute Change: point where a change of characteristics (attributes) occurs.

The flow direction defines the hydrological relationships between different points within a river basin (Rennó *et al*., 2018). Therefore, for the existence of a functional drainage, it is necessary the correct construction of the lines that compose the network through the sequence of points that represents the direction of water flow (**Figure 2**). To do this, there are automatic procedures for assigning the flow direction from the orthometric height (H) obtained from a Digital Elevation Model (DEM) (Bosquilia *et al*., 2015), although the success of this procedure is closely linked to Accuracy of the DEM.

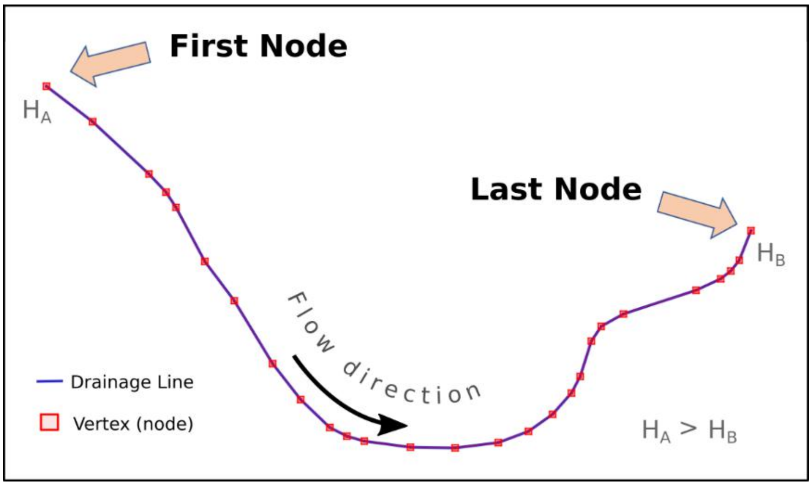

Figure 2: Flow Direction in a Drainage Line.

Yang *et al*. (2017) study the similarities between engineered versus natural drainage networks because both involve gravity-driven and directed flows. In general, they consist of junctions and conduits, which correspond to nodes and edges.

Thus, when it is desired to perform an accurate analysis of the drainage network, it is essential to ensure the correct orientation of the drainage lines, as well as the connectivity between them. A validated drainage network allows the automatic identification of all drainage points and their influence on environmental and hydrographic studies.

Therefore, the objective of this work is to present the main geometrical and topological inconsistencies of a drainage network made available through the Waterways class of OpenStreetMap applied to a case study in the watershed of Alto Paraguai, in the Pantanal of Brazil.

3. Materials and methods

The area of study corresponds to the hydrographic basin of Alto Paraguai which is in the Brazilian states of Mato Grosso and Mato Grosso do Sul, being represented in the maps of **Figure 3**.

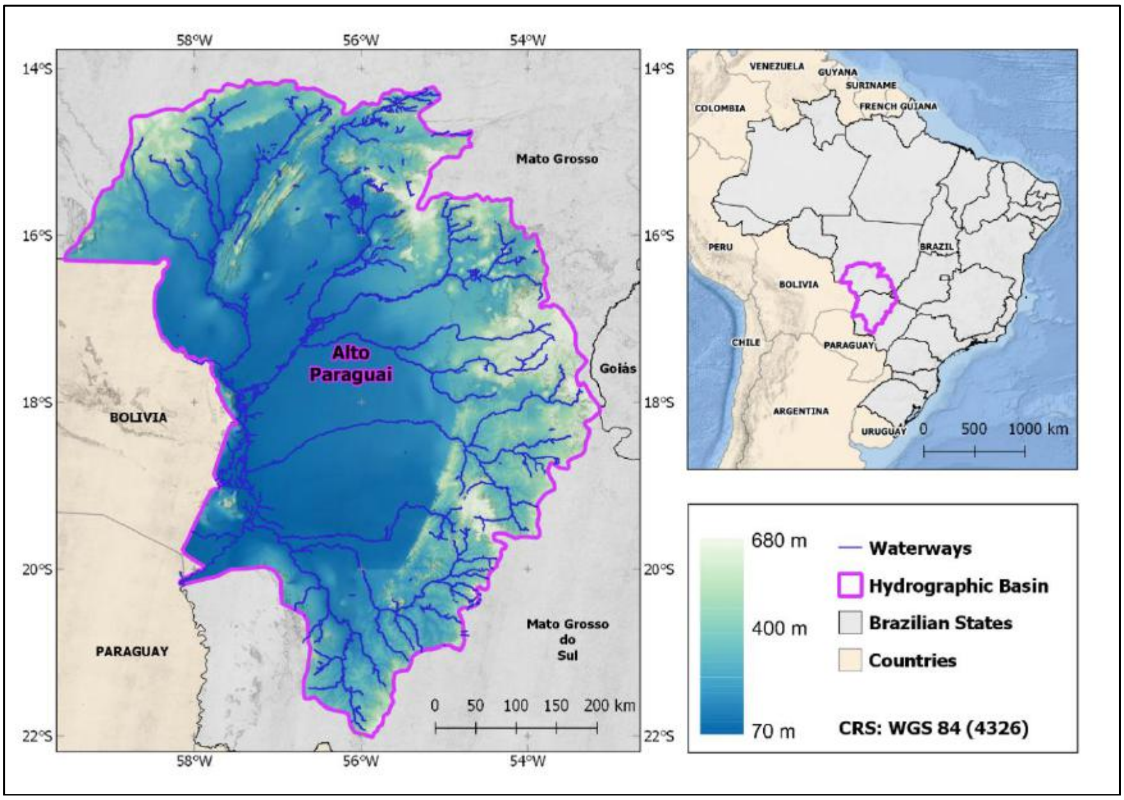

Figure 3: Study Area.

The evaluated data consider the linear features of the waterways class of the OSM (Ramm, 2017), corresponding to all types of rivers, streams, canals and drains. This data can be obtained free of charge through the Geofabrik server (2016). For the execution of the validation, the open source software QGIS 2.18 and algorithms created in Python were used (**Figure 4**). The developed tools were created by this author and they are available in the following Github repository: www.github.com/LEOXINGU/drainage_validation.

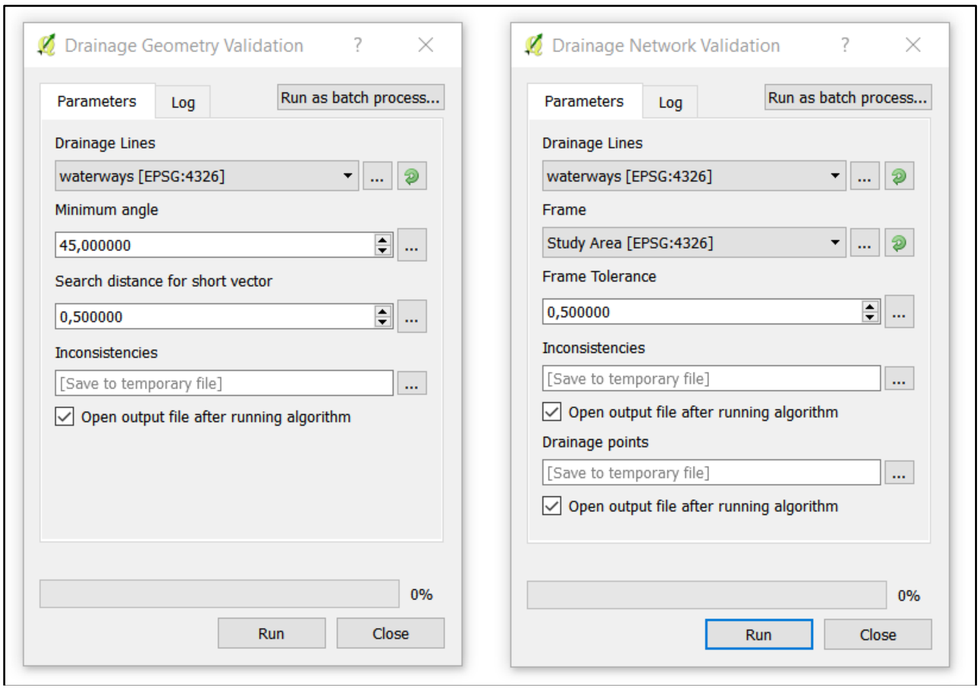

Figure 4: QGIS tools for Drainage Validation (Geometry and Network).

In the geometric validation tool of the drainage network (**Figure 5**) are verified inconsistencies of construction of the geometry, being they self-intersection, overlap, minimum angle, crossing between lines and line not connected.

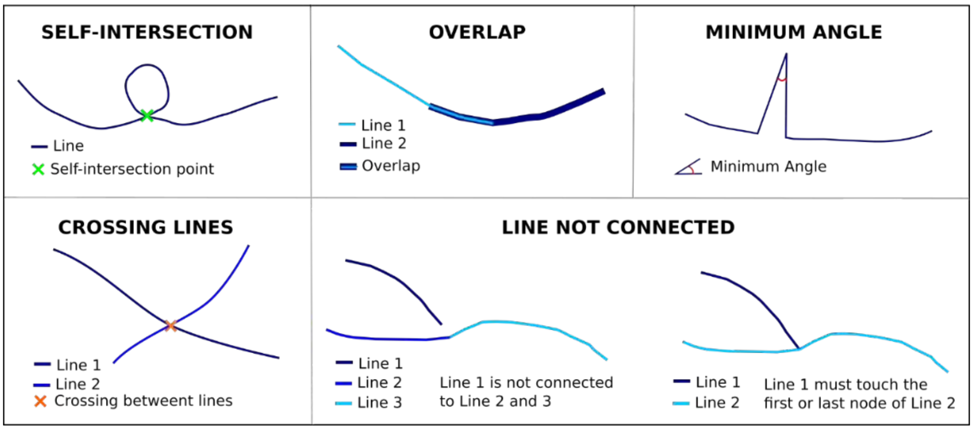

Figure 5: Examples of geometric inconsistencies for drainage lines.

The verification of the geometry problems should be done before the validation of the network, considering that the network validation only makes sense when there are no more problems in the construction of the geometries, so that ensures the connectivity between the drainage lines and solves all situation which, in general, do not occur in the real world, such as the case of self-intersections, overlap and closed angles.

The network inconsistencies are checked based on the first and last points of the list of points that constitute a drainage line. They must be classified into one of the situations for a drainage point (**Figure 6**), otherwise, it is considered an inconsistency (**Figure 7**).

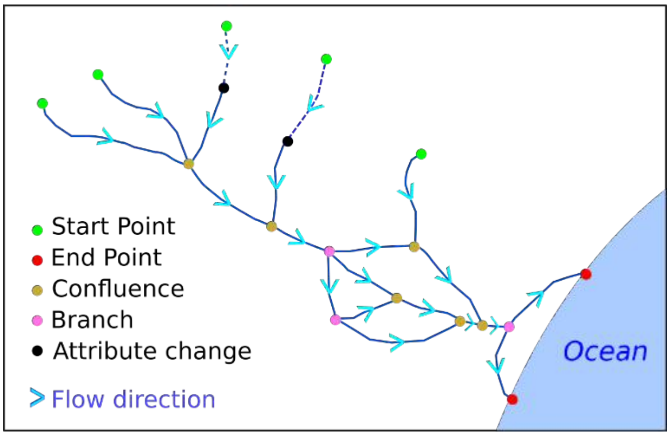

Figure 6: Types of Drainage Point.

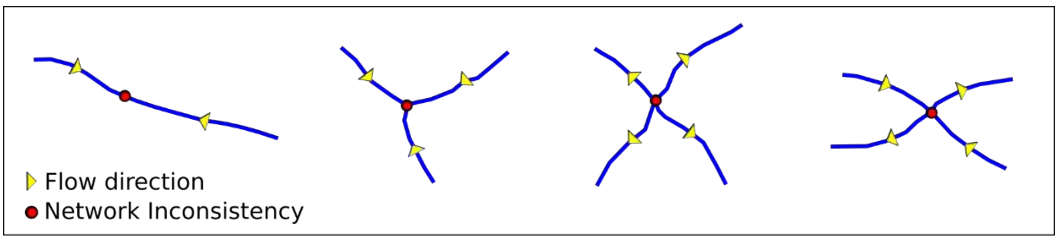

Figure 7: Examples of Network Inconsistency.

The "Drainage Network Validation" tool also checks if there is loop on the network (**Figure 8**), a type of inconsistency that hurts the logic of the drainage network, because the water, following in its flow direction, cannot return to the same point, but it can only follow from upstream to downstream.

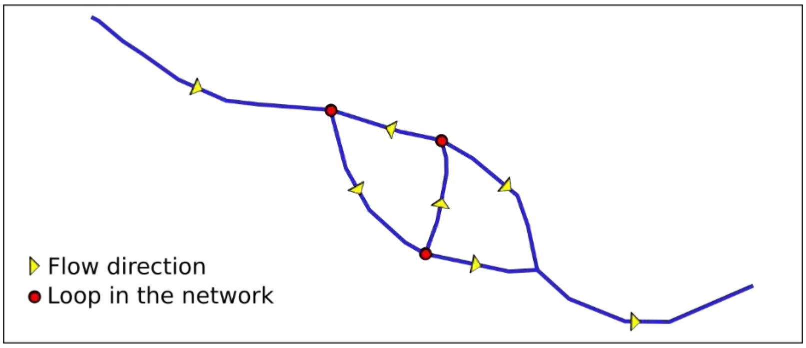

Figure 8: Loop in the drainage network.

4. Results and discussions

A total of 1992 features of the OSM Waterways class that intersect the Alto Paraguai watershed were assessed, making the sum of its lengths a total of 17,368 Km.

For the geometric evaluation, the tool "Drainage Geometry Validation" was used (**Figure 4**), with the distance parameters of 0.5 meters for the search distance between lines that do not connect and minimum angle of 45°. With these parameters, it was reached the number of inconsistencies presented in **Table 1** and **Figure 9**.

Table 1: Drainage geometry inconsistencies.

Inconsistency	*Quantity*
Crossing between lines	11
Line not connected	720
Minimum angle	49
Overlap between lines	58
Self-intersection	1

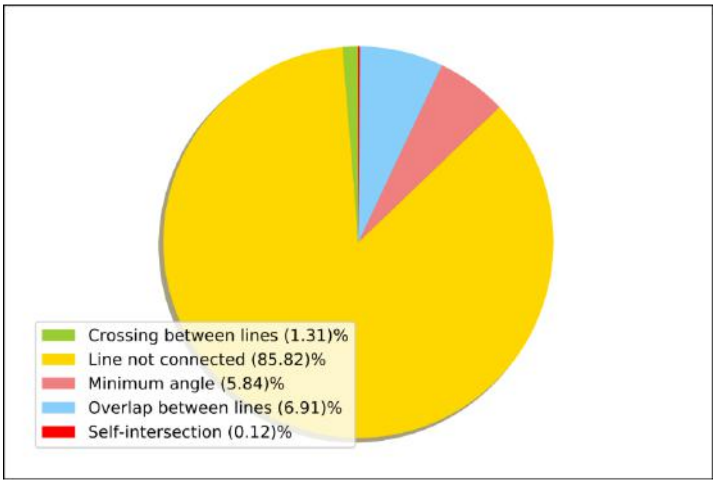

Figure 9: Pie chart of Drainage Geometry Inconsistencies.

It is noted in **Figure 9** that, with the adopted parameters, the most recurring inconsistency is the situation of lines that do not connect. When the search distance for short vector is increased, the number of "line not connected" inconsistencies increase even more, as shown in the chart of **Figure 10**.

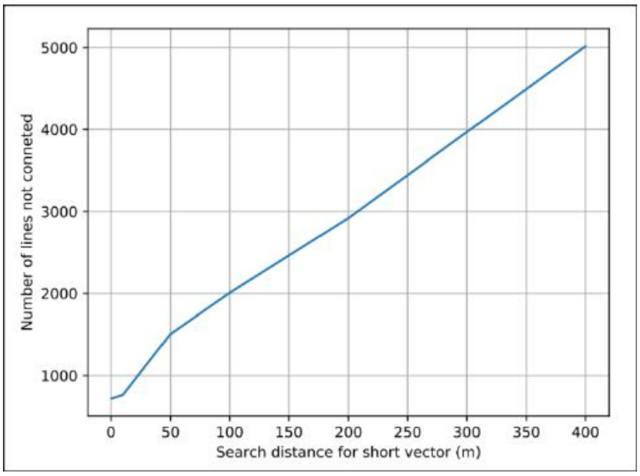

Figure 10: Relation between search distance and the number of not connected lines.

Before the verification of the network inconsistencies, it is desirable to fix all the geometry problems of the features. This correction can be performed by automatic or manual methods (IBGE, 2017).

However, for the evaluation of the drainage network, the "Drainage Network Validation" tool was applied to the original OSM data, without any kind of editing on it, so that other researchers can achieve similar results. In this condition, the quantities of network inconsistencies are presented in **Table 2**, and the coordinates of some cases of problems are presented in **Figure 11**.

Table 2: Drainage network inconsistencies.

Inconsistency	*Quantity*
Network problem	24
Loop	0

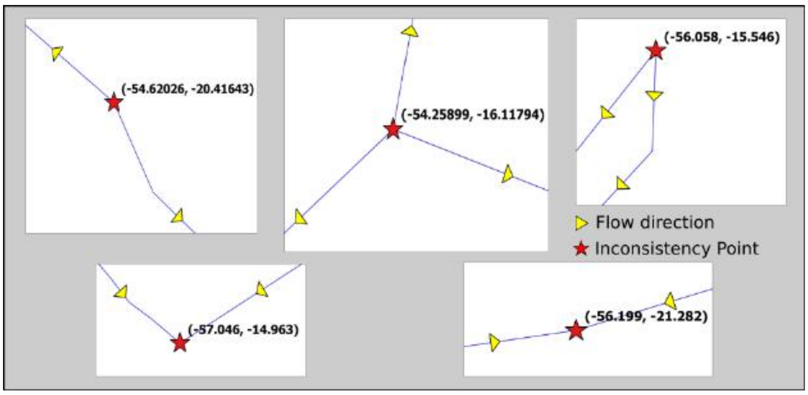

Figure 11: Some cases of network inconsistency found.

The "Drainage Network Validation" tool also aims to generate drainage points. For the lines under study, the number of points generated is given in **Table 3**.

Table 3: Generated Drainage Points.

Drainage Point Type	*Quantity*
Start Point	941
End Point	804
Confluence	157
Branch	11
Attribute change	843

The non-occurrence of “loop” in the drainage network under study can be attributed to the low connectivity between the lines, implying a high number of “end points” and, consequently, a reduced number of “confluence” and “branch” points.

In the real world, the “end point” feature may represent a mouth to where the water flow converges, flowing into a water body (lake or ocean) or, in rarer cases, when it encounters a sink feeding groundwater. Therefore, the occurrence of "end point" is less likely in a drainage network.

In the topological validation, many processes can be automatically corrected, for example, duplicate point, spike, zero-length line, duplicate feature, null geometry and fragmented geometry (IBGE, 2017).

From the problems presented in this work, the crossing between lines, self-intersection and minimum angle can be corrected automatically, for example, using GRASS validation tools (GRASS Development Team, 2017). The overlap between lines only can be automatically corrected when they share same attributes, otherwise, it is necessary operator decision.

The lines not connected, which has been shown the greatest responsible for the geometry and network inconsistencies, can be automatically corrected considering a specific maximum tolerance (IBGE, 2017). However, in **Figure 10**, it was verified that the larger the search distance, the more unconnected lines are identified. This signifies that many of the drainage lines are not connected to the drainage network, pointing to problems of completeness, that is, the omission of lines that should exist to connect them.

Figure 12 shows several examples of lines not connected and omissions in the OSM Waterways, where the reference lines (greater completeness) are part of the hydrographic dataset of the Brazilian National Water Agency (ANA, 2015).

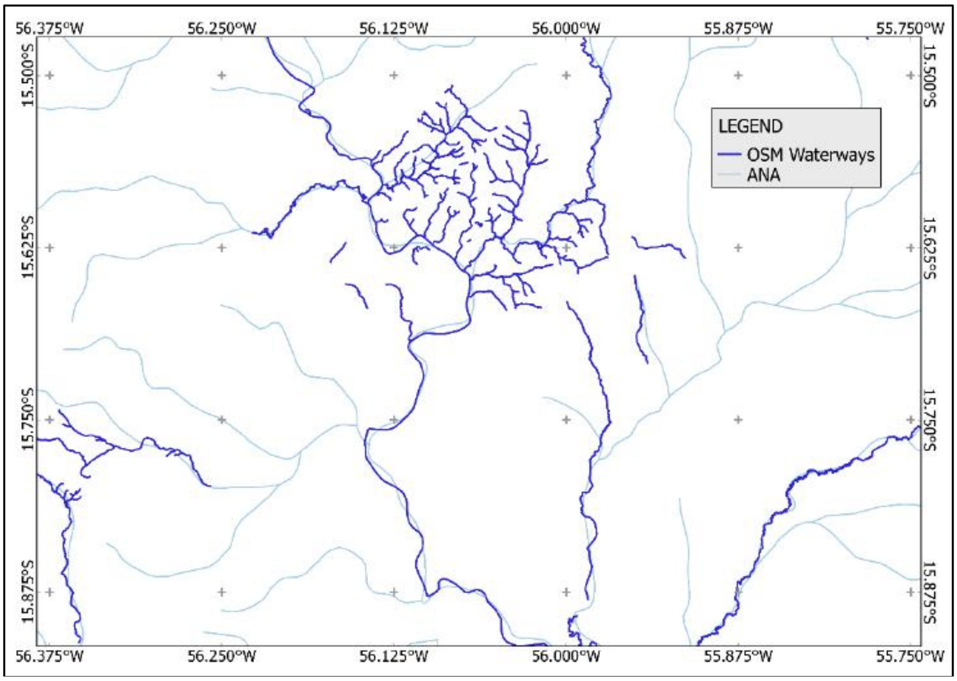

Figure 12: Lines not connected and problems of completeness.

5. Conclusion

This work had as objective to present the essential concepts for execution of the topological inspection of a drainage network. For this, the main problems in the construction of the geometries of the drainage lines were raised. It was also studied the five types of drainage points that can exist in a network, being: start point, end point, confluence, branch and attribute change, that served as the basis for identification of inconsistencies in the network.

Based on the studied concepts, two tools for the QGIS ("Drainage Geometry Validation" and "Drainage Network Validation") were created by this author to identify inconsistencies, being applied in a study case for the drainage network of the OSM Waterways in the watershed of Alto Paraguai.

With the obtained results, it has arrived that the main cause of inconsistencies in the network is related to the lack of connectivity between the lines. Automatic correction methods can be applied to correct some of the inconsistencies, but it is necessary visual inspection of the data, preferably by an experienced operator, for corrections that require decision-making and solution of completeness problems, ensuring correct connectivity between the lines.

The study area includes the Pantanal, whose drainage behavior is quite complex and variable over time, making mapping processes difficult, even those done manually. This is probably one of the reasons for the great number of unconnected lines inconsistencies.

Nevertheless the current standards of geospatial data control quality indicate that the level of compliance must be zero inconsistencies for topological validation (IBGE, 2017; DSG, 2016). This quality procedure proves that all care has been taken to make the vector data in accordance with the logical model and appropriate for the real-world representation, besides allowing the results of studies and analyzes based on this data more reliable.

6. References

Abed-Elmdoust, A., Singh, A. Yang, Z. L. (2017). Emergent spectral properties of river network topology: an optimal channel network approach. **Scientific reports**, *7*(1), 11486.

Albuquerque, L. B., & Oliveira, W. (2015). Caracterização da bacia hidrográfica do córrego Pratinha–Três Lagoas (MS) como subsídio ao planejamento ambiental. **Revista GeoPantanal**, *10*(19), 87-99.

Alther, R., & Altermatt, F. (2018). Fluvial network topology shapes communities of native and non-native amphipods. **Ecosphere**, *9*(2).

ANA - Agência Nacional de Águas. (2015). **Base Hidrográfica Ottocodificada**. 2ª Edição. Brasília. 2015. Avaliable in: http://metadados.ana.gov.br/geonetwork/srv/pt/main.home?uuid=7bb15389-1016-4d5b-9480-5f1acdadd0f5 . Accessed in: Jun 16th, 2018.

Andrades Filho, C. D. O. A., Zani, H., & Dos Santos Gradella, F. (2009). Extração automática das redes de drenagem no pantanal de Aquidauana: estudo comparativo com dados SRTM, ASTER e carta topográfica DSG. **Revista Geografia**. Rio Claro, v.34, Número Especial, p. 731-743.

Bosquilia, R. W. D., Fiorio, P. R., Duarte, S. N., & Mingoti, R. (2015). Comparação entre métodos de mapeamento automático de rede de drenagem utilizando SIG. **Irriga**, *20*(3), 445.

Brovelli, M. A., Minghini, M., Molinari, M. E. (2016). An automated GRASS-based procedure to assess the geometrical accuracy of the OpenStreetMap Paris road network. **The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences**, v. 41, p. 919-925.

Cherem, L. F. S., Magalhães Junior, A. P., & Faria, S. D. (2009). Análise morfológica de rede de drenagem extraída de MDE-SRTM. **Simpósio Brasileiro de Sensoriamento Remoto**, *14*, 7251-7258.

Cristo, S. S. V., & Robaina, L. E. S. (2014). Caracterização da rede hidrográfica na estação ecológica Serra Geral do Tocantins, estados do Tocantins e Bahia. **Geografia Ensino & Pesquisa**, *18*(3), 103-116.

Cruz, D. T., Santos, A. P. (2016). Controle de Qualidade Posicional do Sistema Rodoviário do OpenStreetMap na região central de Viçosa-MG. **VI Simpósio Brasileiro de Ciências Geodésicas e Tecnologias da Geoinformação**.

CONCAR - Comissão Nacional de Cartografia. (2010) **Especificação Técnica para a Estruturação de Dados Geoespaciais Vetoriais**. ET-EDGV 2.1.3. Brasília - DF.

Dos Santos, C. C. P., & Shiraiwa, S. (2012). Extração de redes de drenagem utilizando limiares de área acumulada máxima através de modelos digitais de elevação em diferentes escalas. **Anais 4º Simpósio de Geotecnologias no Pantanal**, Bonito, MS, 20-24 de outubro 2012. Embrapa Informática Agropecuária/INPE, p.50-59.

DSG - Diretoria de Serviço Geográfico. (2011). **Especificações Técnicas para a Aquisição de Dados Geoespaciais Vetoriais**. ET-ADGV 2.1.3. Brasília – DF.

DSG - Diretoria do Serviço Geográfico. (2016). **Norma da Especificação Técnica para Controle de Qualidade de Dados Geoespaciais**. ET-CQDG. 1ª Edição. Brasília – DF.

ESRI. ArcGIS. (2016). **Topology Basics**. Avaliable on: http://desktop.arcgis.com/en/arcmap/10.3/manage-data/topologies/topology-basics.htm. Accessed in: June 14, 2018.

França, L. L. S., Ferreira da Silva, L.F. (2018). Comparison between the Double Buffer Method and the Equivalent Rectangle Method for the quantification of discrepancies between linear features. **Boletim de Ciências Geodésicas**, 24(3).

Geofabrik. (2016). **OpenStreetMap Data Extracts**. Available in: http://download.geofabrik.de/. Accessed in Sept 2017.

Goodchild, M. F. (2007). Citizens as sensors: the world of volunteered geography. **GeoJournal**, 4, 211-222.

GRASS Development Team. (2017). **Geographic Resources Analysis Support System (GRASS 7) Programmer's Manual**. Open Source Geospatial Foundation Project. Electronic document: http://grass.osgeo.org/programming7/.

IBGE – Instituto Brasileiro de Geografa e Estatística. (2017). **Avaliação da qualidade de dados geoespaciais**. Manuais técnicos de geociências. Coordenação de Cartografia. Rio de Janeiro.

ISO – International Organization for Standarlization. (2013). 19.157: 2013. Geographic information – Services. **Quality management systems-Requirements** (ISO 19.157: 2013).

Leonardi, F., & Silva, E. A. D. (2007). Aplicação de rotinas morfológicas para detecção de redes de drenagem. **Anais I Seminário de Recursos Hídricos da Bacia Hidrográfica do Paraíba do Sul**. Taubaté, Brasil, 07-09 novembro 2007, IPABHi, p. 175-182.

Martins Junior, O. G., Mercedes Strauch, J. C., Barreto do Santos, C. J., Ribeiro Borba, R. L., & Moreira de Souza, J. (2016). Informação Geográfica Voluntária no Processo de Reambulação. **Boletim de Ciências Geodésicas**, 22(4).

Monteiro, E. V., Fonte, C. C., & de Lima, J. L. P. (2015). Exatidão posicional de redes hidrográficas extraídas de MDE gerados a partir de MDE globais e de dados extraídos do OpenStreetMap. **VIII Conferência Nacional de Cartografia e Geodésia**.

Nascimento, P. S., Petta, R. A., & Garcia, G. J. (2009). Confecção do mapa de densidade de drenagem através de geotecnologias visando definir a vulnerabilidade aos processos erosivos na sub-bacia do baixo Piracicaba (SP). **Estudos Geográficos: Revista Eletrônica de Geografia**, *6*(1), 19-35.

Paranhos Filho, A. C., Leonardo Mioto, C., Machado, R., Veríssimo Gonçalves, F., de Oliveira Ribeiro, V., Marcelo Grigio, A., & da Silva, N. M. (2017). Controle Estrutural da Hidrografia do Pantanal, Brasil. **Anuário do Instituto de Geociências**, *40*(1).

Passos, J. B. Carvalho, R. B. Penha, A. L. T. França. L. L. S. (2017). Estruturação e validação de dados geográficos em ambiente orientado a objeto do Sistema Gothic. **Anais do XVIII Simpósio Brasileiro de Sensoriamento Remoto** -SBSR. INPE Santos - SP, Brasil. p. 795-802.

Rennó, C. D.; Nobre, A. D.; Cuartas, L. A.; Soares, J. V.; Hodnett, M. G.; Tomasella, J.; Waterloo, M. J. Hand. (2008). A new terrain descriptor using SRTM-DEM: mapping terra-firme rainforest environments in Amazonia. **Remote Sensing of Environment**, New York, v. 112, n. 9, p. 3469-3481.

Rudi, G., Bailly, J. S., & Vinatier, F. (2018). Using geomorphological variables to predict the spatial distribution of plant species in agricultural drainage networks. **PloS one**, *13*(1), e0191397.

Santos, A. P., Domingos, D., Terra Santos, N., Gripp Junior, J. (2016). Avaliação da acurácia posicional em dados espaciais utilizando técnicas de estatística espacial: proposta de método e exemplo utilizando a norma brasileira. **Boletim de Ciências Geodésicas**, 22(4).

Santos Silva, N., Ribeiro, C. A. A. S., Barroso, W. R., Ribeiro, P. E. Á., Soares, V. P., & Silva, E. (2008). Sistema de otto-codificação modificado para endereçamento de redes hidrográficas. An improved stream network addressing system the modified pfafstetter coding scheme. **Revista Árvore**, *32*(5), 891-897.

Sehra, S. S., Singh, J., Rai, H. S. 2014. A Systematic Study of OpenStreetMap Data Quality Assessment. **11th International Conference on Information Technology**: New Generations.

Ramm, F. (2017). **OpenStreetMap Data in Layered GIS Format**. Available in: https://download.geofabrik.de/osm-data-in-gis-formats-free.pdf. Accessed on: Sept 2017.

Yang, S., Paik, K., McGrath, G., Urich, C., Kruger, E., Kumar, P., & Rao, P. S. C. (2017). **Comparing Topology of Engineered and Natural Drainage Networks**. *arXiv preprint arXiv:1707.04911*.