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Trends of streamflow under climate change for 26 Brazilian basins

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Abstract

Changes in the climate system and the hydrologic regime strongly affect all water uses and human activity. The main goal of this study is to evaluate the impact of rainfall pattern change on streamflow for 26 Brazilian basins with hydropower plants. More precisely, the goal is to estimate the trends on average streamflow for the 2011–2100 period. The estimated trends result from the analysis of rainfall obtained from a possible climate scenario, among others. The annual average streamflow for this 90-year period is simulated and compared with records from 83 years of observations (1931–2013). Simulations were carried out using two rainfall-to-streamflow hydrological models: Soil Moisture Accounting Procedure (SMAP) and Stochastic Linear Model (SLM). Results from simulations show important impacts, namely, an increase of streamflow in the southern basins and a decrease in the northern basins. Such changes can lead to disastrous consequences, considering the historical exposure to floods and droughts in the southern and northeast regions, respectively. These findings, in addition to the recent severe drought events that have occurred in such regions, provide awareness of a new cycle of reform to the existing water policies and Brazilian institutional framework, which saw the completion of its first 20 years in 2017.

Keywords: Brazil; Climate change; Hydrological modelling; Rainfall; River basins; Streamflow; Water resources

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Introduction

One of the major challenges facing the scientific community is the assessment of the impact of climate change and rainfall pattern changes on water resources. Water resources availability has been severely impacted by climate change because rainfall has a major influence on the water cycle, thus implying great socio-economic challenges (e.g., Ward, 2007). However, measurement and assessment of changes in rainfall patterns is still a field under discussion both at the global and regional scale. Therefore, it is critical to gain a deeper knowledge about these changes and their consequences for the hydrologic regime.

The description or estimates of the changing rainfall pattern are especially important for countries with a strong dependence on hydropower generation. Therefore, the main goal of this study is to evaluate the impact of rainfall pattern change on streamflow for 26 Brazilian basins with hydropower plants. More precisely, the goal is to estimate the average streamflow trends for the 2011–2100 period (90 years) based on two rainfall–runoff hydrological models which are used to simulate fluctuations in the annual average streamflow during this period. Results from the simulations are compared with records from 83 years (1931–2013) of observations. Major impacts of changes in rainfall patterns on the generation of streamflow were identified. After describing selected major previous studies (general scope and specifically addressing river basins with large hydropower development), we highlight the main contributions of this research at the end of the Introduction section.

Analysis of global rainfall variability was undertaken by Good *et al*. (2016) with tropical and mid-latitude rainfall characteristics derived from extensive station records and high-frequency satellite observations. According to the authors, the inter-annual variation in rainfall totals is shown to be a critical factor governing the year-to-year availability of water resources, yet the connection between inter-annual rainfall variability and underlying event- and season-scale rainfall variability remains unclear.

Research in the field of rainfall pattern change usually focuses on two particular questions: (1) will science be able to identify long-term trends, with data from relatively short periods, and (2) does human activity, such as changes in land use or warming due to the greenhouse effect, influence these trends? Answering these questions requires a major scientific effort within an integrated and comprehensive view of the hydro-climatic processes, both on global and regional scales. Even if the underlying causes of climate change are not fully explained, it is essential to understand its impacts, so that the planning of mitigation and adaptation measures can be effective.

Repeated water scarcity events have occurred in recent years, revealing many countries or regions have a lack of rainfall or storage capacity to meet existing water supply, agriculture, energy, and industry demands. The impact of climate and rainfall changes on the hydrological regime of large basins has drawn the attention of researchers. In countries with a strong dependence on hydropower plants, like Brazil, the growing concerns of public authorities and power generation companies to address critical issues related to possible trends towards the decline of river flows has motivated the development of several research projects and studies.

Barros *et al*. (2009) used a six-month prediction model to transform rainfall into streamflow for all the Brazilian power generating basins, aiming at forecasting purposes. The importance of hydropower production in Brazil and the need for better hydrologic prediction in watersheds for vigorous planning in Brazil is very relevant, both for individual hydro generation companies as well as for operational planning of the overall interconnected electric power system, as pointed out by Viola *et al*. (2012). In Brazil, reference values to define water grants for consumption purposes, auction concession rights for hydropower plants, long-term energy contracts backed by firm energy and electricity prices in the short-term market are calculated by models considering historical series of inflows.

The effect of climate change on hydropower production in Brazil was studied by Lima *et al*. (2014) using distributed models for rainfall to streamflow transformation. In this work, the only one comparable in scale and size to the present study, most of the southern basins showed a significant increase of streamflow while the northern and northeastern basins showed an important depletion of streamflow. As for the southeast and midwest regions, changes of streamflow are small, showing increases and decreases, depending on the climate change run evaluated. Despite distributed rainfall–runoff models being widely used in hydrological studies, the data from the large-scale river basins studied in this work that would be required to calibrate all the parameters of a distributed rainfall–runoff model are not available. Therefore, Soil moisture accounting procedure (SMAP) (which is the rainfall–runoff model most used by the Brazilian National Power Agency) and MEL were used as alternative tools as a compromise solution between the accuracy of results and the availability of data. Moreover, for the first time, the models used by the Brazilian authorities (ANEEL and ONS) to forecast short-term (six-month) flow for hydropower production projections are here proposed for long-term (90-year) projections.

The present study uses lumped models to simulate the rainfall to streamflow process since most of the studied basins are in data-scarce remote areas. This study was not developed for forecasting purposes, but to address the relevant issue of long-term trends on streamflow across the main river basins where the hydropower plants are placed. The streamflow scenarios which were generated by rainfall–runoff models allowed a comparison of the results from the calibration stage, thus adjusting corresponding parameters in order to guarantee consistency. The results from several climate change model runs are discussed in depth in the paper, which highlights impacts on several water uses with an emphasis on hydropower. It is clear that these findings and also the recent water scarcity events (2014–2016) that occurred across several states of Brazil's southern and northeastern regions are strong factors to drive the revision of the current water policies and the institutional water framework of the country. The shift in the culture of water crisis management to a culture of preparedness has to be a key objective, which will require adaptation measures and coordination among different government levels and regional stakeholders.

Methods

Study area

The 26 basins under study represent more than 50% of Brazil's territory, comprising all generating basins of hydroelectric power in the country (Figure 1 and Table 1).

In Brazil, the existing 217 large or medium hydropower plants in operation account for 101.9 GW of installed capacity. The small hydro plants (1,125 units) account for 5.2 GW. Thus, the total hydropower capacity is 107.1 GW (67.3% of the total installed capacity of the country), while the wind power installed capacity is 12.8 GW (8% of the total) and the solar is only 1.5 GW. Most of the large and medium hydropower plants are located in the southeast and south of Brazil, in the Paraná and Southeast Atlantic basins.

Rainfall data

This study uses rainfall data estimated by Collins *et al*. (2001) via the HadCM3 (Hadley Centre Coupled Model, version 3) GCM. Output from the GCM was downscaled to South America by the

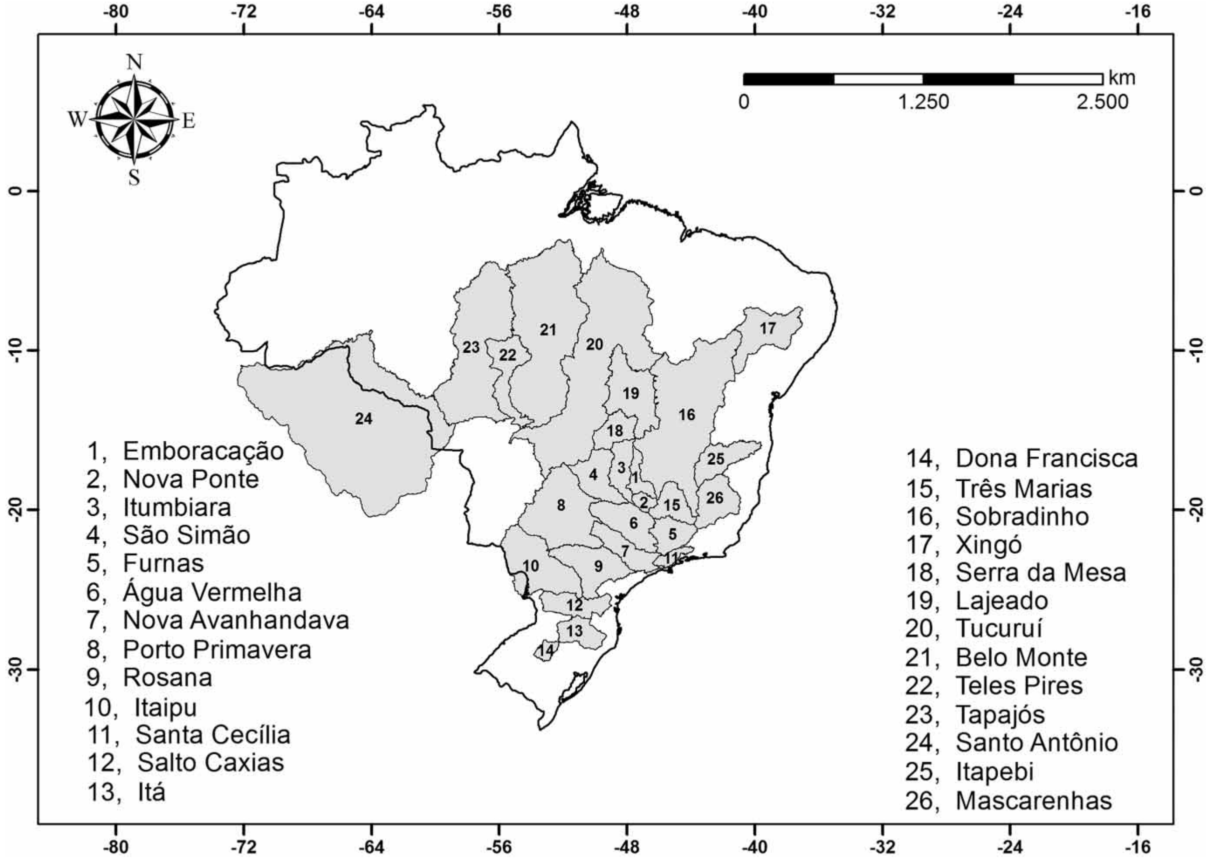

Fig. 1. Main river basins selected for this study. Itaipu (10) and Santo Antônio (24) are transnational basins.

NCEP Eta CPTEC/INPE model. For further details on the NCEP Eta CPTEC/INPE model see Black (1994), Marengo *et al.* (2012) and Chou *et al.* (2012). The GCM HadCM3 model was used because this is the only GCM downscaled for the entire area of South America (and Brazil) at the time the research project was developed (2012–2014). More recently, other downscaling models have been developed and applied (e.g., Cabré *et al.*, 2014; Sales *et al.*, 2015), although they were applied only to sub-regions of South America.

The study presented by Collins *et al.* (2001) included 17 climate change model runs, 16 with perturbations and 1 undisturbed. From these, only four model runs were used in the downscale process (Marengo *et al.*, 2012). These runs are named as follows: High, Mid, Low and Cntrl (control). High, Mid and Low do not denote an increase or decrease in rainfall, but only the sensitivity to perturbations of the coupled climate change model. Cntrl is the model run without perturbations (undisturbed). For further details on this subject see Collins *et al.* (2001) and Marengo *et al.* (2012).

From the rainfall data generated by the NCEP Eta CPTEC/INPE model the following procedure was carried out in this work. Since rainfall is known for each 40 km × 40 km cell, an area-weighted method is used to evaluate the average monthly rainfall in each basin. This function determines the weight of each cell when compared to the total area of the basin to which it belongs. The weight is then multiplied by the amount of rainfall in the cell. The sum of these values is the average rainfall amount per basin.

Table 1. Selected characteristics of the 26 basins and the number of hydropower plants.

Major basin	Region	Number of plants	Basin	Area (km²)
Paraná	Southeast	55	1	29,000
			2	15,300
			3	51,011
			4	85,729
			5	50,464
			6	89,436
			7	62,300
			8	190,760
			9	100,799
			10	149,000
Paraíba do Sul	Southeast	8	11	16,694
Iguaçu	South	9	12	57,000
Uruguai	South	11	13	44,500
Jacuí	South	5	14	14,014
São Francisco			15	50,600
	Northeast	9	16	447,825
			17	110,275
Tocantins			18	50,975
	North	7	19	134,543
			20	572,482
Xingú	North	2	21	480,000
Upper Tapajós	North	0	22	90,707
Tapajós	North	0	23	362,293
			24	988,873
Jequitinhonha	Southeast	2	25	68,100
Doce	Southeast	8	26	73,700

Average monthly rainfall is considered to have sufficient temporal resolution for this study because all basins are large (over 10,000 km^2). Table 2 summarizes the historical (1981–2013), simulated and difference between historical and simulated average annual rainfall for the 26 basins, under the four climate change model runs.

The average monthly rainfall in each basin is the input source for the rainfall to streamflow transformation models SMAP (Soil Moisture Accounting Procedure; process-based) and SLM (Stochastic Linear Model; stochastic).

Streamflow estimation

This work adapts the method presented by Barros *et al.* (2009) to estimate streamflow in all of Brazil's largest hydropower basins. In this work, two hydrologic models (SMAP and SLM) are employed to simulate the rainfall to streamflow process and to simulate fluctuations in the average annual streamflow for the 2011–2100 period. SMAP (Lopes *et al.*, 1982) is a deterministic model based on the Stanford Watershed IV model (Crawford & Linsley, 1966) and on the Mero model (Mero, 1978). SLM is an autoregressive-moving-average (ARMA category). SLM is a stochastic model so it may generate base flows below zero, i.e., physically impossible, thus biasing long-term streamflow simulations, since the groundwater contribution to river flow is the primary source of

Table 2. Historical, simulated (Sim) and difference (Dif) between historical and simulated average annual rainfall for the 26 basins, under the four climate model runs.

Basin	Rainfall (mm)								
		Cntrl		Low		Mid		High	
	Historical	Sim	Dif	Sim	Dif	Sim	Dif	Sim	Dif
1	1,203	1,607	404	1,870	667	1,438	235	1,607	404
2	1,443	1,693	249	1,899	455	1,639	195	1,801	357
3	1,272	1,549	277	1,767	495	1,405	133	1,556	284
4	1,284	1,426	141	1,565	281	1,314	29	1,432	147
5	1,344	1,966	622	2,078	733	2,009	665	2,157	813
6	1,344	1,621	277	1,741	397	1,608	264	1,723	378
7	1,295	1,613	318	1,650	355	1,631	336	1,719	423
8	1,401	1,253	−147	1,301	−99	1,214	−186	1,265	−135
9	1,400	1,746	346	1,729	328	1,766	365	1,843	442
10	1,505	1,546	41	1,500	−4	1,508	3	1,551	46
11	1,380	1,426	45	1,444	63	1,481	100	1,538	157
12	1,696	2,285	589	2,147	451	2,285	588	2,392	696
13	1,801	2,278	477	2,124	323	2,341	540	2,403	602
14	1,894	2,105	211	2,027	133	2,177	283	2,237	343
15	1,181	1,778	597	2,072	891	1,675	494	1,846	665
16	973	881	−91	1,149	176	706	−267	780	−192
17	536	236	−300	341	−194	185	−350	166	−369
18	1,393	1,640	247	1,882	489	1,372	−20	1,537	144
19	1,347	1,246	−101	1,597	249	1,017	−329	1,103	−244
20	1,639	1,246	−392	1,399	−239	1,035	−604	1,086	−553
21	1,917	1,272	−644	1,470	−447	1,169	−747	1,186	−730
22	1,883	1,548	−335	1,763	−120	1,425	−457	1,483	−400
23	1,972	1,492	−480	1,665	−307	1,439	−533	1,447	−525
24	1,463	1,183	−280	1,251	−212	1,130	−333	1,160	−303
25	996	1,084	88	1,476	480	856	−139	975	−21
26	1,168	1,507	338	2,002	834	1,384	215	1,531	362

streamflow during dry weather. To overcome this issue, SMAP is used preliminarily to calculate the base flow in the 26 basins. Results from these simulations are then used on SLM, especially for minimum streamflow restrictions in the drier simulation periods. For calibration and validation of the models, the following data are used:

- Total monthly rainfall (mm) in grids of 200 km × 200 km, covering all areas of the selected river basins, from 01/1995 to 05/2007, provided by the Brazilian Centre for Weather Forecasting and Climate Studies (CPTEC).
- Observations of monthly average streamflow ($m^3 \cdot s^{-1}$) for the 26 selected river basins, collected by the Brazilian Independent System Operator (ONS) for the same period as referred to in the point above.
- Monthly average potential evaporation for the 26 river basins, obtained from the meteorological stations of the Department of Water and Electrical Energy of the São Paulo State Government (DAEE), the São Paulo Energy Company (CESP) and the Brazilian National Meteorology Institute (INMET).

The models were calibrated for the 1995–2005 period. SMAP was calibrated, for each basin, using the following parameters: (i) base streamflow recession constant, (ii) soil-saturation capacity, (iii) groundwater recharge capacity, and (iv) runoff parameter. Initial condition parameters used were the soil moisture and base flow. The recession constant of base streamflow represents the number of months that it takes from the base streamflow peak to recede to half of this value. Soil-saturation capacity is the water depth the soil needs to saturate. Groundwater recharge capacity is the percentage of water that moves from the partially saturated zone to the saturated zone of the basin, contributing to the base streamflow. Runoff parameter is a dimensionless classification parameter, from 1 to 10, representing the rainfall depth that does not infiltrate and is not intercepted. Further detail on the calibration procedure for SMAP can be found in Barros *et al*. (2009) and Lopes *et al*. (1982). SLM was calibrated using the average rainfall depth from the current month and three previous months and the average streamflow from the three previous months (for further details see Barros *et al*., 2009).

Both models were validated for the 2006–2007 period. Table 3 shows goodness-of-fit between the observed and simulated streamflow represented by the Nash–Sutcliffe efficiency coefficient E (Nash & Sutcliffe, 1970). The performance of the two models, as shown in Table 3, is similar. However,

Table 3. Nash–Sutcliffe efficiency coefficients E (for models SMAP and SLM) of the 26 basins.

	E	
Basin	SMAP	SLM
1	0.785	0.771
2	0.911	0.832
3	0.735	0.819
4	0.869	0.897
5	0.941	0.880
6	0.726	0.814
7	0.886	0.839
8	0.745	0.762
9	0.832	0.736
10	0.565	0.675
11	0.730	0.838
12	0.646	0.608
13	0.582	0.534
14	0.729	0.684
15	0.855	0.740
16	0.826	0.841
17	0.030	0.351
18	0.771	0.849
19	0.856	0.804
20	0.625	0.876
21	0.743	0.859
22	0.830	0.889
23	0.711	0.898
24	0.578	0.940
25	0.791	0.853
26	0.809	0.812

both are used, taking the average of the results, mainly considering the need to avoid base flows below zero if only SMAP was used, as explained before.

Streamflow calculated with SMAP and SLM shows a good fit with the observations. Overall, the Nash–Sutcliffe efficiency coefficients are high for most of the basins, both for SMAP and SLM, mostly ranging from 0.60 to 0.90. The only basin with a low efficiency coefficient is the Xingó basin. However, this basin makes a very small contribution to the discharge of the São Francisco River since it is in a semi-arid region of northeastern Brazil.

SMAP and SLM results are combined into SMAP&SLM by an arithmetic mean of their results; that is, each model accounts for 50% of streamflow. This combination of results from both models is widely used by the Brazilian Independent System Operator (ONS) to forecast short-term flow for hydropower production projections. According to ONS (2007) and Barros *et al*. (2009), this procedure has a good performance for the river basins with the largest hydropower plants in Brazil.

The quality of streamflow projections relies heavily on the quality of the rainfall and climate change runs, since the rainfall to streamflow transformation shows a good performance, generally with a range of the Nash–Sutcliffe efficiency coefficient E of around 75%. The simulations carried out show that streamflow change is intensified by the rainfall to streamflow process, where the changes in rainfall lead to even higher changes in streamflow, particularly when rainfall decreases.

Results and discussion

Table 4 presents the specific annual average streamflow estimated with SMAP&SLM for the 26 basins during the 2011–2100 period, compared with the records from the 1931–2013 period. The differences found in streamflow throughout the 26 basins when comparing the results from SMAP&SLM with the historical record are evidenced. These dynamics on streamflow generation are a key issue for future studies and decision-making (e.g., hydropower generation plants, flood and drought management, and water supply). The results of this study present a continuous and coherent evolution of streamflow across the studied 2011–2100 period. As such, and despite it being usual to discuss the evolution of streamflow by time slices (commonly of 30 years), in this paper the discussion is presented for the whole 90-year period. Notwithstanding, it should be stressed that the estimated trends presented in this work result from the analysis of rainfall obtained from a possible climate scenario, among others.

From Table 4 it can be seen that some climate change model runs present changes in streamflow similar to the control run. This happens because, in terms of magnitude, the disturbance of the Mid, Cntrl and, sometimes, the Low runs, do not present a wide range (see Marengo *et al*., 2012). Notwithstanding, in Brazil, where annual rainfall ranges from less than 300 mm/year to more than 3,500 mm/year, small relative differences can lead to substantial absolute differences in the resulting volumes of rainfall and/or streamflow. As an example, we can say that a decrease of 10% in rainfall or in streamflow, in a region where rainfall volumes are historically low, such as the semi-arid region of Brazil where more than 25 million people live, may cause major disruptions to key sectors such as water supply and irrigation.

Discussion of results is divided into two major regions of Brazil: (1) north and northeast, comprising basins 16 to 24, and (2) southeast, centre-west and south, comprising basins 1 to 15, 25 and 26. This division is adapted from the Brazilian hydropower operational planning, that divides the country into four regions (I – South, II – Southeast and Centre-West, III – North and IV – Northeast), here grouped

Table 4. Historical, simulated (Sim) and difference (Dif) between historical and simulated average annual streamflow for the 26 basins, under the four climate change model runs.

	Streamflow ($l \cdot s^{-1} \cdot km^2$)								
		Cntrl		Low		Mid		High	
Basin	Historical	Sim	Dif	Sim	Dif	Sim	Dif	Sim	Dif
1	16.7	17.9	1.1	22.1	5.4	14.9	−1.8	17.8	1.1
2	19.4	21.3	1.9	24.9	5.4	20.3	0.8	23.3	3.8
3	15.1	15.4	0.3	18.9	3.8	13.1	−2.0	15.6	0.5
4	10.0	11.6	1.6	13.6	3.6	9.9	−0.1	11.7	1.7
5	18.3	26.6	8.3	28.5	10.2	27.5	9.2	30.3	11.9
6	13.1	17.3	4.1	19.2	6.0	17.1	4.0	19.0	5.9
7	11.6	18.5	6.9	19.0	7.4	18.9	7.3	20.4	8.8
8	10.6	11.3	0.7	11.9	1.4	10.7	0.1	11.4	0.9
9	12.9	20.7	7.8	20.2	7.3	21.1	8.2	22.2	9.3
10	11.6	19.5	7.9	19.1	7.5	19.3	7.7	20.1	8.5
11	17.7	16.8	−0.9	17.1	−0.6	17.8	0.2	18.9	1.2
12	23.7	46.3	22.5	43.0	19.2	46.2	22.5	48.9	25.2
13	23.3	39.0	15.7	35.6	12.3	40.3	16.9	41.8	18.4
14	23.1	31.3	8.2	29.6	6.6	32.7	9.7	34.1	11.0
15	13.6	21.3	7.7	26.4	12.8	19.5	5.9	22.5	8.9
16	4.4	2.8	−1.6	4.8	0.4	1.7	−2.6	2.2	−2.2
17	1.0	0.2	−0.8	0.4	−0.6	0.1	−0.9	0.1	−0.9
18	15.1	15.8	0.7	19.5	4.4	11.7	−3.5	14.2	−1.0
19	12.3	9.9	−2.4	15.0	2.7	6.8	−5.5	8.0	−4.3
20	14.9	10.2	−4.7	11.8	−3.1	6.9	−8.0	7.6	−7.3
21	16.8	7.6	−9.2	9.8	−7.0	6.4	−10.4	6.7	−10.1
22	25.1	17.3	−7.8	21.0	−4.0	14.9	−10.2	15.9	−9.2
23	22.6	14.7	−7.9	17.6	−5.1	13.6	−9.0	13.8	−8.9
24	19.1	13.3	−5.8	14.4	−4.6	12.4	−6.7	12.8	−6.2
25	5.6	5.5	0.0	10.3	4.8	3.3	−2.3	4.5	−1.1
26	13.1	12.0	−1.1	24.7	11.6	14.0	0.8	16.4	3.3

into 'northern' and 'southern' basins. Figures 2 and 3 depict the amplification in the rainfall to streamflow process for river basins representative of each region.

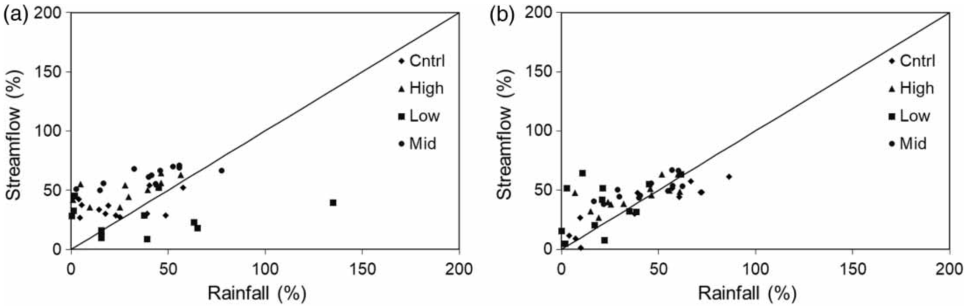

Fig. 2. Annual average streamflow changes vs. annual average rainfall changes in the Sobradinho (a) and Tucuruí (b) basins, under the four climate change model runs.

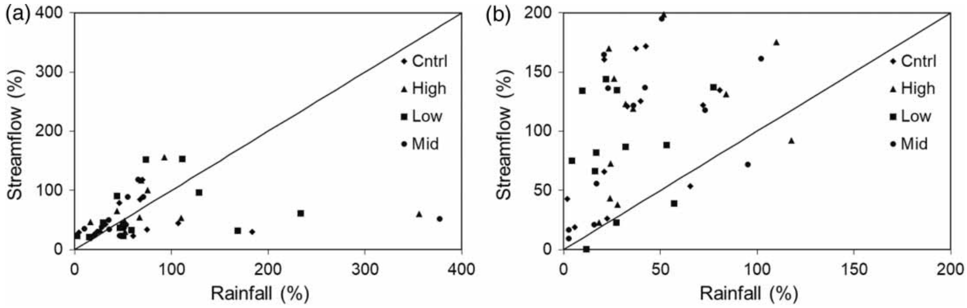

Fig. 3. Annual average streamflow changes vs. annual average rainfall changes in the Furnas (a) and Salto Caxias (b) basins, under the four climate change model runs.

Generally, northern basins will suffer a decrease in streamflow, while an increase is expected in the southern basins. This is explained by the uneven distribution of rainfall in the north and south of Brazil, which is expected to increase further in the future (see Table 2). This unevenness is mainly due to: (1) in the north, the high volume of water in the atmosphere caused by the Amazon rainforest; and (2) in the south, the polar air masses that do not move north of the southeastern region. This asymmetry between rainfall in the north and south of Brazil can be exemplified by the recent year 2014. In this year, the Cantareira system, the system of reservoirs that supply more than 40% of the water to the metropolitan area of São Paulo, corresponding to more than ten million people, suffered a severe drought. At the same time, an historical record was set in the spillway of the Itaipu dam, in a basin just 800 km from the Cantareira system.

North and northeast

In the north and northeast of Brazil, there is evidence of amplification of the rainfall to streamflow process, i.e., that small changes in rainfall led to larger changes in streamflow. The results show that as rainfall increases, there is a greater increase of streamflow. The Sobradinho (Figure 2(a)) and the Tucuruí (Figure 2(b)), respectively, of the northeast and the north regions, are here presented as examples of the rainfall to streamflow process amplification. The Sobradinho basin has a very large artificial lake (more than 4,200 km^2) and controls the streamflow of the São Francisco River, the largest river in the northeast of Brazil. The Tucuruí basin is here presented as it is currently the most important hydropower generating basin in the northern region, and the main source for this region's electric power supply. The figures are plotted from the changes in rainfall and streamflow annual averages, by comparing the estimation for the 2011–2100 period with the records from the 1931–2013 period. The concentration of results above the 1:1 line shows that the increase of streamflow is amplified when compared to the increase of rainfall. This amplification effect is of major importance for river and water resources management, as it shows that rainfall shortages can be even more serious when transformed into decreases of river streamflow.

The Xingó and Belo Monte basins show the most severe decrease in rainfall and streamflow when compared with the other basins, for all the simulated climate change model runs. However, the Xingó basin presents the worst Nash–Sutcliffe efficiency coefficients E (see Table 3) and, as such, it is not discussed here. Results for the Belo Monte basin, a particularly important basin in terms of the ethnic and biological diversity risks raised by the construction of the dam, follow the predominant forecast for the northern region. In this region, according to the simulation results, almost all river basins and all climate change-induced model runs show a significant drop in rainfall and streamflow. For the Tucuruí basin, today's most important hydropower generating basin in the north of Brazil, the reduction in annual rainfall is expected to be from 239 to 604 mm, depending on the climate change run.

Drops in rainfall and streamflow for the northern region seem to be quite substantial. One example is the important drop in rainfall and streamflow (ranging between 212 and 334 mm) in the Santo Antônio basin. This is a key point to be considered in the studies of viability and operation management of the new hydropower plants in this basin (Santo Antônio and Jirau). The predicted decrease in rainfall and streamflow in the north of Brazil may impact on expected results from the expansion of the hydropower system to that area. Although the historical records show high streamflow values, trends for the future are not as favourable as the historical records, which may compromise the existing water resources planning for the region.

In the north, these projected trends may help to mitigate some important problems, such as the large extension of flooded plains, which every year affect thousands of people. However, the distribution of rainfall and streamflow of the northern rivers show that droughts are also becoming more severe. This may lead to very negative impacts, namely, on agricultural production and people's daily lives. If this forecast is confirmed, not only will the water supply for human consumption have to be adapted, but also the availability of water for the agricultural system, which will suffer from more events of extreme drought and dry conditions, but also milder flooding. This may impact on virtually all uses of water resources in the northern region of Brazil.

SMAP-SLM results for the Sobradinho basin in the northeast region show a marked decrease in the São Francisco River streamflow. Historical rain is very low, almost zero, during the May–August period; thus, the increase in drought events will not be especially noticeable during this period. This analysis raises a new concern because the São Francisco River is currently suffering a diversion to areas of acute and severe water shortage, namely, in Pernambuco, Paraíba, Rio Grande do Norte and Ceará states. According to the simulations, the Três Marias basin, located upstream from the Sobradinho basin, will see increased rainfall and streamflow during the studied time range. However, further analysis is required to assess to what extent this can compensate for the forecasted water deficit in the Sobradinho basin.

Southeast, centre-west and south

In many basins of the southeast, centre-west and south regions, the rainfall to streamflow process is relatively stable when compared to the decrease in rainfall. This means that large rainfall shortages do not lead to streamflow shortages of the same magnitude (see Figure 3). The Furnas river basin, in the southeast, is the headwater of a cascade of very important hydropower plants (e.g., Furnas, Água Vermelha, Itaipú) and holds great importance in regulating streamflow. The Salto Caxias basin in the south, with four major reservoirs and seven important plants producing approximately 7,000 MW, is critical for hydropower production in southern Brazil.

Simulation results for the Santa Cecilia basin show a small change in rainfall and streamflow, the latter ranging from -0.9 to $1.2\ \mathrm{l \cdot s^{-1} \cdot km^{-2}}$. This pattern may be caused by the sharp relief of the mountain range around the basin. This mountainous area (Paraíba Valley) has the Serra do Mar mountain range as its southern border. The Atlantic side of Serra do Mar receives approximately an average of 2,500 mm of rainfall per year, much higher than in the Paraíba Valley, with less than 1,500 mm per year.

The northern border of the Santa Cecilia basin is formed by the Serra da Mantiqueira (Mantiqueira Mountain range), with some of the highest peaks in the country, ranging up to 2,700 m in altitude. This mountain range protects the valley from rainfall coming from the north and the ocean (southeast), thus maintaining the valley near historical rainfall levels. On the northern side of the Serra da Mantiqueira important tributaries to the Rio Grande River lead to the Furnas reservoir, where important increases in rainfall and streamflow are expected. The outlook for the Furnas, Três Marias and Mascarenhas basins shows an increase in rainfall and streamflow for all climate change model runs. Since geomorphology plays a major role in concentrating rainfall, this outcome may be explained by the sharp relief in these basins' headwaters and by their proximity to the Atlantic Ocean. Further, other basins at altitudes above 1,000 m also show important increases in rainfall and streamflow (Água Vermelha, Nova Avanhandava, Rosana, Salto Caxias, Itá and Dona Francisca). Results for the Itaipu basin show a possible increase of streamflow ranging from 7.5 to 8.5 $l \cdot s^{-1} \cdot km^{-2}$. Amplification in the transformation process of rainfall to streamflow is particularly noticeable in these basins (e.g., see Figure 3(b)).

In the south of Brazil, the increase of streamflow is notorious for the entire simulation period. The impact in the Salto Caxias basin, between the states of Paraná and Santa Catarina, will affect the northern areas less than the southern areas of the basin. In the southern areas, the increase of streamflow may become a major threat, as this region already has a history of fluvial and flash floods, which may worsen according to the simulation results.

The southeast is the region with the smallest changes both in rainfall and streamflow. The water crisis of 2014 provided strong evidence that the state of São Paulo, and most of the southeast region, needs continuous water resources planning and that changes in streamflow may lead to catastrophic disasters during extreme situations. In the water crisis of 2014, the metropolitan area of the city of São Paulo, where more than 21 million people live, posed some challenging issues. The Cantareira system suffers from strong conflicts with other regions. One of these regions is the state of Rio de Janeiro, also with a very large population and substantial water demand. One of the alternatives currently presented for ensuring the water supply to the greater São Paulo area is the use of the Paraíba do Sul River, or more precisely, the Jaguari reservoir. The predicted impact on the Santa Cecília basin (located in the Paraiba do Sul River basin) shows a change of streamflow from -0.9 to 1.2 $l \cdot s^{-1} \cdot km^{-2}$. The uncertainty denoted by this forecast shows that such an important decision needs to be further evaluated.

Conclusions

This study focuses on streamflow trends in 26 major Brazilian river basins under four climate change model runs. Rainfall was estimated from a regionalized model by NCEP Eta CPTEC/INPE from HadCM3 GCM based on climate change scenario A1B from the IPCC. SMAP and SLM models were used to transform rainfall into streamflow. Average annual streamflow for the 2011–2100 (90-year) period was simulated. The estimated trends are the result of an input of rainfall obtained from a possible climate scenario, among others. Despite some non-stationary effects in selected series of historical observations, the results were compared with historical records from the 1931–2013 (83-year) period. The results from the simulations should be understood as trends of increase or decrease of streamflow in the river basins.

All climate change model runs show a substantial decline of streamflow in the north of Brazil, where the Amazon River basin is located. This should place more attention on the current national energy policy towards an expansion of hydropower across the Amazon region. All large hydropower projects, most recently installed in the Amazon region (e.g., Belo Monte, Jirau, Santo Antonio), are run-of-river plants, thus subject to river flow changes. Therefore, the Brazilian energy planning authorities should take into account the possible decline of inflows in the north of Brazil, as a key risk factor to avoid expanding hydropower in this region. However, the published official energy plan, the PDE 2026 (MME, 2017), does not take into account the declining streamflow scenario since 57% of additional hydropower capacity is placed in the Amazon region for the next ten years. The expansion of hydropower in this region encompasses six plants, whereas only one (3% of the additional capacity) is in the southeast region and nine are in the south region (40% of the additional capacity). The newly planned expansion of hydropower in the Amazon basin over the next ten years will add 2.6 GW to the amount installed (18.55 GW) in the last ten years (Belo Monte: 11.2 GW, Jirau: 3.75 GW and Santo Antonio: 3.6 GW) and more than 8.37 GW, which is the capacity of Tucuruí, thus resulting in a total of 26.9 GW of installed capacity in large projects in the Amazon basin. That is the size of the hydropower production with potential exposure to climate change forecasts of declining streamflow.

In the northeast region, all climate change model runs, with the exception of the Low run, show a considerable decline of streamflow. This has to be a major concern for regional and federal government, as well as for other key stakeholders. As highlighted by De Nys *et al*. (2016), the 2010–2015 drought in the semi-arid part of Brazil's northeast region, which has a population of over 22 million and covers an area of around a million km^2, provided a major catalyst for change. The severity of the drought focused national political attention since it strongly impacted on the three components of the Water-Energy-Food Nexus. In particular, the hydropower generation during 2015–2016 along the cascade of plants of the São Francisco River was kept too near to minimum values, thus requiring hard decisions to manage tight conflicts among several other water uses (irrigation, navigation, urban water supply, ecological flows, etc.). Given the impact of the recent water crises and also the possible declining streamflow, as derived from most model runs of this research work, the current institutional water framework of the northeast region should be completely reviewed. Current principles of the Federal law for water resources, enacted in 1997, have to be effectively put into practice, especially addressing the integrated water resources management. Nevertheless, as mentioned by Barbosa *et al*. (2016), the principles by themselves are not sufficient to guarantee successful practice of a decentralized, participatory and integrated water resources management system. Coordination among different government levels and sectors is considered to be a key element to improve the likelihood of water policy implementation.

In the south of Brazil, all climate change model runs present an important increase of streamflow. Notwithstanding the favourable impact of this forecast for several water resources uses, such as hydropower production, water supply or irrigation, the southern region has historical flooding problems with devastating consequences that can be seriously aggravated by the augmenting of streamflow.

Basins in the southeast region show, generally, a small increase of streamflow due to rainfall changes. This region is of particular importance for Brazil, since it includes the main cities and economic activity, and is responsible for more than 65% of the national hydropower capacity. However, despite the smaller changes in streamflow when compared to other regions, the urban and industrial concentration is a critical factor for future water policies. The impacts on hydropower are not the major concern. The recent water scarcity events (2014–2016) strongly affected large metropolitan areas, including the three biggest ones in the country (São Paulo, Rio de Janeiro and Belo Horizonte), with nearly 40 million of inhabitants in total. Water conflicts appeared across several states, which required the national water law and state regulatory acts to be put into practice. This worked as a stress test for all that has been created in terms of the national institutional water framework. As highlighted by Barbosa *et al*. (2016), a number of solutions were proposed and presented to address the institutional and water governance problems. Coordination among different government levels and sectors was considered a key element under the discussion, with the idea being that coordination could help to find a balance between lower and upper levels, and at the same time, improve integration and participation in current forums (river basin committees).

From the past water crises herein reported, and considering possible results studied in this paper, the difficulties of mitigating substantial decreases or increases in streamflow will be a huge challenge for the next generation of water resources policies and regulatory framework in Brazil. The results of this and similar studies have clear and strong impacts on water management policies for Brazil, both for regional and state water authorities, as well as on the National Water Agency. As mentioned previously, the importance of changes in rainfall patterns has already been clearly recognized from the most recent extreme drought events that have occurred throughout the country since 2012. This affected distinct regions of the country, including not only the historically vulnerable and poor residents of the semi-arid northeast region, but also the richest region and cities of the southeast, creating situations of water deficiency and risks to water supply, energy and food security. Despite the relatively high availability of water resources in the country, the scarcity events in recent years (in fact, since the year 2001) have shown the importance of emphasizing new management and planning solutions for water resources such as: (a) demand-side management (as undertaken in the severe water crisis in the metropolitan region of São Paulo city during the 2014–2016 drought event); (b) water reuse practices, which is just at the beginning stage in Brazil and has shown its relevance during recent droughts; (c) expansion of reservoir storage capacity for water supply, mainly around metropolitan regions; (d) integrated management and planning policies considering multiple uses of water (as undertaken in the São Francisco River basin, also counting a large-scale inter-basin transfer to fulfil water supply and irrigation needs for more than 12 million inhabitants of the northeast region); and (e) expansion of the electric production and power-grid systems, as the Brazilian power sector is currently dependent on renewable energies for 81.7% of its power needs (directly vulnerable to climate-driven impacts), with only 68.1% from hydroelectric production.

Brazil has a large geographical territory, with exposure to diverse climate regimes. If some benefits are to be derived from these events of water scarcity in Brazil, several lessons should be highlighted related to the high potential of the country's exposure to future events of climate extremes, thus suggesting the need for revision of current water policies, and the operational water resources planning and management practices towards a culture of water preparedness. The results of studies like this one, with critical forecasts of declining streamflow across different regions of the country, added to the recent water crisis experiences, should clearly emphasize the societal perception about climate change risk and its impacts, as derived from concrete examples, thus contributing to a progressive recognition that a culture of preparedness is the best hope for disaster mitigation.

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