CAMILA LÚCIA CARDOSO RIBEIRO

COMPORTAMENTO DO ARMAZENAMENTO DE ÁGUA SUBTERRÂNEA EM BACIAS DE CABECEIRA DE MINAS GERAIS

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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Recursos Hídricos, área de concentração em Hidrologia, para a obtenção do título de Doutora.

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GROUNDWATER STORAGE BEHAVIOR IN HEADWATER CATCHMENTS OF MINAS GERAIS, BRAZIL

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Recursos Hídricos, área de concentração em Hidrologia, para a obtenção do título de Doutora.

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RESUMO

Mudanças nos padrões de chuva e temperatura impactam a recarga de aquíferos em bacias hidrográficas, afetando a disponibilidade de água, especialmente em períodos de seca, nos quais o escoamento base mantém as vazões necessárias para suprir as demandas hídricas. O objetivo desta tese é avaliar se as mudanças climáticas estão afetando a produção e o armazenamento de água nas principais bacias do estado de Minas Gerais, e se sim, desde quando e a que taxa de alteração isso está ocorrendo; e simular o armazenamento subterrâneo ao longo do século em cenários futuros de mudanças climáticas. Na primeira parte do estudo foram analisadas bacias de regiões de cabeceira do estado de Minas Gerais, sendo estas as bacias dos rios Jequitinhonha, Piracicaba, São Francisco, Grande e Sapucaí. Foi calculada a evapotranspiração potencial por meio do método de Thornthwaite, e o armazenamento subterrâneo utilizando a metodologia de Brutsaert para as referidas bacias. O teste de Mann-Kendall e o Coeficiente de Sen foram utilizados para avaliar tendências nas séries históricas. De acordo com o teste de Mann-Kendall, a grande maioria das bacias analisadas apresentaram tendência de aumento na temperatura e na evapotranspiração no período analisado (1981-2020). Para a precipitação não foi encontrada tendência significativa em nenhuma delas. As séries anuais de vazões média e mínima em 7 dias consecutivos (Q7) e de armazenamento subterrâneo mostraram tendências de redução na maioria das bacias. A bacia do rio Jequitinhonha é a mais próxima das condições originais de uso do solo, indicando que as mudanças no clima têm impactado quase que exclusivamente sua resposta hidrológica. As bacias dos rios São Francisco e Grande são as mais antropizadas e apresentaram as menores taxas de redução, mostrando-se resilientes às mudanças climáticas. Na segunda parte do estudo foram estudadas as bacias dos rios Grande e Jequitinhonha com seções fluviométricas nas respectivas regiões de cabeceira. Foi utilizado o modelo hidrológico MHD-INPE para a simulação hidrológica, com um horizonte de simulação até o ano de 2099, utilizando-se dados climáticos dos modelos climáticos globais HadGEM2-ES, MIROC5, CanESM2 e BESM regionalizados com o modelo ETA/CPTEC, nos cenários RCPs 4.5 e 8.5. O armazenamento subterrâneo mínimo anual foi obtido utilizando-se o método de Brutsaert. Por meio do Teste de Mann-Kendall e do Coeficiente de Sen, foi analisada a existência de tendências nas séries simuladas. Os resultados obtidos nas fases de calibração e de validação do MHD foram satisfatórios em ambas as bacias. Ao analisar as séries de vazões simuladas, foram verificadas tendências significativas de redução em todas as projeções, em ambas as bacias. Quanto ao armazenamento subterrâneo mínimo anual, em ambas as bacias também foram verificadas tendências significativas de redução em todas as projeções. Os resultados obtidos podem contribuir com a gestão dos recursos hídricos em Minas Gerais, visto que indicam as bacias mais vulneráveis aos impactos das mudanças climáticas. Assim, os resultados podem auxiliar na tomada de decisão e na utilização de ferramentas de gestão dos recursos hídricos, de forma a garantir a disponibilidade hídrica nessas bacias no futuro.

Palavras-chave: mudanças climáticas; modelagem hidrológica; produção de água; impactos do clima.

ABSTRACT

Changes in rainfall and temperature patterns impact aquifer recharge in river basins, affecting water availability, especially during drought periods when baseflow maintains the necessary flows to meet water demands. The objective of this thesis is to evaluate if climate change is affecting water production and storage in the main basins of the state of Minas Gerais, and if so, since when and at what rate of change this is occurring; and to simulate groundwater storage throughout the century in future climate change scenarios. In the first part of the study, river basins located in the headwater regions of the state of Minas Gerais were analyzed, namely the Jequitinhonha, Piracicaba, São Francisco, Grande, and Sapucaí River basins. Potential evapotranspiration was calculated using the Thornthwaite method, and groundwater storage was calculated using the Brutsaert methodology for these basins. The Mann-Kendall test and Sen's coefficient were used to assess trends in historical series. According to the Mann-Kendall test, the most studied sub-basins showed an upward trend in temperature and evapotranspiration, while a nonsignificant trend was found for annual precipitation in some sub-basins. Mean annual streamflow, minimum streamflow over seven consecutive days (Q7,min), and groundwater storage (S) showed downward trends in most sub-basins. The Jequitinhonha sub-basin is the closest hydrological unit to the pristine conditions, indicating that changes in climate have impacted its hydrological response. The São Francisco and Grande River sub-basins are the most anthropized and showed the lowest reduction rates, showing that these sub-basins have a relevant resilience to climate change. In the second part of the study, the Grande and Jequitinhonha River basins were analyzed based on streamflow sections in their respective headwater regions. The MHD-INPE hydrological model was used for hydrological simulation, with a simulation horizon up to the year 2099, using climate data from the global climate models HadGEM2-ES, MIROC5, CanESM2 and BESM regionalized with the ETA/CPTEC model, in the RCPs 4.5 and 8.5 scenarios. The minimum annual groundwater storage was obtained using the Brutsaert method. And the existence of trends in the simulated flow and groundwater storage series was analyzed using the Mann-Kendall test and the Sen's coefficient. The results obtained in the calibration and validation phases of the MHD model were satisfactory in both basins. Analyzing the simulated flow series, significant reduction trends were observed in all projections in both basins. Regarding the minimum annual groundwater storage, significant reduction trends were also observed in all projections in both basins. The results obtained can contribute to water resource management in Minas Gerais, as they indicate the basins most vulnerable to the impacts of climate change. Thus, the results can assist in decision-making and the use of water resource management tools to ensure water availability in these basins in the future.

Keywords: climate change; hydrological modeling; water production; climate impacts.

INDICADORES DE IMPACTO

Os resultados encontrados no presente trabalho proporcionam diferentes impactos sociais, econômicos e tecnológicos, visto que as bacias de estudo são essenciais para o abastecimento de água e para a economia em diferentes regiões do estado de Minas Gerais. Os principais grupos da sociedade impactados são os localizados nas regiões de estudo, porém o estudo pode impactar trabalhos futuros desenvolvidos em outras regiões. No que diz respeito ao âmbito social, os impactos decorrem dos resultados da avaliação da disponibilidade hídrica nas bacias hidrográficas, que garantem o abastecimento de água à população. Assim, os impactos sociais incluem a melhoria da segurança hídrica e da saúde pública, redução de desigualdades e conflitos, e a continuidade de serviços essenciais. A bacia do Rio Jequitinhonha é fundamental para a economia e a sociedade do norte de Minas Gerais, que possui o menor PIB do estado, e, como será apresentado no presente estudo, é altamente vulnerável aos impactos das mudanças climáticas na hidrologia. A bacia do Rio Grande apresenta avançada antropização, o que pode impactar os recursos hídricos, no que diz respeito à qualidade e quantidade de água, devido principalmente, à diminuição da infiltração e consequentemente da recarga de aquíferos, e ao aumento do escoamento superficial direto e carreamento de sedimentos. Assim, o estudo aponta a necessidade urgente de ações de proteção ambiental nessas bacias, a começar por suas sub-bacias de cabeceira, como conservação e recuperação da vegetação nativa, ações de racionamento e restrição do uso da água. Os resultados obtidos da avaliação da disponibilidade hídrica também geram impactos econômicos, visto que as bacias hidrográficas estudadas são de grande interesse principalmente para a geração de energia hidroelétrica. Além disso, o estudo serve como apoio à gestão dos recursos hídricos e ao uso de ferramentas como mecanismos de alocação de água, que incluem a outorga e a cobrança pelo uso da água, de forma a garantir a disponibilidade hídrica para usuários atuais e futuros. Os impactos tecnológicos estão relacionados à produção e disseminação de conhecimento técnico-científico, por meio da elaboração da tese e da publicação de artigos científicos cujos resultados podem subsidiar pesquisas e ações na área. Os impactos deste trabalho estão classificados nas áreas temáticas da Política Nacional de Extensão de: Meio Ambiente, e Tecnologia e Produção. Os impactos da pesquisa estão alinhados aos Objetivos de Desenvolvimento Sustentável (ODS) da Organização das Nações Unidas (ONU), especialmente ao ODS 6 – Água Potável e Saneamento, que visa assegurar a disponibilidade e a gestão sustentável da água e do saneamento para todos; ao ODS 13 – Ação Contra a Mudança Global do Clima, voltado ao combate às mudanças climáticas e seus impactos; e ao ODS 17 – Parcerias e Meios de Implementação, relacionado ao fortalecimento da cooperação para o desenvolvimento sustentável.

IMPACT INDICATORS

The results of this study have different social, economic, and technological impacts, as the study basins are essential to water supply and the economy across different regions of the state of Minas Gerais. The main groups affected are those in the study regions, but the study may also inform future work in other regions. Concerning the social sphere, the impacts generated arise from the results of the assessment of water availability in the river basins, which guarantees water supply for the population. Thus, the social impacts include improved water security and public health, reduction of inequalities and conflicts, and the continuity of essential services. The Jequitinhonha basin is fundamental to the economy and society of northern Minas Gerais, which has the lowest GDP in the state and, as will be shown in this study, is highly vulnerable to the impacts of climate change on hydrology. The Grande basin shows advanced anthropization, which may impact water resources in terms of both quality and quantity, mainly due to decreased infiltration and consequently reduced aquifer recharge, and increased direct surface runoff and sediment transport. Thus, the study points to the urgent need for environmental protection actions, starting with their headwater sub-basins, such as conservation and restoration of native vegetation, and actions to ration and restrict water use. The results obtained from the assessment of water availability also provide economic impacts, since the river basins studied are of great interest for hydroelectric power generation. In addition, the study supports water resource management and the use of tools such as water allocation mechanisms, including water use permits and charges to ensure water availability for current and future users. The technological impacts are related to the production and dissemination of technical and scientific knowledge, through the elaboration of the thesis and the publication of scientific articles whose results can support research and actions in the area. The impacts of this work are classified in the thematic areas of the National Extension Policy of: Environment, and Technology and Production. The impacts of the research are aligned with the United Nations (UN) Sustainable Development Goals (SDGs), especially SDG 6 – Clean Water and Sanitation, which aims to ensure the availability and sustainable management of water and sanitation for all; SDG 13 – Climate Action, focused on combating climate change and its impacts; and SDG 17 – Partnerships for the Goals, related to strengthening cooperation for sustainable development.

SUMÁRIO

PRIMEIRA PARTE

1 INTRODUÇÃO

A gestão dos recursos hídricos é um tema que vem sendo cada vez mais debatido na sociedade atual, em razão de problemas como a escassez de água, decorrentes das alterações nos padrões climáticos. As mudanças climáticas já são um problema atual, e alterações nos padrões de chuvas e de temperatura podem afetar a disponibilidade de água, o que torna a gestão dos recursos hídricos um desafio. Os eventos de secas hidrológicas observados nas últimas décadas têm causado impactos significativos nas vazões dos rios, afetando a disponibilidade hídrica e a geração de energia, sendo que, foram registrados episódios de seca hidrológica de caráter excepcional em diversas bacias hidrográficas (Fernandes et al., 2021).

Outro ponto menos discutido, mas de grande importância, é a gestão dos recursos hídricos subterrâneos, visto que alterações na recarga de aquíferos podem afetar a disponibilidade de água, especialmente em períodos de seca, períodos em que o escoamento base mantém as vazões necessárias para suprir as demandas da população (Hellwig e Stahl, 2018; Schilling et al., 2021; Lee e Ajami, 2023). Existem poucos estudos, sobretudo no Brasil, a respeito dos impactos das mudanças climáticas no escoamento subterrâneo, especialmente em escala regional para Minas Gerais. Ainda são limitadas as pesquisas que integrem métodos indiretos, modelagem hidrológica e cenários climáticos futuros para avaliar a resiliência hidrológica das bacias hidrográficas frente às mudanças no regime climático (Nobre at al., 2019). Dessa forma, torna-se essencial o desenvolvimento de estudos que preencham essa lacuna científica e subsidiem a gestão sustentável dos recursos hídricos.

Galvíncio et al. (2025) simularam as mudanças hidrológicas em cenários climáticos futuros na bacia do reservatório de Sobradinho, no sub-médio curso do rio São Francisco, e obtiveram tendências de redução no armazenamento subterrâneo, especialmente no cenário RCP 8.5. Wang et al. (2021) analisaram os impactos das mudanças climáticas na recarga subterrânea em Taiwan, na China, e verificaram sob os cenários climáticos futuros, taxas de aumento de 32,6% e de redução de 28,9% na recarga subterrânea, em relação ao período de referência. As taxas de aumento foram verificadas no cenário que prevê um aumento da precipitação, enquanto as taxas de redução foram verificadas no cenário com previsões de aumento da evapotranspiração e redução da precipitação. Kadirkhodjaev et al. (2025) ao avaliarem os impactos das mudanças climáticas no armazenamento de água subterrânea no aquífero do rio Akhangaran, no Uzbequistão, simularam uma redução de 7,3% a 58,3% em comparação com o período de 2010 a 2020.

O armazenamento subterrâneo em uma bacia hidrográfica pode ser obtido por meio de diferentes métodos, entre eles a coleta de dados por postos de observação, a estimativa por meio de satélites e a modelagem hidrológica. Porém, todos estes métodos possuem incertezas, e tendo em vista a escassez de dados coletados no país, uma das formas mais eficazes é a simulação do escoamento de base por métodos indiretos, como a metodologia de Brutsaert (Brutsaert, 2008). Essa abordagem é considerada confiável e amplamente aplicável, uma vez que a relação entre vazão e armazenamento permite inferir a dinâmica dos aquíferos mesmo em áreas com poucos dados observacionais (Hameed et al., 2023). A metodologia de Brutsaert (Brutsaert, 2008) utiliza equações matemáticas de base física, para simular o armazenamento de água subterrânea com base em dados de vazões mínimas das médias de 7 dias consecutivos (Q7, min). Como são as vazões mínimas que mantêm o escoamento em épocas de estiagem, a partir destas é possível simular o armazenamento mínimo subterrâneo. A principal vantagem deste método é que requer apenas vazões Q7,min, sendo um método de aplicação relativamente simples, desde que haja a disponibilidade do hidrograma observado ou estimado. Além disso, este é um método robusto, que pode ser aplicado em larga escala, e é sensível a condições de seca, sendo altamente relevante para estudos hidrológicos e para a gestão de recursos hídricos (Brutsaert, 2008).

Como exemplo de aplicações recentes deste método, Wojahn et al. (2024) utilizaram o método de Brutsaert para obter o armazenamento de água subterrânea em bacias de cabeceira de diferentes regiões do Brasil, e observaram tendências de redução no armazenamento ocasionadas por redução na precipitação e aumento na temperatura e na evapotranspiração. Yi et al. (2021) em um estudo na bacia do rio Yangtze, na China, obtiveram o armazenamento subterrâneo pelo método de Brutsaert, e encontraram para este, tendências de aumento devido principalmente ao aumento da temperatura. Hameed et al. (2023) estimaram o armazenamento subterrâneo por meio do método de Brutsaert e encontraram tendências contrastantes no armazenamento em dois períodos distintos, com aumento nos períodos úmidos e redução nos períodos secos, atribuídos às variações na precipitação anual e na evapotranspiração.

Dentre as diferentes abordagens da modelagem hidrológica, os modelos determinísticos chuva–vazão têm sido amplamente empregados para a estimativa do armazenamento subterrâneo e da dinâmica hidrológica em bacias hidrográficas. Esses modelos integram equações de balanço hídrico e de fluxo em meio poroso para representar processos como infiltração, percolação, armazenamento e escoamento, sendo a separação dos componentes do escoamento fundamental para a compreensão da dinâmica hídrica em bacias hidrográficas

(Tucci, 2005; Beven, 2012; Clark et al., 2015). Utilizando-se séries históricas de dados hidrológicos e meteorológicos, mapas de declividade, classes de solos, uso do solo, entre outros, o armazenamento ao longo do tempo em uma bacia pode ser simulado considerando cenários futuros de alterações no uso do solo e de projeções climáticas (Beven, 2012; Addor e Melsen, 2019).

O Modelo Hidrológico Distribuído - MHD é um modelo de grande escala e tem sido aplicado em vários estudos no Brasil (Melo et al., 2022; Zákhia et al., 2021; Negrão et al. 2017; Rodriguez et al., 2017). O MHD é um modelo distribuído por grades regulares, onde o balanço hídrico é simulado em cada grade, e o escoamento propagado pela rede de drenagem, por meio da integração de equações que representam os processos hidrológicos, como interceptação, percolação, escoamento e evapotranspiração (Negrão et al., 2017). O armazenamento é estimado a partir do balanço hídrico aplicado em cada célula da grade, considerando entradas e saídas de água e sua distribuição entre diferentes compartimentos, conforme abordagens clássicas de modelagem hidrológica distribuída (Negrão et al., 2017).

Considerando que o comportamento hidrológico de uma bacia é fortemente influenciado pelas condições climáticas, especialmente pela variabilidade da precipitação e da evapotranspiração, a compreensão de cenários futuros de disponibilidade hídrica depende da integração entre modelos hidrológicos e modelos climáticos (Bárdossy et al., 2022). Os Modelos de Circulação Geral (GCMs, do inglês *General Circulation Models*) permitem o estudo dos cenários atuais e de projeções climáticas (Silva, 2025), exemplos desses modelos são: o Model for Interdisciplinary Research on Climate - MIROC, que apresenta modelos oceânicos e de superfície continental; o HadGEM2-ES, um modelo do sistema terrestre que representa o ciclo do carbono (Rodrigues, 2017); o CanESM2 que acopla um modelo de circulação geral atmosfera-oceano, um modelo de terra-vegetação e um ciclo interativo do carbono terrestre e oceânico (Chylek et al., 2011); e o Brazilian Earth System Model – BESM, composto por um modelo acoplado oceano-atmosfera (Nobre et al., 2013).

Nesse contexto, a análise integrada de modelos hidrológicos e climáticos é fundamental para compreender os impactos das mudanças climáticas sobre a disponibilidade hídrica. No Brasil, esses impactos já vêm sendo observados em diferentes biomas. Marengo et al. (2021) evidenciaram que a redução significativa das chuvas entre 2019 e 2020 resultou em uma seca extrema no Pantanal. Santos et al. (2024) demonstraram uma tendência de aumento da aridez em grande parte do território brasileiro. No Sudeste, eventos críticos também foram registrados, como a seca de 2014–2015, considerada uma das mais severas da história recente, que afetou significativamente a disponibilidade hídrica em Minas Gerais, associada às alterações nos padrões de chuva e temperatura (Coelho et al., 2016; Nobre et al., 2016). As bacias dos rios São Francisco, Jequitinhonha, Grande, Sapucaí e Piracicaba em suas regiões de cabeceira apresentam menor intervenção antrópica em relação às demais bacias hidrográficas do estado (Ribeiro et al., 2024), sendo ideais para a avaliação dos impactos das mudanças climáticas e da resiliência das bacias a esses impactos. Nestas condições, torna-se possível a análise do armazenamento de água subterrânea sob influência de condições climáticas observadas e futuras, auxiliando na gestão dos recursos hídricos, como no planejamento do abastecimento, na definição de outorgas e na proteção de áreas de recarga, e na elaboração de estratégias para a mitigação dos impactos das mudanças climáticas na disponibilidade de água no futuro.

Existem estudos hidrológicos e de modelagem que foram aplicados nessas bacias, evidenciando sua importância para a compreensão da dinâmica hídrica e apoio à gestão dos recursos hídricos. Na bacia do Rio São Francisco, Carvalho et al. (2024) aplicaram modelagem chuva-vazão para previsão de eventos extremos. Lopes (2020) utilizou o modelo SWAT para simular o balanço hídrico na bacia do Rio Piracicaba. Carvalho et al. (2023) analisaram a dinâmica fluvial como subsídio à compreensão do comportamento hidrológico na bacia do Rio Jequitinhonha. Siqueira et al. (2018), aplicou o modelo hidrológico MGB-IPH em grandes bacias brasileiras, incluindo a região do Rio Grande, demonstrando a capacidade do modelo em representar a dinâmica hidrológica e apoiar a gestão de recursos hídricos.

No entanto, apesar da relevância dessas abordagens, existem poucos estudos nestas bacias, sobretudo a respeito do armazenamento de água subterrânea e dos impactos das mudanças climáticas no mesmo, evidenciando a necessidade de ampliação de pesquisas que integrem modelagem hidrológica e cenários climáticos para melhor compreensão da disponibilidade hídrica e suporte à gestão dos recursos hídricos. Assim, o presente estudo torna-se essencial para a avaliação de cenários futuros de disponibilidade de água nas bacias. Podendo auxiliar no uso de ferramentas de gestão dos recursos hídricos, de forma a atender as demandas atuais e futuras dos usuários, assim como a demanda ambiental nas bacias de estudo.

O objetivo deste estudo é analisar as mudanças no armazenamento subterrâneo ao longo das últimas décadas, incluindo suas taxas de variação e a resiliência de sub-bacias de cabeceira, bem como avaliar e simular as vazões e a dinâmica do armazenamento subterrâneo em cenários futuros de mudanças climáticas nessas bacias.

2 REFERENCIAL TEÓRICO

2.1 Gestão de recursos hídricos

A gestão de recursos hídricos é fundamental para garantir a disponibilidade de água nas bacias hidrográficas, especialmente nos períodos de seca, evitando a escassez de água, que pode ocasionar impactos ambientais, econômicos e sociais. O recorte territorial de bacia hidrográfica é considerado a unidade básica de análise para a criação de medidas de integração entre a gestão de recursos hídricos e a gestão ambiental (Carvalho, 2020), de acordo com a Lei Federal 9433/97 (Brasil, 1997) que instituiu a Política Nacional de Recursos Hídricos.

Os planos de recursos hídricos de bacias hidrográficas constituem instrumentos fundamentais da Política Nacional de Recursos Hídricos, orientando a gestão integrada e sustentável das águas superficiais e subterrâneas (Brasil, 1997). Esses planos têm como finalidade diagnosticar a disponibilidade hídrica, identificar conflitos e demandas de uso, além de propor diretrizes, metas e ações para a conservação e recuperação dos recursos hídricos em diferentes escalas temporais (ANA, 2021). No contexto das águas subterrâneas, os planos de bacia assumem papel estratégico ao incorporar estudos hidrogeológicos, estimativas de recarga, vulnerabilidade dos aquíferos e cenários de uso e ocupação do solo, contribuindo para o planejamento de medidas de adaptação frente às mudanças climáticas e aos eventos extremos de seca (Campos et al., 2023). Além disso, revisões recentes de planos integrados de recursos hídricos em bacias brasileiras reforçam a importância do planejamento de longo prazo e da integração entre águas superficiais e subterrâneas na gestão hídrica (ANA, 2023). O monitoramento e a ampliação do conhecimento hidrogeológico também têm sido apontados como fundamentais para subsidiar políticas públicas e fortalecer a segurança hídrica no país (SGB, 2023; ANA, 2024).

As águas subterrâneas são importantes recursos, visto que se tornam a principal fonte de abastecimento de água nos períodos de seca. Além disso, as águas subterrâneas são menos vulneráveis à contaminação, apresentando geralmente boa qualidade, além de grande capacidade de armazenamento de um aquífero, contribuindo significativamente para a segurança hídrica e para a resiliência dos sistemas de abastecimento (Pereira, Abreu e Murillo-Bermudez, 2024).

Na legislação brasileira, há uma limitação a respeito da gestão de águas subterrâneas, sendo a Resolução nº 15/2001 do Conselho Nacional de Recursos Hídricos – CNRH um dos principais marcos, estabelecendo a inserção das águas subterrâneas na gestão integrada dos recursos hídricos. De forma complementar, a Resolução nº 22/2002 estabelece a inserção das águas subterrâneas nos planos de recursos hídricos. A Resolução nº 91/2008 dispõe sobre o enquadramento dos corpos de água superficiais e subterrâneos; a Resolução nº 92/2008 estabelece critérios e procedimentos para a conservação das águas subterrâneas; e a Resolução nº 126/2011 estabelece as diretrizes para o cadastro de usuários de recursos hídricos (ANA, 2024). Em Minas Gerais a Lei 13771, de 11 de dezembro de 2000, dispõe sobre a administração, proteção e conservação das águas subterrâneas no domínio do Estado (IGAM, 2023).

As águas subterrâneas são de domínio dos Estados, assim cada um possui suas próprias leis e instrumentos de gestão. Porém estas muitas vezes não são cumpridas, e o problema se torna ainda maior devido aos limites territoriais dos aquíferos serem diferentes dos limites das bacias hidrográficas e dos estados, havendo aquíferos que abrangem vários estados (ex: Aquífero Guarani abrange 8 estados e o Aquífero Urucuia 6 estados), o que, somado ao fato de ser um tema novo e existirem poucos estudos a respeito dos aquíferos no Brasil, dificulta ainda mais a correta gestão destes recursos (Pereira; Abreu; Murillo-Bermudez, 2024).

No Brasil, as águas subterrâneas desempenham papel fundamental no abastecimento hídrico, sendo a principal fonte de água para aproximadamente 28,3 milhões de brasileiros, o que corresponde a cerca de 14% da população, além de abastecerem total ou parcialmente grande parte dos municípios do país (Andrade; Rörig; Hirata, 2024). Entretanto, apesar de sua relevância, a gestão desses recursos ainda apresenta limitações, caracterizadas por lacunas no monitoramento, insuficiência de dados e menor atenção institucional quando comparada à gestão das águas superficiais. Um dos maiores problemas enfrentados na gestão das águas subterrâneas é a exploração ilegal destes recursos, o que pode levar à ausência de sustentabilidade ou superexploração; conflitos entre usuários; e contaminação de aquíferos pelo bombeamento não planejado (Conicelli e Hirata, 2016).

O conhecimento do comportamento hidrológico de bacias hidrográficas e de seus regimes de variação de vazões é essencial para o planejamento e a gestão sustentável dos recursos hídricos, especialmente diante dos impactos das mudanças climáticas e do aumento das demandas antrópicas (ANA, 2024). Entre os principais instrumentos de gestão destacam-se os mecanismos de alocação de água, cujo objetivo é compatibilizar a disponibilidade hídrica com as demandas atuais e futuras dos diferentes usuários, bem como garantir a manutenção das necessidades ambientais dos ecossistemas aquáticos (ANA, 2024). Esses mecanismos podem operar por meio de orientações do poder público; de processos de negociação entre usuários de água; e de conceitos técnicos e econômicos, como os limites de utilização de corpos hídricos, e a cobrança pelo uso da água, respectivamente (Marques et al., 2022).

O Brasil tem enfrentado nas últimas décadas, eventos recorrentes de seca, com impactos significativos sobre os recursos hídricos. A seca de 2014–2015 no Sudeste é considerada uma das mais severas dos últimos anos, e levou a uma redução expressiva dos níveis dos reservatórios e ao comprometimento do abastecimento público (Coelho et al., 2016; Nobre et al., 2016). A seca extrema no Pantanal entre 2019 e 2020 evidenciou a intensificação desses eventos, com diminuição das vazões, degradação de ecossistemas aquáticos e prejuízos ao uso múltiplo da água (Marengo et al., 2021). Esses eventos estão associados a alterações nos padrões de precipitação e de temperatura, refletindo a influência das mudanças climáticas sobre o ciclo hidrológico. Essas alterações causam impactos como a redução da disponibilidade hídrica, a diminuição da recarga de aquíferos e o aumento da pressão sobre as águas subterrâneas, o que indica a necessidade de estratégias de gestão integradas.

2.2 Processos hidrológicos

O ciclo hidrológico é o fenômeno de circulação fechada da água, impulsionado principalmente pela energia solar, que aquece o ar, a água superficial e o solo, ocasionando na evaporação e na transpiração. O vapor é transportado pelo ar, podendo condensar e formar nuvens, e assim retorna à superfície na forma de precipitação, onde pode infiltrar ou escoar até um curso d’água (Collischonn e Dornelles, 2021; Mello; Silva; Beskow, 2020).

A precipitação é um componente fundamental do ciclo hidrológico, parte dela é interceptada pela vegetação e o restante atinge a superfície do solo, onde pode infiltrar e passar pelo processo de percolação, atuando na formação do lençol freático e de nascentes (Bernardi et al., 2012; Collischonn e Dornelles, 2021; Mello; Silva; Beskow, 2020). A água que percola no solo contribui para a recarga dos aquíferos, sustentando as vazões ao longo do tempo (Collischonn e Dornelles, 2021; Mello; Silva; Beskow, 2020). Vários fatores, como climáticos e geomorfológicos, podem afetar as taxas de recarga. No entanto, um dos processos fundamentais no ciclo hidrológico é a interação entre os processos superficiais e subterrâneos, especialmente por meio do escoamento base, que representa a contribuição do armazenamento subterrâneo para os cursos d’água. O escoamento base sustenta as vazões ao longo do tempo, sendo responsável por uma parcela significativa do escoamento total, principalmente em períodos de estiagem, quando o escoamento superficial é reduzido (Santarosa, 2020; Jasechko et al., 2019).

Com o uso de modelos hidrológicos distribuídos e a integração de dados observacionais e climáticos, é possível representar os processos do ciclo hidrológico na escala de bacia hidrográfica (Wang et al., 2021; Talbot et al., 2025). A bacia hidrográfica é então definida como uma unidade espacial de análise, onde os fluxos de água são controlados por interações entre os processos de precipitação, evapotranspiração, escoamento e armazenamento em diferentes compartimentos (superficial, subsuperficial e subterrâneo) (Seibert e Bergström, 2022; Liu et al., 2017). Estudos recentes destacam que a variabilidade desses fluxos está diretamente associada às mudanças no uso do solo e às alterações climáticas, influenciando a disponibilidade hídrica e a resposta hidrológica das bacias (Fang et al., 2020; Li et al., 2021).

O balanço hídrico é aplicado como ferramenta para quantificar essas interações, incorporando além das entradas e saídas de água, as variações no armazenamento ao longo do tempo, sendo amplamente utilizado em estudos que avaliam a recarga de aquíferos e a resiliência hidrológica frente a eventos extremos (Fan et al., 2019). Estudos recentes integram dados hidrometeorológicos, sensoriamento remoto e modelagem hidrológica para melhorar a representação dos processos e reduzir incertezas nas estimativas de disponibilidade hídrica (Bastiaanssen et al., 2019; Li et al., 2022).

De acordo com Zerga (2025), a bacia hidrográfica integra processos hidrológicos, ecológicos, econômicos e sociais, permitindo o desenvolvimento de estratégias que integram pesquisa científica e gestão dos recursos hídricos. Os processos hidrológicos que ocorrem em bacias hidrográficas podem ser representados por modelos matemáticos, permitindo uma melhor interpretação destes e contribuindo para um melhor planejamento e gestão dos recursos hídricos (Santos et al., 2021).

2.3 Método de Brutsaert

O método de Brutsaert (2008) teve como base as ideias de Brutsaert e Nieber (1977) para a análise do armazenamento subterrâneo em aquíferos não confinados. Esse método é fundamentado em soluções teóricas da equação de Boussinesq e na teoria hidráulica das águas subterrâneas (Lin e Yeh, 2017).

A ideia central do método de Brutsaert é a de que o escoamento base é resultado da drenagem natural de aquíferos subterrâneos não confinados, sem a influência da precipitação ou da evapotranspiração. Considera-se, então, que apenas as características geológicas controlam o escoamento base da bacia, podendo-se inferir sobre mudanças temporais no armazenamento subterrâneo não confinado via escoamento base. Assim, o escoamento base em qualquer seção de um rio pode ser assumido como representativo do fluxo de água subterrânea a montante (Brutsaert e Nieber, 1977).

Os fundamentos do método de Brutsaert estão nos aspectos físicos do armazenamento subterrâneo (S) e na sua conectividade com a geomorfologia da bacia, detalhados em Brutsaert (2008). Uma equação matemática de potencial pode estimar S em função de uma descarga de fluxo de base (Brutsaert, 2008; Rupp e Selker, 2006):

$$S = K\,x\,y \qquad (1)$$

Onde S é o armazenamento de água subterrânea (em mm); y é a vazão transformada em lâmina (mm/dia) (y = Q/A, onde A é a área da sub-bacia); K é um parâmetro de tempo associado à característica de transmissividade hidrogeológica da bacia (dia).

Em períodos de estiagem, o escoamento superficial é sustentado em grande parte pela vazão acumulada nos aquíferos à montante. Dessa maneira, com base nas vazões mínimas pode-se obter o armazenamento mínimo subterrâneo em um período.

A grande vantagem do método de Brutsaert é que este é de fácil aplicação, requer menor número de parâmetros e depende essencialmente de séries de vazão, o que facilita sua aplicação em bacias com disponibilidade limitada de dados. A partir das séries de vazão máximas são obtidas as vazões médias mínimas de 7 dias consecutivos (Q7,min), por meio do cálculo de médias móveis de sete dias consecutivos, onde é selecionado o menor valor obtido, representando assim a condição crítica de vazão mínima associada ao escoamento base. Outra vantagem é que, por possuir fundamentação física, o método de Brutsaert permite uma interpretação mais consistente da dinâmica do armazenamento subterrâneo e da contribuição do escoamento de base (Partington et al., 2012). Por outro lado, a aplicação do método exige séries hidrológicas de boa qualidade e pode apresentar sensibilidade à identificação dos trechos de recessão (Brutsaert, 2008).

Esse método tem sido utilizado em várias partes do mundo sob diferentes condições climáticas e fisiográficas, demonstrando resultados satisfatórios em comparação com outros métodos. Zhu et al. (2020) utilizaram o método de Brutsaert para avaliar as contribuições climáticas nas mudanças de armazenamento subterrâneo em sub-bacias de cabeceira na Austrália, e identificaram que o armazenamento é altamente sensível às mudanças climáticas. No trabalho de Berghuis et al. (2016) foi analisada a sensibilidade do fluxo superficial a mudanças no armazenamento subterrâneo em bacias na Europa, utilizando-se do método de Brutsaert, e verificou-se que o armazenamento controla a sensibilidade hidrológica da bacia. Lin e Yeh (2017) analisaram o armazenamento de água subterrânea, utilizando o mesmo método, no norte de Taiwan, e identificaram variações sazonais bem definidas no armazenamento subterrâneo, com redução do escoamento no período seco, e recarga e recuperação no período chuvoso. Gao et al. (2015) também obtiveram o armazenamento subterrâneo utilizando-se do método de Brutsaert, em bacias na China, e verificaram uma tendência de redução no armazenamento, associado às mudanças climáticas e aumento da demanda hídrica. Zhang et al. (2014) obtiveram o armazenamento subterrâneo pelo mesmo método na Austrália, e observaram uma forte relação entre o escoamento base e o armazenamento subterrâneo.

Métodos baseados em filtros digitais, como o de Eckhardt (Eckhardt, 2005), são de fácil implementação e amplamente utilizados, porém dependem de calibração de parâmetros, o que pode introduzir incertezas e reduzir a representatividade física dos resultados, como a variabilidade hidrológica em diferentes condições climáticas (Xie et al., 2020; Yang et al., 2021). Já métodos empíricos, como o HYSEP (Sloto; Crouse, 1996), apresentam simplicidade operacional, mas carecem de base física, limitando sua capacidade de representar adequadamente os processos hidrológicos (Partington et al., 2012). Assim, embora diferentes métodos apresentem aplicabilidade em função dos dados disponíveis e dos objetivos do estudo, abordagens baseadas em processos físicos, como a de Brutsaert, tendem a fornecer estimativas mais robustas e interpretáveis do escoamento de base e do armazenamento subterrâneo (Li et al., 2022).

2.4 Modelagem hidrológica

Segundo Tucci (2020), um sistema é definido como qualquer estrutura que num determinado tempo de referência inter-relaciona-se com uma entrada ou estímulo de energia, e uma saída ou resposta de energia. Um modelo é a representação de um sistema em uma linguagem que permita entendê-lo e buscar respostas para diferentes entradas, assim um modelo hidrológico pode representar o comportamento de uma bacia hidrográfica e prever condições diferentes das observadas (Tucci, 2020).

Modelos hidrológicos podem representar matematicamente processos físicos como, transformação de chuva em escoamento, evapotranspiração, armazenamento de água no solo e aquíferos, e propagação de ondas de cheias ao longo da rede de drenagem de bacias hidrográficas (Pontes et al., 2015). Os modelos hidrológicos distribuídos dividem as bacias hidrográficas em diferentes unidades para a simulação dos processos hidrológicos (Xiao et al., 2023), podendo assim atingir uma grande representatividade espacial ao considerar diferentes características do solo, uso do solo e geologia da bacia.

De acordo com Caldeira et al. (2018), os modelos hidrológicos podem ser utilizados para diversos fins, como: geração de série sintética de vazões em cursos d'água não monitorados; preenchimento de falhas em séries históricas, conforme aplicado por Fillingham e Kilsby (2015); previsão de inundação em tempo real; estimativa de frequência de vazões de cheia, conforme Viglione et al. (2013); dimensionamentos hidrológicos de estruturas hidráulicas; análise de vazões de referência para outorga de uso da água; avaliação do impacto das mudanças climáticas e de uso do solo sobre os recursos hídricos, como nos estudos de Arnold et al. (2012) e de Wagner et al. (2013); estudos sobre serviços ecossistêmicos de caráter hidrológico; vazão ecológica; entre outros.

A modelagem hidrológica é uma importante ferramenta para a compreensão dos processos hidrológicos e a avaliação de cenários, fornecendo uma base técnica para um melhor gerenciamento dos recursos hídricos (Lopes et al., 2020). Os modelos hidrológicos podem prever comportamentos futuros de um sistema que ainda não foram experimentados em situações reais, assim o uso dessas ferramentas aliadas a um banco de dados e ao SIG consistem em uma importante ferramenta para o planejamento e análise ambiental (Lammoglia, 2024).

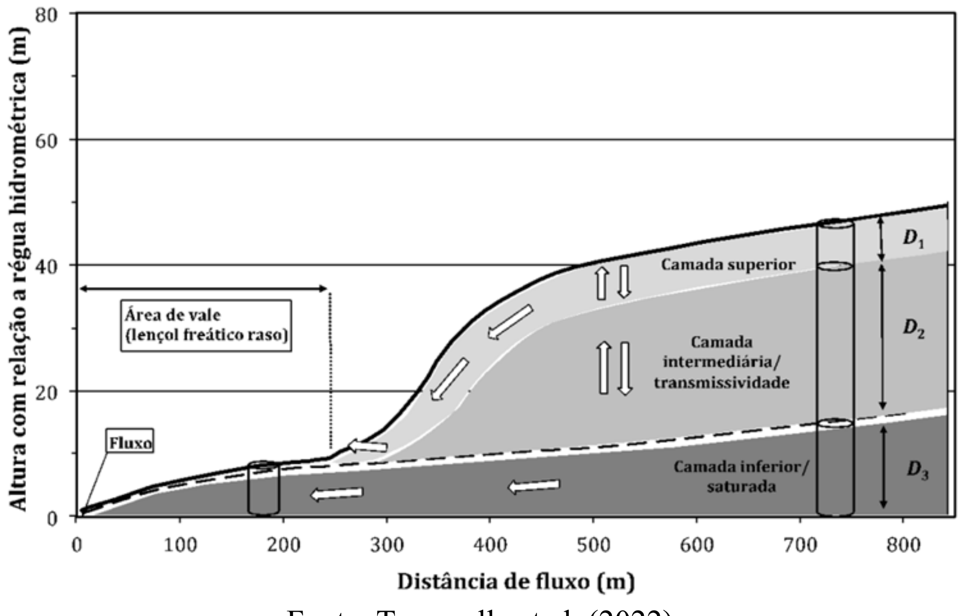
2.4.1 Modelo MHD/INPE

O Modelo Hidrológico Distribuído – MHD foi desenvolvido pelo Instituto Nacional de Pesquisas Espaciais – INPE (Rodriguez e Tomasella, 2016), com base no Modelo de Grandes Bacias – MGB do Instituto de Pesquisas Hidrálicas – IPH (Collischonn et al., 2007). No processo de simulação o MHD combina princípios dos modelos TopModel (Beven e Kirby, 1979) e Xinanjiang (Zhao e Liu, 1995), e no processo de calibração baseia-se no algoritmo do método Shuffled Complex Evolution - SCE-UA (Duan et al., 1992). O modelo também pode ser calibrado por meio do Strength Pareto Evolutionary Algorithm 2 - SPEA2, que é um algoritmo multiobjetivo, e portanto, contribui para a redução de incertezas e para a obtenção de soluções mais robustas na representação dos processos hidrológicos (Zitzler et al., 2001).

O MHD é um modelo de grande escala que integra balanços de água e energia para simular vazões em grandes bacias (Rodriguez e Tomasella, 2016). É um modelo conceitual distribuído por grades regulares, onde o balanço hídrico é simulado em cada grade, ou Unidade de Resposta Hidrológica – URH, e o escoamento é propagado pela rede de drenagem, por meio da integração de equações que representam os processos hidrológicos, como interceptação, percolação, escoamento e evapotranspiração (Negrão et al., 2017). O modelo é composto por quatro módulos, sendo eles: balanço vertical de água no solo; evapotranspiração; fluxo superficial, subsuperficial e subterrâneo; e propagação em canais (Melo, 2019).

O MHD utiliza três camadas para simulação do balanço hídrico: superficial, que gera os fluxos superficial e subsuperficial e flui para a camada seguinte; intermediária, que funciona como um reservatório de água para a vegetação com raízes profundas, podendo ser excluída em solos rasos; e a camada inferior, que controla o fluxo de base e, indiretamente, o fluxo superficial pelo excesso de saturação (Tomasella et al., 2022). Cada camada possui um armazenamento máximo, definido pelo tipo do solo e pela espessura da camada, que são os parâmetros de calibração. Os fluxos verticais entre as camadas do solo são descritos por processos de percolação, onde a camada superior drena para a intermediária, que drena para a inferior (Tomasella et al., 2022) (Figura 1). Enquanto o escoamento subsuperficial lateral é representado com base nos princípios do modelo TOPMODEL, que considera a influência da topografia na distribuição espacial da umidade e na geração do escoamento base (Beven; Kirkby, 1979; Tomasella et al., 2022).

Figura 1 - Esquema conceitual do modelo MHD/Inpe indicando as diferentes camadas, fluxos e direções.



Fonte: Tomasella et al. (2022).

A evapotranspiração é calculada pelo método de Penman-Monteith (Monteith, 1965), onde são utilizados dados de temperatura do ar, velocidade do vento, umidade relativa, pressão atmosférica e radiação solar. Por meio do método de Gash et al. (1995) é obtida a perda de água por interceptação, e fazendo o uso do modelo de distribuição de raízes de Jarvis (1989) é simulada a captura de água do solo até a vegetação (Tomasella et al., 2022). Segundo Tomasella et al. (2022) em cada célula do modelo há um canal associado ao escoamento superficial direto, cujos excedentes do balanço hídrico são transferidos por meio de reservatórios lineares simples. A propagação pela rede de canais é obtida por meio do método de Muskingum-Cunge (Cunge, 1969).

Os dados de entrada do modelo são: meteorológicos, como precipitação, temperatura do ar, velocidade do vento, temperatura do ponto de orvalho, radiação solar de onda curta, pressão atmosférica; mapas de solo e mapas de uso e ocupação do solo; e dados do relevo, como o Modelo Digital de Elevação. Para a calibração do modelo são necessários parâmetros como os de: vegetação, incluindo albedo, índice de área foliar, cobertura de dossel, profundidade radicular; solo, como condutividade hidráulica saturada, pressão de entrada do ar, umidade volumétrica; além de outros parâmetros inerentes ao modelo. Os parâmetros fixos do modelo incluem os de: vegetação, sendo eles ômega crítico, fator de distribuição de raízes, NVeg, albedo, Índice de Área Foliar, altura da vegetação, cobertura da vegetação e profundidade radicular; e solo, que incluem condutividade hidráulica saturada, pressão de entrada do ar, parâmetro b da curva de retenção, e umidade volumétrica na saturação e residual.

O modelo já foi aplicado em vários estudos no Brasil, apresentando resultados satisfatórios para a predição do escoamento sob diferentes cenários, como os de alteração no uso do solo e de mudanças climáticas. Melo et al. (2022) avaliaram o desempenho do modelo MHD-INPE em uma bacia de cabeceira da bacia do rio Grande, comparando-o a um modelo fisicamente baseado e obtendo resultados satisfatórios na simulação das vazões. Zákhia et al. (2021) utilizaram o MHD-INPE associado a modelos climáticos regionalizados pelo Eta/CPTEC para analisar os impactos de mudanças climáticas na bacia do ribeirão Jaguara, localizada na região do Alto Rio Grande, verificando bom desempenho na reprodução do regime hidrológico e na projeção de cenários futuros. Negrão et al. (2017) aplicaram o modelo na previsão de eventos hidrológicos extremos em São Luís do Paraitinga (SP), demonstrando sua capacidade de representar adequadamente respostas hidrológicas associadas a chuvas intensas. De forma complementar, Rodriguez et al. (2017) aplicaram o MHD-INPE em estudos de regionalização hidrológica e avaliação de mudanças no uso e cobertura do solo, evidenciando sua versatilidade para diferentes condições hidrológicas.

2.5 Modelos climáticos

Tendo em vista as recentes mudanças nos padrões climáticos é altamente provável que as mudanças climáticas tenham estado presentes nos regimes de precipitação e temperatura, e na dinâmica hidrológica, principalmente nas últimas décadas (Regoto et al., 2021). De acordo com o sexto relatório do IPCC (2023), se o ritmo atual de emissão de gases de efeito estufa continuar, podem ocorrer aumentos na temperatura média global de 2,5 °C a 4,0 °C até 2100, ocasionando mudanças climáticas globais, com intensificação de eventos extremos como ondas de calor, secas e chuvas intensas. No quinto relatório científico divulgado pelo IPCC (2013), foram levantados quatro cenários climáticos futuros com projeções até 2100, que demonstram as concentrações atmosféricas e suas forçantes radiativas antropogênicas por meio de Caminhos de Concentração Representativa, do inglês *Representative Concentration Pathways* (RCP), sendo estes equivalentes ao forçamento radiativo total em W m^{-2} até o ano de 2100. O RCP 4.5 é um cenário intermediário, que representa um aquecimento global médio de 1,1 a 2,6 ºC, já o RCP 8.5 é o cenário mais pessimista representando um aquecimento de 2,6 a 4,8 ºC até o final do século (Van Vuuren et al., 2011).

Os Modelos de Circulação Geral (GCMs, do inglês *General Circulation Models*) permitem o estudo dos cenários atuais e de mudanças climáticas (Silva, 2025), pois simulam o comportamento dos processos químicos e físicos na atmosfera, além de interagir com componentes de outros sistemas (Chou et al., 2014). Os GCMs levam em conta variações na concentração de gases do efeito estufa, sendo, portanto, uma das ferramentas científicas mais avançadas na simulação do clima (Mello et al., 2015; Ahmed, Ahmad, e Kheir, 2023). Esses modelos representam de forma integrada os principais componentes do sistema climático, incluindo a atmosfera, os oceanos, a biosfera e a criosfera (IPCC, 2021). Além disso, os cenários climáticos associados consideram diferentes trajetórias de concentração de gases de efeito estufa ao longo do tempo, permitindo a análise de possíveis mudanças futuras no clima (Van Vuuren et al., 2011; IPCC, 2023).

O Model for Interdisciplinary Research on Climate - MIROC é um modelo japonês, desenvolvido em cooperação pela Universidade de Tóquio, NIES e JAMSTEC, que apresenta modelos oceânicos e de superfície continental (Watanabe et al., 2011). Já o HadGEM2-ES, que foi desenvolvido pelo Hadley Centre (Collins et al., 2011; Martin et al., 2011), é um modelo do sistema terrestre, e representa o ciclo do carbono. Este modelo inclui a química da atmosfera e um modelo de aerossol com a representação do carbono orgânico e da pluma de poeira (Rodrigues, 2017). Segundo Collins et al. (2011), a resolução do modelo HadGEM2-ES é de 1,875º de longitude e 1,275º de latitude, com uma altitude de até 40 km. Já o MIROC5, apresenta uma resolução de 150 km na horizontal e 40 níveis na vertical (Chou et al., 2014).

O CanESM2 simula processos climáticos usando o Coupled Model Intercomparison Project fase 5 – CMIP 5 para os RCPs, e é um modelo de cobertura global, disponível gratuitamente e que tem sido muito utilizado em estudos hidrológicos e de mudanças climáticas (Chim et al., 2021). Este modelo acopla um modelo de circulação geral atmosfera-oceano, um modelo de terra-vegetação e um ciclo interativo do carbono terrestre e oceânico, e tem resolução horizontal de 2,8125º, e resolução vertical de 35 camadas (Chylek et al., 2011).

O Brazilian Earth System Model - BESM foi desenvolvido pelo Centro de Previsão de Tempo e Estudos Climáticos - CPTEC/INPE, e é composto por um modelo acoplado oceano-atmosfera (Nobre et al., 2013), com resolução horizontal de 40 km e resolução vertical de 38 camadas (Chou et al., 2007). O BESM tem sido utilizado para produzir cenários globais de mudanças climáticas, e, para fornecer condições de fronteira atmosféricas e oceânicas para modelos climáticos regionais, para redução dinâmica dos cenários de mudanças climáticas (Chou et al., 2014).

As projeções dos GCMs possuem resolução espacial grosseira para avaliações de impacto e, para escalas regionais, sendo assim, estas são refinadas por Modelos Climáticos Regionais – RCMs, do inglês *Regional Climate Models* (Maraun et al., 2017). O Instituto Nacional de Pesquisas Espaciais (INPE) desenvolveu no Brasil, produtos de *downscaling* com o RCM Eta, sob os cenários RCP 8.5 e 4.5, todos com resolução de 20 km, como forma de apoio a estudos estratégicos de mudanças no clima e ao Plano Nacional de Adaptação às Mudanças Climáticas (Chou et al., 2014; Almagro; Oliveira, 2019).

Além disso, as projeções climáticas estão sujeitas a incertezas. De acordo com Liu e Gupta (2007) existem dois tipos de incertezas na projeção climática: a incerteza da modelagem, que está relacionada ao ajuste imperfeito do modelo; e a incerteza preditiva, associada a erros de previsão devido, por exemplo, a mudanças dos padrões naturais. As principais fontes de incerteza associadas às projeções climáticas incluem: a variabilidade interna do sistema climático; as diferenças estruturais entre modelos climáticos globais (GCMs); e os cenários futuros de emissão de gases de efeito estufa (Eyring et al., 2016). Em horizontes de curto prazo, a variabilidade natural do sistema climático tende a ser a principal fonte de incerteza, enquanto, em escalas de longo prazo, os modelos e cenários climáticos dominam as fontes de incertezas (Lehner et al., 2020).

REFERÊNCIAS

ADDOR, N.; MELSEN, L. A. Legacy, rather than adequacy, drives the selection of hydrological models. **Water Resources Research**, v. 55, n. 1, p. 378–390, 2019.

AHMED, K.; AHMAD, N.; KHEIR, A. M. S. Global Climate Models and their applications in hydrological and climate impact studies: a review. **Environmental Modelling & Software**, v. 165, 2023.

ALMAGRO, A.; OLIVEIRA, P. T. S. Avaliação da precipitação simulada pelos modelos ETA/HADGEM2-ES e ETA/MIROC5 para o Brasil. *In*: REUNIÃO ANUAL DA SBPC, 71., 2019, Campo Grande. **Anais** [...].

ANA – AGÊNCIA NACIONAL DE ÁGUAS E SANEAMENTO BÁSICO. **Águas Subterrâneas e Segurança Hídrica no Brasil**. Brasília: ANA, 2024.

ANA – AGÊNCIA NACIONAL DE ÁGUAS E SANEAMENTO BÁSICO. **Conjuntura dos Recursos Hídricos no Brasil 2024**. Brasília: ANA, 2024.

ANA – AGÊNCIA NACIONAL DE ÁGUAS E SANEAMENTO BÁSICO. **Panorama da qualidade das águas subterrâneas no Brasil**. Brasília: ANA, 2023.

ANA – AGÊNCIA NACIONAL DE ÁGUAS E SANEAMENTO BÁSICO. **Plano Nacional de Recursos Hídricos 2022–2040: diagnóstico estratégico**. Brasília: ANA, 2021.

ANDRADE, L.; RÖRIG, L.; HIRATA, R. Panorama do uso das águas subterrâneas no Brasil e sua importância para a segurança hídrica. **Revista Águas Subterrâneas**, 2024.

ARNOLD, J. G.; MORIASI, D. N.; GASSMAN, P. W. et al. SWAT: Model use, calibration, and validation. **Transactions of the ASABE**, v. 55, n. 4, p. 1491–1508, 2012.

BÁRDOSSY, A.; PEGRAM, G.; WAGENER, T. Climate change impacts on hydrological processes and water resources. **Hydrological Processes**, v. 36, n. 5, e14567, 2022.

BASTIAANSSEN, W. G. M.; CHEEMA, M. J. M.; VAN DER WAL, T.; HUNINK, J. E. Remote sensing for water productivity and water balance monitoring in river basins. **Agricultural Water Management**, v. 203, p. 1–12, 2019.

BERGHUIJS, W. R.; HARTMANN, A.; WOODS, R. A. Streamflow sensitivity to water storage changes across Europe. **Geophysical Research Letters**, v. 43, n. 5, p. 1980-1987, 2016.

BERNARDI, E. C. S. et al. Bacia hidrográfica como unidade de gestão ambiental. Disciplinarum Scientia| Naturais e Tecnológicas, v. 13, n. 2, p. 159-168, 2012.

BEVEN, K. J.; KIRKBY, M. J. A physically based, variable contributing area model of basin hydrology. **Hydrological sciences journal**, v. 24, n. 1, p. 43-69, 1979.

BEVEN, K. **Rainfall-Runoff Modelling: The Primer**. 2. ed. Chichester: John Wiley & Sons, 2012.

BRASIL. **Lei n. 9.433, de 8 de janeiro de 1997**. Institui a Política Nacional de Recursos Hídricos, cria o Sistema Nacional de Gerenciamento de Recursos Hídricos, regulamenta o inciso XIX do art. 21 da Constituição Federal, e altera o art. 1º da Lei nº 8.001, de 13 de março de 1990, que modificou a Lei nº 7.990, de 28 de dezembro de 1989. Disponível em: < http://www.planalto.gov.br/ccivil_03/leis/l9433.htm>. Acesso em: junho de 2024.

BRUTSAERT, W. Long-term groundwater storage trends estimated from streamflow records: Climatic perspective. **Water Resources Research**, v. 44, n. 2, 2008.

BRUTSAERT, W.; NIEBER, J. L. Regionalized drought flow hydrographs from a mature glaciated plateau. **Water Resources Research**, v. 13, n. 3, p. 637-643, 1977.

CALDEIRA, T. L. et al. Modelagem hidrológica determinística chuva-vazão em bacias hidrográficas: uma abordagem introdutória. **Revista Brasileira de Engenharia e Sustentabilidade**, Pelotas, v. 5, n. 1, p. 22-32, 2018.

CAMPOS, J. E. G.; GUIMARÃES, L. F.; CUNHA, L. S. Groundwater recharge and aquifer vulnerability under climate change scenarios in Brazil. **Journal of South American Earth Sciences**, 2023.

CARVALHO, A. T. F. Bacia hidrográfica como unidade de planejamento: discussão sobre os impactos da produção social na gestão de recursos hídricos no Brasil. Caderno Prudentino de Geografia, n. 42, v. 1, p. 140-161, 2020.

CARVALHO, T. M. N. et al. Unveiling water allocation dynamics under climate variability in the São Francisco River Basin. **Environmental Research Letters**, 2024.

CHIM, K. et al. Identifying future climate change and drought detection using CanESM2 in the upper Siem Reap River, Cambodia. **Dynamics of Atmospheres and Oceans**, v. 94, p. 101182, 2021.

CHOU, S. C. et al. Evaluation of the Eta simulations nested in three global climate models. **American Journal of Climate Change**, v. 3, n. 5, p. 438-454, 2014.

CHOU, S. C. et al. Refinamento estatístico das previsões horárias de temperatura a 2 m do modelo Eta em estações do Nordeste do Brasil. **Revista Brasileira de Meteorologia**, v. 22, p. 287-296, 2007.

CHYLEK, P. et al. Observed and model simulated 20th century Arctic temperature variability: Canadian earth system model CanESM2. **Atmospheric Chemistry and Physics Discussions**, v. 11, n. 8, p. 22893-22907, 2011.

CLARK, M. P.; KAVETSKI, D.; FENICIA, F. et al. A unified approach for process-based hydrologic modeling: 1. Modeling concept. **Water Resources Research**, v. 51, n. 4, p. 2498–2514, 2015.

COELHO, C. A. S.; CARDOSO, D. H. F.; FIRPO, M. A. F. Precipitation diagnostics of an exceptionally dry event in São Paulo, Brazil. **Theoretical and Applied Climatology**, v. 125, p. 769–784, 2016.

COLLINS, W. J. et al. Development and Evaluation of an Earth-System Model-HadGEM2. **Geoscientific Model Development**, v. 4, n. 4, p. 1051-1075, 2011.

COLLISCHONN, W. et al. The MGB-IPH model for large-scale rainfall—runoff modelling. **Hydrological Sciences Journal**, v. 52, n. 5, p. 878-895, 2007.

COLLISCHONN, W.; DORNELLES, F. **Hidrologia para engenharia e ciências ambientais**. Porto Alegre: Associação Brasileira de Recursos Hídricos – ABRHidro, 2021.

CONICELLI, B. P.; HIRATA, R. Gestão das águas subterrâneas urbanas no Brasil: desafios e oportunidades. **Revista do Instituto Geológico**, São Paulo, v. 37, n. 1, p. 71–86, 2016.

CUNGE, J. A. On the subject of a flood propagation computation method (Muskingum method). **Journal of Hydraulic Research**, v. 7, n. 2, p. 205–230, 1969.

DUAN, Q.; SOROOSHIAN, S.; GUPTA, V. Effective and efficient global optimization for conceptual rainfall-runoff models. **Water resources research**, v. 28, n. 4, p. 1015-1031, 1992.

ECKHARDT, K. How to construct recursive digital filters for baseflow separation. **Hydrological Processes**, v. 19, n. 2, p. 507–515, 2005.

EYRING, V.; BONY, S.; MEEHL, G. A. et al. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. **Geoscientific Model Development**, v. 9, p. 1937–1958, 2016.

FAN, Y.; LI, H.; MIAO, C.; XU, Y. Hydrological resilience and groundwater recharge estimation using water balance approaches under climate variability. **Journal of Hydrology**, v. 569, p. 798–812, 2019.

FANG, X.; ZHANG, J.; SHI, P.; LIU, L. Impacts of land use and climate change on hydrological processes in a watershed: A review. **Journal of Hydrology**, v. 589, 125193, 2020.

FERNANDES, V.; CUNHA, A. P. M. A.; CUARTAS, L. A. et al. Secas e os impactos na região Sul do Brasil. **Revista Brasileira de Climatologia**, v. 28, p. 561-584, 2021.

FILLINGHAM, J. H.; KILSBY, C. G. A near real-time hydrological model for filling gaps in river flow records. **Journal of Hydrology**, v. 525, p. 667–679, 2015.

GALVÍNCIO, J. D. et al. Mudanças Hidrológicas Projetadas para o Reservatório de Sobradinho sob Cenários Climáticos do Século XXI com Base em Simulações no SWAT/SUPer. **Revista Brasileira de Geografia Física**, v. 18, n. 04, p. 2640-2656, 2025.

GAO, Z. et al. Groundwater storage trends in the Loess Plateau of China estimated from streamflow records. **Journal of Hydrology**, v. 530, p. 281-290, 2015.

GASH, J. H.; LLOYD, C. R.; LACHAUD, G. Estimating sparse forest rainfall interception with an analytical model. **Journal of Hydrology**, v. 170, n. 1-4, p. 79-86, 1995.

HAMEED, M.; NAYAK, M. A.; AHANGER, M. A. Event-Based Recession Analysis for Estimation of Basin-Wide Characteristic Drainage Timescale and Groundwater Storage Trends. **Water Resources Research**, v. 59, n. 12, p. e2023WR035829, 2023.

HELLWIG, J.; STAHL, K. An assessment of trends and potential future changes in groundwater-baseflow drought based on catchment response times. **Hydrology and Earth System Sciences**, v. 22, n. 12, p. 6209–6224, 2018.

IGAM – INSTITUTO MINEIRO DE GESTÃO DAS ÁGUAS. **Panorama das águas subterrâneas em Minas Gerais**. Belo Horizonte: IGAM, 2023.

INTERGOVERNMENTAL PANEL IN CLIMATE CHANGE - IPCC. **Climate Change 2013: The Physical Science Basis**. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 2013.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE - IPCC. **Climate Change 2023: Synthesis Report.** Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC, 2023.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE - IPCC. **Climate Change 2021: The Physical Science Basis.** Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2021.

JARVIS, N. J. A simple empirical model of root water uptake. **Journal of Hydrology**, v. 107, n. 1-4, p. 57-72, 1989.

JASECHKO, S. Global isotope hydrogeology―review. **Reviews of Geophysics**, v. 57, n. 3, p. 835-965, 2019.

KADIRKHODJAEV, A. et al. Assessing Climate Change Impacts on Groundwater Recharge and Storage Using MODFLOW in the Akhangaran River Alluvial Aquifer, Eastern Uzbekistan. **Water**, v. 17, n. 15, p. 2291, 2025.

LAMMOGLIA, R. **Aplicação do modelo SWAT para simular a vazão na Microbacia Hidrográfica do Rio Capivari/SP**. 2024. 88 p. Tese (Doutorado), Universidade Estadual de Campinas, Campinas, 2024.

LEE, S.; AJAMI, H. Comprehensive assessment of baseflow responses to long-term meteorological droughts across the United States. **Journal of Hydrology**, v. 626, 130256, 2023.

LEHNER, F.; DESER, C.; MAHER, N.; MAROTZKE, J.; SANDERSON, B. M. Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6. **Earth System Dynamics**, v. 11, p. 491–508, 2020.

LI, H.; XU, C.; GUO, S.; ZHANG, Z. Physically based approaches for baseflow estimation and groundwater storage assessment: advances and challenges. **Journal of Hydrology**, v. 610, 127905, 2022.

LI, X.; ZHANG, Y.; WANG, J.; CHEN, X. Integration of hydrometeorological observations, remote sensing and hydrological modeling for improving water resources assessment. **Journal of Hydrology**, v. 610, 127866, 2022.

LI, Z.; LIU, W.; ZHANG, X.; ZHENG, F. Impacts of land use change and climate variability on hydrological processes in a basin scale. **Catena**, v. 202, 105251, 2021.

LIN, K. T.; YEH, H. F. Baseflow recession characterization and groundwater storage trends in northern Taiwan. **Hydrology Research**, v. 48, n. 6, p. 1745-1756, 2017.

LIU, Y.; GUPTA, H. V. Uncertainty in hydrologic modeling: Toward an integrated data assimilation framework. **Water Resources Research**, v. 43, W07401, 2007.

LIU, Y.; WEIHERMÜLLER, L.; VEREECKEN, H.; CLASS, H. Representing flow and transport processes in hydrological models at the catchment scale. **Hydrology and Earth System Sciences**, v. 21, p. 393–414, 2017.

LOPES, T. R. et al. Hydrological modeling for the Piracicaba River basin to support water management and ecosystem services. **Journal of South American Earth Sciences**, v. 103, p. 102752, 2020.

MARAUN, D. et al. Towards process-informed bias correction of climate change simulations. **Nature Climate Change**, v. 7, n. 11, p. 764–773, 2017.

MARENGO, J. A.; CUNHA, A. P.; CUARTAS, L. A. et al. Extreme drought in the Brazilian Pantanal in 2019–2020: characterization, causes, and impacts. **Frontiers in Water**, v. 3, 2021.

MARQUES, G. F.; SILVA, D. D.; BARROS, F. M. Instrumentos econômicos e gestão integrada dos recursos hídricos no Brasil. **Revista de Gestão da Água da América Latina**, v. 19, 2022.

MARTIN, G. M. The HadGEM2 family of met office unified model climate configurations. **Geoscientific Model Development**, New York, v. 4, n. 4, p. 723-757, 2011.

MELLO, C. R. et al. Assessing the climate change impacts on the rainfall erosivity throughout the twenty-first century in the Grande River Basin (GRB) headwaters, Southeastern Brazil. **Environmental Earth Sciences**, v. 73, n. 12, p. 8683–8698, 2015.

MELLO, C. R.; SILVA, A. M.; BESKOW, S. **Hidrologia de bacias hidrográficas**. Lavras: Editora UFLA, 2020.

MELO, P. A. **Desempenho de modelos hidrológicos em uma bacia hidrográfica de cabeceira**. 2019. 90 p. Dissertação (Mestrado). Universidade Federal de Lavras, Lavras, 2019.

MELO, P. A. et al. On the performance of conceptual and physically based modelling approach to simulate a headwater catchment in Brazil. **Journal of South American Earth Sciences**, v. 114, p. 103683, 2022.

MONTEITH, J. L. Evaporation and environment. In: SYMPOSIUM OF THE SOCIETY FOR EXPERIMENTAL BIOLOGY, 19., 1965, Cambridge. Proceedings… Cambridge: Cambridge University Press, 1965. p. 205–234.

NEGRÃO, A. C. et al. Previsão de vazão de eventos extremos utilizando o modelo hidrológico distribuído MHD-INPE e previsões meteorológicas do modelo ETA-INPE para uma alta resolução espacial–estudo de caso: São Luís do Paraitinga (SP). **Revista Brasileira de Cartografia**, v. 69, n. 4, p. 647-657, 2017.

NOBRE, C. A.; MARENGO, J. A.; SELUCHI, M. E.; CUARTAS, L. A.; ALVES, L. M. Some characteristics and impacts of the drought and water crisis in Southeastern Brazil during 2014 and 2015. **Journal of Water Resource and Protection**, v. 8, n. 2, p. 252–262, 2016.

NOBRE, C. A.; MARENGO, J. A.; SOARES, W. R. **Climate Change Risks in Brazil**. Springer, 2019.

NOBRE, P.; MALAGUTTI, M.; URBANO, D. F.; ALMEIDA, R. A. F.; GUILLOD, B. P. Brazilian Earth System Model (BESM) development and application. **Geoscientific Model Development**, v. 6, p. 235–251, 2013.

PARTINGTON, D.; BRUTSAERT, W.; NISHI, Y.; YANG, J. Evaluation of outputs from automated baseflow separation methods against simulated baseflow from a physically based, surface water-groundwater flow model. **Journal of Hydrology**, v. 458–459, p. 28–39, 2012.

PEREIRA, S. Y.; ABREU, M. C.; MURILLO-BERMÚDEZ, J. Águas subterrâneas e segurança hídrica no Brasil: desafios para gestão integrada. **Revista Águas Subterrâneas**, 2024.

PONTES, P. R. M. et al. Modelagem hidrológica e hidráulica de grande escala com propagação inercial de vazões. **Revista Brasileira de Recursos Hídricos**, v. 20, n. 4, p. 888-904, 2015.

REGOTO, P. et al. Observed changes in air temperature and precipitation extremes over Brazil. **International Journal of Climatology**, v. 41, n. 11, p. 5125-5142, 2021.
RODRIGUES, J. A. M. **Impactos antrópicos no regime hidrológico de tributários do Rio Tocantins**. 2017. Dissertação (Mestrado). Universidade Federal de Lavras, Lavras, 2017.

RODRIGUEZ, D. A. et al. Previsões de cheias extremas nos horizontes sazonais e de curto e médio prazos na bacia do rio Madeira: estudo de caso da enchente de 30 de março de 2014 em Porto Velho. **Revista Brasileira de Cartografia**, n. 69/4, p. 827-836, 2017.

RODRIGUEZ, D. A.; TOMASELLA, J. On the ability of large-scale hydrological models to simulate land use and land cover change impacts in Amazonian basins. **Hydrological Sciences Journal,** v. 61, n. 10, p. 1831-1846, 2016.

RUPP, D. E.; SELKER, J. S. Information, artifacts, and noise in dQ/dt–Q recession analysis. **Advances in Water Resources**, v. 29, n. 2, p. 154–160, 2006.

SANTAROSA, L. V. **Impactos antropogênicos e climáticos nos processos hidrológicos: uma abordagem múltipla sobre a função das águas subterrâneas em bacias hidrográficas complexas no estado de São Paulo**. 2020. 123 p. Tese (Doutorado). Universidade Estadual Paulista “Júlio de Mesquita Filho”, São Paulo, 2020.

SANTOS, C. A. C.; SILVA, R. M.; BRAGA, C. C. et al. Aridity trends and climate change impacts across Brazil. **Theoretical and Applied Climatology**, 2024.

SANTOS, F. M.; SILVA, D. D.; MOREIRA, M. C. Aplicação de modelos hidrológicos no planejamento e gestão de recursos hídricos em bacias hidrográficas. **Revista Brasileira de Recursos Hídricos**, v. 26, e15, 2021.

SANTOS, J. Y. G. et al. Modeling the impacts of future LULC and climate change on runoff and sediment yield in a strategic basin in the Caatinga/Atlantic forest ecotone of Brazil. **Catena**, v. 203, p. 105308, 2021.

SANTOS, R. R. et al. Aprimoramentos computacionais da ferramenta ArcLASH. *In*: XXVIII CONGRESSO DE INICIAÇÃO CIENTIFICA DA UNIVERSIDADE FEDERAL DE PELOTAS, 2019, Pelotas. **Anais** [...].

SCHILLING, K. E.; LANGEL, R. J.; WOLTER, C. F.; ARENAS-AMADO, A. Using baseflow to quantify diffuse groundwater recharge and drought at a regional scale. **Journal of Hydrology**, v. 603, 126765, 2021.

SEIBERT, J.; BERGSTRÖM, S. A retrospective on hydrological catchment modelling based on half a century with the HBV model. **Hydrology and Earth System Sciences**, v. 26, p. 1371–1388, 2022.

SERVIÇO GEOLÓGICO DO BRASIL – SGB. **Panorama das águas subterrâneas no Brasil 2023**. Brasília: SGB/CPRM, 2023.

SILVA, N. O. **Projeções climáticas em alta resolução do HighResMIP para a América do Sul e Pantanal no contexto do transporte de umidade**. 2025. 186 p. Tese (Doutorado), Universidade de São Paulo, São Paulo, 2025.

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. Toward continental hydrologic–hydrodynamic modeling in South America. **Hydrology and Earth System Sciences**, v. 22, n. 9, p. 4815–4842, 2018.

SLOTO, R. A.; CROUSE, M. Y. *HYSEP:* **A Computer Program for Streamflow Hydrograph Separation and Analysis**. U.S. Geological Survey Water-Resources Investigations Report 96-4040, 1996.

TALBOT, C.; BRISSETTE, F.; POULIN, A. Advances in integrated hydrological and climate modeling for watershed management. **Hydrological Processes**, 2025.

TOMASELLA, J. et al. **Modelo hidrológico distribuído MHD-INPE: manual de implementação. Versão 2.0**. Instituto Nacional de Pesquisas Espaciais, 2022.

TUCCI, C. E. M. **Modelos hidrológicos**. 3. ed. Porto Alegre: Editora UFRGS/ABRHidro, 2020.

TUCCI, C. E. **Modelos hidrológicos**, Porto Alegre: Editora da UFRGS, 2005.

VAN VUUREN, D. P.; EDMONDS, J.; KAINUMA, M. et al. The representative concentration pathways: an overview. **Climatic Change**, v. 109, p. 5–31, 2011.

VIGLIONE, A.; BLÖSCHL, G.; SALINAS, J. L.; LAHA, A. Flood frequency hydrology: 3. A Bayesian analysis. **Water Resources Research**, v. 49, n. 2, p. 675–692, 2013.

WAGNER, P. D.; KUMAR, S.; SCHNEIDER, K. An assessment of land use change impacts on the water resources of the Mula and Mutha Rivers catchment upstream of Pune, India. **Hydrology and Earth System Sciences**, v. 17, p. 2233–2246, 2013.

WANG, S-J. et al. Evaluation of climate change impact on groundwater recharge in groundwater regions in Taiwan. **Water**, v. 13, n. 9, p. 1153, 2021.

WATANABE, S.; HAJIMA, T.; SAITO, F. et al. MIROC-ESM 2010: model description and basic results of CMIP5-20c3m experiments. **Geoscientific Model Development**, v. 4, p. 845–872, 2011.

WOJAHN, V. S. et al. Groundwater storage trend in headwater basins in different Brazilian regions. **Sustainable Water Resources Management**, v. 10, n. 6, p. 197, 2024.

XIAO, J. et al. Effect of soil spatial aggregation caused by the calculation unit division on runoff and sediment load simulation in the SWAT model. **Journal of Hydrology**, v. 626, p. 130345, 2023.

XIE, J.; WANG, Y.; LIU, B.; ZHANG, M. Evaluation of digital filtering methods for baseflow separation under different climatic conditions. **Journal of Hydrology**, v. 586, 124899, 2020.

YANG, W.; LONG, D.; BAI, P. Impacts of parameter uncertainty on digital filter based baseflow separation across climatic regions. **Hydrological Processes**, v. 35, n. 3, e14088, 2021.

YI, W. et al. Increasing annual streamflow and groundwater storage in response to climate warming in the Yangtze River source region. **Environmental Research Letters**, v. 16, n. 8, p. 084011, 2021.

ZÁKHIA, E. M. S. et al. Impactos das mudanças climáticas em uma bacia hidrográfica no Sul do Estado de Minas Gerais. **Revista Brasileira de Meteorologia**, v. 36, n. 4, p. 667-681, 2021.

ZERGA, B. Integrated watershed management: a review. **Discover Sustainability**, v. 6, n. 1, p. 657, 2025.

ZHANG, L. et al. Long-term annual groundwater storage trends in Australian catchments. **Advances in water resources**, v. 74, p. 156-165, 2014.

ZHAO, R.J.; LIU, X.R. The Xinanjiang model. *In*: SINGH, V. P. **Computer Models of Watershed Hydrology**. Highlands Ranch: Water Resources Publication, 1995. pp. 215–232

ZHU, R. et al. Quantifying climate contributions to changes in groundwater discharge for headwater catchments in a major Australian basin. **Science of the total Environment**, v. 729, p. 138910, 2020.

ZITZLER, E.; LAUMANNS, M.; THIELE, L. **SPEA2: Improving the Strength Pareto Evolutionary Algorithm**. TIK-Report 103. Zurich: ETH Zurich, 2001.

SEGUNDA PARTE

Artigo 1 – Elaborado conforme as normas do periódico – Versão publicada	
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Groundwater storage trend in headwater basins: shreds of evidence from the last decades in Minas Gerais state, Brazil

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Abstract

Changes in rainfall and temperature patterns can impact water security, mainly in tropical and subtropical regions. This study aimed to assess if climate change in Minas Gerais state, Brazil has impacted groundwater storage. Headwaters of four representative basins with minimum land use change were selected to quantify the effects of atmospheric forcing. Daily streamflow time series were used to assess changes in groundwater storage using the Brutsaert method. The Mann-Kendall and Sen tests were applied to evaluate the trends and determine the rate of change. Most studied sub-basins showed an upward trend in temperature and evapotranspiration, while a nonsignificant trend was found for annual precipitation in some sub-basins. Mean annual streamflow, minimum streamflow over seven consecutive days ($Q_{7,\ min}$), and groundwater storage (S) showed downward trends in most sub-basins. The Jequitinhonha sub-basin is the closest hydrological unit to the pristine conditions, indicating that changes in climate have impacted its hydrological response. In contrast, at the Piracicaba sub-basin and Sapucaí sub-basin, it was not clear that climate changes can exclusively explain the decreasing trend in groundwater storage due to the changes in land use from native forest (Atlantic Forest and Cerrado) to pasture. The São Francisco and Grande River sub-basins are the most anthropized and showed the lowest reduction rates, showing that these sub-basins have a relevant resilience to climate change as their geomorphological aspects, i.e., soils, topography, soil-vegetation relationship, and hydrogeology, play a fundamental role in buffering the hydrological impacts. Our results can contribute to water resource management in Minas Gerais state, supporting decision-makers actions to minimize the effects.

Key-words: climate change, water yield, hydrological indicators, headwater basins

Introduction

Given recent changes in climate patterns, especially with impacts on the frequency of extremes, it is highly probable that climate change has been present, mainly in the last decades, affecting the environment, the economy, and society (Regoto et al., 2021). Many studies on the impact of climate change, mainly on the hydrological cycle, have been carried out. However, most have focused on surface water, and much less is known regarding groundwater, especially in the basin's scale. The IPCC (Intergovernmental Panel on Climate Change) stated that detecting impacts caused by climate change on groundwater is more complex due to the lack of observational data (Jiménez Cisneros et al. 2014). According to Zhu et al. (2020), groundwater storage and precipitation have a positive relationship, i.e., the higher the precipitation, the higher the aquifer recharge. However, groundwater storage has a negative relationship with temperature, which can lead to more significant evapotranspiration, reducing groundwater storage. This relationship can be changed depending on the climate and basin's physiographical aspects, such as soil, vegetation, topography, and geology. Therefore, changes in temperature and rainfall affect the water balance in watersheds, with significant consequences for groundwater recharge, streamflow, and water demand, with a particular impact on the dry season (Lee and Ajami, 2023). In regions that have been affected by severe droughts, efficient water resources management becomes essential to guarantee supply and meet the demands in watersheds during critical periods, which have prolonged beyond the droughts as watercourses can take more than three years to recover the baseflow (Lee and Ajami, 2023).

Groundwater storage can also be influenced by other factors, such as changes in land use, land cover, and agricultural practices (Holman, 2006). Given that assessing the impacts of climate change on aquifer recharge is strategic, an analysis of headwater watersheds with minimal anthropogenic interventions proves to be more effective at decoupling the impacts of atmospheric forcing and anthropogenic activity (Jones et al. 2012). This coupled effect has been analyzed in the literature; for instance, Gao et al. (2015) analyzed trends in groundwater storage from streamflow data in the Loess Plateau basins in China. Downward trends in storage were observed in most of the basins, indeed provoked by changes in the climate, such as rising temperatures and precipitation reduction. Zhang et al. (2014) evaluated trends in the groundwater storage of basins in Australia and found downward trends in almost all basins when analyzing long periods, indicating that groundwater storage has been affected by large-scale climate factors. Warku et al. (2022), in a study of the upper Gibe basin in Ethiopia, found trends of increasing temperature and decreasing precipitation over the last 30 years. In response to these changes, a reduction in annual groundwater storage was also observed, which shows that climate variability significantly impacts groundwater recharge in Ethiopia. Decoupling the dynamic of groundwater systems from land surface processes is challenging, requiring detailed hydrogeological data, a network of monitoring wells, and the characterization of surface water and groundwater interactions.

Groundwater storage can be estimated through remote sense, observation wells data, and hydrological models. However, these methods can present limitations such as low spatial resolution and short periods of observation, among others (Liu et al., 2020). A simple approach is the analysis of baseflow as an indicator of changes in the storage of groundwater systems, and the Brutsaert method has been applied worldwide under different climatic, geological, physiographical, and hydrological conditions (Alley et al. 2002; Brutsaert, 2008; Brutsaert, 2010; Mutzner et al. 2013; Zhang et al. 2014; Xiang et al. al. 2016; Kormos et al. 2016; Li et al. 2017). Even in arid and mountainous basins, groundwater hydraulic parameters consistent with field measurements have been predicted (Mendoza et al. 2003). However, in developing countries, where few studies regarding groundwater storage have been conducted, the Brutsaert method arises as an optimal procedure as it is based on baseflow and is applied using only daily streamflow. Baseflow is controlled by the geological and topographical features of the basin, and temporal changes in unconfined groundwater storage can be inferred by the Brutsaert method (Brutsaert and Nieber, 1977). This method can be an important water resource management tool in data-scarce regions. An example of this approach is presented by Lin and Yeh (2017), who obtained groundwater storage in northern Thailand using the Brutsaert method. They also observed downward trends in annual groundwater storage in five and upward trends in three basins. Furthermore, Liu et al. (2020) studied groundwater storage behavior in the Yangtze River basin in China; upward trends were found in 14 of the 19 sub-basins assessed.

Minas Gerais state, in southeast Brazil, has suffered significant droughts recently, especially in the 2010s (Petrucci et al., 2022; Silva and Mello, 2022), mainly caused by reduced rainfall and rising temperatures. In this respect, considering different hydro-climatic regions, predicting how these changes can affect groundwater recharge and water availability in the main state's basins is relevant. This assessment will make it possible to go deeper into the most sensitive hydrological issues (base flow and groundwater storage) in headwater basins, verifying whether, in recent decades, the effects of climate changes are (and how they are) affecting water yield. The results are strategic for water and energy resources management actions, subsidizing future hydrological projections, and sustainable actions.

This study sought to answer the question: Does climate change affect water yield and groundwater storage in the main headwater basins of Minas Gerais state? If so, at what rate of change? Moreover, are these changes taking place in all the regions? To this end, climatic and hydrological data from four headwater regions in Minas Gerais state were analyzed to estimate groundwater storage and its temporal behavior.

Materials and Methods

Study area

The study area covers sub-basins located in the state of Minas Gerais, Brazil. Minas Gerais is home to national rivers, such as the São Francisco River basin, which drains much of the state's area toward the Brazilian northeast region. In addition to the São Francisco River, the Pará, Paraopeba, das Velhas, Paracatu, and Verde Grande Rivers form this basin in Minas Gerais (Melo et al. 2023). The Mantiqueira Range is home to the headwaters of the Grande and Sapucai Rivers, which form the Paraná River basin and have one of the most remarkable hydropower potentials in the country (Bueno et al., 2020). Doce River basin drains towards the east of Minas Gerais state and Espirito Santo and is the main basin located entirely in southeast Brazil. Espinhaço Range in the middle-to-north of Minas Gerais state encompasses the headwater of the Jequitinhonha River basin, the essential water source for a large part of the Minas Gerais and Espirito Santo states, and it is partially under the influence of a semi-arid climate.

Studied basins

The studied basins were the Grande, São Francisco, Doce, and Jequitinhonha (Figure 1). The least anthropized sub-basins typically are in the headwater regions, in line with the pristine aspect. However, even in the headwater region, anthropized areas exist, mainly in the Grande, Sapucaí, and São Francisco basins. Then, two sub-basins were selected in the headwater regions of these basins (Figure 1), aiming to minimize the effects of changes in land use (pasture instead of native vegetation in most of the situations) in the analysis.

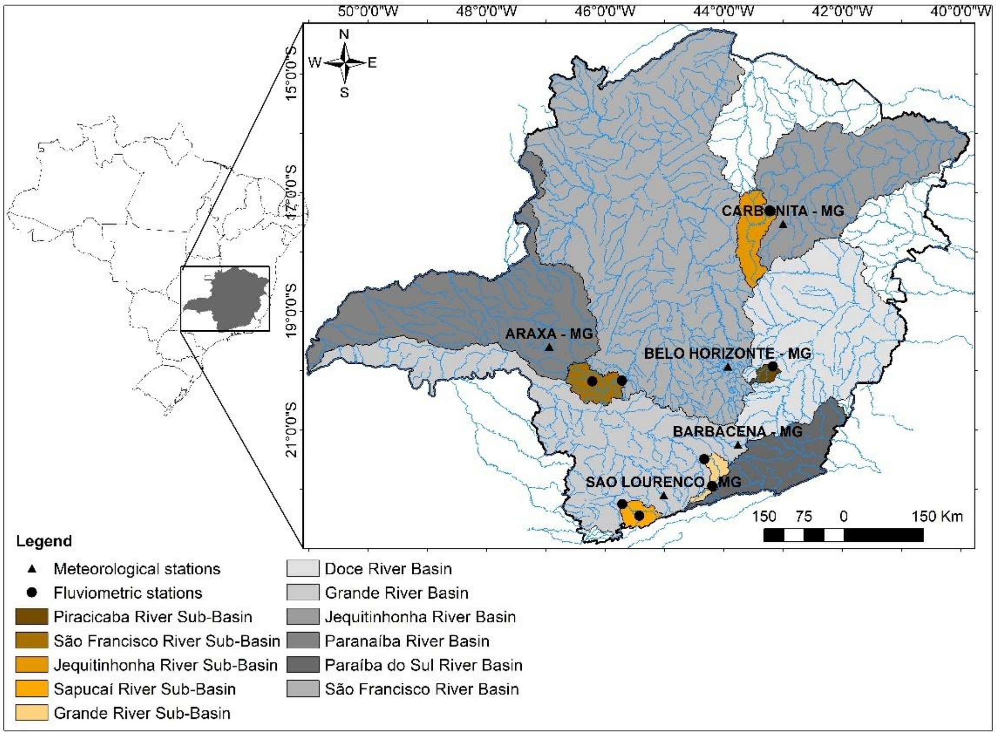

Figure 1. Basins, sub-basins, geographical locations, the respective fluviometric sections, and meteorological stations with the respective historical series.

Datasets

The daily streamflow historical series was obtained from the HidroWeb portal of the National Water Agency (ANA). Table 1 presents the station code, respective names, river, basins, monitoring period, and sub-basin drainage areas.

Table 1. Fluviometric stations of the sub-basins studied (Station and Name), respective basins, start and end of the series, and drainage area.

ID	Station	Name	Sub-Basin/Basin	Starting (dd/mm/yyyy)	Ending	Area (km^2)
2	61012000	Madre de Deus	Grande/Grande	01/01/1981	31/12/2020	2070
	61009000	Bom Jardim de Minas	Grande/Grande	01/01/1981	31/12/2020	529
5	61305000	Santa Rita do Sapucaí	Sapucai/Grande	01/01/1981	31/12/2020	2810
	61271000	Itajubá	Sapucai/Grande	01/01/1981	31/12/2020	869
12	40050000	Iguatama	S.Francisco/S. Francisco	01/01/1981	31/12/2020	5560
	40037000	Fazenda da Barra	S.Francisco/S. Francisco	01/01/1981	31/12/2020	757
17	54010005	Vila Terra Branca	Jequitinhonha/Jequitinhonha	01/01/1981	31/12/2020	7720
20	56610000	Rio Piracicaba	Piracicaba/Doce	01/01/1981	31/12/2020	1160

Table 2. Meteorological stations nearest to the sub-basins studied (Station and Name), respective basins, start and end of the respective series.

Station	Name	Sub-Basin/Basin	Starting (dd/mm/yyyy)	Ending
83689	Barbacena	Grande/Grande	01/01/1981	31/12/2020
83736	São Lourenço	Sapucaí/Grande	01/01/1981	31/12/2020
83579	Araxá	S.Francisco/S. Francisco	01/01/1981	31/12/2020
83485	Carbonita	Jequitinhonha/Jequitinhonha	01/01/1981	31/12/2020
83587	Belo Horizonte	Piracicaba/Doce	01/01/1981	31/12/2020

Rainfall and temperature datasets were obtained from the meteorological stations nearest to the sub-basins (Table 2) in the BDMEP portal of the National Meteorological Institute (INMET).

The gaps in the annual rainfall series were filled using linear regression between the data from the station with gaps and the data from the nearest station. For streamflow, we found gaps mainly for the Grande River basin. However, most of the gaps were found in the rain period, which did not affect the $Q_{7\ min}$ series. For mean annual streamflow, we screened the results of the hydrological simulation conducted by Viola et al. (2015) for the studied basins to fill the gaps. After that, we calculated the mean average streamflow for the respective year, comparing it against the observed in the historical series; we also assessed the annual water balance coherence of the filled years, comparing with the other years.

Given the many gaps in the meteorological datasets, i.e., data for calculating potential evapotranspiration using the Penman-Monteith model are unavailable, as well as for evaporimeters, we adopted the Thornthwaite method, which is based on temperature datasets that have fewer gaps.

Land use, soils, and hydrogeological maps

The land use maps were derived from the MAPBIOMAS platform for the Brazilian territory (Figure 1S - supplementary). The soil maps were derived from the Minas Gerais State (Figure 2S - supplementary) (CETEC, FEAM, UFV, UFLA, 2010), and the hydrogeological maps (Figure 3S - supplementary) were adapted from the CPRM.

There are significant anthropized areas in the Grande River sub-basin at Madre de Deus de Minas fluviometric section, predominantly pasture replacing Atlantic Forest, demonstrating that the pristine characteristic can not be applied to a large part of this sub-basin. Thus, another upstream section, Bom Jardim de Minas, was chosen to reduce the anthropized area, where a wider domain of the Atlantic Forest and rupestrian fields have been observed. In the Grande River sub-basin, there is a predominance of Haplic Cambisol, Humic Cambisol, Yellow and Red-Yellow Latosols, and Litholic Neosol. The basin's hydrogeology is almost entirely characterized as an undifferentiated basement stratigraphic unit formed by quartzite, migmatite, marble, and metapelitic.

In the Sapucaí River sub-basin (Grande River basin), an upstream section (Itajubá) was also considered, where most of the original land cover is still present. The predominant soil classes are Red Argisol, Red-Yellow Argisol, Haplic Cambisol, and Red Yellow Latosol. Since the Sapucaí River sub-basin is located in the Grande River basin, it is also characterized by an undifferentiated basement stratigraphic unit.

The São Francisco River sub-basin at the Iguatama fluviometric station has areas with native land cover, notably the savannah (Brazilian Cerrado). However, it is the most anthropized hydrological unit due to the deforestation of the savannah for pasture occupation. Therefore, another upstream section was used, delineated in the Fazenda da Barra fluviometric section. The predominant soil classes are the Haplic Cambisol, Litholic Neosol, Red Latosol, Red-Yellow Latosol, and Red-Yellow Argisol. Most of the sub-basin is located in the Serra da Saudade formation, Canastra group, and undifferentiated basement, whose lithology is composed of siltstone, mudstone, quartzite, phyllite, marble, metapelitic, among others.

The Jequitinhonha River sub-basin delimited in this study shows very little anthropization. This sub-basin is mainly covered by savannah and Atlantic Forest and is the closest hydrological unit to the pristine aspect. Regarding the soil classes, the rocky outcrops domain of the Jequitinhonha River sub-basin landscape, with Red Latosol and Haplic Cambisol occupying small areas. The sub-basin is laid on the Macaubas Group and Spinaço Supergroup stratigraphic units, where the lithology is composed mainly of quartzite, schist, and meta conglomerate.

The Piracicaba River sub-basin (headwaters of the Doce River basin) is primarily forested but has a large anthropized area characterized by pasture and silviculture. Red Yellow Latosol takes place as the main soil class, although there are areas of Haplic Cambisol and rocky outcrop. Regarding its hydrogeology, this sub-basin is laid mainly in the undifferentiated basement stratigraphic unit, formed by migmatite, marble, and metapelitic rocks.

Methods

Anthropic Transformation Index (ATI)

Because of the anthropization observed in the sub-basins, the Anthropic Transformation Index (ATI) was applied to classify the degree of anthropization and how close they are to the pristine condition. This index was developed by Lémechev (1982) and quantifies anthropogenic pressure on environmental protection areas, watersheds, parks, and other possibilities (Gouveia et al. 2013). It is calculated as follows:

$$ATI = \sum(\%usexweight)/100 \qquad (1)$$

Where "use" is the area (%) of the land use; "weight" is the weight attributed to the land uses according to the anthropogenic alterations, ranging from 0 to 10. Cruz et al. (1998) proposed the following classification: 0 – 2.5: little degraded; 2.5 – 5.0: regular; 5.0 – 7.5: degraded; 7.5 – 10.0: Very degraded.

The weight of each land cover/land use should be assigned based on knowledge of the anthropogenic impacts in the sub-basin (Mateo, 1984). The weights of the different anthropogenic pressures are in Table 3 and were assigned according to the land cover impacts on the environment. Thus, the lowest weight (0) was given to native forests, savannahs, and rupestrian fields with no anthropogenic intervention. A weight of 1 was given to rivers and lakes, as they can be affected by the water withdrawal by users. The highest weight (10) was assigned to urban and mining, as these are the most anthropized areas.

Table 3. Land uses and respective weights were adopted in this study for ATI characterizations.

Land use class	**Weight**
Forest, savannah, and rupestrian fields	0
Silviculture	3
Wetlands, rivers and lakes	1
Pasture	7
Mosaic of uses	8
Urbanization	10
Other non-vegetated areas	6
Rock outcrop	0
Mining	10
Annual and perennial crops	9

Groundwater storage estimating method (Brutsaert, 2008)

The Brutsaert method (Brutsaert, 2008) can be highlighted among the indirect methods for estimating groundwater storage (S) in sub-basins. Daily streamflow series are used to construct minimum streamflow series averaged over seven consecutive days ($Q_{7,\ min}$). Since S sustains baseflow in dry periods, it can be assessed using $Q_{7,\ min}$. (Lin and Yeh, 2017). These streamflows can demonstrate trends linked to S over time, making it possible to assess climate change effects, especially for less anthropized basins (Brutsaert, 2008; 2012).

The fundamentals of this method are laid in the physical aspects of S and its connectivity with the basin geomorphology, detailed in Brutsaert (2008). A mathematical potential equation can estimate S as a function of a baseflow discharge (Brutsaert, 2008; Rupp and Selker, 2006):

$$S = K \times y \tag{2}$$

Where S is the groundwater storage (in mm); y is the flow transformed to depth (mm/day) (y = Q/A, where A is the sub-basin area); K is a time parameter associated with the hydrogeological transmissivity characteristic of the basin (day). Brutsaert and Nieber (1977) developed a methodology for analyzing the temporal behavior of S based on baseflow rates by deriving equation 2, i.e.:

$$\frac{dS}{dt} = K \cdot \frac{dy}{dt} \qquad (3)$$

To assess the S temporal behavior, Brutsaert (2008) suggests applying $Q_{7,\,min}$:

$$\frac{dS}{dt} = K \cdot \frac{dy_{7,min}}{dt} \qquad (4)$$

For the K parameter estimate, we work with equation 4, developing a log-log graph of -dy/dt and y:

$$\frac{dy}{dt} = -\frac{(y_{i-1} - y_{i+1})}{2} \qquad (5)$$

However, to construct this graph, Brutsaert (2008) required a protocol so that streamflow observations used in the analysis must be essentially groundwater flows, i.e., without the effect of precipitation or direct surface runoff. The method's protocol is:

- Eliminate all positive values and zeros of dy/dt.

- Eliminate anomalous values of -dy/dt that may suddenly appear and the four values following their occurrence.

- Eliminate the three data points following the last positive or zero value of dy/dt.

- Eliminate the two data points preceding the first positive or zero value occurrence.

- The enveloping line should be drawn above the 5% smallest values.

This procedure results in a cloud of points from which K is the angular coefficient of the 5% smallest values enveloping by a line. Using the parameter K and the annual minimum seven-day streamflow ($Q_{7,\,min}$) series, the annual minimum groundwater storage is calculated using equation 2.

Temporal behavior of hydrological and climatic variables

The Mann-Kendall test (Mann, 1945; Kendall, 1975) using the R software was applied to detect possible trends in the historical series. Sen's test (Sen, 1968) was also applied to the series that showed a trend to characterize the rate at which the trend occurs.

The tests were applied to annual data on rainfall and evapotranspiration and average, maximum, and minimum temperatures. Trends were assessed in the historical series of mean annual streamflow, obtained from the historical series of daily streamflow, in the annual minimum streamflow of seven consecutive days ($Q_{7,\ min}$), and the annual S historical series.

RESULTS AND DISCUSSION

Land use and anthropization in the sub-basins

Table 2 shows the results of the Anthropic Transformation Index (ATI) in the sub-basins. The Jequitinhonha sub-basin is the least anthropized, has the lowest ATI, and is classified as little degraded. The other basins were classified as regular or degraded, with the São Francisco River being the most degraded.

Table 4. Anthropogenic Transformation Index (ATI) for the study sub-basins in Minas Gerais state.

Basin	River/Sub-basin	ATI	Classification
Grande	Grande/Madre de Deus	3.88	Regular
	Grande/Bom Jardim	3.13	Regular
Jequitinhonha	Jequitinhonha/Vila Terra Branca	1.01	Little degraded
Doce	Piracicaba/Piracicaba	3.56	Regular
São Francisco	São Francisco/Iguatama	5.62	Degraded
	São Francisco/Fazenda da Barra	4.69	Regular
Grande	Sapucaí/Santa Rita do Sapucaí	5.10	Degraded
	Sapucaí/Itajubá	3.42	Regular

Temporal behavior of climatic variables

Figure 2 shows the temporal behavior of the mean maximum, mean annual, and mean minimum annual temperatures observed at the weather stations closest to the sub-basins (Figure 1). Also, the maps present the trends from the Mann-Kendall test and the classes for the Sen coefficient for the respective historical series. An upward trend in the three temperatures occurred approximately from the mid-1980s onwards, especially mean maximum temperatures.

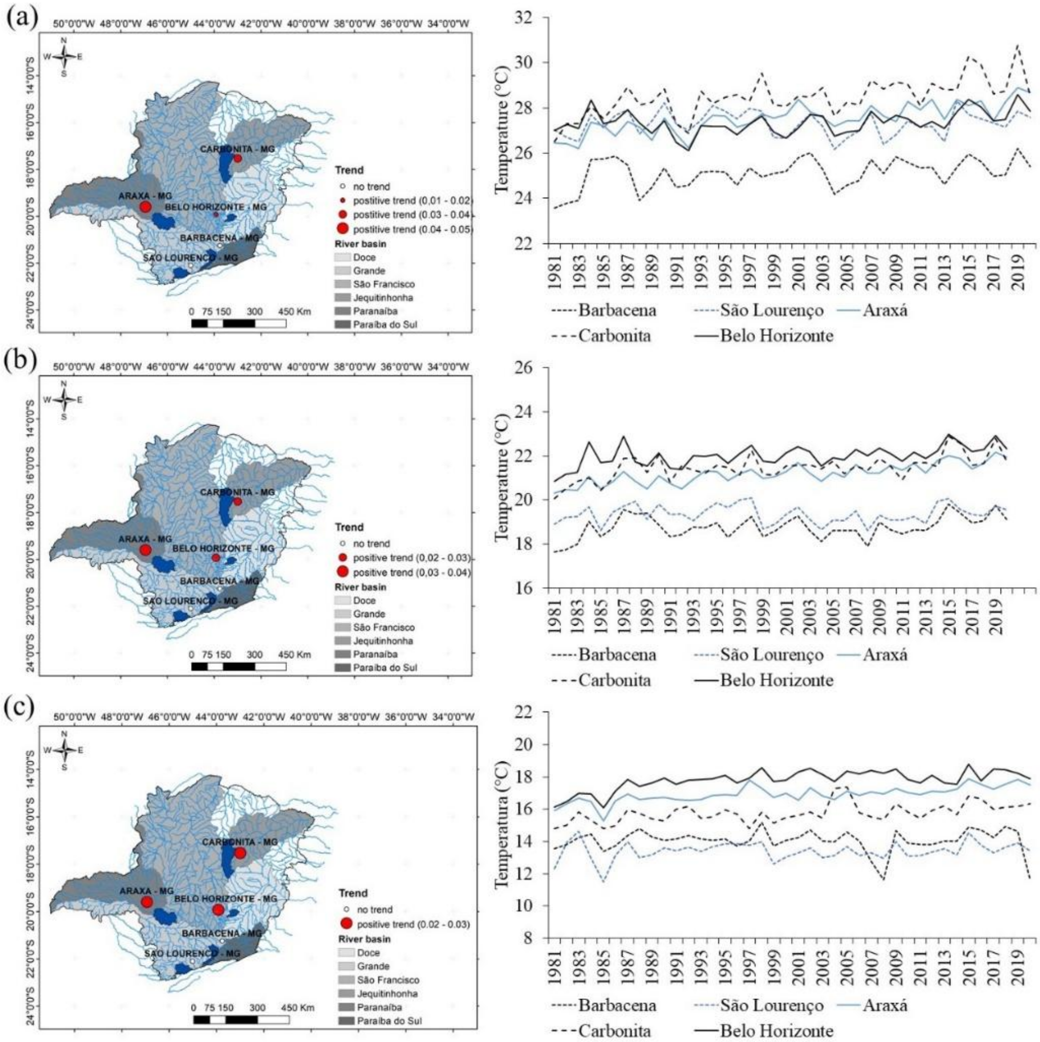

Figure 2. Temporal behavior and the Mann-Kendall test for the mean maximum annual temperature (a), mean annual temperature (b), and mean minimum annual temperature (c) in the Grande, Sapucaí, São Francisco, Jequitinhonha, and Piracicaba sub-basins. Units in °C/year.

Table 5 shows the results of Sen's test for the series that demonstrated a probability of rejecting the null hypothesis at a significance level of 5% in the Mann-Kendall test.

Table 5. Sen's test for the maximum annual temperature, mean annual temperature, and minimum annual temperature in the Grande, Sapucaí, São Francisco, Jequitinhonha, and Piracicaba sub-basins (ºC/year).

Station	**Name**	**River/Basin**	**Sen's coefficient**		
			Temperature		
			Maximum	**Mean**	**Minimum**
83689	Barbacena	Grande/Grande	-	-	-
83736	São Lourenço	Sapucaí/Grande	-	-	-
83579	Araxá	S.Francisco/S. Francisco	0.043	0.033	0.027
83485	Carbonita	Jequitinhonha/Jequitinhonha	0.038	0.024	0.025
83587	Belo Horizonte	Piracicaba/Doce	0.016	0.025	0.029

The stations near the São Francisco sub-basin, the Jequitinhonha sub-basin, and the Piracicaba sub-basin showed an upward trend in mean maximum temperature, mean annual temperature, and mean minimum temperature. The highest rates of increase in maximum and annual mean temperature were observed in the São Francisco sub-basin (Araxá station) (0.043°/year and 0.033°/year, respectively). The greatest anthropization observed in this sub-basin (pasture instead of savannah) could also lead to increased temperatures, not only the changing climate, i.e., there is a local effect on the temperature caused by changes in the albedo of the sub-basin, absorbing more heat with a greater soil exposition. We observed the highest rate of increase in the mean annual minimum temperature in the Piracicaba sub-basin (Belo Horizonte station), with a rate of 0.029°/year. In the case of the sub-basin, there is likely an overestimation of this temperature because we used the Belo Horizonte weather station, which is entirely in the urban area.

Ávila et al. (2014) evaluated temperature trends in Minas Gerais state using historical series up to 2010 and observed an upward trend in October and January. They also observed an upward trend of up to 1.5ºC per decade in minimum temperatures in July. In this study, mean annual and mean minimum temperatures showed upward trends between 0.03 - 0.04°C per year and maximum temperatures of 0.04 - 0.05°C per year at the stations with the most significant increase. The present study used data from 1961 to 2022 and detected similar increase rates as Ávila et al. (2014), i.e., between 0.03 and 0.05°C/year. It can, therefore, be seen that temperatures have been evolving in the Minas Gerais state in the last decades.

We did not observe significant trends in the annual precipitation from 1980 to 2020. However, we can observe a slight downward trend for the Sapucaí and the Jequitinhonha sub-basins (São Lourenço and Carbonita stations), meaning these sub-basins have received less rainfall (Figure 3). These slight trends were observed due to the climate behavior in Minas Gerais in the last ten years, characterized by increased temperatures and less precipitation, especially in summer (Silva et al., 2022; Silva and Mello, 2019). Oliveira et al. (2021) analyzed precipitation series in the Araçuaí River basin (MG), a sub-basin of the Jequitinhonha basin, and found downward trends in monthly precipitation from 1995 to 2011, even using a shorter historical series and not considering the last decade datasets. Therefore, we can highlight a possible decrease in the annual precipitation in the Jequitinhonha basin, which, combined with the increase in the temperature, can deeply affect the basin's hydrology.

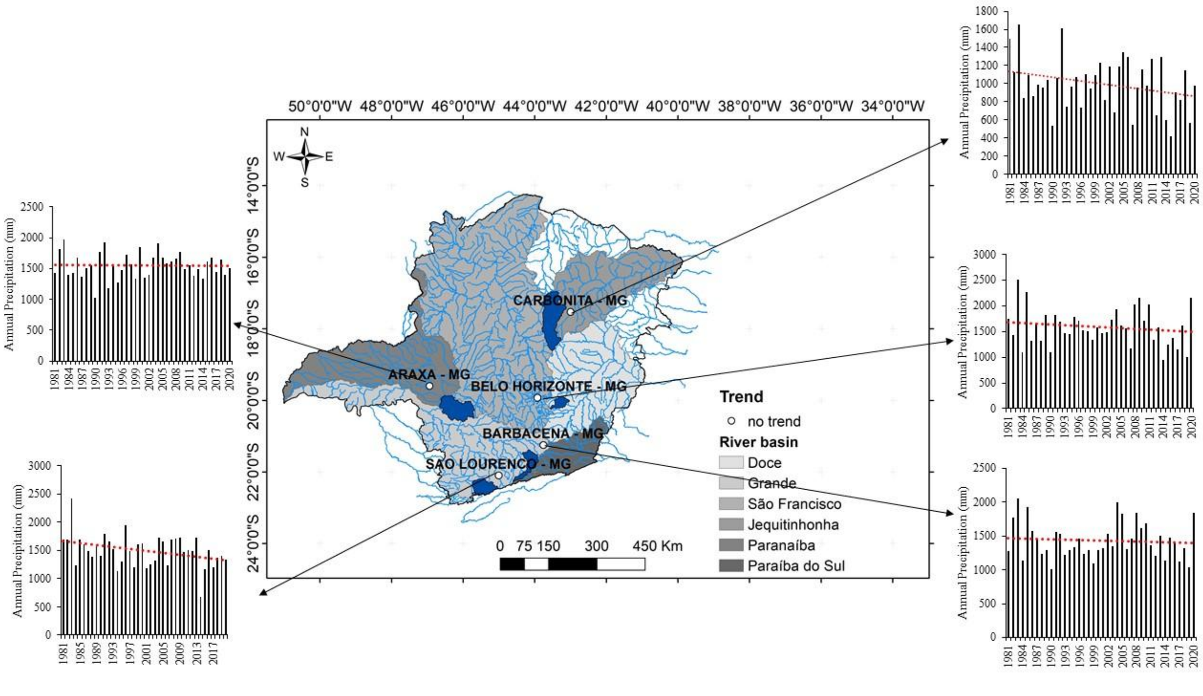

Figure 3. Temporal behavior of annual precipitation in the Grande, Sapucaí, São Francisco, Jequitinhonha, and Piracicaba sub-basins and the Mann-Kendal results. Units in mm/year.

Campos and Chaves (2020) carried out a study of trends in precipitation in the Cerrado (Savannah) biome from 1977 to 2010, where 71% of the stations showed a downward trend, of which 14% were statistically significant, and 28% showed an upward trend, of which only 1% was significant. The central and western regions showed the sharpest reductions in precipitation. In contrast, the regions comprising Minas Gerais, São Paulo, and Maranhão, which account for 17% of the Cerrado biome's area, showed increased precipitation. When analyzing the entire Cerrado region, the dry season months showed a downward trend in most of the series, demonstrating a possible intensification of the dry season in this region.

Since the Thornthwaite method depends only on temperature, evapotranspiration followed the same trend. The stations near the São Francisco, Piracicaba, and Jequitinhonha sub-basins (Araxá, Belo Horizonte, and Carbonita stations) showed an upward trend (Figure 4), more remarkable at the São Francisco sub-basin (2.39 mm/year) (Table 6). In the sub-basins towards the south of Minas Gerais, under the Mantiqueira Range domain, the potential evapotranspiration did not show a significant trend, which can indicate that the elevation has played an important role in buffering the increased temperature due to impacts of the climate. Based on annual precipitation and evapotranspiration behavior over time, Minas Gerais state has faced impacts from changing in climate from at least the 1990s, with intensification in the last ten years. Increased ET and decreased P are new patterns for the state and overall southeast Brazil, and they implicate reduced water availability (P – ET), which was seen in the Jequitinhonha basin.

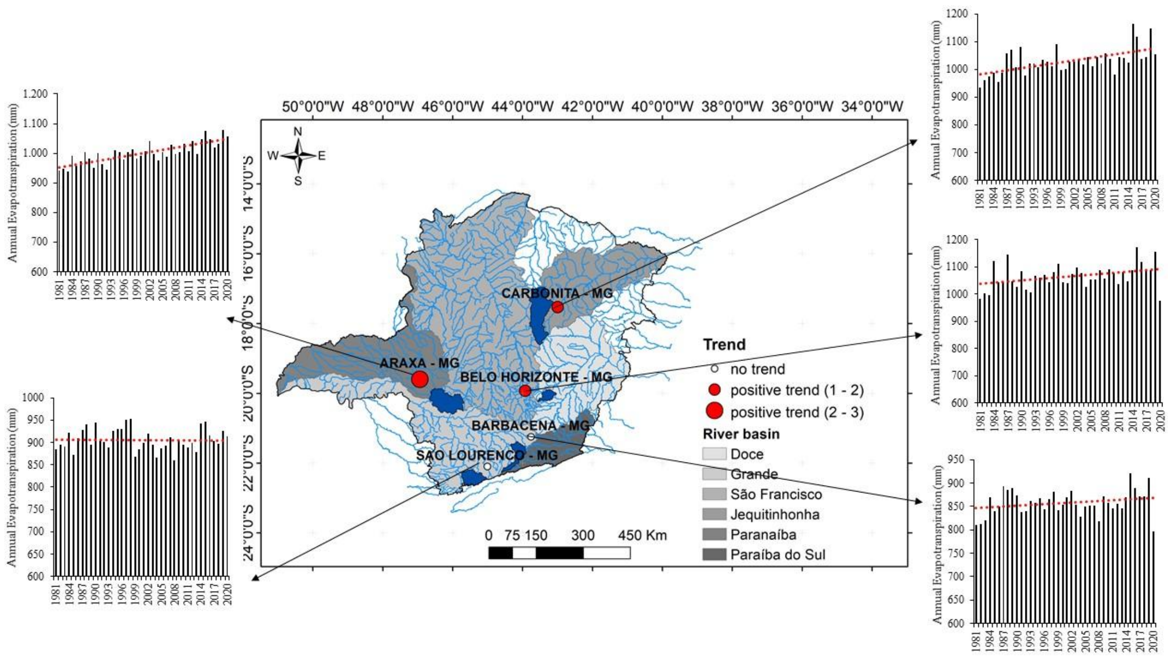

Figure 4. Annual potential evapotranspiration in Grande, Sapucaí, São Francisco, Jequitinhonha, and Piracicaba sub-basins and the Mann-Kendal test with the Sen's coefficient. Units in mm/year.

Table 6. Sen's test for the annual potential evapotranspiration in the Grande, Sapucaí, São Francisco, Jequitinhonha, and Piracicaba sub-basins.

Station	**Name**	**River/Basin**	**Sen's coefficient Potential evapotranspiration**
83689	Barbacena	Grande/Grande	-
83736	São Lourenço	Sapucaí/Grande	-
83579	Araxá	S.Francisco/S. Francisco	2.39
83485	Carbonita	Jequitinhonha/Jequitinhonha	1.94
83587	Belo Horizonte	Piracicaba/Doce	1.55

Temporal behavior of the hydrological variables

This section presents the trend behavior of the mean annual streamflow and the mean minimum streamflow in seven consecutive days ($Q_{7, min}$) for the headwater sub-basins studied in Minas Gerais. According to the results of the Mann-Kendall test (Figure 5), in the Jequitinhonha, Grande, Sapucaí, and Piracicaba sub-basins, a significant downward trend was observed, which magnitude was more significant in the Jequitinhonha sub-basin (1.05 m^3/s/year) (Table 7). Jequitinhonha has the lowest ATI and is, therefore, the least anthropized, which indicates that this reduction in mean annual streamflow is linked to alterations in climate. However, a slight downward can be seen in the São Francisco sub-basin (Iguatama station), likely due to the significant increase in ET.

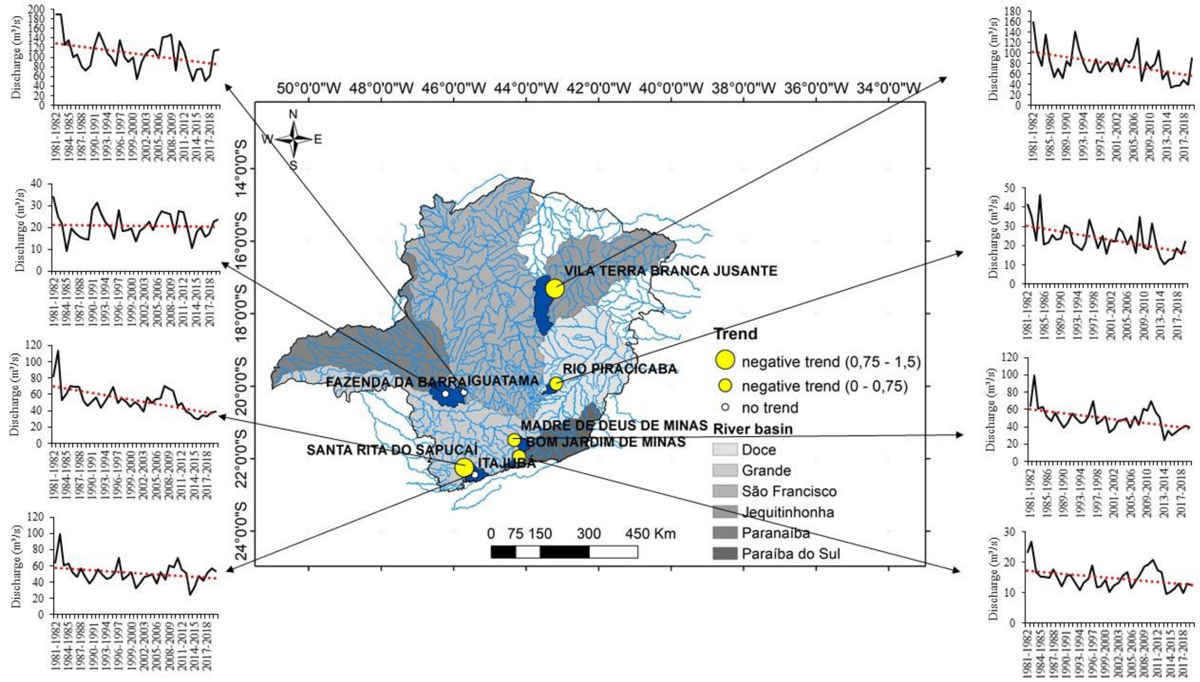

Figure 5. Mean annual daily streamflow at Madre de Deus, Bom Jardim de Minas, Santa Rita do Sapucaí, Itajubá, Iguatama, Fazenda da Barra, Vila Terra Branca, and Piracicaba and the Mann-Kendall test with Sen's coefficient for the sub-basins. Units in m³/s/year.

Table 7. Sen’s test for the mean annual daily streamflow in Madre de Deus, Bom Jardim de Minas, Santa Rita do Sapucaí, Itajubá, Iguatama, Fazenda da Barra, Vila Terra Branca, and Piracicaba sub-basins.

Station	**Name**	**River/Basin**	**Sen’s coefficient Streamflow**
61012000	Madre de Deus	Grande/Grande	-0.5
61009000	Bom Jardim de Minas	Grande/Grande	-0.1
61305000	Santa Rita do Sapucaí	Sapucai/Grande	-0.78
61271000	Itajubá	Sapucai/Grande	-
40050000	Iguatama	S.Francisco/S. Francisco	-
40037000	Fazenda da Barra	S.Francisco/S. Francisco	-
54010005	Vila Terra Branca	Jequitinhonha/Jequitinhonha	-1.05
56610000	Rio Piracicaba	Piracicaba/Doce	-0.32

Souza and Reis (2022) conducted a streamflow trend study in Brazil's main basins. They found positive trends in the mean annual streamflow of the stations in south Brazil and negative trends in almost all Brazilian regions except Amazonia, for which a characteristic pattern was not identified. In addition, trends of intensification of the extremes were observed, which were more significant in the northeast and south. The Jequitinhonha sub-basin is in a region of Minas Gerais that keeps similarities with the northeast Brazilian region, i.e., drier climate and a higher vulnerability to climate change, with a trend to desertification (Tomazella et al. 2018).

Melo et al. (2023) found evidence of a streamflow reduction in all the São Francisco River physiographic regions. There was no pattern of changes in the mean annual precipitation, but an increase was observed in the temperature and evapotranspiration in all regions. According to the author, this region's warmer and drier climate is probably associated with climate change and was the determining factor for the observed reduction in streamflow in upper São Francisco. In the lower and middle São Francisco basin, anthropogenic activities have a more significant influence. Milliman et al. (2008) found a reduction of approximately 20% in the mean annual streamflow of the São Francisco basin between 1951 and 2000 due to climate change at a regional scale and anthropogenic activities. However, differing from the cited studies, the São Francisco sub-basins did not present a downward trend in the mean annual streamflow because we studied the sub-basins in the headwater, where the impacts of a warmer and drier climate have been less significant than in sub-basins in downstream side, towards to north of the state.

According to the Mann-Kendall Test, all the sub-basins showed a downward trend to the $Q_{7,\,min}$ (Figure 6). The most significant reduction was observed in the Sapucaí sub-basin (0.43 $m^3/s/year$) (Table 8), showing that this sub-basin is under intense hydrological stress due to a significant decrease in P since ETp is not significant for the region of this basin, which means changes in climate have been affected Mantiqueira Range notably by a consistent reduction in precipitation.

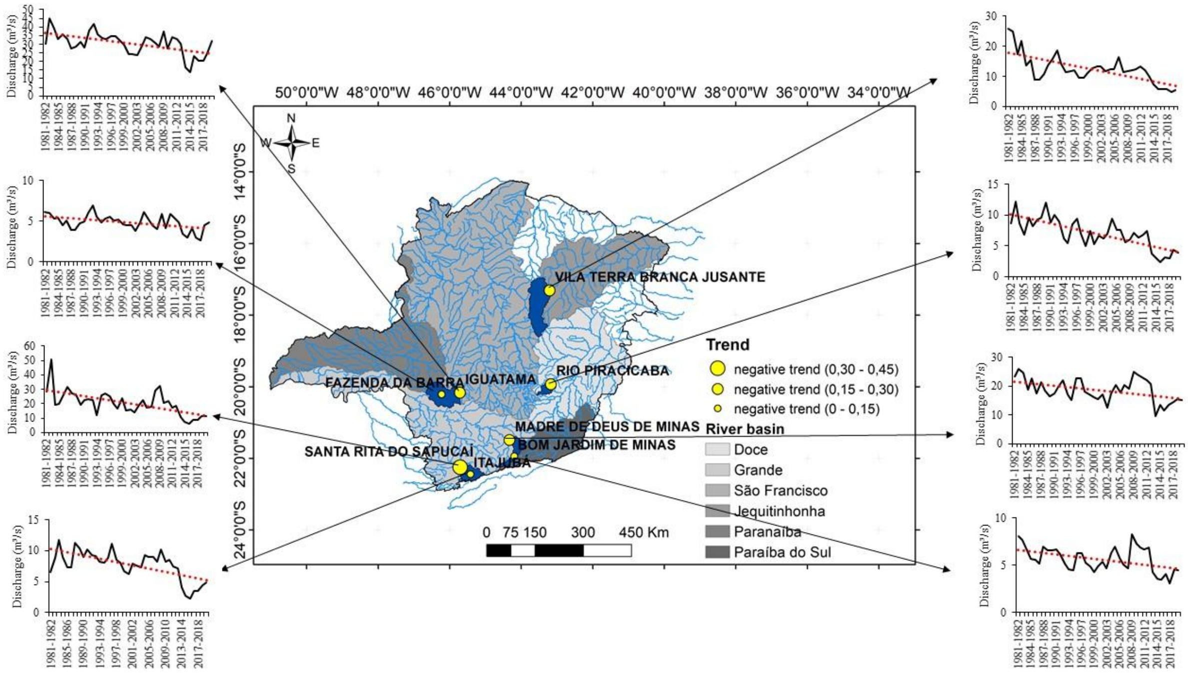

Figure 6. Minimum annual streamflow ($Q_{7,\,min}$) in Madre de Deus de Minas, Bom Jardim de Minas, Santa Rita do Sapucaí, Itajubá, Iguatama, Fazenda da Barra, Vila terra Branca, and Piracicaba sub-basins, in addition to the Sen's coefficient trend classes for the $Q_{7,\,min}$ in the studied sub-basins. Units in m³/s/year.

Table 8. Sen’s test for the minimum annual streamflow ($Q_{7,\,min}$) in Madre de Deus, Bom Jardim de Minas, Santa Rita do Sapucaí, Itajubá, Iguatama, Fazenda da Barra, Vila Terra Branca, and Piracicaba sub-basins.

Station	**Name**	**River/Basin**	**Sen’s coefficient Streamflow**
61012000	Madre de Deus	Grande/Grande	-0.15
61009000	Bom Jardim de Minas	Grande/Grande	-0.06
61305000	Santa Rita do Sapucaí	Sapucai/Grande	-0.43
61271000	Itajubá	Sapucai/Grande	-0.13
40050000	Iguatama	S.Francisco/S. Francisco	-0.28
40037000	Fazenda da Barra	S.Francisco/S. Francisco	-0.04
54010005	Vila Terra Branca	Jequitinhonha/Jequitinhonha	-0.25
56610000	Rio Piracicaba	Piracicaba/Doce	-0.15

The Piracicaba River sub-basin also showed a decrease in the $Q_{7, min}$ (0.15 m³/s/year). Campos (2022) analyzed the dynamics of environmental vulnerability in the Doce River basin, which covers part of the Minas Gerais and Espírito Santo states. They observed that 39 of the 45 stations analyzed showed negative trends in $Q_{7, min}$. Of the 12 stations in the headwater of Piranga River, eight showed decreasing trends in $Q_{7, min}$. However, most of the downward baseflow behavior in the Doce River basin and sub-basins is related to land use, i.e., this basin has been overwhelmed by anthropogenic actions since its headwater sub-basins. Intense recovery work is needed to face the additional impacts of climate change (Campos, 2022).

The Jequitinhonha sub-basin, where the reduction trend in $Q_{7, min}$ was observed (0.25 m³/s/year), is the least anthropized, allowing this negative trend to be related to climate change. As previously noted, temperatures generally increased in this sub-basin, i.e., there is a direct relationship between the water availability reduction and an increase in air temperature and a decrease in precipitation, which leads to a reduction in water availability in this sub-basin.

Groundwater storage temporal behavior

The K parameter is a time scale characteristic of the groundwater flow process in basins (Brutsaert, 2008), and is obtained using the daily $Q_{7,min}$ datasets of the entire period from the fluviometric station series. In the sub-basins of this study, the K parameter ranged from 30 to 50, with an average of 40 (40 ± 10), which is close to the values found in other studies (Table 9). In the original research of Brutsaert (Brutsaert, 2008) for basins in the United States, average values for the K parameter were found to be 45 ± 15 days. Gao et al. (2015) found an average value of 30 ± 15 days for basins in China. In a study in northern Thailand, Lin and Yeh (2017) obtained values between 34 and 84 days, averaging 54 ± 16 days.

Table 9. K parameter of the Brutsaert method, groundwater storage (S), mean annual precipitation (P), and S/P relation for the sub-basins.

Basin	**Station code**	**K (days)**	**S (mm)**	**P (mm)**	**S/P (%)**
Grande River	61012000	39.8	30.9	1433.5	2.2
	61009000	29.6	27.3		
Sapucaí River	61305000	49.1	30.8	1497.5	2.1
	61271000	36.6	28.1		
São Francisco River	40050000	35.4	19.2	1548.4	1.2
	40037000	41.9	23		
Jequitinhonha River	54010005	38.6	5.4	998.2	0.5
Piracicaba River	56610000	45.6	23.7	1584.5	1.5

Sanchéz-Murillo et al. (2015), also in basins in the United States, obtained an average value for K of 33 ± 15 days. In sub-basins with a predominance of basalt and flatter landscapes, K varied from 12.5 to 20 days, whereas it ranged from 33.3 to 66.7 days in sub-basins with metamorphic and sedimentary rocks. It can be observed that most of the sub-basins in the present study have a predominance of metamorphic rocks (Figure 3S - supplementary). There is also a large proportion of sedimentary rocks in the São Francisco sub-basin, which demonstrates the physical relationship between S and the hydrogeology of the basin.

The Sapucaí and Grande sub-basins present higher S, with the highest percentage of metamorphic and sedimentary rocks for the former sub-basin, and the relationship between the baseflow/sub-surface flow and the Atlantic Forest in the Mantiqueira Range in the later sub-basin the main causes for S behavior. Pinto et al. (2016) and Mello et al. (2019) showed that the Atlantic Forest in the Mantiqueira Range promotes improved water infiltration through preferential flows and a better soil structure because of organic matter accumulation over time. This is relevant because it is a geomorphological aspect that can help in the resilience of the headwater basins to climate change impacts on the hydrology, i.e., preserving the highland forests is a management strategy for buffering climate change impacts, reducing the effects of hydrological droughts.

The Jequitinhonha sub-basin encompasses mainly metamorphic rocks; however, it has a higher percentage of outcrop rocks that reduce the infiltration and groundwater storage. This sub-basin is highly vulnerable to climate change impacts on hydrology because its geomorphological aspects (shallow soils and poor aquifer properties) do not contribute to keeping water storage in the basin. This basin is fundamental for the economy and society of the northern Minas Gerais state, which has the lowest GPD of the state. Thus, environmental protection actions are urgent in this basin, starting with its headwater sub-basins.

In the present study, S ranged from 5.4 mm to 30.9 mm, representing 0.5% to 2.2% of annual precipitation. Grande and Sapucaí sub-basins showed the highest relation with P, meaning a higher efficiency in the groundwater recharge processes, as also pointed out by Mello et al. (2019) in an experimental water budget study in the Mantiqueira Range. Wendland et al. (2015), when studying the deep recharge of the Guarani Aquifer based on water balance in a representative watershed between February/2004 and January/2007, obtained values varying from 0.4% and 2.4%, i.e., values similar which were obtained using a more straightforward method.

We estimated the lowest S to the Jequitinhonha sub-basin, where the lowest precipitation and increased evapotranspiration were observed and a downward trend of -0.11 mm/year (Table 10), respectively. The Jequitinhonha sub-basin has shown a behavior compatible with impacts from climate change as the rates are smooth, which suggests impacts more related to climate change than anthropogenic actions that promote more acute changes. Jequitinhonha sub-basin has more fragile geomorphological aspects, i.e., despite its pristine character, it has low hydrological resilience caused by shallow soils, steep topography, and hydrogeology that is poor in terms of storage and slow transmissivity. Using GRACE satellite products, Vishwakarma et al. (2021) showed that the entire Jequitinhonha basin significantly reduced groundwater storage up to 2015, corresponding to -1.6 mm/year. Our study assessed groundwater storage only in the headwater region, showing a more minor decay. Therefore, this result strengthens our findings regarding groundwater storage and baseflow ($Q_{7, min}$) that this sub-basin is under hydrological stressors.

The groundwater storage trends are presented in Figure 7. A low S was estimated in the São Francisco sub-basin, similar to Jequitinhonha sub-basin, with a reduction trend of, respectively, 0.18 and 0.19 mm/year. São Francisco sub-basin showed a higher mean annual precipitation than Jequitinhonha, accompanied by a higher evapotranspiration trend, which demonstrates a greater influence of the land use in this sub-basin in the groundwater storage. The Sapucaí sub-basin and the Piracicaba sub-basin showed the highest value of S and P, respectively; however, these sub-basins showed the highest downward trends to S (0.66 and 0.46 mm/year and 0.54 mm/year, respectively), which also reflects a high anthropization in these sub-basins.

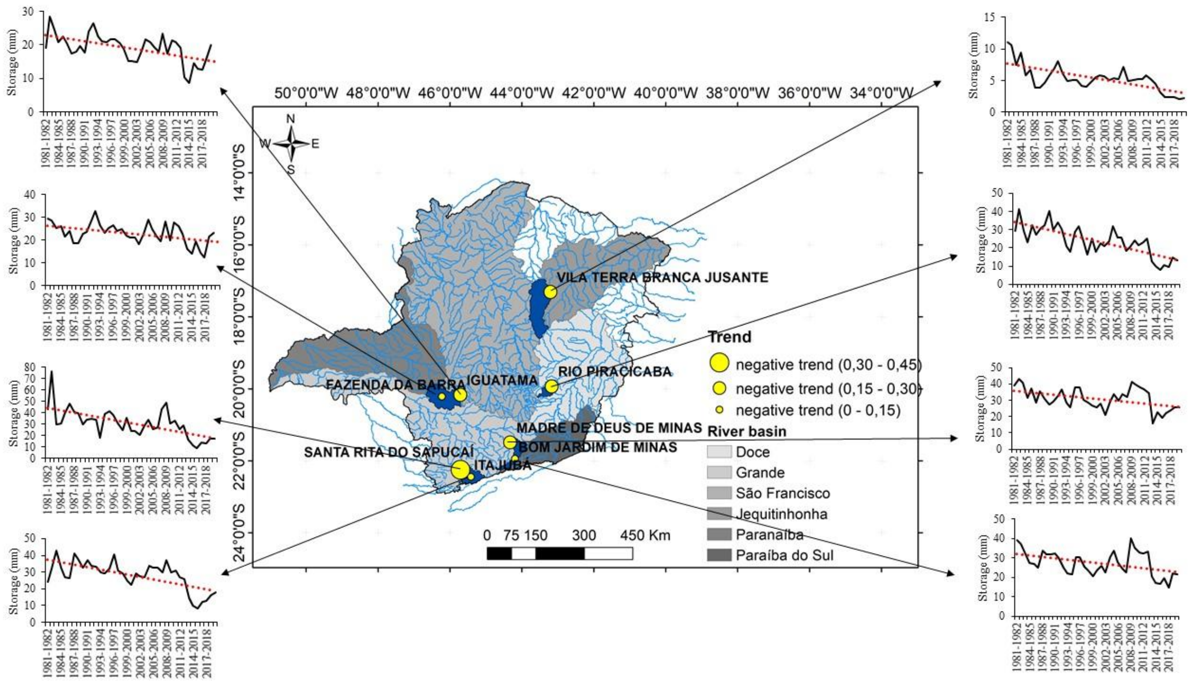

Figure 7. Groundwater storage in Madre de Deus de Minas, Santa Rita do Sapucaí, Iguatama, Vila Terra Branca, Piracicaba, Bom Jardim de Minas, Itajubá, and Fazenda da Barra, and trend of the Sen's coefficient for the groundwater storage in the sub-basins studied. Units in mm/year.

Table 10. Sen's test for the minimum annual groundwater storage in Madre de Deus, Bom Jardim de Minas, Santa Rita do Sapucaí, Itajubá, Iguatama, Fazenda da Barra, Vila Terra Branca, and Piracicaba sub-basins.

Station	**Name**	**River/Basin**	**Sen's coefficient Groundwater storage**
61012000	Madre de Deus	Grande/Grande	-
61009000	Bom Jardim de Minas	Grande/Grande	-0.28
61305000	Santa Rita do Sapucaí	Sapucai/Grande	-0.66
61271000	Itajubá	Sapucai/Grande	-0.46
40050000	Iguatama	S.Francisco/S. Francisco	-0.18
40037000	Fazenda da Barra	S.Francisco/S. Francisco	-0.19
54010005	Vila Terra Branca	Jequitinhonha/Jequitinhonha	-0.11
56610000	Rio Piracicaba	Piracicaba/Doce	-0.54

Lin and Yeh (2017), where groundwater storage was also obtained using the Brutsaert method in northern Thailand, estimated decreasing trends in annual S in five sub-basins, ranging from -0.053 to -0. 0950 mm/year, and increased trends in three sub-basins varied from 0.111 to 0.141 mm/year. Gao et al. (2015) developed a study in 38 basins on the Loess Plateau in China, and S was estimated from 1955 to 2010. Reduction trends were detected in 20 basins, with an average of -0.0299 mm/year, and in 10 basins, increasing trends were estimated with an average of 0.00467 mm/year. Liu et al. (2020), when analyzing S in the Yangtze River basin in China, found positive trends in 14 of the 19 sub-basins, with a maximum value of 2.53 mm/year.

Zhang et al. (2014) evaluated long-term trends in 17 basins in Australia and found negative rates in almost all basins over 45 years, with the highest rate being -0.241 mm/year. These trends persist over long periods (~ 100 years), but over shorter periods (one or two decades), they can change; thus, short periods can be inadequate to obtain significant signals on groundwater storage analyses, as large-scale climate phenomena, such as ENSO and the Pacific Decanal Oscillation, can impact the result, being fundamental long-term series.

Hydrological resilience of the sub-basins

The hydrological resilience of a basin concerns its ability to absorb change and maintain or quickly recover its hydrological function. Resilient basins present stability in water yield when faced with changes in environmental conditions, such as climate change and land use. In contrast, non-resilient basins can suffer changes in water yield in the face of these changes and spend much time recovering the baseflow (Lee and Ajami, 2023).

Analyzing the sub-basins that showed trends in climate, we observed upward trends in potential evapotranspiration and temperature, mainly in the São Francisco sub-basin. Regarding land use, the greatest anthropization has also been found in this sub-basin. Yet, the São Francisco sub-basins showed a nonsignificant trend in the mean annual streamflow. The lowest reduction rate in the mean annual streamflow (0.1 $m^3/s/year$) was observed in the Grande sub-basin (Bom Jardim station). In the São Francisco sub-basin (Fazenda da Barra station) and Grande sub-basin (Bom Jardim station) were found the lowest reduction rates in $Q_{7,\ min}$ (0.06 and 0.04 $m^3/s/year$, respectively). There are a few rocky outcrops in these sub-basins, and the predominant soil is the Cambisol (Figure 2S). Oxisols are also significant in these sub-basins, which can contribute to their resilience in the face of climate change impacts on the water resources, mainly baseflow. However, the critical factor for maintaining baseflow consists of the role of the Atlantic Forest (Grande River sub-basins) and Savannah (Brazilian Cerrado) (São Francisco sub-basins), which act to favor the water infiltration in the soils. Therefore, preserving these remnants is vital to minimize the impacts of climate change on the water security of these sub-basins, especially in developing a protocol of sustainable actions related to land use.

There was a nonsignificant trend in groundwater storage in the Grande River sub-basin (Madre de Deus station). This aspect indicates that this sub-basin can be resilient to climate change, which is associated with its geomorphological elements, particularly the existence of Oxisols, which are more resilient to water erosion and show a much higher infiltration capacity than the Cambisols (Pinto et al. 2016). It is relevant to highlight the differences between the two sub-basins of the Grande River. Bom Jardim de Minas station is characterized by the Atlantic Forest as the primary land use, whereas Madre de Deus (a downstream section) has been more affected by deforestation to implant agriculture, especially in the Oxisols and pasture in the Cambisols. Thus, the capacity for water yield in this sub-basin highly depends on the Atlantic Forest and Cambisol relationship (Pinto et al., 2016), showing less resilience than the later sub-basin.

In the Sapucaí sub-basin (Santa Rita station), the highest rates of reduction in the mean annual streamflow, $Q_{7, min,}$ and groundwater storage (S) were observed (0.78 and 0.43 m³/s/year, and 0.66 mm/year, respectively), and this sub-basin did not show significant trends in the climate variables. Thus, land use (predominantly pasture over the Atlantic Forest) is mainly responsible for these hydrological aspects, indicating a high vulnerability to droughts and low resilience to land-use changes. This sub-basin is also in the Mantiqueira Range and keeps the same aspects as the Grande River sub-basin in Bom Jardim de Minas station.

In the Jequitinhonha sub-basin, a trend of increase of 0.038°C/year in maximum temperature was observed. This sub-basin is closest to the pristine condition and showed downward trends in groundwater storage. This aspect demonstrates that its geomorphological conditions are insufficient to buffer climate change, characterizing a greater vulnerability. It was observed in this sub-basin that the terrain is predominantly occupied by rocky outcrops, which represent 43% of the sub-basin area, partially explaining the lower resilience of this sub-basin. Besides, its hydrogeology does not have the features of a productivity aquifer, i.e., storage and transmissivity, such as Schist, Quartzite, and Phyllite. As a result, the sub-basin hydrological conditions become more susceptible to climate fluctuations and, therefore, more vulnerable to climate change.

The Piracicaba sub-basin presented increasing trends in the average and minimum temperatures of, respectively, 0.02 and 0.03°/year, and an upward trend in potential evapotranspiration (1.55 mm/year, respectively). The Mann-Kendal test detected a downward trend in groundwater storage. Nevertheless, differing from Jequitinhonha, part of the reduction in baseflow occurs due to land use changes, i.e., making it difficult to attribute this hydrological behavior only to changes in the climate. Besides, this aspect demonstrates that its geomorphological conditions are not enough to buffer changes in climate and/or land use, like in the São Francisco and Grande sub-basins, characterizing a high hydrological vulnerability, such as strong undulated topography, hydrogeology formed by a lithology (Migmatite, Marble, and Metapelitic rocks) with small storage capacity, and low transmissivity.

Conclusions

Given the results, the headwater regions of the Minas Gerais state have shown increased temperature and evapotranspiration in the last decades, intensified in the previous decade. Changes in the annual precipitation were observed in three headwater regions of the state, proportioned by the climate in the last decade.

A reduction in the mean annual streamflow, minimum streamflow over seven consecutive days ($Q_{7,\ min}$), and groundwater storage were detected in the sub-basins. The downward trends in the Jequitinhonha River sub-basin can be associated with climate change as this sub-basin presents a clear pristine aspect. Sapucaí and Piracicaba sub-basins present a downward behavior in their hydrological variables that can also be attributed to the changes in land use. Both sub-basins present low hydrological resilience, mainly due to the land use.

Finally, it was concluded that climate change has contributed to decreased streamflow and groundwater storage, especially in less resilient sub-basins, due to geomorphological, soil, and hydrogeological aspects. This represents additional stressors to the sub-basins, and measures must be taken to preserve the natural resources in the headwater regions of the state.

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References

Alley, WM, Healy, RW, LaBaugh, JW, Reilly, TE (2002) Flow and storage in groundwater systems. Science, 296 (5575): 1985-1990.

Ávila LF, Mello CR, Yanagi SNM, Neto OBS (2014) Tendências de temperaturas mínimas e máximas do ar no Estado de Minas Gerais. Pesq Agropec Bras 49: 247-256.

Brutsaert, W. (2010) Annual drought flow and groundwater storage trends in the eastern half of the United States during the past two-third century. Theor Appl Climatol, 100 (1-2): 93- 523.

Brutsaert W (2008) Long-term groundwater storage trends estimated from streamflow records: climatic perspective. Water Resour Res 44: W02409.

Brutsaert W, Nieber JL (1977) Regionalized drought flow hydrographs from a mature glaciated plateau. Water Resour Res 13: 637–643.

Campos, JA (2022). Dinâmica da vulnerabilidade ambiental da bacia hidrográfica do Rio Doce como subsídio ao planejamento e gestão de recursos ambientais e hídricos. Dissertation, Universidade Federal de Viçosa, Viçosa (In Portuguese).

Campos JO, Chaves HML (2020). Tendências e Variabilidades nas Séries Históricas de Precipitação Mensal e Anual no Bioma Cerrado no Período 1977-2010. Rev Bras de Meteorol 35: 157-169.

CETEC, FEAM, UFV, UFLA, 2010. Mapa de solos do Estado de Minas Gerais, 1. In: Secretaria do Meio Ambiente e Desenvolvimento Sustentável. Fundação Estadual do Meio Ambiente - FEAM, Belo Horizonte.

Cunha ZA, Mello CR, Beskow S, Vargas MM, Guzman JA, Moura MM (2023) A Modeling Approach for Analyzing the Hydrological Impacts of the Agribusiness Land-Use Scenarios in an Amazon Basin. Land 12: 1422.

Gao Z, Zhang L, Cheng L, Zhang X, Cowan T, Cai W, Brutsaert W (2015) Groundwater storage trends in the Loess Plateau of China estimated from streamflow records. J Hydrol 530: 281–290.

Gouveia RGL, Galvanin EAS, Neves SMAS (2013) Aplicação do indíce de transformação antrópica na análise multitemporal da bacia do córrego do Bezerro Vermelho em Tangará da Serra-MT. *Rev Árvore* 37: 1045-1054.

Holman IP (2006) Climate Change Impacts on Ground-Water Recharge: Uncertainty, Shortcomings, and the Way Forward. Hydrogeol J 14: 637-647.

Huang P, Wang G, Guo L, Mello CR, Li K, Ma J, Sun S (2023) Most Global Gauging Stations Present Biased Estimations of Total Catchment Discharge. Geophys Res Lett 50: e2023GL104253.

Jiménez Cisneros, BE, Oki, T, Arnell, NW, Benito, G, Cogley, JG, Döll, P, Jiang, T, Mwakalila, SS (2014). Freshwater resources. In: Field, CB, Barros, VR, Dokken, DJ, Mach, KJ, Mastrandrea, MD, Bilir, TE, Chatterjee, M, Ebi, KL, Estrada, YO, Genova, RC, Girma, B, Kissel, ES, Levy, AN, MacCracken, S, Mastrandrea, PR, White, LL (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229–269.

Jones J, Creed IF, Hatcher KL, Warren RJ, Adams MB, Benson MH, Boose E, Brown WA, Campbell JL, Covich A, Clow DW, Dahm CN, Elder K, Ford CR, Grimm NB, Henshaw DL, Larson KL, Miles ES, Miles KM, Sebestyen SD, Spargo AT, Stone AB, Vose JM, Williams MW (2012) Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites. BioScience 62: 390–404. DOI:10.1525/bio.2012.62.4.10

Kendall M (1975) Multivariate Analysis. Charles Griffin & Company, London.

Kormos, PR, Luce, CH, Wenger, SJ, Berghuijs, WR (2016) Trends and sensitivities of low streamflow extremes to discharge timing and magnitude in Pacific Northwest mountain streams. Water Resour Res, 52(7): 4990-5007.

Lee S, Ajami H (2023) Comprehensive assessment of baseflow responses to long-term meteorological droughts across the United States. *J. Hydrol*, 626, 130256.

Lémechev T (1982) On hydrological heterogeneity catchment morphology and catchment response. *J. Hydrol* 100: 375-375.

Lin K, Yeh H (2017) Baseflow recession characterization and groundwater storage trends in northern Taiwan. Hydrol Res 48(6), 1745–1756.

Liu X, Liu C, Brutsaert W (2020) Mutual consistency of groundwater storage changes derived from GRACE and from baseflow recessions in the Central Yangtze River basin. J Geophys Res Atmos 125: e2019JD031467.

Mann HB (1945) Nonparametric tests against trend. Econometrica, 13: 245-259.

Mateo J (1984) Apuntes de Geografia de Los Paisajes. La Habana: Universitaria.

Mello CR, Ávila LF, Lin H, Terra MCNS, Chappell NA (2019) Water balance in a neotropical forest catchment of southeastern Brazil. Catena, 173: 9-21.

Melo LS, Costa V, Fernandes WS (2023) Assessing the Anthropogenic and Climatic Components in Runoff Changes of the São Francisco River Catchment. Water Resour Manag 37: 3615-3629.

Mendoza GF, Steenhuis TS, Walter MT, Parlange JY (2003). Estimating basin-wide hydraulic parameters of a semi-arid mountainous watershed by recession flow analysis. J. Hydrol., 279(1–4):57–69

Milliman JD, Farnsworth KL, Jones PD, Xu KH, Smith LC (2008) Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951-2000. Glob Planet Change 62: 187–194.

Mutzner, R, Bertuzzo, E, Tarolli, P, Weijs, SV, Nicotina, L, Ceola, S, Tomasic, N, Rodriguez-Iturbe, I, Parlange, MB, Rinaldo, A (2013). Geomorphic signatures on Brutsaert base flow recession analysis. Water Resour. Res., 49, 5462-5472.

Oliveira PHF, Vieira FR, Christofaro C, Rocha WW, Silva AC (2021) Alterações no regime de vazão e precipitação em trecho da Bacia do Rio Araçuaí, Minas Gerais: caminhamos para a escassez hídrica? *Rev Espinhaço*, 10(2).

Pinto LC, Mello CR, Norton LD, Owens PR, Curi N (2016) Spatial prediction of soil-water transmissivity based on fuzzy logic in a Brazilian headwater watershed. Catena 143: 26-34.

Regoto P, Dereczynski C, Chou SC, Bazzanela AC (2021) Observed changes in air temperature and precipitation extremes over Brazil. Int J Climatol 41: 5125-5142.

Sánchez-Murillo R, Brooks ES, Elliot WJ (2015) Baseflow recession analysis in the inland Pacific Northwest of the United States. Hydrogeol J 23: 287–303.

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63: 1379-1389.

Silva VO, Mello CR (2020) Meteorological droughts in part of southeastern Brazil: Understanding the last 100 years. An. Acad. Bras. Cienc. 93: e20201130 doi.org/10.1590/0001-3765202120201130

Silva VO, Mello CR, Chou SC (2022) Projections of severe droughts in future climate in Southeast Brazil: a case study in Southern Minas Gerais State, Brazil. Theor Appl Climatol 148: 1289 - 1302.

Souza SA, Reis Jr. DS (2022) Trend Detection in Annual Streamflow Extremes in Brazil. *Water,* 14: 1805.

Tomasella J, Vieira RMS, Barbosa AA, Rodriguez DA, Santana MO, Sestini MF (2018) Desertification trends in the Northeast of Brazil over the period 2000–2016. Int J Appl Earth Obs Geoinf 73: 197-206.

Viola, MR, Mello, CR, Chou, SC, Yanagi, SN, Gomes, JL (2015). Assessing climate change impacts on Upper Grande River Basin hydrology, Southeast Brazil. Int J Climatol, 35, 1054-1068.

Vishwakarma BD, Bates P, Sneeuw N, Westaway RM, Bamber JL (2021) Re-assessing global water storage trends from GRACE time series. Environ Res Lett 16: 034005.

Warku F, Korme T, Wedajo G, Nedow D (2022) Impacts of land use/cover change and climate variability on groundwater recharge for upper Gibe watershed, Ethiopia. Sustain Water Resour Manag, 8(2): 3-16.

Wendland E, Gomes LH, Troeger U (2015) Recharge contribution to the Guarani Aquifer System estimated from the water balance method in a representative watershed. An Acad Bras Cienc 87: 595-609.

Xiang, L, Wang, H, Steffen, H, Wu, P, Jia, L, Jiang, L. et al. (2016) Groundwater storage 693 changes in the Tibetan Plateau and adjacent areas revealed from GRACE satellite gravity 694 data. Earth Planet Scientific Letters, 449: 228-239.

Zhang L, Brutsaert W, Crosbie R, Potter N (2014) Long-term annual groundwater storage trends in Australian catchments. Adv Water Resour 74: 156–165.

Zhu R, Zheng H, Croke B, Jakeman A (2020). Quantifying climate contributions to changes in groundwater discharge for headwater catchments in a major Australian basin. Sci. Total Environ. 729, 138910

Supplementary material

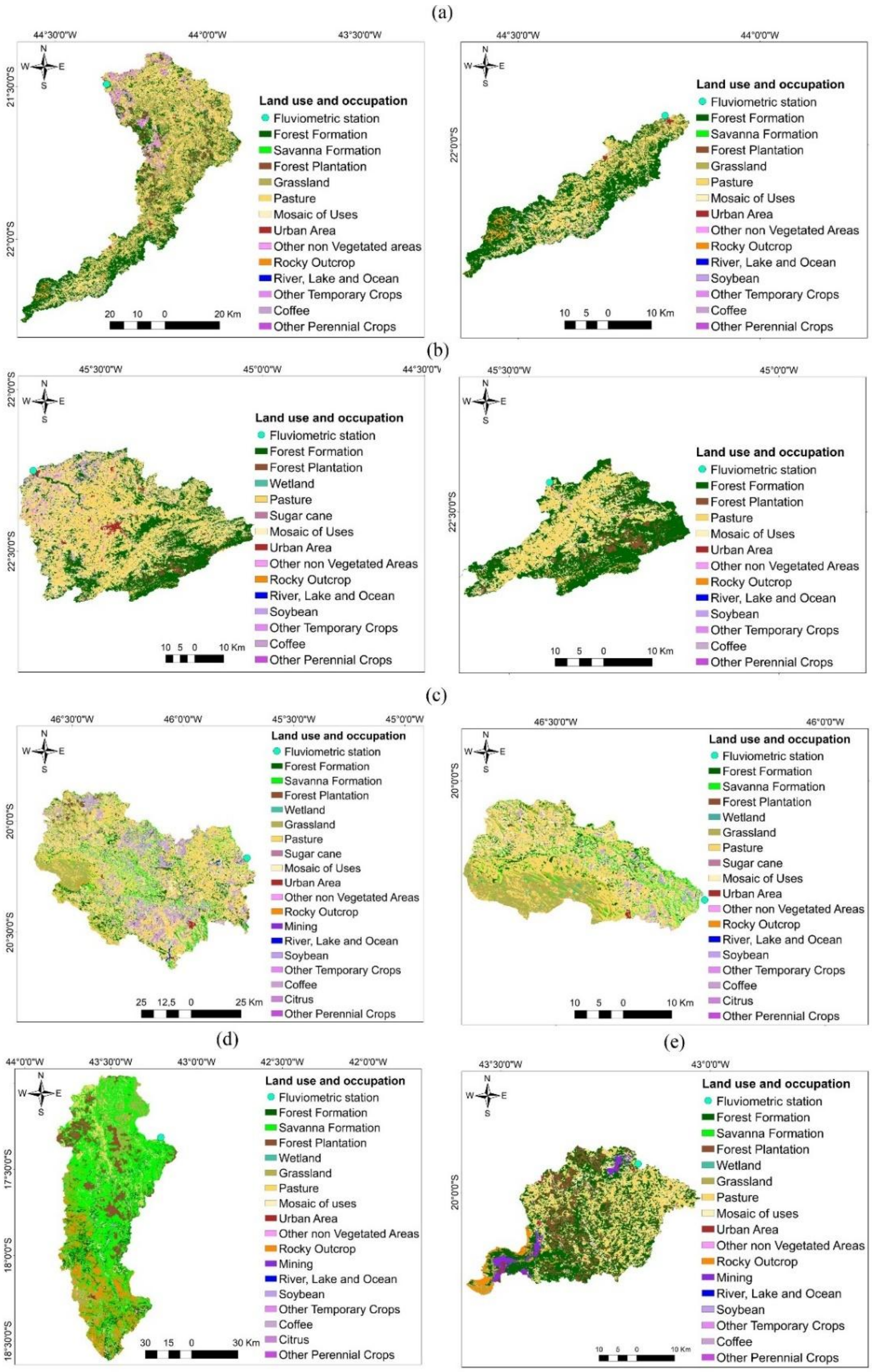

Figure 1S. Land use maps of the Grande (a), Sapucaí (b), São Francisco (c), Jequitinhonha (d), and Piracicaba (e) sub-basins.

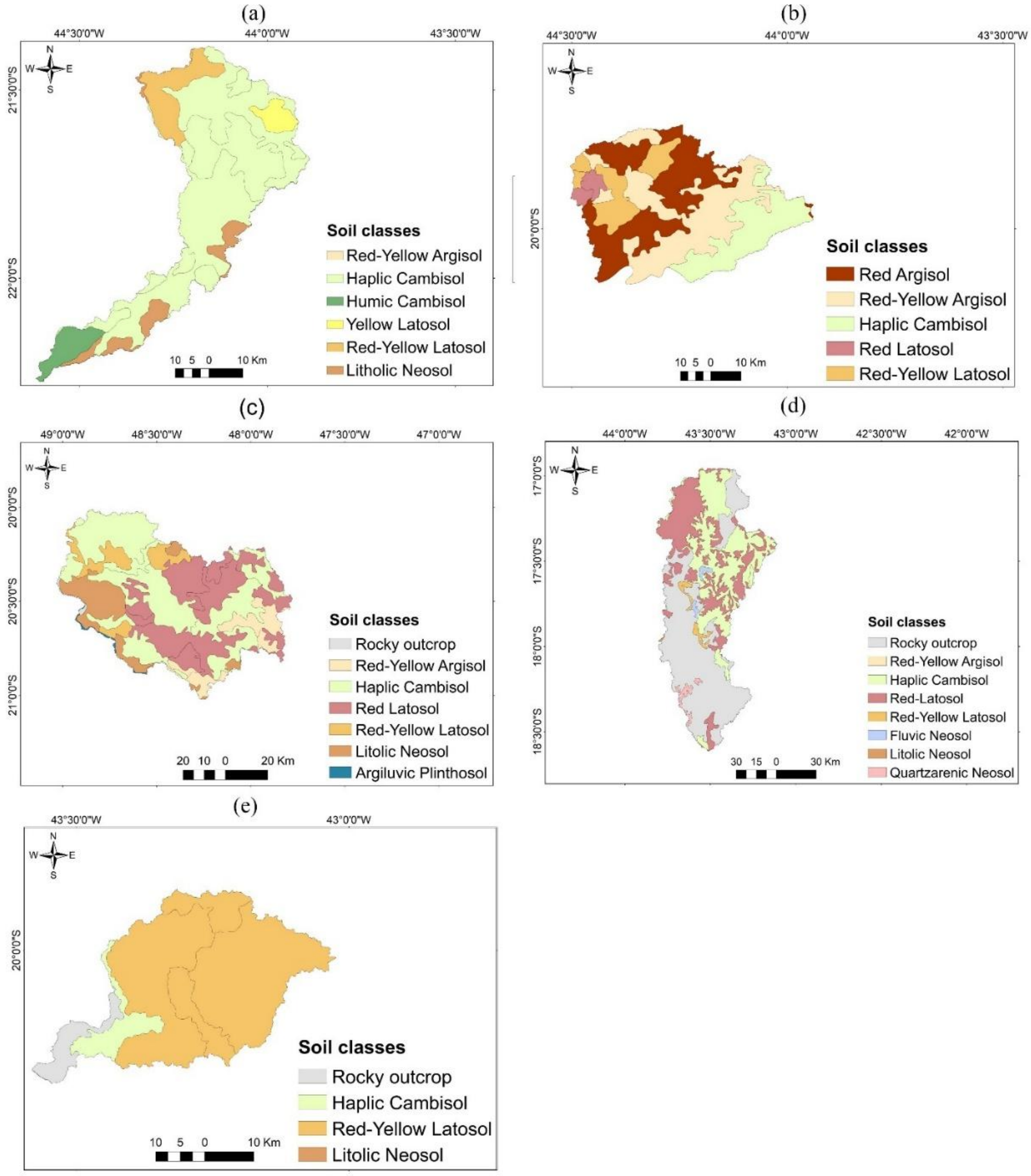

Figure 2S. Soil maps of the Grande (a), Sapucaí (b), São Francisco (c), Jequitinhonha (d), and Piracicaba (e) sub-basins.

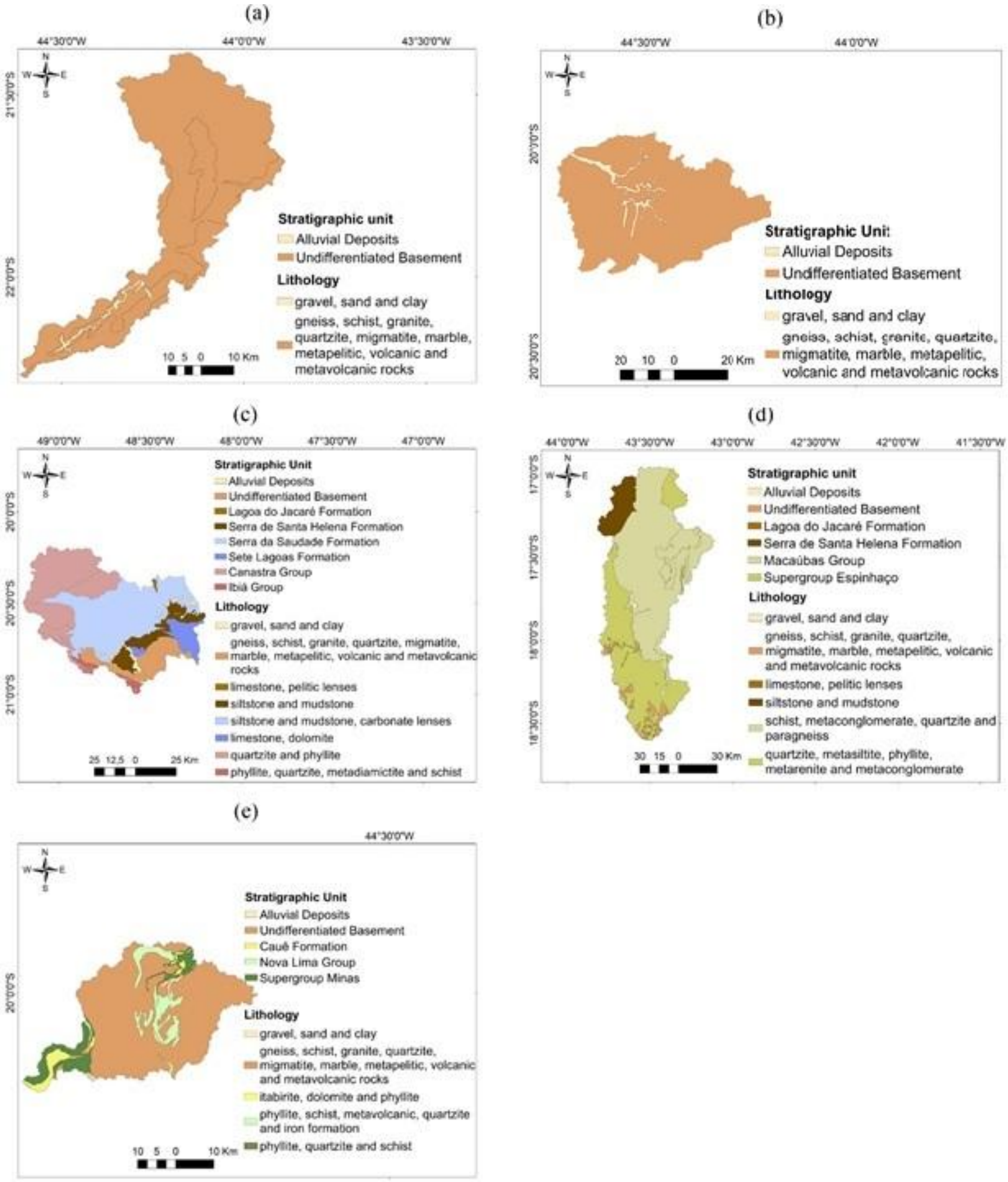

Figure 3S. Hydrogeological maps of the Grande (a), Sapucaí (b), São Francisco (c), Jequitinhonha (d), and Piracicaba (e) sub-basins.

'Statements and Declarations'

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Competing Interests
The authors have no relevant financial or non-financial interests to disclose.

Author Contributions
All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Camila Lucia Cardoso Ribeiro and Carlos Rogério de Mello. The first draft of the manuscript was written by Carlos Rogério de Mello and Jorge Alberto Guzman. All authors read and approved the final manuscript."

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Título do artigo	Groundwater storage projection in headwater basins under different climate conditions in Southeast Brazil
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Groundwater storage projection in headwater basins under different climate conditions in Southeast Brazil

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Area of focus: geological and water resources engineering

Abstract

Groundwater resources in watersheds are rapidly depleting due to increased water use. In southeastern Brazil, droughts have intensified over the past 20 years, driven by changes in temperature and rainfall regimes. This study assessed groundwater in two headwater basins with contrasting climates in Minas Gerais State, namely the Grande and Jequitinhonha River basins, under climate warming scenarios to quantify potential impacts on water storage. The selection of these watersheds was intended to serve as a reference for potential future climate impacts in this region, given that human intervention in these watersheds was relatively low over the last 20 years. The MHD-INPE hydrological model was used for simulations, with climate projections extending through 2099. Minimum annual groundwater storage was estimated using the Brutsaert method and baseflow simulations, and the Mann–Kendall test and Sen's slope estimator were used to assess trends in groundwater storage. Our analysis revealed significant decreasing trends in groundwater storage in both watersheds. Compared with the baseline, reductions were observed in all projections, with the largest decline in the 2071–2099 projection under RCP 8.5 in the Grande River basin (74.4%), indicating that this basin may become less resilient to climate change over the century. These findings may support decision-making through water resources management tools, such as water allocation mechanisms, thereby helping mitigate impacts on the future.

Keywords: Climate change; hydrological modeling; water yield; hydrological impacts.

Introduction

Climate warming has recently become part of everyday life and is expected to intensify over the coming decades, potentially causing significant changes in climate patterns. One of its main consequences is the alteration of hydrological regimes, which in turn affects water resources, intensifies natural disasters, causes loss of biodiversity, and increases economic and human vulnerability.

Groundwater storage is essential for water supply in a watershed, especially during dry periods, when groundwater flow sustains streamflow. Climate change is directly affecting groundwater storage, leading to water scarcity (Ribeiro et al., 2024). Therefore, it is essential to assess the impact of these changes on water resources to support mitigation actions (Mello et al., 2025). However, it is relatively complex to evaluate these impacts separately from those caused by land-use change. Studies applying methods such as Budyko (Budyko, 1974) have been conducted; however, analyses of groundwater flow, the most relevant indicator of water yield, are not possible with such methods (Bruno et al., 2026; Ghaneei et al., 2026). Thus, studies in headwater basins using process-based hydrological models tend to be more appropriate because land-use changes are reduced in these basins (*pristine catchments*), keeping them closer to original conditions (Jones et al., 2012).

To evaluate future changes in streamflow patterns driven by climate or land-use changes, deterministic rainfall-runoff hydrological modeling is preferred for its physical structure. Model predictions from physically based rainfall-runoff models are linked to physical climatic, hydrological, geomorphological, soil, and land-use data, among others, as input variables to better predict hydrological responses across contrasting scenarios over time when actual data are not available (Caldeira et al., 2018). On the other hand, Global Circulation Models (GCMs) provide insights into how climatic conditions may evolve in the future under scenarios that account for greenhouse gas emissions, population growth, energy sources, and technological development. However, these projections have a spatial resolution incompatible with hydrological models, which are structured at a finer scale to represent watershed responses, necessitating refinement of their outputs. This refinement should be carried out by Regional Climate Models (RCMs) (Maraun et al., 2017), which aim to preserve physical and chemical atmospheric processes at smaller scales.

Using multiple climate models may help capture the uncertainties associated with climate change, enabling a broader assessment of the variability of hydrological impacts (Déqué et al., 2007; Wang et al., 2021). Mustafa et al. (2019) used an ensemble of climate and hydrological models to quantify uncertainties in groundwater-level forecasting in Bangladesh. They observed that groundwater levels varied markedly across climate and hydrological models, demonstrating that ensemble use should be preferred. Gil-García et al. (2024) developed a model that considers uncertainties in water resource allocation under climate change impacts, using climate, hydrological, and microeconomic models. Their results showed that climate change can lead to nonlinear changes in water allocation in decision-support systems, and the use of multiple climate models and scenarios is therefore recommended in most hydrological studies' predictions (Kim and Chung, 2026). Thus, uncertainty in climate projections may lead to management practices or policies that overexploit groundwater resources.

Research shows that combining climate and hydrological models is a common approach to evaluate how climate change affects water systems (Wang and Hejazi, 2011; Greve et al., 2014). Many studies report declines in groundwater recharge, groundwater flow, and streamflow across different regions (Mizyed, 2018; Kalugin, 2019; Olarinoye et al., 2023). For example, reductions in groundwater recharge (14–24%) and flow (12–17%) have been observed, along with significant decreases in streamflow and even groundwater depletion in some areas (Mizyed, 2018; Kalugin, 2019; Olarinoye et al., 2023).

Several basin-specific studies also project declining streamflow due to reduced precipitation, leading to longer dry seasons and lower baseflow (Mohor et al., 2015; Michels-Brito et al., 2021; Mello et al., 2021). However, results are not uniform everywhere — some regions may experience increased streamflow alongside reduced groundwater contributions (Viola et al., 2015; Cunha et al., 2023). Overall, the findings indicate that climate change is likely to significantly alter hydrological patterns and water fluxes, with potential consequences for water availability, ecosystem functioning, and water resources management, although the magnitude and direction of these impacts vary regionally.

Minas Gerais state, in southeastern Brazil, is home to nationally important rivers, especially for hydroelectric power generation. Several regions of the state have been impacted by significant droughts, particularly during the 2010s (Petrucci et al., 2022; Silva and Mello, 2022), caused by significant reduction and irregular rainfall, accompanied by a significant increase in temperature. Therefore, studies that analyze how these changes may affect groundwater flow and water availability over the century are essential for water resources management, given the contrasting climatic conditions in Minas Gerais. The central hypothesis of this study is that significant baseflow reduction will occur throughout the 21st century, regardless of current climatic conditions, with rates of decline that may increase the state's vulnerability to prolonged hydrological droughts.

Thus, the objectives of this study are: (i) to analyze the future behavior of streamflow in two headwater basins in Minas Gerais under contrasting climatic conditions caused by climate change; (ii) to simulate the future behavior of streamflow using an ensemble of climate models and greenhouse gas emission scenarios throughout the 21st century; (iii) to estimate groundwater storage from the simulated streamflow data; and (iv) to evaluate the vulnerability of water resources in these headwater basins by quantifying projected changes in streamflow and groundwater storage and their implications for long-term water availability.

Materials and Methods

Basins under study

The study basins comprise the Grande (GRB) and Jequitinhonha River (JRB) basins, delineated by streamflow gauging stations with drainage areas of 2,070 km^2 and 7,720 km^2, respectively. Both are located predominantly in the headwater regions of their respective basins in the state of Minas Gerais, Brazil (Figure 1). The Mantiqueira Range shelters the GRB headwaters, the main tributary of the Paraná River, and one of the country's most significant hydropower potentials (Bueno et al., 2020). According to the Köppen climate classification, most of this basin is characterized by a Cwa climate, defined as humid subtropical with a hot, rainy summer and a dry winter, with rainfall concentrated between October and March. In areas closer to the Mantiqueira Range, the predominant climate is Cwb, similar to Cwa but with milder temperatures due to the influence of higher elevations (Mello et al., 2012).

The Espinhaço Range, located in north-central Minas Gerais, shelters the JRB headwaters, an important water source for extensive areas of Minas Gerais and Espírito Santo states. Climatic conditions in this basin range from humid, predominantly Aw (tropical with a dry winter), to semiarid, classified as BSh (hot semiarid), with lower rainfall totals and greater precipitation irregularity than in the Grande River basin (Martins et al., 2018).

GRB and JRB were selected for this study not only because they are essential for regional water supply, but also because they are situated in climatically contrasting areas of Minas Gerais, with different susceptibilities to climate change. Differences in land use were also considered: JRB has largely retained a pristine character, whereas GRB has been more intensively anthropized. Ribeiro et al. (2024) further reported declining trends in streamflow and groundwater storage in both basins over recent decades, attributing them mostly to changes in climate in southeastern Brazil over the last 20 years.

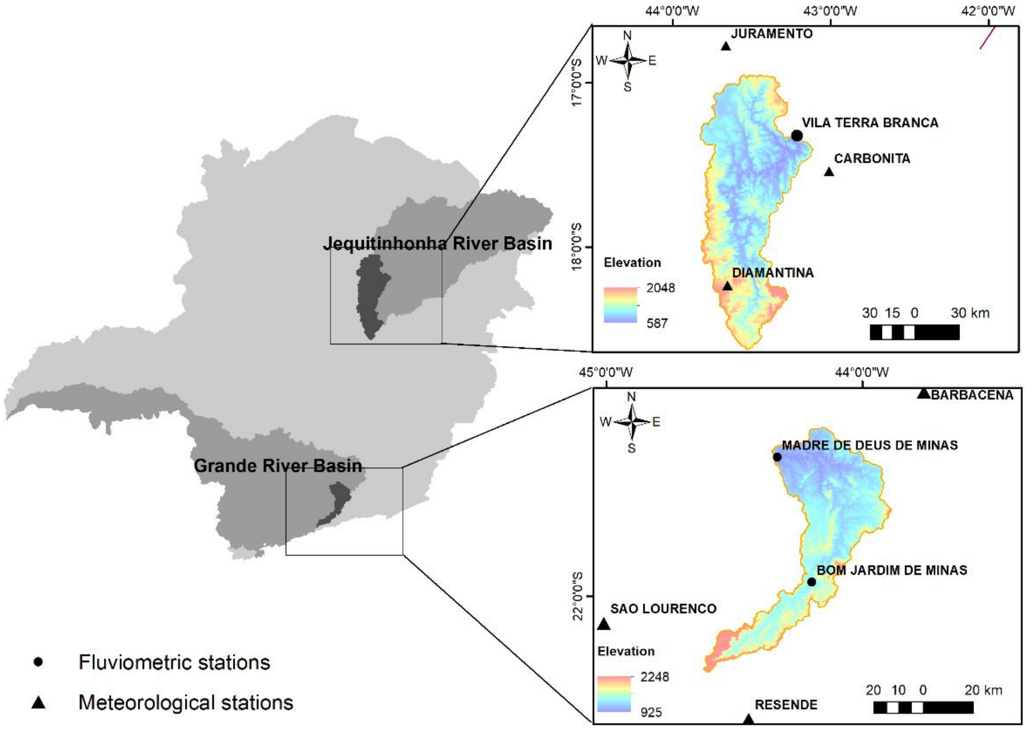

Figure 1. Geographic location of the Grande and Jequitinhonha River basins in their headwater regions, including streamflow reaches, meteorological stations, and the respective gauging stations.

Figure 2 presents the land use (a), soil (b), and hydrogeological (c) maps of the basins. The land use and land cover maps were obtained from the 2023 annual products made available by the MapBiomas platform, generated from Landsat satellite imagery with a spatial resolution of 30 m. The soil maps were developed from the Minas Gerais state's soil map at a scale of 1:650,000 (UFV/DPS-LABGEO, 2024). The hydrogeological maps were obtained from the Geological Survey of Brazil (CPRM) at a scale of 1:5,000,000 (CPRM, 2021).

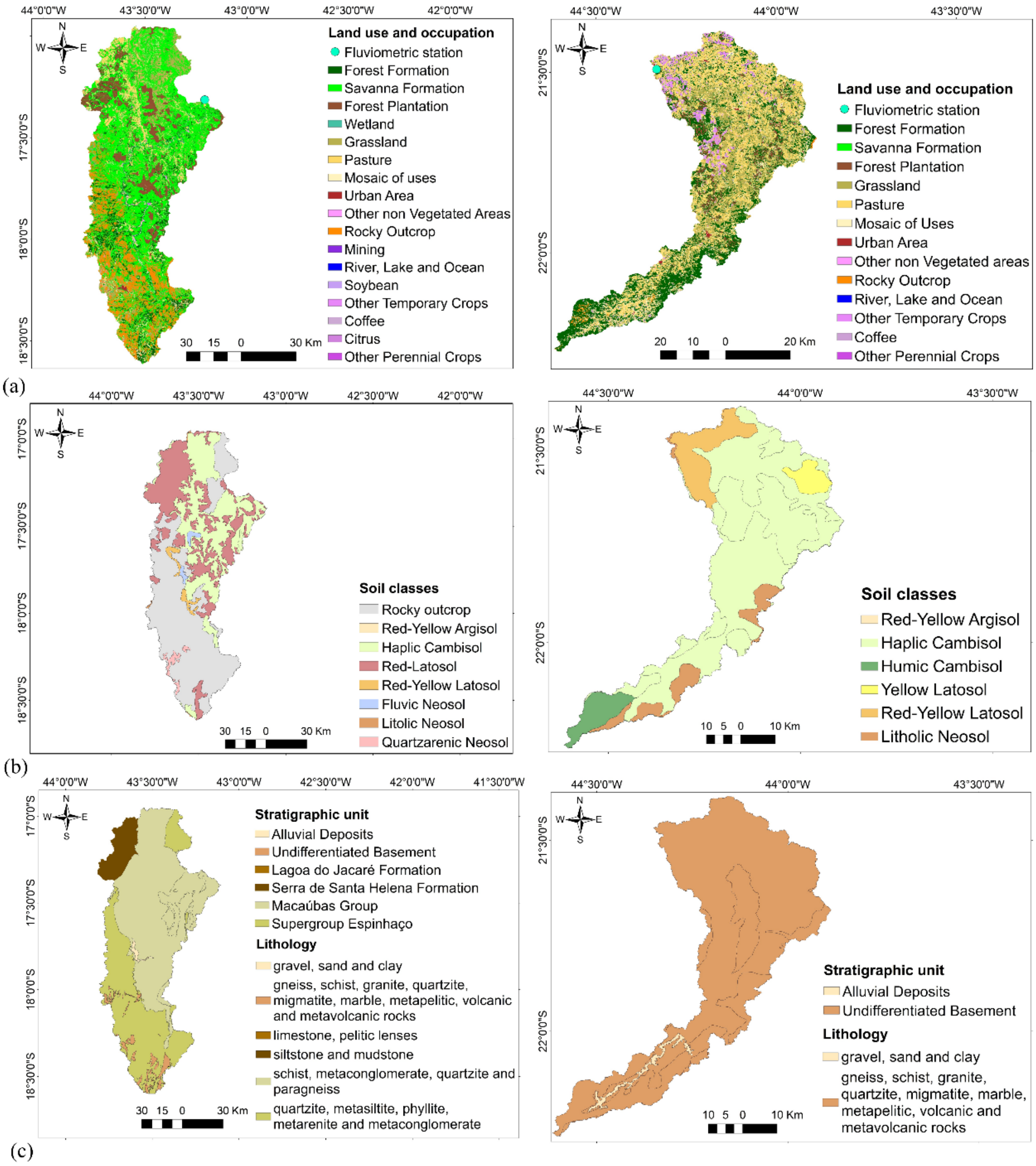

Figure 2. Land use (a), soil (b), and hydrogeological (c) maps of the Grande and Jequitinhonha River basins.

GRB headwaters considered in this study (Figure 1) include anthropized areas, predominantly grasslands that have replaced Atlantic Forest, especially towards the northern sector, where agriculture and livestock production are more intensive (Figure 2a). However, these land uses date back to the 1960s and have remained approximately constant over time, predating the onset of recent climatic changes. The predominant soils are Haplic Cambisols, Humic Cambisols, Yellow and Red-Yellow Oxisols, and Litholic Neosols (Figure 2b). Hydrogeologically, the basin is almost entirely characterized by an undifferentiated basement stratigraphic unit composed of quartzite, migmatite, marble, and metapelitic rocks (Figure 2c).

JRB, as delineated in this study, exhibits limited anthropogenic disturbance. It is covered predominantly by Cerrado and Atlantic Forest vegetation and is less anthropized than GRB (Figure 2a). Regarding soil classes, rocky outcrops dominate the landscape, whereas Red Oxisols and Haplic Cambisols occupy smaller areas (Figure 2b). The basin lies within the stratigraphic units of the Macaúbas Group and the Espinhaço Supergroup, whose lithology is composed mainly of quartzite, schist, and metaconglomerate (Figure 2c).

Acquisition of Climatic and Hydrological Data

Observed streamflow and daily precipitation data were obtained from the HidroWeb platform of the National Water and Basic Sanitation Agency (ANA), whereas meteorological data on air temperature, wind speed, relative humidity, atmospheric pressure, and solar radiation were obtained from stations available through the BDMEP portal of the National Institute of Meteorology (INMET). Table 1 summarizes codes, names of the streamflow gauges and meteorological stations, time series used and the basins' areas.

Table 1. Streamflow and meteorological stations in the Grande River and Jequitinhonha basins, time series used in this study, and respective drainage areas.

Basin	**Station Type**	**Station Code**	**Station Name**	**Start Date**	**End Date**	**Drainage Area (km^2)**
Grande River basin	Fluviometric	61012000	Madre de Deus	01/01/1994	31/12/2017	2070
	Meteorological	83689	Barbacena	01/01/1994	31/12/2017	
	Meteorological	83736	São Lourenço	01/01/1994	31/12/2017	
	Meteorological	83738	Resende	01/01/1994	31/12/2017	
	Meteorological	83687	Lavras	01/01/1994	31/12/2017	
	Rain Gauge	2144001	Bom Jardim de Minas	01/01/1994	31/12/2017	
	Rain Gauge	2144005	Itumirim	01/01/1994	31/12/2017	
	Rain Gauge	2144006	Luminárias	01/01/1994	31/12/2017	
	Rain Gauge	2144007	Madre de Deus de Minas	01/01/1994	31/12/2017	
	Rain Gauge	2144010	São Vicente de Minas	01/01/1994	31/12/2017	
	Rain Gauge	2144018	Aiuruoca	01/01/1994	31/12/2017	
	Rain Gauge	2144019	Andrelândia	01/01/1994	31/12/2017	
	Rain Gauge	2144021	Fazenda Laranjeiras	01/01/1994	31/12/2017	
	Rain Gauge	2144022	Fazenda Paraíba	01/01/1994	31/12/2017	
	Rain Gauge	2144025	Carvalhos	01/01/1994	31/12/2017	
	Rain Gauge	2144038	Carrancas	01/01/1994	31/12/2017	
	Rain Gauge	2244057	Ponte do Costa	01/01/1994	31/12/2017	

Jequitinhonha	Fluviometric	54010005	Vila Terra Branca	01/01/1981	31/12/2020	7720
River basin	Meteorological	83452	Juramento	01/01/1981	31/12/2020	
	Meteorological	83485	Carbonita	01/01/1981	31/12/2020	
	Meteorological	83538	Diamantina	01/01/1981	31/12/2020	

Missing values in the time series were filled using the *SPELLmap* (Guzman et al., 2013), which uses the Inverse Distance Weighting (IDW) interpolator (Watson, 1985). In this approach, interpolated values are estimated as a weighted mean based on the inverse distance between the station with missing data and neighboring stations, so that closer observations exert greater influence. The nearest neighboring stations to those considered in this study (Table 1) were used for gap filling.

Improving the rainfall data spatial representation

Precipitation is a particularly sensitive input in hydrological modeling, especially in JRB, which has only three meteorological and rainfall stations. To improve the spatial representation of precipitation, a stepwise back-correction function procedure proposed by Hernandez et al. (2026) was applied. First, a baseline period was established using long-term precipitation records from the stations closest to the study basins. Streamflow was then simulated using the observed precipitation data, and an initial model calibration was performed by comparing simulated and observed streamflow using performance metrics such as NSE, KGE, and PBIAS.

A reanalysis algorithm was then applied to propagate a gradual correction to the lowest level of the model representation, in which a nonlinear correction function is introduced subject to mass-conservation constraints (Hernandez et al., 2026). The performance metrics were used as the basis for the reanalysis, and the discrepancy between simulated and observed streamflow was quantified. An error function was then used to estimate a precipitation correction factor, which was applied linearly to the precipitation data while accounting for a limiting error between observed and corrected precipitation at each station. The model was subsequently recalibrated using the corrected precipitation data, thereby generating updated parameter values. This procedure was repeated as long as the performance metrics continued to improve. Exponential and rational functions were considered as error functions to calculate the correction factor at each iteration (Hernandez et al., 2026). The error function proposed by Hernandez et al. (2026) relates streamflow error to the precipitation correction factor, indicating how discrepancies between observed and simulated streamflow can be translated into systematic adjustments to the model representation of precipitation. The correction assumes that the general spatial pattern of precipitation remains unchanged, although its magnitude may differ, thereby enabling reconstruction of the effects of unmeasured local precipitation, referred to as mean local uncertainty due to random errors.

Finally, the reanalysis was validated using a frequency analysis of maximum precipitation values to assess the statistical consistency between the observed and corrected datasets. The maximum daily precipitation series was grouped into intervals to construct an empirical frequency distribution. Absolute, relative, and cumulative frequencies were then calculated for both observed and corrected datasets and plotted as comparative distribution curves. This procedure enabled the determination of whether the corrected maximum values exceeded the statistical envelope of the observed values, thereby ensuring that the corrections remained within ranges consistent with local hydrometeorological variability and did not generate artificial extreme values (Hernandez et al., 2026).

Global Circulation Models – climate datasets for future climate

Future climate data were projected using a multi-model ensemble. Multi-model analyses are recommended in climate change studies because they help quantify projection uncertainty by accounting for differences in model structure and parameterization (Melo et al., 2024). The use of an ensemble of multiple climate models can also help reduce uncertainty associated with a single model, thereby supporting a more comprehensive assessment of hydrological impacts (Déqué et al., 2007; Wang et al., 2021).

This study used climate projections from the BESM, CanESM2, HadGEM2-ES, and MIROC5 GCMs, all of which are part of the CMIP5 ensemble and were dynamically downscaled for South America by CPTEC/INPE. These GCMs have shown satisfactory skill in representing regional climatological patterns and climate extremes, and provide the temporal resolution required for the analyses conducted in this study. In addition, they span a range of climate sensitivities, which is essential for addressing the uncertainty inherent in future projections (Knutti and Sedláček, 2013; Flato et al., 2013). According to Chou et al. (2014) and Lyra et al. (2018), CanESM2, HadGEM2-ES, and MIROC5 are among the CMIP5 models that perform best at simulating climate over South America, owing to the availability of regionally gridded historical datasets validated for Brazil.

The spatial resolution of these GCMs projections (40 km) is too coarse for assessing hydrological impacts at the basin sizes considered in this study. Therefore, they were refined using a Regional Climate Model (RCM), the Eta/CPTEC model, which is a physically downscaling model adapted to Brazilian conditions, particularly southeastern Brazil, and was used to downscale the climate projections to a 20-km spatial resolution.

The Representative Concentration Pathway (RCP) scenarios were developed by the IPCC. They are based on atmospheric greenhouse gas concentrations and technological progress in renewable energy production, with anthropogenic radiative forcing, expressed in W m^{-2}, through 2100. Accordingly, RCP 4.5 and RCP 8.5 correspond to radiative forcing levels of 4.5 W m^{-2} and 8.5 W m^{-2}, respectively (Santos et al., 2019). RCP 4.5 represents an intermediate-emissions scenario that considers emissions stabilization by mid-century and a projected warming of 1.1 to 2.6 ºC by the end of the century. RCP 8.5 represents the most pessimistic scenario, assuming continuously increasing emissions through 2100 and warming of 2.6 to 4.8 ºC (Santos et al., 2019).

Climate change scenarios are not exact or definitive representations of the future. Rather, they are constructed from assumptions about current atmospheric greenhouse gas concentrations and possible developments in several economic sectors, especially energy. Even with these limitations, such scenarios are valuable because they support the design of resilience and adaptation strategies and provide useful pathways for scientific and policy analysis.

The Representative Concentration Pathways (RCPs) were introduced in the IPCC Fifth Assessment Report (AR5) and are based primarily on radiative forcing trajectories (IPCC, 2014). In this study, the GCMs associated with these scenarios provide high-resolution datasets for South America at a 20-km resolution (Chou et al., 2014), which are not available from other GCMs in Brazil. More recently, the IPCC introduced the Shared Socioeconomic Pathways (SSPs), which updated the framework for climate change assessment (IPCC, 2021). Considered separately, however, neither framework is fully sufficient: the RCPs do not explicitly incorporate societal development pathways, whereas the SSPs require assumptions about the implementation of climate policies. Therefore, RCPs and SSPs should be viewed as complementary approaches, and their combined use can produce more robust and policy-relevant scenarios by integrating both risk assessment and mitigation strategies (O'Neill et al., 2020).

Air temperature and precipitation data downscaled by Eta/CPTEC at 20 km resolution were provided by INPE in bias corrected *NetCDF* format. Statistical techniques such as Linear Scaling (LS), Distribution Mapping (DM), and Quantile Mapping (QM) are commonly applied to correct biases in Eta/CPTEC projections. Relative humidity, atmospheric pressure, wind speed, and sunshine duration were also provided in *NetCDF* format. However, these variables had not undergone bias correction. Thus, a bias-adjustment procedure to address numerical inconsistencies was provided. This correction was performed using the Linear Scaling (LS) method, which is based on the ratio between the observed and projected monthly means for the reference period of each meteorological variable (Shrestha et al. 2017) (Equations 1 and 2).

$$V^{*}_{contr}(d) = V_{contr}(d)\left[\frac{\mu_m(V_{obs}(d))}{\mu_m(V_{contr}(d))}\right] \quad (1)$$

$$V^{*}_{scen}(d) = V_{scen}(d)\left[\frac{\mu_m(V_{obs}(d))}{\mu_m(V_{contr}(d))}\right] \quad (2)$$

In these equations, V(d) denotes the daily value of the meteorological variable; µm denotes its monthly mean; and *contr*, *scen*, and *obs* refer to the baseline, scenario, and observed datasets, respectively. Values of V(d) below 1 indicate that the projections overestimate the observed data, whereas values above 1 indicate underestimation.

The MHD/INPE hydrological model

Figure 3 presents a schematic representation of the MHD/INPE model, including the flow between layers and the method used to calculate each component of the water balance.

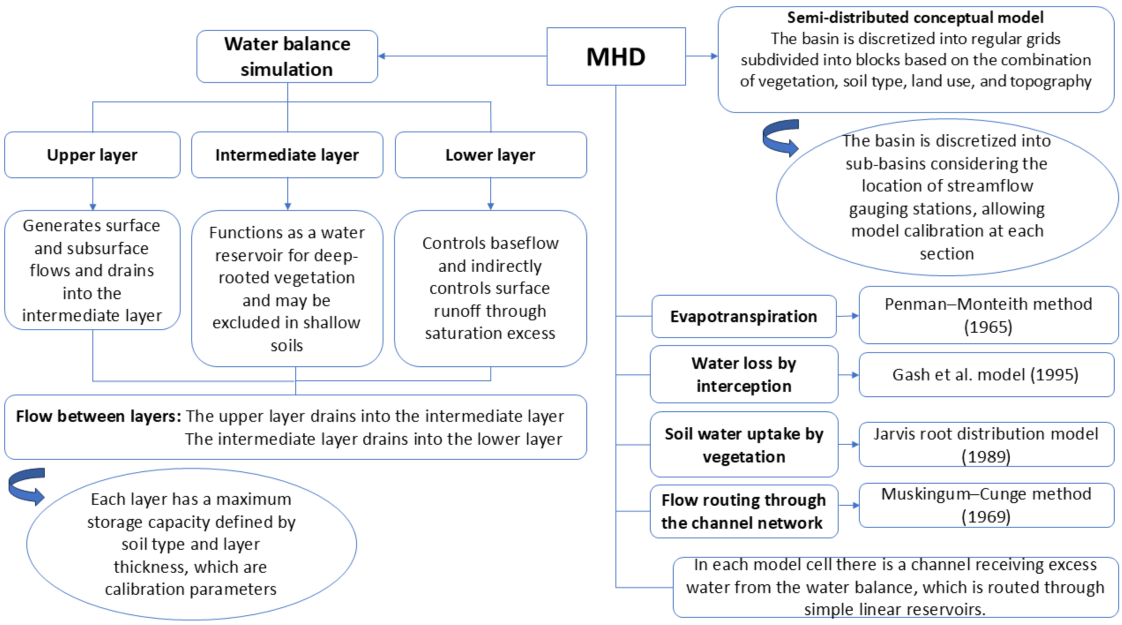

Figure 3. Schematic representation of the operation of the MHD/INPE model (adapted from Tomasella et al. 2022).

The fixed vegetation parameters of the MHD model include critical omega, root distribution factor, NVeg, albedo, leaf area index, vegetation height, vegetation cover, and rooting depth. The fixed soil parameters comprise the air-entry pressure, the b parameter of the soil-water retention curve, and the volumetric water content at saturation and residual conditions. Additional input data include meteorological data, soil and land-use maps, and slope data.

Data Preparation for Hydrological Modeling

Spatial data were prepared using *TerraViewHidro* 0.4.4. Scenes from the ALOS PALSAR sensor, with a 12.5-m spatial resolution, were obtained from the Alaska Satellite Facility Distributed Active Archive Center of the National Aeronautics and Space Administration (NASA). The MHD model was implemented in GNU Fortran. A spatial resolution of 2 km was adopted, and modeling was performed separately for each basin based on the corresponding streamflow gauging sections. Annual land-use and land-cover maps from *MapBiomas* were also used, together with hydrometeorological data, including meteorological inputs and observed streamflow.

The hydrological processing of the Digital Elevation Model (DEM) was carried out in *TerraViewHidro* to derive flow direction, accumulated contributing area, and the drainage network. This information was subsequently used to delineate the basins and the drainage areas computed from the fluvial gauging sections. Slope and channel length were also extracted for each grid cell. The Topographic Index was derived from the DEM, basin shapefiles, flow-direction data, and basin flow-routing parameters.

Based on the flow-direction and accumulated-area data, the *Height Above the Nearest Drainage* (HAND) hydrological environment classifier was also generated. This classifier can replace the conventional soil map and regularize topography with respect to elevations along the drainage network (Tomasella et al., 2022). Hydrological Response Units (HRUs) were then generated by overlaying the HAND environment types and land-use classes. For GRB and JRB, respectively, 18 and 20 HRUs were obtained by combining three HAND environment types and eight land-use classes.

Calibration, Validation, and Simulation

Model calibration, validation, and simulation were conducted at the daily time scale using daily precipitation, meteorological variables, and observed streamflow. Calibration was performed in a lumped manner for each basin, using the respective gauging section as the reference point. Although the model provides a spatially distributed representation of hydrological processes, parameter fitting was based on the integrated hydrological response of each basin at the streamflow gauging station.

Model calibration was performed using the SPEA2 algorithm, a multi-objective optimization approach that optimizes the objective functions Nash-Sutcliffe Efficiency (NSE) and the Nash-Sutcliffe Efficiency of the logarithm of streamflow (lNSE). In addition to NSE and lNSE, model performance was evaluated using the coefficient of determination (R^2) and the PBIAS index. For model's performance criteria, we considered the statistical indices from Moriasi et al. (2015).

The model also provides the following outputs: relative volume error (ErrV), which indicates whether streamflow is underestimated or overestimated, with ideal values ranging from -10% to +10%; mean evaporation based on observed data (ETobs); simulated evapotranspiration (ETcal); and the statistical index ErrE, which expresses the difference between ETobs and ETcal, allowing evaluation of the model's ET estimates.

For the JRB, we used a long-term streamflow series from 1981 to 2020. For the model's warm-up, 1981 was used; the period 1982-2000 was used for calibration; and 2001-2020 was used for validation. A long-term series from 1994 to 2017 was used for GRB, with 1994 used for warm-up, 1995-2005 for calibration, and 2006-2017 for validation.

During the simulation of the impacts, the model was forced with the ensemble obtained by averaging the climate projections from the four GCMs for the baseline (1961-2005) and for the RCP4.5 and RCP8.5 scenarios over the periods 2006-2040, 2041-2070, and 2071-2099. These meteorological inputs include precipitation (mm), air temperature at 2 m height (ºC), dew point temperature at 2 m height (ºC), wind speed at 10 m height (m/s), surface atmospheric pressure (mB), and incoming global shortwave radiation.

Groundwater Storage Estimation

Groundwater storage (S) was estimated using the method proposed by Brutsaert (2008). First, daily simulated streamflow series were used to derive the annual minimum 7-day moving average value ($Q_{7,min}$). There is a strong connection between S and Q7,min, which sustains baseflow during dry periods; thus, $Q_{7,min}$ can be used as a proxy of S (Lin and Yeh, 2017). This approach enables identification of temporal trends in groundwater storage and, consequently, assessment of the effects of climate change, particularly in less anthropized basins (Brutsaert, 2008, 2012).

The theoretical basis of this method lies in the physical characteristics of S and its connection to basin geomorphology, as detailed by Brutsaert (2008). Annual minimum groundwater storage was calculated using Equation 3, which estimates S as a linear function of baseflow discharge (Brutsaert, 2008; Rupp and Selker, 2006).

$$S = K \times y \tag{3}$$

In this equation, S is groundwater storage (mm); y is streamflow converted to depth (mm day^{-1}) (i.e., y = Q/A, where A is the basin area); and K is a parameter associated with the basin's hydrogeological transmissivity characteristics (day).

Brutsaert and Nieber (1977) developed a methodology for analyzing the temporal behavior of S based on baseflow rates by deriving equation 3, i.e.:

$$\frac{dS}{dt} = K \cdot \frac{dy}{dt} \tag{4}$$

To assess the S temporal behavior, Brutsaert (2008) suggests applying Q7, min:

$$\frac{dS}{dt} = K \cdot \frac{dy_{7,min}}{dt} \tag{5}$$

For the K parameter estimate, we work with equation 5, developing a log-log graph of -dy/dt and y:

$$\frac{dy}{dt} = -\frac{(y_{i-1} - y_{i+1})}{2} \tag{6}$$

However, to construct this graph, Brutsaert (2008) required a protocol stipulating that streamflow observations used in the analysis must represent essentially groundwater flows, i.e., without the effects of precipitation or direct surface runoff. The method's protocol is:

- Eliminate all positive values and zeros of dy/dt.

- Eliminate anomalous values of -dy/dt that may suddenly appear and the four values following their occurrence.

- Eliminate the three data points following the last positive or zero value of dy/dt.

- Eliminate the two data points preceding the first positive or zero value occurrence.

- The enveloping line should be drawn above the 5% smallest values.

This procedure results in a cloud of points from which K is the angular coefficient of the 5% smallest values enveloped by a line. Using the parameter K and the annual minimum seven-day streamflow (Q7, min) series, the annual minimum groundwater storage is calculated using equation 3.

Temporal behavior of hydrological variables

For the analysis of simulated streamflow during the baseline, estimated daily streamflow were compared to observed streamflow series in each basin. Extreme-value statistical analysis was then performed to derive the statistical descriptors of the Flow Duration Curves (FDCs) (Ley et al., 2011): QSM, MWL, MWH, and SEASON. The *Quantile Slope of the Mid-Segment* (QSM) (Equation 7) is a descriptor of streamflow magnitude that represents the average variability of streamflow coefficients and corresponds to the slope of the FDC for intermediate flows (Ley et al., 2011). The *Mean Wetness of Low Flows* (MWL) (Equation 8) and the *Mean Wetness of High Flows* (MWH) (Equation 9) describe the low-flow and high-flow segments, respectively, indicating hydrological responses to extreme values (Ley et al., 2011). The SEASON descriptor (Equation 10) represents seasonality, i.e., the difference between streamflow in the wet season (October to March) and the dry season (April to September) (Ley et al., 2011).

$$QSM = \frac{quantil 0{,}8 - quantil\ 0{,}2}{média} \quad (7)$$

Where the 0.8 and 0.2 quantiles correspond to streamflow values with 80% and 20% exceedance frequency, respectively.

$$MWL = \frac{\sum_{l=1}^{L} Ql}{L} \quad (8)$$

Here, $l = 1, 2, \ldots L$ represents streamflow values with exceedance frequence > 0.95.

$$MWH = \frac{\sum_{h=1}^{H} Qh}{H} \quad (9)$$

Where $h = 1, 2, \ldots H$ represents streamflow values with exceedance frequency < 0.05.

$$SEASON = \frac{médiaCheia - médiaSeca}{média} \quad (10)$$

The Mann-Kendall test (Mann, 1945; Kendall, 1975), implemented in R, was used to detect trends in the simulated streamflow and groundwater storage series. Sen's slope estimator (Sen, 1968) was subsequently applied to series exhibiting significant trends to quantify the rate of change. All tests were applied to the simulated streamflow and groundwater storage data at the 5% significance level.

Results and Discussion

Calibration and Validation of the MHD/INPE Model

The model was initially calibrated using observed precipitation data. The reanalysis method was then applied to the precipitation series, after which the model was recalibrated to optimize the performance metrics. Table 2 compares the calibration and validation results obtained using observed precipitation data against the best results achieved after applying the precipitation-correction error function in both basins. We can see that the model's performance improved substantially after reanalysis, particularly for NSE in JRB and across all performance metrics in GRB.

Table 2. Performance metrics obtained before and after reanalysis in the JRB and GRB using the MHD/INPE model.

	Jequitinhonha River basin				**Grande River basin**			
	Calibration	Reanalysis	Validation	Reanalysis	Calibration	Reanalysis	Validation	Reanalysis
KGE	0.81	0.80	0.77	0.75	0.81	0.85	0.75	0.90
NSE	0.74	0.77	0.70	0.76	0.76	0.83	0.70	0.90
PBIAS	-2%	-3%	-6%	-0.2%	-1%	3%	24%	7%

The precipitation series obtained through reanalysis was compared with the observed series using three main indicators: (i) maximum daily precipitation, (ii) the relative frequency distribution of precipitation events, and (iii) maximum mean monthly precipitation. The results of these analyses are reported by Hernandez et al. (2026). Overall, the corrected maximum precipitation values remained within the observed maximum range, thereby avoiding excessive overestimation of extreme events. The relative density functions also showed good agreement between observed and corrected precipitation, indicating that the correction method adequately preserved the statistical distribution of maximum precipitation events. In addition, the seasonal pattern of mean monthly precipitation was maintained after correction. Therefore, the precipitation correction method captured part of the uncertainty associated with spatial and temporal variability, improving the representation of basin-average precipitation and, consequently, the performance of the hydrological simulations in both basins. The reanalyzed precipitation data were subsequently used as input to calibrate and validate the MHD model. Table 3 presents the best-calibrated values for each MHD model parameter in the JRB and GRB, obtained using the SPEA2 algorithm.

Table 3. Calibrated parameter values obtained during the MHD model calibration phase using the SPEA2 algorithm.

Parameter	**Basin**	
	JRB	GRB
Surface soil layer depth – D1 (m)	3.38	0.27
Subsurface soil layer depth – D2 (m)	5.83	10.00
Groundwater layer depth – D3 (m)	26.81	0.10
Saturated hydraulic conductivity multiplier factor fKss	0.55	0.41
Horizontal transmissivity - Tsub (m2 dia-1)	0.38	1.39
Transmissivity decay coefficient with depth - μ	1.15	3.23
Soil anisotropy factor – α	169.16	0.002
Minimum groundwater storage – Csi (%)	0.008	0.024
Surface runoff routing delay time (s)	0.001	447.15
Groundwater flow routing delay time (s)	1313.22	90.94

The performance metrics for JRB showed an NSE classified as “good” and another as “very good” in both the calibration and validation phases (Table 4). Both R^2 and R^2l were classified as “good.” ErrV indicated an underestimation of the simulated streamflow relative to the observed series, and its value remained within the ±10% range, which can therefore be considered acceptable. During calibration, ETCal was slightly lower than ETObs, whereas in validation, the opposite was observed, with ETCal slightly higher than ETObs; the ErrE values reflect this difference. PBIAS values indicated a tendency toward overestimation of simulated streamflow during calibration and underestimation during validation; nevertheless, PBIAS behavior still supports classification of the model performance as “very good.”

In GRB, NSE was classified as “very good” in both the calibration and validation phases. The lNSE results were also classified as “very good”, as were the R^2 and R^2l. ErrV indicated underestimation of the simulated streamflow, but within the acceptable range. In both calibration and validation, ETCal exceeded ETObs, whereas PBIAS indicated a tendency toward overestimation of simulated streamflow; however, the model’s performance could be classified as “very good” in calibration and “good” in validation.

Table 4. Performance metrics obtained for JRB and GRB during the model calibration and validation.

Basin		NSE	lNSE	R^2	R^2l	ErrV	ErrE	ETCal	ETObs	Pbias
JRB	Calibration	0.77	0.85	0.77	0.85	-0.027	-0.024	1.79	1.83	0.03
	Validation	0.76	0.83	0.78	0.85	-0.04	0.027	1.78	1.73	-0.002
GRB	Calibration	0.83	0.90	0.86	0.91	-0.015	0.051	2.21	2.11	0.03
	Validation	0.90	0.92	0.90	0.92	-0.066	0.102	2.27	2.06	0.07

The calibration and validation results obtained for both basins were comparable to those reported in other studies that also applied the MHD model (Oliveira et al., 2023; Melo et al., 2022; Michels-Brito et al., 2021; Negrão et al., 2017; Paiva et al., 2024; Rodriguez et al., 2017; Lopes et al., 2017), indicating overall satisfactory performance.

Tomasella et al. (2019) reported lower MHD model performance in the headwater sub-basins of the Doce River basin, mainly because precipitation is more spatially variable there. This limitation is largely associated with orographic effects and with the insufficient density of rain-gauge networks to adequately represent rainfall. Melo et al. (2022) further showed that when rainfall fields are interpolated in headwater basins, hydrological models become more sensitive to interpolation errors due to smaller drainage areas and limited compensation for such uncertainties. In comparison, the results obtained in the present study indicate better model performance in headwater basins, which can be attributed to the precipitation reanalysis procedure adopted here. This approach appears to be a promising tool for hydrological simulation in basins with sparse rain-gauge stations.

Figures 4 and 5 show the streamflow historical series simulated by the MHD relative to the observed streamflow during calibration (a) and validation (b) in JRB and GRB, respectively. In both basins, peak flows are visually underestimated; however, overall, there was good agreement between the observed and simulated data. The underestimation of peak flows may be attributed to the combined effects of limitations in rainfall estimation, uncertainties in observed streamflow data, particularly extreme values, the temporal resolution of the hydrological model, and simplifications inherent in routing flow through the drainage network. For example, uncertainties are associated with the rating curves used to derive observed streamflow, especially during extreme events, when direct measurements are scarcer and extrapolations of stage-discharge relationships are less reliable (Di Baldassarre and Montanari, 2009). The use of daily precipitation implicitly assumes a uniform distribution of rainfall throughout the day, which may fail to adequately represent intense, short-duration convective events. Routing with the Muskingum-Cunge method is influenced by the temporal resolution used. In daily simulations, the method tends to attenuate the flood wave along the drainage network, reducing simulated peak values and increasing hydrograph dispersion.

Oliveira et al. (2022) used the MHD for a hydrological study in a tropical basin in São Paulo state, Brazil, and found more pronounced biases of baseflow overestimation and peak-flow underestimation in sub-basins. Mohor et al. (2015), when calibrating MHD in the Tapajós River basin in the Amazon, observed underestimation of peak flows at most stations and limitations in simulating the lower part of the recession curve at some stations. Rodriguez et al. (2017), in a hydrological modeling study in the Madeira River basin (Bolivia, Brazil, and Peru), also observed underestimation and temporal advancing of the peak flows with the MHD. Underestimation of peak flows has been observed due to limitations in the structures of hydrological models, as most do not account for the nonlinearity of the rainfall-runoff process. In addition, factors such as the time step and the adequate representation of spatial rainfall variability, especially at the daily scale, must also be considered (Viola et al., 2009).

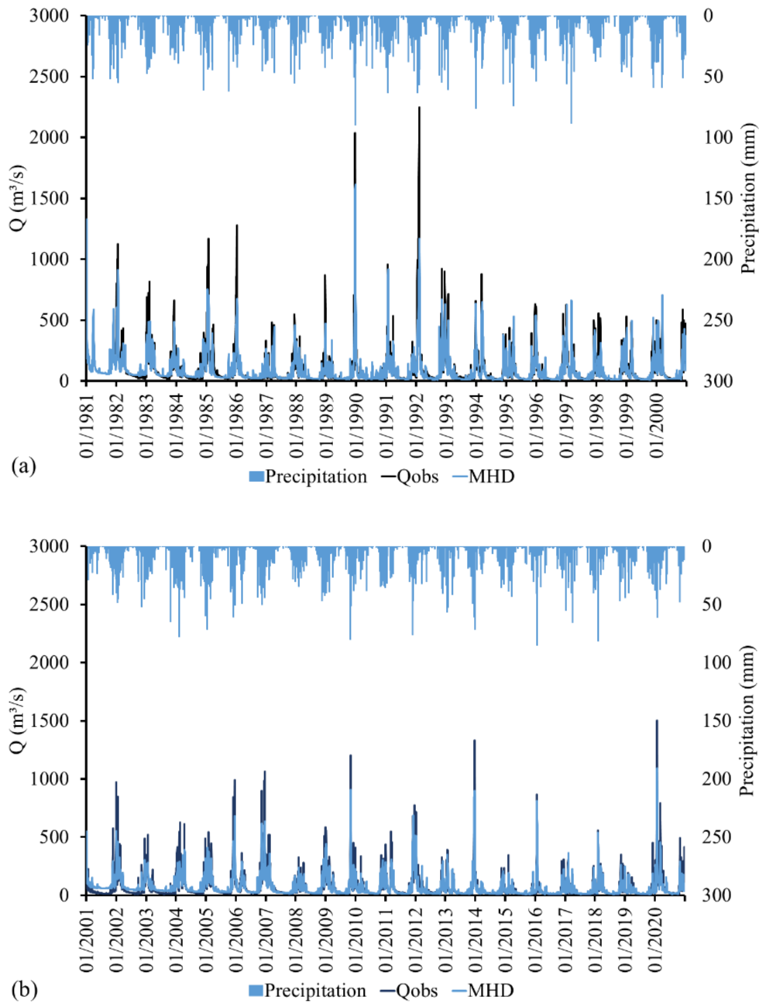

Figure 4. Observed and simulated hydrographs produced by the MHD, the corresponding hyetographs, for the calibration (a) and validation (b) in the JRB.

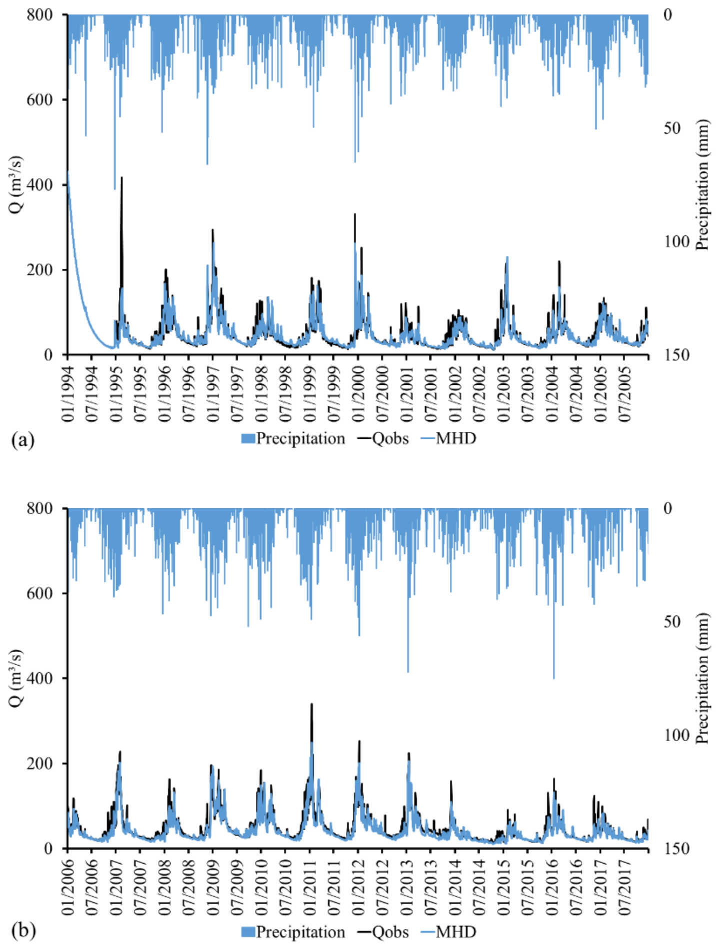

Figure 5. Observed and simulated hydrographs produced by the MHD model, the corresponding hyetographs, for the calibration (a) and validation (b) in the GRB.

Simulation of climate impacts on basins' hydrology

The climate impacts simulation was conducted at a daily time step for the baseline (1961-2000) and for the RCP 4.5 and RCP 8.5 scenarios over three periods over the century (2006-2040, 2041-2070, and 2071-2099). In Figures 6 and 7, we compare the FDC descriptors derived from observed and simulated climate data at the baseline. In JRB, the MWH and MWL indicators, respectively, associated with the high-flow and low-flow segments, reveal contrasting biases. The simulated MWH underestimated the observed value, suggesting difficulty in representing higher-magnitude streamflow. Conversely, simulated MWL overestimated the observed MWL, indicating that MHD tended to represent drought conditions as less severe than those observed. The SEASON indicator values, which represent the difference between streamflow in the dry and wet seasons, were similar, indicating that, overall, seasonality of the hydrological regime was adequately represented. However, QSM simulated using reference-period data was overestimated. Because QSM reflects the mid-range variability of runoff coefficients, steeper FDC slopes indicate greater streamflow responsiveness to precipitation due to increased intra-seasonal variability, which influences rainfall-runoff responses (Ley et al., 2011). Overall, these FDC descriptors in the simulation were close to those derived from the observed data.

Simulation based on the baseline data in GRB showed slight underestimation of MWH and overestimation of MWL. These results indicate a pattern similar to that observed in JRB, although less pronounced, showing that MHD reproducibility of the hydrological regime in GRB is more consistent. The values obtained for both SEASON and QSM indicators at baseline were very close to those derived from observed data, indicating adequate representation of seasonality and hydrological variability. Overall, the results indicate satisfactory model performance in reproducing the hydrological characteristics of both basins during the baseline. The differences between the FDC indicators obtained in the simulations in the baseline and those using observed data are expected, since in addition to uncertainties from the hydrological model parameterization, there are uncertainties generated by the climate models, downscaling process, radiative forcing of the RCP scenarios, and the bias correction of these data (Oliveira et al., 2017).

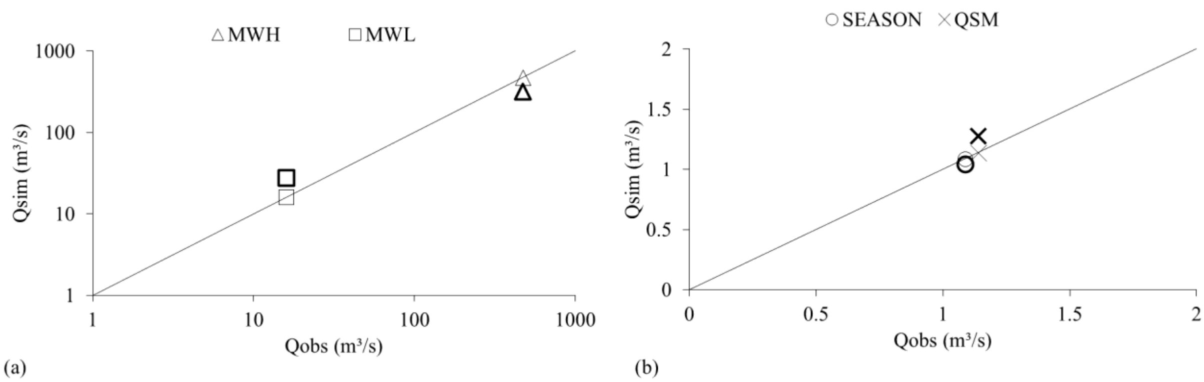

Figure 6. Comparison of the FDC indicators MWH, MWL, SEASON, and QSM calculated using streamflow simulated by MHD using observed and simulated climate data in the baseline in JRB.

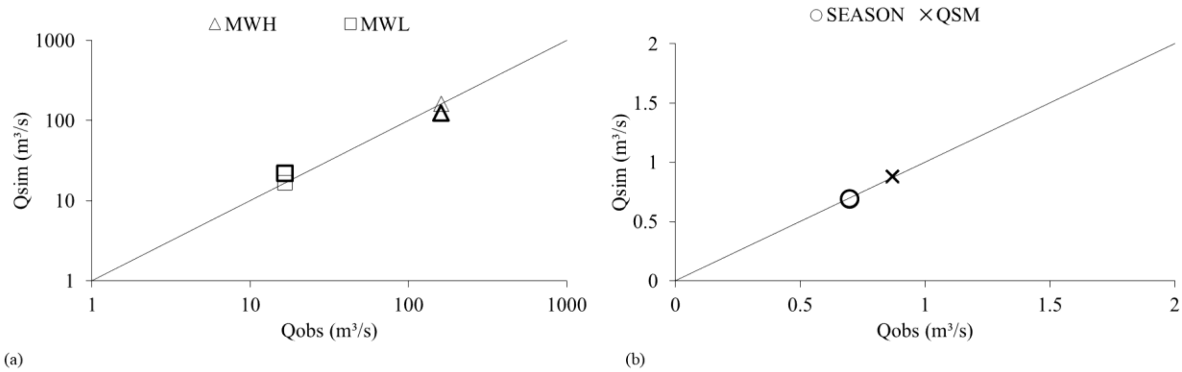

Figure 7. Comparison of the FDC indicators MWH, MWL, SEASON, and QSM calculated using streamflow simulated by MHD using observed and simulated climate data in the baseline in GRB.

The hydrographs simulated for the different climate scenarios with the MHD, and the Mann-Kendall and Sen tests applied to the simulated streamflow series for JRB and GRB are presented in Figures 8 and 9, respectively. JRB showed a significant downward trend in all projections except for the baseline. This reduction was greater in the 2041-2070 and 2071-2099 periods for both RCP scenarios. Ribeiro et al. (2024) conducted a hydrological study in JRB, observing significant reductions in annual mean daily streamflow and the minimum 7-day moving average flow ($Q_{7,\ min}$) from 1981 to 2020. The same study also reported an Anthropogenic Transformation Index (ITA) that classified this basin as "slightly degraded." Despite its largely *pristine* condition, rocky outcrops predominate in JRB (43% of its area), reducing its infiltration capacity. JRB's hydrogeology (schists, quartzites, and phyllites) shows characteristics that lead to low-productivity aquifers, namely low storage and low transmissivity. Consequently, the hydrological conditions of this basin tend to be more sensitive to climatic fluctuations and, therefore, more vulnerable to climate change.

In GRB, significant downward trends were also observed in all projections, with the greatest reduction in the 2041-2070 projection under RCP 8.5. In a study of the Furnas hydropower reservoir in GRB, Mello et al. (2021) observed a reduction in precipitation during 2007-2040 under RCP 4.5 and during 2071-2099 under RCP 8.5, with a consequent reduction in streamflow, particularly in baseflow. Ribeiro et al. (2024) also identified downward trends in mean annual daily streamflow and minimum 7-day moving average flow ($Q_{7,min}$) in GRB but much less significant, indicating that this basin is more resilient to climate change than the JRB. This resilience is linked to the basin's geomorphological characteristics, particularly the predominance of Oxisols, which are more resistant to water erosion and have high values of soil hydraulic conductivity (Pinto et al., 2016). Oxisols are characterized by deep soils with a large volume of well-distributed pores throughout the profile, properties that favor water storage and help maintain high soil moisture contents even during drought periods (Sena et al., 2021). A high soil hydraulic conductivity enhances infiltration and percolation, reducing surface runoff and promoting groundwater recharge (Cunha et al., 2015; Pessoa and Libardi, 2022). Thus, the physical and hydraulic properties of Oxisols play a fundamental role in basin-scale hydrological regulation, contributing to greater resilience under climate change.

Marques and Rodriguez (2019), when analyzing the water supply system of the Metropolitan Region of Rio de Janeiro and the lower Paraíba do Sul River basin using the MHD forced with GCMs, observed that the system may experience water deficit, especially in baseflow, since all Q90 streamflow projections were lower than the current demand in part of the basin. Paiva et al. (2024), also using the MHD in the Paraíba do Sul River basin, observed under RCP4.5 a reduction in maximum and minimum discharges during the 2016-2035 period, followed by an increase in 2036-2055. Under RCP8.5, they observed a downward trend in minimum flows during the first period and a larger reduction during the second period.

A comparison of the two study basins suggests that JRB is more susceptible to climate change impacts than GRB. In addition to geomorphological characteristics associated with low water yield, JRB is mostly located in northern Minas Gerais, a semi-arid region, marked by greater rainfall variability and recurrent prolonged droughts and meteorological dry spells (Ferreira and Silva, 2012). In contrast, GRB not only has more resilient geomorphological features but also receives higher rainfall totals, particularly due to orographic effects, in areas near the Mantiqueira Range, where annual precipitation can be greater than 2,300 mm (Mello et al., 2008), thereby contributing to greater water availability in this basin (Cândido and Nunes, 2011).

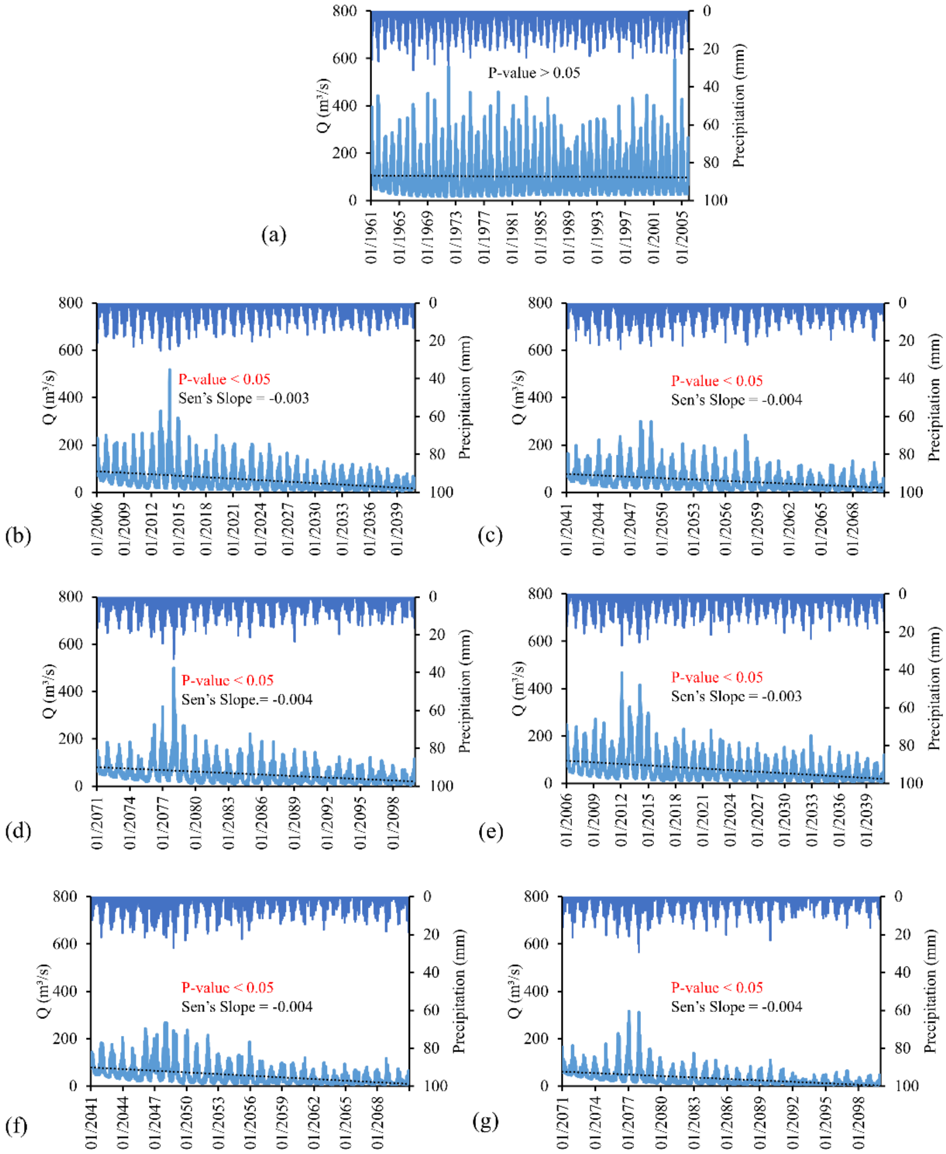

Figure 8. Simulated hydrographs in JRB for baseline (a), RCP 4.5 scenario for the periods 2006-2040 (b), 2041-2070 (c), and 2071-2099 (d), and RCP 8.5 scenario for the periods 2006-2040 (e), 2041-2070 (f), and 2071-2099 (g). P-values shown in red indicate statistically significant trends.

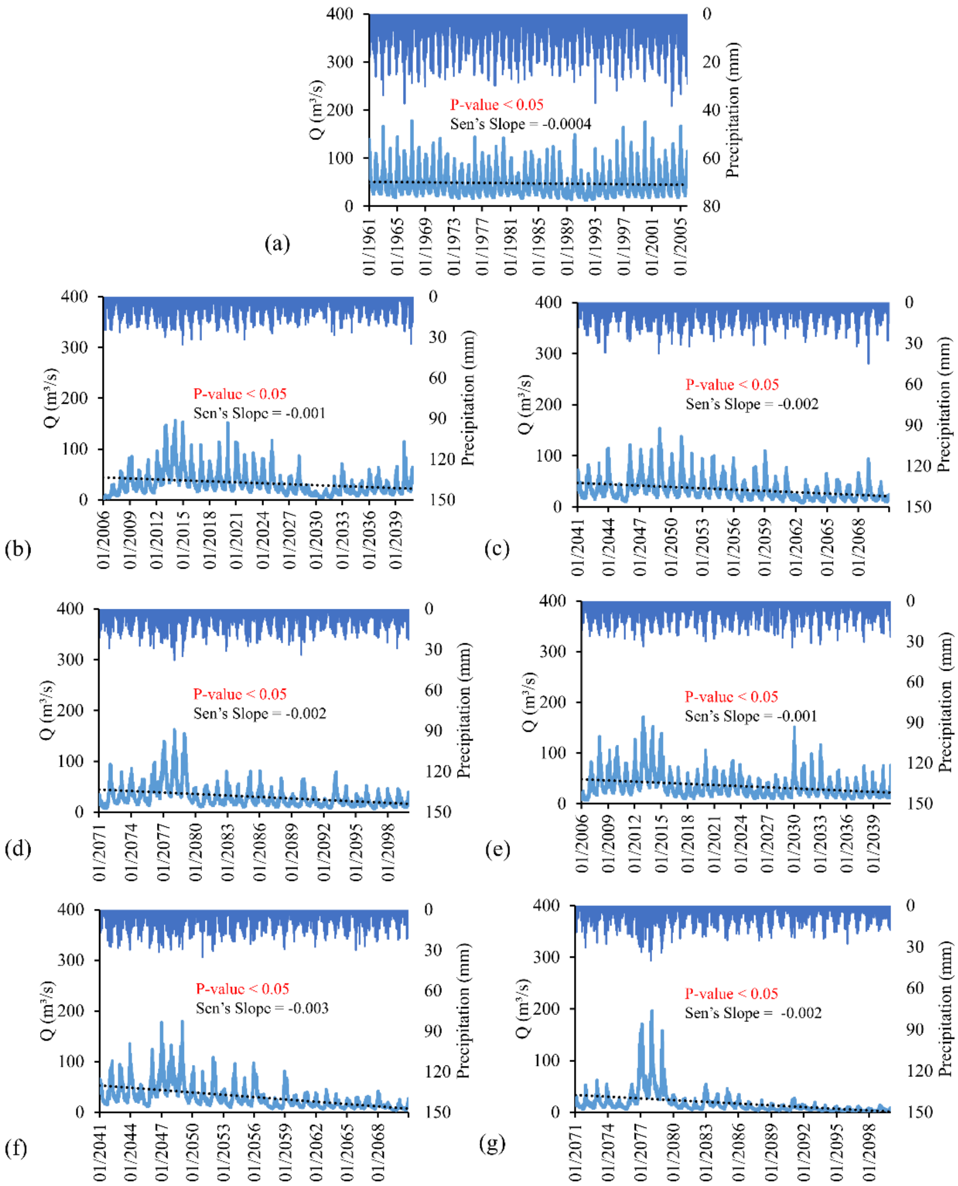

Figure 9. Simulated hydrographs in GRB for the reference period (a), RCP 4.5 scenarios for the periods 2006-2040 (b), 2041-2070 (c), and 2071-2099 (d), and RCP 8.5 scenarios for the periods 2006-2040 (e), 2041-2070 (f), and 2071-2099 (g). P-values shown in red indicate statistically significant trends.

Estimation of Groundwater Storage (S) in the studied basins

Figure 10 compares groundwater storage estimated from the observed-data period with that obtained from the baseline simulation for the same interval in JRB and GRB. In JRB, minimum groundwater storage was 6.2 mm during the observed period and 6.6 mm in baseline, while in GRB, they corresponded to 15.4 mm and 17.7 mm. In both basins, the simulation in the baseline slightly overestimated groundwater storage for most of the period.

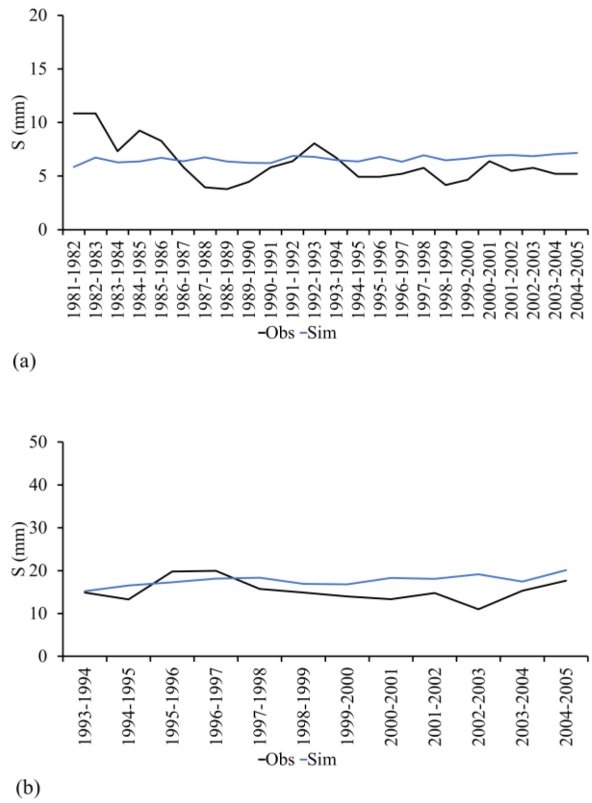

Figure 10. Comparison of the groundwater storage data obtained using the observed-data period and the baseline data in JRB (a) and GRB (b).

Figures 11 and 12 present the minimum annual groundwater storage estimates obtained with the Brutsaert method, and the Mann-Kendall and Sen tests results, for JRB and GRB, respectively. JRB has shown a decline in groundwater storage when compared to the baseline (Figure 13), highlighting the 2071-2099 projection under RCP 4.5, with a reduction of 49.6%. Considering RCP 8.5, reductions ranged from 31% to 44%, with the largest reduction occurring in the 2071–2099 projection (44%). In GRB, groundwater storage also has declined, with the largest reduction occurring in the 2071-2099 projection under RCP 8.5 (74.4%).

Analysis of the trend-test results shows that in the Jequitinhonha River basin downward trends were observed in all projections except for the reference period, with the greatest reduction occurring in the 2041-2070 projection under RCP 4.5. Under RCP 8.5, the greatest reduction was also observed in the 2041-2070 projection. In the Grande River basin, significant downward trends were observed across all projections, with the greatest reduction occurring in the 2041-2070 projection under RCP 8.5, which was also the period with the largest reduction in streamflow.

The larger streamflow reductions projected for the GRB are likely associated with the more pronounced precipitation reductions projected for this basin. The trend analysis indicated that precipitation reduction rates were consistently greater in the GRB than in the JRB across all future scenarios and projection periods. Furthermore, the highest precipitation reduction rates in the GRB were observed under the RCP 8.5 scenario during the 2041–2070 and 2071–2099 projection periods. Given the strong dependence of streamflow on precipitation inputs, larger decreases in rainfall are expected to reduce both direct runoff and groundwater recharge, resulting in lower water availability and more substantial reductions in river discharge. Therefore, the greater magnitude of streamflow decline observed in the GRB appears to be primarily driven by the more severe precipitation reductions projected for the basin under future climate conditions.

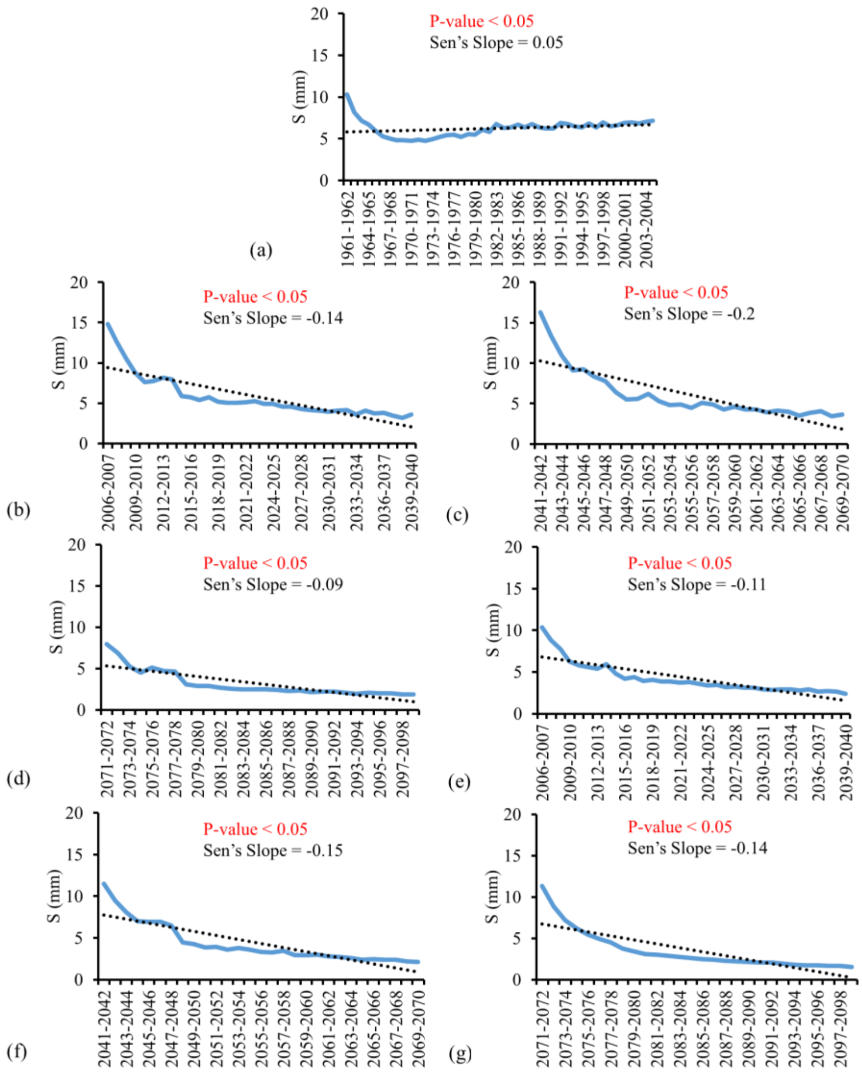

Figure 11. Estimated minimum annual groundwater storage (mm) for the baseline (a), RCP 4.5 scenario for the periods 2006-2040 (b), 2041-2070 (c), and 2071-2099 (d), and RCP 8.5 scenario for the periods 2006-2040 (e), 2041-2070 (f), and 2071-2099 (g), in JRB. P-values shown in red indicate statistically significant trends.

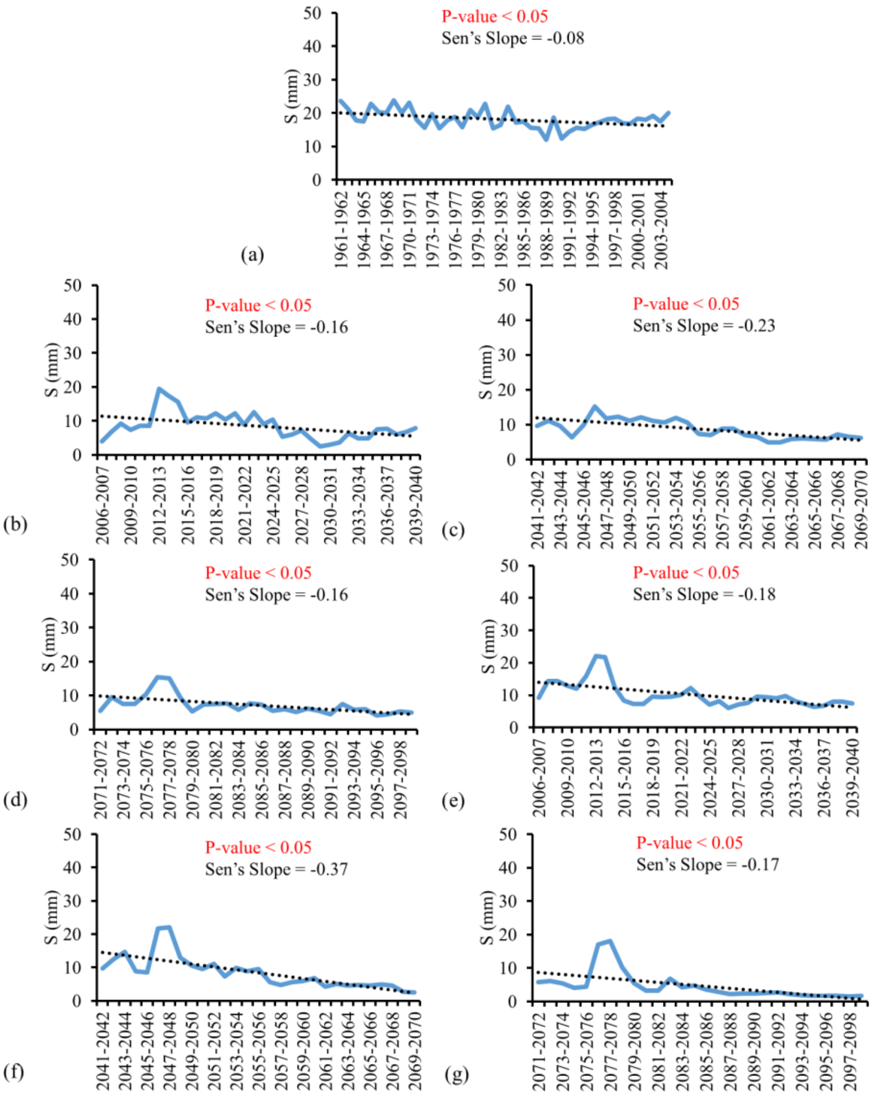

Figure 12. Estimated minimum annual groundwater storage (mm) for the baseline (a), RCP 4.5 scenario for the periods 2006-2040 (b), 2041-2070 (c), and 2071-2099 (d), and RCP 8.5 scenario for the periods 2006-2040 (e), 2041-2070 (f), and 2071-2099 (g), in GRB. P-values shown in red indicate statistically significant trends.

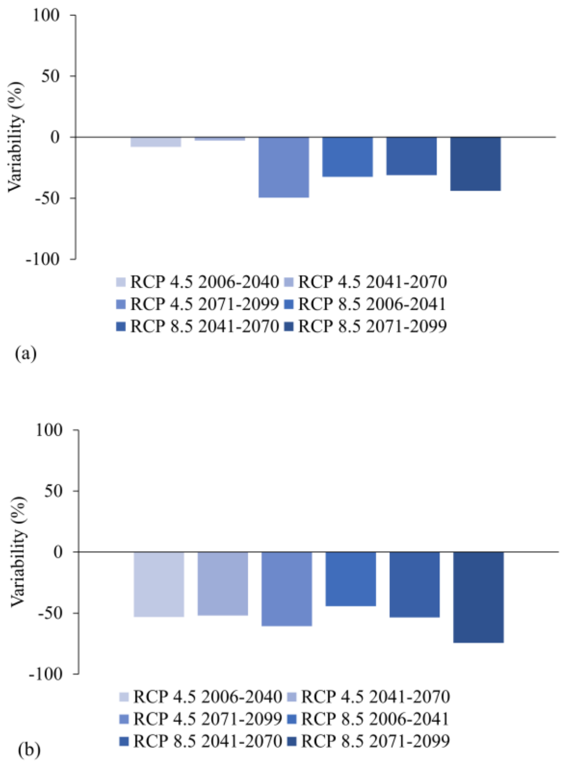

Figure 13. Variability of estimated minimum annual groundwater storage in different future scenarios relative to the baseline for JRB (a) and GRB (b).

Ribeiro et al. (2024) reported a minimum annual groundwater storage (*S*) of 5.4 mm in JRB and 30.9 mm in GRB over the 1981-2020 period. These values are comparable to those obtained in the present study for the baseline based on the MHD outputs. The higher S value in GRB is justified by the greater baseflow contribution and subsurface flow, which are influenced by the interaction between Atlantic Forest, soils and geology in the Mantiqueira Range. Pinto et al. (2016) and Mello et al. (2019) showed that this interaction enhances water infiltration via preferential flow paths and improves soil structure through the long-term accumulation of organic matter. By contrast, JRB is largely covered by rocky outcrops, which limit infiltration and groundwater storage. Consequently, this basin is highly vulnerable to the impacts of climate change because its geomorphological characteristics do not favor the natural basin hydrological regulation, i.e., the water storage in the basin. Compared with the baseline, both basins showed strong reductions under future scenarios, mainly under RCP 8.5, with the largest reduction in the 2006-2040 time slice projection for the GRB (53%). This result can be explained by the greater precipitation reductions projected for the GRB, with reduction rates consistently higher than those for the JRB across all future scenarios and projection periods. Therefore, although the JRB exhibits lower hydrological resilience due to its physical characteristics, the more severe climatic forcing projected for the GRB resulted in greater reductions in groundwater storage.

Ribeiro et al. (2024) detected a downward trend in groundwater storage in JRB of -0.11 mm/year for the 1981-2020 period. This trend may be associated with climate change because, despite the basin's pristine character, this basin has shown limited hydrological resilience caused by shallow soils, steep topography, and unfavorable hydrogeology (low storage and low transmissivity).

These authors also studied GRB and found a nonsignificant trend in groundwater storage during the same period (1981-2020). This basin has a "regular" Anthropogenic Transformation Index (ITA) (Ribeiro et al., 2024) as part of the basin exhibits substantial anthropogenic disturbance. GRB was more affected by deforestation for agricultural expansion, especially over Oxisols, and grassland implementation on Cambisols in the Mantiqueira Range region. Thus, the water-yield capacity in GRB may be more closely related to deforestation in the Atlantic Forest, as discussed by Mello et al. (2025). In this study, a significant downward trend in groundwater storage was simulated, especially in 2041-2070 period and RCP 8.5. This result is likely associated with the more pronounced reductions in precipitation projected for the GRB, which may contribute to substantial decreases in groundwater storage. Furthermore, although land-use changes were not explicitly evaluated in this study, alterations in land cover and anthropogenic disturbances within the basin may also contribute to changes in hydrological processes and groundwater dynamics. Therefore, the projected declines in groundwater storage are likely driven primarily by future climatic changes, potentially exacerbated by ongoing land-use transformations.

The projected reductions in groundwater storage are likely driven primarily by climate-related factors, especially greater decreases in precipitation and increased atmospheric water demand expected under future warming scenarios. Although anthropogenic land-use changes may influence basin hydrology, they were not explicitly evaluated in this study. Therefore, the simulated reductions in groundwater storage are more directly associated with projected climatic changes that affect groundwater recharge and basin water availability.

Our results suggest that GRB may become less resilient over the next century due to the combined effects of climate change and ongoing land-use change. Forest restoration and soil-conservation measures are urgent, particularly in pasture and agricultural areas located in hydrologically sensitive zones, like Cambisols and groundwater-recharge areas, to reduce surface runoff and increase soil water infiltration in the basin (Mello et al., 2025; Rodrigues et al., 2021; Oliveira et al., 2023). In addition, plans for native vegetation restoration in strategic areas have been identified as a key strategy for climate-change adaptation to increase hydrological resilience (Ellison et al., 2017; Brancalion et al., 2019; IPCC, 2022).

Conclusions

The MHD/INPE model showed satisfactory performance in JRB and GRB. Our simulation results indicate reductions in streamflow in all projections for both basins regarding the baseline. Significant downward trends were also identified in all future projections. Our results reveal that JRB has low resilience to climate change due to its geomorphology, soils and hydrogeology.

GRB has shown a downward trend in streamflow, which may be associated with climate change, despite the basin exhibiting greater anthropogenic disturbance and having been affected by deforestation in the Mantiqueira Range region, which is a fragile environment in the context of soil hydrology and erosion.

Regarding minimum groundwater storage, downward trends were observed in all projections in both basins. Relative to the baseline, both basins showed significant reductions under all future scenarios, especially RCP 8.5. Therefore, although GRB is more resilient to climate change, it may also be affected by the combined impacts of climate change and the land-use changes already observed. Conversely, restoration of forest cover in strategic areas may enhance groundwater recharge and increase basin resilience to climate change. These findings reinforce the relevance of ecological restoration and conservative soil management practices as tools for water management and water security in this basin.

Our findings help clarify how groundwater storage may respond to climate change, which is essential for water-resources planning. They can support management instruments such as defining reference flows, water-use planning, and adaptation strategies for climate variability. In addition, understanding groundwater storage dynamics is crucial to ensuring water security in headwater basins, which often sustain streamflow during dry periods.

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References

Brancalion PHS, Lamb D, Chazdon RL, Holl KD et al (2019) Global restoration opportunities in tropical forests. Science 366

Bruno E, Fiori A, Russo D (2026) Limitations of Budyko-based approaches for groundwater and baseflow assessments under climate and land use change. Journal of Hydrology 642

Brutsaert W (2008) Long-term groundwater storage trends estimated from streamflow records: climatic perspective. Water Resour Res 44: W02409.

Brutsaert W (2012) Are the North American deserts expanding? Some climate signals from groundwater storage conditions. Ecohydrology 5(5):541-549.

Brutsaert W, Nieber JL (1977) Regionalized drought flow hydrographs from a mature glaciated plateau. Water Resour Res 13: 637–643.

Budyko MI (1974) Climate and Life. Academic Press, New York

Bueno IT, Mello CR, Alves GJ et al (2020) Hydrological behavior and ecosystem services in headwater catchments of the Serra da Mantiqueira, southeastern Brazil. Journal of South American Earth Sciences 103.

Caldeira TL, Oliveira VA, Steinmetz AA, Viola MR, Beskow S (2018) Modelagem hidrológica determinística chuva-vazão em bacias hidrográficas: Uma abordagem introdutória. Revista Brasileira de Engenharia e Sustentabilidade 5(1):22-32.

Cândido DH, Nunes LH (2011) Influência da orografia na precipitação da área entre o vale do rio Tietê e a Serra da Mantiqueira. GEOUSP - Espaço e Tempo, 24:08-27.

Chou SC, Lyra A, Mourão C, Dereczynski C, Pilotto I, Gomes J, ... Marengo J (2014) Evaluation of the Eta simulations nested in three global climate models. American Journal of Climate Change 3(5):438-454.

CPRM – Serviço Geológico do Brasil (2021) Bases hidrogeológicas do Brasil. CPRM, Brasília. Available at: Geoportal SGB – Domínios Hidrogeológicos. Accessed 10 May 2023.

Cunge JA (1969) On the subject of a flood propagation computation method (Muskingum method). J Hydraul Res 7(2):205–230.

Cunha JE, Ferreira MM, Oliveira LFC (2015) Condutividade hidráulica e processos de infiltração em solos tropicais sob diferentes usos. Geoderma 245–246:56–65

Cunha ZA, Mello CR, Beskow S, Vargas MM, Guzman JA, Moura MM (2023) A Modeling Approach for Analyzing the Hydrological Impacts of the Agribusiness Land-Use Scenarios in an Amazon Basin. Land 2023 12:1422.

Déqué M, Rowell DP, Lüthi D, Giorgi F, Christensen JH, Rockel B, ... Van Den Hurk BJJM (2007) An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections. Climatic Change 81(Suppl 1):53-70.

Di Baldassarre G, Montanari A (2009) Uncertainty in river discharge observations: a quantitative analysis. Hydrol Earth Syst Sci 13:913–921.

Ellison D, Morris CE, Locatelli B et al (2017) Trees, forests and water: cool insights for a hot world. Global Environmental Change 43:51–61

Ferreira DBS, Silva JM (2012) Variabilidade climática e disponibilidade hídrica no norte de Minas Gerais: implicações para a gestão de recursos hídricos. Revista Brasileira de Climatologia 11(7):45–62

Flato G, Marotzke J, Abiodun B et al (2013) Evaluation of climate models. In: Stocker TF et al (eds) Climate Change 2013: The Physical Science Basis. Cambridge University Press, Cambridge, pp 741–866

Gash JHC, Lloyd CR, Lachaud G (1995) Estimating sparse forest rainfall interception with an analytical model. J Hydrol 170:79–86.

Ghaneei M, Wagener T, Li H (2026) Assessing groundwater contributions and hydrological resilience beyond Budyko frameworks. Hydrological Processes 40

Gil-García L, Montilla-López NM, Gutiérrez-Martín C, Sánchez-Daniel Á, Saiz-Santiago P, Polanco-Martínez JM, ... Pérez-Blanco CD (2024) Actionable human-water systems modeling under uncertainty. Hydrology and Earth System Sciences Discussions 2024:1-34.

Greve P, Orlowsky B, Mueller B, Sheffield J, Reichstein M, Seneviratne SI (2014) Global assessment of trends in wetting and drying over land. Nature Geoscience 7:716–721

Guzman JA, Moriasi DN, Chu ML, Starks PJ, Steiner JL, Gowda PH (2013) A tool for mapping and spatio-temporal analysis of hydrological data. Environmental modelling & software 48:163-170.

Hernandez DA, Guzman JA, Villamizar SR, Chu ML, Ribeiro C, Mello CR (2026). A Stepwise Back-Correction Function for Precipitation Representation on Hydrologic Models. Environmental Modelling & Software 198, 106908.

IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva

IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

IPCC (2022) Climate Change 2022: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge

Jarvis NJ (1989) A simple empirical model of root water uptake. J Hydrol 107:57–72.

Jones JA, Creed IF, Hatcher KL, Warren RJ, Adams MB, Benson MH, ... Williams MW (2012) Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites. BioScience 62(4):390-404.

Kalugin AS (2019) The impact of climate change on surface, subsurface, and groundwater flow: a case study of the Oka River (European Russia). Water Resources 46(Suppl 2):S31-S39.

Kendall MG (1975) Rank Correlation Methods, 4th edition. Charles Griffin, London, U.K.

Kim JH, Chung ES (2026) Insights into uncertainties in future drought analysis using hydrological simulation model. Hydrology and Earth System Sciences 30(1):227-247.

Knutti R, Sedláček J (2013) Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373

Ley R, Casper MC, Hellebrand H, Merz R (2011) Catchment classification by runoff behaviour with self-organizing maps (SOM). Hydrology and Earth System Sciences 15(9):2947-2962.

Lin K, Yeh H (2017) Baseflow recession characterization and groundwater storage trends in northern Taiwan. Hydrol Res 48(6):1745–1756.

Lyra A, Tavares P, Chou SC, Sueiro G, Dereczynski C, Sondermann M, ... Giarolla A (2018) 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.

Mann HB (1945) Nonparametric tests against trend. Econometrica: Journal of the econometric society 245-259.

MAPBIOMAS. Mapeamento Anual da Cobertura e Uso do Solo do Brasil. Available at: < https://brasil.mapbiomas.org/colecoes-mapbiomas/> Accessed 10 May 2023.

Maraun D, Shepherd TG, Widmann M, Zappa G, Walton D, Gutiérrez JM, ... Mearns LO (2017) Towards process-informed bias correction of climate change simulations. Nature Climate Change 7(11):764-773.

Marques AC, Rodriguez DA (2019) Avaliação de Cenários de Mudanças Climáticas no Planejamento dos Recursos Hídricos do Sistema de Águas da Região Metropolitana Rio de Janeiro e do Baixo Paraíba do Sul. Anuario do Instituto de Geociencias 42(4).

Martins FB, Gonzaga G, Santos DF, Reboita MS (2018) Classificação climática de Köppen e de Thornthwaite para Minas Gerais: cenário atual e projeções futuras. Revista Brasileira de Climatologia.

Mello CR, Guzman JA, Vieira NP, Viola MR, Beskow S, Guo L, ... Rodrigues AF (2025) Mitigating severe hydrological droughts in the Brazilian tropical high-land region: A novel land use strategy under climate change. International Soil and Water Conservation Research.

Mello CR, Ávila LF, Lin H, Terra MCNS, Chappell NA (2019) Water balance in a neotropical forest catchment of southeastern Brazil. Catena 173:9–21.

Mello CR, Norton LD, Curi N, Yanagi SNM (2012) Sea surface temperature (SST) and rainfall erosivity in the Upper Grande River Basin, Southeast Brazil. Ciência e Agrotecnologia 36:53-59.

Mello CR, Vieira N, Guzman JA, Viola MR, Beskow S, Alvarenga LA (2021) Climate change impacts on water resources of the largest hydropower plant reservoir in Southeast Brazil. Water 13(11):1560.

Mello CR, Viola MR, Norton LD, Silva AM, Weimar FA (2008) Development and application of a simple hydrologic model simulation for a Brazilian headwater basin. Catena 75(3):235-247.

Melo PA, Alvarenga LA, Tomasella J, Santos ACN (2024) Uncertainty analysis on long-term runoff projection from the Budyko framework and a conceptual hydrological model. Journal of Water and Climate Change 15(8):3850-3866.

Melo PA, Alvarenga LA, Tomasella J, Santos ACN, Mello CR, Colombo A (2022) On the performance of conceptual and physically based modelling approach to simulate a headwater catchment in Brazil. Journal of South American Earth Sciences 114:103683.

Michels-Brito A, Rodriguez DA, Junior WLC, Vianna JNS (2021) The climate change potential effects on the run-of-river plant and the environmental and economic dimensions of sustainability. Renewable and Sustainable Energy Reviews 147:111238.

Mizyed N (2018) Climate change challenges to groundwater resources: Palestine as a case study. Journal of water resource and protection 10(2):215-229.

Mohor GS, Rodriguez DA, Tomasella J, Júnior JLS (2015) Exploratory analyses for the assessment of climate change impacts on the energy production in an Amazon run-of-river hydropower plant. Journal of Hydrology: Regional Studies 4:41-59.

Monteith JL (1965) Evaporation and environment. In: Symposium of the Society for Experimental Biology, 19. Cambridge University Press, Cambridge, pp 205–234.

Moriasi DN, Gitau MW, Pai N, Dutta S (2015) Hydrologic and water quality models: performance measures and evaluation criteria. Transactions of the ASABE 58:1763–1785

Mustafa SMT, Hasan MM, Saha AK, Rannu RP, Van Uytven E, Willems P, Huysmans M (2019) Multi-model approach to quantify groundwater-level prediction uncertainty using an ensemble of global climate models and multiple abstraction scenarios. Hydrology and Earth System Sciences 23(5):2279-2303.

Negrão AC, Rodriguez DA, Chou SC, Medeiros GS, Junior JLS, Camargo CP (2017) Previsão de vazão de eventos extremos utilizando o modelo hidrológico distribuído MHD-INPE e previsões meteorológicas do modelo ETA-INPE para uma alta resolução espacial–estudo de caso: São Luís do Paraitinga (SP). Revista Brasileira de Cartografia 69(4):647-657.

Olarinoye T, Foppen JW, Veerbeek W, Morienyane T, Komakech H (2023) Exploring the future impacts of urbanization and climate change on groundwater in Arusha, Tanzania. In Groundwater (pp. 79-93). Routledge.

Oliveira CMM, Alvarenga LA, Beskow S, Cunha ZAD, Vargas MM, Melo PA, ... Silva VO (2023) Hydrological Model Performance in the Verde River Basin, Minas Gerais, Brazil. Resources 12(8):1-13.

Oliveira KD, Tomasella J, Caram RO, Falck AS, Sanches IDA (2022) Impacts of sugarcane expansion on water availability in a river basin in southeastern Brazil. Catena 216:106437.

Oliveira PTS, Sobrinho TA, Mingoti R (2023) Soil and water conservation practices and hydrological response in tropical agricultural watersheds. Agricultural Water Management 281

Oliveira VA, Mello CR, Viola MR, Srinivasan R (2017) 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(15):5005-5023.

O'Neill BC, Carter TR, Ebi KL, Harrison PA, Kemp-Benedict E, Kok K, Kriegler E, Preston BL, Riahi K, Sillmann J, van Ruijven BJ, van Vuuren DP, Carlisle D, Conde C, Fuglestvedt JS, Green C, Hasegawa T, Leininger J, Monteith S, Pichs-Madruga R (2020) Achievements and needs for the climate change scenario framework. Nat Clim Change 10:1074–1084.

Paiva ACE, Martins M, Canamary EA, Rodriguez DA, Tomasella J (2024) Inter-basin water transfers under changing climate and land use: Assessing water security and hydropower in the Paraíba do Sul River basin, Brazil. Journal of South American Earth Sciences 133:104707.

Pessoa RM, Libardi PL (2022) Dinâmica da água no solo e propriedades físico-hídricas de Latossolos sob condições tropicais. Revista Brasileira de Ciência do Solo 46

Petrucci E, Oliveira LA, Silva RC (2022) Secas pluviométricas no estado de Minas Gerais, de 1980 a 2017. RA’EGA 54:129-153.

Pinto LC, Mello CR, Norton LD, Owens PR, Curi N (2016) Spatial prediction of soil-water transmissivity based on fuzzy logic in a Brazilian headwater watershed. Catena 143:26-34.

Ribeiro CLC, Mello CR, Guzman JA (2024) Groundwater storage trend in headwater basins: shreds of evidence from the last decades in Minas Gerais state, Brazil. Environmental Earth Sciences 83(10):327.

Rodrigues DBB, Silva DD, Pruski FF (2021) Impacts of land use change on hydrological processes in Brazilian basins. Catena 198

Rodriguez DA, Lopes LG, Carriello F, Lázaro J, Júnior S, Pinto GL ... Chou SC (2017) Previsões de cheias extremas nos horizontes sazonais e de curto e médio prazos na bacia do rio Madeira: estudo de caso da enchente de 30 de março de 2014 em Porto Velho. CEP 24210:346.

Rupp DE, Selker JS (2006) On the use of the Boussinesq equation for interpreting recession hydrographs from sloping aquifers. Water resources research 42(12).

Santos CA, Rocha FA, Ramos TB, Alves LM, Mateus M, Oliveira RPD, Neves R (2019) Using a hydrologic model to assess the performance of regional climate models in a semi-arid watershed in Brazil. Water 11(1):170.

Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. Journal of the American statistical association 63(324):1379-1389.

Sena MM, Reis AM, Oliveira GC, Silva VR (2021) Propriedades físico-hídricas de Latossolos e implicações hidrológicas em bacias hidrográficas brasileiras. Revista Brasileira de Ciência do Solo 45

Shrestha M, Acharya SC, Shrestha PK (2017) Bias correction of climate models for hydrological modelling–are simple methods still useful?. Meteorological Applications 24(3):531-539.

Silva VO, Mello CR, Chou SC (2022) Projections of severe droughts in future climate in Southeast Brazil: a case study in Southern Minas Gerais State, Brazil. Theoretical and Applied Climatology 148(3):1289-1302.

Tomasella J, Gonçalves AS, Falck AS, Caram RO, Diniz FLR, Rodriguez DA, ... Siqueira GC (2019) Probabilistic flood forecasting in the Doce Basin in Brazil: Effects of the basin scale and orientation and the spatial distribution of rainfall. Journal of Flood Risk Management 12(1): e12452.

Tomasella J, Santos ACN, Falck AS, Melo PA, Caram RO (2022). Modelo hidrológico distribuído MHD-INPE: manual de implementação. Versão 2.0. Instituto Nacional de Pesquisas Espaciais.

Universidade Federal de Viçosa – UFV, Departamento de Solos – DPS/LABGEO (2024) Base de dados de solos do estado de Minas Gerais. DPS/LABGEO, Viçosa. Available at: DPS/LABGEO – UFV. Accessed 10 May 2023.

Viola MR, Mello CR, Acerbi Jr FW, Silva AMD (2009) Modelagem hidrológica na bacia hidrográfica do Rio Aiuruoca, MG. Revista Brasileira de Engenharia Agrícola e Ambiental 13: 581-590.

Viola MR, Mello CR, Chou SC, Yanagi SN, Gomes JL (2015) Assessing climate change impacts on Upper Grande River basin hydrology, southeast Brazil. International Journal of Climatology 35(6):1054-1068.

Wang D, Hejazi M (2011) Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. Water Resources Research 47:W00J12

Wang SJ, Lee CH, Yeh CF, Choo YF, Tseng HW (2021) Evaluation of climate change impact on groundwater recharge in groundwater regions in Taiwan. Water 13(9):1153.

Watson DF (1985). A refinement of inverse distance weighted interpolation. Geo-processing 2: 315-327.

'Statements and Declarations'

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TERCEIRA PARTE

3 CONSIDERAÇÕES FINAIS

Este estudo apresentou os resultados obtidos para o armazenamento subterrâneo em sub-bacias de cabeceira do estado de Minas Gerais, com base em dados históricos, assim como a simulação das vazões e do armazenamento subterrâneo futuro nas bacias dos rios Jequitinhonha e Grande. Verificou-se que fatores como a geomorfologia das bacias, associados às mudanças climáticas e alterações no uso do solo, podem contribuir para a redução no escoamento nas bacias ao longo do século.

O estudo indicou as bacias menos resilientes às mudanças climáticas, possibilitando que sejam tomadas medidas para garantir a disponibilidade hídrica nessas bacias no futuro. A bacia do rio Jequitinhonha encontra-se preservada, porém, apresenta baixa resiliência devido a suas características geomorfológicas, apresentando as maiores reduções no escoamento. A bacia do rio Grande apresenta acentuada antropização, e apresentou redução no armazenamento subterrâneo no futuro, o que pode impactar os recursos hídricos nesta bacia.

Concluiu-se que modelos hidrológicos, como o MHD/INPE, associados à modelos climáticos, juntamente com cenários futuros de emissão de gases, podem projetar o escoamento em diferentes cenários de mudanças climáticas, apresentando bom desempenho. Assim, os resultados obtidos nesse estudo podem auxiliar na gestão de recursos hídricos, especialmente no uso de mecanismos que possibilitem que a oferta atenda à demanda dos usuários, como a alocação de recursos hídricos.

A integração dos resultados obtidos nos dois artigos da tese, indica que, embora a bacia do rio Rio Grande apresente atualmente maior capacidade de regulação hidrológica e maior resiliência frente às mudanças climáticas, essa condição pode ser progressivamente comprometida pela intensificação das alterações no uso e cobertura do solo. Os resultados do Artigo 1 demonstraram a importância da interação entre cobertura florestal, características pedológicas e manutenção da disponibilidade hídrica, especialmente em áreas associadas a Cambissolos e zonas de recarga hídrica. Nesse contexto, a expansão de áreas agrícolas e de pastagens em regiões hidrologicamente sensíveis pode reduzir a infiltração, aumentar o escoamento superficial e comprometer a manutenção das vazões de estiagem, reduzindo a capacidade adaptativa da bacia frente às mudanças climáticas futuras.

Por outro lado, os resultados também sugerem que ações de restauração florestal e manejo conservacionista do solo podem contribuir para manutenção ou ampliação da resiliência hidrológica da bacia, especialmente em áreas estratégicas para recarga hídrica e conservação do fluxo de base. Dessa forma, os resultados obtidos reforçam a importância da integração entre planejamento do uso do solo, conservação ambiental e gestão de recursos hídricos como estratégia de adaptação às mudanças climáticas e promoção da segurança hídrica regional.

Para estudos futuros sugere-se a integração de modelagem hidrológica, dados hidrogeológicos e cenários de uso do solo, permitindo avaliar de forma mais completa os fatores que controlam o armazenamento subterrâneo. Além disso, sugere-se a ampliação do estudo para um maior número de bacias hidrográficas e diferentes contextos hidro climáticos, de forma a identificar padrões regionais e aumentar a robustez das conclusões.