Estimating the impact of climate change on water levels in a data-poor river basin in southeastern Brazil

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ABSTRACT

In basins with multiple water uses, it is possible a conflict over water use may occur. This probability increases under a water scarcity scenario. Therefore, it is important to estimate the possible impact of climate change on water availability in this type of basin, to support the decision-making of its users. The Ribeirão do Cipó is an example of a Brazilian watershed susceptible to this situation. Besides having poor hydrological data, it is used for public water supply, electricity generation and recreation. The present work developed a methodology for estimating water availability impacted by climate change, which was particularly applied to this watershed. The methodology consisted of feeding the rainfall–runoff hydrological model called soil moisture accounting procedure with precipitation and evapotranspiration data projected by the Eta-CPTEC regional climate model and nested to three global climate models. The outputs methods were obtained in terms of average monthly flow, for 2010–2039, 2040–2069 and 2070–2099 for the representative concentration pathway (RCP) 4.5 and RCP 8.5 scenarios. Despite the small amount of hydrological data available on the basin, the results were similar to those of the methods used as reference, thus demonstrating that the methodology used can be an alternative in estimating flow for climate change scenarios.

Key words: Average monthly flow, Climate models, Hydrologic modeling, Multiple uses, Small river basins, Water availability

HIGHLIGHTS

- Methodology for estimating flows affected by climate change in a small basin.
- Comparison of projected and historical period allows a solid method to estimate flows for basins with lack of data.
- Higher CO_2 concentration has a direct correlation with maximum flows.
- The forecast model results show a methodology consistency.
- Long projection did not preclude the flow simulation since the models did not present anomalies.

GRAPHICAL ABSTRACT
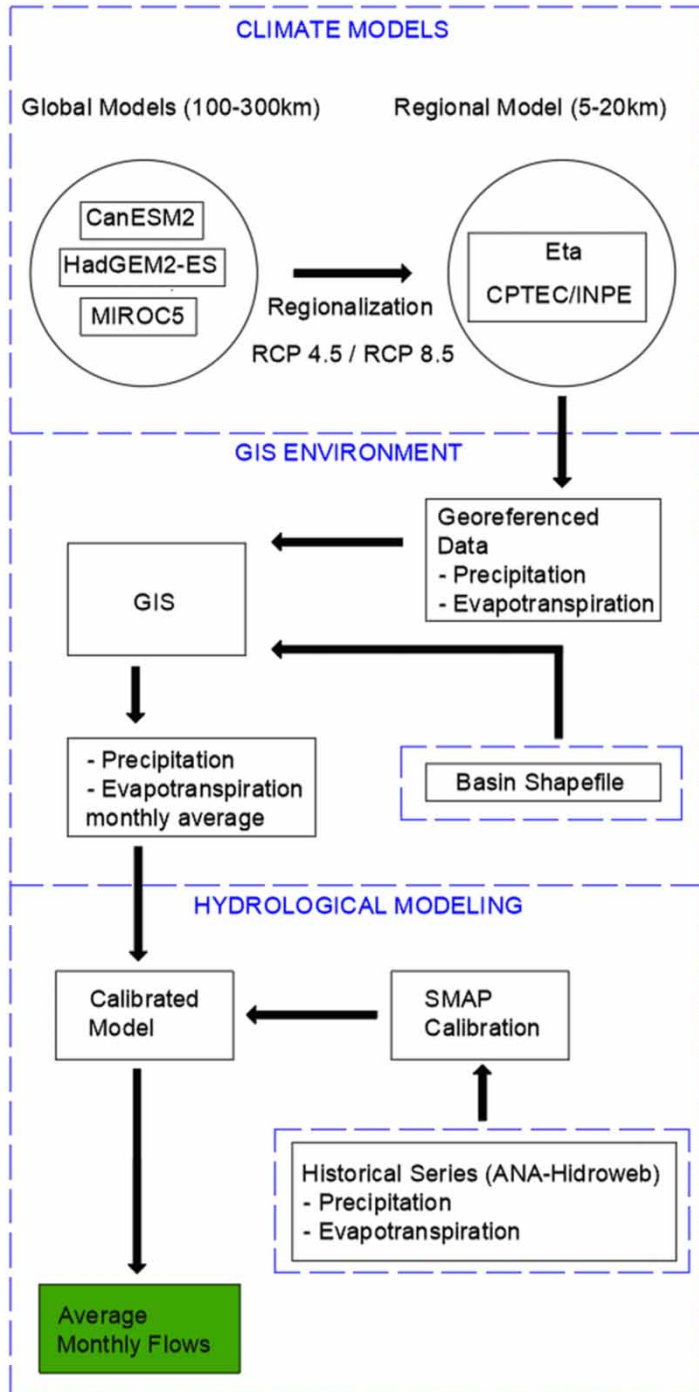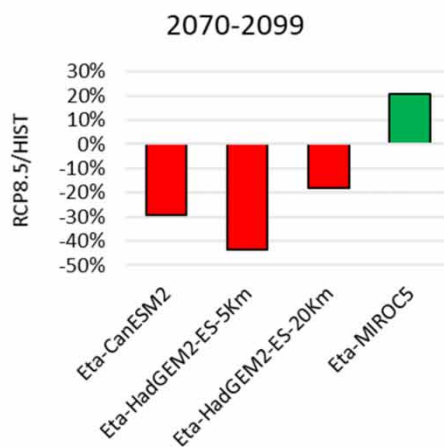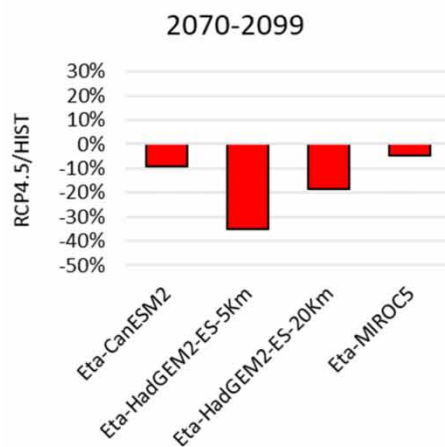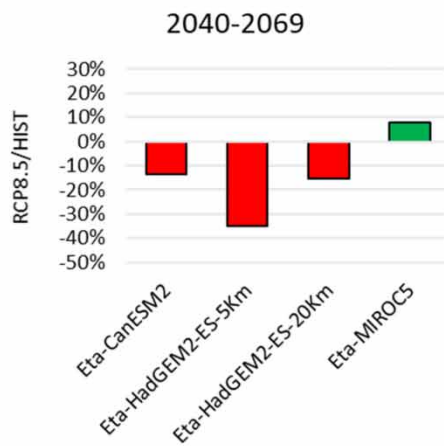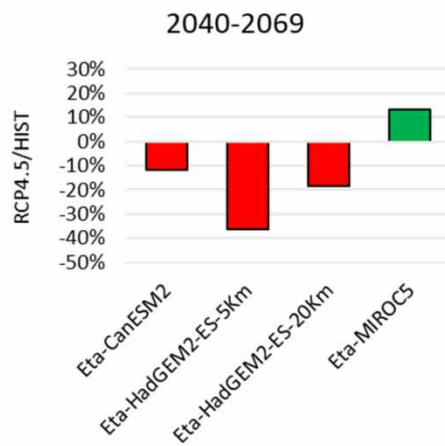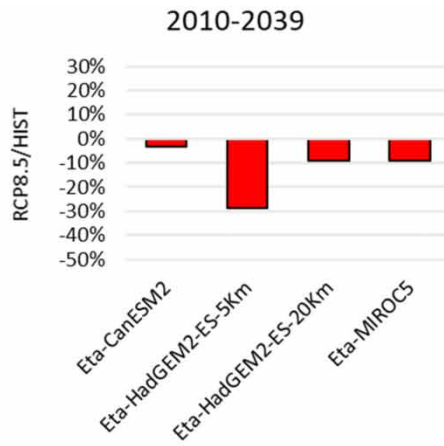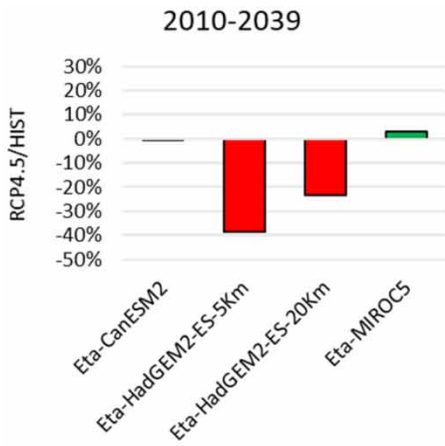
INTRODUCTION

The greenhouse effect is a natural process which occurs in the world due to the absorption of solar radiation by gases present in the atmosphere, such as carbon dioxide (CO_2). However, the planet is suffering an additional warming as a result of the emission of greenhouse gases by human activities. The proportionality between the concentration of CO_2 in the atmosphere and the average global temperature is an indication of warming (Arrhenius, 1896; Revelle & Suess, 1957; Tucci, 2005; Callendar, 2007; Silva, 2015).

The emissions have reached their highest levels nowadays. According to the Intergovernmental Panel on Climate Change (IPCC, 2014), it is evident that anthropogenic actions are changing the climate and these changes are affecting various natural systems.

The hydrological cycle is one of the affected systems. In addition to the increase in global temperature, climate change causes changes in precipitation and evapotranspiration regimes which in turn influence water availability in river basins (Tucci, 2005).

The Cipó River watershed, focus of this study, has a regularization dam serving five hydroelectric plants operating downstream, totaling an installed capacity of approximately 34.7 MW (ERHA, 2012). The same dam still allows the capture of 0.42 m^3/s for public water supply, besides being a place for tourism and leisure. Considering these multiple uses of the water resource, it is important that there is information to support the decision-making regarding the management of this resource (SUPRAM, 2012).

CIPÓ RIVER BASIN (CIPÓ DAM)

The water resources of the municipality of Poços de Caldas are comprised of the Rio Grande Basin. The basin belongs to the Paraná Hydrographic Region in the southeast of the country and occupies an area of approximately 143,000 km^2 divided between the states of São Paulo and Minas Gerais (CBH Grande, 2019). Figure 1(a) illustrates the delimitation of the basin.

In 2006, 35 conflicts were identified over the use of water resources in the basin. To manage these conflicts and other aspects of this important basin, there is the River Basin Committee, known as CBH Grande. Since it includes more than one state, this is an interstate committee (CBH Grande, 2019).

According to Figure 2(b), the Rio Grande Basin is composed of 14 tributary basins, the so-called Water Resources Management Units (UGRHs), six of them in São Paulo and eight in Minas Gerais. All of them also have their state committees, and the basin comprising the municipality of Poços de Caldas is the Hydrographic Basin of the Minas Gerais Affluents of the Mogi-Guaçu and Pardo Rivers, managed by the GD6 Committee (CBH Grande, 2019).

The committee has already developed the Water Resources Plan within the management instruments, regulated the Right to Use Water Resources and is also implementing the Water Resources Information System (IGAM, 2019).

Water Resources Plan established five components to define goals and objectives in different planning horizons to achieve a projected reality for the watershed. Among these components, Water Availability and Extreme Hydrological Events (IGAM, 2010) stand out.

Concerning extreme events, the plan predicts the expansion of the hydrometeorological monitoring network and the implementation of warning systems. These programs are mainly aimed at foreseeing and reducing the effects of floods. However, extreme aridity events may also occur, which will influence water availability (IGAM, 2010).

The GD6 management unit has nine reservoirs. Seven of them are located in Poços de Caldas, with the exception of the Saturnino de Brito Dam, all are downstream of the Cipó Dam, which is a sub-basin of the Pardo River.
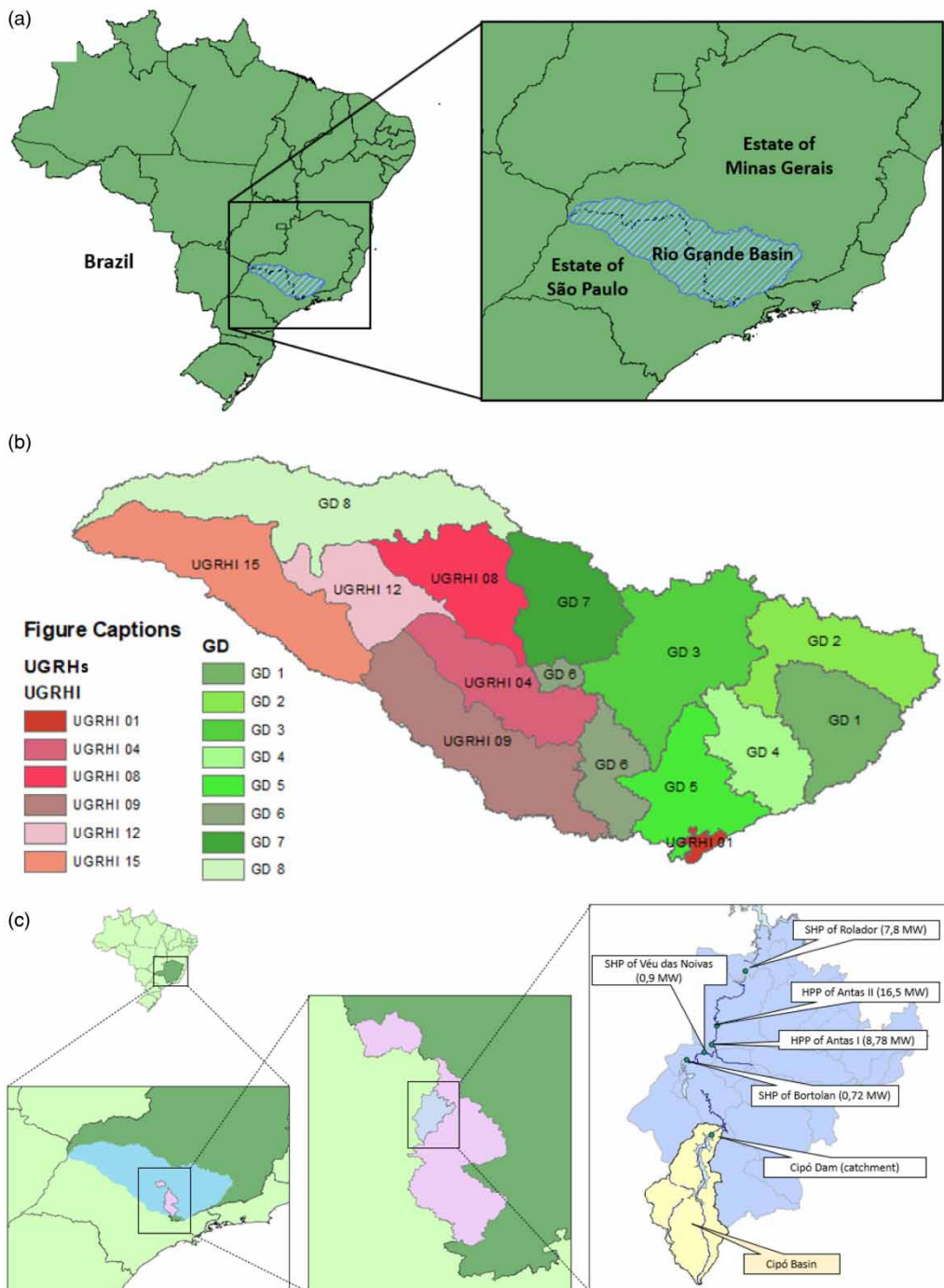
Fig. 1 | (a) Location and delimitation of the Rio Grande Basin. (b) Map of the affluent hydrographic basins of the Rio Grande Basin. (c) Location and delimitation of the study area – Cipó River Basin. UGRHI = UGRHs of São Paulo; GD = UGRHs of Minas Gerais. *Sources*: (a) and (b) adapted from CBH Grande (2019); (c) by authors.
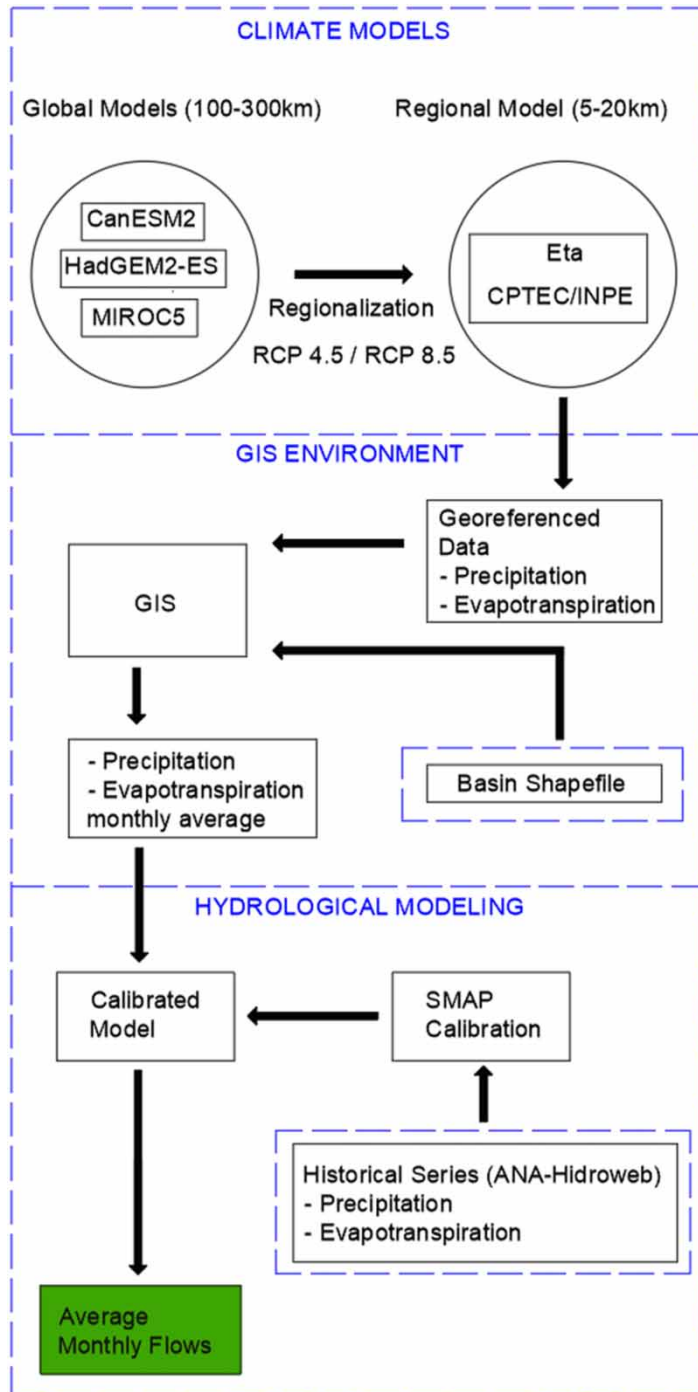
Fig. 2 | Map of the processes performed in the methodology development, subdivided into three macro steps: climate models, GIS environment and hydrological modeling. *Source*: by authors.

The presence of the main reservoirs of the Pardo River basin under the influence area of the dam indicates the strategic importance of the Cipó River Basin for the management of water resources in the region.

According to the Water Resources Plan, the Ribeirão das Antas watershed, which encompasses the Cipó River watershed and the Saturnino de Brito dam, was declared in a conflicting condition in 2009 by the Minas Gerais Institute of Water Management (IGAM). The reason was a request for a grant in the previous year when it was verified that the limit flow for grants had already been exceeded. The grant is the instrument whereby the state government authorizes a user to utilize or interfere in a water resource when it has verified the capacity of water use without jeopardizing its other functions (DAEE, 2019). Although at that time new requests for grants were suspended, the basin is no longer in a state of conflict according to the official method adopted by the state of Minas Gerais to calculate the $Q_{7.10}$ flow, which corresponds to a specific minimum flow of 7 days of duration and a return period of 10 years. The plan also points out that even though it is within the authorized flow limit, the Ribeirão das Antas Basin is very near this one in comparison to the neighboring basins (IGAM, 2010).

As can be noted in Table 1, most reservoirs have the purpose of generating energy. The city of Poços de Caldas has its electrical energy services provided by the municipal autarky known as the Municipal Department of Electricity (DME).

Although this large use of water resources is focused on power generation, there are other demands for reservoir water, especially for water collection for public supply, which in the municipality is carried out by the Municipal Department of Water and Sewage (DMAE).

These multiple uses require an integrated management of the resource. In the past, a strong drought led to a drop in the level of the Cipó River Dam, thus compelling the concessionaire to reduce its energy generation for guaranteeing water supply. The solution to this energy generation deficit was to purchase it from the market, which caused an increase in costs for consumers.

Considering the importance attributed by the basin committee to issues related to water availability and extreme events, the history of conflicts resulting from the use in the studied site as well as the repetition of this problem in other regions, the purpose of this study was found. Therefore, a methodology for forecasting flows impacted by climate change was investigated and adapted for the basin under consideration, which could be reproduced elsewhere.

REFERENCE METHODS

Lopes et al. (2008) developed a model for estimating flows to the National Interconnected System (SIN) for electricity production using climate forecasts. Precipitation estimates for South America were used by the Center for Weather Forecasting and Climate Studies (CPTEC), spatially distributed in 200 km × 200 km grids and at

Table 1 | Countries with their respective GCMs, name of the institution where they were developed, RCP scenarios and resolution used.

Country	Model	Institution	RCP scenarios	Resolution
Canada	CanESM2	Canadian Centre for Climate Modeling and Analysis	4.5/8.5	20 × 20 km
England	HadGEM2-ES	Met Office Hadley Centre	4.5/8.5	5 × 5 km
England	HadGEM2-ES	Met Office Hadley Centre	4.5/8.5	20 × 20 km
Japan	MIROC5	Japan Agency for Marine-Earth Science and Technology	4.5/8.5	20 × 20 km

Source: by authors.

monthly intervals for a semiannual horizon. These data fed the soil moisture accounting procedure (SMAP) and linear stochastic model (MEL) hydrological models, which generated flow forecasts for 16 basins and sub-basins, where most of the energy and storage of the SIN is located. The results obtained by the two models, as well as a combination of both, fed the Decision Support System (SSD) called GERAVAZ, which assists in decision-making related to energy planning, besides providing quality information in a friendly graphical interface. On the basis of the results, the authors concluded that the methodology was successful in predicting flows in the areas studied. However, as the transformation from rain into flow showed good results, it was emphasized that the precision of flow estimates is directly related to the precision of precipitation estimates. As a potential improvement in the predictions, a reduction in the size of the rainfall forecast grids was identified, thus rendering the model more discrete.

Chou *et al*. (2014) used the regional climate model (RCM) Eta model in a resolution of 20 km × 20 km, nested to two GCMs (global climate models): HadGEM2-ES and MIROC5 to evaluate climate variations under two scenarios of greenhouse gas concentration in the atmosphere (representative concentration pathway (RCP) 4.5 and RCP 8.5) in South America. The forecasts were divided into three climate normals: 2011–2040, 2041–2070 and 2071–2100. The responses to climate change were greater in the Eta-HadGEM2-ES model than in Eta-MIROC5. Rainfall projections indicated a reduction in southeastern Brazil, which would intensify by the end of the 21st century. For this period, a higher frequency in extreme events of temperature and precipitation was also estimated. Despite the increase in the number of extreme rainfall events, in terms of annual totals, a reduction was predicted. The authors concluded that the different behaviors presented by the nested models and in two RCP scenarios indicate the existence of uncertainties in the assessment of climate change. Hence, additional models should be used for the understanding of climate change modeling.

Lyra *et al*. (2018) applied the combination of the Eta-HadGEM2-ES models to assess climate change in the metropolitan regions of the cities of São Paulo, Rio de Janeiro and Santos. The RCM Eta was applied with a spatial resolution of 5 × 5 km, which was considered quite high to evaluate temperature and precipitation in the RCP 4.5 and RCP 8.5 scenarios projected for the 1961–2100 period. In the comparison between the simulations and the values observed for the historical period (1961–1990), it was concluded that there was a good adjustment of the data. Furthermore, it was noted that the resolution of 5 km represented better the observed data than that of 20 km. The extreme values of precipitation and temperature were consistent with the observed; however, in both resolutions, the precipitation values related to the South Atlantic Convergence Zones (SACZ) were underestimated. The peak precipitation values (daily rainfall of above 150 mm) were also not well represented, but they are infrequent events. Future forecasts indicated a large increase in temperature, especially during summer, and a reduction in precipitation, especially in the RCP 8.5 scenario. Annual rainfall was reduced by 40–50%, thus indicating an aridity trend.

Tiezzi *et al*. (2019) conducted a study of the impact on the flow rates of 26 hydrographic basins in Brazil having hydroelectric plants, caused by changes in precipitation. The average flow tendency of the river basins was estimated for the period 2011–2100. Rain data estimated by Collins *et al*. (2001) by means of the HadCM3 GCM were used, which fed the RCM Eta, discretized in cells of 40 × 40 km. These data fed into the SMAP rain-flow and stochastic linear model (MEL), which generated the flow projections. The results found indicated a trend towards a reduction of flow in the northern basins and an increase in the southern basins. Specifically in the southeast, the flow increase was small, although the projections indicated a decrease in precipitation indices. Considering this phenomenon, the authors concluded that reductions in precipitation indices do not lead to a decrease of the same magnitude in flows.

This study aimed to adapt the best practices for estimating flows affected by climate change, applying them to a small river basin with multiple uses. The methodology consisted of combinations of the RCM Eta-CPTEC nested

with the GCMs: CanESM2, HadGEM2-ES and MIROC5, with the SMAP hydrological model in the RCP 4.5 and RCP 8.5 scenarios. These combinations produced eight different projections for the average monthly flow of the Cipó River watershed, a 75 km^2 basin used for power generation, public supply and leisure in the municipality of Poços de Caldas-MG.

RCPs are based on scenarios of radiative forcing due to greenhouse gases. The radiative forcing can be explained simply as the balance between the energy provided by the sun and that reflected by the planet. It is measured in W/m^2 and when it has positive values can be interpreted as a warming of both atmosphere and Earth's surface. The number after the acronym corresponds to the radiative forcing value of the scenario, i.e. for RCP 2.6, its value is 2.6 W/m^2. This is an optimistic scenario, in which emissions will peak in the middle of the century and reduce by 2100, restricting the increase in global temperature to not more than 2 °C. The RCP 4.5 and RCP 6.0 are intermediate scenarios for stabilizing emissions in 2100, whereas the RCP 8.5 is a pessimistic scenario, in which no effort will be made to combat emissions, which will increase after 2100 (IPCC, 2014). For better reading of the article, presenting the nomenclature conventions adopted for the models used:

- Eta – Model Eta version CPTEC/Brazil;
- CanESM2 – Global Climate Model CanESM2;
- HadGEM2-ES – Global Climate Model HadGEM2-ES;
- MIROC5 – Global Climate Model MIROC5;
- Eta-CanESM2 – Regional Climate Model Eta in a 20 × 20 km resolution coupled to the Global Climate Model CanESM2;
- Eta-MIROC5 – Regional Climate Model Eta in a 20 × 20 km resolution coupled to the MIROC5 Global Climate Model;
- Eta-HadGEM2-ES-20 km – Regional Climate Model Eta in a 20 × 20 km resolution coupled to the HadGEM2-ES Global Climate Model; and
- Eta-HadGEM2-ES-5 km – Regional Climate Model Eta in a 5 × 5 km resolution coupled to the HadGEM2-ES Global Climate Model.

MATERIALS AND METHODS

Study area

The hydrographic basin of Cipó River comprises the reservoir under study, which, among other uses, is used for energy generation and public water supply in the municipality of Poços de Caldas in Minas Gerais state.

The Cipó River is an affluent of the Rio das Antas, which flows into the Rio Pardo, belonging to the Water Resources Planning and Management Unit (UPGRH) GD6: Minas Gerais Affluents of the Mogi-Guaçu and Pardo Rivers, contained in the Rio Grande Basin (GD1–GD8) (Reis, 2014).

The 'Lindolpho Pio da Silva Dias Dam – Cipó River Dam' was installed in 1999, creating a reservoir with a flooded area of 4.6 km^2. The purpose of the dam is to regulate the flow for power generation and public water supply. Furthermore, tourism, leisure and navigation activities are allowed in the reservoir (SUPRAM, 2012).

The maximum capture of 0.42 m^3/s is allowed, which is enough to meet about 47% of the demand for urban public supply. The capture and other processes up to distribution are carried out by the Municipal Department of Water and Sewage of Poços de Caldas (DMAE), while the operation of the reservoir and hydroelectric plants is under the responsibility of the Municipal Department of Electricity of Poços de Caldas (DME) (Reis, 2014).

Figure 1(c) indicates the location and delimitation of the study area, and Figure 2 shows the three macro steps in which the study was developed.

Climate models

The precipitation and evapotranspiration predictions resulting from the nesting of the RCM with the GCMs in two RCP scenarios were obtained from the project entitled 'Projections of Climate Change for South America Regionalized by the Eta Model (PROJECT)'.

The project is an initiative of the Center for Weather Forecasting and Climate Studies (CPTEC), which belongs to the National Institute for Space Research (INPE) and aims at promoting access and availability of data from regionalized simulations in an automated way.

The regionalization available consists of simulating the climate of South, Central America and the Caribbean by RCM Eta, using as boundary conditions in the GCMs: CanESM2, HadGEM2-ES and MIROC5. Due to the high computational demand required by the projections, only the climate variables of the Southeast Brazil regionalized by the HadGEM2-ES model were available in 5×5 km cells during the period the article was developed. Regarding the regionalization of other models, including the HadGEM2-ES, climate projections were provided in 20×20 km cells.

In the PROJETA environment, it was possible to define the climatic scenarios according to Table 1, the frequency of data (annual, monthly, daily and 3 h), to delimit the area of interest and to choose the period of data in the 2006–2099 interval for the climatic variables of interest. Due to the RCP scenarios referring to the levels of radioactive force in the year 2100 and aiming to obtain data corresponding to three climatological normals, projections were generated for the periods 2010–2039, 2040–2069 and 2070–2099. As the objective of the work was to estimate flows for watershed planning purposes, the selected frequency was the monthly one.

The data, obtained in .CSV format files, were used as input for the geographic information system (GIS) platform.

GIS environment

Georeferenced data on precipitation and evapotranspiration were treated in the GIS environment in order to obtain the delimited monthly average values for the Cipó River Basin. The software used was ARCGIS®.

The procedures performed were essentially the following:

- Projection of the drainage area of the hydrographic basin (a);
- Insertion of the 20 km or 5 km grids (b);
- Data insertion (precipitation and evapotranspiration) (c);
- Union of data to grids (d);
- Intersection of the grids containing the data to the basin area (e); and
- Dissolution of the polygons formed to the basin area, and obtaining the monthly average values (f).

Figure 3 shows the graphic display, obtained by using the software and corresponding to each step of the procedure, in the resolution of grids of 5×5 km. For the 20×20 km grids, the images are similar, only changing the amount and size of the cells.

The results obtained were then transformed into a spreadsheet to feed the SMAP hydrologic model.

Hydrologic model

The SMAP (Lopes et al., 1981) was applied for the flow projections. This is a deterministic model and it is based on the principle of mass balance using two mathematical reservoirs, one representing the soil and the other the aquifer.

Further information on the methodology of the model can be obtained in Lopes (1999): Manual of the SMAP model.
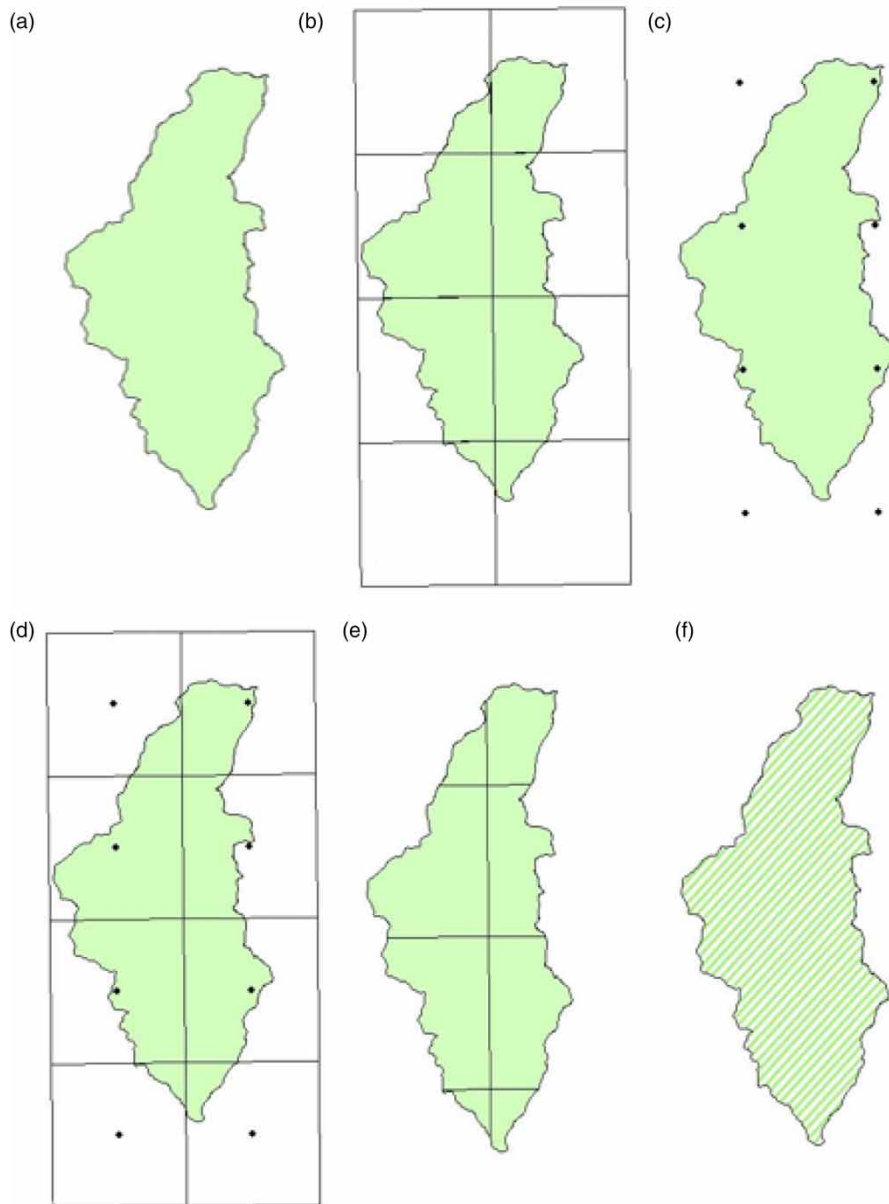
Fig. 3 | Interfaces visualized in the ArcGIS software corresponding to each step of the procedure for calculating precipitation and average evapotranspiration in the Cipó River Basin. *Source*: by authors.

The application of precipitation and evapotranspiration projections to the hydrological model required the previous calibration.

Five years of consecutive precipitation, evapotranspiration and flow data are recommended for a good calibration. Due to the unavailability of evapotranspiration and flow data for the studied watershed, a calibration using observed data from a nearby watershed was undertaken as an alternative. Such recommendation was

found in Lopes (1999) for SMAP calibration and in Klemes (1986), cited by Silveira *et al.* (1998) and Pereira *et al.* (2016) for the validation of hydrological simulation models.

The data from 1969 to 1974 were used from the Machado River basin, located in the municipality of the same name, approximately 80 km away from the studied basin. The data were obtained from the HidroWeb Portal, a tool of the National Hydrometeorological Network (RHN), which hosts and provides access to monitoring data of parameters related to rivers and rainfall.

According to the recommendations for calibration, data were used after a period of drought. Also, in accordance with good practices, the semi-automatic calibration was performed, starting by checking the adherence of the hydrogram at the initial moment by manually entering the initial basic flow and humidity data (Ebin and Tuin, respectively). Subsequently, through trial and error, the adjustment of the calculated and observed hydrograms was verified by changing the value of the base flow recession constant (Kkt).

Once the best adjustment was achieved, due to the difficulty in evaluating the other parameters such as soil saturation capacity (Str), surface runoff parameter (Pes) and underground recharge parameter (Crec), the automatic calibration was used by means of the Excel Solver tool.

Besides the visual evaluation through the graphic interpretation of the calculated and observed hydrograms, the evaluation was also made using two quantitative statistical indexes: Nash–Sutcliffe (NSE) and percentage bias (Pbias).

The suggestion for classifying the model adjustment according to the classification hereafter is as follows (Lopes, 1999):

- Very good for NSE greater than 0.6 and Pbias less than 10;
- Good for NSE between 0.6 and 0.4 and Pbias between 10 and 15;
- Satisfactory for NSE between 0.4 and 0.1 and Pbias between 15 and 25; and
- Unsatisfactory for NSE less than 0.1 and Pbias greater than 25.

After automatic calibration, the procedure was repeated several times, until the best adjustment was found between the statistical indices and the visual analysis of the hydrograms. Depending on the purpose of using the water resource, it is preferred that a certain aspect of the hydrogram is more faithful to reality than the whole adjustment. In the present study, since it is a multi-purpose hydrographic basin, special attention was devoted to the hydrogram recession stretches, in order to attenuate overestimations of minimum flows, which would create a false water availability scenario.

Following calibration, the model was then applied, which consisted of calculating the flow through the equation obtained by calibrating the model and fed with the projections of precipitation and evapotranspiration.

As previously mentioned, the projections encompassed the 2010–2099 period, thus generating 90 years of data corresponding to three climatological normals. The choice of period was also based on the fact that 2100 is the reference year for CO_2 concentration levels in the Earth's atmosphere in each RCP scenario.

As the hydrological model was calibrated based on data from another river basin, flows were also estimated for the historical period of 1961–1990, whose data were available at PROJETA. This projection was carried out because an estimate calibrated with data from another location could introduce a trend to absolute values inconsistent with the basin reality. Therefore, all the projected data were compared with the historical period. Hence, the results were also presented in relative form, thus mitigating the calibration impacts.

RESULTS AND DISCUSSION

As can be observed in Figure 4, the calibration by hydrograms showed disparities between the observed and calculated peaks. Despite the difference between the values, the peaks occurred at the same time, which is an

important characteristic when predicting extreme events. Moreover, according to the statistical indexes classification, the adjustment was considered 'very good' by the Pbias method, being obtained the value of 3, whereas in the NSE method, the index also approached the classification 'very good', with a value of 0.58.

Tables 2 and 3 contain the average, maximum and minimum monthly flow values for the RCP 4.5 and RCP 8.5 scenarios, respectively, grouped into three climatological normals corresponding to the periods 2010–2039, 2040–2069 and 2070–2099. The Q_{MLT} and $Q95\%$ reference flows were also calculated for comparison with values found in the Water Supply Master Plan (HYDROS, 2013) and in the Preliminary License concomitant with the Dam Expansion Installation License (SUPRAM, 2018).

Table 4 presents the same calculations for the historical period 1961–1990.

The extreme values found were highlighted in the tables. In both scenarios (RCP 4.5 and RCP 8.5), the highest projected monthly flow occurred during the third period, i.e. 2070–2099, when the CO_2 concentration in the global atmosphere will reach its highest values. Contrary to the maximum flow, the lowest monthly flow was registered in the first period, 2010–2039.

Despite this divergence in the periods, the lowest monthly flow of both scenarios was projected by the Eta-HadGEM2-ES-20 km model, a result consistent with that found in the historical period projection. On the other hand, the largest monthly flow of RCP 4.5 scenario was achieved by the Eta-HadGEM2-ES-5 km model, while the largest monthly flow of RCP 8.5 by Eta-MIROC5. However, the second-largest flow was calculated by the Eta-HadGEM2-ES-5 km model, also during the period 2070–2099. This model also showed the highest monthly flow in the historical period.

Comparing both scenarios, it was observed that the RCP 8.5 scenario presented both the lowest average monthly flow value and the highest value in relation to the RCP 4.5 scenario. The historical period was the one with the highest flow values, both for maximum and minimum flows and also for reference flows in almost all models.

In addition, it was observed that almost all the lowest average, maximum and minimum monthly flow values obtained were those projected by the Eta-HadGEM2-ES-20 km model, whereas the highest values mainly alternated between those projected by the Eta-CanESM2 and Eta-MIROC5 models. This behavior presented the same trend in both RCP scenarios and in the historical period.
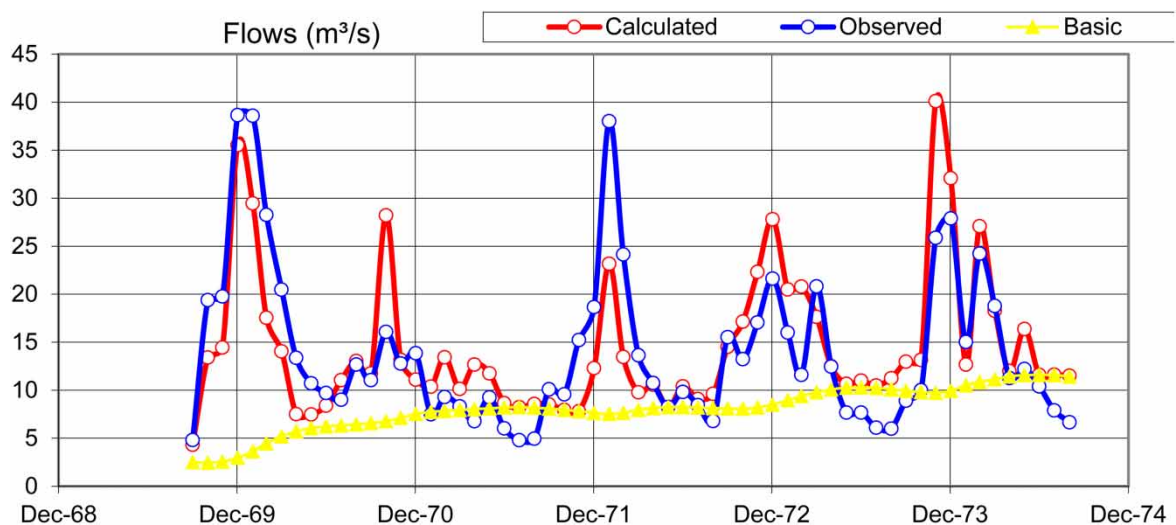

Fig. 4 | SMAP model calibration curves with Machado River Basin data. *Source*: by authors.

Table 2 | Average, maximum and minimum monthly flows (m³/s) for the 2010–2039, 2040–2069 and 2070–2099 periods and reference flows Q_{MLT} and $Q_{95\%}$ for the 2010–2099 period projected for the RCP 4.5 scenario.

RCP 4.5

Monthly flow (m³/s)	Period	Eta-CanESM2	Eta-HadGEM2-ES-5 km	Eta-HadGEM2-ES-20 km	Eta-MIROC5
Average	2010–2039	2.03	1.40	1.09	1.89
	2040–2069	1.79	1.44	1.16	2.07
	2070–2099	1.85	1.47	1.16	1.74
Maximum	2010–2039	5.04	4.73	2.65	5.66
	2040–2069	6.50	6.31	5.83	6.02
	2070–2099	4.82	7.38	5.13	5.45
Minimum	2010–2039	0.99	0.65	0.56	0.92
	2040–2069	0.90	0.67	0.59	1.08
	2070–2099	0.87	0.70	0.62	0.94
Q_{MLT}	2010–2099	1.89	1.44	1.14	1.90
$Q_{95\%}$	2010–2099	1.02	0.75	0.65	1.06

Table 3 | Average, maximum and minimum monthly flows (m³/s) for the 2010–2039, 2040–2069 and 2070–2099 periods and reference flows Q_{MLT} and $Q_{95\%}$ for the 2010–2099 period projected for the RCP 8.5 scenario.

RCP 8.5

Monthly flow (m³/s)	Period	Eta-CanESM2	Eta-HadGEM2-ES-5 km	Eta-HadGEM2-ES-20 km	Eta-MIROC5
Average	2010–2039	1.97	1.62	1.30	1.66
	2040–2069	1.76	1.47	1.21	1.97
	2070–2099	1.44	1.28	1.17	2.21
Maximum	2010–2039	5.75	8.29	5.49	4.25
	2040–2069	6.67	5.89	3.89	6.52
	2070–2099	7.10	8.25	7.51	8.84
Minimum	2010–2039	1.02	0.72	0.55	0.87
	2040–2069	0.73	0.68	0.70	0.89
	2070–2099	0.70	0.68	0.63	1.12
Q_{MLT}	2010–2099	1.72	1.46	1.22	1.95
$Q_{95\%}$	2010–2099	0.84	0.77	0.69	1.02

Concerning the Q_{MLT} and $Q_{95\%}$ reference flows, the study carried out in the Master Plan has found the respective values for the Cipó River Basin: 1.44 and 0.27 m³/s. On the other hand, in the license to expand the project (SUPRAM, 2018), the value of 2.05 m³/s for Q_{MLT} was informed, while the flow of $Q_{95\%}$ was not informed; however, the $Q_{7.10}$ flow of 0.33 m³/s was reported. According to the preliminary diagnosis of water availability conducted by the Rio Grande Integrated Water Resources Plan (PIRH Grande) (CBH Grande, 2020), $Q_{7.10}$ flows from the basin could be reasonably converted at 70% of $Q_{95\%}$. Therefore, by converting the value informed

Table 4 | Average, maximum and minimum monthly flows (m^3/s) and reference flows Q_{MLT} and $Q_{95\%}$ corresponding to the historical period 1961–1990.

Historical period

Monthly flow (m^3/s)	Period	Eta-CanESM2	Eta-HadGEM2-ES-5 km	Eta-HadGEM2-ES-20 km	Eta-MIROC5
Average	1961–1990	2.04	2.27	1.42	1.83
Maximum	1961–1990	5.33	9.20	3.99	4.21
Minimum	1961–1990	1.00	0.92	0.69	1.07
Q_{MLT}	1961–1990	2.04	2.27	1.42	1.83
$Q_{95\%}$	1961–1990	1.21	1.69	1.00	1.16

in the license, a value of approximately 0.47 m^3/s was obtained for $Q_{95\%}$. The projections were consistent with the literature, although they presented higher $Q_{95\%}$ values.

Although data are apparently correlated, this comparison was cautious. As previously mentioned, the calibration of the hydrological model with data from another basin generated uncertainties regarding absolute values. Therefore, a comparison of the average monthly flows of the RCP 4.5 and RCP 8.5 scenarios with the average monthly flows of the historical period was performed (Figure 5). Hence, it was postulated that each value had the same degree of deviation, which was eliminated or at least reduced by obtaining the relative value.

In general, it was noticed that a great part of the projected future flows were reduced in relation to the historical period, except for the Eta-MIROC5 model, where the RCP 4.5 scenario showed a tendency for an increase in the flow and was only reduced in the last period 2070–2099 and the RCP 8.5 scenario started with a reduction, but in the subsequent periods, it showed an increase.

The three other models presented a well-defined trend. The Eta-CanESM2 model showed a slight reduction in the flow for the first period in relation to the historical period for both scenarios and a greater decrease in the following periods.

The Eta-HadGEM2-ES model demonstrated a reduction in the projected flow over the historical period, in both grid resolutions, 5 and 20 km, and both RCP scenarios for all periods. However, while in the RCP 4.5 scenario the variation was more stable in all three periods, in the RCP 8.5 scenario it has increased along them. Nevertheless, variations were greater in the RCP 4.5 scenario, the opposite effect to what was expected.

The maximum and minimum variations found for each model in the RCP 4.5 scenario were approximately −12 to 0% (Eta-CanESM2), −39 to −35% (Eta-HadGEM2-ES-5 km), −23 to −18% (Eta-HadGEM2-ES-20 km) and −5 to 13% (Eta-MIROC5).

Regarding the RCP 8.5 scenario, the variations were about −29 to −3% (Eta-CanESM2), −44 to −29% (Eta-HadGEM2-ES-5 km), −18 to −9% (Eta-HadGEM2-ES-20 km) and −9 to 21% (Eta-MIROC5).

The analysis of the calibration graph of the SMAP model showed that the model accurately predicted the moment when extreme values would occur, although it generally underestimated peak values, thus suggesting that the projected extreme values indeed could be even more accentuated. On the other hand, according to Lopes et al. (2008) and Tiezzi et al. (2019), the calculated and observed flows had a good adjustment based on statistical indices.

Regarding the models used, the Eta-CanESM2 model demonstrated similar behavior to the Eta-HadGEM2-ES-5 km model, which due to its higher resolution, was assumed in this work to be the most precise. The behavior was a reduction of the average and minimum monthly flows over time in the scenario of greater climate change and in relation to the historical period; however, the reduction found in the Eta-CanESM2 model was not as

Fig. 5 | Variations in the average monthly flows of the RCP 4.5 and RCP 8.5 scenarios in relation to the historical period for each model and period. *Source*: by authors.

pronounced as in the Eta-HadGEM2-ES-5 km model, thus indicating that the latter would be appropriate only to represent trends and could underestimate the absolute values.

The results obtained by the Eta-HadGEM2-ES-5 km model indicated that the flows in the Cipó basin can be reduced considerably in the future, as well as pointing to extreme events of both maximum and minimum flows, evidencing the influence of climate variations on water availability. Lyra *et al*. (2018), who also employed the Eta-HadGEM2-ES-5 km model, observed that daily rainfall of greater than 150 mm was not well represented. As in the localities studied by Lyra *et al*. (2018), the municipality of Poços de Caldas lacks a large history of events of such magnitude, although they have previously occurred (SARDINHA *et al*., 2016). Therefore, this fact should be considered when intending to apply the methodology in regions with rainfall indices of this size.

The Eta-HadGEM2-ES-20 km model exhibited a quite similar behavior to the Eta-HadGEM2-ES-5 km model, although it showed less variation in the values obtained with respect to the historical period, indicating that the size of the cells influences the projections. Chou *et al*. (2014), who have also applied the Eta-HadGEM2-ES-20 km model, estimated a reduction in precipitation in the southeast region for the end of the 21st century, as well as an increase in the frequency of extreme events. These results were consistent with those found for the same model in this work, bringing more robustness to the methodology used.

The Eta-MIROC5 model exhibited a random behavior in its predictions, suggesting that it would not be the most appropriate to perform projections in the studied region. In comparison with the Eta-HadGEM2-ES-20 km model, Chou *et al*. (2014) found that it was less responsive to climate variations, in agreement with results from the present study.

Concerning the basin size and the period studied, Lopes *et al*. (2008) estimated the flows of the main Brazilian hydrographic basins with hydroelectric power generation affected by climate change in short six-month projection periods. On the other hand, Tiezzi *et al*. (2019), while using the same basins, performed 90-year projections (2011–2100), demonstrating that despite the long projection period, the models did not show behavior anomalies, which may occur in case of long simulation intervals. The contribution of this work was to perform projections for a long period (90 years), although in a small river basin. The absence of anomalies in the behavior of the projections showed that the methodology can also be applied to small or large basins for long periods.

CONCLUSIONS

In general, the exposed methodology corresponded well to the expected, presenting similar responses to those obtained by the methods used as a basis. As a positive aspect, the projection in a resolution of 5×5 km, considered very high, and the good response of the models for a small river basin can be mentioned. It is important to emphasize that the methodology contains its limitations, such as the calibration of the SMAP hydrological model using data from another river basin, due to the nonexistence of historical data series for the basin studied. Even being a solution employed in such cases, this procedure leads to errors, which end up accumulated during the modeling process. Nevertheless, for the Brazilian reality, in which there are practically no data regarding small basins, the methodology can be used as an initial estimate of the order of magnitude of flow, thus contributing to the management of basins lacking historical data. In addition, although the 5×5 km resolution projections only exist for the southeast region of Brazil so far, the 20×20 km resolution projections also showed good results, which demonstrate the possibilities of using the methodology.

While the methodology has shown satisfactory results, on the other hand, they are of great concern and will bring challenges to the municipality of Poços de Caldas in the management of the Cipó River Basin. The Eta-HadGEM2-ES-5 km model forecast, considered the most precise among those used, pointed to average monthly flow reductions of around 30–40% in a climate change scenario over the next decades.

Considering that in this same river basin water is captured to supply almost half of the population, while supplying five hydroelectrical plants downstream with an installed power of almost 35 MW, the concessionaires should look for other options to attend to the population. Both a new hydroelectric power plant and a new water catchment and treatment plant are huge works, which require investments and long-term planning. Hence, there is a need for information to subsidize the decision-making of the managers.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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