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Artigo Original

# Regionalization of average flow: a brief review of the literature

## Regionalização de vazões médias: uma breve revisão da literatura

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## Abstract

The sustainable management of water resources require planning techniques that are dependent on reliable estimates of water bodies flows data. The knowledge of water availability is essential for decision-making; however, data series are generally limited, insufficient and do not cover all places of interest, making it difficult or impossible to carry out strategic water resource planning. In this way, the temporal and spatial gaps can be filled based on robust methodologies. To fill the gaps in the data, spatial information transfer techniques are used, which are called hydrological regionalization. Thus, this article presents a brief bibliographical review, as well as, different applications of the average flow regionalization methods. This method is an important tool to support decision making in the planning and management of water resources. The results found in the researches related to the applicable methodologies of flow regionalization emphasize that the physical, climatic and hydrological diversities of the river basin characteristics require the adoption of specific methods directed to each unit, since the complexity of the ecosystem interactions makes the procedure difficult.

**Keywords**: Water Resources; Regionalization; Average Flows

## Resumo

O aproveitamento dos recursos hídricos adequado a uma gestão sustentável requer técnicas de planejamento que são dependentes de estimativas confiáveis de dados de vazões dos corpos de água. O conhecimento da disponibilidade hídrica é essencial à tomada de decisão, no entanto, as séries de dados geralmente são limitadas, insuficientes e não cobrem todos os locais de interesse, dificultando ou impedindo a realização de um planejamento estratégico dos recursos hídricos. Dessa forma, as lacunas temporais e espaciais podem ser preenchidas com base em metodologias robustas. Para suprir as lacunas existentes nos dados são utilizadas técnicas de transferência espacial de informações que são chamadas de regionalização hidrológica. Diante do exposto, o presente artigo expõe uma breve revisão bibliográfica, bem como, diferentes aplicações dos métodos de regionalização de vazões médias. Esse método, apresenta-se como uma importante ferramenta para subsidiar tomadas de decisão no âmbito do planejamento e da gestão dos recursos hídricos. Os resultados encontrados nas pesquisas relacionadas às metodologias aplicáveis de regionalização de vazões destacam que as diversidades físicas, climáticas e hidrológicas das características das bacias hidrográficas, exigem a adoção de métodos específicos direcionados a cada unidade, visto que a complexidade das interações ecossistêmicas dificulta o procedimento.

**Palavras-chave:** Recursos Hídricos; Regionalização; Vazões Médias

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## 1 Introduction

Water is one of the main natural resources for the basic maintenance of the living beings. The availability of that resource has variability due to factors that compose the ecological system, that is, environmental factors of local characteristics. Examples of these characteristics are the precipitation, evapotranspiration, solar radiation, and others, as the relief, geology, geomorphology, soil types, land use and occupation and modifications in the fluvial system, among others.

Knowledge about the water availability from certain regions and hydrological processes is a challenge for science. The proper use of the water resources requires planning techniques that are dependent on reliable estimates of maximum, minimum and average flows (Baena, 2002; Cecílio et al., 2018). The existing studies include mainly quantitative assessments, however, the high cost of installing, operating and maintaining of the data collection stations, problematizes the availability of the stations that provide such information (Barbosa et al., 2005).

According to Tucci (2002), a stations network of hydrometric data collection hardly covers all the necessary places of interest. In this case, the insufficiency of data found in the historical series is one of the main difficulties of making flow estimates (Bazzo et al., 2017). To fill these gaps are used of spatial transfer techniques of the information, between climatically similar sites (Barbosa et al., 2005; Cecílio et al., 2018) or similar hydrological behavior (Tucci, 2002; Bazzo et al., 2017).

The technique known as regionalization of hydrological flows allows the filling of gaps found in historical series and, optimizes the obtaining of precise statistics in places with short series or without data (Alexandre and Martins, 2005; Cecílio et al., 2018). In view of the above, the present article proposes a bibliographic review and presentation of applications of the medium flow regionalization methods.

## 2 Literature review

Hydrological regionalization is defined by Barbosa et al. (2005), as the set of procedures and statistical methods that aim to exploit to the maximum existing hydrologic data of given region, allowing the estimate of the hydrological flow in places with insufficient or no data. These methods can be used to better exploit the point samples of data and, consequently, improve the variable estimates, verify the consistency of historical series and to identify the lack of observational stations (Tucci, 2001).

The statistical methods applied for hydrological regionalization, according to Barbosa et al. (2005), allow to obtain indirectly the water bodies flows in sections that which there are no data, or where, due to physical or economic factors, it is not possible to install a hydrometric station. The author mentions that the physical and climatic characteristics of the hydrographic basin are considered in the statistical decision-making, because they exert a major role in the region hydrological behavior. In addition, choice of the mathematical functions that are used in the statistical analysis is fundamental for the best water resources management, evaluations of the stations number in the hydrometric network and for different hydrological studies of hydrographic basins (Obregon et al., 1999; Bazzo et al., 2017).

The hydrological variables used in the mathematical models of flow regionalization have a certain pattern whose state is indeterminate and originated from random events, that is, a stochastic behavior in the time and space (Barbosa et al., 2005). According to Tucci (2002), the best understanding of this stochastic behavior of the variables representing a hydric system depends ultimately on observed information from the same system. Also emphasizes that no mathematical model or technique can create data, that is, they can only explore the observed information.

Observed information for the application of flow regionalization is spatially transferred and exploited at maximum to obtain the system hydrological conditions (Bazzo et al., 2017). The applications generally use the existing flows and when this information is representative, the results are good, but if the data are deficient, the results are also compromised (Obregon et al., 1999). Thus, it is understood that a multivariate of elements is necessary to determine the change in the hydrological characteristics and, finally, to represent them indirectly in other places of the river basin (Cecílio et al., 2018).

These multivariate elements that determines the change of hydrological characteristics transforms the estimate of their values in a complex and dependent system of the statistical analysis of known values. In this way, observation of variables such as precipitation and flow in different places of a region is behavior's estimation basis of these variables, in the site and places without measurement (Tucci, 2002). In this sense, Barbosa et al. (2005) and Cecílio et al. (2018), reports that variables as mean rainfall, annual total, or total rainfall is normally used as independent variables to represent the effect of climate on statistical analyzes. In addition, the physical characteristics such as drainage area, drainage density, length and slope of the main water course also enter as independent variables. These physical elements explain the spatial distribution of the flow and the correspondence with the region's hydrological regime (Tucci, 2002). The independent variables are of great importance in the river basin's hydrological behavior (Bazzo et al., 2017).

Hydrological behavior's understanding is essential for the management of river basin resources and for this reason, the observed variable's quality can be determinant for the realization of hydrological regionalization closer to the real. Observed variable's quality according to Tucci (2002), depends on qualitative preliminary evaluation, that is, a detailed screening based on the establishment of satisfactory criteria. From these criteria, the data series that did not reach the minimum selection conditions are discarded and, the series that met the criteria are checked and improved from historical data's analysis or even of the selected collection points. The author also comments that the screening consists in the verification of information consistency regarding the local and regional coherence of the series values.

Hydrological and climatic data are collected at the measurement stations. Normally, the available rainfall series are longer than the flow series. In regions with poor data, it is possible to extend flow series through hydrological models, with the transformation of precipitation values to flow values, resulting in flow series more representative for regionalization (Obregon et al., 1999). The precipitation occurrence in a river basin is observed as a sample of water input value in the system and the surface flow (fluviometric data in the river's section) as water output value in the system. From that, occurs the information transfer from one place to another, in areas of similar hydrological and climatic behavior. Therefore, the hydrological flows regionalization principle is based on the spatial similarity of variables, functions or parameters that allow that transfer (Tucci, 2002).

According to Tucci (2002), variables are expressions used to identify the behavior of a phenomenon as the river section's instantaneous flow, but by having a relation with one or more explanatory variables (independent variables), becomes a function such as a permanence curve and the probability of minimum flows or the relationship between impermeable areas and housing density. The author mentions that the parameter is interpreted as a characteristic of a water system (e.g., basin area, time of concentration and others).

Explanatory or independent variables are used to estimate the value of regionalized variables (Bazzo et al., 2017; Cecílio et al., 2018). However, Tucci (2002), explains that the basic conditions should be easily determined, avoiding indirect methods, because with the correlation variable's introduction between them there will probably be no increase in information, besides the importance of analyzing the levels of uncertainty for the dependent variable's estimation. That estimation is performed based on flow calculation models, which are statistically applicable to any river section of the basin considered (Barbosa et al., 2005).

## 2.1 Regionalization of average flows and applicability

The mean flow rate can be interpreted according to the values used for the calculation, for example, the average flow rate of one month is obtained based on the observations of this variable during the same month in several years, or the average flood flow is represented by the averages per year. The most common term when it comes to mean flows is the nomenclature of long-term average flows, which can be defined as the average of this variable from the available series in one location (Tucci, 2002).

According to Tucci (2002), regionalization of average flow and their statistical distribution can be realized based on two steps: dimensionless probability curve of annual flows; and regression equation between the average flow of annual averages or the average long period flow according to the physical and climatic characteristics of the basin.

In the two mentioned steps, we detail: average flows selection of each station; long-term average flow determination and dimensionless flow rates; evaluation of the station trend plotting the dimensionless curves in a graph and elaboration of the regions in which the stations present the same tendency of aggregation and finally, the regression equation is applied (Tucci, 2002). According to the same author, the specific flow is represented by the equation where its variable is constant for a region, as long as its mean varies linearly with the area of the basin. Usually, the time interval of an average flow hydrograph is one day because it is related to its use in water supply, power generation, irrigation, navigation, among others. The values are presented as monthly, annual and long-term averages.

According to Alexandre and Martins (2005), the average long-term flow rate allows us to characterize the largest flow possible to be regularized in a basin allowing the evaluation of the upper limits (abstracting losses) of the water availability of a water course. It also explains that this is defined as the mean of the annual average flows for the entire data series, being denominated as specific when divided by the river basin area.

Tucci (2002) pointed out that the average flow does not represent the occurrence of flows over time and may have great variability, but that is important for the water resources use and conservation. The author explains that, in the case of annual variability, the main statistic used is standard deviation, which is provided by the variation of the daily averages, as occurs in the basins with shorter concentration time and natural or artificial regularization capacity. According to Barbosa et al. (2005), the quantification of the average long-term flow allows the knowledge of this demand-availability relationship. This calculation allows the indication of the energy potential of a basin, representing the largest flow possible to be regularized and thus entering the volume calculation of regularization when the construction of a reservoir is being planned.

The planning, design and operation of any work related to water resources in a river basin, whether for the use, control or protection thereof, are based on the estimate of the demand required for such work in view of the water availability in the place. This availability is measured by the water balance of the region, being extremely important for this estimation the information about the main hydrological variables that interfere in this process, especially precipitation and flow (Barbosa et al., 2005).

In places without data, the average flow estimate of a river basin is obtained from water balance calculation, that is, based on the specific flow determination of the sites with data. According to Tucci (2002), this estimation allows the upper limits evaluation of the water use of a source for the different purposes. The author also points out that changes in water availability, as well as these river flows, may be related to changes in land use and in the basin flow system, mainly with the reservoirs construction and changes in the river basin drainage.

## 2.2 Methodologies for flow regionalization

The studies of hydrological variable regionalization are very broad, ranging from the methodologies selection to be used in process to choose the variable data to be regionalized. These studies cover flow regionalization methodologies in different ways, varying in aspects such as: definition or not of homogeneous regions in the study area, variables considered in the process, calculations used in the methods, among others.

According to Almeida (2010), the high number of studies done with hydrological regionalization evidences the variety of aspects to be considered and analyzed in the process, and it is extremely necessary to apply different techniques as well as their improvements, aiming to provide progress in the current methodologies.

In Brazil, a widely used method is the proposed by Eletrobrás (1985), which uses regional regression models to fill flow data in regions with no data or few data. In addition, methodologies that do not need the definition of homogeneous regions have been studied and applied, such as the linear interpolation method proposed by Chaves et al. (2002).

### 2.2.1 Regional regression method proposed by Eletrobras (1985)

The regional regression method of hydrological variables proposed by Eletrobras (1985) has main characteristic the use of regional regression equations applied to regions identified as hydrologically homogeneous. This method has objective of obtaining flow data at any position of the drainage network in the study basin (Novaes, 2005, Lisboa et al., 2008; Almeida, 2010; Cecílio et al., 2018). Equations generated in this case aim to estimate the value of the variable to be regionalized (the flow rate) through explanatory variables, such as the physical and climatic characteristics of the drainage basins for each homogeneous region (Novaes et al., 2008; Bazzo et al., 2017).

The regionalization methodological steps for the proposed process are: (a) the limit's definition of the study area; (b) dependent and explanatory variable definition; (c) variable data selection; and (d) regional function elaboration, which depend on regional relations and the definition of homogeneous regions (Tucci, 2002; Cecílio et al., 2018). Tucci (2002) points out that there are some basic conditions that must be considered to choose of the explanatory variables, such as: they must be easily determined; indirect methods should be avoided for their determination; the variables should provide uncertainty levels for the dependent variable estimation. The author also points out that to regionalize average flow data, for example, the basin area and precipitation data at the study area should be considered as the main explanatory variables.

When set hydrologically homogeneous regions, it is important to consider series of physical, climatic, geological and topographic factors. According to Tripathi, Srinivas and Govindaraju (2008), some characteristics influence more than others in the selection and definition of homogeneous areas. However, the authors point out that defining region as homogeneous taking into just its characteristics is not enough, since statistical tests are necessary to aid and confirm this classification.

### 2.2.2 Interpolation method by spatial proximity

The interpolation method by spatial proximity is based on the principle that the flow at the site of interest can be estimated by a linear relation of proportion between the flows and drainage areas of the nearest fluviometric stations (Novaes et al., 2007; Almeida, 2010; Cecílio et al., 2018).

Samuel et al. (2011) point out that spatial proximity approach involves model parameters transfer between river basins of different location, using interpolation techniques, which are functions of geographic location. Among the spatial proximity approaches are cited Kriging methods, Inverse Distance Weighting (IDW) and average parameters.

It should be noted that linear interpolation methodology does not provide for study area segregation in homogeneous regions and can be applied in several river sections of the same hydrographic basin that has stations with a historical flow series (Almeida, 2010).

Some authors, such as Novaes et al. (2007) and Gasparini (2014), propose an adaptation to this method. That adaptation is summarized in include the precipitation variable in the flow calculation, considering that local flow also has a direct relation with the amount of rain in its respective drainage area.

### 2.2.3 Chaves (2002) method

Chaves et al. (2002), proposed a similar method to the previous and, also does not need to divide the study area into homogeneous regions. However, the Chaves et al. (2002) method is performed in a Geographical Information System (GIS) environment and because of that, it considers relative weights to the distances between the points of interest, upstream or downstream, when there is interest in determining the flow at a point located between two stations (Novaes et al., 2007, Gasparini, 2014; Cecílio et al., 2018).

Some authors modified the Chaves method (2002) inserting the precipitation variable in calculations. Thus, it is considered that the flow is influenced by both drainage area and precipitation of the local. In the same way, the distance between points and the amount of rain presents different relative weights (Novaes et al., 2007; Gasparini, 2014; Cecílio et al., 2018).

### 2.2.4 Method by Physical Similarity

The regionalization methodology by physical similarity considers that similar watersheds in terms of characteristics can have similar model parameters and, then, the flow characteristics are also similar. Thus, this method seeks to find the main attributes of the location, without information that is more similar to the basins that have data and then estimates the model parameter values to the destination location, calculating the average of the basin parameter values already calibrated (Samuel et al., 2011).

Hailegeorgis et al. (2015) point out that the main attributes considered to establish similar river basins include hypsometric curves, land use, drainage density, catchment area, land slope, soil geology and soil type.

### 2.2.5 Estimates of average flows without regionalization

Although the regionalization process is the usual methodology for the average flow estimation in places with little data available or no data, there are procedures that allow regionalization verification to obtain simple estimates of the river basin average flow. The main steps are the calculation of the water balance, the specific flow rate and the regression with the basin area (Tucci, 2002).

Flow estimation performed by the simplified water balance method considers that outflow at a given location and time would be the difference between precipitation at this time and the evapotranspiration. In this situation, the flow determination depends on data availability, since although rainfall data are usually known, evapotranspiration data are terms that present great uncertainties due to their estimation difficulty (Tucci, 2002).

It is also possible to estimate the flow in locations with no data by determining the specific flow of locations with available data. Thus, a relation of these specific flows (calculated from specific flow maps or obtained from nearby river basins) with the local area without data, resulting in the average flow of the basin with no data. Considering that this procedure extrapolates data from one basin to another, some aspects must be considered before being carried out, such as: average precipitation and drainage area of the river basins should be similar, there should be no major difference in soil cover, soil geology, between others (Tucci, 2002).

Finally, the regression procedure with the basin area considers the good correlation between area and the average flow of the basin in question. Thus, the average flow rate can be estimated by a power function that presents, as well as the area, coefficients determined by the least squares method (Tucci, 2002).

## 3 Discussion

In studies presented in the literature can be found several applications regarding the regionalization of average flows. In several locations in Brazil and the world, applying different methodologies and presenting results that deserve to be evaluated and discussed.

In studies presented in the literature can be found several applications regarding the regionalization of average flows. In several locations in Brazil and the world, applying different methodologies and presenting results that deserve to be evaluated and discussed.

The study developed by Barbosa et al. (2005) proposed the construction of mathematical models of flow regionalization in the Carmo river basin (Minas Gerais state). For regionalization purposes, the entire basin was considered as a single homogeneous region, and the classical regression methodology was used for the process. In the study was considered the independent variables: physical and climatic factors of the river basin. With the results, were constructed mathematical models based on linear and nonlinear regressions for maximum, minimum and average flows. The authors report that, in the case of average flows, the models were significant for the climatic variables represented by the total annual and total of the semester rainier.

Alexandre and Martins (2005) discuss the use of regression method in the long-term average flow regionalization, using as explanatory variables seven climatic and physiographic characteristics of the Ceará state river basins. Based on this, the authors adopted a regional model that used as explanatory variables the river basin mean slope, mean precipitation and percentage river basin.

Novaes et al. (2007) and Gasparini (2014), in their work evaluated the minimum flow regionalization, average long-term flows and maximum flows (in Gasparini's case), for the Paracatu river basin (Minas Gerais state) and the Itapemirim river basin (Espírito Santo state), respectively. The authors applied five different methodologies: traditional by regression; linear interpolation; proposed method by Chaves et al. (2002); and two other methods that modify the methodologies of interpolation and of Chaves et al. (2002), by the precipitation variable addition in the calculations. Novaes et al. (2007) did not observe significant differences in the performance of the different methods in the study area, but Gasparini (2014) points out that the results regarding the linear regression method presented better performance in the regionalization process. Gasparini (2014) points out that the modified methods were better than the original ones for all flows and, the linear interpolation methodology presented the worst performance, possibly due to the significant proportional differences between the drainage areas of the interest sections and of the fluviometric stations.

In another study, carried out by Lisboa et al. (2008), the minimum flows, the seven-day flow rate and the 10-year return period, and the long-term average annual flow of the Paracatu river basin (Minas Gerais state) were estimated and regionalized by the traditional method. The flow rate regionalization equations were obtained in two stages: identification of three hydrologically homogeneous regions and subsequent adjustment of regional regressions between flows and area drainage of the river basin (basin physical characteristics and single independent variable used). Regression models were obtained for each homogeneous region that showed a constant increase of the flows as the drainage area increased.

Almeida (2010) analyzed the three methodologies for the regionalization of average long-term flows: regional regression proposed by Eletrobras (1985), linear interpolation and proposed method by Chaves et al. (2002). The author points out that the best flow estimates were obtained through the regression method and the most significant explanatory variable in the equations was the drainage area. Almeida (2010) also points out that equations presenting combinations with precipitation, river basin mean slope and slope between spring's river and the mouth's river also correspond to the best observed adjustments.

Moreira e Silva (2014) evaluated several methodologies for regionalization of minimum and average flows of long period in the Paraopeba river basin (Minas Gerais state). The main methodologies evaluated by the authors were related to the applications of the regional regression equations and linear interpolation. In the analysis of the results, the authors highlight that errors were verified in the flow estimates in the regions near the spring's river. Finally, among the types of regionalization applied in the study, the regional regression method (pointed by the authors as traditional) is what best allowed the value estimations.

At the international level it is possible to highlight the studies developed by Samuel et al. (2011) and Hailegeorgis et al. (2015), which are discussed in the following paragraphs.

Samuel et al. (2011) studied average flows regionalization data for basins with little or no data in Ontario (Canada). They were applied and compared four distinct methodologies: multiple linear regression method, interpolation method by spatial proximity, method by physical similarity, and a method combination of physical similarity and spatial proximity (where the average flows in uncalibrated river basins was estimated using the spatial proximity approach in case of physically similar locations). The authors point to results that demonstrate the methodology with better performance was the approach of coupled regionalization (spatial proximity and physical similarity).

Hailegeorgis et al. (2015) evaluated four regionalization methodologies to transfer locally calibrated flow data through three different rainfall-flow transformation models, in 26 river basins located in Norway. The methods considered were regional calibration, regional median parameters, nearest neighbor and physical similarity. The authors concluded that the results of the regionalization processes depended on the rainfall-flow transformation models used. Further pointing out that, in general, the performance of all methods of regionalization were equivalents. However, the authors have indicated that the comprehensive identification of suitable regionalization methods is necessary for more reliable forecast in uncalibrated basins.

Although the studies presented have the objective of testing and comparing methodologies of flow regionalization, in most of the works, the procedures are performed in a Geographic Information Systems (GIS) environment. Its application can be perceived either in the methodological procedure itself (as in the case of the interpolation method), as a support to obtain the physical and climatic data of the interest basin (such as through the Digital Elevation Model - DEM) or to assist in data spatialization.

## 4 Conclusion

The process of average flow regionalization is an important tool to support decision-making in the planning and management of water resources. In this sense, the process supports to obtain and explore necessary information to study the water availability in river basins.

The studies presented methodologies applied to the average flow regionalization. In view of this, the great variety of physical, climatic and hydrological characteristics was highlighted and, therefore, there is a need to adopt specific methods directed to the characteristics of each river basin. In this way, the diversity in the ecosystem interactions makes the procedure somewhat complex.

In addition, the importance of the technology uses such as geographic information systems and geoprocessing for space analysis is concluded. In this way, the analyzes are performed in an integrated way to the location of the stations with data collected and the results obtained in the regionalization. From tools such as GIS, locations with the need to install new stations can be identified, aiming to fill areas with data deficiencies or no hydrological data.

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