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GIS Automation for Spatialization of Water Availability
Automatização SIG para Espacialização da Disponibilidade Hídrica

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Abstract

The application of regionalization methods is one of the most important procedures for the estimation of the streamflow discharge in ungauged rivers catchments and its automation can reduce both processing time and susceptibility to errors. The Environmental Systems Research Institute (ESRI), in cooperation with the Center for Research in Water Resources at University of Texas (CRWR), has developed the *ArcHydro* toolset, a geospatial data model designed for hydrological models and used to accumulate attributes in the hydrographical net, among other functionalities. The present paper addresses the automation of the low flow index Q_{95} accumulation in the Doce River Basin by *ArcHydro* and the application of the regionalization method based on the proportionality of the ratio discharge per unit of drainage area. The effects of the reservoirs operation on water availability were computed automatically in this process and reliable results time savings were achieves.
Keywords: *ArcHydro*; flow accumulation; regionalization

Resumo

A aplicação de métodos de regionalização é uma das principais ferramentas para se conhecer a vazão em determinado local sem dados e a automatização desse procedimento pode implicar redução de tempo e menor suscetibilidade a erros. A ESRI, em cooperação com a CRWR, desenvolveu o módulo *ArcHydro* que é um modelo geoespacial projetado para modelos hidrológicos que permite, dentre outras funcionalidades, acumular atributos ao longo da hidrografia. O presente trabalho demonstrou a automatização da acumulação da disponibilidade hídrica na bacia do rio Doce por meio do módulo *ArcHydro* utilizando o método de regionalização baseado na proporcionalidade da vazão específica. Os efeitos da regularização dos reservatórios presentes na bacia foram computados nesse cálculo de forma automatizada. O processamento se mostrou eficiente, oferecendo resultados confiáveis com economia de tempo.
Palavras-chave: *ArcHydro*; acumulação de vazão; regionalização

1 Introduction

One of the objectives of water resource management in Brazil is to ensure the necessary water availability in adequate quality standards for the current and future generations. Therefore, the quantitative and qualitative control of water use is mandatory and can be achieved through the implementation of management strategies of the water resources legal framework (Law 9,433 of 1997), such as water rights, use of water charge and water body classification. The main expedient for achieving this control is the knowledge of the reference flow defined by the regulatory body.

Given the scarcity of hydrological information, the hydrologic regionalization technique has been used for the transfer of data from spatially gauged stations to locations that require the management of water resources and lack the necessary information (ungauged basins). Several methods for this purpose, such as those described by Eletrobras (1985a), Eletrobras (1985b), Chaves *et al*. (2002) and Novaes *et al*. (2009) are available.

One of the widespread and consecrated regionalization methods is based on the proportionality of the ratio between the discharge and drainage area (specific yield), which was applied, for example, to several basins of Report Conjecture of Water Resources of Brazil (ANA, 2009), one of the main important Brazilian documents about water resources. Its methodological explanation can be found in Moreira (2010).

The water availability for each stretch of hydrography through this method can be obtained through the assignment of a specific yield to each streamflow segment, calculation of the incremental flow in that section, flow accumulation in the network and consideration of the reservoirs effects on the flow, if any.

The flow accumulation stage can be considered complex if computed manually, especially for medium to large extent basins. In general, manual processes are more susceptible to errors and demand more time. Therefore, when subjected to automation through GIS tools (Geographic Information System), this step becomes quite efficient and reduces the processing time and likelihood of errors.

Based on his geodatabase format, the Environmental Systems Research Institute (ESRI), in cooperation with the Center for Research in Water Resources at University of Texas (CRWR), has developed the *ArcHydro* module, which is a geospatial data model designed for hydrological models that summarizes geospatial and temporal data related to water resources for hydrological analyses. One of its functionalities is the accumulation of attributes along the hydrography. Besides, it computes the effects of the reservoirs on the calculation of water availability over the flow accumulation.

Several studies have been developed with *ArcHydro* tool, and it has been used for delimitation of watersheds (Lopes *et al.*, 2011; Adami *et al.*, 2011; Zhang *et al*., 2010; Ramme & Krüger, 2007).

This study addresses the automation of the water availability estimation along the hydrographic through *ArcHydro* module, based on the proportional method of specific yield considering the effects of the operation of the reservoir. This process was applied for the Doce River Basin.

2 Doce River Basin

The area of the Doce River Basin comprehends approximately 83,400 km^2, of which 86% belong to Minas Gerais state and 14% to Espírito Santo state. It covers all or part of areas of 228 municipalities, 202 in Minas Gerais and 26 in Espírito Santo (Ribeiro *et al*., 2005).

It is situated in the Southeast of Brazil, between parallels 18° 45' and 21° 15' southern latitude and meridians 39° 55' and 43° 45' western longitude (Figure 1).

The Doce River, with a length of 853 km, is formed from Piranga and Carmo Rivers, whose sources are located on the slopes of mountains of Mantiqueira and Espinhaço, where the altitudes reach 1,200 m.

Its main tributaries are rivers Piracicaba, Santo Antonio, Suaçuí Grande, Pancas and São José, on the left bank, and rivers Hull, Matipó, Caratinga-Cuieté, Manhuaçu and Guandu, on the right bank (Ribeiro et al., 2005).

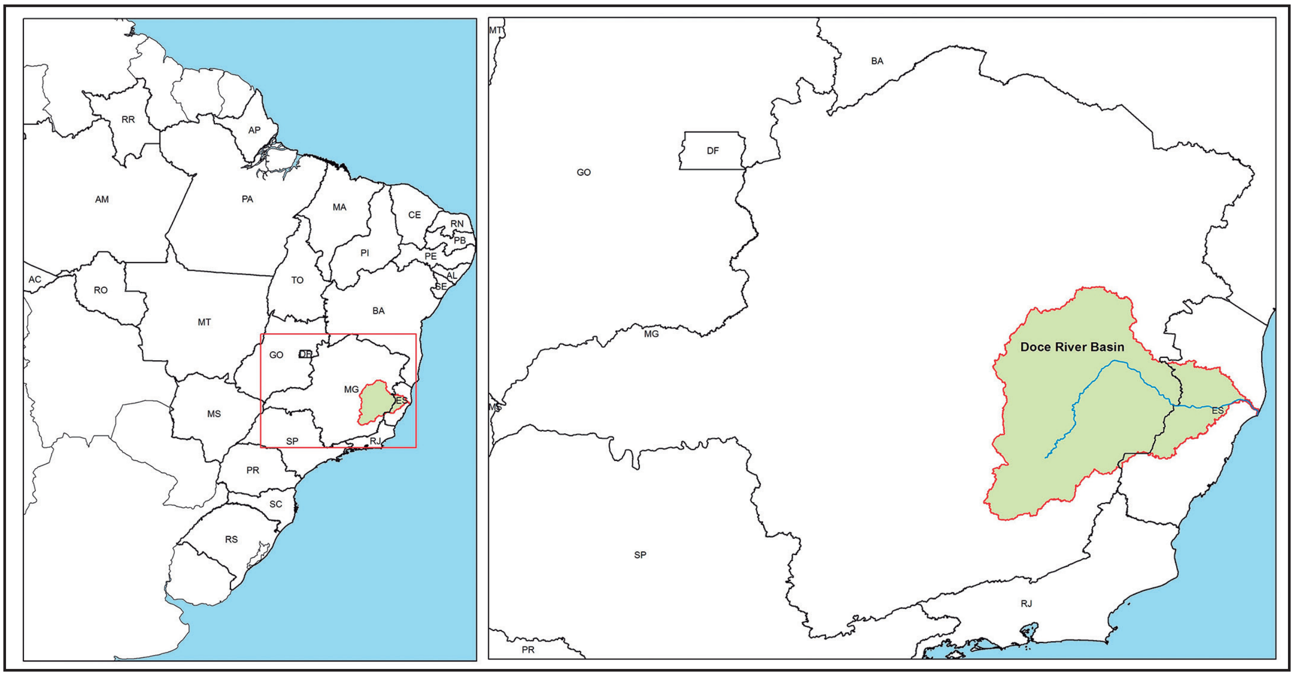

Figure 1Location of the Doce River Basin.

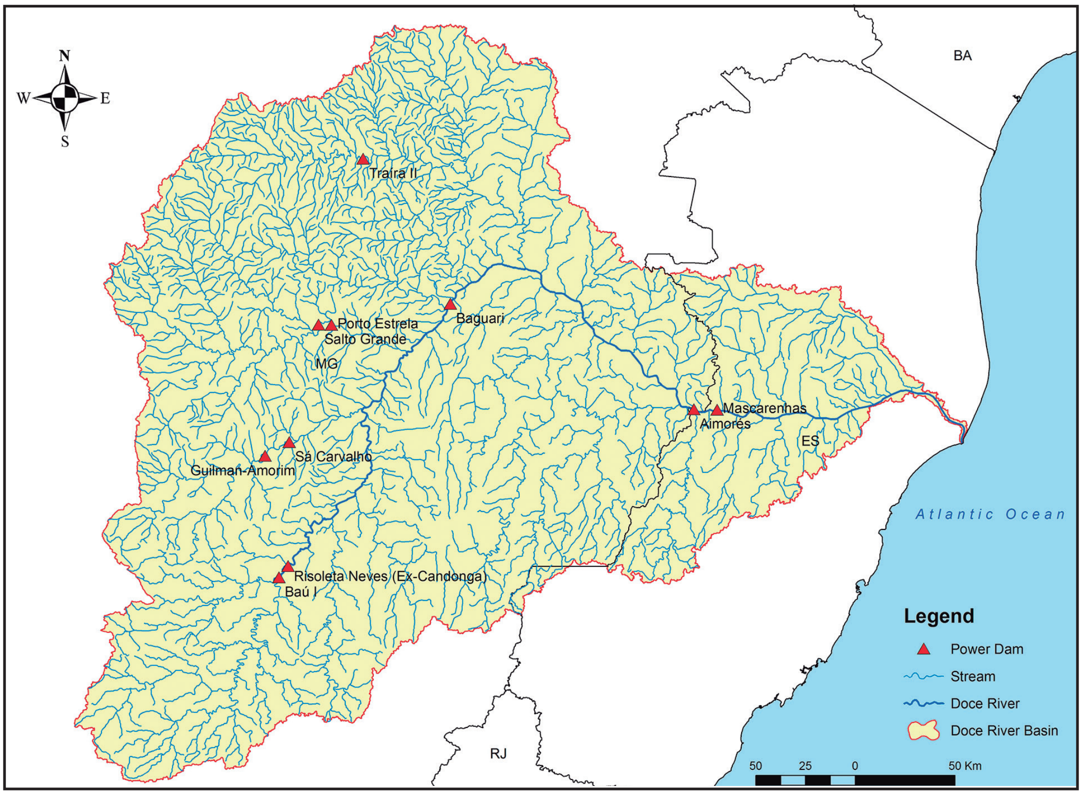

Figure 2 Location of the hydroelectric plants in the Doce River Basin.

3 Reservoirs Effects

None of the reservoirs installed in the Doce River Basin have shown potential to be operated (IGAM, 2009). Figure 2 shows the distribution of the reservoirs.

For the insertion of the reservoir effects in the estimation of the water availability in the Doce River Basin, the Risoleta Neves, Aimorés, Mascarenhas and Sá Carvalho reservoirs were considered.

The effect of the reservoirs changes the water availability in downstream stretches of hydroelectric plants and those with backwater effect. In such hydrographic segments, the streamflow was considered the Q_{95} natural daily or an operative minimum flow in the reservoir defined by the National Electric System Operator (ONS, 2011).

Table 1 shows a summary of the reservoir effects and Table 2 lists the segments with backwater effect.

4 Database

To apply of the proportional regionalization method of the specific yield, the specific rates provided in the Water Resources Plan for the Doce River Basin (IGAM, 2009) were used and shown in Table 3.

The study was conducted in Otto Codification river database, in shape format, produced by ANA, available on the website www.ana.gov.br. The scale of the database is 1:1.000.000.

Reservoirs	Water Availability *
Risoleta Neves	Daily natural flow Q_{95} (60.96 m³/s) on reservoir segments. On downstream add the incremental flow.
Sá Carvalho	Between the dam and the powerhouse, the water availability is equal to the restriction of minimum flow (20 m³/s), plus the incremental flow of the segment. After the powerhouse, the water availability is equal to the daily natural flow Q_{95} (30.8 m³/s) plus the incremental flow.
Aimorés	Between the dam and the powerhouse, the availability is equal to the restriction of minimum flow (16 m³/s), plus the incremental flow of the segment. After the powerhouse, the water availability is equal to the daily natural flow Q_{95} (279.2 m³/s) plus the incremental flow.
Mascarenhas	Daily natural flow Q_{95} (315.38 m³/s) on reservoir segments. On downstream add to the incremental portions.

Table 1 Reservoirs effects considered in this study. * The daily natural flow Q95 values were obtained in the Technical Note of the National Water Agency (ANA) Nº 27/2012 /GEREG/SRE-ANA.

Reservoirs	Segment with backwater effect *	Streamflow (m³/s)
Risoleta Neves	127036	60.96
Sá Carvalho	126628	30.80
Aimorés	126541 126484 126464 126436	279.20
Mascarenhas	126591 126593 126585 126582 126561	315.38

Table 2 Segments with backwater effect as influence of hydroelectric plants. * The code corresponds to the attribute "Cotrecho" in the Otto Codification river database used in Brazil, produced by the National Water Agency (ANA) and available in www.ana.gov.br

Sub-basin	Q_{95} (L/s/km²)
PirangaRiver	6.61
Do Carmo River	11.20
Casca River	5.01
Matipó River	4.57
Incremental D01	6.44
Piracicaba River	6.84
Incremental D02	5.96
Santo Antônio River	5.26
Incremental D03	5.96
Corrente Grande River	5.07
Suaçui Pequeno River	4.10
Suaçui Grande River	2.34
Incremental D04	5.09
Caratinga River	2.62
Incremental D05	5.66
Maqnhuaçu River	3.68
Incremental D06	4.22
Guandu River	3.38
Incremental Guandu	3.76
Santa Joana River	1.58
Incremental Santa Maria do Doce	3.76
Pancas River	1.56
São José River	2.47
Barra Seca River	3.76
River Doce Basin	3.76

Table 3 Specific yields used in the application of proportionality regionalization method obtained in the Integrated Water Resources Plan Basin of the Doce River

5 Application of *ArcHydro* Module for the Obtaining of the Water Availability Accumulated Along the Hydrographic Segments

The water availability for each river stretch through the regionalization method of proportionality of the specific yields obtained through the assignment of a specific flow for each segment, calculation of the incremental flow in that section, flow accumulation in the network and addition of reservoirs effects to the flow, if any.

The *ArcHydro* module is applied in the flow accumulation and addition steps for automating the computation of water availability.

The hydrography, when in an area where the terrain has a dendritic drainage pattern, has a flow behavior which water drains from upstream to downstream by gravity action and is characterized by a single flow direction focus to river mouth, except in coastal zones.

From the point of view of geometric representation, the basin can be considered a set of vectors arranged in a hierarchical way representing a simplified network (by *graphos*).

Each network segment (edge), or hydrography segment, is between two nodes in the river database used by ANA for the management of water resources. The nodes are representations of confluences, headwaters and mouth of the basin. Each of these sections is identified by its particular segment of river code according to the codification by Otto Pfafstetter (cotrecho). Vector files representing hydrographic features have no structure and can be classified as a type of *Spaguetti Structure* (Peuquet, 1984 *apud* Aronoff, 1989). Figure 3 shows a generic example of a hydrographic base model.

The *ArcHydro* data model is based on a different sequence encoding key to relate the various hydrographic layers, as well as the vectors resulting from the data processing module (by *ArcHydro* tools). Maidment (2002) detailed the characteristics of *ArcHydro* data model (Figure 4).

A first intervention in the database is the compatibilization with the *ArcHydro* data model. The hierarchical structuring of the base map can be generated by the *Network Analyst* extension.

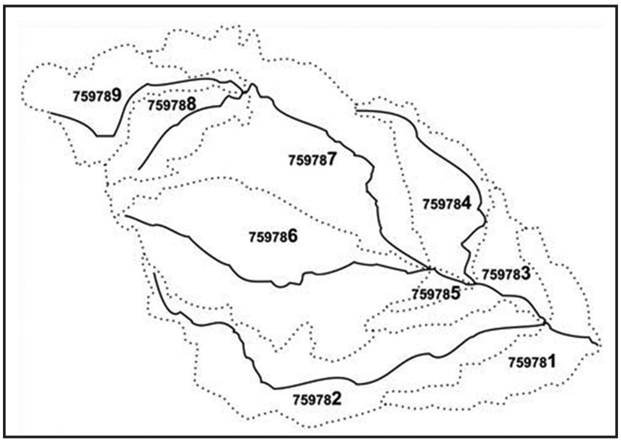

Figure 3 Generic example of a river segments model with Otto Pfafstetter codes (ANA, 2006).

Once the representative vectors of river features have been incorporated into a geodatabase within a feature dataset, a *geometric network* type structure from which can be constructed and the direction of flow through the drainage system can be determined (Figure 5).

Sequential codes of *ArcHydro* data model (*HydroID*) are incorporated in the database from a code management tool. Then the feature classes can relate through these identifiers.

For each river segment in the network, an algorithm in this tool identifies the river segment immediately downstream (*NextDownID*) and stores its key (Figure 6). This process computes the accumulation of a certain variable over the network from the headwaters (sources) to the mouth (sink) (Figure 7).

Over the drainage system there are situations in which the flow is partially obstructed, such as the presence of reservoirs, on these sites the flow is controlled. These controls must be models in the network.

The influence of the upstream flow on the accumulation is disregarded and the remaining streams are incorporated into the accumulation in the downstream segments. Such changes are incorporated individually and manually for each control (reservoir), directly in the attribute table of the feature class that represents the network segments.

Once such modifications have been modeled, the accumulation process develops automatically with all the effects of flow control.

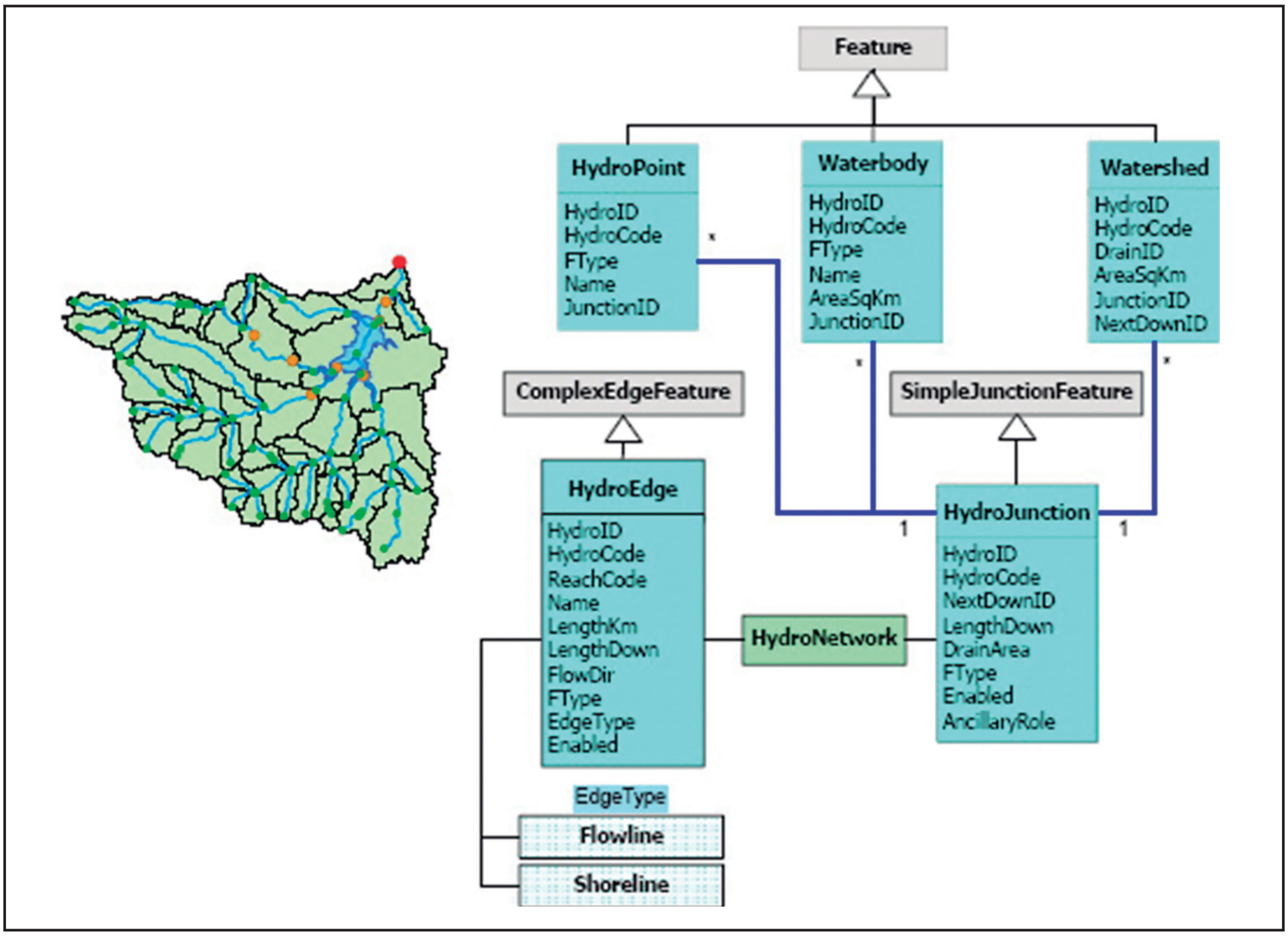

Figure 4 Example of an ArcHydro data model (Maidment, 2002).

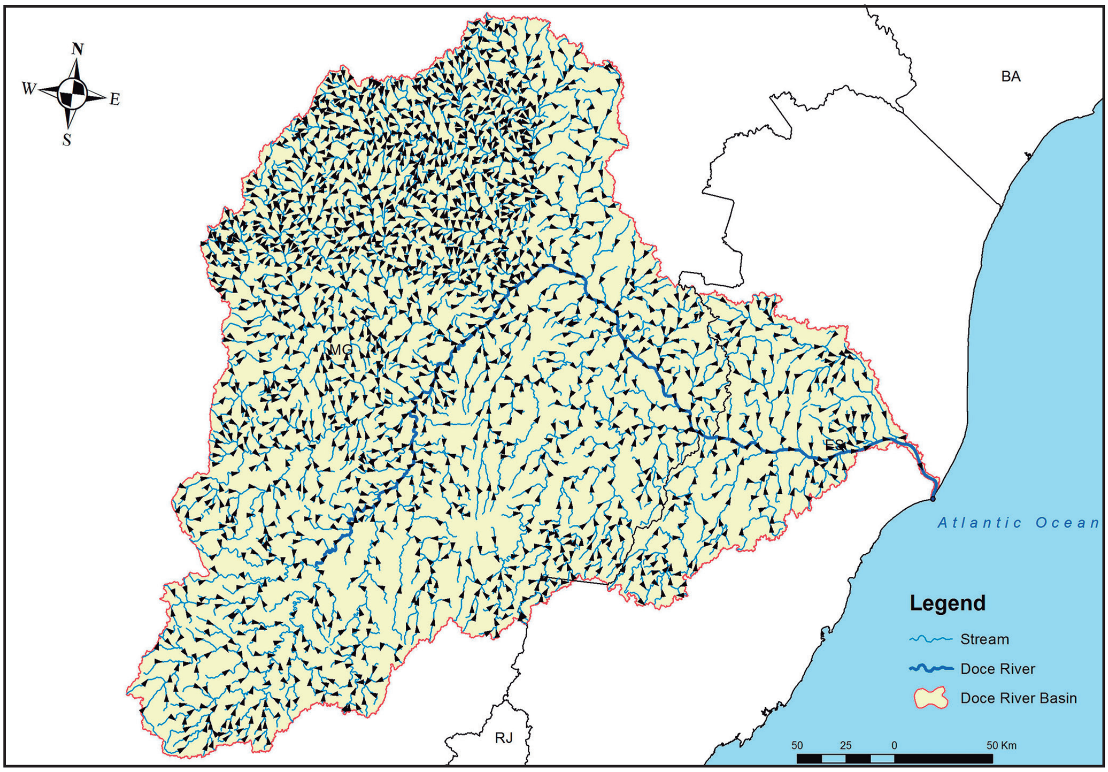

Figure 5 Hierarchical river network with the defined flow directions.

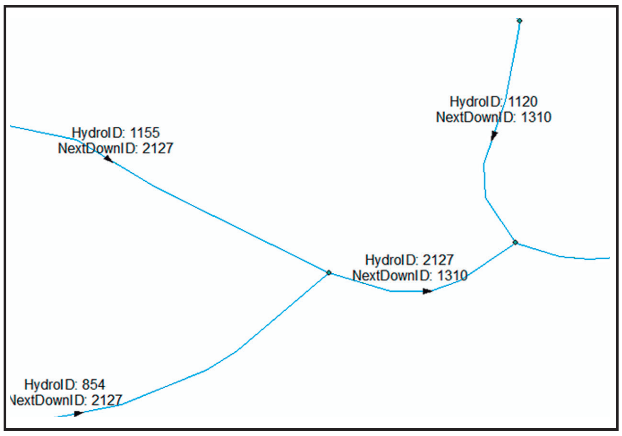

Figure 6 Example of an ArcHydro sequence encoding.

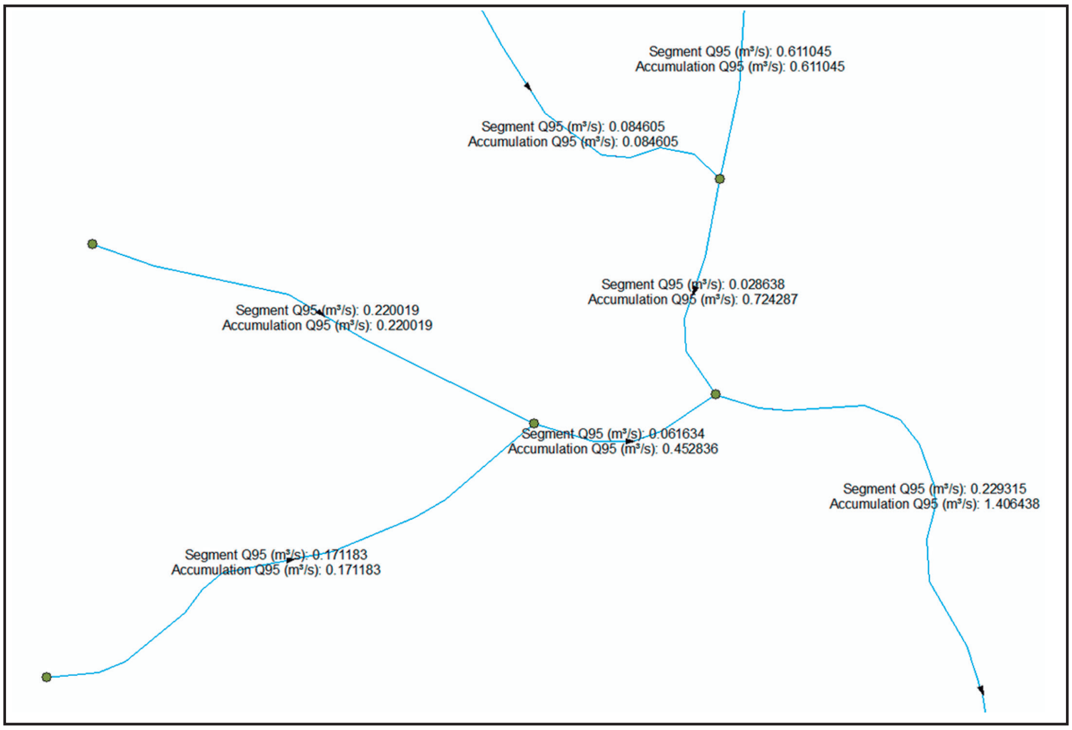

Figure 7 Example of downstream accumulation.

Figure 8 shows the difference between an accumulation without flow control (without an operated reservoir) and another with flow control (with an operated reservoir). In the flow control situation (Figure 8b), two reservoirs were considered (Aimorés and Mascarenhas). In this case the segment where they are located received the key *NextDownId* = -1 so the upstream flow was accumulated only up to that location. From the segment immediately downstream, the accumulation is restarted with the value of its respective flow.

Finally, the segments immediately upstream the flow controls, up to the limit of flood levels, are on the effect of backwater. In the case of water availability, the implications of this effect should be incorporated at the end of the accumulation process and can be performed in each case directly in the attribute table of the feature class.

For cases in which the flow regionalization is calculated by the application of regression equations, which take into account the proportionality of the drainage area upstream of each segment analyzed, the accumulation process does not apply to a specific attribute, but to different polygons that represent the contribution of each segment area that needs to be accumulated. In such cases, the features are aggregated through relationships modeled according to *ArcHydro* tool, which has a specific tool for this area accumulation.

6 Application to the Doce River Basin

The automation of the flow accumulation with the reservoir effects provided water availability for the Doce River Basin quickly and efficiently. This procedure avoided a manual processing of the streamflow for each segment and provided time-savings.

The map below shows the behavior of water availability along the riverbeds. The dark blue colors indicate higher flow rates and the light blue colors represent lower values (Figure 9). The flow accumulated, Q_{95}, at the mouth of the Doce River was 340.43 m^3/s.

Table 4 shows the changes made manually and directly in the attribute table for the segments downstream the flow control.

7 Concluding Remarks

The use of *ArcHydro* module to accumulate water availability along the hydrography was adequate and easy in the Doce River Basin. It was also efficient and quick, and provided reliable results and time savings in comparison to the manual processing. The module can be applied to other studies of water availability.

The reservoir effects can be modeled directly on the geometric network attribute table which ensures integrity of calculations downstream of the flow control.

The automation of water availability studies using the *ArcHydro* is an advantageous process because of the achieved benefits.

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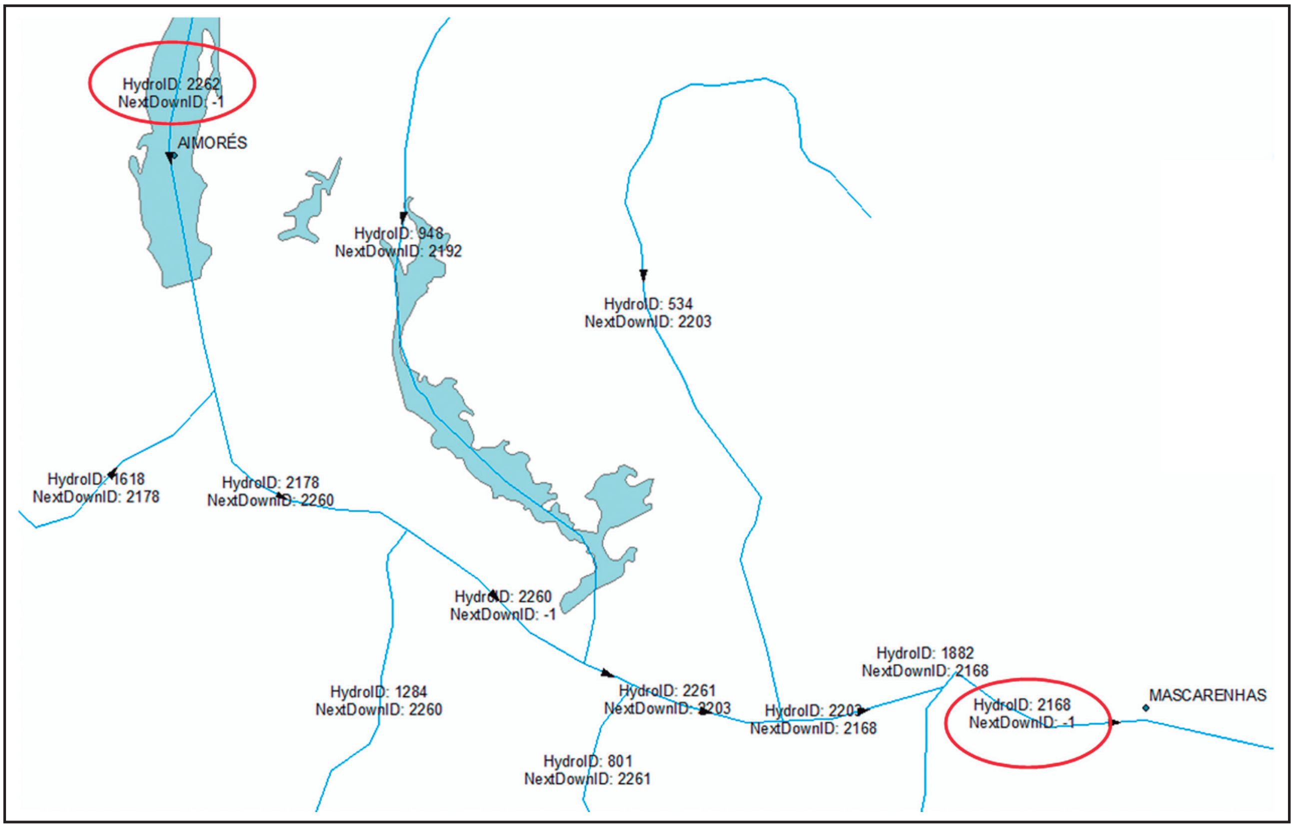

Figure 8 Modeling the effect of flow control in the hierarchy of network. (a) sequential coding before modeling. (b) sequential coding after the parameterization of flow controls.

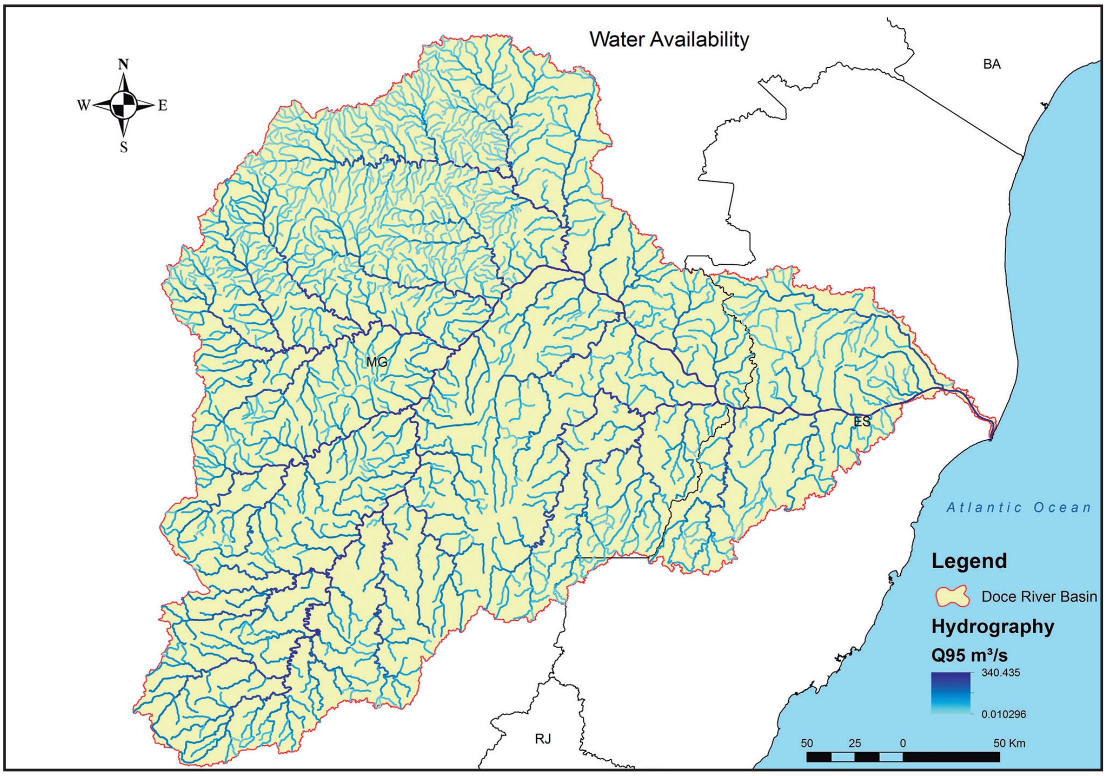

Figure 9 Map of water availability in the Doce River Basin after the automation process.

HydroID	Reservoir Name	Q_{95} without reservoir effect (m^3/s)	Q_{95} with reservoir effect (m^3/s)
1996	Ris. Neves	72.984	63.664
1643	Sá Carvalho	30.134	20.845
1264	Sá Carvalho	32.878	31.004
1609	Aimorés	354.497	315.384
1633	Aimorés	355.175	315.384
1652	Mascarenhas	363.803	316.142

Table 4 Changes in flow rates as a function of flow controls.

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