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Impact of climate change on the flow of the Doce River basin

Impacto das mudanças climáticas na vazão na bacia do Rio Doce

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ABSTRACT

This study verified the impacts of climate change on river flow in the Doce River basin, using the MGB and RCM Eta projections. Despite the differences between the trends, the basin will certainly be affected by the reduction of precipitation and the increase in temperature between 2025 and 2099. Results show considerable reductions in the trends of the average flow of the basin. In 2025 - 2049, these reduction trends are greater than 64% in 50% of river reaches, according to Eta-HadGEM2-ES RCP 8.5. In 2050 - 2074, the flows simulated with Eta-CanESM2 and Eta-HadGEM2-ES RCP 8.5 achieve reductions greater than 84% and 77%, respectively, in 50% of the simulated reaches. In 2075 - 2099 the reduction trends of Eta-CanESM2 and Eta-HadGEM2-ES RCP 8.5 are greater than 91% and 79%, respectively, in 50% of the drainage reaches.

Keywords: Climate change; RCM Eta; Hydrological modeling; Doce River basin.

RESUMO

Este estudo verificou os impactos das mudanças climáticas na vazão na bacia do rio Doce, utilizando o MGB e projeções do MCR Eta. Apesar das diferenças entre as tendências, certamente a bacia sofrerá problemas com a redução da precipitação e o aumento de temperatura entre 2025 e 2099. Os resultados mostram reduções consideráveis nas tendências da vazão média da bacia. Em 2025 - 2049, essas tendências de redução são maiores que 64% em 50% dos trechos de rios, segundo o Eta-HadGEM2-ES RCP 8.5. Em 2050 - 2074, as vazões simuladas com o Eta-CanESM2 e do Eta-HadGEM2-ES RCP 8.5 alcançam reduções maiores que 84% e 77%, respectivamente, em 50% dos trechos simulados. Em 2075 - 2099 as tendências de redução do Eta-CanESM2 e do Eta-HadGEM2-ES RCP 8.5 são maiores que 91% e 79%, respectivamente, em 50% dos trechos de drenagem.

Palavras-chave: Mudanças climáticas; RCM Eta; Modelagem hidrológica; Bacia do Rio Doce.

INTRODUCTION

Climate changes alter climate characteristics and consequently the hydrological cycle, with more intense rainfall, floods, precipitation deficit and more pronounced droughts in several regions, in addition to increases in temperature extremes (Intergovernmental Panel on Climate Change, 2012, 2021; Arnell & Gosling, 2016). When associated with inadequate planning of water use, they can lead to many environmental problems related to water resources (Nearing et al., 2004).

Brazil has a huge water storage, distributed heterogeneously in the national territory. The growing water demand due to the increased population and economic activities with high water consumption have contributed to water *stress*, especially in the Southeast region. The largest uses of water in the Southeast region are for human supply, irrigation and industry (Agência Nacional de Águas, 2020), which has been affected by the lack of water due to unplanned urbanization (Marengo et al., 2017).

Decisions related to water resources in Brazil are mostly based on historical series of hydrological and climate data. However, the use of time series based on past observations can lead to mistaken decisions regarding the use of natural resources (Lima et al, 2014), since Brazil is vulnerable to climate change (Lucena et al., 2009; Marengo et al., 2017; De Paula, 2020).

Studies considering the impacts of climate projections on water resources are necessary for an adequate basin management (Marengo et al., 2017). As tools to estimate the impact of climate change on the hydrological cycle of river basins, distributed hydrological models whose parameters have a conceptual/physical representation of hydrological processes have been increasingly used at different scales (Qin et al., 2020; Rodrigues et al., 2020; Zhao et al., 2019; Bajracharya et al., 2018; Santos et al., 2014). In this sense, several studies have evaluated the influence of climate change on water resources in Brazil (Queiroz et al., 2016; Oliveira et al., 2017b; Schuster et al., 2020; Sorribas et al., 2016; Brêda et al., 2020; Viola et al., 2014; Andrade et al., 2020).

Investigation on the effects of climate change on flow has been carried out by hydrological modeling studies using projections of global climate models (GCM), with spatial resolution of hundreds of kilometers (Raulino et al., 2021; Guo et al., 2020), and regional climate models (RCM), with resolution of tens of kilometers (Alvarenga et al., 2016; Santos et al., 2019; Xu et al., 2019; Andrade et al., 2020), as input data of hydrological models. The main function of GCMs is to contribute to the understanding of the dynamics of climate system components on a large scale, such as temperature of the atmosphere and the oceans, precipitation, winds, clouds, ocean currents, as well as carry out climate projections (Intergovernmental Panel on Climate Change, 2014a). In this context, RCMs are able to better capture surface characteristics and important local effects in assessing climate change, providing details necessary to represent climatic conditions for local scale studies (Chou et al., 2014a, 2014b; Laprise et al., 2008). For this reason, regionalization has been carried out, which uses RCM forced by GCM.

Understanding the effects of climate change on the flow rate is essential for the development of an efficient management of water resources and mitigation and adaptation strategies in the face of climate change for the Brazilian river basins. The water resources of the Doce River basin, located in southeastern Brazil, are essential for the states of Minas Gerais and Espírito Santo, as they provide water for domestic use, agriculture, mining, industrial complexes and electricity generation (Agência Nacional de Águas, 2016). However, the historical series already demonstrates a reduction in the average annual flow in this basin (1939 - 2008), according to Coelho (2009). In this sense, this study aims to investigate the impacts of climate change on the flow of the Doce River basin, using the MGB hydrological model (Pontes et al., 2017) and future projections of RCM Eta (Marengo et al., 2011).

STUDY AREA

The Doce River basin (Figure 1) is located in southeastern Brazil, integrating the hydrographic region of the Southeast

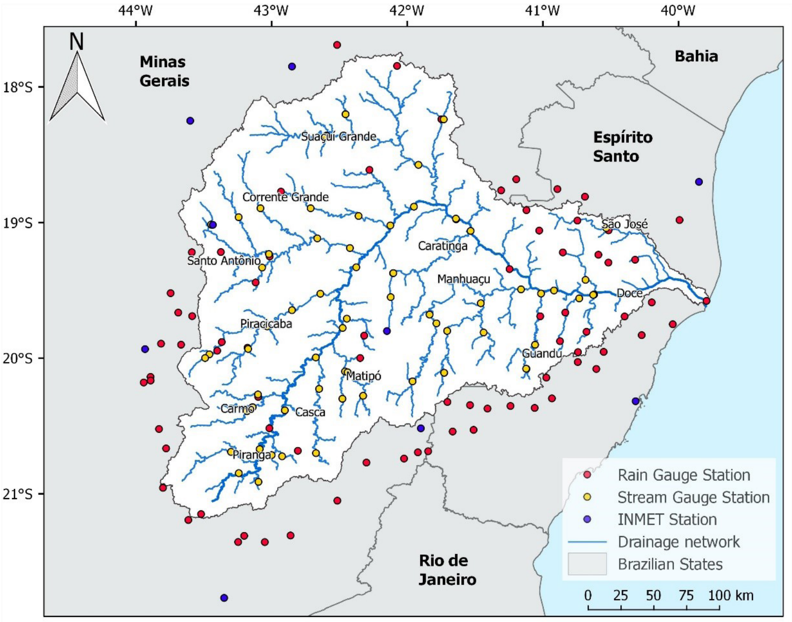

Figure 1. Location of the Doce River basin, its main tributaries and the fluviometric, rainfall and climate stations (INMET).

Atlantic between latitudes 17°45’ and 21°15’ S and longitudes 39°30’ and 43°45’ W, with a drainage area of 83,465 km^2; 86% of its territory is in the state of Minas Gerais and 14% in Espírito Santo (Coelho, 2007). The basin of Doce River comprises 225 municipalities, of which 200 belong to the state of Minas Gerais and 25 to Espírito Santo, and a population of about 3.6 million inhabitants (Agência Nacional de Águas, 2016), with more than 70% of the total population of the basin living in urban areas.

The basin of Doce River is inserted in a region of humid tropical climate, being marked by climatic heterogeneity (Pinto et al., 2015). The rainfall regime in the basin has two well-defined periods, the rainy period, from October to March, and the dry period, between April and September (Cupolillo, 2008).

In addition to hosting the largest steel complex in Latin America, the basin of Doce River has as its main economic activities the agriculture and livestock, represented by the cultivation of coffee, sugarcane, cattle and pig farming; sugar-alcohol agro-industry; mining; pulp, steel and dairy industry; trade; industrial complexes; and electricity generation (Plano Integrado de Recursos Hídricos da Bacia Hidrográfica do Rio Doce, 2010).

The Doce River basin has 98% of its area inserted in the Brazilian Atlantic Forest biome and the remaining 2% belonging to the Cerrado, but due to the great suppression of native vegetation, the forests remain only in the steepest areas of the basin. In 59% of the basin area, pasture predominates, followed by native vegetation, which covers 27% of the territory, another 5% are occupied by agricultural areas and 4% by reforested areas, according to the mapping of land use and land cover in the Doce basin in 2013 (Agência Nacional de Águas, 2016).

Although the Doce River basin has great economic importance and environmental relevance, few studies have investigated the flow regime in the basin (Oliveira & Quaresma, 2017a; Coelho, 2009). The insufficiency of studies about flow variations from historical series and modeled projections hinder the development of water resources management and planning in the face of the impacts of climate change.

MATERIALS AND METHODS

MGB

The MGB hydrological model was chosen for this study because it presents good results in the representation of hydrological processes on a large scale (Paz et al., 2013; Lopes et al., 2018; Siqueira et al., 2018; Fleischmann et al., 2019) and has been applied to assess the impacts of climate change on water resources in several studies in large river basins in Brazil (Queiroz et al., 2016; Schuster et al., 2020) and South America (Brêda et al.2020).

The MGB (Pontes et al., 2017; Collischonn & Tucci, 2001; Collischonn et al., 2007) is a conceptual distributed hydrological model that performs the vertical balance of water and energy in the soil, considering the processes of evapotranspiration, interception, generation and propagation of surface, subsurface and underground flows and the flow propagation in the drainage network (Collischonn & Tucci, 2001).

In the MGB, the Doce River basin was discretized in 1488 unit catchments, which are small areas of contribution for each corresponding river reach. The unit catchments were further divided into Hydrological Response Units (URH), which consist of the combination of soil type, land use, and land cover maps, from Fan et al. (2015).

The flow propagation in the drainage network within the MGB was carried out through the inertial flow propagation method, included in the MGB by Pontes et al. (2017), an approximation of the equations of Saint Venant (Chow et al., 1988; Chanson, 2004), which disregards the term of advective inertia in the dynamic equation. The MGB had its parameters calibrated in the period from 1990 to 2014 and validated in the period from 1970 to 1989, using historical series of daily hydrological data.

The flow and precipitation data were obtained from daily historical series of 62 fluviometric stations (Table 1) and 101 rainfall stations (Figure 1), respectively, belonging to the National Water Agency (ANA) database, obtained through the Hydrological Information System (HidroWeb). The flow gauges used contain data consisting of at least 80% of the months without failures, with a maximum of 5 days without information. The monthly climate data used in the model were normal climatological (1961 - 1990), made available by the National Institute of Meteorology (INMET).

MGB Model Calibration and validation

The calibration of the MGB for the basin of Doce River was performed at the locations of the fluviometric stations with observed data available, considering the performance statistics, the Nash-Sutcliffe efficiency coefficient of logarithms $-ENSLog$ (Equation 1), Pearson correlation coefficient $-r$ (Equation 2) and relative total volume error $-PBIAS$ (Equation 3).

$$ENSLog = 1 - \frac{\sum_{i=1}^{N}\left(log\left(C_i\right) - \left(\log\left(O_i\right)\right)^2\right.}{\sum_{i=1}^{N}\left(log\left(O_i\right) - \left(\log\left(\bar{O}\right)\right)^2\right.} \tag{1}$$

$$r = \frac{\sum_{i=1}^{N}\left(C_i - \bar{C}\right)\left(O_i - \bar{O}\right)}{\sqrt{\left[\sum_{i=1}^{N}\left(C_i - \bar{C}\right)^2\right]\left[\sum_{i=1}^{N}\left(O_i - \bar{O}\right)^2\right]}} \tag{2}$$

$$PBIAS = \frac{\sum_{i=1}^{N}\left(C_i - O_i\right)*100}{\sum_{i=1}^{N} O_i} \tag{3}$$

Where C_i is the modeled variable in the time interval i, O_i is the observed variable in the same time interval, N is the number of time intervals, $\bar{C}$ is the mean of the modeled variables and $\bar{O}$ is the mean of the observed variables.

The $ENSLog$ considers the logarithm of the simulated and observed flows for the statistical calculations, favoring a better evaluation of the adjustments of minimum flows (Wöhling et al., 2013; Ferreira et al., 2020).

The r describes the linear relationship between simulated and observed data, ranging from -1 to 1. If r is equal to 0 there is no linear relationship and if r is equal to 1 or -1 there is a perfect positive or negative linear relationship, respectively.

The $PBIAS$ measures the average tendency of the simulated data to be greater or less than the observed data. Its ideal value

Table 1. Fluviometric Gauges of the Doce River basin with daily flow data.

Gauge	Name	Latitude	Longitude	Gauge	Name	Latitude	Longitude
56998400	Barra de São Gabriel	-19.04	-40.53	56800000	Senhora Do Porto	-18.89	-43.08
56995500	Ponte do Pancas	-19.42	-40.69	56787000	Fazenda Barraca	-19.33	-43.07
56994510	Colatina Corpo de Bombeiros	-19.53	-40.62	56775000	Ferros	-19.23	-43.02
56994500	Colatina	-19.53	-40.63	56765000	Dom Joaquim	-18.96	-43.24
56993551	Jusante Córrego da Piaba	-19.56	-40.73	56750000	Conceição do Mato Dentro	-19.01	-43.45
56992400	UHE Mascarenhas Barramento	-19.50	-40.92	56719998	Belo oriente	-19.33	-42.38
56992000	Baixo Guandu	-19.52	-41.01	56696000	Mario de carvalho	-19.52	-42.64
56991500	Laranja da Terra	-19.90	-41.06	56688080	UHE São Carvalho Barramento Antônio Dias	-19.65	-42.85
56990990	Afonso Cláudio Montante	-20.08	-41.12	56659998	Nova Era IV	-19.77	-43.03
56990000	São Sebastião da Encruzilhada	-19.49	-41.16	56640000	Carrapato (Brumal)	-19.97	-43.46
56989400	Assarai Montante	-19.59	-41.46	56631900	ETA (São Bento Mineração)	-20.00	-43.49
56989001	Mutum	-19.81	-41.44	56610000	Rio Piracicaba	-19.93	-43.17
56988500	Ipanema	-19.80	-41.71	56570000	PINGO D'ÁGUA	-19.71	-42.45
56983000	Dores de Manhumirim	-20.11	-41.73	56539000	Cachoeira dos Óculos Montante	-19.78	-42.48
56978000	Santo Antônio do Manhuaçu	-19.68	-41.84	56510000	Instituto Florestal Raul Soares	-20.10	-42.46
56976000	Fazenda Bragança	-19.74	-41.79	56500000	Abre Campo	-20.30	-42.48
56960005	Fazenda Vargem Alegre	-20.17	-41.96	56484998	Raul Soares Montante	-20.10	-42.44
56940002	Barra do Cuietão Jusante	-19.06	-41.53	56460000	Matipó	-20.28	-42.33
56935000	Dom Cavati	-19.37	-42.10	56425000	Fazenda Cachoeira D'antas	-19.99	-42.67
56928000	Inhapim	-19.55	-42.12	56415000	Rio Casca	-20.23	-42.65
56920000	Tumiritinga	-18.97	-41.64	56385000	São Miguel Do Anta	-20.70	-42.67
56891900	Vila Matias Montante	-18.57	-41.92	56337000	Fazenda Ocidente	-20.27	-43.10
56870000	Santa Maria do Suaçuí	-18.20	-42.45	56335001	Acaiaca Jusante	-20.36	-43.14
56860000	São Pedro do Suaçuí	-18.36	-42.60	56240000	Fazenda Paraíso	-20.39	-43.18
56851000	Campanário	-18.24	-41.73	56110005	Ponte Nova Jusante	-20.38	-42.90
56850000	Governador Valadares	-18.88	-41.95	56090000	Fazenda Varginha	-20.71	-43.00
56846080	UHE Baguari Barramento	-19.02	-42.13	56085000	Seriquite	-20.72	-42.92
56846000	Porto Santa Rita	-18.95	-42.36	56075000	Porto Firme	-20.67	-43.09
56845000	Fazenda Corrente	-18.89	-42.71	56065000	Senador Firmino	-20.91	-43.10
56825000	Naque Velho	-19.19	-42.42	56055000	Braz Pires	-20.85	-43.24
56820080	UHE Porto Estrela Barramento	-19.12	-42.66	56028000	Piranga	-20.69	-43.30

is 0, while positive values indicate overestimation and negative values, underestimation by the model.

Future data on climate change

The daily future climate data, used as MGB input data to assess the impact of climate change on the flow of the Doce River basin, were obtained from the projections of RCM Eta, made available by the National Institute for Space Research (INPE/CPTEC), forced by GCM BESM (Nobre et al., 2013), MIROC5 (Watanabe et al., 2010), CanESM2 (Arora et al., 2011) and HadGEM2-ES (Collins et al., 2011; Martin et al., 2011) with spatial resolution of 20 km, referred to in this work as Eta-BESM, Eta-MIROC5, Eta-CanESM2 and Eta-HadGEM2-ES.

The projections of the RCM Eta driven by the GCMs are based on the scenarios of future emissions of gases and aerosols RCP 4.5 and RCP 8.5 of the IPCC-AR5 (Intergovernmental Panel on Climate Change, 2014a; Van Vuuren et al., 2011), expressed in terms of radioactive forcing. RCP 4.5 is an intermediate scenario, with moderate greenhouse gas emissions, in which there is stabilization at 4.5 W/m^2 (~ 650 ppm CO$_{2eq}$) after 2100, and RCP 8.5 consists of a more pessimistic scenario, in which the terrestrial system is expected to reach a radiative forcing of 8.5 W/m^2 (~ 1370 ppm CO2eq) in 2100 (Moss et al., 2010; Van Vuuren et al., 2011).

The RCM Eta data used were precipitation and climatic variables for the calculation of evapotranspiration: temperature, incident short-wave solar radiation, relative humidity, wind speed and atmospheric pressure on the surface.

The RCM Eta simulations had their performance evaluated in several studies, such as Almagro et al. (2020), Chou et al. (2014b) and Lyra et al. (2017). In Brazil, RCM Eta has been widely used in studies to assess the impact of climate change on water resources (Adam & Collischonn, 2013; Viola et al., 2014; Santos et al., 2019; Andrade et al., 2020; Queiroz et al., 2016; Oliveira et al., 2017b).

Bias correction method

Climate projections present biases, making it difficult to represent real hydrological conditions (Muerth et al., 2013) due to systematic errors of the models. For this reason, in many studies, bias correction methods are applied to reduce the differences between climate projections and observed climate data (Christensen et al., 2008; Teutschbein & Seibert, 2012).

In this study, the correction of precipitation bias and other climatic variables for hydrological modeling was performed, seeking to reduce even greater biases in the flow (Brêda et al., 2020). Teutschbein & Seibert (2012) compared different available bias correction methodologies that can be implemented to correct biases in climate models. Based on the results of Teutschbein & Seibert (2012), linear scaling (Lenderink et al., 2007) was applied to correct the bias of the RCM Eta projections. The method adjusts the daily values of climate projections from the relationship between the monthly averages observed and simulated by climate models in the historical period, generating a correction coefficient for each month. For the precipitation is applied approach of multiplicative bias correction (Equation 4), in which the ratio of the mean monthly observed precipitation and simulated precipitation in historical period multiply the daily simulated precipitation. For the other climatic variables is applied approach of additive bias correction (Equation 5), in which the difference of the mean monthly observed climatic variable and simulated in historical period is added to the daily simulated climatic variable. The multiplicative approach for precipitation is more suitable because the rainfall time series usually consists of large peaks between several null values (dry days), thus an additive approach can lead to negative values of precipitation and not be representative on high extremes. In addition, this approach has been used consistently in the literature (Bravo et al., 2014; Brêda et al., 2020).

$$P_{cor}(d) = P_{sim}(d) \times \left(\frac{\overline{P}_{his,\ obs}(m)}{\overline{P}_{his,\ sim}(m)} \right) \tag{4}$$

$$Y_{cor}(d) = Y_{sim}(d) + \left(\overline{Y}_{his,obs}(m) - \overline{Y}_{his,sim}(m) \right) \tag{5}$$

where $P_{cor}(d)$ is the corrected daily simulated precipitation, $P_{sim}(d)$ is the daily simulated precipitation without correction, $\overline{P}_{his,\ obs}(m)$ is the monthly average of the precipitation observed for the historical period, $\overline{P}_{his,sim}(m)$ is the monthly average of the simulated precipitation for the historical period, $Y_{cor}(d)$ is the corrected daily simulated climatic variable, $Y_{sim}(d)$ is the daily simulated climatic variable without correction, $\overline{Y}_{his,\ obs}(m)$ is the monthly average of the climatic variable observed for the historical period, $\overline{Y}_{his,sim}(m)$ is the monthly average of the simulated climatic variable for the historical period.

For the correction of rainfall, daily data observed from the 101 selected rainfall stations were used, considering the historical period (1986 - 2005). To correct the other climatic variables, monthly averages were obtained from the *Climatic Research Unit* - CRU (New et al., 2002) with a spatial resolution of 10 minutes, from 1961 to 1990. In addition, raw data from the RCM Eta for the period 1986 - 2005 were used to calculate the monthly correction coefficient, applied in the future period (2025 - 2099).

Assessment of climate change impacts on flow

Once its parameters were calibrated and validated, the results of the simulations with the MGB for the historical period (1986 - 2005) were compared with the results of future periods. Three future periods of 25 years were simulated: from 2025 to 2049, from 2050 to 2074 and from 2075 to 2099. The analysis of the variation of precipitation, temperature and average flow was performed according to the projections of Eta-BESM, Eta-MIROC5, Eta-CanESM2 and Eta-HadGEM2-ES under RCP 4.5 and RCP 8.5.

RESULTS AND DISCUSSION

Calibration and validation

In general, the statistics indicate that the MGB model performed satisfactorily in representing the flows of the Doce River basin (Figure 2). In the calibration period (1990 - 2014), *ENSLog* (Figure 2a) presented values greater than 0.75 and 0.50 in 45% and 100% of the stations, respectively.

r (Figure 2b) presented values higher than 0.80 in 61% of the stations, indicating that increasing values of observed flows are accompanied by a trend of growth of simulated flows, while decreasing values of observed flows by a trend of decrease of simulated flows.

With the results of *PBIAS* (Figure 2c), it is verified that in the calibration period, the flows were overestimated in less than 10% in 55% of the evaluated stations, while they were underestimated in less than 10% in 24% of them. In only 3% of the stations, the simulated flows showed a tendency to overestimate the observed flows greater than 15%, with no underestimation greater than -15%. Compared to the classification of Moriasi et al. (2007) for *PBIAS*, 79% of the stations presented results considered very good, 18% had results considered good and 3% of the stations had satisfactory results.

For the validation period (1970 - 1989), *ENSLog* (Figure 2d) presented values higher than 0.75 in 41% of the stations and higher than 0.5 in 93% of them. The *r* (Figure 2e) was greater than 0.80 in 71% of the stations, showing a strong positive linear relationship between the observed and simulated flows. The values of *PBIAS* (Figure 2f) indicate that in 30% of the stations the observed flows were overestimated by less than 10%, while in 43% of them the flows were underestimated by less than 10%. In addition, 93% of all stations had *PBIAS* less than ±15%. Compared to the classification of Moriasi et al. (2007), 73% of the stations had very good results, 20% of them had good results and 7% of them were satisfactory.

For a visual analysis of the general adjustment of daily flows, some observed and simulated flow hydrographs are presented in Figure 3. The hydrographs show that the simulated flows present expressive seasonality, with well-defined peaks and valleys in accordance with the observed flows.

Precipitation and temperature

The spatial distribution of the relative variation of precipitation (Figure 4), as well as the relative variation of the mean for the entire basin (Figure 5), obtained from the precipitation projections of Eta-BESM, Eta-MIROC5, Eta-CanESM2 and Eta-HadGEM2-ES under RCP 4.5 and RCP 8.5 show that, despite the large differences between the variation trends, the basin of

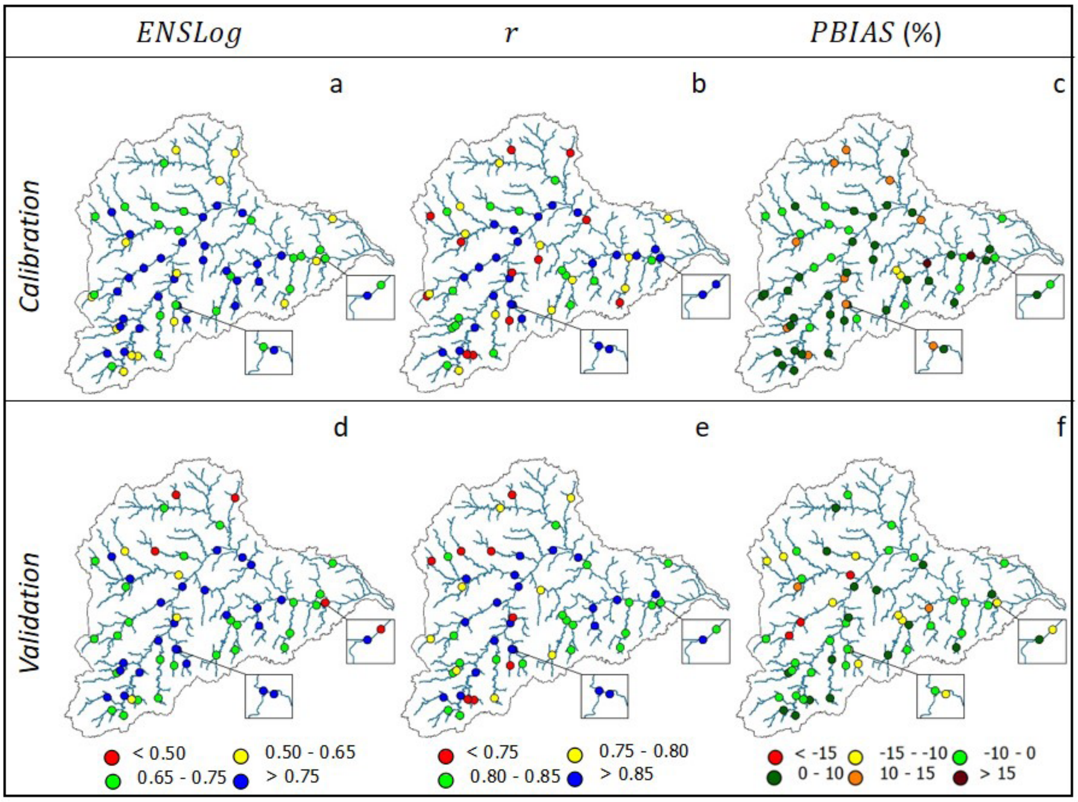

Figure 2. Spatial distribution of performance statistics calculated for the flow of MGB applied to the basin of Doce River, in the calibration (a, b, c) and validation period (d, e, f).

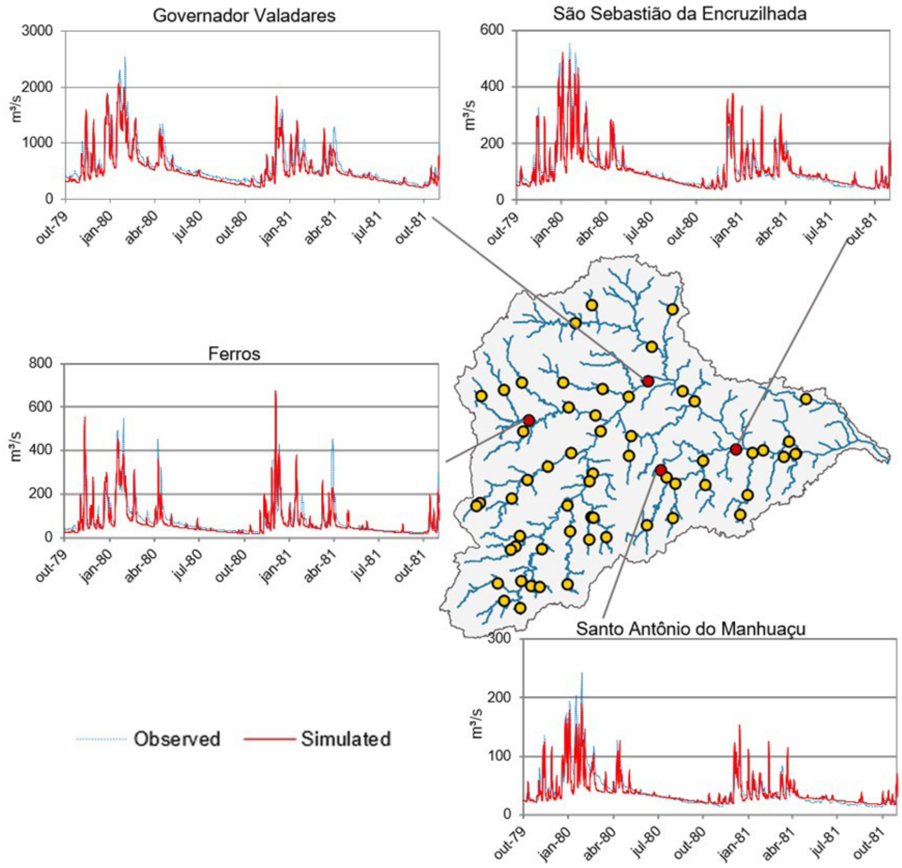

Figure 3. Observed and simulated flow hydrographs for different fluviometric stations.

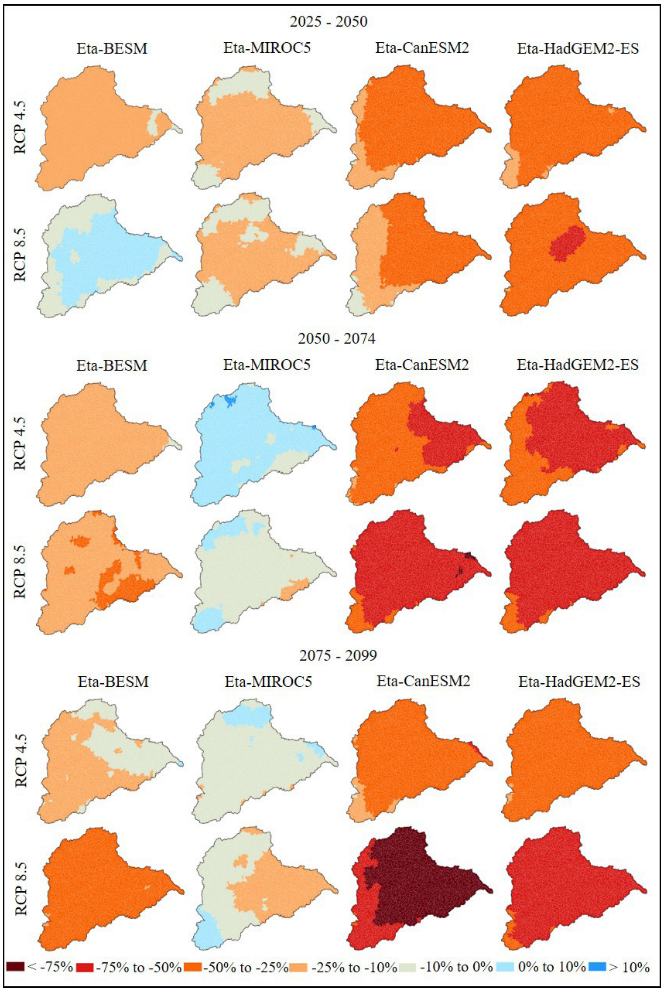

Figure 4. Spatial distribution of the relative variation of the average precipitation obtained from the projections of Eta-BESM, Eta-MIROC5, Eta-CanESM2 and Eta-HadGEM2-ES under RCP 4.5 and RCP 8.5.

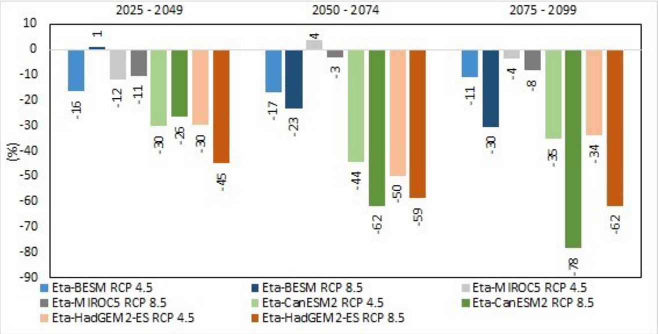

Figure 5. Relative variation of the mean precipitation for the entire basin, obtained from the projections of Eta-BESM, Eta-MIROC5, Eta-CanESM2 and Eta-HadGEM2-ES under RCP 4.5 and RCP 8.5.

Doce River will certainly suffer problems with the reduction of precipitation in relation to the historical period (1986 - 2005).

The projections of the climate models and the RCP 4.5 and RCP 8.5 scenarios indicate reduction trends for the average precipitation of the Doce River basin (Figure 5), with the exception of Eta-BESM RCP 8.5 in 2025 - 2049 and Eta-MIROC5 RCP 4.5 in 2050 - 2074, which indicate a slight increase trend of about 1% and 4%, respectively. Although the projections of Eta-MIROC5 RCP 8.5 in 2050 - 2074 and Eta-MIROC RCP 4.5 and RCP 8.5 in 2075 - 2099 point to increasing trends in some regions of the Doce River basin (Figure 4), the variation in the average of the basin points to a decreasing trend in precipitation. The most rigorous reduction trends for average rainfall come from the projections of Eta-CanESM2 and Eta-HadGEM2-ES for all periods analyzed. Chou et al. (2014a), when evaluating the projections of Eta-HadGEM2-ES (2011 - 2099) for South America under RCP 4.5 and RCP 8.5, observed that precipitation tends to reduce in all regions for Eta-HadGEM2-ES, corroborating the results found in this study.

As shown in Figure 5, the average basin precipitation can achieve 45% reductions in 2025 - 2049, according to the projections of Eta-HadGEM2-ES RCP 8.5. In the period 2050 - 2074, the average precipitation of the basin can reduce up to 62%, according to the projections of Eta-CanESM2 RCP 8.5. In 2075 - 2099, the average precipitation of the basin can reduce up to 78% according to the projections of Eta-CanESM2 RCP 8.5. Lyra et al. (2017) also observed a strong reduction in average precipitation for the projections of Eta-HadGEM2-ES 05 km at the end of the 21st century, which is greater than 50% for Rio de Janeiro and between 40% and 45% for the metropolitan region of São Paulo and Santos, with emphasis on RCP 8.5.

The spatial distribution of the absolute variation of the average temperatures of the basin of Doce River in 2025 - 2049, 2050 - 2074 and 2075 - 2099 under the scenarios RCP 4.5 and RCP 8.5 is presented in Figure 6 and the average absolute variation of the basin is shown in Figure 7. The results indicate that, despite the differences in projections for the Doce River basin, the trends of all climate models indicate an increase in temperature in the basin between 2025 and 2099.

The temperature shows higher increasing trends according to the projections of Eta-CanESM2 RCP 8.5 and Eta-HadGEM2 RCP 8.5 for all future periods analyzed (Figure 6). In 2025 - 2049, there is a possible increase of more than 2°C in the average temperature of the basin, in relation to the historical period (Figure 7). In 2050 - 2074, the most pronounced trends in average basin temperature show an increase greater than 3°C (Figure 7).

In the period 2075 - 2099, the temperature may increase by more than 5°C in most of the basin, according to the projections of Eta-CanESM2 RCP 8.5 and Eta-HadGEM RCP 8.5 (Figure 6). In general, the basin tends to suffer more pronounced temperature increases, especially at the end of the 21st century, according to the projections of the RCM Eta.

According to Salazar et al. (2007), the global climate models of the IPCC-AR4 and the regional models indicate a trend of temperature increase in the range of 2 to 6°C in South America until 2100, similar to the results of Figure 6 and Figure 7 presented in this study. Increasing the temperature can intensify evapotranspiration and consequently reduce the amount of water in the soil. Therefore, there may be replacement of biomes by other types of vegetation more adapted to the lower amount of water in the soil, such as the reduction of tropical forest cover

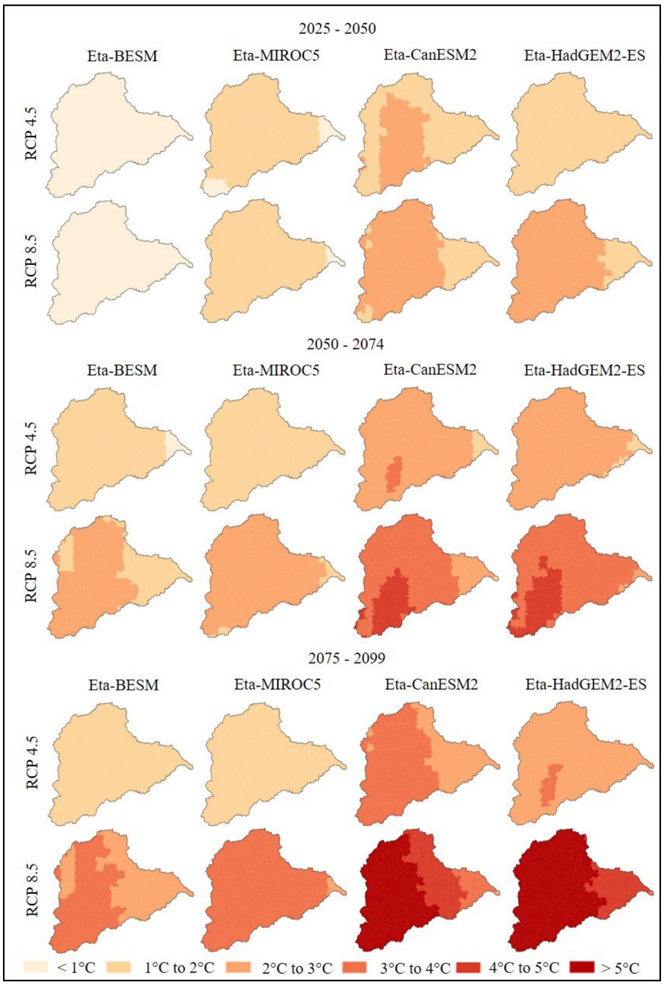

Figure 6. Spatial distribution of the relative variation of the average temperature obtained from the projections of Eta-BESM, Eta-MIROC5, Eta-CanESM2 and Eta-HadGEM2-ES under RCP 4.5 and RCP 8.5.

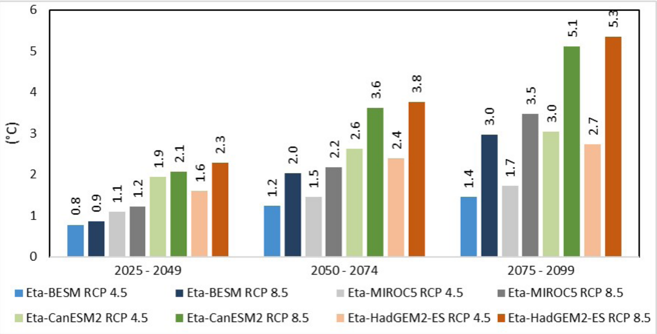

Figure 7. Absolute variation of the average temperature in the basin of Doce River simulated with the projections of Eta-BESM, Eta-MIROC5, Eta-CanESM2 and Eta-HadGEM2-ES under RCP 4.5 and RCP 8.5.

areas and the replacement by savannas. South America, where the Doce River basin is located, houses unique ecosystems and has one of the largest biodiversities on the planet, in addition to a variety of ecoclimate gradients (Intergovernmental Panel on Climate Change, 2014b). However, changes in vegetation cover due to climate change can negatively impact the ecological diversity of plants and animals.

Flow rate

The variations of the simulated average flows in each river reach and Box plot according to the projections of Eta-BESM, Eta-MIROC5, Eta-CanESM2 and Eta-HadGEM2-ES for each scenario and period considered are shown in Figure 8 and Figure 9 for the period 2025 - 2049, in Figure 10 and Figure 11 for the period 2050 - 2074, in Figure 12 and Figure 13 for the period 2075 - 2099 . B*ox plot* were made to complement the analysis of the variation of the average flow in the river reaches of the Doce River Basin.

The maps on Figure 8 show the variation of the average flows for the period 2025 - 2049 and demonstrate a predominant reduction trend, with more severe trends in the simulations with the projections of the Eta-HadGEM2-ES RCP 8.5. The most optimistic trends are the simulated flows with the projections of Eta-BESM RCP 8.5, including increasing flow trends in some sections of simulated rivers. Based on the medians of the *box plots* (Figure 9), it is verified that 50% of the river reaches present reduction trends less than 4% in the simulations with the projections of Eta-BESM RCP 8.5 and greater than 64% in the simulations with the projections of Eta-HadGEM2-ES RCP 8.5. The *box plots* of the variation trends of the simulations with Eta-CanESM2 have a large interquartile distance and long whiskers, revealing greater disagreement between the variations of the river reaches of the basin. There is a large difference between the results generated under RCP 8.5, since the most optimistic and strict trends of 2025 - 2049 occur in this scenario.

This work agrees with the results of studies applied in basins near the basin of Doce River (Nóbrega et al., 2011; Alvarenga et al., 2016; Oliveira et al., 2017b). In assessing the impact of climate change on the Lavrinhas river basin (MG), Alvarenga et al. (2016) obtained reductions in average monthly flows between -50% and -65% in 2011 - 2040 with Eta-HadGEM2-ES under RCP 8.5. Oliveira et al. (2017b) showed that the reduction in the average monthly flow of the Rio Grande basin (MG and SP) in 2007 - 2040 can vary between -41% and -56% based on Eta-HadGEM2-ES in relation to the two scenarios (RCP 4.5 and RCP 8.5) and between -14% and -29% with Eta-MIROC5 RCP 8.5, which are close to the average flow reductions in 2025 - 2049 obtained in the Doce River basin based on the projections of Eta-HadGEM2-ES and Eta-MIROC5.

In the period 2050 - 2074 (Figure 10), there is a predominance of flow reduction trends. The simulations with Etapa-MIROC5 point to more moderate reduction trends in flows, as well as an increase trend in river reaches, especially under RCP 4.5. In 50% of the simulated sections, the flows tend to increase by more than 2% according to the simulations with Eta-MIROC5 RCP 4.5, according to the median of the *box plot* of Figure 11. The trends of the simulated flows with the projections of Eta-CanESM2 and Eta-HadGEM2-ES RCP 8.5 are the most stringent reduction of the period, achieving reductions greater than 84% and 77%, respectively, in 50% of the simulated sections (Figure 11).

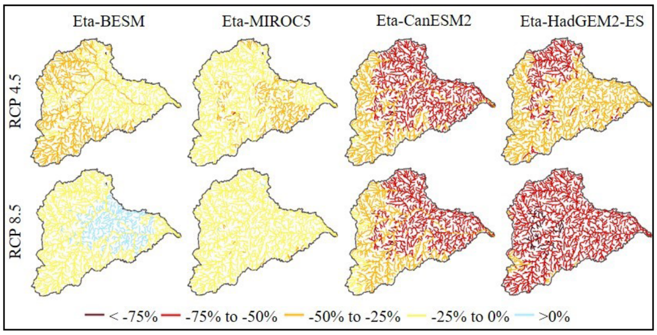

Figure 8. Simulated average flow variation (2025 - 2049) with the projections of Eta-BESM, Eta-MIROC5, Eta-CanESM2 and Eta-HadGEM2-ES under RCP 4.5 and RCP 8.5.

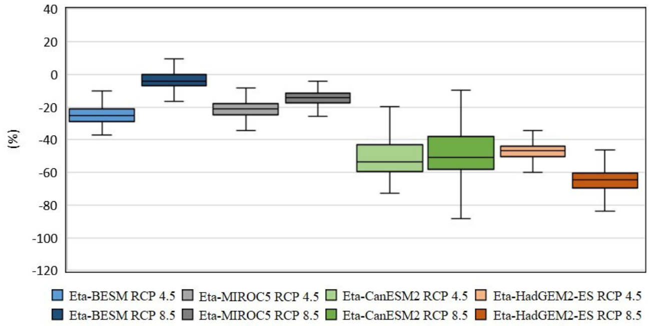

Figure 9. *Box plot* of the average flow variation (2025 - 2049) in all river reaches under RCP 4.5 and RCP 8.5.

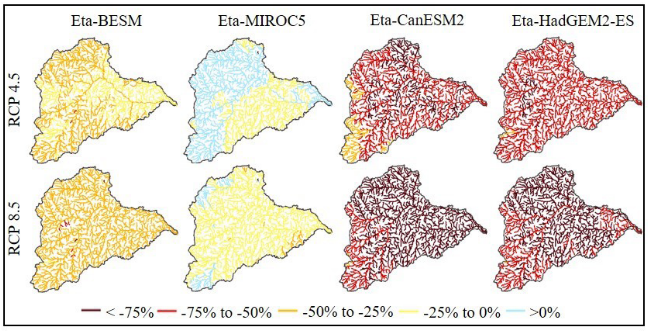

Figure 10. Simulated average flow variation (2050 - 2074) with the projections of Eta-BESM, Eta-MIROC5, Eta-CanESM2 and Eta-HadGEM2-ES under RCP 4.5 and RCP 8.5.

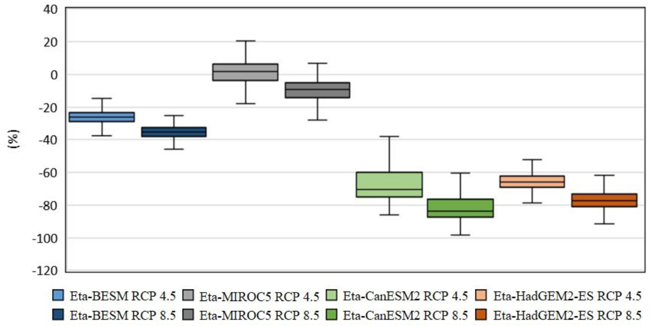

Figure 11. *Box plot* of the average flow variation (2050 - 2074) in all river reaches under RCP 4.5 and RCP 8.5.

Nóbrega et al. (2011) showed that the average flow of the Rio Grande basin (MG and SP) may vary from -20% to +18% in 2040 - 2069 using six GCM of CMIP3 and a +2°C heating scenario, showing the differences between the simulated flows with the projections of the climate models. Alvarenga et al. (2016) obtained reductions in the average monthly flow from -20% to -68%, in the rainy season, in the Lavrinhas river basin (MG) in 2041 - 2070 with Eta-HadGEM2-ES under RCP 8.5. It can be seen that, for the middle of the 21st century, studies in nearby Brazilian river basins, as well as in the Doce River basin, point to increasing flow trends, as well as considerable reductions.

When evaluating the flow variations in all simulated drainage reaches of the Doce River basin for the period 2075 - 2099 (Figure 12), it is observed that the flows simulated with the projections of Eta-MIROC5 RCP 4.5 present the most optimistic trends, while those simulated with the projections of Eta-CanESM2 and Eta-HadGEM2-ES under RCP 8.5 present the most severe reduction trends.

In relation to the trends of future flows generated with the projections of Eta-MIROC5 RCP 4.5, the reductions are less than -4% in 50% of the drainage reaches of the basin according to the median of the *box plot* (Figure 13). The upper whiskers of the *box plot*, as well as the map of Figure 12, shows a positive trend of simulated flow with the projections of Eta-MIROC5 RCP 8.5 in some rivers reaches in the 2075 – 2099 period. In 2075 - 2099 the reduction trends of Eta-CanESM2 and Eta-HadGEM2-ES RCP 8.5 are greater than 91% and 79%, respectively, in 50% of the drainage Figure 13 sections.

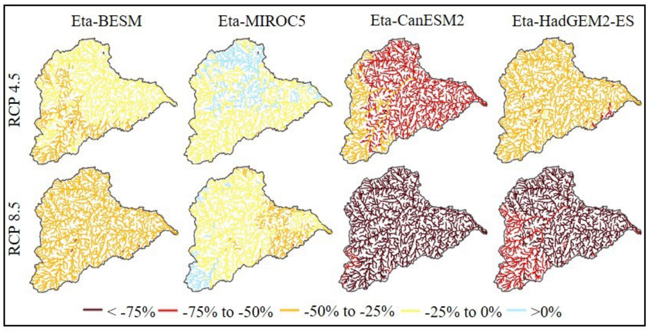

Figure 12. Simulated average flow variation (2075 - 2099) with the projections of Eta-BESM, Eta-MIROC5, Eta-CanESM2 and Eta-HadGEM2-ES under RCP 4.5 and RCP 8.5.

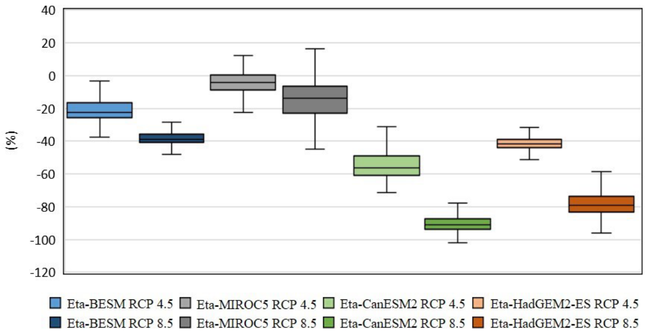

Figure 13. Box plot of the average flow variation (2075 - 2099) in all river reaches under RCP 4.5 and RCP 8.5.

Oliveira et al. (2017b) also found that the most severe reduction trends at the end of the 21st century for the Rio Grande basin (MG and SP) in relation to the projections of Eta-HadGEM2-ES under RCP 8.5 ranges from -49% to -69%.

Trends in future flows can vary greatly throughout the 21st century due to the climate models used, in addition to the location of the region of study, as identified in studies in Brazilian river basins (Alvarenga et al., 2016; Oliveira et al., 2017b; Santos et al., 2019; Andrade et al., 2020; Schuster et al., 2020).

The results of this study demonstrate considerable differences in the impacts of climate change on the average flow due to climate models and climate scenarios, which are directly related to variations in rainfall and temperature in the basin of Doce River.

Variations in flows in the basin of Doce River were sensitive to changes in precipitation, and significant reductions are expected according to the projections of certain models. This is explained by the non-linear relationships in the generation of flow, differences in the magnitude between the volumes of precipitation and flow, and the flow coefficient of the Doce River basin, which influences the fact that the coefficient of elasticity between rain and flow is normally greater than 1 (Brêda et al., 2020; Ribeiro Neto et al., 2016). In addition, climate model projections indicate an increase in temperature in all periods of the 21st century and, according to the Intergovernmental Panel on Climate Change (2007), changes in temperature affect evapotranspiration, which can compensate for small increases in precipitation and further increase the effect of decreased precipitation in surface waters.

CONCLUSION

Climate models and future climate scenarios indicate significant differences between rainfall trends at the Doce River basin. However, most of them indicate that the basin may suffer serious problems with significant reductions in average rainfall throughout the 21st century. The average temperatures of the Doce River basin tend to increase considerably in the future as it advances in the three future periods analyzed, especially under RCP 8.5 at the end of the 21st century.

The results of this study show that the basin of Doce River may have problems related to the reduction of flows in the three future periods analyzed. Although the simulations with the projections of regional climate models show different magnitudes of reduction, the reduction will still be considerable. The decreased flow in the basin may compromise the supply of water for human consumption and the availability of water for agriculture, industry, and electricity generation, which are important for eastern Minas Gerais and northwestern Espírito Santo.

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REFERENCES

Adam, K., & Collischonn, W. (2013). Análise dos impactos de mudanças climáticas nos regimes de precipitação e vazão na bacia hidrográfica do Rio Ibicuí. *Revista Brasileira de Recursos Hídricos*, *18*(3), 69-79. http://dx.doi.org/10.21168/rbrh.v18n3.p69-79.

Agência Nacional de Águas – ANA. (2016). *Encarte especial sobre a Bacia do Rio Doce: rompimento da barragem em Mariana/MG*. Brasília, DF: ANA. Retrieved in 2022, July 15, from https://arquivos.ana.gov.br/RioDoce/EncarteRioDoce_22_03_2016v2.pdf

Agência Nacional de Águas – ANA. (2020). *Conjuntura dos recursos hídricos no Brasil 2020: informe anual*. Brasília, DF: ANA. Retrieved in 2022, July 15, from https://www.snirh.gov.br/portal/centrais-de-conteudos/conjuntura-dos-recursos-hidricos/conjuntura-2020

Almagro, A., Oliveira, P. T. S., Rosolem, R., Hagemann, S., & Nobre, C. A. (2020). Performance evaluation of Eta/HadGEM2-ES and Eta/MIROC5 precipitation simulations over Brazil. *Atmospheric Research*, *244*, 105053. http://dx.doi.org/10.1016/j.atmosres.2020.105053.

Alvarenga, L. A., Mello, C. R., Colombo, A., Cuartas, L. A., & Chou, S. C. (2016). Hydrological responses to climate changes in a headwater watershed. *Ciência e Agrotecnologia*, *40*(6), 647-657. http://dx.doi.org/10.1590/1413-70542016406027716.

Andrade, C. W. L., Montenegro, S. M. G. L., Montenegro, A. A. A., Lima, J. R. S., Srinivasan, R., & Jones, C. A. (2020). Climate change impact assessment on water resources under RCP scenarios: a case study in Mundaú River Basin, Northeastern Brazil. *International Journal of Climatology*, *41*, 1-17. http://dx.doi.org/10.1002/joc.6751.

Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, *134*(3), 387-401. http://dx.doi.org/10.1007/s10584-014-1084-5.

Arora, V. K., Scinocca, J. F., Boer, G. J., Christian, J. R., Denman, K. L., Flato, G. M., Kharin, V. V., Lee, W. G., & Merryfield, W. J. (2011). Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases. *Geophysical Research Letters*, *38*(5), 1-6. http://dx.doi.org/10.1029/2010GL046270.

Bajracharya, A. R., Bajracharya, S. R., Shrestha, A. B., & Maharjan, S. B. (2018). Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal. *The Science of the Total Environment*, *625*, 837-848. http://dx.doi.org/10.1016/j.scitotenv.2017.12.332.

Bravo, J. M., Collischonn, W., da Paz, A. R., & Allasia, D. D. F. (2014). Impact of projected climate change on hydrologic regime of the Upper Paraguay River basin. *Climatic Change*, *127*(1), 27-41. http://dx.doi.org/10.1007/s10584-013-0816-2.

Brêda, J. P. L. F., Dias, R. C. P., Collischon, W., Bravo, J. M., Siqueira, V. A., & Steinke, E. B. (2020). Climate change impacts on South American water balance from a continental-scale hydrological model driven by CMIP5 projections. *Climatic Change*, *159*(4), 503-522. http://dx.doi.org/10.1007/s10584-020-02667-9.

Chanson, H. (2004). *The hydraulics of open channel flow: an introduction* (2nd ed.). Amsterdam: Elsevier.

Chou, S. C., Lyra, A., Mourão, C., Dereczynski, C., Pilotto, I., Gomes, J., Bustamante, J., Tavares, P., Silva, A., Rodrigues, D., Campos, D., Chagas, D., Sueiro, G., Siqueira, G., & Marengo, J. (2014a). Assessment of climate change over South America under RCP 4.5 and 8.5 downscaling scenarios. *American Journal of Climate Change*, *3*(5), 512-525. http://dx.doi.org/10.4236/ajcc.2014.35043.

Chou, S. C., Lyra, A., Mourão, C., Dereczynski, C., Pilotto, I., Gomes, J., Bustamante, J., Tavares, P., Silva, A., Rodrigues, D., Campos, D., Chagas, D., Sueiro, G., Siqueira, G., Nobre, P., & Marengo, J. (2014b). Evaluation of the eta simulations nested in three global climate models. *American Journal of Climate Change*, *3*(5), 438-454. http://dx.doi.org/10.4236/ajcc.2014.35039.

Chow, V. T., Maidment, D. R., & Mays, L. W. (1988). *Applied hydrology*. New York: McGraw-Hill Book Company.

Christensen, J. H., Boberg, F., Christensen, O. B., & Lucas-Picher, P. (2008). On the need for bias correction of regional climate change projections of temperature and precipitation. *Geophysical Research Letters*, *35*(20), 1-6. http://dx.doi.org/10.1029/2008GL035694.

Coelho, A. L. N. (2007). *Alterações hidrogeomorfológicas no Médio-Baixo Rio Doce/ES* (Tese de doutorado). Instituto de Geociências, Universidade Federal Fluminense, Niterói.

Coelho, A. L. N. (2009). Bacia hidrográfica do Rio Doce (MG/ES): uma análise socioambiental integrada. *Revista Geografares*, *7*(7), 131-146.

Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., & Woodward, S. (2011). Development and evaluation of an Earth-System model–HadGEM2. *Geoscientific Model Development*, *4*(4), 1051-1075. http://dx.doi.org/10.5194/gmd-4-1051-2011.

Collischonn, W., & Tucci, C. E. M. (2001). Simulação hidrológica de grandes bacias. *Revista Brasileira de Recursos Hídricos*, *6*(1), 95-118. http://dx.doi.org/10.21168/rbrh.v6n1.p95-118.

Collischonn, W., Allasia, D., Da Silva, B. C., & Tucci, C. E. (2007). The MGB-IPH model for large-scale rainfall – runoff modelling. *Hydrological Sciences Journal*, *52*(5), 878-895. http://dx.doi.org/10.1623/hysj.52.5.878.

Cupolillo, F. (2008). *Diagnóstico hidroclimatológico da Bacia do Rio Doce* (Tese de doutorado). Instituto de Geociências, Universidade Federal de Minas Gerais, Belo Horizonte.

De Paula, G. (2020). The distributional effect of climate change on agriculture: evidence from a Ricardian quantile analysis of Brazilian census data. *Journal of Environmental Economics and Management*, *104*, 102378. http://dx.doi.org/10.1016/j.jeem.2020.102378.

Fan, F. M., Buarque, D. C., Pontes, P. R. M., & Collischonn, W. (2015). Um mapa de unidades de resposta hidrológica para a América do Sul. In *Anais do XXI Simpósio Brasileiro de Recursos Hídricos*. Porto Alegre: ABRH.

Ferreira, P. M. D. L., Paz, A. R. D., & Bravo, J. M. (2020). Objective functions used as performance metrics for hydrological models: state-of-the-art and critical analysis. *Revista Brasileira de Recursos Hídricos*, *25*, 1-15. http://dx.doi.org/10.1590/2318-0331.252020190155.

Fleischmann, A. S., Collischonn, W., & Paiva, R. C. D. (2019). Estimating design hydrographs at the basin scale: from event-based to continuous hydrological simulation. *Revista Brasileira de Recursos Hídricos*, *24*, 1-10. http://dx.doi.org/10.1590/2318-0331.241920180109.

Guo, Y., Fang, G., Xu, Y. P., Tian, X., & Xie, J. (2020). Identifying how future climate and land use/cover changes impact streamflow in Xinanjiang Basin, East China. *The Science of the Total Environment*, *710*, 136275-136276. http://dx.doi.org/10.1016/j.scitotenv.2019.136275.

Intergovernmental Panel on Climate Change – IPCC. (2007). *Climate Change 2007: impacts, adaptation and vulnerability*. Retrieved in 2022, July 15, from https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg2_full_report.pdf

Intergovernmental Panel on Climate Change – IPCC. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation: a special report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. Retrieved in 2022, July 15, from https://www.ipcc.ch/site/assets/uploads/2018/03/SREX_Full_Report-1.pdf

Intergovernmental Panel on Climate Change – IPCC. (2014a). *Climate Change 2014: synthesis report*. Retrieved in 2022, July 15, from https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf

Intergovernmental Panel on Climate Change – IPCC. (2014b). *Climate Change 2014: impacts, adaptation, and vulnerability*. Retrieved in 2022, July 15, from https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartA_FINAL.pdf

Intergovernmental Panel on Climate Change – IPCC. (2021). Summary for policymakers. In Intergovernmental Panel on Climate Change (Ed.), *Climate change 2021: the physical science basis*. Retrieved in 2022, July 15, from https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf

Laprise, R., Elía, R., Caya, D., Biner, S., Lucas-Picher, P., Diaconescu, E., Leduc, M., Alexandru, A., & Separovic, L. (2008). Challenging some tenets of Regional Climate Modelling. *Meteorology and Atmospheric Physics*, *100*(1), 3-22. http://dx.doi.org/10.1007/s00703-008-0292-9.

Lenderink, G., Buishand, A., & Van Deursen, W. (2007). Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach. *Hydrology and Earth System Sciences*, *11*(3), 1145-1159. http://dx.doi.org/10.5194/hess-11-1145-2007.

Lima, J. W. M., Collischonn, W., & Marengo, J. A. (2014). *Efeitos das mudanças climáticas na geração de energia elétrica*. São Paulo: AES Tietê.

Lopes, V. A. R., Fan, F. M., Pontes, P. R. M., Siqueira, V. A., Collischonn, W., & Marques, D. M. (2018). A first integrated modelling of a river-lagoon large-scale hydrological system for forecasting purposes. *Journal of Hydrology (Amsterdam)*, *565*, 177-196. http://dx.doi.org/10.1016/j.jhydrol.2018.08.011.

Lucena, A. F. P., Szklo, A. S., Schaeffer, R., Souza, R. R., Borba, B. S. M. C., Costa, I. V. L., Pereira Júnior, A. O., & da Cunha, S. H. F. (2009). The vulnerability of renewable energy to climate change in Brazil. *Energy Policy*, *37*(3), 879-889. http://dx.doi.org/10.1016/j.enpol.2008.10.029.

Lyra, A., Tavares, P., Chou, S. C., Sueiro, G., Dereczynski, C., Sondermann, M., Silva, A., Marengo, J., & Giarolla, A. (2017). Climate change projections over three metropolitan regions in Southeast Brazil using the non-hydrostatic Eta regional climate model at 5-km resolution. *Theoretical and Applied Climatology*, *132*(1), 663-682. http://dx.doi.org/10.1007/s00704-017-2067-z.

Marengo, J. A., Chou, S. C., Kay, G., Alves, L. M., Pesquero, J. F., Soares, W. R., Santos, D. C., Lyra, A. A., Sueiro, G., Betts, R., Chagas, D. J., Gomes, J. L., Bustamante, J. F., & Tavares, P. (2011). Development of regional future climate change scenarios in South America using the Eta CPTEC/HadCM3 climate change projections: climatology and regional analyses for the Amazon, São Francisco and the Paraná River basins. *Climate Dynamics*, *38*, 1829-1848. http://dx.doi.org/10.1007/s00382-011-1155-5.

Marengo, J. A., Tomasella, J., & Nobre, C. A. (2017). Climate change and water resources. In B. C. Mattos, T. J. Galizia & B. S. M. Cortesão (Eds.), *Waters of Brazil*. Switzerland: Springer.

Martin, G. M., Bellouin, N., Collins, W. J., Culverwell, I. D., Halloran, P. R., Hardiman, S. C., Hinton, T. J., Jones, C. D., McDonald, R. E., McLaren, A. J., O'Connor, F. M., Roberts, M. J., Rodriguez, J. M., Woodward, S., Best, M. J., Brooks, M. E., Brown, A. R., Butchart, N., Dearden, C., Derbyshire, S. H., Dharssi, I., Doutriaux-Boucher, M., Edwards, J. M., Falloon, P. D., Gedney, N., Gray, L. J., Hewitt, H. T., Hobson, M., Huddleston, M. R., Hughes, J., Ineson, S., Ingram, W. J., James, P. M., Johns, T. C., Johnson, C. E., Jones, A., Jones, C. P., Joshi, M. M., Keen, A. B., Liddicoat, S., Lock, A. P., Maidens, A. V., Manners, J. C., Milton, S. F., Rae, J. G. L., Ridley, J. K., Sellar, A., Senior, C. A., Totterdell, I. J., Verhoef, A., Vidale, P. L., & Wiltshire, A. (2011). The HadGEM2 family of met office unified model climate configurations. *Geoscientific Model Development*, *4*(3), 723-757. http://dx.doi.org/10.5194/gmd-4-723-2011.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885-900. http://dx.doi.org/10.13031/2013.23153.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., & Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*, 747-756. http://dx.doi.org/10.1038/nature08823.

Muerth, M. J., St-Denis, B. G., Ricard, S., Velazquez, J. A., Schmid, J., Minville, M., Caya, D., Chaumont, D., Ludwig, R., & Turcotte, R. (2013). On the need for bias correction in regional climate scenarios to assess climate change impacts on river runoff. *Hydrology and Earth System Sciences*, *17*(3), 1189-1204.

Nearing, M. A., Pruski, F. F., & O'Neal, M. R. (2004). Expected climate change impacts on soil erosion rates: a review. *Journal of Soil and Water Conservation*, *59*(1), 43-50.

New, M., Lister, D., Hulme, M., & Makin, I. (2002). A high-resolution data set of surface climate over global land areas. *Climate Research*, *21*, 1-25. http://dx.doi.org/10.3354/cr021001.

Nobre, P., Siqueira, L. S. P., Almeida, R. A. F., Malagutti, M., Giarolla, E., Castelão, G. P., Bottino, M. J., Kubota, P., Figueroa, S. N., Costa, M. C., Baptista Junior, M., Irber Junior, L., & Marcondes, G. G. (2013). Climate simulation and change in the Brazilian climate model. *Journal of Climate*, *26*(17), 6716-6732. http://dx.doi.org/10.1175/JCLI-D-12-00580.1.

Nóbrega, M. T., Collischonn, W., Tucci, C. E. M., & Paz, A. R. (2011). Uncertainty in climate change impacts on water resources in the Rio Grande Basin, Brazil. *Hydrology and Earth System Sciences*, *15*(2), 585-595. http://dx.doi.org/10.5194/hess-15-585-2011.

Oliveira, K. S. S., & Quaresma, V. S. (2017a). Temporal variability in the suspended sediment load and streamflow of the Doce River. *Journal of South American Earth Sciences*, *78*, 101-115. http://dx.doi.org/10.1016/j.jsames.2017.06.009.

Oliveira, V. A., Mello, C. R., Viola, M. R., & Srinivasan, R. (2017b). Assessment of climate change impacts on streamflow and hydropower potential in the headwater region of the Grande River basin, Southeastern Brazil. *International Journal of Climatology*, *37*, 5005-5023. http://dx.doi.org/10.1002/joc.5138.

Paz, A. R., Collischonn, W., Bravo, J. M., Bates, P. D., & Baugh, C. (2013). The influence of vertical water balance on modelling Pantanal (Brazil) spatio-temporal inundation dynamics. *Hydrological Processes*, *28*(10), 3539-3553. http://dx.doi.org/10.1002/hyp.9897.

Pinto, W. P., Lima, G. B., & Zanetti, J. B. (2015). Análise comparativa de modelos de séries temporais para modelagem e previsão de regimes de vazões médias mensais do rio Doce, Colatina - Espírito Santo. *Ciência e Natura*, *37*(3), 1-11.

Plano Integrado de Recursos Hídricos da Bacia Hidrográfica do Rio Doce. (2010). *Plano Integrado de Recursos Hídricos da Bacia Hidrográfica do Rio Doce e Planos de Ações para as Unidades de Planejamento e Gestão de Recursos Hídricos no Âmbito da Bacia do Rio Doce* (Vol. 1). Relatório Final. Retrieved in 2022, July 15, from https://www.cbhdoce.org.br//wp-content/uploads/2016/12/PIRH_Doce_Volume_I.pdf

Pontes, P. R. M., Fan, F. M., Fleischmann, A. S., Paiva, R. C. D., Buarque, D. C., Siqueira, V. A., Jardim, P. F., Sorribas, M. V., & Collischonn, W. (2017). MGB-IPH model for hydrological and hydraulic simulation of large floodplain river systems coupled with open source GIS. *Environmental Modelling & Software*, *94*, 1-20. http://dx.doi.org/10.1016/j.envsoft.2017.03.029.

Qin, P., Xu, H., Liu, M., Du, L., Xiao, C., Liu, L., & Tarroja, B. (2020). Climate change impacts on Three Gorges Reservoir impoundment and hydropower generation. *Journal of Hydrology (Amsterdam)*, *580*, 1-13. http://dx.doi.org/10.1016/j.jhydrol.2019.123922.

Queiroz, A. R., Lima, L. M. M., Lima, J. W. M., Silva, B. C., & Scianni, L. A. (2016). Climate change impacts in the energy supply of the Brazilian hydro-dominant power system. *Renewable Energy*, *99*, 379-389. http://dx.doi.org/10.1016/j.renene.2016.07.022.

Raulino, J. B. S., Silveira, C. S., & Lima Neto, I. E. (2021). Assessment of climate change impacts on hydrology and water quality of large semi-arid reservoirs in Brazil. *Hydrological Sciences Journal*, *66*(8), 1321-1336. http://dx.doi.org/10.1080/02626667.2021.1933491

Ribeiro Neto, A., Paz, A. R., Marengo, J. A., & Chou, S. C. (2016). Hydrological processes and climate change in hydrographic regions of Brazil. *Journal of Water Resource and Protection*, *8*(12), 1103-1127.

Rodrigues, J. A. M., Viola, M. R., Alvarenga, L. A., Mello, C. R., Chou, S. C., Oliveira, V. A., Uddameri, V., & Morais, M. A. V. (2020). Climate change impacts under representative concentration pathway scenarios on streamflow and droughts of basins in the Brazilian Cerrado biome. *International Journal of Climatology*, *40*(5), 2511-2526. http://dx.doi.org/10.1002/joc.6347.

Salazar, L. F., Nobre, C. A., & Oyama, M. D. (2007). Climate change consequences on the biome distribution in tropical South America. *Geophysical Research Letters*, *34*(9), 1-6.

Santos, C. A. S., Rocha, F. A., Ramos, T. B., Alves, L. M., Mateus, M., Oliveira, R. P., & Neves, R. (2019). Using a hydrologic model to assess the performance of regional climate models in a semi-arid watershed in Brazil. *Water (Basel)*, *11*(1), 1-17. http://dx.doi.org/10.3390/w11010170.

Santos, J. Y. G., Silva, R. M., Carvalho Neto, J. G., Montenegro, S. M. G. L., Santos, C. A. G., & Silva, A. M. (2014). Assessment of land-use change on streamflow using GIS, remote sensing and a physically-based model, SWAT. *Proceedings Of The International Association Of Hydrological Sciences*, *364*, 38-43. http://dx.doi.org/10.5194/piahs-364-38-2014.

Schuster, R. C., Fan, F. M., & Collischonn, W. (2020). Scenarios of climate change effects in water availability within the patos Lagoon's Basin. *Revista Brasileira de Recursos Hídricos*, *25*, 1-15. http://dx.doi.org/10.1590/2318-0331.252020190061.

Siqueira, V. A., Paiva, R. C. D., Fleischmann, A. S., Fan, F. M., Ruhoff, A. L., Pontes, P. R. M., Paris, A., Calmant, S., & Collischonn, W. (2018). Toward continental hydrologic–hydrodynamic modeling in South America. *Hydrology and Earth System Sciences*, *22*(9), 4815-4842. http://dx.doi.org/10.5194/hess-22-4815-2018.

Sorribas, M. V., Paiva, R. C. D., Melack, J. M., Bravo, J. M., Jones, C., Carvalho, L., Beighley, E., Forsberg, B., & Costa, M. H. (2016). Projections of climate change effects on discharge and inundation in the Amazon basin. *Climatic Change*, *136*, 555-570. http://dx.doi.org/10.1007/s10584-016-1640-2.

Teutschbein, C., & Seibert, J. (2012). Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. *Journal of Hydrology (Amsterdam)*, *456-457*, 12-29. http://dx.doi.org/10.1016/j.jhydrol.2012.05.052.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., & Rose, S. K. (2011). The representative concentration pathways: an overview. *Climatic Change*, *109*, 5-31. http://dx.doi.org/10.1007/s10584-011-0148-z.

Viola, M. R., Mello, C. R., Chou, S. C., Yanagi, S. N., & Gomes, J. L. (2014). Assessing climate change impacts on Upper Grande River Basin hydrology, Southeast Brazil. *International Journal of Climatology*, *35*(6), 1054-1068. http://dx.doi.org/10.1002/joc.4038.

Watanabe, M., Suzuki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., Takemura, T., Chikira, M., Ogura, T., Sekiguchi, M., Takata, K., Yamazaki, D., Yokohata, T., Nozawa, T., Hasumi, H., Tatebe, H., & Kimoto, M. (2010). Improved Climate Simulation by MIROC5: mean states, variability, and climate sensitivity. *Journal of Climate*, *23*(23), 6312-6335. http://dx.doi.org/10.1175/2010JCLI3679.1.

Wöhling, T., Samaniego, L., & Kumar, R. (2013). Evaluating multiple performance criteria to calibrate the distributed hydrological model of the upper Neckar catchment. *Environmental Earth Sciences*, *69*(2), 453-468. http://dx.doi.org/10.1007/s12665-013-2306-2.

Xu, R., Hu, H., Tian, F., Li, C., & Khan, M. Y. A. (2019). Projected climate change impacts on future streamflow of the Yarlung Tsangpo-Brahmaputra River. *Global and Planetary Change*, *175*, 144-159. http://dx.doi.org/10.1016/j.gloplacha.2019.01.012.

Zhao, P., Lü, H., Yang, H., Wang, W., & Fu, G. (2019). Impacts of climate change on hydrological droughts at basin scale: A case study of the Weihe River Basin, China. *Quaternary International*, *513*, 37-46. http://dx.doi.org/10.1016/j.quaint.2019.02.022.

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