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Estimation of flow components by recursive filters: case study of Paracatu River Basin (SF-7), Brazil

Quantificação dos componentes de vazão por meio de filtros recursivos: estudo de caso da Bacia do Rio Paracatu (SF-7), Brasil

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Abstract

The quantification of flow components is important for water resource management. The base, interflow, and runoff flows of nested basins of the Paracatu River (SF-7) were estimated with recursive signal filters in this study. At first, stationary analysis and multivariate gap filling were applied to the flow data. A methodology is presented, proposing filter calibration with the runoff influence and inflection of the recession curve for dry season. Filters are improved with a logic constraint that limits water flow overestimation within algorithm iteration. The results were coherent with previous studies and with hydrogeological and climatological maps.

Keywords: Hydrogeology; Hydrology; Recursive signal filters; Base flow; Aquifers; Water resource management.

Resumo

A quantificação dos componentes de vazão é importante para a gestão de recursos hídricos. Empregaram-se, neste estudo, filtros recursivos de sinais para delimitação dos fluxos de base, interfluxo e rápido de sub-bacias aninhadas na Bacia do Rio Paracatu (SF-7). Preliminarmente, os dados de vazão tiveram sua consistência avaliada por meio de análises de estacionalidade e preenchimento multivariado das lacunas de dados. Apresenta-se uma metodologia em que os filtros são calibrados pela influência do escoamento superficial e pela inflexão na curva de recessão do período sazonal de seca. Os filtros foram aprimorados por uma restrição lógica, que limita a sobre-estimação da vazão à cada iteração do algoritmo. Os resultados foram condizentes com estudos prévios e com mapeamentos hidrogeológicos e climatológicos.

Palavras-chave: Hidrogeologia; Hidrologia; Filtros recursivos de sinais; Fluxo de base; Aquíferos; Gestão de recursos hídricos.

INTRODUCTION

Hydrograph separation between superficial runoff components and the base flow is important for water resource management, especially when referring to dry and flood conditions (Tularam and Ilahee, 2008); reservoir navigation and maintenance (McMahon and Mein, 1986); ecological flow, salinity and algae management (Santhi et al., 2008); and nutrient and contaminant outflows into water body (Reay et al., 1992; Dolezal and Kvítek, 2004; Schilling and Zhang, 2004). The components of hydrograph separation can also serve as input data for more complex models, such as those for water budget and hydrological forecasting (Corzo and Solomatine, 2007). By analyzing the groundwater contribution to each sub-basin flow of water courses, it is possible to adequately define how each area effectively contributes for recharging and discharging of the aquifers.

Specific mapping of the groundwater discharge by separation of its hydrograph components, in nested basins, can be a useful diagnostic tool for articulating issues involving environmental policies and water resources, with the objective of developing a sustainable management framework. This applies to the geo-environmental management context in which government intends to gradually implement management policies, such as water tax and payment for environmental services. Mapping makes it possible to recognize the relative importance of each basin sub-region regarding the underground water supplied to the rivers. With this information, water and soil conservation managements can be valued, mainly in the most critical areas. Thus, one of the adapted policies could be that whoever best contributes to the recharge maintenance of the aquifer would pay less for water usage, or maybe, as a counterpart, would be paid for the environmental service provided. Since most water resource conflicts occur during dry seasons, when river flow is sustained mainly by groundwater discharge, the base flow (and its respective mapping) quantifies the most critical characteristics to be considered. In addition, quick flow mapping could indicate areas that are interesting for the implementation of flow retention and regularization techniques, which involve water containment during the rainy season and its liberation during the dry season.

As proposed by Johnson et al. (1999), Dillon (2005) and Martins Junior (2006), the final objective of a policy that integrates orderly sustainable land and water use would be to hydrogeologically and economically quantify the feasibility of increasing infiltration in areas of greater recharge potential during the rainy season, in order to guarantee an adequate minimum flow during the dry season and improve water quality.With future demanding more refined environmental management, the standards established by distinct entities (federal, state and municipal, together with those directly involved with watersheds) could provide the needed degrees of protection or conservation, which would be gradually defined as hydrogeological knowledge increases. Therefore, at a given site, scientifically reliable intervention could be practiced for the sustainable usage of its natural resources.

Gap filling in hydrological data series

The stationary evaluation of hydrological data in time series is justified by the fact that it is assumed to be necessary for hydrological and hydrogeological statistical modeling (Tucci, 2009; Souza et al., 2009), including its use to estimate input data for gaps in the flow data series. Noteworthy is the methodological attitude proposed by Müller et al. (1998), who claims that stationary study of hydrological time series should be employed as a tool to aggregate information and for comparative analyses, which would be more than simply hypothesis rejection testing.

As a preparatory step for filling in the flow gaps from the stream gauges, the Brazilian National Water Agency (Souza et al., 2009) recommends the grouping support approach of gauging stations. This methodology consists of selecting data from stations that are topologically closer downstream and upstream of the gauging station from which the gaps are being filled. It is also feasible to include data from stations in nearby basins, providing these basins have homogeneously physiographic characteristics. The stations whose data present the greatest correlating coefficients are used for filling in the gaps. Rodriguez (2004), Novaes (2005), Moreira (2006), Latuf (2007) and Souza (2009) used the gauging station support approach for hydrological studies at the Paracatu River Basin.

Schafer and Graham (2002), Allison (2002) and Enders (2010) classified expectation maximization (EM) (Hartley, 1958; Dempster, Laird, Rubin, 1977) and multiple imputation (MI) as the most robust methods available for gap analysis in statistical databases. The algorithms from both methods are present in the Statistical Package for the Social Sciences (SPSS) software model — missing values. Presti et al. (2010) indicate that using multivariate techniques (such as EM and MI) increase the statistical reliability of hydrological data gap filling. Thus, it is possible to work with greater gap percentages or shorter time series. Furthermore, since accurate flow estimates of the hydrogeological basin require daily runoff data, extra statistical care must be provided to ensure that data validation is more reliable, rather than when working with only a series of monthly measurements.

A typical case of discharge estimation improvement using multivariate techniques for gap filling occurs when one stream gauge receives water input from two or more supporting affluent gaging stations, with significantly different discharge behavior. Analogically, another case, but in a more complex scenario, refers to the spatiotemporal heterogeneity of rainfall occurrence registered in nearby gauging stations and in the station requiring gap fillings.

Amisigo and Vand de Giesen (2005), in applied studies, demonstrated that the EM technique provides more precise estimations of flow data gaps, when compared to the classical regression ones. Enders (2010) mathematically showed how EM estimation is more robust in relation to data distribution presuppositions, when compared to conventional regression techniques. In addition, EM input presents an advantage over multivariate regression by maximizing its statistical power through information obtained from the distribution curve of incomplete cases, and by estimating the original time series variance level (Enders, 2010).

Meanwhile, MI adds a random residual to the selected multiple regressions (analogically to a stochastic multiple regression), so that the results maintain the original variance of the observations as a whole. However, even though this random residual keeps the original variance, it distances the input value "at the same measurement" in relation to its maximum probability value, thus reducing data estimation reliability. Cano and Andreu (2010) alerted that in series with significant time correlation such as that with hydrological data, the sum of random residual by the conventional MI algorithms could lead to results that are less compatible with the natural behavior of real data.

Also, Enders (2010) stated that the methodology options of MI algorithms are not as mature, consolidated, and tested as those of EM. On the other hand, an existing broad study by Amisigo and Vand de Giesen (2005) about EM, applied to gap filling in hydrologic data, brought more security for using such methodology.

Presti et al. (2010) suggested that in unimodal oscillating climates (contrast between dry and rainy seasons, as in the case of the Paracatu River Basin), the gap filling should be applied separately for two periods of the year: rainy and drought. Thus, the distinct water flow dynamics at each of these two seasons will be captured with more assurance in their correlation. In the dry season, it is expected that the coefficient of the recession curve in logarithmic scale, in each basin, will be one of the defining characteristics of the correlation for lag filling. The rainy period, in turn, would present a major influence from the flux characteristics referring to the separation between superficial, subsurface, and groundwater flows.

Base flow estimation

Field and direct inference methods are amongst the most widely used for base flow inference. The field methods include direct monitoring of the aquifer level (by wells and/or piezometers), correlations parting from water temperature obtained by direct measurement or tracers, and infiltration monitoring by lysimeters. However, the employment of these techniques for large basins involves exorbitant costs due to the extensive sampling network required and creates uncertainty because of the spatial heterogeneity of hydrogeological processes.

Regarding techniques that try to specify the base flow by indirect inference, the most common are: water budget, hydrograph component separation, calculation of the flow recession (equation from Rorabaugh, 1964), and systematic comparison between rainfall events for hydrological pulses analysis (Su, 1995).

Nevertheless, because the hydrograph separation methods focus only on the base flow of watercourses, they do not incorporate the quantitative loss concerning river evapotranspiration and deep percolation that crosses beneath the gauging station (Risser et al., 2005). These two factors are important for the recharge analysis of the aquifers since they interfere in the water budget of the basin.

Base flow separation by means of computational calculations eliminates the imprecision and inherent subjectivity of the traditional graphic methods as those proposed by Barnes (1939). However, Risser et al. (2005) noticed that conventional hydrograph separation by numerical methods (PART, local minimums fixed intervals, fluctuating intervals) might create difficulties for comparing base flow estimates of different-sized basins (including the nested ones). An increase in basin area implies: greater runoff time, flood lessening, bed friction on the flow, partially simultaneous flow contributions from tributaries, and regional hydrogoeological flow, among other factors, which can rarely be automatically calibrated by the available algorithms. Figure 1 highlights how these methods can generate distortions in base flow separation.

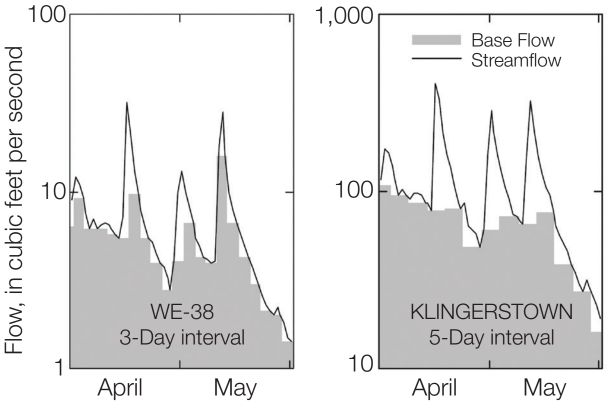


Figure 1. Effects of flow separation based on an interval change from three to five days, by the fixed interval method (Hysep software), considering the discharge from basins WE-38 (2.8 square miles) and East Mahantango Creek – Klingestown (45 square miles) from April to May of 1996 (Risser et al., 2005). Risser et al. (2005) demonstrate how the interval change is arbitrary and does not adequately identify inflection points on the curve in any of the hydrographs.

The numerical methods for recharge calculations through recession curve analysis, theoretically, are not affected by this limitation. As such, instead of starting with the recognition of the inflection point (like hydrograph separation methods), the methods for analyzing recession begin by identifying flow peaks, after which the flow recession behavior is calculated (Rutledge, 1993, 1998, 2000). In order to analyze flow recession, it is necessary to calibrate the critical time (tc), that is, the period to cease the influence of runoff. To achieve such thing, Rutledge (1993) and Welderufael and Woyessa (2010) refer to the empirical formula made by Lynsley et al. (1975):

$$N = 0.827 * A^{0.2} \tag{1}$$

where:
N: time (in days) after hydrographic peaking to stop the participation of runoff; and
A: is the area of the basin, in km^2.

Notwithstanding, this formula presumes that the rainfall event covered the entire basin — a criterion that makes the equation less reliable with the basin area increase.

For greater reliability of the recession curve analysis, it is necessary to identify relatively long and continuous recession periods (without intercurrent flow peaks) (Halford and Mayer, 2000). Care must be taken so that abnormally low flow periods are not presented as part of the standard behavior of the water system (Rutledge, 2003). Halford and Mayer (2000) and Larocque et al. (2010) observed that the manual and automatic hydrograph separation methods, when applied based on analysis of recession at closely spaced peaks related to intercurrent rain, could lose their reference criteria and as such diminish the reliability of the component separation process. Furthermore, it would tend to overestimate the base flow value by considering a recession flux, which is still under the effects of superficial and subsurface runoff from recent rainfall events (Figure 2).

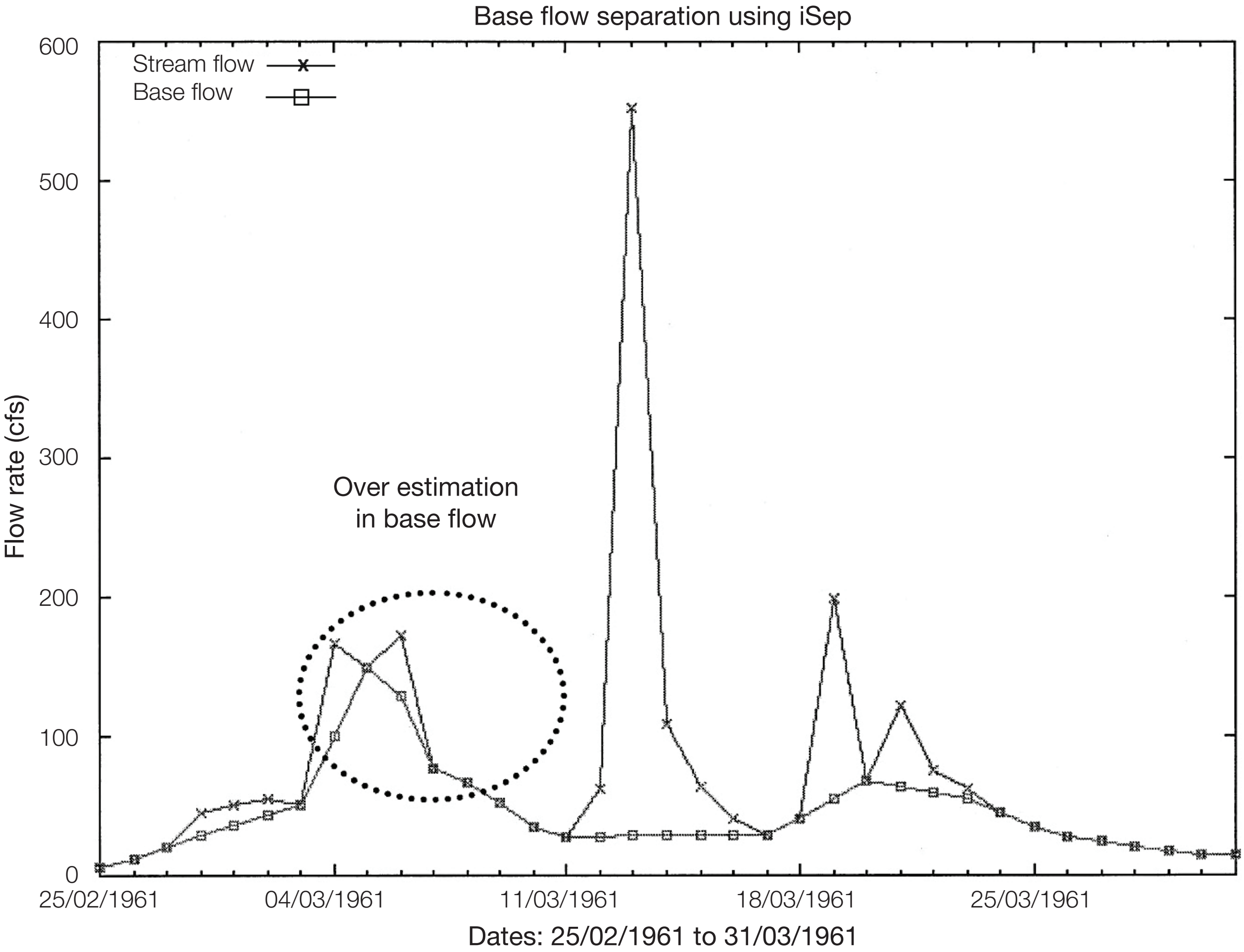


Figure 2. An example that demonstrates an overestimation of the base flow by the minimum-place method for the hydrograph of the Little Eagle Creek Basin in Speedway, Indiana, USA (Lim et al., 2005). Overestimation with this method is frequent when there are two discharge peaks close to each other, masking the inflection point referent to the first peak.

In order to incorporate the advantages of recession analysis into criteria for hydrograph separation without distorting them by the use of temporal interval variables, an alternative would be to use digital recursive filters. With their use, it is presumed that the low-frequency waves of the hydrograph inform the base flow, while the high ones relate to the runoff (Lim et al., 2005). The sum of both waves corresponds to the total flow of the hydrograph.

Peters and Van Lanen (2005) and Brodie and Hostetler (2005) state that the inherent disadvantage of the recursive filters is that they rely only on the hydrograph form, without a sustainable base of physical parameters. To overcome this problem, Ghanbarpour, Teimouri and Gholami (2008), Asmeron (2008), Tularam and Ilahee (2008) and Lim et al. (2007, 2010) proposed the possibility of calibrating the recursive filter parameters, based on the recession curve analysis of the hydrograph.

OBJECTIVES

This article had as a general objective to present a study about flow components of the sub-basins of Paracatu River, furnishing data to improve the management of its water resources. To achieve this, the following specific tasks were undertaken:

- stationary analysis of the flow average and variance for the gauging stations in Paracatu River Basin;
- discharge gap filling with the use of the multivariate techniques EM and MI;
- filter calibrating with double parameters, i.e., runoff influence and recession curve inflection;
- incorporation of a logical restrictor to estimate the base flow of recursive filters, impeding an overestimation of the base flow participation in the total discharge calculated by each iteration of the algorithm;
- spatial analysis of the relationship between base flow estimation and its geographical data regarding climate and hydrology.

It is worthnoting that preexisting studies using recursive filters have yet to focalize on the comparison of basins with diverse sizes. This article, by encompassing the concatenation between Paracatu Basin and its nested basins through readings from internal gauging stations, presents unique scientific data.

METHODOLOGY

Paracatu River Basin characterization

The Paracatu River Basin is almost totally located in Northwestern Minas Gerais, in Brazil with a small upstream area in the State of Goiás and Federal District (Figure 3). The basin has an extension of 45,154 km^2, and it is the largest among all the affluents that flow directly into the São Francisco River.

The Paracatu River Basin has a megathermic rainy climate of the Aw type (IGAM, 2006). It is a typically rainy tropical with high temperatures and oscillating unimodal precipitation concentrated in the months from October to April, when it rains an average of 93% of the total annual rainfall (Mulholland, 2009). Figure 4 shows the rainfall distribution. From the basin's climatic characterization by Ruralminas (1996), it becomes evident that there is a spatial correlation between the precipitation data and other climatic variables, such as temperature,

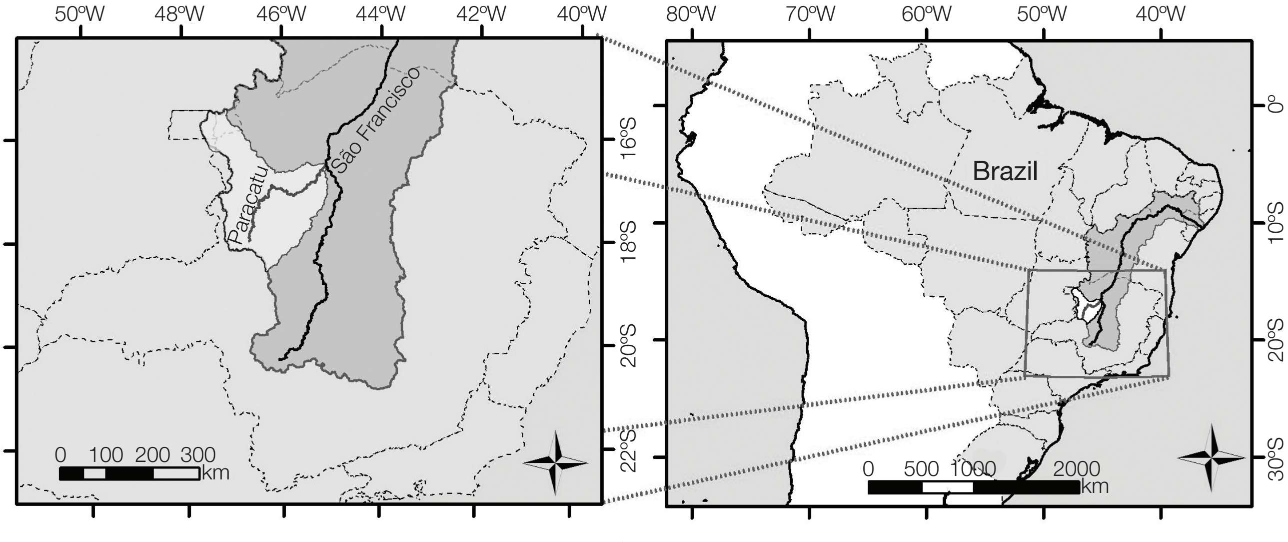


Figure 3. Location of the Paracatu River Basin, nested in São Francisco River Basin, highlighted within Brazilian states.

solar radiation, humidity, evapotranspiration, cloudiness, water stress, and storm frequency.

The Paracatu River Basis stratigraphy presents distinct rock systems that support aquifers (Figure 5). By means of the graphic method proposed by Barnes (1939), the Minas Gerais Technological Center Foundation (CETEC, 1981) estimated that, for the Paracatu River Basin, at different points, from 32 to 48% of the watercourse flow is maintained by underground aquifers. This contribution increases as the watercourse passes through recharge areas of cretaceous sandstones and tertiary-quaternary sedimentary cover, and therefore they were characterized as favorable recharge areas. In addition, these calculations considered that the infiltration and contribution from the fractured and Karst formations of Bambuí aquifer would be very low or virtually nonexistent when compared with the aforementioned granular aquifers. Ramos and Paixão (2004) also highlighted the importance of porous sedimentary aquifers for the perpetuation of rivers feeding São Francisco River Basin.

Areado and Urucuia Formations (Cretaceous) are characterized by free aquifers that furnish a significant amount of water through hillside sources (CETEC, 1981) and possibly through direct effluence along streams. They are formed by thick sandstone (up to 140 m) and lie directly on an impermeable substrate of the Bambuí group (Eo-Cambrian) (CETEC, 1981). However, the underlying mesofractures identified in the Bambuí Formation may increase the complexity of these aquifers through the combination of fractured and granular aquifers (Martins Junior, 2006). Mata da Corda Formation, with up to 100 m thickness, also has a porous aquifer overlying the Aerado Formation (RURALMINAS, 1996).

Morphologically, porous aquifers of the older tertiary-quaternary cover lie underneath part of the São Francisco Residual Plateaus, forming tabular surfaces with a height of more than 900 m (Andrade, 2007). In the Paracatu River Basin, the tabular surfaces are scarcely reworked and have almost no drainage. These characteristics are due to a thick sedimentary layer with high infiltration potential (CETEC, 1981). The main discharge areas are located at the foothills of the elevations, along the flank or edges of the plateaus, where there is contact between the aquifer and an impermeable substrate. These aquifers have an average thickness of 10 m and can exceptionally attain 30 m (RURALMINAS, 1996), with a registered record of up to 80 m (Mourão, 2001).

The more recent tertiary-quaternary sedimented aquifers are located in the river plains of Rio Paracatu River Basin, lying atop the Bambuí Group pelites with low permeability, whereupon there is frequent exudation in the contact area of two lithologies (CETEC, 1981; Mourão, 2001). Due to predominant geomorphology of the plane surfaces of this aquifer system (Andrade, 2007), CETEC (1981) hypothesize that local and regional base flows exist where there are hydraulic connections between aquifers and rivers — in this way, the aquifers function as flow regulators of such

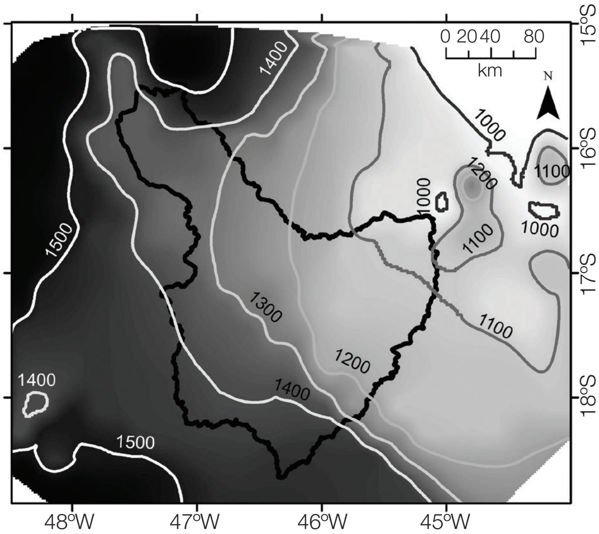


Figure 4. Annual average rainfall for Paracatu River Basin (in mm), based on data from Nunes and Nascimento (2004).

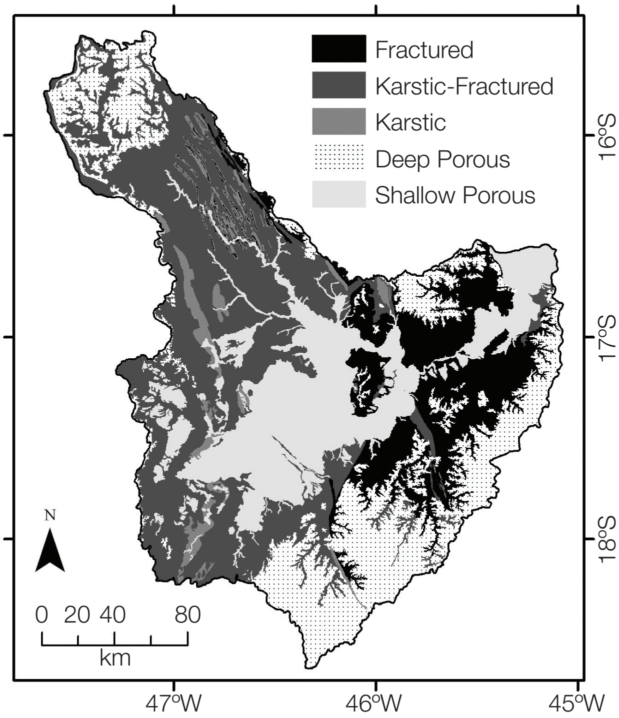


Figure 5. Rock systems containing aquifers in the Paracatu River Basin. This is inferred by means of lithostratigraphic data supplied by Martins Junior (2006).

watercourses. The water storage potential is less than in the other porous aquifers of the basin, due to the narrowness — an average of 5 m (RURALMINAS, 1996).

Fractured aquifers occur in the Bambuí and Canastra Groups, as well as in the Paracatu, Vazante, and Paranoá Formations. Their storage capacity depends on their fracture extension, continuity and interconnections, together with their opening and interior void volume. In comparison with granular aquifers, the possibility of direct rain infiltration in these fractured rock reservoirs is small because the fractures are narrow (Mourão, 2001). The recharge happens by vertical infiltration from an upper shallow aquifer or by deeper infiltration from the cretaceous and tertiary-quaternary sedimentary layer covers, as well as by points where both fracture and drainage coincides, that is, through watercourses controlled by fracture direction (RURALMINAS, 1996).

The Karstic aquifers of the Paracatu Basin predominantly correspond to geomorphological areas consisting of ridges and steep slopes (Andrade, 2007). Since they are distributed along the deformation zone of the Unaí Ridge and were submitted to strong tectonism (transcurrent and thrust faulting, as well as folding structures), it is assumed that there is a high degree of fracturing. Furthermore, the presence of sinkholes, caves and sinks indicates endokarst development by dissolution. It can also be presumed that these aquifers enable a significant hydrogeological flow. In evolved Karstic forms, the expressive flow from their inherent ducts produces aquifers with accentuated recession coefficients because as the water leaves them quickly, they provide little water for the springs during the apex of the dry season.

The quaternary alluvial deposits are usually found along the drainage system, in flood plains and in terraces. They are active zones for water exchange, for receiving recharge from the rivers during rainy periods, and for discharging it during dry periods (Mourão, 2001).

In the transition areas between the residual plateaus and the São Francisco depression in Paracatu Basin, the dominant reworked geomorphological features of the hills and slopes are regions where the hydrological role of transient flow occurs. This is because their localization is between the aquifer systems and due to the fact that the greater inclination disfavors rain infiltration in these areas. Nevertheless, it is good to remember that all surfaces with a weathered cover contribute in part to groundwater recharging.

Component flow estimation of the basins with gauging stations

Data source for the analyses performed for this article is the record of gauging stations flow available on the Internet for all regions in Brazil, supplied by the hydrological Information system (Hidroweb) of the Brazilian National Water Agency (ANA, 2008).

Rodriguez (2004), Novaes (2005), Moreira (2006) and Souza (2009) opted for the period between 1970 and 2000 (30 years), and selected and evaluated the use of 19 to 21 gauging stations at the Paracatu River Basin as consistent. However, the analysis of the operation history of these stations shows that a greater part of them became operative between 1975 and 1976. Consequently, by choosing a main set of stations from 1976 to 2000, it was possible to mount a basic block of 23 stations, minimizing the gap filling and series extension uncertainties. July of 2001 was the period's limit due to the beginning of interventions for the construction of the Queimado Hydroelectric Power Plant, at the sub-basin of Preto River after which the hydrological behavior of the area would influence data.

Two gauging stations were also selected with periods inferior to that of the main block: 426450000 (1974 – 1984) and 42350000 (1973 – 1981). These stations received differential treatment that will be further elaborated in this article.

The location of the gauging stations used in this article with their respective nested basins is shown in Figure 6. The basin drainage delimitations related to gauging stations were elaborated on the basis of a hydrologically consistent digital elevation model. It was based on the topographic treatment of Shuttle Radar Topography Mission (SRTM) — data and on the IBGE hydrography (1:100.000), reconditioned with the Hydrotools for ArcGis 10 extension and with pre-processing algorithms of the Saga 2.0.8 program in order to obtain altimetric consistency regarding the runoff from the slopes, the lentic water bodies, and the drainage network.

Stationary analysis was performed by means of tests combined with Fisher's equality of variance and Student's equality of averages, as recommended by Tucci (2002) and by the Brazilian National Water Agency (Souza et al., 2009). About the gauging station data, tests for average, minimum and maximum stationarity at 1 and 5% level of significance were performed to analyze the average and monthly variations, with successive tests of minimum five-year groupings in continuous combinations for all the possibilities of grouping in series, for the hydrological period from 1976 to 2000. Analogously, stationarity tests were also performed for the period of 1957 to 2000 at the oldest four gauging stations of the Basin. The tests were carried out on SisCAH 1.0 program, which is available without any costs at the Brazilian National Water Agency website.

For the gap filling methodology, a combination of methods was used: support station selection; rainy and dry season data separation; and value estimation using the EM and MI algorithms in order to compare the consistency of the results for each method.

The preliminary grouping of support stations considered: areas of homogeneous water systems proposed by Euclydes (2004); drainage pattern areas by Martins Junior (2009); spatial variations of the cartographic bases (geology, geomorphology, soil, slope, and height) by Martins Junior (2006); topological connection of the drainage network; stationarity tests; and correlation coefficient among the discharges time series. Also taken into account were the areas with a homogeneous annual rainfall rate, which would also be spatially correlated with the other climatic parameters of the basin.

Filling in the gaps with EM and IM involved using data from before 1976, when available, to amplify the comparison possibility for the statistical distribution of the daily discharge at the referenced gauging station with those of the selected support gauging stations. For the gauging stations that were not affected by the construction of the Queimada Hydroelectric Plant, discharge data from 2001 on were also used.

From the point of view of existing conflicts concerning water usage in the Paracatu Basin for irrigation (Pruski et al., 2007), it can be questioned if this water

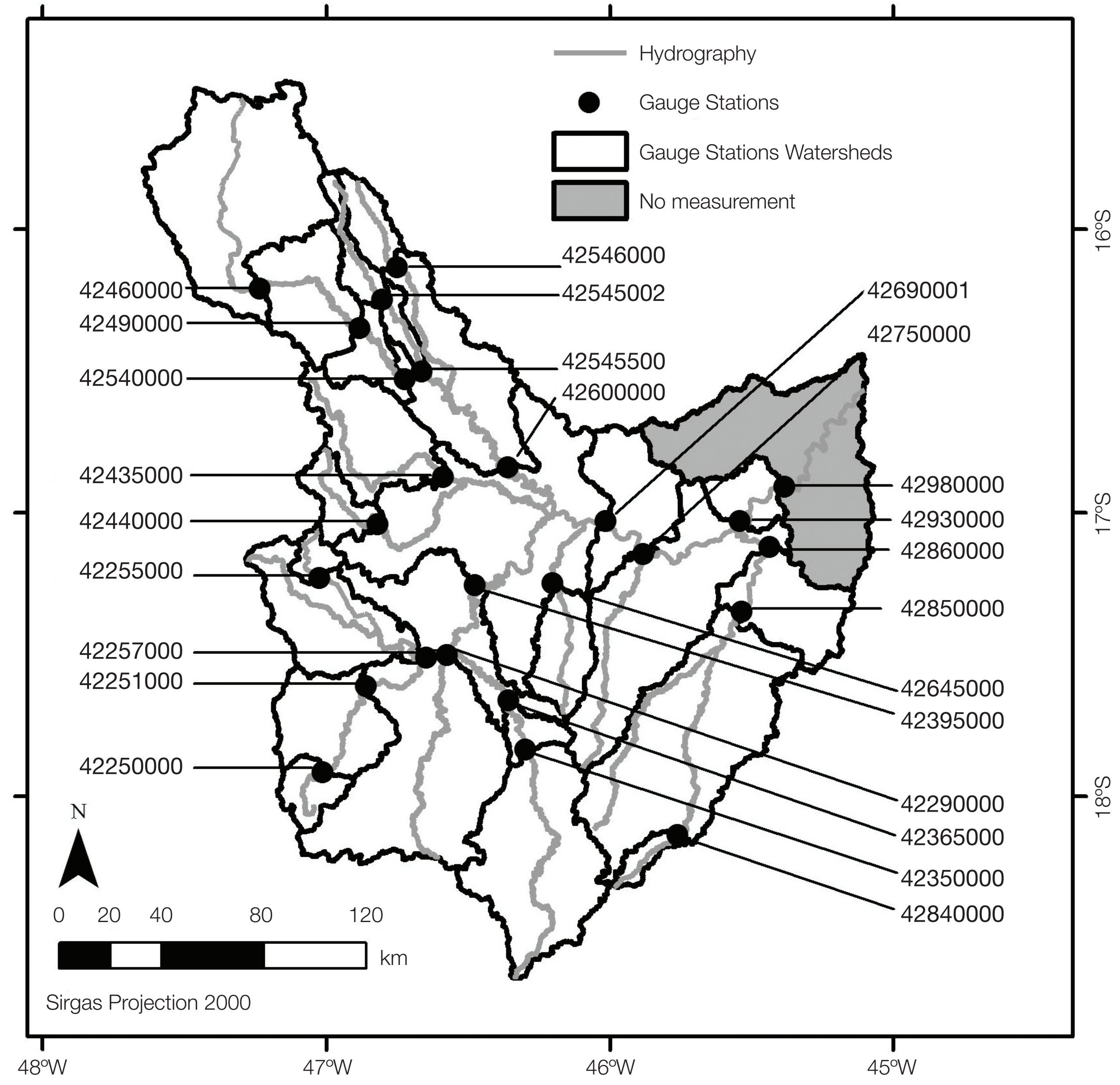


Figure 6. Gauge stations and their respective basins.

consumption does not influence the consistency of the discharge analysis for the gauging stations. However, research performed by Rodriguez (2008) demonstrated that this water consumption for irrigation presented less than 10% effect on the minimum ($Q_{7,10}$) and permanent (Q_{95}) discharges of Paracatu Basin. Vasconcelos (2010), when analyzing the study performed by Rodriguez (2008), regarding a comparison of the gauging station locations in relation to the irrigation areas, pointed that the existing gauging stations are located in the main river beds. These are far downstream from the tributaries used for irrigation, so that the readings from the gauging station already incorporate this usage, together with the discharge from larger tributaries. Thus, the impact of local irrigation is masked and is difficult to measure, although it reduces the bias in regional hydrological analyses.

Hydrograph separation

Nathan and McMahon (1990) and Albuquerque (2009) stated that the available hydrograph separation methods do not present a criterion that permits reliable delimitation of the subsurface flow, which is found in the hydrograph region between the base flow and surface discharge. To improve this situation, this study proposed combining the results of two recursive filters used as follows: calibrated in reference to the recession exponential curve for the dry season, more accurately corresponding to the base flow; and calibrated in reference to the influential point of runoff discharge using the Lynsley et al. (1975) empirical formula, which corresponds to the sum of the base with the subsurface flow. Both parameters were calibrated so that they may attend the best possible approximation to the conventional graphic projection models for the recession curve (Barnes, 1939), and the undulatory overlying of the hydrological response units (Su, 1995). In order to calibrate the runoff discharge point of influence, isolated rain peaks, without data gaps, were chosen to be in accordance with the empirical formula referred by Lynsley et al. (1975). The concept model for this type of hydrograph is presented in Figure 7.

Another problem found regarding the recursive filters is the mathematical possibility that the base flow estimation is superior to the total discharge value for the river at some hydrograph periods. To overcome this problem, Gregor (2010) proposed that a cut should be done in the overestimated discharge at the end of the filter algorithm application. Whereas, Chapman (1999) suggested (although not explicitly implements) that by using an internal constraint at each algorithmic iteration would provide greater consistency for the one-parameter filter. Adopting the recommendation from Chapman (1999), the following logic restrictor was implemented: if base flow ≤ total discharge; then, maintain base flow values; if not, base flow equals total discharge.

Table 1 presents the tested filters. The option was for one-parameter filters because they could be more objectively calibrated (Chapman, 1999).

Statistical procedures for the spatialization of the hydrogeological data in nested basins were based on its concatenation and overlap, in accordance with the methodology used by Holtschlag (1997). This allowed to elaborate

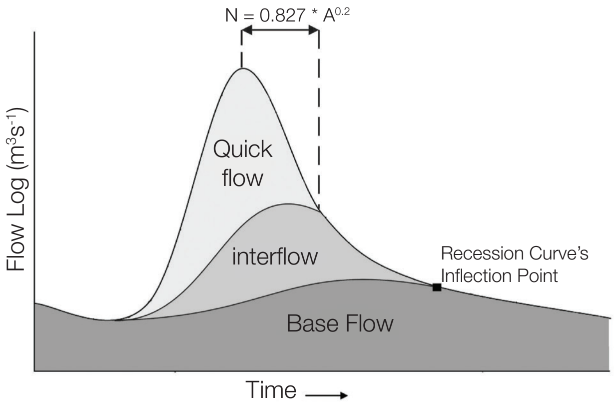


Figure 7. Conceptual hydrograph for runoff partitioning.

Table 1. Recursive filters evaluated in this paper.

Recursive Filter	Author
$q_{f(i)} = \frac{3\alpha - 1}{3 - \alpha} q_{f(i-1)} + \frac{2}{3 - \alpha} (q_{(i)} - \alpha q_{(i-1)})$	Chapman (1991)
$q_{b(i)} = \frac{\alpha}{2 - \alpha} q_{b(i-1)} + \frac{1 - \alpha}{2 - \alpha} q_{(i)}$	Chapman and Maxwell (1996)
$q_{f(i)} = \alpha q_{f(i-1)} + (q_{(i)} - q_{(i-1)}) \frac{1 + \alpha}{2}$	Lyne and Hollick (1979) – "Bflow"
$q_{b(i)} = \alpha q_{(i)} + (1 - \alpha)\ q_{b(i-1)}$	Tularam and Ilahee (2008) – "EWMA filter"

α**:** filter parameter; q: total flow; q_f: quick flow; q_b: base flow.

digital geographic information bases about the flow components' contribution towards the discharge at the stretches of the nested basins of the Paracatu River.

RESULTS AND DISCUSSION

Stationarity

The analyzed gauging stations obtained satisfactory results for stationarity tests regarding the discharge averages and variance at a 5% level of significance. Only station 4286000 was rejected from the stationary variation of minimum events at a 5% level of significance; and 42365000 was rejected for stationary variance of maximum events at a 5% level of significance. Only one of them had its average stationarity rejected at a 1% level of significance (passing the test at the 5% level). The rest of the rejections referred to variance at a 1% level.

In cases where rejection occurred during the test, their patterns and tendencies were evaluated. An attempt was made to find the breaking point, i.e., the period that best demarcates the stationary difference in accordance with the standard deviation for the constraining periods. Hydrological data analysis shows a period of frequent discharge peaks between 1976 and 1985, causing a different impact on each nested basin. Such data was in agreement with discharge studies done by plotting of the average monthly hydrographs, performed by Carvalho et al. (2004) for the Paracatu River Basin. This flood interlinking elevated the historical variances of this period, reflecting on stationarity tests for variances at a level of 1%, especially in tests for maximum events. From 1994 until 2000, there is a lessening in the discharge variance of the rivers, provoking rejection in some stationarity tests at a 1% significance level. The gauging stations referring to basins of greater contribution (for example, those on the main bed of the Paracatu River), as expected, presented less interference on variance stationarity since they dampened the flooding effects (for maximum events) and had a possible effect from the regional hydrogeologic flow (for annual averages and minimum events).

In long-term stationarity tests (1957 – 2000), the four gauging stations were approved in the test for the average stationarity of the monthly discharge at a 1% level of significance. For the stationarity test of variance, the effect of the flood peaks from 1976 to 1985 made three tests (one for monthly minimum, another for monthly average, and the last, for monthly maximum) fail the significance test at the 1% level — although they all passed at the 5% one. Analyses of the two test blocks for stationarity (one from 1957, and the other from 1976) corroborated the statement that there was a period of lesser parameter variance from 1957 to 1975, as well as from 1993 to 2000.

The good results concerning the stationarity tests for average discharge bring additional reliability for gap filling. Despite rejection of the stationarity hypothesis for variances at a significance level of 1%, it is believed that this break in stationarity does not present a mandatory impediment to the statistical procedures, considering the results presented in this study. Remember that stationary results for variance served as criteria for the selection of support stations to fill in the gaps, generating a grouping of gauging stations under similar conditions. Nonetheless, the tests presented are as a safeguard for future comparative studies.

Gap filling

As previously discussed, the available state-of-art methodological options for gap filling (EM and MI) seek a solution that is a compromise between forecast reliability and variance data maintenance. For base discharge separation (hydrogeological flow), the estimative results were analyzed with preference to a greater reliability for forecasting from the data, keeping in mind that the data filled in will be utilized in mathematical-statistical models that are sensible to temporal correlation patterns.

Figures 8 and 9 present comparative examples of the results obtained by estimation using EM and MI. In Figure 8, a gap filling was simulated for an area and original data was used for comparison. For consistency in the MI data, a constraint was used for non-negative data. In both graphics, estimation using EM came closest to the original hydrograph. Figures 8 and 9 show how estimation by MI, although following an average tendency, created an abnormal variance that did not respect the temporal correlation of the hydrograph, corroborating with the theoretical caution proposed by Cano and Andreu (2010). Although the EM line in the graph of Figure 8 is slightly above the original hydrograph, the theoretic base of this method guarantees that in filled in periods as a whole, the average and discharge variance will be the closest possible approximation with original data.

For each gauging station, gap-filling values were conferred by exploration through visual analysis of the discharge graphs, assuring that the input data was consistent from a hydrological point of view and followed the trends of the support stations.

Flow component delimitation

The filters proposed by Chapman (1991) and Chapman and Maxwell (1996) presented similar results. However, they did not demonstrate hydrological reliability, because the estimated base flow did not coincide with the recession curve during the annual dry season (Figure 10).

The filters mentioned by Lyne and Hollick (1979) and by Tularam and Ilahee (2008), after calibration, presented identical visual behaviors. Notwithstanding, the filter mentioned by Lyne and Hollick (1979) was chosen because it is the most widely found in literature (Lim et al., 2005; Combalicer et al., 2008; Asmeron, 2008; Santhi et al., 2008; Albuquerque, 2009; Welderufael and Woyessa, 2010; Biller, 2010), making it easier to compare with other studies.

The end of the N period (number of days after the hydrographic peak, when the runoff discharge participation ceased) of Lynsley et al. (1975) empirical equation coincided in a greater part of the hydrographs, with a change in the inclination of the depletion line for the rain peak, corroborating with the reliability of its application. Calibrating the filters with the combined double parameters made it possible to clearly separate the interflow wave from the base one (Figure 11).

For the two stations of the isolated series (inferior to the period of the main block), a comparison of the chosen filter with the support stations was done during the same period for which a series of data was available. Following this, the results were compared with those for the complete period (1976 – 2001). Average annual discharge value variation, base flow, interflow, and quick flow were used to adjust the respective results for the filter on the isolated series. The average adjustment for the basin data for station 42350000 (1974 – 1984) was -9%, while for 42645000 (1973 – 1981), it was -0.63%.

The results of the calibrated application of the filter at each station and the concatenation of the drainage basins with the data concerning total discharge, quick flow, interflow, and base flow, including the specific discharge, are presented in Tables 2 and 3.

For comparison, Table 3 also presents the base flow index (BFI) as a result from hydrograph separation of some of the stations when using Barnes (1939) graphic method, performed by CETEC (1981) and RURALMINAS (1996).

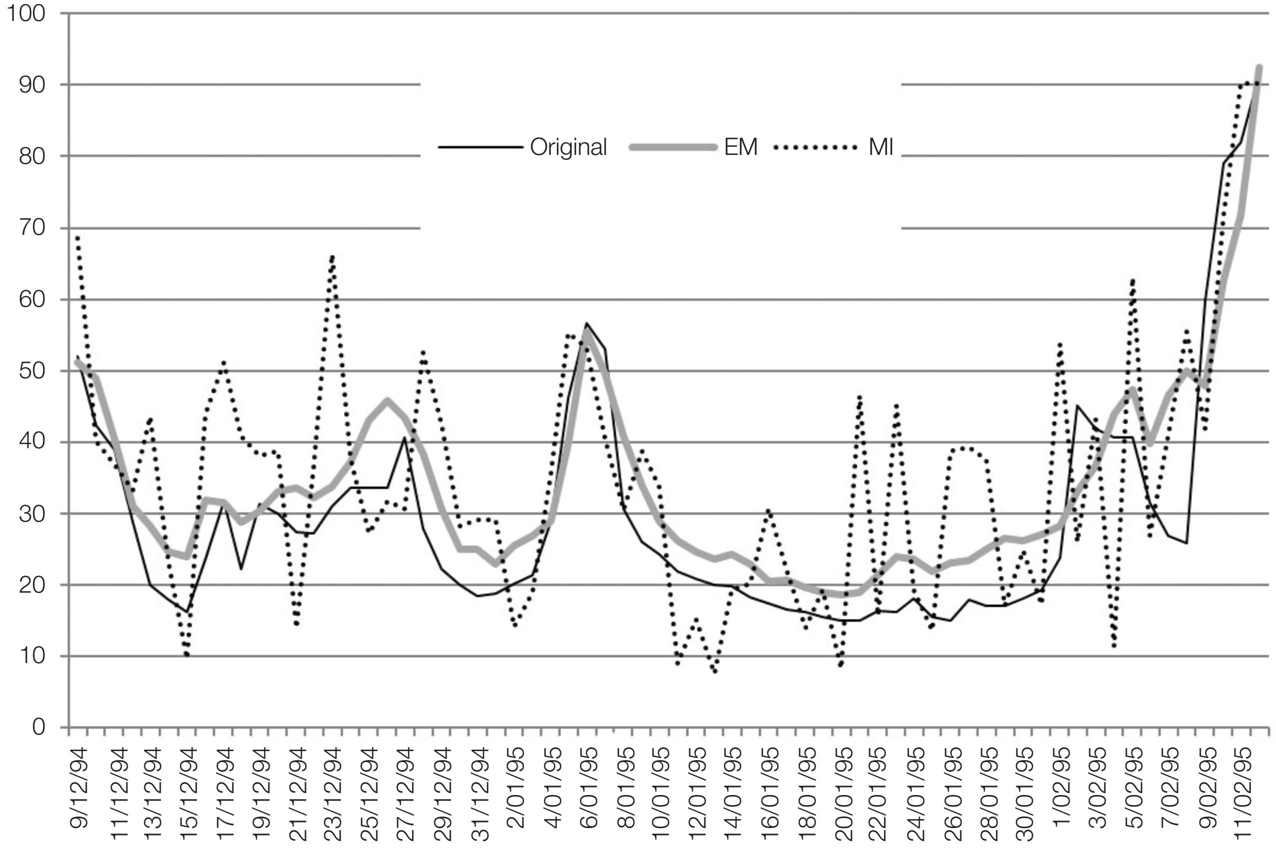


Figure 8. Graph comparing gap filling during the rainy season for Station 42251000 by expectation maximization (EM) and multiple imputation (MI). Excerpt from the hydrologic year of 1994. The support stations used for the gap filling by EM and MI were: 42250000, 42255000, 42257000, 42290000, 42350000, and 42365000, for which discharge data were available for the hydrologic years from 1965 to 2005.

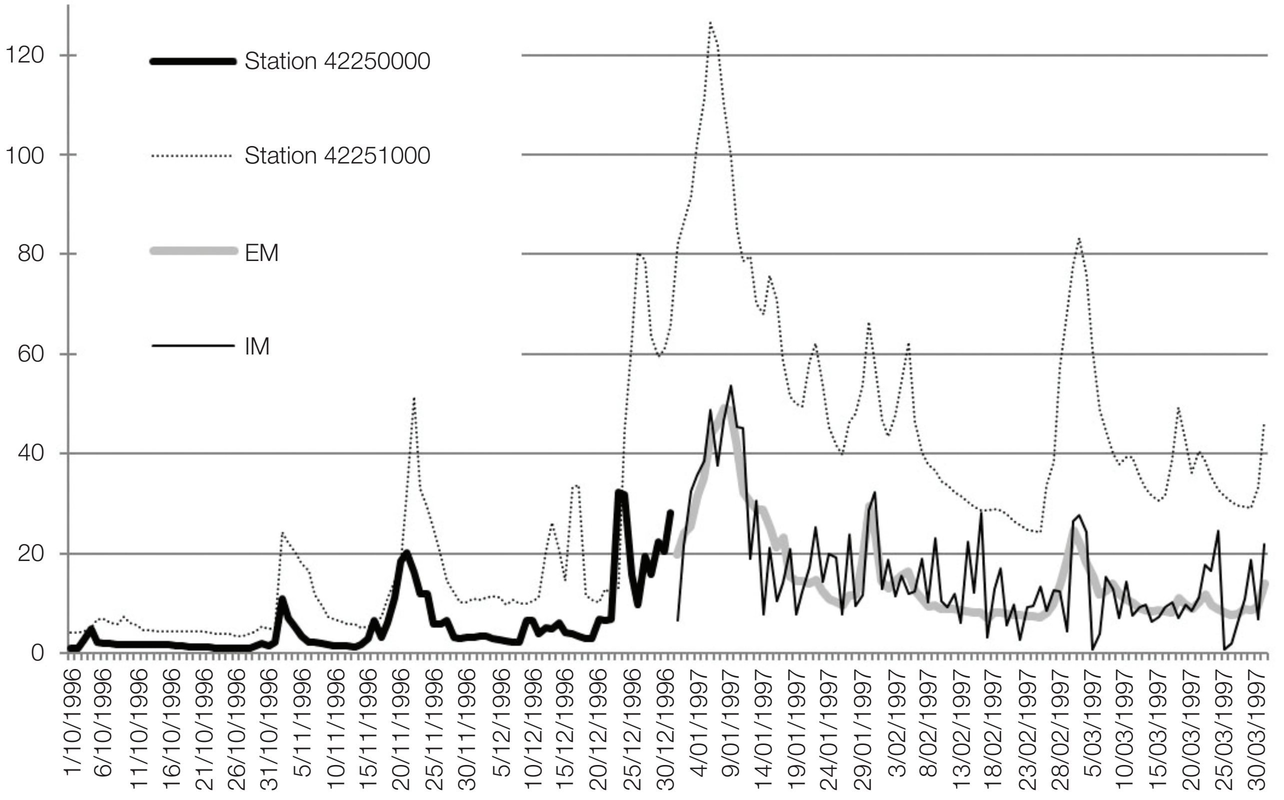


Figure 9. Graph comparing gap filling during the rainy season for Station 42250000 by expectation maximization (EM) and multiple imputation (MI), in the hydrologic year of 1996. Station 42251000 is immediately downstream from the 42250000 one.

The delimitation in RURALMINAS (1996) was done for 1939 to 1989, while the delimitation in CETEC (1981) used only one hydrological year, between 1969 and 1974 for different stations. The BFI, which is equivalent to the division of the base flow by the total discharge, is relatively stable at long term in basins, even with the annual discharge variations, which makes feasible the comparison between estimates of different periods (Santhi et al., 2008). Comparison of the estimated indexes from the recursive filters with the estimated base flow by graphic methods demonstrated similar tendencies. Notwithstanding, with data presented in Table 3, it is possible to perceive how the graphic method incorporates in different proportions the interflow in relation to the base flow in each basin, demonstrating the inherent subjectivity of this technique.

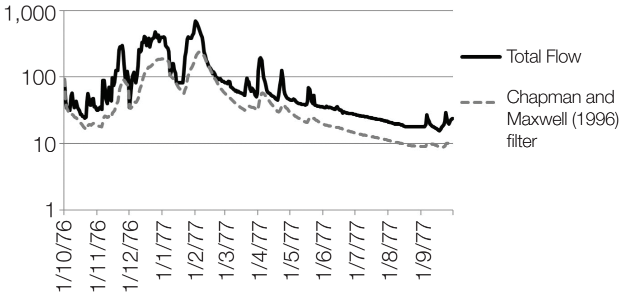


Figure 10. Application of the Chapman and Maxwell Filter (1995), with parameter α = 0.925, for the daily discharge data from Station 42290000, hydrologic year of 1976. Discharge is in logarithmic scale. Notice that the estimated discharge for the base flow during the dry season does not coincide with the total one.

As can be seen in Table 2, the average of parameters (α, as presented in Table 1) calibrated for the filters (in the two calibration forms) is superior to 0.925, which is referenced in literature (Nathan and McMahon, 1990; Ghanbarpour, Teimouri, Gholami, 2008). Despite the fact that the hydrological characteristics of Paracatu River Basin have their differences in relation to basins with a temperate climate, this study case generated a hypothesis that the lack of calibration for the influence of runoff discharge, together with the inflexion of the recession curve, could have led the studies with filters, performed in preexisting ones, to overestimate the base flow discharge values. This is in agreement with Asmeron (2008), who stated that the 0.995 parameter seemed more coherent with the hydrographic curves for the Blue Nile Basin in Ethiopia.

Analysis of the specific discharge maps (Figure 12) collated in Tables 2 and 3 shows that the base flow contribution is more significant at the headwaters of the basin because of heavier rainfall, especially in the western portion. This

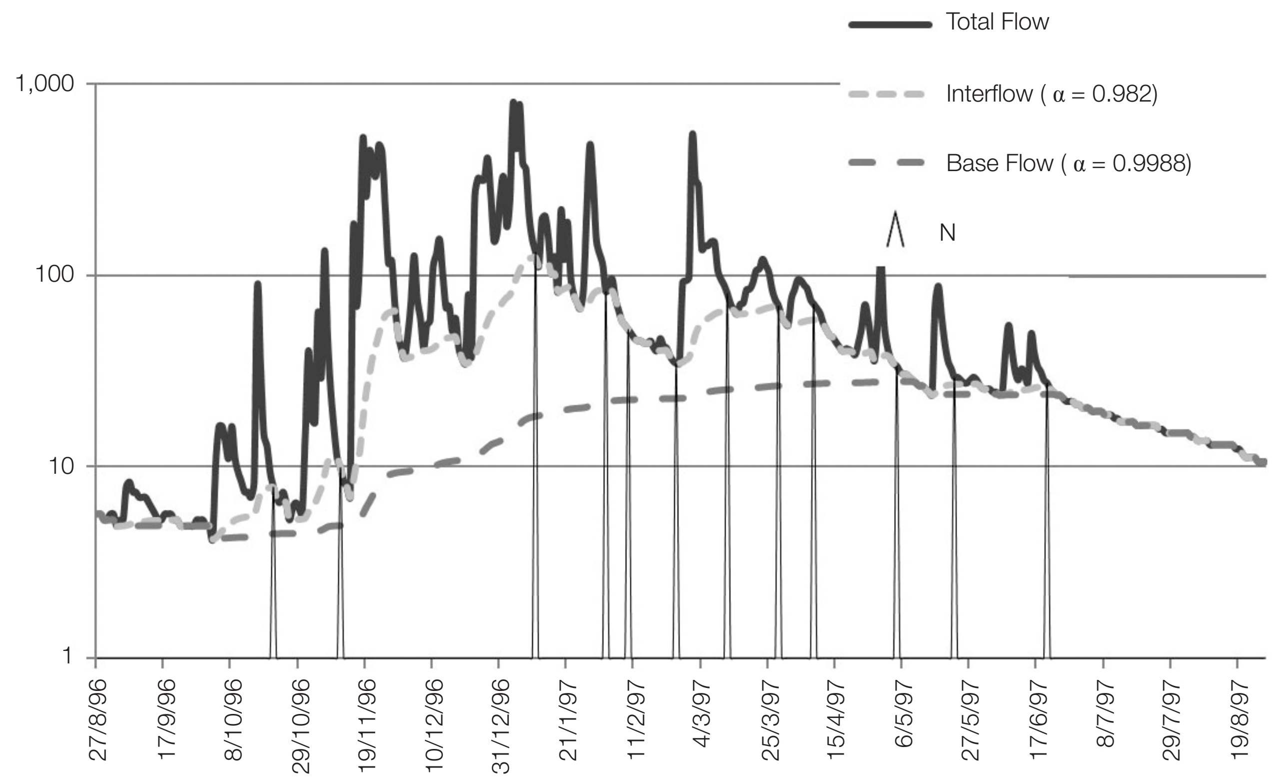


Figure 11. Separation of the interflow and base flow at Station 42860000, hydrologic year of 1996, using a Bflow filter (Lyne and Hollick, 1979). The arrows indicate the dates (N) that correspond to the moments in which runoff discharge influence ceased, according to Lynsley et al. (1975) empirical equation.

configuration also reinforces the recharge role of the plateaus that have a porous sedimentary lithology at the basin headwaters. As the stream flows downward towards the lowlands of the central area of Paracatu Basin, the base flow contribution becomes significantly less expressive. This result is also coherent with that related by Tucci (2002), who observed a specific discharge reduction as basin area increased in many flow records of rivers in Brazil.

However, it is interesting to note how certain increases in specific total discharge, base, and interflow occur after stations 42930000 (Lower Paracatu), 42490000 (Middle Preto River) and 42350000 (Lower Prata River). It is possible that there are regional underground flows crosscutting below the station and surface downstream. This phenomenon seems to mainly occur in areas that have shallow lateritic-debris porous aquifers, which receive water from Karstic-fissured aquifers.

As a final comment, it is necessary to recognize that the automatic hydrographic separation methods analyze only form patterns of waves representing discharge pulses, and as such, they do not directly identify the source of discharge components. Therefore, the automatic method results are referred to hydrogeological processes only as the base flow, interflow, and quick flow really correspond to underground, subsurface, and runoff flows respectively. In this context, Kirchner (2003) and Gonzales et al. (2009) studies can be cited for demonstrating that the regional groundwater flow generally responds to rain as quickly as runoff does, due to the piston effect of precipitation in the recharge areas of the basin, while the clay soil of the lowlands retards and dilutes the interflow for a more ample period. In areas under Karstic influence, there is also a plausible hypothesis in that the interflow partially corresponds to the endokarstic duct flow, even after runoff discharge has finished. These hypotheses bring forward a recommendation that future studies with tracers could improve the understanding of hydrogeological processes involved.

CONCLUSIONS

The stationary analysis brought greater reliability to the knowledge about the Paracatu River Basin discharge. The discharge gap-filling measures estimation by EM were more reliable than those estimated by the MI for data from the gauging station series used in this study. However, scientific literature as well as management entities would greatly benefit if future studies involved a more comprehensive, systematic, quantitative, and comparative analysis of EM and MI methods' efficiency.

The Bflow (Lyne and Hollick, 1979) and EWMA (Tularam and Ilahee, 2008) filters demonstrated a behavior that was consistent for hydrograph separation. Chapman (1991) and Chapman and Maxwell (1996) filters did not behave consistently, since in several temporal segments, they did not match the recession curve during the dry season.

With the double calibration method presented in this study, it became possible to estimate more reliably the base flow, interflow, and quick flow. The logic restrictor did not permit overestimation of the discharge, increasing the consistency of the results, which were coherent with Barnes (1939) manual graphic method, although the filters more reliably distinguished the difference between the base flow

Table 2. Area data, N (days of runoff discharge influence – Linsley et al., 1979), utilized BFLW filter parameters and annual discharge of the base flow, interflow and quick flow.

Code	River	Station	Basin area (km^2)	Area of the concatenated strech	N (day)
42250000	Claro River	Limoeiro Farm	462.59	462.59	2.83
42251000	Escuro River	Córrego do Ouro Farm	1,881.39	1,418.80	3.73
42255000	Santa Isabel Stream	Nolasco Farm	247.83	247.83	2.51
42257000	Escurinho River	Barra do Escurinho	1,997.82	1,749.99	3.79
42290000	Paracatu River	BR-040 Bridge	7,730.41	3,851.20	4.94
42350000	Prata River	Porto Diamante	3,009.88	3,009.88	4.12
42365000	Prata River	BR-040 Bridge	3,337.19	327.31	4.23
42395000	Paracatu River	Santa Rosa	12,808.72	1,741.12	5.49
42435000	Barra da Égua Creek	Barra da Égua Farm	1,589.26	1,589.26	3.56
42440000	São Pedro Creek	Poções Farm	553.24	553.24	2.95
42460000	Preto River	Limeira Farm	3,926.72	3,926.72	4.27
42490000	Preto Preto	Unaí	5,388.18	1,461.46	4.58
42540000	Preto River	Santo Antônio do Boqueirão	5,956.22	568.04	4.68
42545002	Roncador Creek	Roncador Farm	425.39	425.39	2.90
42545500	Roncador Creek	"O"Resfriado Farm	681.70	256.31	3.12
42546000	Salobro Creek	Santa Cruz Farm	527.35	527.35	2.84
42600000	Preto River	Porto dos Poções	9,453.35	2,288.08	5.14
42645000	Verde River	Rio Verde Farm	879.53	879.53	3.29
42690001	Paracatu River	Porto da Extrema	30,162.26	4,878.16	6.49
42750000	Paracatu River	Caatinga	31,620.35	1,458.09	6.55
42840000	Santo Antônio River	Veredas	214.59	214.59	2.41
42850000	Sono River	Cachoeira das Almas	4,372.21	4,157.62	4.40
42860000	Sono River	Cachoeira do Paredão	5,697.26	1,325.05	4.63
42930000	Paracatu River	Porto do Cavalo	40,787.63	3,470.01	6.89
42980000	Paracatu River	Porto Alegre	41,353.26	565.63	6.92

Continues...

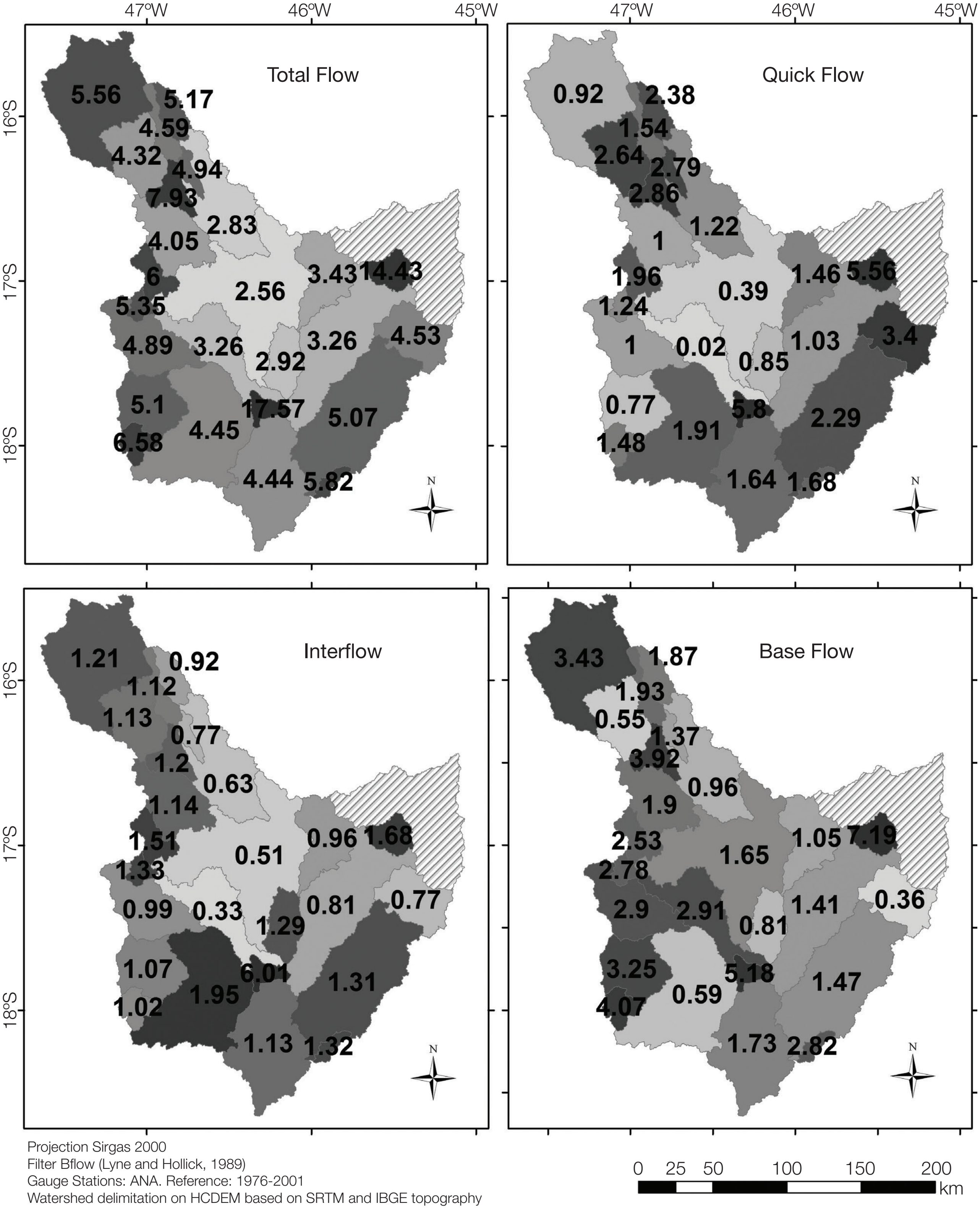
Table 2. Continued

Code	Bflow Filter's α parameter		Annual discharge by basin (m^3.s)				Annual Discharge by stretch (m^3.s)			
	Base flow	Interflow	Total	Base	Interflow	Quick	Total	Base	Interflow	Quick
42250000	0.991	0.94	3,042.14	1,883.82	471.49	686.83	3,042.14	1,883.82	471.49	686.83
42251000	0.992	0.932	10,272.11	6,495.71	1,992.04	1,784.36	7,229.97	4,611.89	1,520.55	1,097.53
42255000	0.996	0.935	1,327.04	688.61	330.45	307.99	1,327.04	688.61	330.45	307.99
42257000	0.994	0.96	9,883.07	5,762.31	2,058.92	2,061.84	8,556.03	5,073.70	1,728.47	1,753.85
42290000	0.998	0.96	37,296.61	14,536.76	11,555.12	11,204.74	17,141.43	2,278.74	7,504.16	7,358.54
42350000	0.9985	0.977	13,357.42	5,204.40	3,412.75	4,931.70	13,357.42	5,204.40	3,412.75	4,931.70
42365000	0.9985	0.95	19,107.86	6,898.34	5,380.98	6,828.54	5,750.44	1,693.94	1,968.23	1,896.84
42395000	0.998	0.97	62,072.30	26,502.71	17,505.78	18,063.81	5,667.83	5,067.61	569.68	30.53
42435000	0.9963	0.965	6,431.05	3,020.66	1,819.63	1,591.02	6,431.05	3,020.66	1,819.63	1,591.02
42440000	0.997	0.965	3,318.21	1,397.94	833.45	1,086.83	3,318.21	1,397.94	833.45	1,086.83
42460000	0.9955	0.955	21,837.01	13,473.71	4,747.93	3,615.37	21,837.01	13,473.71	4,747.93	3,615.37
42490000	0.997	0.965	28,146.95	14,271.79	6,403.81	7,471.35	6,309.94	798.08	1,655.88	3,855.98
42540000	0.997	0.97	32,653.45	16,498.50	7,085.02	9,096.94	4,506.50	2,226.71	681.21	1,625.59
42545002	0.998	0.94	1,952.24	819.43	478.42	654.39	1,952.24	819.43	478.42	654.39
42545500	0.9983	0.965	3,217.61	1,170.18	676.74	1,370.70	1,265.37	350.75	198.32	716.31
42546000	0.999	0.975	2,726.97	983.94	486.62	1,256.41	2,726.97	983.94	486.62	1,256.41
42600000	0.9974	0.975	45,070.14	20,855.40	9,701.16	14,513.58	6,472.11	2,202.78	1,452.78	2,789.53
42645000	0.999	0.935	2,567.18	711.90	1,137.07	746.55	2,567.18	711.90	1,137.07	746.55
42690001	0.9971	0.973	131,929.40	60,558.86	33,475.50	37,895.04	12,470.52	8,070.25	2,478.41	1,893.25
42750000	0.9971	0.97	136,929.60	62,092.17	34,873.59	40,026.83	5,000.20	1,533.31	1,398.09	2,131.79
42840000	0.9985	0.955	1,249.75	605.35	284.31	360.09	1,249.75	605.35	284.31	360.09
42850000	0.9984	0.975	22,337.61	6,721.81	5,745.23	9,870.57	21,087.86	6,116.46	5,460.92	9,510.48
42860000	0.9988	0.982	28,339.20	7,201.71	6,759.19	14,378.40	6,001.59	479.90	1,013.96	4,507.83
42930000	0.9976	0.976	176,576.10	74,173.48	44,433.48	57,969.10	11,307.30	4,879.60	2,800.70	3,563.87
42980000	0.998	0.978	184,740.70	78,241.19	45,384.84	61,114.66	8,164.60	4,067.71	951.36	3,145.56

and interflow. The values found for the Bflow filter parameters were superior to the standard ones found in literature. This could mean that the pre-existing studies with this filter might have overestimated the base flow, even when the subsurface flow was incorporated into their values.

As a suggestion for future studies, the methodology proposed in this article could be enhanced by algorithm developments for automatic calibration of the filters. The automatic identification of the recession curve's inflection point is already performed by BFI algorithm (Wahl and Wahl, 1988, 1995), and Lynsley et al. (1975) empirical formula is already incorporated in algorithms, such as Rora and Part (Rutledge, 1993, 1998).

The cartographic presentation of the specific discharge of the base flow and interflow of the downstream nested basins demonstrated coherency with studies and geo-referenced bases from climatology and hydrogeology (Figures 4 and 5). The maps are useful products for watershed management.



Projection Sirgas 2000
Filter Bflow (Lyne and Hollick, 1989)
Gauge Stations: ANA. Reference: 1976-2001
Watershed delimitation on HCDEM based on SRTM and IBGE topography

Figure 12. Maps for the specific discharge and flow components of each section of the basin.

Table 3. Specific annual discharge and discharge indexes for base flow, interflow, and quick flow in the Paracatu River Basin.

	Base flow index using Barnes (1939) Graphic Method		Index per basin			Index for the stretch			Specific discharge by basin ($m^3.s/km^2$)				Specific discharge by stretch ($m^3.s/km^2$)			
Code	CETEC (1981)	Ruralminas (1996)	Base	Interflow	Quick	Base	Interflow	Quick	Total	Base	Interflow	Quick	Total	Base	Interflow	Quick
42250000	–	0.61	0.62	0.15	0.23	0.62	0.15	0.23	6.58	4.07	1.02	1.48	6.58	4.07	1.02	1.48
42251000	–	0.66	0.63	0.19	0.17	0.64	0.21	0.15	5.46	3.45	1.06	0.95	5.10	3.25	1.07	0.77
42255000	–	0.64	0.52	0.25	0.23	0.52	0.25	0.23	5.35	2.78	1.33	1.24	5.35	2.78	1.33	1.24
42257000	–	–	0.58	0.21	0.21	0.59	0.20	0.20	4.95	2.88	1.03	1.03	4.89	2.90	0.99	1.00
42290000	–	0.51	0.39	0.31	0.30	0.13	0.44	0.43	4.82	1.88	1.49	1.45	4.45	0.59	1.95	1.91
42350000	0.30	0.58	0.39	0.26	0.37	0.39	0.26	0.37	4.44	1.73	1.13	1.64	4.44	1.73	1.13	1.64
42365000	–	–	0.36	0.28	0.36	0.29	0.34	0.33	5.73	2.07	1.61	2.05	17.57	5.18	6.01	5.80
42395000	0.32	–	0.43	0.28	0.29	0.89	0.10	0.01	4.85	2.07	1.37	1.41	3.26	2.91	0.33	0.02
42435000	–	0.57	0.47	0.28	0.25	0.47	0.28	0.25	4.05	1.90	1.14	1.00	4.05	1.90	1.14	1.00
42440000	–	0.58	0.42	0.25	0.33	0.42	0.25	0.33	6.00	2.53	1.51	1.96	6.00	2.53	1.51	1.96
42460000	–	0.74	0.62	0.22	0.17	0.62	0.22	0.17	5.56	3.43	1.21	0.92	5.56	3.43	1.21	0.92
42490000	–	–	0.51	0.23	0.27	0.13	0.26	0.61	5.22	2.65	1.19	1.39	4.32	0.55	1.13	2.64
42540000	–	0.66	0.51	0.22	0.28	0.49	0.15	0.36	5.48	2.77	1.19	1.53	7.93	3.92	1.20	2.86
42545002	–	–	0.42	0.25	0.34	0.42	0.25	0.34	4.59	1.93	1.12	1.54	4.59	1.93	1.12	1.54
42545500	–	–	0.36	0.21	0.43	0.28	0.16	0.57	4.72	1.72	0.99	2.01	4.94	1.37	0.77	2.79
42546000	–	–	0.36	0.18	0.46	0.36	0.18	0.46	5.17	1.87	0.92	2.38	5.17	1.87	0.92	2.38
42600000	0.69	0.62	0.46	0.22	0.32	0.34	0.22	0.43	4.77	2.21	1.03	1.54	2.83	0.96	0.63	1.22
42645000	0.43	0.54	0.28	0.44	0.29	0.28	0.44	0.29	2.92	0.81	1.29	0.85	2.92	0.81	1.29	0.85
42690001	–	0.58	0.46	0.25	0.29	0.65	0.20	0.15	4.37	2.01	1.11	1.26	2.56	1.65	0.51	0.39
42750000	–	0.59	0.45	0.25	0.29	0.31	0.28	0.43	4.33	1.96	1.10	1.27	3.43	1.05	0.96	1.46
42840000	–	0.60	0.48	0.23	0.29	0.48	0.23	0.29	5.82	2.82	1.32	1.68	5.82	2.82	1.32	1.68
42850000	–	–	0.30	0.26	0.44	0.29	0.26	0.45	5.11	1.54	1.31	2.26	5.07	1.47	1.31	2.29
42860000	0.32	0.51	0.25	0.24	0.51	0.08	0.17	0.75	4.97	1.26	1.19	2.52	4.53	0.36	0.77	3.40
42930000	–	–	0.42	0.25	0.33	0.43	0.25	0.32	4.33	1.82	1.09	1.42	3.26	1.41	0.81	1.03
42980000	0.48	0.55	0.42	0.25	0.33	0.50	0.12	0.39	4.47	1.89	1.10	1.48	14.43	7.19	1.68	5.56

The methodology developed for this study is easily replicable for other Brazilian basins, as well for those worldwide, whenever gauging station information is available. The reliability verification of its results, however, does not mean that a more extensive understanding of the hydrological, hydrogeological, and climatic phenomena occurring at the basins is not necessary.

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