TerraHidro: A Distributed Hydrology Modelling System With High Quality Drainage Extraction

Sergio Rosim, João Ricardo de Freitas Oliveira, Alexandre Copertino Jardim, Laércio Massaru Namikawa, Camilo Daleles Rennó

Image Processing Division

National Institute for Space Research

São José dos Campos, Brazil

{sergio, joao, camilo, laercio, alexandre}@dpi.inpe.br

***Abstract*—This paper presents the current development stage of TerraHidro, a Distributed Hydrology Modeling System created to design Geographic Information Systems (GIS) applications for water flow in hydrographical basins. TerraHidro proposes a different computational representation to deal with water flow in GIS applications. At first, this paper presents the conceptual model of TerraHidro, where the structure used to develop applications is independent from the structures used to extract local flow paths. Since the local flows are primary information for network drainage extractions, the Priority First Search (PFS) method used by TerraHidro to extract these local flows is presented here. PFS method also gives realistic results in flat areas and eliminates all spurious pits in the DEM data with small modifications in the elevation values. Examples of drainage networks are presented and a comparison between TerraHidro and ArcGIS Hydro Tools are presented.**

***Keywords; local flow; distributed hydrological models; PFS method; drainage network*.**

I. INTRODUCTION

The local flow distribution in a water basin is the most important factor in order to model distributed hydrological systems that aim at hydrological resources management. The underlying premise is that terrain topography is the main landscape contributor in defining these local flows [1][2]. Mathematical representations of terrain topography and sets of functions to extract superficial local water flow have been explored by GIS users for a long time. The basis for terrain topography representation in GIS is to partition the region extents. A *Cell* is the unit of this partition set and the *local flow* is the *water flow* for each *cell* considering the status of its neighbor *cells* according to a specific chosen neighborhood rule.

The most common data structures found in GIS libraries and systems for terrain representation dedicated to hydrological modeling are the DEM (Digital Elevation Model - DEM) [3] with regular grids, Irregular Triangular Networks – TIN [4], Contour Lines based representation [5], and Irregular Polygons Tessellations [6]. Each chosen surface representation carries its own local water flow extraction functions and its own local flow data structure. The local flow representation is dependent of the data structure used to represent the terrain topography. For instance, DEM local flow extraction uses the 8-neighbor concept and creates a local flow representation, called *Local Drain Direction* (LDD) [3]. It is stored in the same structure DEM, forming a regular grid of local flow directions.

This situation takes hydrological modeling to a condition where there is a strong coupling between the quality of the local flow representation and the parameters for the used terrain data structure, in particular its spatial resolution with direct implications on the model outcomes [7]. Distributed hydrological modeling environments normally assume a unique data structure for terrain representation. This may simplify software development but it can’t make use of the properties of the other terrain data structures. The concept proposed by the TerraHidro [8][9][10][11], a distributed hydrological system, assists the simplification of software development and at the same time allows the use of different terrain data structures. In this way, the decoupling of terrain data structure and local flow data structure eliminates the need to code a given operator for each one of the used terrain structures [8].

Currently, TerraHidro works only with DEM structure to extract and develop applications and it is a plugin of the geographic visualizer TerraView that loads and stores data in a geographical library called TerraLib [2], an open source geographical library implemented in C++ language that has been developing at the Image Processing Division of National Institute for Space Research, in São José dos Campos a Brazil city situated in the São Paulo region. This approach has allowed TerraHidro project team of designers and programmers keep focused on the development of system functionality of TerraHidro. TerraView main goal is to make available to the GIS Community an easy geographic data viewer with resources that include database queries and data analysis, exemplifying the use of the TerraLib library.

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TerraLib is an open-source GIS software library. TerraLib supports coding of geographical applications using spatial databases, and stores data in different DBMS including MySQL, PostgreSQL and other databases. Figure 1 shows relationship among Terrahidro, TerraView and TerraLib.

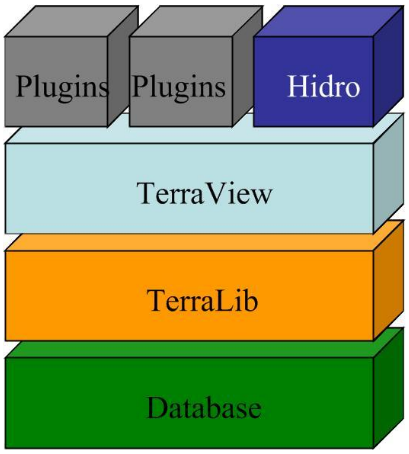

Figure 1 TerraHidro, TerraView and TerraLib relationship

The focus of TerraHidro development has been to obtain the best quality for each generated result. Optimizations, such as reducing processing time, are considered whenever they are not detrimental to the results quality.

This paper is structured as follows: Section two describes the steps required to obtain the drainage network, Section three presents the method used by TerraHidro to define the local flows, Section four shows the results obtained, and Section five has the conclusions.

II. DRAINAGE EXTRACTION AND BASIN DELIMITATION

Drainage has been used for several applications involving water resources. To extract the drainage, first of all, the local flow and the accumulation area must be determined. Local flow is a flow between two neighbor cells considering the steepest downstream path among a cell and each of its eight neighbor cells. Figure 2 shows this concept.

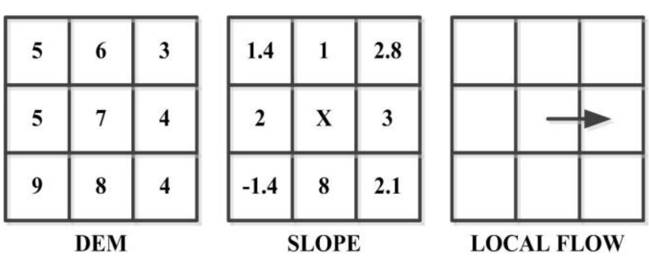

Figure 2 Local flow extraction to X cell

After this step, the accumulation areas are calculated from the local flows. Each Y cell receives a value that is the size of the area of all cells that are on the path arriving at Y cell. The next step requires the definition of the accumulation area subset called drainage network. The user defines a threshold value and all grid cells with values equal or greater than this threshold value are defined as drainage cells. At this point, TerraHidro can define the river reaches that delineate the drainage segments. The segments are between the water sources and junctions, between junctions, and between junctions and drainage mouth. Basin delimitation, the next processing step, can be executed by selecting one or more points on the drainage. TerraHidro finds the basin for each given point or for each river reach. In the end, the basins can be used as grid cell, as vector forms. Figures 3, and 4 present this concept. Figure 3 has drainage network segments. Each segment is represented by a different color. Figure 4 shows the watershed for each segment.

III. PFS AND OTHER DRAINAGE EXTRACTION METHODS

The extracted drainage is the basic information to develop hydrological applications. For this reason, the method used to extract the drainage must minimize the effects of errors from DEM generation, such as the ones present in the Shuttle Radar Topographic Mission (SRTM) data set with 90 meters of horizontal resolution is used in this work. Although the SRTM data is used worldwide, it contains a large number of spurious pits among other problems. Spurious pits are false end points of flow. The drainage extraction should ensure that the drainage is connected in the adopted resolution with small changes in the original SRTM values, generating the most real drainage possible.

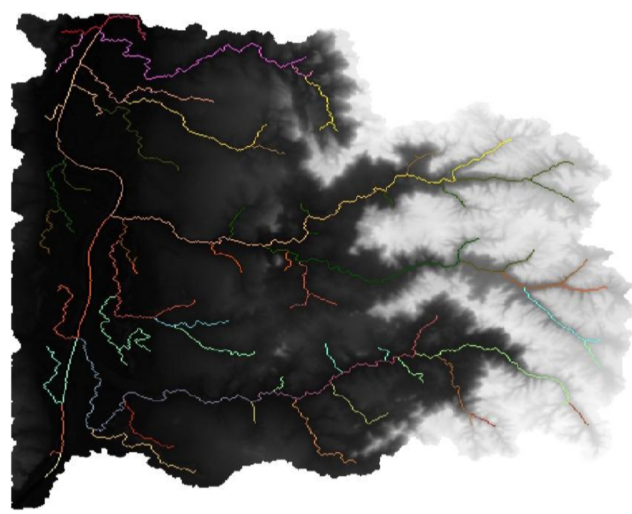

Figure 3 River segments.

Given that the core of water resource applications are drainage networks, the drainage extraction method used by TerraHidro will be described in the next section.

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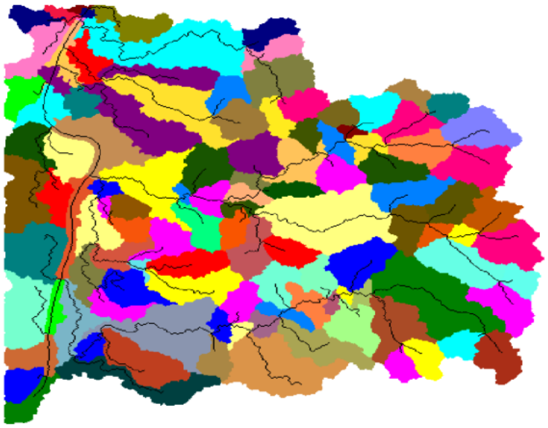

Figure 4 Watersheds delimitation. Each watershed corresponds one river segment.

TerraHidro uses two approaches to solve the spurious pits problem. In the first one, the mean is calculated for each pit using the neighborhood 8 of the pit. If the pit remains, or generates a new pit in one of the neighbors, their value is not replaced by the mean, and then it uses the PFS method to solve the problem [12]. The basic idea of this method is to link a pit with a nearby grid cell with lower elevation creating a optimum path between both cells. Next step is to define a new elevation value for each grid cell in this path creating a monotonic down slope from pit cell to lower elevation cell. By applying the method for every pit, PFS creates a fully connected drainage network generating elevation value changes only in the path. Figure 4 shows the diagram of TerraHidro method to eliminate pits. PFS has presented better results when compared with others methods according studies made in [13]. Figure 5 shows the diagram of TerraHidro method to eliminate pits.

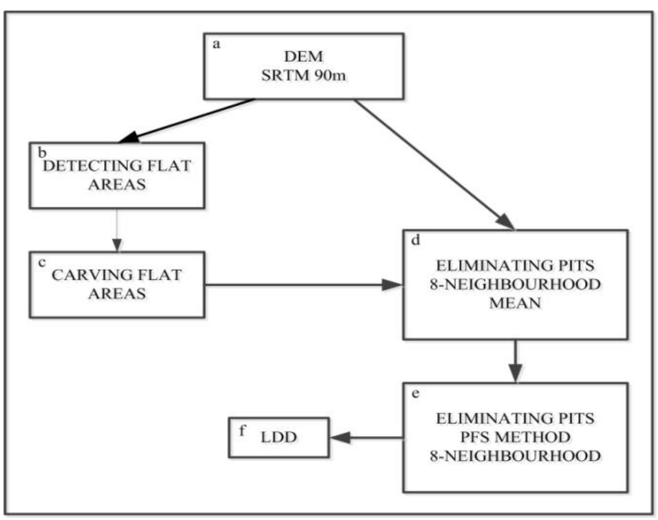

Figure 5 Pit removal schema.

The pit removal schema follows the sequence presented below:

(a) In the first step, the SRTM data set is inserted into the TerraHidro system. Next, the user chooses between two paths: either create drainage in the flat regions and then proceed to the pit elimination or proceed directly to eliminate the pits.

(b) SRTM creates spurious flat areas on large water bodies. TerraHidro recognizes and delimits these areas to be used in the carving processes. This step is necessary because PFS method don't produce good results in the flat areas [14].

(c) The carving process creates a down path slope from the border of the flat area until reaching the center of this area. This is executed for every point on the border of the flat area. The drainage flows at the center of the flat area. Figure 6 shows the schematic representation of the carving process and Figure 7 presents two real geographical areas in the Brazilian Amazon region. The water body areas were highlighted with yellow ellipses to exemplify this type of case.

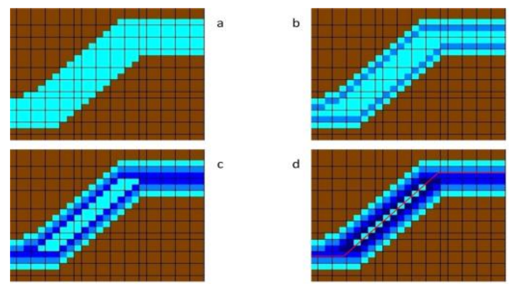

Figure 6 (a) Plane area delimited; (b), (c) intermediate carving processes; (d) water body carved with water flow path (red line).

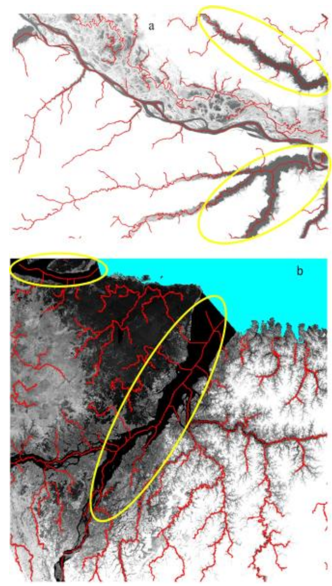

Figure 7 Drainage networks of plane areas (yellow ellipses) (a) Purus basin and (b), (c) Tapajós basin.

(d) For each grid ***C*** cell of altimetry that contains a pit, TerraHidro calculates the mean values of its eight

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neighboring cells. If this procedure does not create a new pit in this neighborhood, the value computed is assigned to ***C*** cell, thus eliminating the pit. Otherwise, the pit of the ***C*** cell remains. Figure 8 presents an example of this pit removal procedure.

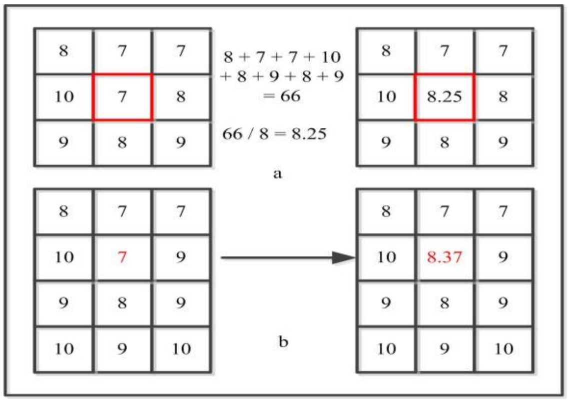

Figure 8 Pit removal by 8-neighbourhood media average calculus. (a) Without generating new pit; (b) generating new pit..

(e) Pits that are not removed by the mean calculation procedure are eliminated using Priority First Search - PFS method. This method finds a path between a pit and a nearby grid cell with lower elevation. For each neighboring cell of the one containing the initial pit, the differences between elevation values are calculated and stored in a queue. The path to the smallest value is selected. When there are equal differences for more than one neighbor, the cell that is closest to the one that contains the pit will be selected. The process is repeated from the selected cell. The minimum distance is always calculated in relation to the position of the cell containing the initial pit when points differences are tied. At this point, the new elevation value for each cell belonging to the path between the two pits is calculated accordingly to its distance from these pits. Figure 9 shows this procedure.

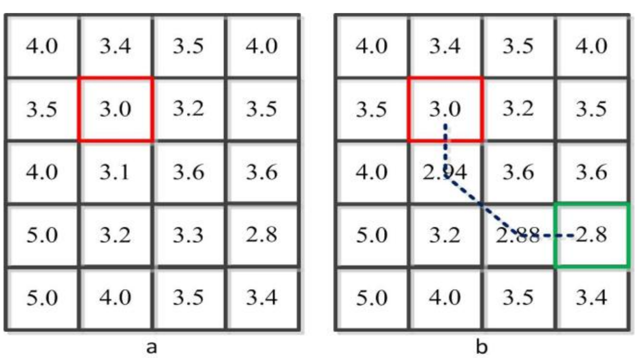

Figure 9 Carving processes to eliminate pits. (a) Initial pit identification (red color); (b) path found by PFS method (final pit in green color).

The modified PFS method eliminates all the pits in the existing elevation grid ensuring flow inside the entire study region.

IV. RESULTS

TerraHidro has been used in large geographical areas. The focus has been to test TerraHidro in actual extensive watershed areas using computers with typical RAM memory capacity, for example, 3 GB. TerraHidro has extracted drainage networks successfully for the test areas eliminating all pits. This qualifies TerraHidro as a robust system, giving also very good results in terms of drainage network extraction and watershed delimitation. Amazonian and sub Amazonian basins and South America region have been used by TerraHidro to extract drainage networks, using the SRTM data set with 90 meters spatial resolution.

Figure 10 shows the drainage network for the Taquaruçu River basin region. The DEM of this region has 2.024 rows, 1.875 columns (3.734.280 image size) and 396.769 pits.

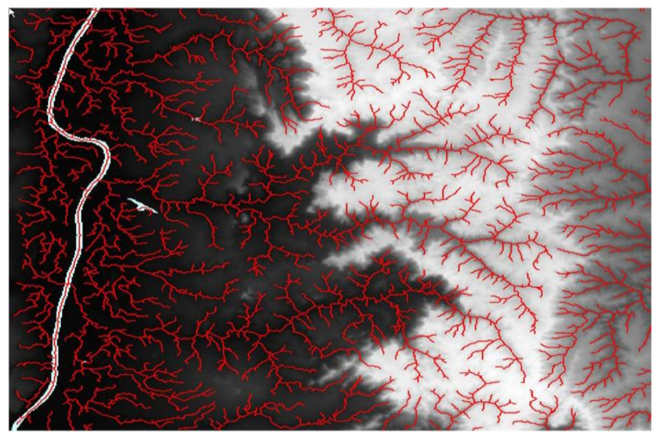

Figure 10 Drainage network of Taquaruçu basin (red color)green).

Figure 11 Presents results of the drainage extraction of Xingu River region, another Amazon sub basin. The information of this DEM is: 15.962 rows, 7.202 columns (144.958.324 image size)) and 6.472.113 pits. The image on the right side is the zoomed area in of the yellow rectangle in the image on the left side.

The next watershed is the Tapajós River Amazon sub basin, which can be seen in Figure 12. This region has 19.201 rows, 9.601 columns (184.348.801 image size) and 8.647.984 pits. In the image on the right side, it is possible to see the carving in the plane area into the river (up to down in the middle of image).

Figure 13 presents Purus River, that is another Amazonian sub basin. Also here it is possible to see the drainage flowing by the middle of the large rivers correcting these plane areas. The data of the Purus River basin are: 12.000 rows, 15.600 columns (187.2000.000 cells) and 13.279.394 pits.

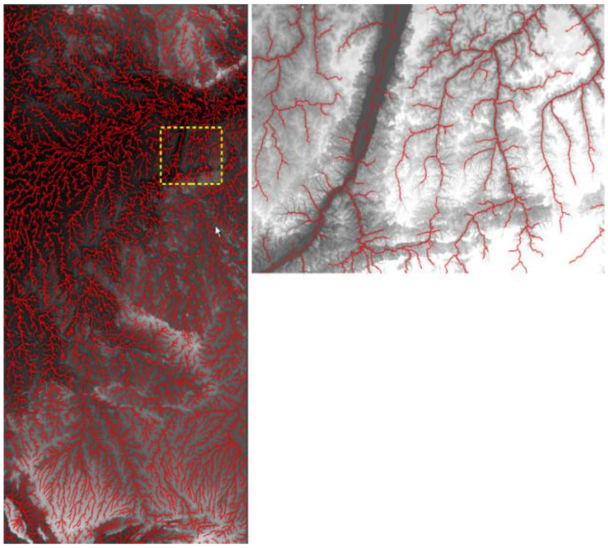

Figure 11 Drainage network of Xingu basin.

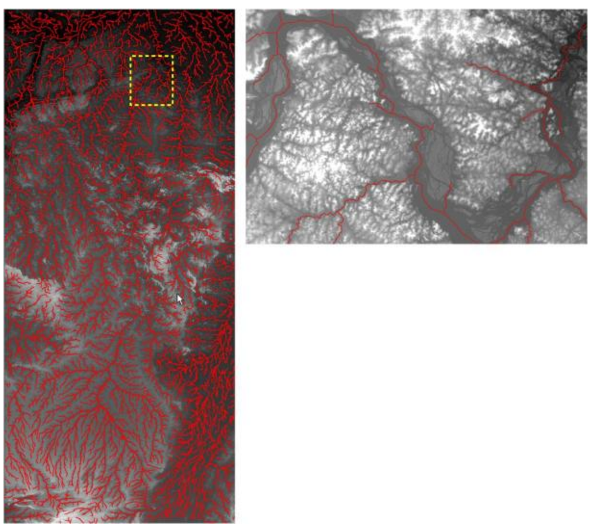

Figure 12 Drainage network of Tapajós basin.

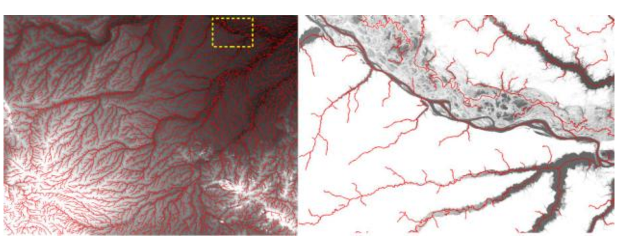

Figure 13 Drainage network of Purus basin.

The last Amazon sub basin processed by TerraHidro was the Tocantins River basin. Figure 14 shows the drainage extracted by TerraHidro from a region with 21.602 rows, 14.402 columns (311.112.004 image size)) and 15.893.139 pits.

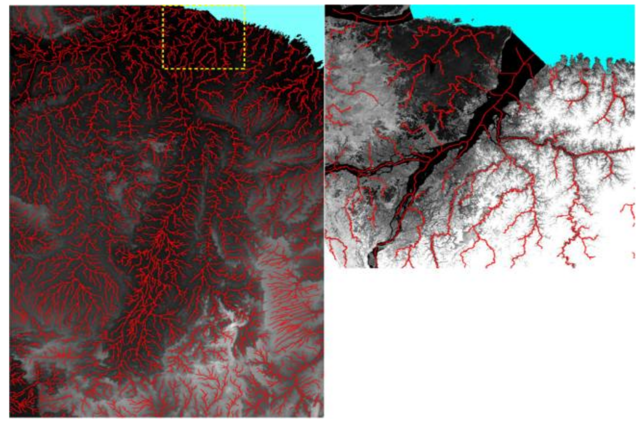

Figure 14 Drainage network of Tocantins basin.

The whole Amazon basin was also processed. Figure 15 shows in red color the delimitation of this basin. In green color, it is possible to see part of the Amazon basin river network. The data of the Purus River basin are: 32,400 rows, 38,400 columns (1,244,160,000) and 65,670,466 pits.

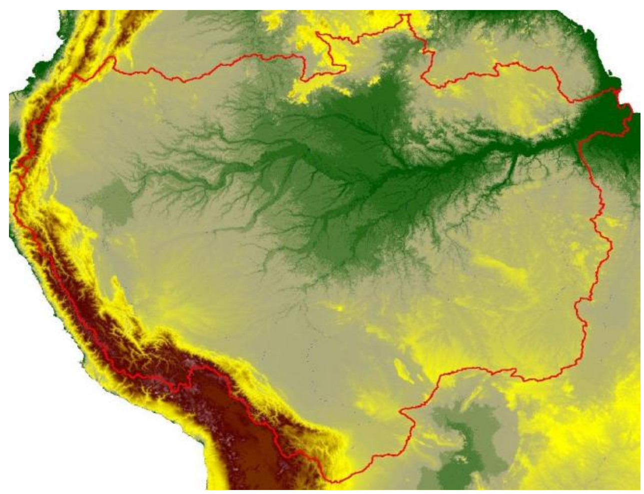

Figure 15 Drainage network of Amazonian basin.

The whole South America region was also processed. Figure 16 presents the drainage networks with the most important South American rivers. The information of the DEM are: 60.001 rows, 84,001 columns (5,040,144,001 image size) and 161.135.443 pits.

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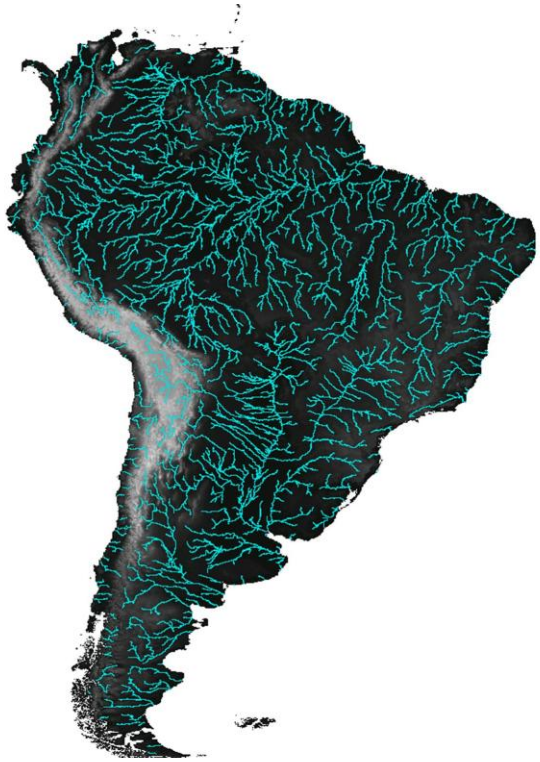

Figure 16 Drainage network of South America region.

Drainage networks have also been extracted for the African countries of Somalia, Kenya and South Sudan. Figures 17, 18 and 19 show the drainage (blue color) and the corresponding watersheds for each drainage segment.

Figure 17 Drainage network and watersheds for each drainage segment for Somalia country.

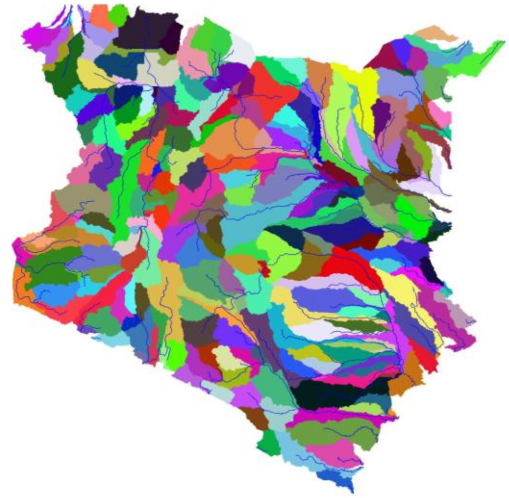

Figure 18 Drainage network and watersheds for each drainage segment for Kenya country.

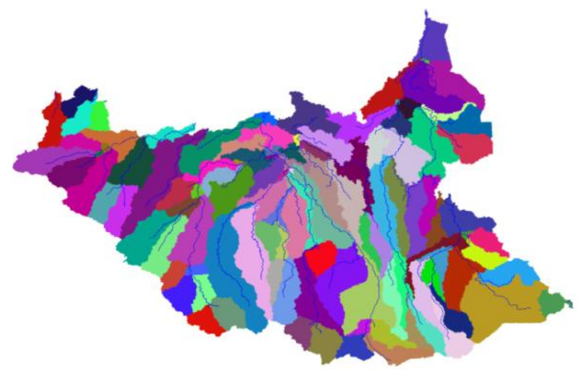

Figure 19 Drainage network and watersheds for each drainage segment for South Sudan country.

Finally, a comparison between ArcGIS Hydro Tools and TerraHidro regarding drainage network quality is presented in the Figure 20. In the top figure, the ArcGIS Hydro Tools results appear in blue lines and the TerraHidro ones are in red lines. The results obtained by ArcGIS in the flat areas indicates that the method D8 is used directly in these areas without prior corrections. The parallel lines generated by ArcGIS indicate incorrect representation of the drainage within the flat areas. TerraHidro, for the same areas, identify automatically each flat areas creating a path through the middle of the flat area, following its longitudinal direction. All path into flat area arrives at this longitudinal path in a physical way.

This comparison aims to show that TerraHidro have a method to determine the path in the flat areas generating coherent drainage networks. Parallel lines that appear in ArcGIS Hydro Tools drainage networks are caused by the method used in ArcGIS that converts pits in flat areas and, after that, uses D8 method in these flat areas. The method used by TerraHidro system does not produce these errors because a path between from a pit is found without the need to create flat areas.

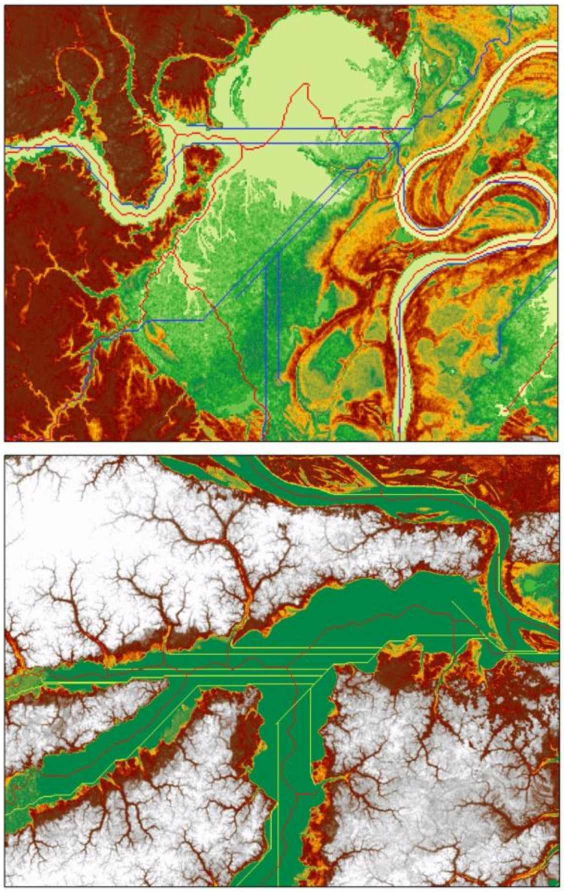

Figure 20 Comparison of quality of drainage network extraction between TerraHidro and ArcGIS Hydro Tools.

V. CONCLUSION

The concept of the TerraHidro distributed hydrology modeling system and its current development stage were described here. The PFS method to extract drainage network was shown together with improvements to define drainage into the flat areas such as large rivers and lakes. In addition, the 8-neighbor mean to eliminate pits without creating others in its neighborhood was presented.

Several results were presented here. All of them used large regions to show the quality of the extracted drainage and to test the robustness of TerraHidro. Drainage extractions were executed using a PC computer with 2 GB of RAM memory.

A comparison of the drainage extracted by TerraHidro and ArcGIS Hydro Tools was made for Purus Amazon sub basin. The comparison showed that TerraHidro produces more realistic drainage than ArcGIS Hydro Tools do.

All processing used SRTM 90 meters data set. Other data sets such as ASTER-GDEM will be used in the future.

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REFERENCES

[1] C. D. Rennó, “Construção de um Sistema de Análise e Simulação Hidrológica: Aplicação a Bacias Hidrográficas (in portughese),” Ph.D. thesis, National Institute for Space Research, São José dos Campos, 2003.

[2] J. F. O’Callaghan and D. M. Mark, “The Extraction of Drainage Networks from Digital Elevation Data,” Computer Vision, Graphics, and Image Processing, 28:323–344, 1984.

[3] P. A. Burrough and R. A. “McDonnell, Principles of Geographical Information Systems.” Oxford University Press, New York, 1998.

[4] L. P. Chew, “Constrained Delaunay triangulations,” Algorithmica 4(1):98-108, 1989.

[5] W. R. Dawes and D. L, Short, “TOPOG Series Topographic Analysis and Catchment Drainage Modelling Package: User Manual,” Canberra, CSICO, 1988.

[6] J. Fairfield and P. Leymarie, “Drainage Networks from Grid Digital Elevation Models” Water Resource Research, 30(6):1681–1692, 1962.

[7] J. Garbrecht, F. L. Ogden, P. A. DeBarry and D. R. Maidment, “GIS and Distributed Watershed Models. I:Data Coverages and Sources,” Journal of Hydrologic Engineering, 6(6):506-514, 2001.

[8] S. Rosim, “Estrutura baseada em grafos para representação unificada de fluxos locais para modelagem hidrológica distribuída. 2008. 110 p. (INPE-15320-TDI/1363). (PhD thesis in applied computation) - Instituto Nacional de Pesquisas Espaciais, São José dos Campos, 2008.

[9] S. Rosim, A. M. V. Monteiro, C. D. Rennó, J. R. F Oliveira, “Terrahydro - A distributed hydrological system using graph structure for unified water flow representation,” Proc. of IEEE Geoscience and Remote Sensing Symposium (IGARSS), Vancouver, 2011.

[10] E. S. Abreu, S. Rosim, C. D. Rennó, J. R. F. Oliveira, A. C. Jardim, J. O. Ortiz, L. V. Dutra, “Terrahidro a distributed hydrological system to delimit large basins,” Proc. of IEEE Geoscience and Remote Sensing Symposium (IGARSS), Munich**,** 2012. v. 1, pp. 300-301.

[11] S. Rosim, A. M. V. Monteiro, C. D. Rennó, J. R. F. Oliveira, “Uma ferramenta open source que unifica representações de fluxo local para apoio à gestão de recursos hídricos no Brasil,” Informática Pública, v. n. 1, p. 29-49, 2008.

[12] A R. Jones, “Algorithms for using a DEM for mapping catchment areas of stream sediment samples”, Computers & Geosciences 28 (2002) 1051–1060.

[13] B W. Collischonn, D. C. Buarque, A. R. da Paz, C. A. Bulhões Mendes, and F. M. Fan, “Impact of Pit Removal Methods on DEM Derived Drainage Lines in Flat Regions”, AWRA 2010 Spring Speciality Conference Orlando, FL.

[14] R. Jana, T. V. Reshmidevi, P. S. Arun, T. I. Eldho, “An enhanced technique in construction of the discrete drainage network from low resolution spatial database,” Cumputers & Geosciences archive, v. 33, I. 6, June 2007, Pergamon Press, Inc. Tarrytown, NY, pp. 717-727, 2007.