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River discharge in South America: agreement and contradictions between recent alteration and projected changes

Vazões dos rios da América do Sul: concordância e contradições entre alterações recentes e projetadas

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ABSTRACT

Climate scenarios are important information for water planning, but, in some cases, they disagree with recent climate alterations, which affects their robustness and reliability. Robustness evaluation can help identifying areas that should be prioritized by in water sector adaptation to climate change. Although crucial, this kind of analysis has been overlooked in most climate change assessments, for instance in South America. This study assesses the robustness and reliability of river discharge scenarios by comparing them with observed and modelled data. Areas where current changes and scenarios agree are more likely to experience changes and, therefore, water planners should pay special attention to them. Tocantins-Araguaia, São Francisco, Western Northeast Atlantic and upper La Plata basins agreed with a discharge decrease, indicating that climate change should be prioritized in planning. Orinoco and upper-western Amazon basins showed strong disagreement between recent and projected discharge alterations, with positive change in last decades, showing that scenarios in these regions should be carefully interpreted. With this, water planners could interpret Northeastern and upper-central South America as presenting more likely scenarios in comparison to Amazon and Orinoco basins.

Keywords: Climate change impacts; South America; Discharge alteration; Robustness.

RESUMO

Cenários climáticos fornecem informações importantes para o planejamento de recursos hídricos. Contudo, eles mostram inconsistências com mudanças climáticas recentes em alguns casos, o que afeta sua robustez e confiabilidade. A avaliação de robustez pode auxiliar na identificação de áreas prioritárias na adaptação de recursos hídricos a mudanças climáticas. Mesmo sendo relevante, esse tipo de análise tem sido menosprezado em avaliações de mudanças climáticas, por exemplo, na América do Sul. Nesse estudo, avaliamos a robustez e confiabilidade de cenários de alteração de vazão os comparando com dados observados e modelados recentes. Projeções climáticas são mais prováveis de acontecer em regiões que mostram concordância entre mudanças recentes e projetadas, logo, a gestão deve dar mais peso aos cenários nestes locais. As bacias Tocantins-Araguaia, São Francisco, Atlântico Ocidental e do Prata (porção norte) concordam com o decréscimo de vazão, indicando que a mudança climática deve ser priorizada no planejamento. As bacias Orinoco e Amazônica mostraram forte discordância entre alterações recentes e projetadas de vazão, com tendências de aumento nas últimas décadas. Isso mostra que cenários futuros nessas regiões devem ser interpretados com cuidado. Sendo assim, a gestão de recursos hídricos poderia considerar que as regiões noroeste e alto-central da América do Sul apresentam projeções mais prováveis em comparação com as bacias Amazônica e Orinoco.

Palavras-chave: Impactos de mudanças climáticas; América do Sul; Alteração de vazão; Robustez.

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INTRODUCTION

Hydrology is mostly regulated by climatologic drivers, such as precipitation and other atmospheric forcings. Despite the highly irregular behavior of these variables in the short term, they present long term patterns, upon which most of water management planning takes place (Smith, 1992; Milly et al., 2008). Changes in these long term patterns impose challenges for water management, and must be accounted for by water managing and resilient structural design for the future (Bayazit, 2015; Milly et al., 2008; Organisation for Economic Co-operation and Development, 2022). According to IPCC (Intergovernmental Panel on Climate Change, 2021), climate has been suffering notorious influence of human activities over the last two centuries. These interactions alone are estimated to have contributed with approximately 1.07 ^{o}C for the increase of global surface temperature between 1850-1900 and 2010-2019 (Intergovernmental Panel on Climate Change, 2021). The organization also mentioned other significant changes that can be almost certainly attributed to anthropic actions, such as the increase of precipitation over land, corroborated by Contractor et al. (2021) and Du et al. (2022).

These effects can have great implications in the socioeconomic wellbeing of South American people. The continent suffered with extreme events (e.g., Amazon River flood and Pantanal drought) that affected many people and ecosystems in the last years (2021 and 2020), assessed by multiple studies (Cuartas et al., 2022; Espinoza et al., 2022; Libonati et al., 2022; Naumann et al., 2021; Marengo et al., 2021). Taking Brazil as an example, as it is the largest country in South America, here we describe the impact that climate has on its population. Between 2012 and 2017, some regions in Brazil have experienced lower rainfall than average, significantly affecting reservoirs' volume and operation. Following a moderated volume recovery in 2018, after December 2019, country's National Integrated System (SIN) active storage reached its lowest value in 5 years (Agência Nacional de Águas e Saneamento Básico, 2020). Water and Sanitation National Agency's (ANA) Report (Agência Nacional de Águas e Saneamento Básico, 2020) stated that many Brazilian regions presented low precipitation in 2019, especially the Paraguay and Paraná basins. In the latter, many water supply systems nearly collapsed. This kind of struggle may worsen with the intensification of climatic extremes, which has been reported by IPCC (Intergovernmental Panel on Climate Change, 2021).

A common way to assess climate change impacts in the future is through climate models such as General Circulation Models (GCM), or even Regional Climate Models (RCM), which simulate future conditions of Earth's atmosphere and oceans. Several scientific studies in the field of hydrology have assessed how climate change may affect water resources by integrating climate models outputs into hydrologic models (Borges de Amorim & Chaffe, 2019a; Brêda et al., 2020). Recent research using climate projections to force process-based models gathered evidence that climate change is likely to affect hydrological patterns in the future (Borges de Amorim & Chaffe, 2019b; Brêda et al., 2020). Borges de Amorim & Chaffe (2019b) presented a synthesis of climate change studies upon Brazilian water resources. Their results showed a drying effect over most of the country's territory, except for Southern Brazil, which presented a wetting pattern. This behavior is also seen in the results from Brêda et al. (2020), which conducted a climate change impact evaluation over South American hydrology. Most of upper portion of South America is expected to experience drier conditions (e.g., Orinoco and Amazon basins), whereas the bottom portion (e.g., Uruguay basin) may present wetter conditions (Borges de Amorim & Chaffe, 2019b; Brêda et al., 2020; Jong et al., 2021; Queiroz et al., 2016, 2019; Ribeiro Neto et al., 2016; Sorribas et al., 2016; Zaninelli et al., 2019).

As water planners must use this kind of assessment to support long-lasting decision making, it is important to evaluate result's reliability in different regions and under different scenarios (Mach et al., 2017). However, a great deal of climate change studies in Brazil and South America overlooks a robustness-wise characterization of impact scenarios (Borges de Amorim & Chaffe, 2019b). Therefore, our analysis aims to identify where current climate change impact assessments may be more reliable, based on recent river discharge alteration.

Agreement analyses are used when assessing result reliability in climate studies (e.g., Blöschl et al., 2019, Gudmundsson et al., 2021, Kundzewicz et al., 2017, World Meteorological Organization, 2007; Yang et al., 2021). This kind of approach assumes that when two or more independent sources of information converge to a similar outcome, their result is more reliable. These sources can be from observation, modelling, experimental data and others (Mach et al., 2017; Mastrandrea et al., 2011).

The description of projection's robustness is important as it fits in the confidence analysis step from AR5 expert-judgement for characterizing evidence (Intergovernmental Panel on Climate Change, 2014; Mach et al., 2017). It is based on the type, amount, quality and consistency of evidence and its degree of agreement (Mastrandrea et al., 2011). Evidence robustness serves as basis for confidence analysis. An increase in number of sources and in the agreement between them is directly linked to the increase of confidence of findings (Mach et al., 2017).

For the present robustness analysis, we compare signals of trends and relative change of mean annual river discharges from 1980 to 2019 with the ones obtained by climate scenarios for the end of 21st century. We assume that regions which present same signal for recent discharge alteration and for climate change scenarios are better represented by climate models and consequently present a more reliable estimate for the future.

MATERIAL AND METHODS

The study consisted in evaluating the consistency between recent discharge alteration and trend signals and the ones from projected climate change impacts on discharge for late 21st century. Analyses were performed for South American river domain based on hydrological model MGB-SA (Siqueira et al., 2018). We chose to perform the study based on modelled data to provide a comprehensive picture of South American rivers, without biases due to irregular spatial distribution of gauges. We conducted a validation analysis for signal of discharge change based on Brazilian gauging network. This was convenient due to data availability and representation of a wide range of hydrological conditions (e.g., from arid to wet regions, seasonal and non-seasonal regimes). It was considered adequate, given previous performance evaluation for MGB-SA (Siqueira et al., 2018; Wongchuig Correa et al., 2017).

The next sections provide detailed descriptions of the process, which is represented by the flowchart in Figure 1.

Hydrological model

Aiming at providing an overall picture of recent and projected changes in discharge of South American rivers, we used the continental and distributed hydrological model MGB-SA, developed by Siqueira et al. (2018). MGB-SA is a fully coupled hydrologic-hydrodynamic model built for South America's territory. It represents the river system by river reaches of approximately 15 km extent and a drainage area equal or superior to 1,000 km^2. Each river reach is associated with a unit catchment, which is also discretized in Hydrological Response Units (HRU) with similar soil, vegetation and land use and cover characteristics. The vertical water balance is calculated for each HRU, and the resulting runoff is propagated downstream by using two methods: a linear reservoir approach for hillslope routing, and a 1D local inertial (hydrodynamic) method for river routing. The model uses as rainfall and runoff input data the Multi-Source Weighted Ensemble Precipitation (MSWEP, v1.1), a 3-hourly dataset of combined satellite, reanalysis and daily gauge data (Beck et al, 2017). As input for climate variables used to define evapotranspiration (ET), it was used mean monthly data (1961-1990) from Climate Research Unit Global Climate v.2 (New et al., 2002). MGB-SA was validated for discharge, water level, terrestrial water storage (TWS) and ET, obtaining satisfactory results according to multiple efficiency metrics.

The simulations developed by Siqueira et al. (2018) produced discharge time series from 1990 to 2010. For this study, some adjustments were performed to extend the assessment period. The first version of the MGB-SA model was calibrated with MSWEP v1 precipitation data, described earlier, but this database is now outdated, as it only provides precipitation data until 2015. Therefore, the time series was extended using precipitation data from the GPM IMERG (Skofronick-Jackson et al., 2017), which was bias-corrected through quantile mapping method in order to present a precipitation distribution similar to the original precipitation database. This resulted in a discharge time series from 1979 to present (2021). The first year (1979) was not considered in the analysis due to the influence of model's initial condition over discharge values.

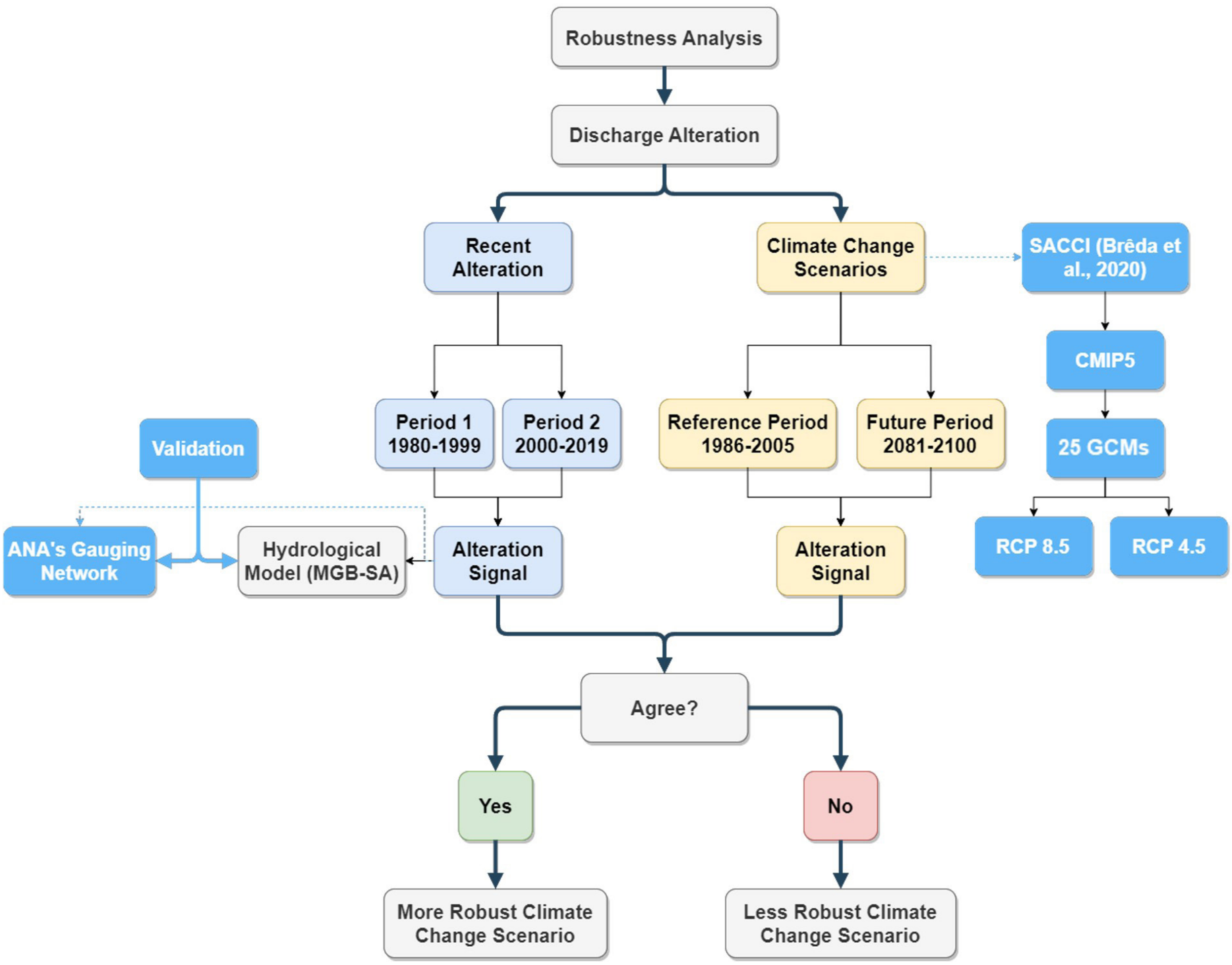

Figure 1. Flowchart of methodology. Divides the discharge alteration analysis in (i) Current State (light blue) and (ii) Climate Change Scenarios (yellow), indicating the data used for each analysis. Their final outputs are the discharge Alteration Signals, which are then compared resulting in the robustness status.

Database

Observation data

The in situ data used for this comparison was obtained from Brazilian Water Agency (ANA) database, HidroWeb (Agência Nacional de Águas e Saneamento Básico, 2021). The criterium for selection of gauging stations was based on data quality and availability in each one of the reference periods (1980-1999 and 2000-2019) and is detailed in the following section.

Gauging station selection

ANA's hydrometric network comprises 15,536 daily discharge gauging stations, which passed through a series of automatic filters to remove measurements that presented incoherent values of discharge. The filters applied are presented below:

- Negative streamflow: measurements less than zero were changed to "missing data".
- Unrealistic streamflow: values larger than 1,000 $mm.d^{-1}$ were considered incoherent with reality, and so were changed to "missing data".
- Abrupt zero: identified if there were 0 $m^3.s^{-1}$ instead of "missing data". This verification considered intermittent rivers by evaluating the frequency curves. In the case of streamflow being larger than zero in 90% of the time, measurements equal to zero are considered "missing data". Otherwise, in the case of the previous time step being larger than a threshold (defined as 50 $m^3.s^{-1}$), the measurement equal to zero is considered an abrupt zero, and, thus, converted to "missing data".
- Constant values: identified if there were long periods of constant discharge values. For each value in the series, it was quantified how many times that value was repeated. In case this value presented 50% more repetitions in sequence than 95% of the remaining ones, it was substituted for "missing data".

Furthermore, gauges with drainage area lower than 1,000 km^2 were removed. This consideration was necessary due to MGB-SA model resolution. This process resulted in an ensemble of about 1,250 gauges.

The remaining stations were then filtered by data availability in each reference period (1980-1999 and 2000-2019). This process consisted in discarding years with less than 80% of data and then discarding gauging stations that had more than 25% of years discarded for at least one of the reference periods. The result was a sample of 581 discharge gauges (Figure 2).

Scenarios of river discharge change

Brêda et al. (2020) assessed South American Climate Change Impacts (SACCI) on multiple long-period hydroclimate variables at the end of 21st century under RCP 4.5 and RCP 8.5 emission scenarios. The authors forced MGB-SA model with bias corrected data from an ensemble of 25 GCMs (Table A1 in Appendix A). Their analysis compared 1986-2005 and 2081-2100 20-year periods. SACCI's results were divided between mean and significant changes and coefficient of variation for each scenario. The significance level was defined as 5%. Results were presented for temperature, precipitation, evapotranspiration, runoff, aridity index, and river discharge. An agreement analysis between the GCMs ensemble was conducted for precipitation and river discharge, in which it was considered to be an agreement if 2/3 of the GCMs showed the same alteration signal, towards wetter or dryer conditions.

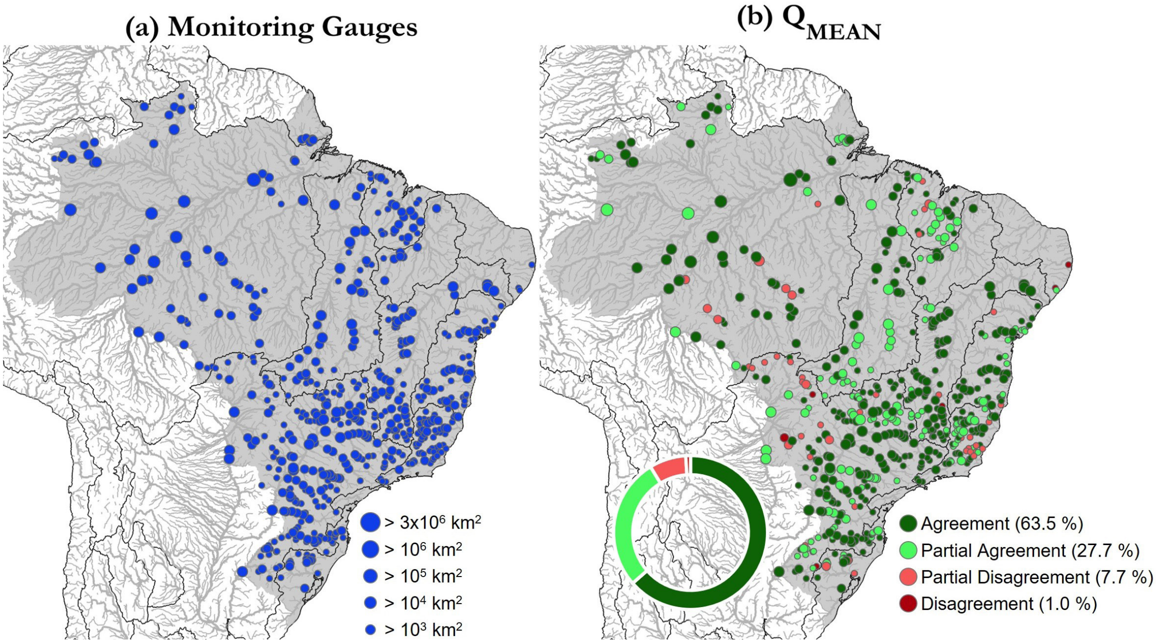

Figure 2. (a) Spatial distribution of the 581 gauges used for MGB-SA's validation, and (b) agreement results between observation and simulation data for mean discharges.

The results for river discharge were evaluated for a river network with drainage area > 10,000 km². SACCI's results can be visualized through a WebGIS application (Miranda et al., 2021).

Period change analysis

MGB-SA time series was divided into two periods: 1980-1999 and 2000-2019. Those 20-year time windows were defined because they encompassed the full extent of the model's dataset, and the climate change impact simulation used for comparison also used 20-year periods. Then, the alteration was calculated as the percentual difference between discharge's mean values from each of those periods. Alteration values within the range ±10% were considered neutral.

Besides average alteration, it was also calculated significant changes through Student's t-Test (Student, 1908) for a 5% level of significance. The analysis consisted in comparing the two 20-year samples used to define discharge alteration (1980-1999 and 2000-2019) and determining whether they were statistically different or not. Student's t-test compares sample's mean and variance values. T-value is defined by the difference between samples' means divided by the combined variance of both groups. The H_0 hypothesis ($mean_{1980\text{-}1999} = mean_{2000\text{-}2019}$) is rejected if the t-value obtained is greater in module than the inverse of the bicaudal probability for given significance level ($\alpha = 0.05$) and degrees of freedom ($N_{1980\text{-}1999} + N_{2000\text{-}2019} - 2 = 38$).

Despite 30-year periods being the standard recommendation for assessing climatological normals, the increase of predictive capacity for periods larger than 10 years are relatively low for average values (World Meteorological Organization, 2007, 2017). Kundzewicz el at. (2017) stated that trend detection performed in many river stations covering a large area could make up for data extent issues. Moreover, 20-year time slices were applied by Brêda et al. (2020) for evaluating climate change impacts on South American rivers, which were used for comparison in the present study.

Trend analysis

We also assessed discharge's trend between 1980 and 2019 (40 years) through Mann-Kendall (MK) test (Kendall, 1975; Mann, 1945) for a 5% significance level. MK test is a nonparametric statistical analysis for monotonic trend detection in a sample, and it has been extensively used for trend detection of hydroclimatic variables (Ahmad et al., 2018; Araújo Silva, 2011; Bartiko, 2020; Ricardo et al., 2013; Wongchuig Correa et al., 2017; Xu et al., 2003; Yue & Pilon, 2004). As a nonparametric test, MK is less suitable than parametric methods for normally distributed data, but this difference is not substantial (Yue & Pilon, 2004). The method is described by the following equations, for a time series $X(1,2,\ldots,n)$.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign\left(X_j - X_k\right) \tag{1}$$

$$V(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{g} e_i\left(e_i - 1\right)\left(2e_i + 5\right)\right] \tag{2}$$

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{V(S)}}, if\ S > 0 \\ 0, if\ S = 0 \\ \dfrac{S+1}{\sqrt{V(S)}}, if\ S < 0 \end{cases} \tag{3}$$

Equation 1 compares each term of a sample with all its subsequent terms, summing all these comparisons' signs (±1). The second term of Equation 2 is used when there are ties in the sample, where g is the number of tied groups and e is the number of ties in the i^{th} group (Machiwal & Jha, 2012). Ties were not considered in the study, being applied just the first term of Equation 2. Then, the result of $|Z|$ (absolute value of Equation 3) is compared to $Z_{1-\frac{\alpha}{2}}$, where, if greater, there is a significant change with Z's sign for an α level of significance.

Since sample's autocorrelation can affect MK test results (Bartiko, 2020; Wongchuig Correa et al., 2017; Yue et al., 2002), we performed the Trend Free Pre-Whitening (TFPW) method (Yue et al., 2002). This process consists in correcting eventual lag-1 autocorrelation in a series through the following equations.

$$\beta = median\left(\frac{x_j - x_i}{j - i}\right) \forall i < j \tag{4}$$

$$Y_t = X_t - \beta t \tag{5}$$

$$Y_t^{'} = Y_t - \phi Y_{t-1} \tag{6}$$

$$Y_t^{''} = Y_t^{'} + \beta t \tag{7}$$

Equation 4 is a comparison between $x_j\left(2,3,\ldots,j\right)$ to all its predecessors x_i, where x a term of the time series and $j > i$. The median of these value results in the slope of its linear trend β. Then, the slope effect is subtracted from the sample (Equation 5), resulting in a new sample Y_t. This sample is tested for autocorrelation on lag-1 and striped of its influence by Equation 6, where ϕ is the autocorrelation value for lag 1. Finally, Equation 7 adds the linear trend effect to $Y_t^{'}$, resulting in $Y_t^{''}$, a sample with no autocorrelation and with the same linear trend effect as the original one. When the sample does not present autocorrelation on lag-1 or a linear trend, MK test can be applied on the original series.

RESULTS AND DISCUSSION

Validation of hydrologic model

It was necessary to compare the alterations of simulated and observed discharges to confirm the model capacity for the proposed analysis. Even though MGB-SA was validated by Siqueira et al. (2018), the authors did not analyze the model's capability to reproduce long term alterations on discharge. Wongchuig Correa et al. (2017) confirmed the capacity of MGB to represent interannual variability in terms of minimum, mean, and maximum values but only for the Amazon basin. Therefore, model's performance regarding multiyear streamflow alteration must be ensured in order to support the usage of simulated data in the study.

To evaluate MGB-SA's representation of discharge alteration, the period change analysis' procedure was applied for ANA's observation data and the model's simulation data. Then, their results were compared at the respective river reaches. The degree of agreement between observed and simulated alteration was categorized in 4 classes: (i) Agreement, (ii) Partial Agreement, (iii) Disagreement and (iv) Partial Disagreement.

(i) Both alterations have equal sign and are higher (lower) than +10% (-10%), or both are within the neutral range (± 10%);

(ii) One alteration is higher (lower) than +10% (-10%) and the other is within the neutral range and has equal sign;

(iii) Both alterations are out of the neutral range and have opposite signs;

(iv) One alteration is higher (lower) than +10% (-10%) and the other is within the neutral range and has opposite sign.

The result of this validation is presented in Figure 2. The agreement (both partial and total) between modeled and observed alterations of mean annual flows was 91.2%. This result indicates that MGB-SA is capable of representing recent long term alterations in mean river flows in most cases.

Recent discharge alteration

Since significant alterations and trends in discharge of South American rivers presented similar patterns, they were displayed in the same maps (Figure 3b), where river reaches in blue (red) showed positive (negative) values for at least one of both methods (Student's t-test and MK test), whereas the grey ones did not show significant values for neither of them. For more detail, Figure A1 in the Appendix B shows the results for significant trend and alteration separately. Figure 3a displays the mean alteration between 1980-1999 and 2000-2019 for mean discharges in the last decades.

From the river streams where it was not found significant trend/alteration, 73% were within the neutral range. And from the ones within the neutral range, 18% presented significant trend/alteration. In general, the neutral range of ±10% represents the non-significant changes. As seen in the maps, northeast, southwest, and north areas are the ones that most show significant trends and alterations in natural river flow.

Caution is necessary for interpreting results regarding MK test. Chen & Grasby (2009) showed that MK test applied on short time series may not represent discharge's real long-term trends.

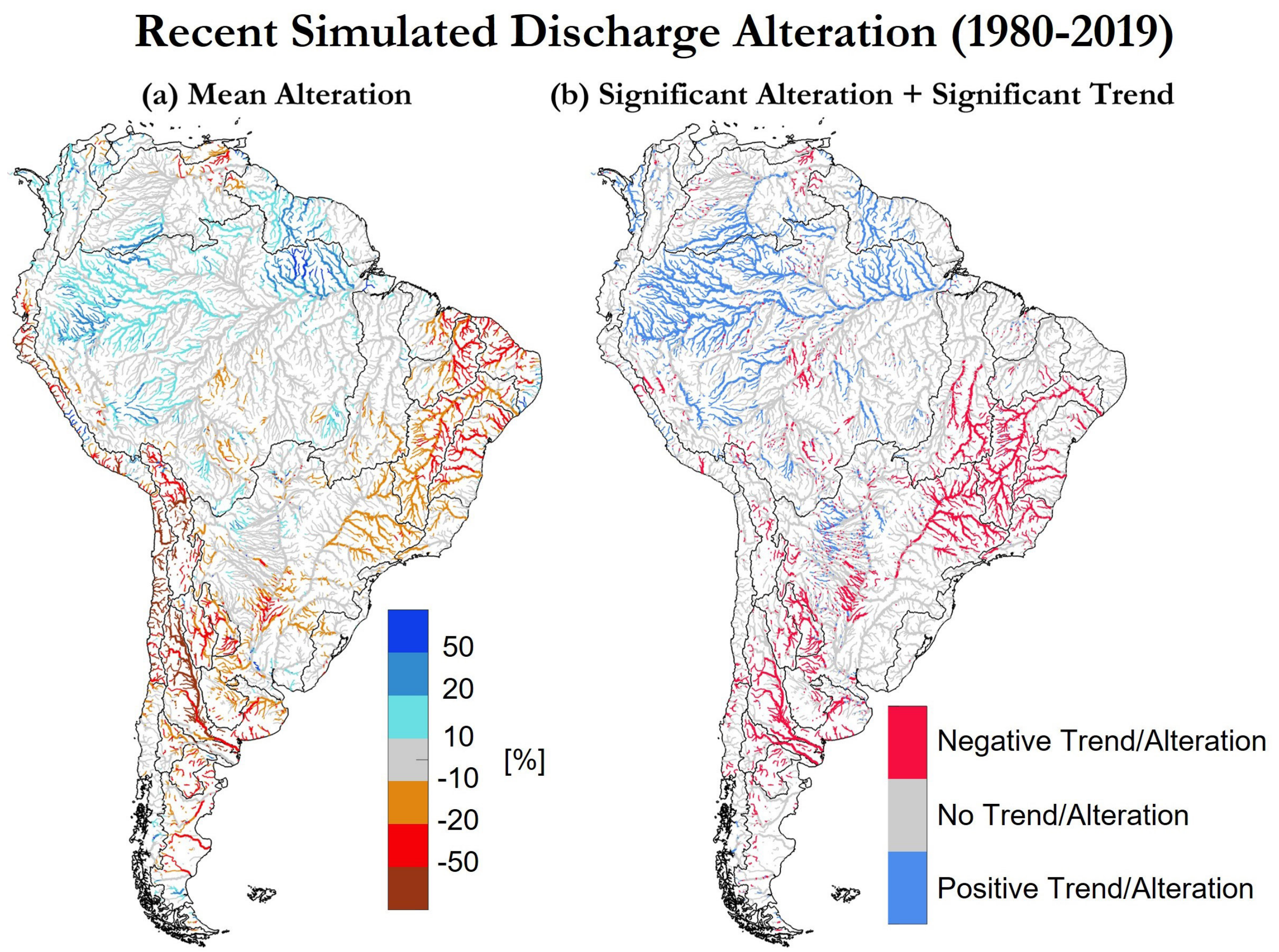

Figure 3. (a) Mean alteration and (b) significant trend/alteration (α=0.05) for mean discharges for the period 1980-2019, based on MGB-SA simulation data.

This is due to the influence of low-frequency oscillations in ocean phenomena over rainfall and river regimes. This can be especially problematic when the extent of data's record is less than half wavelength of river discharge's low-frequency oscillation in a given locality (Chen & Grasby, 2009). The authors stablished that the trend of river discharge time series shorter than 60 years should be analyzed carefully.

Another issue that should be pointed out is the time window influence over discharge alteration/trend value. Relevant hydrological events left in or out of the assessment period can affect the analysis' result and its comparison with other studies.

Here we discuss MGB-SA results for river discharge recent alteration and trend by comparing them with other studies over South America. Many authors have assessed past and recent trends in hydrology time series over different South American basins and regions (Bartiko, 2020; Castino et al., 2017; Fleischmann, 2021; Perez et al., 2021; Wongchuig Correa et al., 2017).

River discharge in La Plata basin showed significant increase in early 1970s, associated with positive (negative) ENSO and PDO (AMO) phases (Castino et al., 2017; Perez et al., 2021; Rocha & Souza Filho, 2020). Perez et al. (2021) proposed that was not until 1995 that the region presented a decrease trend of hydrological variables. After this period, La Plata basin presented mostly negative trends of river discharge (Perez et al., 2021; Rocha & Souza Filho, 2020). However, the Andean side (western) shows an increase of river discharge for the same latitude range (Castino et al., 2017). Northeastern South America presents a consistent negative trend of river discharge over a large area (Bartiko, 2020; Rocha & Souza Filho, 2020).

Wongchuig Correa et al. (2017) assessed discharge trends in the Amazon basin from 1981-2010. They observed positive trends of mean and maximum discharge mostly over north and northwestern regions from the basin. As for southern Amazon basin, the study showed negative trends, especially for minimum and mean discharges (Wongchuig Correa et al., 2017). Fleischmann (2021) presented results of an inundation area increase of 20% in central Amazon from 1980 to 2020, associated to a raise of rainfall over basin's north region (Motta Paca et al., 2020; Funatsu et al., 2021; Haghtalab et al., 2020; Heerspink et al., 2020). This increased precipitation would be related to a hydroclimate shift in late 1990s which lead to historic water level records in June 2021 (Espinoza et al., 2022; Fleischmann, 2021). The spatial pattern of these trends matches the one found by Wongchuig Correa et al. (2017).

Focusing on Brazilian territory, the northeast, central and upper-southeast regions present well spread downward trends in magnitude and frequency of flood events, whereas north and south regions show upward trends (Bartiko, 2020). This pattern was also observed by Rocha & Souza Filho (2020), that evaluated changes in key Brazilian hydropower reservoir systems: Furnas (southeast), Sobradinho (northeast), Tucuruí (north) and Itaipu (south). The authors pointed to a uniform trend behavior on northeast (negative) and south (positive) regions, with the area in between presenting a transition from one state to the other.

The present study shows patterns similar to the referred ones, especially in South America's north and northeast regions, in which discharge alteration and trend were more substantial. As for southeastern South America (southern Brazil), our results for streamflow changes did not match the strong positive signal presented by Bartiko (2020) and Rocha & Souza Filho (2020). This can be due to differences between assessment periods, and/or methods.

Recent alteration *vs.* Climate scenarios

This item presents the comparison between discharge alterations from 1980 to 2019 and projected for the end of 21st century. We were able to compare mean discharge alteration directly (stream by stream) with Brêda et al. (2020) results, since they also used MGB-SA in their assessment and provided their river network's result shapefile. The comparison was displayed in form of agreement between recent alteration and future scenario signals (similar to what was done previously with ANA's gauge data and MGB-SA simulation data). The result was represented by the following categories: (i) Agreement, (ii) Partial Agreement, (iii) Disagreement, (iv) Partial Disagreement and (v) Undefined. The first 4 categories are the same representation seen on Figure 2, as for class (v), it stands for river streams for which the GCM ensemble did not converge on an alteration signal. Figure 4 exhibits (a) mean discharge alteration between 1980-1999 and 2000-2019, (b) the impacts over mean discharge obtained by Brêda et al. (2020) for late 21st century under RCP 8.5 scenario, alongside (c) the agreement between them. It is worth mentioning that changes between RCP 4.5 and RCP 8.5 scenarios are given mainly by alteration intensity and not in its signal, as observed in the studies of Brêda et al. (2020) and Ribeiro Neto et al. (2016). Furthermore, Schwalm et al. (2020) stated that total CO_2 emissions up to 2050 are more in agreement with RCP 8.5 scenario than with RCP 4.5. Thus, we chose to show only the severe scenario (RCP 8.5), instead of both RCP 4.5 and RCP 8.5.

The comparison between discharge alteration and trend from 1980 to 2019 and the ones projected for late 21st century showed some regions with uniform behavior and others with more irregular patterns. Northeastern and upper Central regions (São Francisco, Tocantins-Araguaia, Western Northeast Atlantic and upper La Plata basins) show wide agreement between past and projected alterations, both indicating decreasing river discharge. As for Northern basins, such as Amazon and Orinoco, there is a disagreement between results, with climate scenarios indicating decrease in river discharge, whereas recent alteration indicates the opposite.

An inconsistency between recent and projected changes may indicate poor model performance in portraying future climate and hydrology, a bad representation of current streamflow tendencies (due to limited observation data), or even that climate change signal might be weaker than other influences' (e.g., natural variability). Still, it could be that future climate is well represented, but trend signal shift in the next decades. This way, signal agreement might be perceived as a robustness indicator that climate change is the main influence in local's hydrology (Blöschl et al., 2019), however, disagreeing signals do not rule out good model performance.

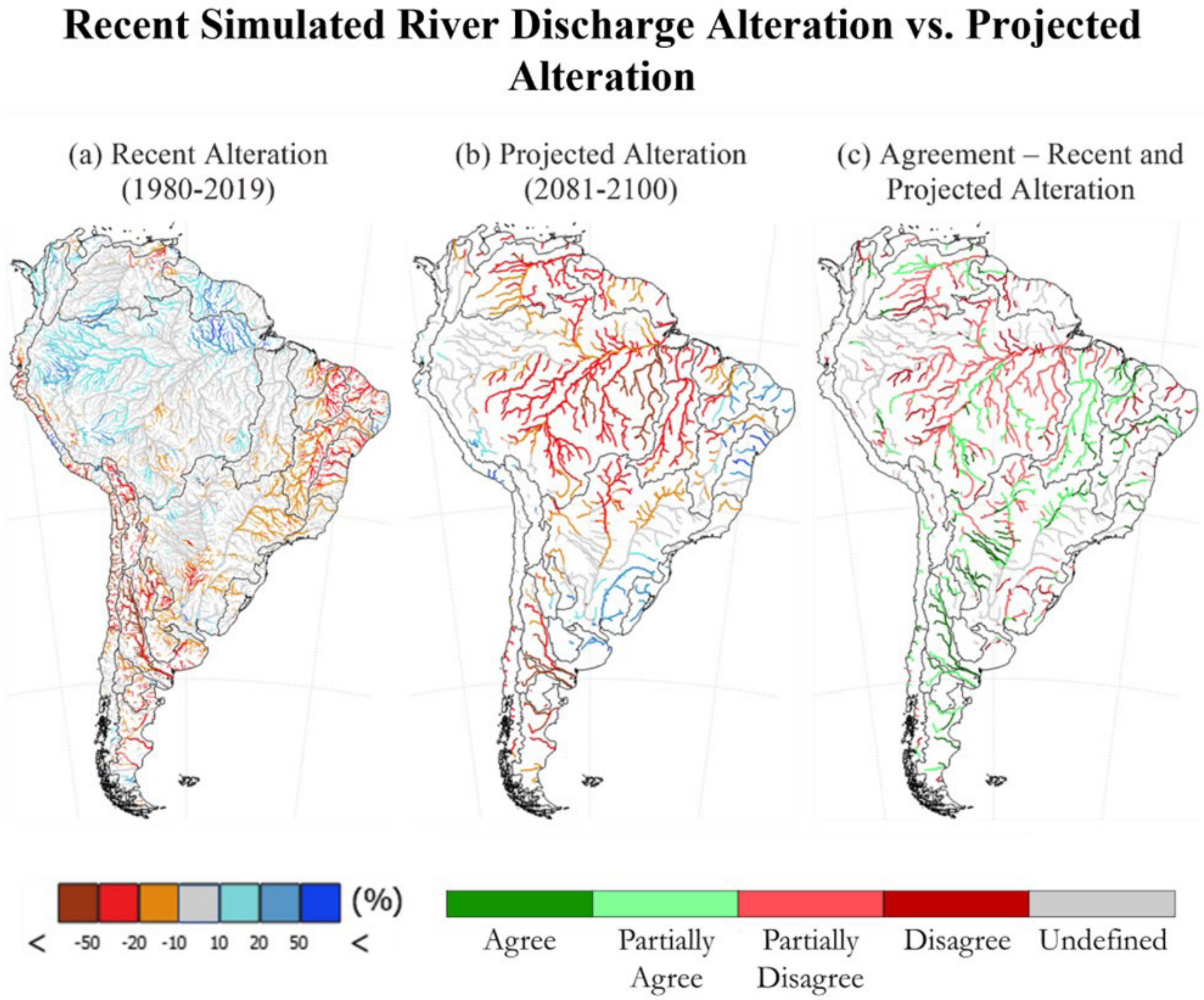

Figure 4. (a) Mean river discharge recent alteration (between 1980-1999 and 2000-2019) computed from MGB-SA outputs, (b) SACCI's climate scenarios for RCP 8.5 scenario by the end of 21st century (between 1986-2005 and 2081-2100) for mean river discharges, and (c) the agreement between their signal towards wetter, drier or neutral conditions. Undefined stands for rivers where less than 2/3 of SACCI's GCMs agreed on alteration signal.

Climate scenarios for central South America show a transition zone from drier conditions, in the upper portion, to wetter conditions, in the lower portion. This transitional pattern was also seen in recent alteration, except for southeastern South America, which did not show positive anomalies in our analysis, disagreeing with climate scenarios for the region (Brêda et al., 2020; de Jong et al., 2021; Ribeiro Neto et al., 2016), though we found our results for the region to be dissonant from other studies (Bartiko, 2020; Rocha & Souza Filho, 2020). Southern South America basins and areas that drain Central Andes were not analyzed, since MGB-SA does not consider snowmelt and it is an important process in these regions (Brêda et al., 2020; Siqueira et al., 2018).

CONCLUSIONS

The study assessed the reliability and robustness of climate change scenarios of South American hydrology projected for late 21st century by comparing scenarios of river discharge change to recent river discharge alteration and trend. The results indicated decreasing flow patterns in Northeastern Brazil, Upper Paraná basin and part of Argentina, and increasing flow patterns in Northern South America (especially in the Amazon basin) for recent past. There was an agreement between recent past and future scenarios for Northeastern Brazil and Upper Paraná basin, whereas most of Amazon showed a disagreement. Agreeing regions may indicate a more robust result, since there are two sources pointing towards the same behavior. Where these sources disagree, projected impacts may carry more uncertainty. Aside from climate change analysis, the study demonstrated that continental scale hydrological models are capable of capturing multiyear mean discharge changes.

What is considered to be the main issue is the extent of the period assessed (40 years), since MK test may not represent true discharge trend in periods shorter than 60 years (Chen & Grasby, 2009), and the discharge alteration was calculated based on two 20-year samples (the usual climatological normal period is 30 years).

Also, MGB-SA dataset's uncertainties and performance metrics were not directly addressed, nor confidence bands were defined for discharge alteration. We addressed the latter issue by assuming a ±10% threshold to report a discharge change. Concerning recommendations, similar analyses with larger time series and different hydrological variables (e.g., soil moisture and total water storage) might be useful. Also, new climate assessments can be compared with our results.

The agreement analysis can help identifying regions where future climate scenarios are more likely to occur. Agreeing behavior between recent alteration and impact scenario add robustness to the evidence from future climate change impacts. This way, water sector should have more confidence in robust scenarios and take them into account for long term planning. Another possible interpretation is that agreeing regions present evidence that recent change tends to follow a more permanent behavior towards the climate change scenario, whereas the same cannot be concluded for the disagreeing ones. Finally, our study contributes for robustness and reliability understanding of climate change impacts over South American rivers.

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DATA AVAILABILITY

The datasets generated and/or analyzed during the current study, and other supplementary material, are available in the "river discharge in south america" repository, at the following link: https://ln5.sync.com/dl/f0e6f0a00/jfv6ny3n-3yqzd5kh-i4xgfvq2-qfhu594m. It is worth mentioning that SACCI's dataset is also available at https://www.ufrgs.br/sacci/main_en.html , and at https://www.ufrgs.br/lsh/products/climate-change-in-south-america/, and MGB-SA simulation data through 1990 to 2010 can be found at https://sarts-samewater.herokuapp.com/.

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Authors contributions

Pedro Torres Miranda: Conceived the presented hypothesis, and methodology. programmed and performed most of the methods, except for the river gauging station's data quality filtering, which was conducted by Cléber Henrique de Araújo Gama, discussed the results and contributed to the manuscript's writing.

Rodrigo Cauduro Dias de Paiva: Conceived the presented hypothesis, and methodology, discussed the results and contributed to the manuscript's writing.

Cléber Henrique de Araújo Gama: Programmed and performed the river gauging station's data quality filtering, discussed the results and contributed to the manuscript's writing.

João Paulo Lyra Fialho Brêda: Provided MGB-SA's and SACCI's datasets, and contributed with analyses regarding these topics, discussed the results and contributed to the manuscript's writing.

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APPENDIX A. GCM ENSEMBLE DATA.

The data from the table below was acquired through the material from Brêda et al. (2020). It is important to state that the present study did not use GCM output directly. We used the results from Brêda et al. (2020), which are postprocessed hydrological model outputs.

Table A1. Information regarding the GCM ensemble from CMIP5 used by Brêda et al. (2020).

ID	GCM (Reference)	Institution	Country	Simulation Variant
1	ACCESS1.0 (Bi et al., 2013)	Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology (CSIRO-BOM)	Australia	r1i1p1
2	ACCESS1.3 (Bi et al., 2013)			r1i1p1
3	BCC-CSM1.1 (Xin et al., 2013)	Beijing Climate Center (BCC)	China	r1i1p1
4	BCC-CSM1.1 (m) (Xin et al., 2013)			r1i1p1
5	BNU-ESM (Ji et al., 2014)	Beijing Normal University (BNU)	China	r1i1p1
6	CanESM2 (Arora et al., 2011)	Canadian Centre for Climate Modelling and Analysis (CCCma)	Canada	r1i1p1
7	CNRM-CM5 (Voldoire et al., 2013)	Centre National de Recherches Météorologiques (CNRM-CERFACS)	France	r1i1p1
8	CSIRO-Mk3-6-0 (Rotstayn et al., 2010)	Commonwealth Scientific and Industrial Research Organisation (CSIRO)	Australia	r1i1p1
9	GFDL-CM3 (Donner et al., 2011)	Geophysical Fluid Dynamics Laboratory (GFDL)	USA	r1i1p1
10	GFDL-ESM2G (Dunne et al., 2012)			r1i1p1
11	GFDL-ESM2M (Dunne et al., 2012)			r1i1p1
12	GISS-E2-H (Miller et al., 2014)	NASA Goddard Institute for Space Studies (NASA-GISS)	USA	r1i1p1
13	GISS-E2-R (Miller et al., 2014)			r1i1p1
14	HadGEM2-CC (Collins et al., 2011)	Met Office Hadley Centre (MOHC)	United Kingdom	r1i1p1
15	HadGEM2-ES (Collins et al., 2011)			r1i1p1
16	HadGEM2-AO (Baek et al., 2013)	MOHC + National Institute of Meteorological Research, Korea Meteorological Administration (NIMR-KMA)	UK + South Korea	r1i1p1
17	INM-CM4 (Volodin et al., 2010)	Russian Academy of Sciences, Institute of Numerical Mathematics (INM)	Russia	r1i1p1
18	IPSL-CM5A-LR (Dufresne et al., 2013)	Institut Pierre Simon Laplace (IPSL)	France	r1i1p1
19	IPSL-CM5A-MR (Dufresne et al., 2013)			r1i1p1
20	IPSL-CM5B-LR (Hourdin et al. 2013)			r1i1p1
21	MIROC-ESM-CHEM (Watanabe et al., 2010)	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (MIROC)	Japan	r1i1p1
22	MIROC-ESM (Watanabe et al., 2011)			r1i1p1
23	MIROC5 (Watanabe et al., 2010)			r1i1p1
24	MRI-CGCM3 (Yukimoto et al., 2012)	Meteorological Research Institute (MRI)	Japan	r1i1p1
25	NorESM1-M (Bentsen et al., 2012)	Bjerknes Centre for Climate Research, Norwegian Meteorological Institute (NCC)	Norway	r1i1p1

APPENDIX B. SIMULATED DISCHARGE CHANGES.

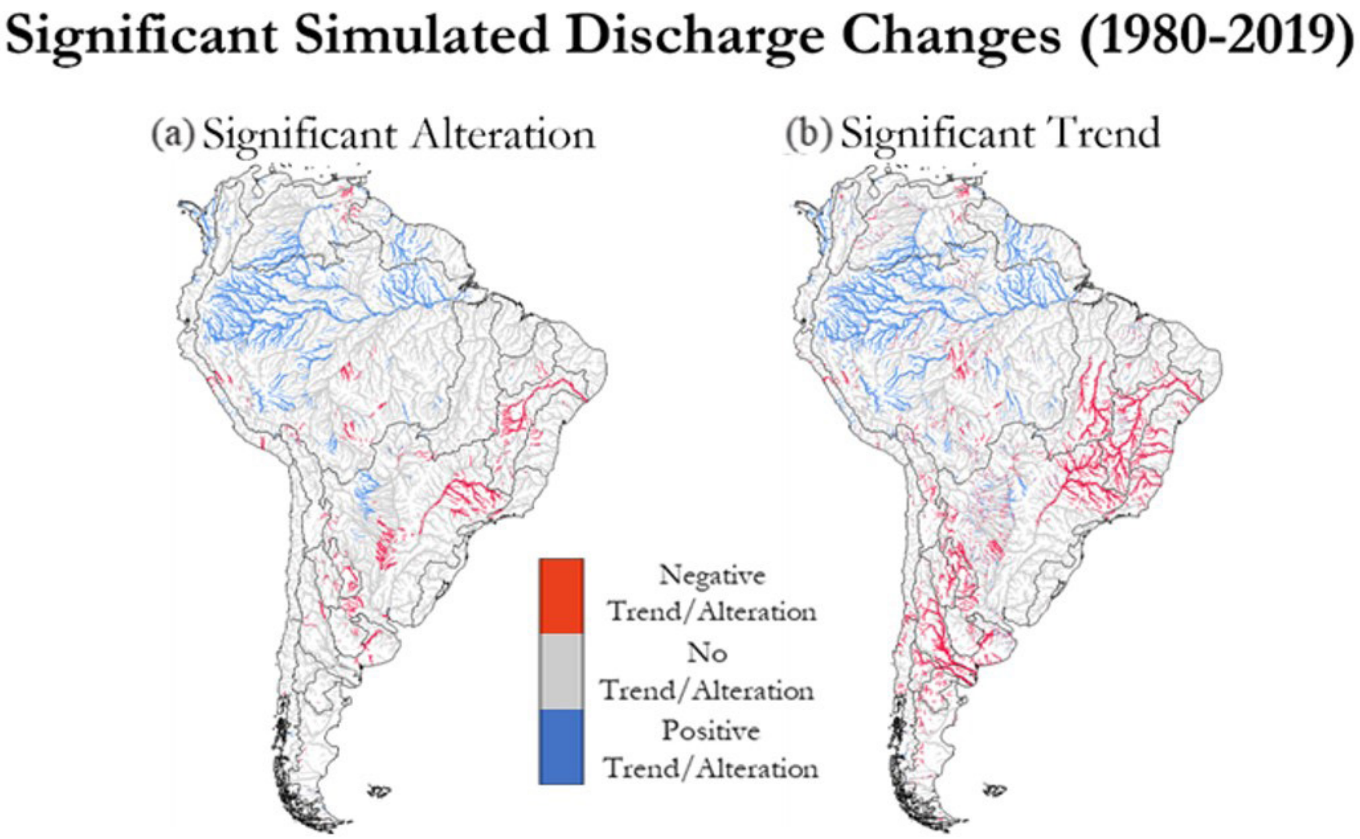

Figure A1. Significant (a) alteration and (b) trend with α=0.05 for mean discharges for the period 1980-2019, based on MGB-SA simulation data.