

RESSALVA

Atendendo solicitação da
autora, o texto completo desta
tese será disponibilizado
somente a partir de 30/01/2028.

PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS E MEIO AMBIENTE

**Modeling Complex Water Systems (CWS): Integrated Water Resources
Management Supported by Qualitative and Quantitative Water Resource
Assessments**

CAROLINA STAGER QUAGGIO

Instituto de Geociências e Ciências Exatas
Campus de Rio Claro

Rio Claro/SP
2026

UNIVERSIDADE ESTADUAL PAULISTA
“Júlio de Mesquita Filho”
Instituto de Geociências e Ciências Exatas
Câmpus de Rio Claro

CAROLINA STAGER QUAGGIO

**MODELING COMPLEX WATER SYSTEMS (CWS): INTEGRATED WATER
RESOURCES MANAGEMENT SUPPORTED BY QUALITATIVE AND
QUANTITATIVE WATER RESOURCE ASSESSMENTS**

Tese de Doutorado apresentada ao
Instituto de Geociências e Ciências
Exatas do Câmpus de Rio Claro, da
Universidade Estadual Paulista “Júlio de
Mesquita Filho”, como parte dos
requisitos para obtenção do título de
Doutor em Geociências e Meio
Ambiente.

Orientador: Prof. Dr. Didier Gastmans
Coorientador: Prof. Dr. Daniel Carlos
Guimarães Pedronette

Rio Claro - SP

2026

Q1m

Quaggio, Carolina Stager

Modeling complex water systems (CWS) : integrated water resources management supported by qualitative and quantitative water resource assessments / Carolina Stager Quaggio. -- Rio Claro, 2026

190 p. : il., tabs., mapas

Tese (doutorado) - Universidade Estadual Paulista (UNESP), Instituto de Geociências e Ciências Exatas, Rio Claro

Orientador: Didier Gastmans

Coorientador: Daniel Carlos Guimarães Pedronette

1. Ciclo hidrológico. 2. Sistemas adaptativos complexos. 3. Hidrogeologia. 4. Hidroquímica. 5. Hidrologia. I. Título.

IMPACTO POTENCIAL DESTA PESQUISA

A pesquisa tem impacto potencial de estimular a transformação da atual Gestão Integrada dos Recursos Hídricos (ODS 6.5) em prol do aumento da resiliência hídrica, sustentabilidade e gestão participativa, com a definição de Sistemas Hídricos Complexos como conceito estratégico para uma gestão sistêmica e holística do ciclo hidrológico.

POTENTIAL IMPACT OF THIS RESEARCH

This research has the potential to stimulate a change in the current status of Integrated Water Resources Management (SDG 6.5) leading to increased water resilience, sustainability, and participatory management, by defining Complex Water Systems as a strategic concept for systemic and holistic management of the hydrological cycle.

UNIVERSIDADE ESTADUAL PAULISTA
“Júlio de Mesquita Filho”
Instituto de Geociências e Ciências Exatas
Câmpus de Rio Claro

CAROLINA STAGER QUAGGIO

**MODELING COMPLEX WATER SYSTEMS (CWS): INTEGRATED WATER
RESOURCES MANAGEMENT SUPPORTED BY QUALITATIVE AND
QUANTITATIVE WATER RESOURCE ASSESSMENTS**

Tese de Doutorado apresentada ao
Instituto de Geociências e Ciências
Exatas do Câmpus de Rio Claro, da
Universidade Estadual Paulista “Júlio de
Mesquita Filho”, como parte dos
requisitos para obtenção do título de
Doutor em Geociências e Meio
Ambiente.

Comissão Examinadora

Prof. Dr. DIDIER GASTMANS
CEA/UNESP/Rio Claro (SP)

Profa. Dra. ALEXANDRA VIEIRA SUHOGUSOFF
IGc/USP/São Paulo (SP)

Dra. ISADORA AUMOND KUHN
Serviço Geológico do Brasil/Porto Alegre (RS)

Prof. Dr. ANDRÉ SIMÕES BALLARIN
EESC/USP/São Carlos (SP)

Prof. Dr. GERSON CARDOSO DA SILVA JUNIOR
IGEO/UFRJ/Rio de Janeiro (RJ)

Conceito: Aprovado.

Rio Claro (SP), 30 de Janeiro de 2026.

ACKNOWLEDGEMENTS

Agradecimentos

À minha família, Gloria, Silvio, Fabiana, Lucas, Paula e Abuela. Por serem meus maiores torcedores.

Ao meu companheiro, Diego. Por ser meu porto seguro.

Aos amigos da vida, por estarem comigo em todos os momentos, Amanda Risk, Rodeio, Donzela, Pocahontas, Danoninho, Jaú e Escala.

Ao meu orientador, Didier. Por confiar e acreditar no meu trabalho, pelos ensinamentos e paciência.

Ao meu co-orientador, Daniel. Por me ensinar os caminhos das pedras na programação.

Ao LARHIA e as pessoas inspiradoras e apaixonadas pelo que fazem, Lucas (Juquinha), Vinícius, Marcela, Didier, Rafaela, Natália, Marcelo Cardio, Bruno, Amanda, Zayra, e Ana Beatriz. Pelo apoio, pelas conversas, e pela amizade.

Ao meu orientador no intercâmbio, Jan Boll, e aos amigos da Washington State University (WSU), Sara, Coti, Supriya, Ankit e Philip. Por me acolherem e me fazerem sentir à vontade em Pullman.

As maravilhosas da República Casa da Mãe, as tranqueiras de curva de rio, Escala, Lijão, Mari, Pri e Dandan. Obrigada pelas risadas e carinho.

Aos muitos profissionais que participaram do Projeto FEHIDRO e tornaram essa pesquisa possível. A equipe do projeto. Ao pessoal do DAEE de Barretos e comitê de bacias, Claudio, Guto, Leandro, Luiz, Caio e Luciana. Aos motoristas da UNESP, os guias das estradas a fora, Flávio, Edson Kbeça, José Carlos, Maximus e Sérgio. A todos que de alguma forma contribuíram, mas não foram mencionados.

O presente trabalho recebeu apoio do Fundo Estadual de Recursos Hídricos (FEHIDRO) Projeto 2019-BPG_COB-14, contrato nº 66/2020, realizado por convenio entre a UNESP e o SAAEB.

O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Código de Financiamento 001. Processo nº 88887.637660/2021.

O presente trabalho foi realizado com apoio da Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Brasil. Processos nº 2022/14.849-7 e nº 2023/13.079-6. As opiniões, hipóteses e conclusões ou recomendações expressas neste material são de responsabilidade do(s) autor(es) e não necessariamente refletem a visão da FAPESP.

RESUMO

As interações entre as componentes do ciclo hidrológico determinam a intensidade, caminhos e intercâmbios da água entre os reservatórios atmosféricos, superficiais e subterrâneos. Para compreender a interligação entre os reservatórios de água e a sociedade, esta pesquisa explora o conceito de Sistema Hídrico Complexo (SHC) dentro no contexto da Gestão Integrada dos Recursos Hídricos (GIRH) do estado de São Paulo. A área de estudo é a bacia do Baixo Pardo Grande (BXPG), uma bacia complexa localizada no nordeste de São Paulo que passou por mudanças significativas no uso do solo e flutuações na demanda por água superficial e subterrânea nas últimas décadas. O contexto geológico inclui rochas vulcânicas e sedimentares mesozoicas da intracratônica Bacia Sedimentar do Paraná. Existem três unidades hidrogeológicas principais: os sistemas aquíferos Guarani, Serra Geral e Bauru (doravante SAG, SASG e SAB). O objetivo desta pesquisa é avaliar os aspectos qualitativos e quantitativos do SHC do BXPG usando uma abordagem integradora de dados multidisciplinares. Uma visão holística e sistemática do balanço hídrico é usada para quantificar as mudanças no SHC e identificar os principais agentes de mudança, integrando dados hidroclimáticos de sensoriamento remoto, estações de monitoramento, transições no uso do solo e gestão hídrica. Após a filtragem, os conjuntos de dados incluem informações de 108 estações pluviométricas, 24 estações fluviométricas e três poços de monitoramento, bem como dados pontuais de 815 medições de águas subterrâneas e 1.549 outorgas de águas superficiais e subterrâneas. Historicamente, mudanças climáticas afetaram a bacia regionalmente e foram associadas ao aumento das temperaturas e à diminuição das precipitações. Já as mudanças no uso do solo afetaram principalmente as sub-bacias a jusante que transicionaram para o uso agrícola. Além disso, o aumento da frequência dos períodos de seca tem interferido na recarga do SAB, arenoso e não confinado. Visto a menor disponibilidade de dados quantitativos das águas subterrâneas, um modelo hidrogeológico conceitual é proposto baseado em dados qualitativos de 207 amostras de águas subterrâneas com informações hidro(geo)químicas, isotópicas e de tempo de residência. As águas subterrâneas são recarregadas pela precipitação nas porções aflorantes do SAB e SASG. As assinaturas isotópicas enriquecidas no SAB e SASG, com $\delta^{18}\text{O}$ maior que -7 ‰, sugerem que processos de evaporação podem ocorrer durante a recarga. Por outro lado, o SAG é completamente confinado, com idade de águas subterrâneas fósseis e assinaturas empobrecidas, com $\delta^{18}\text{O}$ menor que -8 ‰. Diversos processos de interação água-rocha moldam a composição hidroquímica das águas subterrâneas, como a dissolução de minerais carbonáticos e silicatos, formação de minerais secundários, trocas iônicas e mistura de águas subterrâneas, que variam em função do confinamento e disponibilidade mineralógica dos aquíferos. No BXPG, a análise do SHC mostrou que a GIRH tradicional tem dificuldade em mitigar os impactos das mudanças climáticas e em aumentar a resiliência hídrica. Assim, são necessárias medidas transformadoras para melhorar a capacidade de adaptação do SHC. Para criar caminhos sustentáveis futuros, a GIRH deve melhorar as redes de monitoramento, estabelecer um sistema de dados dinâmico que apoie a tomada de decisões informadas e forneça informações hidro(geo)lógicas confiáveis, e incentivar a diversificação do uso da terra para melhorar o balanço hídrico do SHC e preparar o caminho para uma transformação a longo prazo.

Palavras-chave: Baixo Pardo Grande, ciclo hidrológico, sistemas adaptativos complexos, hidrogeologia, hidroquímica e hidrologia.

ABSTRACT

Interactions among components of the hydrologic cycle determine the intensity, pathways and exchanges of water between atmospheric, surface, and groundwater reservoirs. To understand the interconnection between the water reservoirs and the society, this research explores the Complex Water System (CWS) concept within the São Paulo state Integrated Water Resources Management (IWRM) framework. The study area is the Baixo Pardo Grande (BXPG) basin, a complex basin located in northeastern São Paulo that has experienced significant land use changes and fluctuating surface and groundwater demands over the past few decades. The geological context includes Mesozoic volcanic and sedimentary rocks from the intracratonic Paraná Sedimentary Basin. There are three main hydrogeological units: Guarani, Serra Geral and Bauru aquifer systems (thereafter GAS, SGAS and BAS). The objective of this research is to evaluate qualitative and quantitative aspects of the BXPG CWS using a data-driven, integrative approach. A holistic and systematic view of the water balance is used to quantify changes in the CWS and identify their main drivers by integrating remote sensing and on-ground time series datasets, land use transitions, and water management frameworks. After filtering, the on-ground datasets include information from 108 rain gauges, 24 streamflow stations, and three monitoring wells, as well as data points from 815 groundwater measurements and 1,549 water grant records. Historically, climate change events have affected the basin regionally and are associated with increasing temperatures and decreasing rainfall. Meanwhile, land use changes have mostly affected downstream sub-basins that have transitioned to agricultural use. Additionally, the increased frequency of droughts has interfered with the recharge of the sandy, unconfined BAS. Due to the limited quantitative data on groundwater, a conceptual hydrogeological model is proposed based on qualitative data from 207 groundwater samples, which include hydro(geo)chemical, isotopic, and residence time information. Groundwater is recharged by precipitation within the outcrop portions of the BAS and SGAS. The enriched isotopic signatures in the BAS and SGAS, and with $\delta^{18}\text{O}$ greater than -7 ‰, suggest that evaporation processes may occur during recharge. Conversely, the GAS is completely confined, of fossil groundwater age, and with depleted $\delta^{18}\text{O}$ signatures smaller than -8 ‰. The hydrochemistry of groundwater is shaped by multiple water-rock interaction processes, such as the dissolution of carbonate and silicate minerals, the formation of secondary minerals, ionic changes, and groundwater mixing. These processes vary depending on the confinement of the aquifers and the availability of minerals. In the BXPG, the CWS analysis showed that traditional IWRM has difficulty mitigating the impacts of climate change and enhancing water resilience. Thus, transformative measures are needed to improve CWS's ability to adapt. To create sustainable pathways for the future, IWRM must improve monitoring networks, establish a living data system that supports informed decision-making and provides reliable hydro(geo)logical information, and encourage diversification of land use to improve CWS water balance and pave the way for long-term transformation.

Keywords: Baixo Pardo Grande, water cycle, complex adaptative system, hydrogeology, hydrochemistry, and hydrology.

LIST OF FIGURES

Figure 1 – Complex adaptive relationships in the water reservoirs of the hydrological cycle within the Baixo Pardo Grande (BXPG) basin context.	16
Figure 2 – Characterization maps of the WRMU 12 – Baixo Pardo Grande Basin, within the context of the Paraná Sedimentary Basin represented on continental and regional maps (a, b, c). (d) Inhabitants by municipality according to the latest CENSUS (IBGE, 2022). (e) Percentage of water demand per use. (f) Percentage of water discharge source between groundwater and surface water.	28
Figure 3 – Water demand on the basin according to the sources (a) and surface water (b) and groundwater (c) categorized by the use.	29
Figure 4 – Socioeconomic development indexes for WRMU-12. (a) Population growth according to SEADE. (b) Basin's Gross Domestic Product (GDP) categorized by income type. (c) Municipal GDP per capita. (d) Water and wastewater service volumes (consumed/treated) on the left axis, and percentage of the served population on the right axis.	30
Figure 5 – Terrain characterization maps of the WRMU 12 – Baixo Pardo Grande Basin. (a, b, c) Continental and regional contexts. (d) Digital Elevation Model from Miranda (2005), including the names of the main rivers and sub-basin numbers. (e) Terrain slope expressed as a percentage.	31
Figure 6 – Geological characterization maps of the WRMU 12 – Baixo Pardo Grande Basin. (a) Paraná Sedimentary Basin. (b) Zoomed view of São Paulo State. (c) Hydrogeological map of WRMU 12. (d) Hydrogeological section from LARHIA, DAEE, and SAAEB (2023).	32
Figure 7 – Thickness maps of the hydrogeological units in the Water Resources Management Unit (WRMU) 12 – Baixo Pardo Grande Basin, adapted LARHIA, DAEE, and SAAEB (2023). Continental and regional maps are shown on the left (a, b, c), (d) Bauru Aquifer System (BAS), (e) Serra Geral Aquifer System (SGAS), (f) Guarani Aquifer System (GAS).	33
Figure 8 - Flowchart for the consulted sources, datasets, filtering, and units.	42
Figure 9 – Maps for the consulted datasets: (a) streamflow stations, (b) rain gauges, (c) surface water rights, (d) groundwater rights, and (e) monitoring wells over the Digital Elevation Model (DEM)(MIRANDA, 2005), with the main river names.	45
Figure 10 – Groundwater level measurements for the Bauru Aquifer Systems (BAS – a), Serra Geral Aquifer System (SGAS – b), and Guarani Aquifer System (GAS – c).	47
Figure 11 – Percentage of data for the rain gauge and streamflow (a, b), as well as a histogram (c, d) and relation with amount of available data (c1, d1), and count of normality (e, f) and trend (g, h) tests results for the daily-monthly-annual time scale. Blue tones refer to rainfall, while green tones refer to streamflow.	50
Figure 12 – Histograms for information on the GWE per year from the water grants (a), and GWE of the two piezometers in the BAS (W1 – b, W2 – c) and the GAS (d) monitoring well.	52

Figure 13 – Pie charts for the water rights according to the water source (a), groundwater source (b), water demand (c), water demand for agricultural (d), industrial (e), and supply (f) according to the water source.	53
Figure 14 – Location of the selected rain gauge (a, b) and streamflow stations (c, d) classified by the number of daily records (a, c) and according to the time periods (b, d), and the location of the stations over the DEM (e).	58
Figure 15 – Basin's time series for the remote sensing data (a, f) and variation during the periods presented on boxplots (b, c, d, e) at annual scale.	62
Figure 16 – FDC for streamflow station SF15 (a – upstream) and SF30&31 (b – downstream), box plot for streamflow (a, b – 1), rainfall (a, b – 2) in the closest rain gauge, and groundwater elevation (GWE) from the BAS monitoring wells (c, d) compared to the rainfall from remote sensing and the closest rain gauge, months are classified as dry using SPEI values.	64
Figure 17 - Land Use and Land Cover (LULC) use percentage per sub-basin; the paired sub-basins are shaded.	65
Figure 18 – Relations between rainfall and evapotranspiration (a, b) and surface runoff and rainfall (c, d) for the SB02 (a, c) and SB09 (b, d). RL: regression lines.	67
Figure 19 – Reconstructed timeline of the CWS, based on information about water governance (top), hydroclimatic change (middle), and time series significant breakpoints, spatially distributed (bottom).	69
Figure 20 – Location map of the BXPG groundwater samples, classified by the type of information available.	76
Figure 21 – Overview of the hydro(geo)chemical, isotopic and statistical analysis methodology.	79
Figure 22 - Hydro(geo)chemical characteristics of the aquifers: Diagram of Piper (a); Ca (b) and Na (c) minerals stability; calcite saturation index versus P_{CO_2} (d) and SiO_2 saturation index (e); and samples location map (f), classified by the hydrochemical type.	84
Figure 23 - Water stable isotopes correlation, $\delta^{18}O$ and δ^2H , with the Local Meteoric Water Line (LMWL) from Rio Claro, for the BXPG basin groundwater samples and aquifer's signature regression line (RL).	85
Figure 24 – BXPG aquifers hydrogeological conceptual model.	88
Figure 25 - PC1 x PC2 results with isotope data for all aquifers (a) samples and separated for the BAS (b), SGAS (c), and GAS (d).	92
Figure 26 - Oxygen-18 ($\delta^{18}O$) isoscapes (left column) and GWE (right column) for the BAS (a, b), SGAS (c, d) and GAS (e, f).	94
Figure 27 – Oxygen-18 ($\delta^{18}O$) isoscapes (left column) with real and synthetic data and isoscapes residual maps from Figure 26 (right column), in percentage, for the BAS (a, b), SGAS (c, d) and GAS (e, f).	96

LIST OF TABLES

Table 1 – Description of the aquifer systems present in the Baixo Pardo Grande Basin.	35
Table 2 – Description of the datasets used in this research.....	37
Table 3 – Description of available files.....	43
Table 4 – Hydrochemical groups description by aquifer.	89

LIST OF ACRONYMS

AI: Artificial Intelligence	GWS: Groundwater Hydrogeological model supplementary material
ANA: National Water Agency of Brazil	HLA: Holistic Assessment supplementary material
ANN: Artificial Neural Networks	IAEA: International Atomic Energy Agency
BAS: Bauru Aquifer System	IBE: Ionic Balance Error
BXPG: Baixo Pardo Grande	IBGE: Brazilian Institute of Geography and Statistics
CBH: Comitê de Bacia Hidrográfica	IPCC: Intergovernmental Panel on Climate Change
CDTN: Nuclear Technology Development Center, Brazil	IWRM: Integrated Water Resources Management
CETESB: Environmental Sanitation Technology Company	KMO: Kaiser–Meyer–Olkin test
CMIP: Coupled Model Intercomparison Project	kNN: k-Nearest Neighbors
CRP: Coordinated Research Project	kNN-1: kNN with 1 neighbor
CONAMA: Conselho Nacional do Meio Ambiente	LARHIA: Laboratory of Water Resources and Environmental Isotopes
CWS: Complex Water System	LMWL: Local Meteoric Water Line
DAEE (now SPÁguas): Department of Water and Electric Energy	LR: Linear Regression
DEM: Digital Elevation Model	LULC: Land Use and Land Cover
DP: Data Paper supplementary material	MAE: Mean Absolute Error
DT: Decision Trees	ML: Machine Learning
EC: Electrical Conductivity	MLP: Multilayered Perceptron
EMBRAPA: Brazilian Company of Farming Research	MSE: Mean Square Error
ETP: Evapotranspiration	NA: Not Applicable
FEHIDRO: São Paulo State Water Resources Fund	NDC: Nationally Determined Contributions
FA: Factor analysis	PAC2050: Climate Action and Sustainable Development Plan for São Paulo
FDC: Flow Duration Curve	PCA: Principal Component Analysis
FEWS NE: Famine Early Warning Systems Network	PEARC: São Paulo State Plan for Climate Adaptation and Resilience
FLDAS: Famine Early Warning Systems Network Land Data Assimilation System	PEMC: São Paulo State Policy on Climate Change
GAS: Guarani Aquifer System	PNMC: Brazilian National Policy on Climate Change
GDP: Gross Domestic Product	Q: Flow
GHG: Greenhouse Gases	r: Pearson correlation coefficient
GNIP: Global Network for Isotopes in Precipitation	R: Rainfall
GWE: Groundwater Elevation	

RBF: Radial Basis Function
RHN: Hydrometeorological National Network
RL: Regression Line
RIMAS: Integrated Water Monitoring Network of the SGB
RMP: Piezometric Monitoring Network of the SPÁguas
RMSE: Root Mean Square Error
ROF: Runoff
RT: Recharge Time
R²: Coefficient of determination
SAAEB: Autonomous Service of Water and Sewage of Bebedouro
SBXX: Sub-basin *number from 01 to 10*
SEADE: São Paulo State Data Analysis System Foundation
SF: Streamflow
SGAS: Serra Geral Aquifer System
SGB: Geological Survey of Brazil
SIAGAS: Groundwater Information System of the SGB
SIDAS D: Groundwater Information System of the SPÁguas, digital archives
SIDAS ARC: Groundwater Information System of the SPÁguas, physical archives
SNIS: National Sanitation Information System
SOE: Sistema de Outorga Eletrônica

SPÁguas: São Paulo State Water Agency
SPEI: Standardized Precipitation Evaporation Index
SRTM: Shuttle Radar Topography Mission
SVR: Support Vector Regression
SVM: Support Vector Machines
T: Transit Time
T0: time period up to 1990
T1: time period 1991-2000
T2: time period 2001-2010
T3: time period 2011-2020
TDS: Total dissolved solids
UN: United Nations
UNCED: United Nations Conference on Environment and Development
UNEP: United Nations Environment Programme
UNFCCC: United Nations Framework Convention on Climate Change
VIF: Variance Inflation Factor
WMO: World Meteorological Organization
WARM: Water Resources Management Journal
WRMU: Water Resources Management Units
WS: Water Surplus
WTP: Water Treatment Plants
XAI: Explainable AI

TABLE OF CONTENTS

1 INTRODUCTION	15
2 OBJECTIVES	20
3 CLIMATE CHANGE AND THE WATER CYCLE	21
4 STUDY AREA	27
4.1 SOCIO-ECONOMIC CHARACTERISTICS	27
4.2 HYDRO-GEOGRAPHICAL CHARACTERISTICS	30
5 METHODOLOGY AND DATASETS OVERVIEW	36
6 PART 1: HOLISTIC ASSESSMENTS OF COMPLEX WATER SYSTEM	40
6.1 RAINFALL, STREAMFLOW, AND GROUNDWATER DATASET FROM A COMPLEX BASIN IN NORTHEASTERN SÃO PAULO, BRAZIL	41
6.1.1 Data source and selection	41
6.1.1.1 Rain gauge and streamflow station	44
6.1.1.2 Monitoring wells	45
6.1.1.3 Groundwater data points	46
6.1.1.4 Water demand	47
6.1.2 Time series processing	48
6.1.3 Data Overview	49
6.1.3.1 Rain gauges and streamflow stations time series	49
6.1.3.2 Data points	51
6.1.3.3 Groundwater datasets	51
6.1.3.4 Water demand and uses	53
6.1.4 Data records	54
6.1.5 Technical Validation	55
6.1.5.1 Uncertainty and future perspectives	56
6.1.6 Data Availability	56
6.1.7 Code Availability	56
6.2 A HOLISTIC ASSESSMENT OF CLIMATE CHANGE, LAND USE, AND WATER GOVERNANCE THROUGH COMPLEX WATER SYSTEMS	57
6.2.1 Methodology and data	57
6.2.1.1 Land Use and Land Cover (LULC)	57
6.2.1.2 Hydroclimatic remote sensing data	57
6.2.1.3 Ground monitoring stations	57
6.2.1.4 CWS changes tracking	59
6.2.2 Results	61
6.2.2.1 Temporal and spatial behavior of the CWS	61

6.2.2.2 Hydrological responses of LULC change in the CWS	65
6.2.3 Discussion	68
6.2.4 Conclusions	71
7 PART 2: HYDRO(GEO)CHEMICAL MODELING AS A COMPLEMENTARY TOOL FOR INTEGRATED WATER RESOURCES MANAGEMENT	73
7.1 DATA AND METHODS	75
7.1.1 Groundwater samples	75
7.1.2 Tritium (^3H) concentrations	76
7.1.3 Krypton-Helium (^{81}Kr - ^4He) chronometer	77
7.1.4 Groundwater elevation (GWE)	77
7.1.5 Hydrochemical and isotopic assessment	77
7.1.6 Multivariate analysis	79
7.1.7 Machine Learning (ML) regression model	81
7.2 RESULTS	82
7.2.1 Physicochemical characteristics	82
7.2.2 Water isotope signatures and residence time	84
7.2.3 Multivariate analysis	85
7.2.4 ML regression model	86
7.3 DISCUSSIONS	87
7.3.1 Hydrochemical and isotopic evolution	87
7.3.2 Groundwater flow	93
7.3.3 ML synthetic data to support IWRM	95
7.4 CONCLUSIONS	97
8. CONCLUSIONS	99
REFERENCES	102
DP SUPPLEMENTARY MATERIAL	122
HLA SUPPLEMENTARY MATERIAL	149
GWS SUPPLEMENTARY MATERIAL	160

1 INTRODUCTION

The water cycle describes the continuous movement of water between the atmosphere, land surface, subsurface and ocean environments. Variations in the water balance arise from the finite availability, consumption, and recycling of water among atmospheric, surface water, and groundwater components. Because these components are interconnected, changes in one part of the system can propagate through others. This integrated perspective is captured by the concept of a Complex Water System (CWS), defined as a group of interacting water components that respond collectively to both endogenous and exogenous drivers, where system interactions are more significant than individual components (HUGGINS et al., 2023).

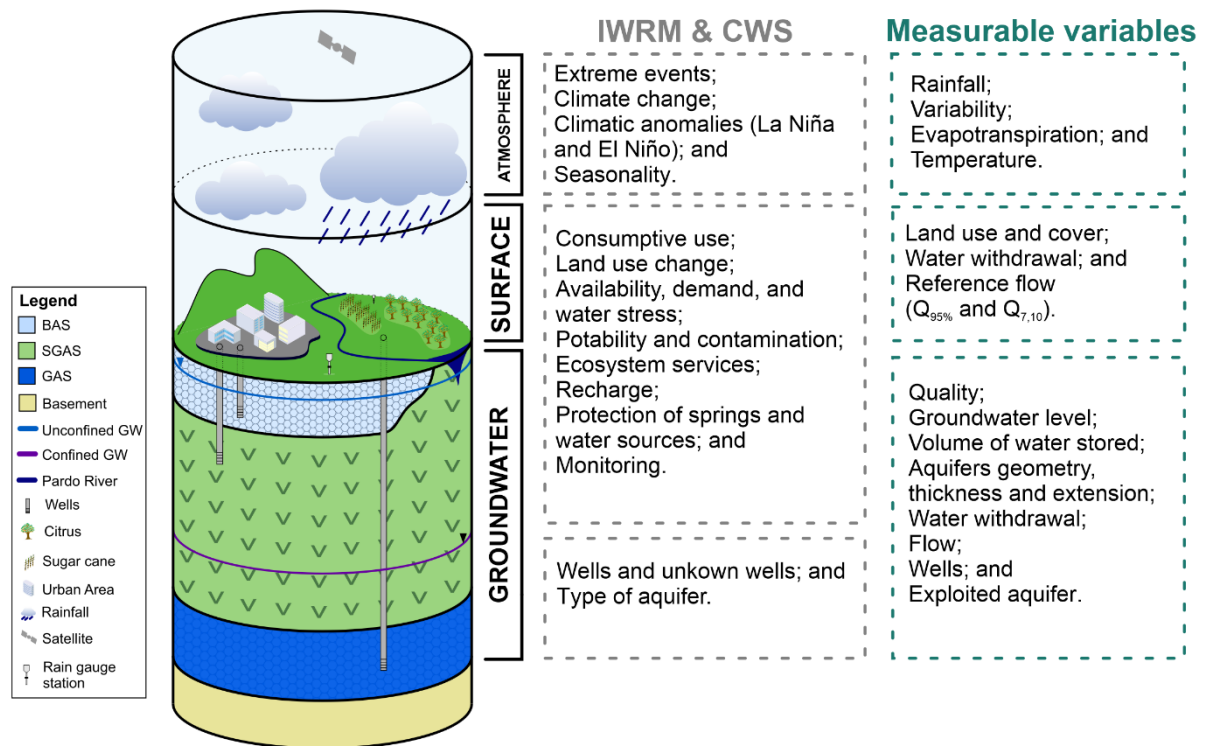
Hydrological processes within CWS are influenced by multiple natural factors, including topography, soils, geology, hydrogeology, climate, and land use (TAO et al., 2022), as well as by human water management practices (ZHAO et al., 2025). Consequently, human interventions in freshwater systems can redistribute natural water resources at regional to global scales (ABBOTT et al., 2019; SEO et al., 2023) and potentially affect the resilience of CWSs under climate change.

Humans exert a pivotal role in the water cycle. For instance, in order to support an ever-increasing population (UNESCO, 2019), human activities are causing consequences that may be irreversible (GUNDERSON et al., 2017). Documented consequences include the loss of water quality (SCHWARZENBACH et al., 2010), increasing water scarcity (MEKONNEN; HOEKSTRA, 2016), loss of biodiversity (MANTYKA-PRINGLE et al., 2015), groundwater overexploitation (FAMIGLIETTI, 2014), water conflicts (ANGELAKIS et al., 2021; PETERSEN-PERLMAN; VEILLEUX; WOLF, 2017), and effects on recharge processes and baseflow (HEALY; COOK, 2002). These changes observed in the CWS have the potential to diminish the quality of life for affected populations and intensify the effects of climate change.

The magnitude of environmental impacts of human activities, in addition to the climate-related impacts, has motivated global initiatives to protect the environment and promote sustainable global development. In this context, Integrated Water Resources Management (IWRM) is a widely adopted management strategy that considers the water cycle as an interconnected system, integrated to environmental management (PADOVESI-FONSECA; FARIA, 2022), that monitors the interrelated aspects of water quality and quantity, and promotes mutual surface and groundwater

monitoring (PAGNOCCHESCHI, 2016). IWRM is responsible for creating the mechanisms to promote the participation of stakeholders from different sectors of society (SAVENIJE; VAN DER ZAAG, 2008). To address the climate- and human-induced adaptations observed in CWS, it is imperative to constantly rethink the IWRM strategy in order to rapidly respond to fast and emergent changes. Effective management requires quantifying changes to CWS functions and communicating complex hydrological information clearly to support IWRM (Figure 1).

Figure 1 – Complex adaptive relationships in the water reservoirs of the hydrological cycle within the Baixo Pardo Grange (BXPG) basin context.



The 'IWRM & CWS' column lists the observed adaptations in the water reservoirs, while the 'Measurable Variables' column lists the features that define reservoir behavior. BAS: Bauru Aquifer System. SGAS: Serra Geral Aquifer System. GAS: Guarani Aquifer System. GW: groundwater.

Source: prepared by the author, 2026.

In Brazil, the Federal Government regulates water resources through the Water Law (Lei 9.433, BRASIL, 1997), which establishes instruments for managing water resources. The 1988 Brazilian Federal Constitution (BRASIL, 1988) has granted the domain over groundwater resources to the states, whereas the domain over streamflow is shared between the Union and the states. If a river crosses state boundaries, the domain is federal; otherwise, it is classified as belonging to the state.

Groundwater management, on the other hand, is the sole responsibility of the states, even though groundwater does not follow political boundaries but rather geomorphological and hydrogeological settings. This legal arrangement is often criticized for its lack of coordination of shared management between the States and the Federal Government (VILLAR; HIRATA, 2022). Moreover, both the state and the Union participate in the management of transboundary aquifers.

Brazil faces significant challenges in maintaining continuous monitoring networks (MELO et al., 2020), which undermines effective IWRM. The creation and maintenance of monitoring networks enable the government to measure and manage water resources in accordance with Water Law. To overcome data sparsity, climate change studies frequently employ a combined approach, integrating observed and remote sensing data (BALLARIN et al., 2023a; CHAGAS; CHAFFE; BLÖSCHL, 2022; CUNHA et al., 2018; MARENGO et al., 2020, 2023). This approach supports CWS analysis by facilitating deeper understanding of the interactions and linkages between water reservoirs, which can occur on multiple and simultaneous spatial and temporal scales.

The ability of a remote sensing technique to represent a geographical phenomenon depends on the spatial resolution of the data, the calibration model, and the frequency of data acquisition. Conversely, hydrological techniques, being empirical, aim to characterize phenomena through well-defined mathematical equations based on in situ data. In addition to robust process quantification, hydrological techniques require multidisciplinary analytical capabilities to represent water's socio-ecological functions at multiple temporal and spatial scales (HUGGINS et al., 2023). Hydrological studies often integrate isotopic, hydro-physicochemical, hydro(geo)chemical, geological, and computational methods to evaluate the quantitative and qualitative aspects of water resources.

For hydro(geo)logy, water resources and environmental management and sustainability, ML algorithms can improve the assessment of complex interactions and provide useful insights into natural and decision-making processes. In such cases, hybrid modeling is recommended due to the expected complexity (TAO et al., 2022). When applied to hydrologic studies, ML can represent hydrologic processes that would otherwise not be identified by traditional hydrologic techniques (NEARING et al., 2021). However, purely data-driven ML methods are not well suited for dealing to complex

geoscience questions, despite their overall superior efficiency and accuracy in geoscience inference and prediction (ZHAO et al., 2024).

The objective of this research is to evaluate the qualitative and quantitative aspects of CWS in order to understand its adaptation and to support informed IWRM decision-making. The novelty of this thesis lies in integrating hydroclimatic remote sensing, rain gauge, streamflow, and groundwater level data to quantify the extent of changes in the water balance, assess its main drivers, and support the consolidation of CWS as a concept to be used within the IWRM framework. Additionally, it expands the CWS concept from the quantitative to the qualitative aspects by proposing a hydro(geo)chemical conceptual model, complemented by stable isotopes and residence time data, which contributed to understanding water-rock processes. Machine Learning (ML) models have been employed to replicate the conceptual model from groundwater samples data. These models have also been used to produce synthetic isotopic fingerprints.

This research is presented in manuscript format and is divided into two parts, which covers qualitative and quantitative aspects of the CWS. Detailed information on the authorship and journal is as follows:

1. *Quantitative*

- a. Quaggio, C.S.; Santarosa, L.V.; Moffatt, P.; Sacchi, M.D.; Valdambrini, B.; Soares, A.R.; Boll, J.; Gastmans, D. A Holistic Assessment of Climate Change, Land Use, and Water Governance Through Complex Water Systems. *Water Resour Manage* 40, 135 (2026). <https://doi.org/10.1007/s11269-025-04375-4>
- b. Quaggio, C.S.; Santarosa, L.V.; Valdambrini, B.; Soares, A.R.; Gastmans, D. Rainfall, Streamflow, and Groundwater Dataset from a Complex Basin in Northeastern São Paulo, Brazil. Submitted to Scientific Data.

2. *Qualitative*

- a. Quaggio, C.S.; Ramos, M.A.C.; Arruda, N.S.; Valdambrini, B.; Constantino, A.P.; Kirchheim, R.; Pedronette, D.C.G.; Gastmans, D. Hydro(Geo)Chemical Modeling as a Complementary Tool for Integrated Water Resources Management.

The first part provides a holistic assessment of the CWS in the BXPG, based on quantitative analysis of spatial and temporal changes in the water balance. A data descriptor of the accessed time series and data points are presented. Then, time series with more than ten years of data were used to access the CWS historical change over the past 30 years, by integrating IWRM management decisions, data-driven hydrological analysis, and reconstructing a timeline to assess the combined effect of Land Use and Land Cover (LULC) or/and climate change in the CWS dynamics. This section addresses the following scientific question: How can an understanding of CWS behavior help define the main drivers of changes in the water balance? How can IWRM be improved by performing a CWS analysis?

The second part presents the construction of the hydro(geo)chemical conceptual model based on groundwater samples, along with the isotopic analysis and ML results. Specifically, this section addresses the following scientific questions: Can the isotopic composition elucidate groundwater flow and mixing processes within the well-documented hydro(geo)chemical evolution of the Paraná Sedimentary Basin? Is there a better ML regression algorithm for estimating the isotopic composition of groundwater?

8. CONCLUSIONS

This thesis introduces the concept of CWS within IWRM frameworks by representing the water balance and socio-environmental functions as a unique water system. In this system, adaptation is understood as the equilibrium resulting from the influence of exogenous and endogenous factors. A CWS was modelled using data from the Baixo Pardo Grande (BXPB) basin, located in northeastern São Paulo. This region is particularly well-suited for such analysis due to its significant land-use changes, fluctuating surface and groundwater demands over recent decades, and its hydrogeological context within the Paraná Sedimentary Basin, formed by three layered aquifers of regional importance. This complexity is often observed in global hydrological contexts.

In the BXPB, the CWS influencing factors were associated with climate change, historical LULC, local governance, and water use — groundwater and surface water. Although climate change is considered an exogenous factor, its influence began in the nineties and became intertwined with the effects of LULC. However, LULC, local governance, and water use are endogenous factors shaped by the decisions and actions of communities within the basin. IWRM and water governance within BXPB were consolidated in 1996 with the CBH-BPG water committee, with the participation of the population, local water authorities, water users, universities, and other stakeholders. Historically, CBH-BPG deliberations have focused on supplying the growing demand for water, consolidating legal frameworks, and investing in water infrastructure projects and hydrogeological knowledge.

The effects of climate change are evident in the overall increase in temperature and reduction in precipitation, reflected by the decrease in streamflow. This could potentially impact river-aquifer interactions. An increase in the frequency and duration of droughts can reduce the recharge of the sandy and unconfined BAS, consequently reducing rivers baseflow.

LULC changed from pastureland to agricultural land, primarily sugarcane, over the last 30 years. The hydrological effects of monoculture consolidation depend on how long the land has been used for agriculture. In sub-basins that transitioned to agriculture between 2000 and 2010, there was a noticeable increase in surface runoff after the transition, followed by a reduction and homogenization of surface runoff and evapotranspiration. Sub-basins with a long history of agriculture use have more

consistent evapotranspiration and experienced a reduction in surface runoff after 2010. These results demonstrate the homogenization of the water balance due to single land use over an extended period of time, intertwined with an overall reduction in precipitation due to the effects of climate change.

There are only three monitoring wells in the BXPG basin, which hinders the assessment of the effects of historical LULC and climate change on groundwater and on the local river-aquifer connection in the CWS modeling. Further studies can address these aspects. Nevertheless, combining GWE maps, hydro(geo)chemical modeling, groundwater isotopic signatures, and residence time data enabled the development of a comprehensive conceptual model of groundwater in the basin that aligns with the well-documented hydrogeology of the Paraná Sedimentary Basin.

In the BXPG basin, the hydrochemical characteristics of the groundwater are similar between aquifers due to their common rock origin within the Paraná Sedimentary Basin. To distinguish between the aquifers, traditional modelling of groundwater hydro(geo)chemical, stable isotope, residence time data, and statistical grouping analysis were used. The BXPG conceptual model was validated with literature, which enabled the filling of isotopic data gaps by producing synthetic $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data with ML regression models. The ML synthetic isotope data provided details about groundwater pathways that align with groundwater flow maps. Due to the “black box” nature of ML algorithms, knowledge of the hydrogeological framework of the Paraná Sedimentary Basin was crucial to support the isotopic estimation.

Groundwater in the BXPG is mostly recharged by precipitation within the outcrop portions of for the BAS and SGAS. Enriched isotopic signatures in the BAS and SGAS, greater than -7‰ and plotted below the LMWL, suggest that evaporation processes may occur during recharge. In these aquifers, the groundwaters is mostly Ca-Mg— HCO_3 hydrochemical type, open to atmospheric CO_2 , with shorter residence times and younger ages. Conversely, the GAS is completely confined, formed mostly by the Na— HCO_3 hydrochemical type, close to atmospheric CO_2 , of fossil groundwater age, and with depleted $\delta^{18}\text{O}$ signatures smaller than -8‰ . The water-rock interaction processes that shaped the hydrochemistry of groundwater in BXPG are associated with the dissolution of carbonate and silicate minerals under different confinement conditions and mineral availability; the formation of secondary minerals; ionic changes; and groundwater mixing.

Hydrochemically, processes of groundwater mixing are observed in samples with higher concentrations of Na, SO₄ and HCO₃ in deeper wells from the GAS relative to the contribution of groundwater from the underlying Permian units. Isotopically, the depleted isotopic signature characteristic of the GAS can be used to indicate groundwater mixing in the basin. Groundwater mixing between the SGAS and GAS is observed in the eastern portion of the basin, in areas of higher terrain, and near urban areas. The depleted signatures observed in the three aquifers in the southern portion of the basin may demonstrate the influence of major river streams in facilitating groundwater mixing. Additionally, the concentration of pumping wells in urban areas may induce greater groundwater mixing rates. In the case of BXPG, where the depleted GAS groundwater can mix with other groundwater, IWRM faces an additional challenge. Overexploitation of groundwater in the basin can eventually lead to the exhaustion of the GAS fossil groundwater and compromise its quality.

Integrating remote sensing and on-ground data enabled the identification of exogenous and endogenous CWS factors that influence the behavior of water balance components across spatial and temporal dimensions. The limitations of the modeling are the quality and quantity of the hydro(geo)logical information. To produce more accurate results, it is imperative to invest in monitoring initiatives, particularly for groundwater, as well as in the creation of living data systems that facilitate informed decision-making regarding water and LULC management.

In the face of upcoming challenges related to climate change scenarios, energy transition, and food production, there is an increasing urgency to enhance resilience and find sustainable pathways for socioeconomic development. Traditional IWRM is not resilient enough to compensate for the effects of climate change. Transformative measures are needed to improve CWS's ability to adapt. One such measure is creating basin-scale LULC adaptation plans that propose optimal hydrological and spatial solutions to improve environmental health and produce regional, collective benefits from local adaptations. Ultimately, all decisions and initiatives must be considered within the framework of water governance, with active social participation in the development of new pathways.

REFERENCES

- ABBOTT, B. W.; BISHOP, K.; ZARNETSKE, J. P.; MINAUDO, C.; CHAPIN, F. S.; KRAUSE, S.; HANNAH, D. M.; CONNER, L.; ELLISON, D.; GODSEY, S. E.; PLONT, S.; MARÇAIS, J.; KOLBE, T.; HUEBNER, A.; FREI, R. J.; HAMPTON, T.; GU, S.; BUHMAN, M.; SARA SAYEDI, S.; URSACHE, O.; CHAPIN, M.; HENDERSON, K. D.; PINAY, G. Human domination of the global water cycle absent from depictions and perceptions. **Nature Geoscience**, v. 12, n. 7, p. 533–540, 2019. Available at: <<https://www.nature.com/articles/s41561-019-0374-y>>. Access: 15 oct. 2024.
- AGGARWAL, P. K.; MATSUMOTO, T.; STURCHIO, N. C.; CHANG, H. K.; GASTMANS, D.; ARAGUAS-ARAGUAS, L. J.; JIANG, W.; LU, Z.-T.; MUELLER, P.; YOKOCHI, R.; PURTSCHERT, R.; TORGERSEN, T. Continental degassing of 4He by surficial discharge of deep groundwater. **Nature Geoscience**, v. 8, n. 1, p. 35–39, 2015. Available at: <<https://www.nature.com/articles/ngeo2302>>. Access: 24 oct. 2024.
- ANA, AGÊNCIA NACIONAL DE ÁGUAS E SANEAMENTO BÁSICO. **Conjuntura dos recursos hídricos no Brasil 2021**: relatório pleno. Brasília: ANA, 2022. Available at: <https://www.snirh.gov.br/portal/centrais-de-conteudos/conjuntura-dos-recursos-hidricos/conjuntura_2021_pdf_final_revdirec.pdf>. Access: 15 oct. 2024.
- ANGELAKIS, A. N.; VALIPOUR, M.; AHMED, A. T.; TZANAKAKIS, V.; PARANYCHIANAKIS, N. V.; KRASILNIKOFF, J.; DRUSIANI, R.; MAYS, L.; EL GOHARY, F.; KOUTSOYIANNIS, D.; KHAN, S.; GIACCO, L. J. D. Water Conflicts: From Ancient to Modern Times and in the Future. **Sustainability**, v. 13, n. 8, p. 4237, 2021. Available at: <<https://www.mdpi.com/2071-1050/13/8/4237>>. Access: 15 oct. 2024.
- APPELO, C. A. J.; POSTMA, D. **Geochemistry, groundwater and pollution**. 2. ed. London: CRC Press, 2004. Available at: <<https://doi.org/10.1201/9781439833544>>.
- ÁVILA, A.; JUSTINO, F.; WILSON, A.; BROMWICH, D.; AMORIM, M. Recent precipitation trends, flash floods and landslides in southern Brazil. **Environmental Research Letters**, v. 11, n. 11, p. 114029, 2016. Available at: <<https://dx.doi.org/10.1088/1748-9326/11/11/114029>>. Access: 15 oct. 2024.
- BALLARIN, A. S.; SONE, J. S.; GESUALDO, G. C.; SCHWAMBACK, D.; REIS, A.; ALMAGRO, A.; WENDLAND, E. C. CLIMBra - Climate Change Dataset for Brazil. **Scientific Data**, v. 10, n. 1, p. 47, 2023a. Available at: <<https://www.nature.com/articles/s41597-023-01956-z>>. Access: 15 oct. 2024.
- BALLARIN, A. S.; UCHÔA, J. G. S. M.; DOS SANTOS, M. S.; ALMAGRO, A.; MIRANDA, I. P.; DA SILVA, P. G. C.; DA SILVA, G. J.; GOMES JÚNIOR, M. N.; WENDLAND, E.; OLIVEIRA, P. T. S. Brazilian Water Security Threatened by Climate Change and Human Behavior. **Water Resources Research**, v. 59, n. 7, p. e2023WR034914, 2023b. Available at: <<https://onlinelibrary.wiley.com/doi/abs/10.1029/2023WR034914>>. Access: 15 oct. 2024.

BALLARIN, A. S.; WENDLAND, E.; ZAERPOUR, M.; HATAMI, S.; MEIRA NETO, A. A.; PAPALEXIOU, S. M. Frequency Rather Than Intensity Drives Projected Changes of Rainfall Events in Brazil. **Earth's Future**, v. 12, n. 1, p. e2023EF004053, 2024a. Available at: <<https://onlinelibrary.wiley.com/doi/abs/10.1029/2023EF004053>>. Access: 15 oct. 2024.

BALLARIN, A. S.; OLIVEIRA, P. T. S.; UCHÔA, J. G. S. M.; LIMA, C. H. R.; ZAERPOUR, M.; GODOY, M. R. V.; MEIRA NETO, A. A.; PAPALEXIOU, S. M.; WENDLAND, E. Escalating threat of human-perceived heatwaves in Brazil. **Environmental Research Communications**, v. 6, n. 11, p. 111004, 2024b. Available at: <<https://iopscience.iop.org/article/10.1088/2515-7620/ad9140>>. Access: 8 jan. 2026.

BALLARIN, A. S.; VARGAS GODOY, M. R.; ZAERPOUR, M.; ABDELMOATY, H. M.; HATAMI, S.; GAVASSO-RITA, Y. L.; WENDLAND, E.; PAPALEXIOU, S. M. Drought intensification in Brazilian catchments: implications for water and land management. **Environmental Research Letters**, v. 19, n. 5, p. 054030, 2024c. Available at: <<https://iopscience.iop.org/article/10.1088/1748-9326/ad3e18>>. Access: 8 jan. 2026.

BANERJEE, D.; GANGULY, S.; KUSHWAHA, S. Forecasting Future Groundwater Recharge from Rainfall Under Different Climate Change Scenarios Using Comparative Analysis of Deep Learning and Ensemble Learning Techniques. **Water Resources Management**, v. 38, n. 11, p. 4019–4037, 2024. Available at: <<https://doi.org/10.1007/s11269-024-03850-8>>. Access: 24 nov. 2024.

BARBOSA FILHO, J.; DE OLIVEIRA, I. B. Development of a groundwater quality index: GWQI, for the aquifers of the state of Bahia, Brazil using multivariable analyses. **Scientific Reports**, v. 11, n. 1, p. 16520, 2021. Available at: <<https://www.nature.com/articles/s41598-021-95912-9>>. Access: 26 dec. 2024.

BATISTA, L. V.; GASTMANS, D.; SÁNCHEZ-MURILLO, R.; FARINHA, B. S.; DOS SANTOS, S. M. R.; KIANG, C. H. Groundwater and surface water connectivity within the recharge area of Guarani aquifer system during El Niño 2014–2016. **Hydrological Processes**, v. 32, n. 16, p. 2483–2495, 2018. Available at: <<https://onlinelibrary.wiley.com/doi/10.1002/hyp.13211>>. Access: 4 jan. 2026.

BENAAFI, M.; HAMANAH, W. M.; AL-WAJIH, E. Modelling the Isotope composition of groundwater using hydrochemical properties in eastern Saudi Arabia: Implementation of innovative data intelligence techniques. **Journal of Hydrology: Regional Studies**, v. 57, p. 102138, 2025. Available at: <<https://www.sciencedirect.com/science/article/pii/S2214581824004877>>. Access: 30 dec. 2025.

BENZ, S. A.; IRVINE, D. J.; RAU, G. C.; BAYER, P.; MENBERG, K.; BLUM, P.; JAMIESON, R. C.; GRIEBLER, C.; KURYLYK, B. L. Global groundwater warming due to climate change. **Nature Geoscience**, v. 17, n. 6, p. 545–551, 2024. Available at: <<https://www.nature.com/articles/s41561-024-01453-x>>. Access: 11 nov. 2024.

BERGHUIJS, W. R.; COLLENTEUR, R. A.; JASECHKO, S.; JARAMILLO, F.; LUIJENDIJK, E.; MOECK, C.; VAN DER VELDE, Y.; ALLEN, S. T. Groundwater

recharge is sensitive to changing long-term aridity. **Nature Climate Change**, v. 14, n. 4, p. 357–363, 2024. Available at: <<https://www.nature.com/articles/s41558-024-01953-z>>. Access: 15 oct. 2024.

BERKES, F.; ROSS, H. Panarchy and community resilience: Sustainability science and policy implications. **Environmental Science & Policy**, v. 61, p. 185–193, 2016. Available at: <<https://www.sciencedirect.com/science/article/pii/S1462901116300843>>. Access: 15 oct. 2024.

BLEIDORN, M. T.; PINTO, W. de P.; SCHMIDT, I. M.; MENDONÇA, A. S. F.; REIS, J. A. T. Dos. Methodological approaches for imputing missing data into monthly flows series. **Revista Ambiente & Água**, v. 17, p. e2795, 2022. Available at: <<https://www.scielo.br/j/ambiagua/a/DS6nBnWsZWJzjWYCSGjt3Qj/?lang=en>>. Access: 10 oct. 2025.

BONOTTO, D. M. Hydro(radio)chemical relationships in the giant Guarani aquifer, Brazil. **Journal of Hydrology**, v. 323, n. 1, p. 353–386, 2006. Available at: <<https://www.sciencedirect.com/science/article/pii/S0022169405004440>>. Access: 20 dec. 2024.

BRASIL. **Constituição da República Federativa do Brasil de 1988**. Brasília, 1988. Available at: <https://www.planalto.gov.br/ccivil_03/constituicao/constituicao.htm>.

BRASIL. **Política Nacional de Recursos Hídricos – Lei 9.433**, de 8 janeiro de 1997. Brasília, 1997. Available at: <https://www.planalto.gov.br/ccivil_03/leis/l9433.htm>. Access: 08 jan. 2026.

BRASIL. Comitê Interministerial sobre Mudança do Clima. **Plano Nacional Sobre Mudança do Clima – PNMC**. Brasília, 2008. Available at: <https://antigo.mma.gov.br/estruturas/smcq_climaticas/_arquivos/sumrio_executivo_pnmc.pdf>.

BRASIL. **Política Nacional sobre Mudança do Clima – Lei 12.187**, de 29 de dezembro de 2009. Brasília, 2009. Available at: <https://www.planalto.gov.br/ccivil_03/_ato2007-2010/2009/lei/l12187.htm>.

BRASIL. Ministério da Saúde. **Portaria GM/MS nº 888**, de 4 de Maio de 2021. Brasília, 2021. Available at: <<https://www.in.gov.br/en/web/dou/-/portaria-gm/ms-n-888-de-4-de-maio-de-2021-318461562>>.

BRASIL. Comitê Interministerial sobre Mudança do Clima. **Plano Clima: Estratégias gerais e planos setoriais para mitigação e adaptação**. Brasília, 2024. Available at: <<https://www.gov.br/mma/pt-br/composicao/smc/plano-clima/apresentacao-plano-clima-atualizada-mai24-lgc-1.pdf>>. Access: 08 jan. 2026.

CAMACHO, C. R.; GETIRANA, A.; ROTUNNO FILHO, O. C.; MOURÃO, M. A. A. Large-Scale Groundwater Monitoring in Brazil Assisted With Satellite-Based Artificial Intelligence Techniques. **Water Resources Research**, v. 59, n. 9, e2022WR033588, 2023. Available at:

<<https://onlinelibrary.wiley.com/doi/abs/10.1029/2022WR033588>>. Access: 24 nov. 2024.

CATTELL, R. B. The Scree Test for the Number of Factors. **Multivariate Behavioral Research**, v. 1, n. 2, p. 245–276, 1966. Available at: <https://doi.org/10.1207/s15327906mbr0102_10>. Access: 19 set. 2025.

CETESB, COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO. **Qualidade das águas subterrâneas no estado de São Paulo 2016-2018**. São Paulo: CETESB, 2019. Available at: <<https://cetesb.sp.gov.br/aguas-subterraneas/wp-content/uploads/sites/13/2019/10/Relat%C3%B3rio-de-Qualidade-das-%C3%81guas-Subterr%C3%A2neas-no-Estado-de-S%C3%A3o-Paulo-2016-2018.pdf>>.

CETESB, COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO. **Qualidade das águas subterrâneas no estado de São Paulo: boletim 2023**. São Paulo: CETESB, 2024. Available at: <https://cetesb.sp.gov.br/aguas-subterraneas/wp-content/uploads/sites/13/2024/11/Boletim2023-AguaSubterranea_Texto_061124.pdf>.

CHAGAS, V. B. P.; CHAFFE, P. L. B.; BLÖSCHL, G. Climate and land management accelerate the Brazilian water cycle. **Nature Communications**, v. 13, n. 1, p. 5136, 2022. Available at: <<https://www.nature.com/articles/s41467-022-32580-x>>. Access: 15 oct. 2024.

CHEBOTAREV, I. I. Metamorphism of natural waters in the crust of weathering—1. **Geochimica et Cosmochimica Acta**, v. 8, n. 1, p. 22–48, 1955. Available at: <<https://www.sciencedirect.com/science/article/pii/0016703755900156>>. Access: 15 dec. 2025.

CHRISTOFOLETTI, S. R.; MORENO, M. M. T. Características das rochas da Formação Corumbataí utilizadas na indústria de revestimento cerâmico. **Geociências**, v. 23, n. 1/2, p. 79–88, 2004. Available at: <https://www.revistageociencias.com.br/geociencias-arquivos/23_1/7.pdf>. Access: 18 dec. 2024.

CLARK, I. D.; FRITZ, P. **Environmental Isotopes in Hydrogeology**. Boca Raton: CRC Press, 2013.

CONAMA, CONSELHO NACIONAL DO MEIO AMBIENTE. **Resolução CONAMA no 357, de 17 de Março de 2005**, 2005. Available at: <https://conama.mma.gov.br/?option=com_sisconama&task=arquivo.download&id=450>.

CUNHA, A. P. M. A.; TOMASELLA, J.; RIBEIRO-NETO, G. G.; BROWN, M.; GARCIA, S. R.; BRITO, S. B.; CARVALHO, M. A. Changes in the spatial–temporal patterns of droughts in the Brazilian Northeast. **Atmospheric Science Letters**, v. 19, n. 10, p. e855, 2018. Available at: <<https://rmets.onlinelibrary.wiley.com/doi/10.1002/asl.855>>. Access: 16 oct. 2024.

DAEE, DEPARTAMENTO DE ÁGUAS E ENERGIA ELÉTRICA; IG/SMA, INSTITUTO GEOLÓGICO/SECRETARIA DO MEIO AMBIENTE; IPT, INSTITUTO DE PESQUISAS TECNOLÓGICAS; CPRM, SERVIÇO GEOLÓGICO DO BRASIL. **Mapa de Águas Subterrâneas do Estado de São Paulo 1:1.000.000**, 2005.

DE CARVALHO, J. D.; DE MELO, M. C.; GALVÃO, P. G. P.; MIRANDA, W. L.; LASMAR, B. E. Groundwater in water scarcity context in the São Francisco River Basin (MG). **Ambiente & Sociedade**, v. 27, 2024. Available at: <<https://www.scielo.br/j/asoc/a/sfRRxkw7n4BpxMRhnytKt6f/?lang=en>>. Access: 15 oct. 2024.

DIAS, F.; SUHADOLNIK, N.; CAMARGO, H.; DA SILVA, S. Predicting the pulse of the Amazon: Machine learning insights into deforestation dynamics. **Journal of Environmental Management**, v. 362, p. 121359, 2024. Available at: <<https://www.sciencedirect.com/science/article/pii/S0301479724013458>>. Access: 24 nov. 2024.

DÍAZ-GONZÁLEZ, L.; USCANGA-JUNCO, O. A.; ROSALES-RIVERA, M. Development and comparison of machine learning models for water multidimensional classification. **Journal of Hydrology**, v. 598, p. 126234, 2021. Available at: <<https://www.sciencedirect.com/science/article/pii/S002216942100281X>>. Access: 24 nov. 2024.

DÍAZ-GONZÁLEZ, L.; ROSALES-RIVERA, M.; CHÁVEZ-ALMAZÁN, L. A.; UNIVERSIDAD AUTÓNOMA DEL ESTADO DE MORELOS. Comprehensive assessment of groundwater quality in Mexico and application of new water classification scheme based on machine learning. **Revista Mexicana de Ingeniería Química**, v. 22, n. 2, p. 1–30, 2023. Available at: <<http://rmiq.org/iqfvp/Numbers/V22/No2/IA235.pdf>>. Access: 24 nov. 2024.

DINNO, A. Nonparametric Pairwise Multiple Comparisons in Independent Groups using Dunn's Test. **The Stata Journal**, v. 15, n. 1, p. 292–300, 2015. Available at: <<https://doi.org/10.1177/1536867X1501500117>>. Access: 14 dec. 2025.

DOMINGUEZ, D.; DEL VILLAR, L. de J.; PANTOJA, O.; GONZÁLEZ-RODRÍGUEZ, M. Forecasting Amazon Rain-Forest Deforestation Using a Hybrid Machine Learning Model. **Sustainability**, v. 14, n. 2, p. 691, 2022. Available at: <<https://www.mdpi.com/2071-1050/14/2/691>>. Access: 24 nov. 2024.

DOS SANTOS, V.; GASTMANS, D.; SÁNCHEZ-MURILLO, R.; FELIPPE GOZZO, L.; VIANNA BATISTA, L.; LILLA MANZIONE, R.; MARTINEZ, J. Regional atmospheric dynamics govern interannual and seasonal stable isotope composition in southeastern Brazil. **Journal of Hydrology**, v. 579, p. 124136, 2019. Available at: <<https://www.sciencedirect.com/science/article/pii/S0022169419308716>>. Access: 20 dec. 2024.

DUARTE, V. B. R.; VIOLA, M. R.; GIONGO, M.; ULIANA, E. M.; DE MELLO, C. R. Streamflow forecasting in Tocantins river basins using machine learning. **Water Supply**, v. 22, n. 7, p. 6230–6244, 2022. Available at: <<https://doi.org/10.2166/ws.2022.155>>. Access: 24 nov. 2024.

ENFORS-KAUTSKY, E.; JÄRNBERG, L.; QUINLAN, A.; RYAN, P. Wayfinder: a new generation of resilience practice. **Ecology and Society**, v. 26, n. 2, 2021. Available at: <<https://www.ecologyandsociety.org/vol26/iss2/art39/>>. Access: 27 may. 2025.

ESRI. **ArcGIS Desktop 10.8**, 2021. Available at: <<https://desktop.arcgis.com/en/system-requirements/latest/arcgis-desktop-system-requirements.htm>>

EZAKI, S.; HYPOLITO, R.; PÉREZ-AGUILAR, A. Experimental fluorine liberation from Precambrian granites and Carboniferous-Permian sedimentary rocks associated with crystalline and sedimentary aquifers, Paraná Basin, southeastern Brazil. **Geochemical Journal**, v. 50, n. 5, p. 379–392, 2016.

FAMIGLIETTI, J. S. The global groundwater crisis. **Nature Climate Change**, v. 4, n. 11, p. 945–948, 2014. Available at: <<https://www.nature.com/articles/nclimate2425>>. Access: 29 dec. 2024.

FETTER, C. W. **Applied Hydrogeology**. 4. ed. New Jersey: Prentice-Hall, 2001. Available at: <https://arjzaidi.wordpress.com/wp-content/uploads/2015/09/unimasr-com_e7ce669a880a8c4c70b4214641f93a02.pdf>. Access: 2 jul. 2025.

FILONCHYK, M.; PETERSON, M. P.; ZHANG, L.; HURYNOVICH, V.; HE, Y. Greenhouse gases emissions and global climate change: Examining the influence of CO₂, CH₄, and N₂O. **Science of The Total Environment**, v. 935, p. 173359, 2024. Available at: <<https://www.sciencedirect.com/science/article/pii/S004896972403506X>>. Access: 6 nov. 2024.

FRANÇA, A. B.; ARAÚJO, L. M.; MAYNARD, J. B.; POTTER, P. E. Secondary porosity formed by deep meteoric leaching: Botucatu eolianite, southern South America. **AAPG Bulletin**, v. 87, n. 7, p. 1073–1082, 2003. Available at: <<http://search.datapages.com/data/doi/10.1306/02260301071>>. Access: 4 jan. 2026.

FRANZINI, A. S. **Projeto Rede Integrada de Monitoramento das Águas Subterrâneas: relatório diagnóstico sistema aquífero Bauru-Caiuá nos estados de São Paulo, Mato Grosso do Sul e Paraná bacia sedimentar do Paraná**. Belo Horizonte: CPRM, 2012. Available at: <<https://rigeo.sgb.gov.br/handle/doc/22253>>. Access: 18 dec. 2024.

FREEZE, A.; CHERRY, J. **Groundwater**. New Jersey, 1979. Available at: <<https://gw-project.org/pt-br/books/agua-subterranea/>>

GALLO, G.; SINELLI, O. Estudo hidroquímico e isotópico das águas subterrâneas na região de Ribeirão Preto (SP). **Revista Brasileira de Geociências**, v. 10, p. 12, 1980. Available at: <<http://bjg.siteoficial.ws/1980/n2/gallo.pdf>>

GALVÃO, C. de O.; BRAGA, C. F. C. **Brasil 2040: Cenários e alternativas de adaptação à mudança do clima**. Brasília: Governo Federal do Brasil, 2015. Available at: <[https://www.agroicone.com.br/\\$res/arquivos/pdf/160727143013_BRASIL-2040-Resumo-Executivo.pdf](https://www.agroicone.com.br/$res/arquivos/pdf/160727143013_BRASIL-2040-Resumo-Executivo.pdf)>.

GASTMANS, D.; CHANG, H. K.; HUTCHEON, I. Groundwater geochemical evolution in the northern portion of the Guarani Aquifer System (Brazil) and its relationship to diagenetic features. **Applied Geochemistry**, v. 25, n. 1, p. 16–33, 2010a. Available at: <<https://www.sciencedirect.com/science/article/pii/S0883292709002662>>. Access: 18 dec. 2024.

GASTMANS, D.; CHANG, H. K.; HUTCHEON, I. Stable isotopes (2H , 18O and 13C) in groundwaters from the northwestern portion of the Guarani Aquifer System (Brazil). **Hydrogeology Journal**, v. 18, n. 6, p. 1497–1513, 2010b. Available at: <<http://link.springer.com/10.1007/s10040-010-0612-2>>. Access: 4 jan. 2026.

GASTMANS, D.; HUTCHEON, I.; MENEGÁRIO, A. A.; CHANG, H. K. Geochemical evolution of groundwater in a basaltic aquifer based on chemical and stable isotopic data: Case study from the Northeastern portion of Serra Geral Aquifer, São Paulo state (Brazil). **Journal of Hydrology**, v. 535, p. 598–611, 2016. Available at: <<https://www.sciencedirect.com/science/article/pii/S0022169416300415>>. Access: 20 dec. 2024.

GASTMANS, D.; MENEGÁRIO, A. A.; HUTCHEON, I. Stable isotopes, carbon-14 and hydrochemical composition from a basaltic aquifer in São Paulo State, Brazil. **Environmental Earth Sciences**, v. 76, n. 4, p. 150, 2017. Available at: <<https://doi.org/10.1007/s12665-017-6468-1>>. Access: 15 oct. 2024.

GESUALDO, G. C.; SONE, J. S.; GALVÃO, C. de O.; MARTINS, E. S.; MONTENEGRO, S. M. G. L.; TOMASELLA, J.; MENDIONDO, E. M. Unveiling water security in Brazil: current challenges and future perspectives. **Hydrological Sciences Journal**, v. 66, n. 5, p. 759–768, 2021. Available at: <<https://doi.org/10.1080/02626667.2021.1899182>>. Access: 15 oct. 2024.

GUNDERSON, L.; COSENS, B.; CHAFFIN, B.; ARNOLD, C.; FREMIER, A.; GARMESTANI, A.; CRAIG, R.; GOSNELL, H.; BIRGE, H.; ALLEN, C.; BENSON, M.; MORRISON, R.; STONE, M.; HAMM, J.; NEMEC, K.; SCHLAGER, E.; LLEWELLYN, D. Regime shifts and panarchies in regional scale social-ecological water systems. **Ecology and Society**, v. 22, n. 1, 2017. Available at: <<https://www.ecologyandsociety.org/vol22/iss1/art31/>>. Access: 15 oct. 2024.

HEALY, R. W.; COOK, P. G. Using groundwater levels to estimate recharge. **Hydrogeology Journal**, v. 10, n. 1, p. 91–109, 2002. Available at: <<https://doi.org/10.1007/s10040-001-0178-0>>. Access: 25 feb. 2026.

HIRATA, R.; GESICKI, A.; SRACEK, O.; BERTOLO, R.; GIANNINI, P. C.; ARAVENA, R. Relation between sedimentary framework and hydrogeology in the Guarani Aquifer System in São Paulo state, Brazil. **Journal of South American Earth Sciences**, v. 31, n. 4, p. 444–456, 2011. Available at: <<https://www.sciencedirect.com/science/article/pii/S0895981111000307>>. Access: 18 dec. 2024.

HUANG, R.; MA, C.; MA, J.; HUANGFU, X.; HE, Q. Machine learning in natural and engineered water systems. **Water Research**, v. 205, p. 117666, 2021. Available at:

<<https://www.sciencedirect.com/science/article/pii/S0043135421008617>>. Access: 23 nov. 2024.

HUGGINS, X.; GLEESON, T.; CASTILLA-RHO, J.; HOLLEY, C.; RE, V.; FAMIGLIETTI, J. S. Groundwater Connections and Sustainability in Social-Ecological Systems. **Groundwater**, v. 61, n. 4, p. 463–478, 2023. Available at: <<https://onlinelibrary.wiley.com/doi/abs/10.1111/gwat.13305>>. Access: 15 oct. 2024.

HUSSAIN, M. M.; MAHMUD, I. pyMannKendall: a python package for non parametric Mann Kendall family of trend tests. **Journal of Open Source Software**, v. 4, n. 39, p. 1556, 2019. Available at: <<https://joss.theoj.org/papers/10.21105/joss.01556>>. Access: 15 oct. 2024.

HYDROVERSEBR; ALTHOFF, D.; CALEGARIO, T. **HydroBR package**, 2022. Available at: <<https://github.com/hydroversebr/hydrobr>>. Access: 15 oct. 2021.

IBGE, INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Produto Interno Bruto dos Municípios**. Brasília, 2021. Available at: <<https://www.ibge.gov.br/estatisticas/economicas/contas-nacionais/9088-produto-interno-bruto-dos-municipios.html?=&t=resultados>>. Access: 28 dec. 2024.

IBGE, INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Censo 2022**. Brasília, 2023. Available at: <<https://censo2022.ibge.gov.br/etapas/divulgacao-dos-resultados.html>>. Access: 1 jan. 2023.

IPCC, INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. **AR6 Synthesis Report**: Climate Change 2023 — IPCC. 2023a. Available at: <<https://www.ipcc.ch/report/sixth-assessment-report-cycle/>>. Access: 6 nov. 2024a.

IPCC, INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. **Technical Summary**. Em: Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2023b. Available at: <<https://www.ipcc.ch/report/ar6/wg2/>>.

KAISER, H. F. The varimax criterion for analytic rotation in factor analysis. **Psychometrika**, v. 23, n. 3, p. 187–200, 1958. Available at: <<https://doi.org/10.1007/BF02289233>>. Access: 19 set. 2025.

KAISER, H. F. A second generation little jiffy. **Psychometrika**, v. 35, n. 4, p. 401–415, 1970. Available at: <<https://doi.org/10.1007/BF02291817>>. Access: 19 set. 2025.

KAYITESI, N. M.; GUZHA, A. C.; MARIETHOZ, G. Impacts of land use land cover change and climate change on river hydro-morphology- a review of research studies in tropical regions. **Journal of Hydrology**, v. 615, p. 128702, 2022. Available at: <<https://www.sciencedirect.com/science/article/pii/S0022169422012720>>. Access: 8 may. 2025.

KENDALL, M.; GIBBONS, J. D. **Rank Correlation Methods**. 5. ed. New York: Oxford University Press, 1990.

KEREBIH, M. S.; KESHARI, A. K. Prediction of groundwater level using artificial neural network as an alternative approach: a comparison assessment with numerical groundwater flow model. **Hydrological Sciences Journal**, v. 69, n. 13, p. 1691–1701, 2024. Available at: <<https://doi.org/10.1080/02626667.2024.2393421>>. Access: 24 nov. 2024.

KIM, J.; RYU, J. H. Quantifying a Threshold of Missing Values for Gap Filling Processes in Daily Precipitation Series. **Water Resources Management**, v. 29, n. 11, p. 4173–4184, 2015. Available at: <<https://doi.org/10.1007/s11269-015-1052-5>>. Access: 10 oct. 2025.

KIRCHHEIM, R. E.; CHANG, K. H.; GASTMANS, D.; EZAKI, S.; STRADIOTO, M. R. Aplicação de gases nobres e seus isótopos na hidrogeologia. **Derbyana**, v. 42, 2021. Available at: <<https://revistaig.emnuvens.com.br/derbyana/article/view/744>>. Access: 30 dec. 2025.

KIRCHHEIM, R. E.; GASTMANS, D.; CHANG, H. K.; GILMORE, T. E. The use of isotopes in evolving groundwater circulation models of regional continental aquifers: The case of the Guarani Aquifer System. **Hydrological Processes**, v. 33, n. 17, p. 2266–2278, 2019. Available at: <<https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.13476>>. Access: 15 oct. 2024.

KONECKY, B. L.; MCKAY, N. P.; FALSTER, G. M.; STEVENSON, S. L.; FISCHER, M. J.; ATWOOD, A. R.; THOMPSON, D. M.; JONES, M. D.; TYLER, J. J.; DELONG, K. L.; MARTRAT, B.; THOMAS, E. K.; CONROY, J. L.; DEE, S. G.; JONKERS, L.; CHURAKOVA (SIDOROVA), O. V.; KERN, Z.; OPEL, T.; PORTER, T. J.; SAYANI, H. R.; SKRZYPEK, G. Globally coherent water cycle response to temperature change during the past two millennia. **Nature Geoscience**, v. 16, n. 11, p. 997–1004, 2023. Available at: <<https://www.nature.com/articles/s41561-023-01291-3>>. Access: 15 oct. 2024.

KRAFT, B.; JUNG, M.; KÖRNER, M.; KOIRALA, S.; REICHSTEIN, M. Towards hybrid modeling of the global hydrological cycle. **Hydrology and Earth System Sciences**, v. 26, n. 6, p. 1579–1614, 2022. Available at: <<https://hess.copernicus.org/articles/26/1579/2022/>>. Access: 24 nov. 2024.

LARHIA, LABORATÓRIO DE RECURSOS HÍDRICOS E ISÓTOPOS AMBIENTAIS; DAEE, DEPARTAMENTO AUTÔNOMO DE ÁGUA E ESGOTOS; SAAEB, SERVIÇO AUTÔNOMO DE ÁGUA E ESGOTO DE BEBEDOURO. **Elaboração de Estudos Hidrogeológicos para Avaliação das Condições de Exploração dos Sistemas Aquíferos Guarani, Bauru e Serra Geral na UGRHI 12 – BPG**. São Paulo, BR: FEHIDRO No. 66/2020, 2023. Available at: <https://sigrh.sp.gov.br/public/uploads/deliberation//CBH-BPG/27213/del_295-23-relatorio-aq-guarani-r05_v03_05_jun_23-2.pdf>. Access: 27 may. 2025.

LEBAC, LABORATÓRIO DE ESTUDOS DE BACIAS; AIEA, AGÊNCIA INTERNACIONAL DE ENERGIA ATÔMICA. **Characterization of fossil**

groundwater systems using long-lived radionuclides: Complementary Isotopic Studies in the Southern, Western and Eastern Compartments of the Guarani Aquifer System - Groundwater Dating Along Defined Flow Paths. AIEA: CRP F30063, 2016.

LEVIA, D. F.; CREED, I. F.; HANNAH, D. M.; NANKO, K.; BOYER, E. W.; CARLYLE-MOSES, D. E.; VAN DE GIESEN, N.; GRASSO, D.; GUSWA, A. J.; HUDSON, J. E.; HUDSON, S. A.; IIDA, S.; JACKSON, R. B.; KATUL, G. G.; KUMAGAI, T.; LLORENS, P.; RIBEIRO, F. L.; PATAKI, D. E.; PETERS, C. A.; CARRETERO, D. S.; SELKER, J. S.; TETZLAFF, D.; ZALEWSKI, M.; BRUEN, M. Homogenization of the terrestrial water cycle. **Nature Geoscience**, v. 13, n. 10, p. 656–658, 2020. Available at: <<https://www.nature.com/articles/s41561-020-0641-y>>. Access: 15 oct. 2024.

LUCAS, E. W. M.; SOUSA, F. de A. S. De; SILVA, F. D. dos S.; ROCHA JÚNIOR, R. L. Da; PINTO, D. D. C.; SILVA, V. de P. R. Da. Trends in climate extreme indices assessed in the Xingu river basin - Brazilian Amazon. **Weather and Climate Extremes**, v. 31, p. 100306, 2021. Available at: <<https://www.sciencedirect.com/science/article/pii/S2212094721000049>>. Access: 15 oct. 2024.

LUO, S.; TETZLAFF, D.; SMITH, A.; SOULSBY, C. Long-term drought effects on landscape water storage and recovery under contrasting landuses. **Journal of Hydrology**, v. 636, p. 131339, 2024. Available at: <<https://www.sciencedirect.com/science/article/pii/S0022169424007340>>. Access: 24 nov. 2024.

MANN, H. B. Nonparametric Tests Against Trend. **Econometrica**, v. 13, n. 3, p. 245–259, 1945. Available at: <<https://www.jstor.org/stable/1907187>>. Access: 15 oct. 2024.

MANTYKA-PRINGLE, C. S.; VISCONTI, P.; DI MARCO, M.; MARTIN, T. G.; RONDININI, C.; RHODES, J. R. Climate change modifies risk of global biodiversity loss due to land-cover change. **Biological Conservation**, v. 187, p. 103–111, 2015. Available at: <<https://www.sciencedirect.com/science/article/pii/S0006320715001615>>. Access: 15 oct. 2024.

MANZANO, M.; GUIMARAENS, M. Hidroquímica del Sistema Acuífero Guaraní e implicaciones para la gestión. **Boletín Geológico y Minero**, v. 123, n. 3, p. 281–295, 2012. Available at: <<https://www.cohife.org/advf/CORRIENTES/E27.pdf>>.

MAPBIOMAS. **MapBiomass Brasil Coleção 8**. Available at: <<https://brasil.mapbiomas.org/#>>. Access: 1 dec. 2023.

MARENGO, J. A.; ALVES, L. M.; AMBRIZZI, T.; YOUNG, A.; BARRETO, N. J. C.; RAMOS, A. M. Trends in extreme rainfall and hydrogeometeorological disasters in the Metropolitan Area of São Paulo: a review. **Annals of the New York Academy of Sciences**, v. 1472, n. 1, p. 5–20, 2020. Available at: <<https://onlinelibrary.wiley.com/doi/abs/10.1111/nyas.14307>>. Access: 15 oct. 2024.

MARENGO, J. A.; SELUCHI, M. E.; CUNHA, A. P.; CUARTAS, L. A.; GONCALVES, D.; SPERLING, V. B.; RAMOS, A. M.; DOLIF, G.; SAITO, S.; BENDER, F.; LOPES, T. R.; ALVALA, R. C.; MORAES, O. L. Heavy rainfall associated with floods in southeastern Brazil in November–December 2021. **Natural Hazards**, v. 116, n. 3, p. 3617–3644, 2023. Available at: <<https://doi.org/10.1007/s11069-023-05827-z>>. Access: 15 oct. 2024.

McNALLY, A.; ARSENAULT, K.; KUMAR, S.; SHUKLA, S.; PETERSON, P.; WANG, S.; FUNK, C.; PETERS-LIDARD, C. D.; VERDIN, J. P. A land data assimilation system for sub-Saharan Africa food and water security applications. **Scientific Data**, v. 4, n. 1, p. 170012, 2017. Available at: <<https://www.nature.com/articles/sdata201712>>. Access: 15 oct. 2024.

McNALLY, A.; NASA/GSFC/HSLFLDAS. **Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS) V001 (FLDAS_NOAH01_C_GL_M)**. NASA/GSFC/SED/ESD/GCDC/GESDISC, 2018. Available at: <<https://catalog.data.gov/dataset/flidas-noah-land-surface-model-l4-global-monthly-0-1-x-0-1-degree-merra-2-and-chirps-v001-f>>. Access: 15 oct. 2024.

MEKONNEN, M. M.; HOEKSTRA, A. Y. Four billion people facing severe water scarcity. **Science Advances**, v. 2, n. 2, p. e1500323, 2016. Available at: <<https://www.science.org/doi/10.1126/sciadv.1500323>>. Access: 15 oct. 2024.

MELO, D. C. D.; ANACHE, J. A. A.; ALMEIDA, C. das N.; COUTINHO, J. V.; RAMOS FILHO, G. M.; ROSALEM, L. M. P.; PELINSON, N. S.; FERREIRA, G. L. R. A.; SCHWAMBACK, D.; CALIXTO, K. G.; SIQUEIRA, J. P. G.; DUARTE-CARVAJALINO, J. C.; JHUNIOR, H. C. S.; NÓBREGA, J. D.; MORITA, A. K. M.; LEITE, C. M. C.; GUEDES, A. C. E.; COELHO, V. H. R.; WENDLAND, E. The big picture of field hydrology studies in Brazil. **Hydrological Sciences Journal**, v. 65, n. 8, p. 1262–1280, 2020. Available at: <<https://doi.org/10.1080/02626667.2020.1747618>>. Access: 15 oct. 2024.

MENG, S. X.; MAYNARD, J. B. Use of statistical analysis to formulate conceptual models of geochemical behavior: water chemical data from the Botucatu aquifer in São Paulo state, Brazil. **Journal of Hydrology**, v. 250, n. 1, p. 78–97, 2001. Available at: <<https://www.sciencedirect.com/science/article/pii/S0022169401004231>>. Access: 4 jan. 2026.

MIA, Md. Y.; HAQUE, Md. E.; ISLAM, A. R. M. T.; JANNAT, J. N.; JION, Most. M. M. F.; ISLAM, Md. S.; SIDDIQUE, Md. A. B.; IDRIS, A. M.; SENAPATHI, V.; TALUKDAR, S.; RAHMAN, A. Analysis of self-organizing maps and explainable artificial intelligence to identify hydrochemical factors that drive drinking water quality in Haor region. **Science of The Total Environment**, v. 904, p. 166927, 2023. Available at: <<https://www.sciencedirect.com/science/article/pii/S0048969723055523>>. Access: 24 nov. 2024.

MILANI, E.; FRANÇA, A. B.; MEDEIROS, R. Á. Source rocks and reservoir rocks of the Paraná Basin, eastern belt of outcrops, Paraná State. **Boletim de Geociencias da Petrobras**, v. 15, p. 135–162, 2006.

MIRANDA, E. E. **Brasil em Relevo**. Campinas: Embrapa Monitoramento por Satélite, 2005. Available at: <<http://www.relevobr.cnpm.embrapa.br>>. Access: 28 mar. 2024.

MONTANHEIRO, F.; KIANG, C. H. Nitrato no Aquífero Adamantina: o caso do Município de Monte Azul Paulista, SP. **Revista do Instituto Geológico (Descontinuada)**, v. 37, n. 2, p. 25–44, 2016. Available at: <<https://revistaig.emnuvens.com.br/rig/article/view/33>>. Access: 20 dec. 2024.

NAGHETTINI, M.; PINTO, É. J. de A. **Hidrologia estatística**. Belo Horizonte: CPRM, 2007. Available at: <<https://rigeo.sgb.gov.br/handle/doc/454>>. Access: 15 oct. 2024.

NARDY, A. J. R.; MACHADO, F. B.; OLIVEIRA, M. A. F. D. As rochas vulcânicas mesozóicas ácidas da Bacia do Paraná: litoestratigrafia e considerações geoquímico-estratigráficas. **Revista Brasileira de Geociências**, v. 38, n. 1, p. 178–195, 2008. Available at: <<http://ppegeo.igc.usp.br/index.php/rbg/article/view/7576/7003>>. Access: 18 dec. 2024.

NASIR, N.; KANSAL, A.; ALSHALTONE, O.; BARNEIH, F.; SAMEER, M.; SHANABLEH, A.; AL-SHAMMA'A, A. Water quality classification using machine learning algorithms. **Journal of Water Process Engineering**, v. 48, p. 102920, 2022. Available at: <<https://www.sciencedirect.com/science/article/pii/S2214714422003646>>. Access: 24 nov. 2024.

NEARING, G. S.; KRATZERT, F.; SAMPSON, A. K.; PELISSIER, C. S.; KLOTZ, D.; FRAME, J. M.; PRIETO, C.; GUPTA, H. V. What Role Does Hydrological Science Play in the Age of Machine Learning? **Water Resources Research**, v. 57, n. 3, p. e2020WR028091, 2021. Available at: <<https://onlinelibrary.wiley.com/doi/abs/10.1029/2020WR028091>>. Access: 19 nov. 2024.

NEFF, H. Rq-Mode Principal Components Analysis of Ceramic Compositional Data. **Archaeometry**, v. 36, n. 1, p. 115–130, 1994. Available at: <<https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1475-4754.1994.tb01068.x>>. Access: 18 set. 2025.

NRDC, NATURAL RESOURCES DEFENSE COUNCIL. **The Paris Agreement on Climate Change**. New York, 2017. Available at: <<https://www.nrdc.org/sites/default/files/paris-agreement-climate-change-2017-ib.pdf>>

OAS, ORGANIZATION OF AMERICAN STATES. **Guarani Aquifer: strategic program of actions**. Washington: OAS, 2009. Available at:

<<https://www.ceregas.org/publicaciones/proteccion-ambiental-y-desarrollo-sostenible-del-sistema-acuifero-guarani-sag/>>. Access: 15 oct. 2024.

O'BRIEN, R. M. A Caution Regarding Rules of Thumb for Variance Inflation Factors. **Quality & Quantity**, v. 41, n. 5, p. 673–690, 2007. Available at: <<https://doi.org/10.1007/s11135-006-9018-6>>. Access: 20 dec. 2024.

OSTERTAGOVÁ, E.; OSTERTAG, O.; KOVÁČ, J. Methodology and Application of the Kruskal-Wallis Test. **Applied Mechanics and Materials**, v. 611, p. 115–120, 2014. Available at: <<https://www.scientific.net/AMM.611.115>>. Access: 14 dec. 2025.

PADOVESI-FONSECA, C.; FARIA, R. S. De. Desafios da gestão integrada de recursos hídricos no Brasil e Europa. **Revista Mineira de Recursos Hídricos**, v. 3, p. e022003–e022003, 2022. Available at: <<https://periodicos.meioambiente.mg.gov.br/NM/article/view/221>>. Access: 15 oct. 2024.

PAGNOCCHESCHI, B. **Governabilidade e governança das águas no Brasil**. In: Governança Ambiental no Brasil: instituições, atores e políticas públicas. Brasília: Adriana Maria Magalhães de Moura, 2016.

PEEL, M. C.; FINLAYSON, B. L.; MCMAHON, T. A. Updated world map of the Köppen-Geiger climate classification. **Hydrology and Earth System Sciences**, v. 11, n. 5, p. 1633–1644, 2007. Available at: <<https://hess.copernicus.org/articles/11/1633/2007/>>. Access: 15 oct. 2024.

PEIXOTO, L. O. M.; DA COSTA PEREIRA, J. L. G. F. da S.; FERNANDES, C. V. S.; CENTENO, J. A. S.; DE AZEVEDO, J. C. R. Modeling and predicting caffeine contamination in surface waters using artificial intelligence and standard statistical methods. **Environmental Monitoring and Assessment**, v. 197, n. 1, p. 30, 2024. Available at: <<https://doi.org/10.1007/s10661-024-13423-2>>. Access: 26 dec. 2024.

PETERSEN-PERLMAN, J. D.; VEILLEUX, J. C.; WOLF, A. T. International water conflict and cooperation: challenges and opportunities. **Water International**, v. 42, n. 2, p. 105–120, 2017. Available at: <<https://doi.org/10.1080/02508060.2017.1276041>>. Access: 15 oct. 2024.

PIPER, A. M. A graphic procedure in the geochemical interpretation of water-analyses. **Eos, Transactions American Geophysical Union**, v. 25, n. 6, p. 914–928, 1944. Available at: <<https://onlinelibrary.wiley.com/doi/abs/10.1029/TR025i006p00914>>. Access: 2 jul. 2025.

QUAGGIO, C. S.; GASTMANS, D.; KIRCHHEIM, R.; BATISTA, L. V. Variações na composição das águas subterrâneas do Sistema Aquífero Serra Geral em território brasileiro e sua relação com anomalias hidrogeoquímicas. **Águas Subterrâneas**, v. 32, n. 3, p. 283–294, 2018. Available at: <<https://aguassubterraneas.abas.org/asubterraneas/article/view/29085>>. Access: 15 oct. 2024.

QUAGGIO, C. S.; GASTMANS, D.; LUNARDI, M.; SANTAROSA, L. V.; BETANCUR, S. B.; GEMEINER, H. Zoneamento Hidrogeoquímico dos Sistemas Aquíferos do Estado de São Paulo como Ferramenta de Gestão das Águas Subterrâneas.

Anuário do Instituto de Geociências, v. 43, n. 4, p. 176–188, 2020. Available at: <<https://revistas.ufrj.br/index.php/aigeo/article/view/39936>>. Access: 1 jan. 2025.

QUAGGIO, C. S.; GASTMANS, D.; MARTINS, V. T. de S.; GILMORE, T. E. Combined use of statistical Bayesian model and strontium isotopes deciphering the high complexity groundwater flow in the Guarani Aquifer System (GAS). **Applied Geochemistry**, v. 146, p. 105473, 2022. Available at:

<<https://www.sciencedirect.com/science/article/pii/S0883292722002773>>. Access: 15 oct. 2024.

REGOTO, P.; DERECHYNSKI, C.; CHOU, S. C.; BAZZANELA, A. C. Observed changes in air temperature and precipitation extremes over Brazil. **International Journal of Climatology**, v. 41, n. 11, p. 5125–5142, 2021. Available at:

<<https://onlinelibrary.wiley.com/doi/abs/10.1002/joc.7119>>. Access: 15 oct. 2024.

REIS, M. M. **Potencial hidromineral das águas hipertermiais do sistema aquífero Guarani no Estado de São Paulo**. Adviser: Chang Hung Kiang. Dissertation (Master degree on Geoscience and Environment) – Institute of Geosciences and Exact Sciences, São Paulo State University, Rio Claro, 2011. Available at: <<http://hdl.handle.net/11449/92821>>. Access: 20 dec. 2024.

RIGGS, H. C. **Book 4: Hydrologic Analysis and Interpretation**. In: Techniques of Water-Resources Investigations Reports. Denver: USGS, 1968.

RÖRIG, F. S.; HIRATA, R.; BARBATI, D. O. From global to local scale: How international experiences contribute to the fossil water management of the Guarani Aquifer System. **Environmental Science & Policy**, v. 157, p. 103777, 2024. Available at:

<<https://www.sciencedirect.com/science/article/pii/S1462901124001114>>. Access: 15 oct. 2024.

SACCHI, M. D.; MANZIONE, R. L.; GASTMANS, D. How much rainwater contributes to a spring discharge in the Guarani Aquifer System: insights from stable isotopes and a mass balance model. **Isotopes in Environmental and Health Studies**, v. 60, n. 4, p. 400–416, 2024. Available at:

<<https://doi.org/10.1080/10256016.2024.2397469>>. Access: 4 jan. 2026.

SAKIZADEH, M. **Artificial intelligence for the prediction of water quality index in groundwater systems**. Modeling Earth Systems and Environment, v. 2, n. 1, p. 8, 2015. Available at: <<https://doi.org/10.1007/s40808-015-0063-9>>. Access: 24 nov. 2024.

SANTAROSA, L. V.; DE OLIVEIRA FERREIRA SILVA, C.; HIRIGOYEN, A.; QUAGGIO, C. S. Water Consumption Assessment of Afforestation and Natural Vegetation Areas with a Remote Sensing Approach. **Water**, v. 17, n. 11, p. 1597, 2025. Available at: <<https://www.mdpi.com/2073-4441/17/11/1597>>. Access: 27 may. 2025.

SANTAROSA, L. V.; PINTO, GUILHERME VITURI FERNANDES; SEBASTIÁN, B. L., Juan; GASTMANS, D. Remote sensing to quantify potential aquifer recharge as a complementary tool for groundwater monitoring. **Hydrological Sciences Journal**, v. 69, n. 16, p. 2455–2465, 2024. Available at: <<https://doi.org/10.1080/02626667.2024.2412741>>. Access: 15 may. 2025.

SANTOS, E. B.; LUCIO, P. S.; SANTOS E SILVA, C. M. Estimating return periods for daily precipitation extreme events over the Brazilian Amazon. **Theoretical and Applied Climatology**, v. 126, n. 3, p. 585–595, 2016. Available at: <<https://doi.org/10.1007/s00704-015-1605-9>>. Access: 15 oct. 2024.

SANTOS, M. R.; ROISENBERG, A.; IWASHITA, F.; ROISENBERG, M. Hydrogeochemical spatialization and controls of the Serra Geral Aquifer System in southern Brazil: A regional approach by self-organizing maps and k-means clustering. **Journal of Hydrology**, v. 591, p. 125602, 2020. Available at: <<https://www.sciencedirect.com/science/article/pii/S0022169420310635>>. Access: 26 dec. 2024.

SÃO PAULO (State). **Política Estadual de Mudanças Climáticas** – PEMC – Lei no 13.798. 2009. Available at: <<https://www.al.sp.gov.br/repositorio/legislacao/lei/2009/lei-13798-09.11.2009.html>>.

SÃO PAULO (State). **Decreto no 65.881**, de 20 de julho de 2021. São Paulo, 2021. Available at: <<https://www.al.sp.gov.br/repositorio/legislacao/decreto/2021/decreto-65881-20.07.2021.html>>.

SÃO PAULO (State). **PAC20250**: Plano de Ação Climática e desenvolvimento sustentável para São Paulo. Governo do Estado de São Paulo, 2022. Available at: <https://www.prefeitura.sp.gov.br/cidade/secretarias/upload/meio_ambiente/arquivos/Sum_ExecutivoSP_Baixa.pdf>.

SÃO PAULO (State). **Plano Estadual de Adaptação e Resiliência Climática de São Paulo (PEARC)** – consulta pública. Governo do Estado de São Paulo, 2024. Available at: <https://smastr16.blob.core.windows.net/home/2024/11/PEARC_Consulta_Publica.pdf>.

SATIZÁBAL-ALARCÓN, D. A.; SUHOGUSOFF, A.; FERRARI, L. C. Characterization of groundwater storage changes in the Amazon River Basin based on downscaling of GRACE/GRACE-FO data with machine learning models. **Science of The Total Environment**, v. 912, p. 168958, 2024. Available at: <<https://www.sciencedirect.com/science/article/pii/S0048969723075873>>. Access: 24 nov. 2024.

SAVENIJE, H. H. G.; VAN DER ZAAG, P. Integrated water resources management: Concepts and issues. Physics and Chemistry of the Earth, Parts A/B/C, Integrated Water Resources Management in a Changing World. **Physics and Chemistry of the Earth**, v. 33, n. 5, 2008. Available at:

<<https://www.sciencedirect.com/science/article/pii/S147470650800017X>>. Access: 15 oct. 2024.

SCHWARZENBACH, R. P.; EGLI, T.; HOFSTETTER, T. B.; GUNTEN, U. Von; WEHRLI, B. Global Water Pollution and Human Health. **Annual Review of Environment and Resources**, v. 35, n. Volume 35, 2010, p. 109–136, 2010. Available at: <<https://www.annualreviews.org/content/journals/10.1146/annurev-environ-100809-125342>>. Access: 15 oct. 2024.

SEADE, SISTEMA ESTADUAL DE ANÁLISE DE DADOS. **Sistema Seade de Projeções Populacionais**: População urbana e rural. Available at: <<https://repositorio.seade.gov.br/dataset/populacao-urbana-e-rural>>. Access: 7 jun. 2021.

SEO, K.-W.; RYU, D.; EOM, J.; JEON, T.; KIM, J.-S.; YOUM, K.; CHEN, J.; WILSON, C. R. Drift of Earth's Pole Confirms Groundwater Depletion as a Significant Contributor to Global Sea Level Rise 1993–2010. **Geophysical Research Letters**, v. 50, n. 12, p. e2023GL103509, 2023. Available at: <<https://onlinelibrary.wiley.com/doi/abs/10.1029/2023GL103509>>. Access: 15 oct. 2024.

SHAPIRO, S. S.; WILK, M. B. An analysis of variance test for normality (complete samples). **Biometrika**, v. 52, n. 3–4, p. 591–611, 1965. Available at: <<https://doi.org/10.1093/biomet/52.3-4.591>>. Access: 15 oct. 2024.

SHEN, C. A Transdisciplinary Review of Deep Learning Research and Its Relevance for Water Resources Scientists. **Water Resources Research**, v. 54, n. 11, p. 8558–8593, 2018. Available at: <<https://onlinelibrary.wiley.com/doi/abs/10.1029/2018WR022643>>. Access: 20 nov. 2024.

SHEN, C.; APPLING, A. P.; GENTINE, P.; BANDAI, T.; GUPTA, H.; TARTAKOVSKY, A.; BAITY-JESI, M.; FENICIA, F.; KIFER, D.; LI, L.; LIU, X.; REN, W.; ZHENG, Y.; HARMAN, C. J.; CLARK, M.; FARTHING, M.; FENG, D.; KUMAR, P.; ABOELYAZEED, D.; RAHMANI, F.; SONG, Y.; BECK, H. E.; BINDAS, T.; DWIVEDI, D.; FANG, K.; HÖGE, M.; RACKAUCKAS, C.; MOHANTY, B.; ROY, T.; XU, C.; LAWSON, K. Differentiable modelling to unify machine learning and physical models for geosciences. **Nature Reviews Earth & Environment**, v. 4, n. 8, p. 552–567, 2023. Available at: <<https://www.nature.com/articles/s43017-023-00450-9>>. Access: 24 nov. 2024.

SHOUROV, M. H. **pyhomogeneity**: A python package for homogeneity test., 2020. Available at: <<https://github.com/mmhs013/pyhomogeneity>>. Access: 6 oct. 2025.

SHRESTHA, N. Factor Analysis as a Tool for Survey Analysis. **American Journal of Applied Mathematics and Statistics**, v. 9, n. 1, p. 4–11, 2021. Available at: <<https://pubs.sciepub.com/ajams/9/1/2/index.html>>. Access: 19 sep. 2025.

SILVA, A.; COTA, S. Groundwater age dating using single and time-series data of environmental tritium in the Moeda Syncline, Quadrilátero Ferrífero, Minas Gerais,

Brazil. **Journal of South American Earth Sciences**, v. 107, p. 103009, 2021.

Available at:

<<https://www.sciencedirect.com/science/article/pii/S0895981120305526>>. Access: 17 dec. 2024.

SILVA, S. R. Da; CHANG, H. K. Hidroquímica dos Sistemas Aquíferos Bauru e Guarani na Região Metropolitana de Bauru (SP). **Águas Subterrâneas**, v. 24, n. 1, 2010. Available at:

<<https://aguassubterraneas.abas.org/asubterraneas/article/view/19648>>. Access: 4 jan. 2026.

SINGH, K. P.; GUPTA, S.; MOHAN, D. Evaluating influences of seasonal variations and anthropogenic activities on alluvial groundwater hydrochemistry using ensemble learning approaches. **Journal of Hydrology**, v. 511, p. 254–266, 2014. Available at: <<https://www.sciencedirect.com/science/article/pii/S0022169414000092>>. Access: 24 nov. 2024.

SOARES, A. R. **Observações de Longo Prazo da Composição Isotópica da Chuva na Região Central do Estado de São Paulo**. São Paulo: FAPESP 2024/06442-0 and 2024/23661-7, 2024.

SOUZA, C. M.; Z. SHIMBO, J.; ROSA, M. R.; PARENTE, L. L.; A. ALENCAR, A.; RUDORFF, B. F. T.; HASENACK, H.; MATSUMOTO, M.; G. FERREIRA, L.; SOUZA-FILHO, P. W. M.; DE OLIVEIRA, S. W.; ROCHA, W. F.; FONSECA, A. V.; MARQUES, C. B.; DINIZ, C. G.; COSTA, D.; MONTEIRO, D.; ROSA, E. R.; VÉLEZ-MARTIN, E.; WEBER, E. J.; LENTI, F. E. B.; PATERNOST, F. F.; PAREYN, F. G. C.; SIQUEIRA, J. V.; VIERA, J. L.; NETO, L. C. F.; SARAIVA, M. M.; SALES, M. H.; SALGADO, M. P. G.; VASCONCELOS, R.; GALANO, S.; MESQUITA, V. V.; AZEVEDO, T. Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Archive and Earth Engine. **Remote Sensing**, v. 12, n. 17, p. 2735, 2020. Available at: <<https://www.mdpi.com/2072-4292/12/17/2735>>. Access: 15 oct. 2024.

SRACEK, O.; HIRATA, R. Geochemical and stable isotopic evolution of the Guarani Aquifer System in the state of São Paulo, Brazil. **Hydrogeology Journal**, v. 10, n. 6, p. 643–655, 2002. Available at: <<http://link.springer.com/10.1007/s10040-002-0222-8>>. Access: 4 jan. 2026.

STECHEMESSER, A.; KOCH, N.; MARK, E.; DILGER, E.; KLÖSEL, P.; MENICACCI, L.; NACHTIGALL, D.; PRETIS, F.; RITTER, N.; SCHWARZ, M.; VOSSEN, H.; WENZEL, A. Climate policies that achieved major emission reductions: Global evidence from two decades. **Science**, v. 385, n. 6711, p. 884–892, 2024. Available at: <<https://www.science.org/doi/10.1126/science.adl6547>>. Access: 8 nov. 2024.

STRADIOTO, M. R. **Caracterização hidrogeoquímica, isotópica e diagenética do sistema aquífero Bauru no Estado de São Paulo**. Adviser: Chang Hung Kiang. Thesis (Doctorate degree on Geoscience and Environment) – Institute of Geosciences and Exact Sciences, São Paulo State University, Rio Claro, 2016. Available at: <<http://hdl.handle.net/11449/138943>>. Access: 20 dec. 2024.

STRADIOTO, M. R.; TERAMOTO, E. H.; CAETANO-CHANG, M. R.; CHANG, H. K. Water-Rock Interactions in the Bauru Aquifer System – São Paulo State, Brazil.

Procedia Earth and Planetary Science, 15th Water-Rock Interaction International Symposium, WRI-15, p. 388–391, 2017. Available at:

<<https://www.sciencedirect.com/science/article/pii/S1878522016301321>>. Access: 15 may. 2025.

STRADIOTO, M. R.; TERAMOTO, E. H.; CHANG, H. K. Nitrato em águas subterrâneas do Estado de São Paulo. **Revista do Instituto Geológico**

(Descontinuada), v. 40, n. 3, p. 1–12, 2019. Available at:

<<https://revistaig.emnuvens.com.br/ig/article/view/672>>. Access: 1 jan. 2025.

TAO, H.; HAMEED, M. M.; MARHOON, H. A.; ZOUNEMAT-KERMANI, M.; HEDDAM, S.; KIM, S.; SULAIMAN, S. O.; TAN, M. L.; SA'ADI, Z.; MEHR, A. D.; ALLAWI, M. F.; ABBA, S. I.; ZAIN, J. M.; FALAH, M. W.; JAMEI, M.; BOKDE, N. D.; BAYATVARKESHI, M.; AL-MUKHTAR, M.; BHAGAT, S. K.; TIYASHA, T.; KHEDHER, K. M.; AL-ANSARI, N.; SHAHID, S.; YASEEN, Z. M. Groundwater level prediction using machine learning models: A comprehensive review.

Neurocomputing, v. 489, p. 271–308, 2022. Available at:

<<https://www.sciencedirect.com/science/article/pii/S092523122200282X>>. Access: 15 oct. 2024.

TERAMOTO, E. H.; GONÇALVES, R. D.; CHANG, H. K. Hydrochemistry of the Guarani Aquifer System modulated by mixing with underlying and overlying hydrostratigraphic units. **Journal of Hydrology: Regional Studies**, v. 30, p. 100713, 2020. Available at:

<<https://www.sciencedirect.com/science/article/pii/S2214581820301877>>. Access: 15 oct. 2024.

TOBIAS, S.; CARLSON, J. E. Brief Report: Bartlett's Test of Sphericity and Chance Findings in Factor Analysis. **Multivariate Behavioral Research**, v. 4, n. 3, p. 375–377, 1969. Available at: <https://doi.org/10.1207/s15327906mbr0403_8>. Access: 19 sep. 2025.

UCHÔA, J. G. S. M.; OLIVEIRA, P. T. S.; BALLARIN, A. S.; MEIRA NETO, A. A.; GASTMANS, D.; JASECHKO, S.; FAN, Y.; WENDLAND, E. C. Widespread potential for streamflow leakage across Brazil. **Nature Communications**, v. 15, n. 1, p. 10211, 2024. Available at: <<https://www.nature.com/articles/s41467-024-54370-3>>. Access: 3 jan. 2025.

UN, UNITED NATIONS. **Kyoto Protocol to the United Nations Framework Convention on Climate Change**, 1998. Available at:

<<https://unfccc.int/resource/docs/convkp/kpeng.pdf>>.

UN, UNITED NATIONS. **The Paris Agreement**, 2015. Available at:

<https://unfccc.int/sites/default/files/english_paris_agreement.pdf>.

UNESCO, UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION. **UN World Water Development Report 2019**: leaving no one

behind. Paris: UNESCO, 2019. Available at: <https://www.unwater.org/publications/un-world-water-development-report-2019>. Access: 15 oct. 2024.

UNFCCC, UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE. **What is the Kyoto Protocol?** UNFCCC, 2024. Available at: https://unfccc.int/kyoto_protocol. Access: 8 nov. 2024.

USGS, U.S. GEOLOGICAL SURVEY. **PHREEQC Version 3**, 2025. Available at: <https://www.usgs.gov/software/phreeqc-version-3>. Access: 9 sep. 2025.

VALLE JÚNIOR, L. C. G.; VENTURA, T. M.; GOMES, R. S. R.; DE S. NOGUEIRA, J.; DE A. LOBO, F.; VOURLITIS, G. L.; RODRIGUES, T. R. Comparative assessment of modelled and empirical reference evapotranspiration methods for a brazilian savanna. **Agricultural Water Management**, v. 232, p. 106040, 2020. Available at: <https://www.sciencedirect.com/science/article/pii/S0378377419314489>. Access: 24 nov. 2024.

VALLEJO, C. A. M.; MANZIONE, R. L. Multidimensional forecasting of precipitation and potential evapotranspiration in the Paranapanema river basin using neural network time series. **Journal of South American Earth Sciences**, v. 142, p. 104961, 2024. Available at: <https://www.sciencedirect.com/science/article/pii/S0895981124001834>. Access: 24 nov. 2024.

VICARIO, S. A.; HORNBERGER, G. M.; MAZZOLENI, M.; GARCIA, M. Drivers and trends of streamflow droughts in natural and human-impacted basins across the contiguous United States. **Journal of Hydrology**, v. 655, p. 132908, 2025. Available at: <https://www.sciencedirect.com/science/article/pii/S002216942500246X>. Access: 9 may. 2025.

VICENTE-SERRANO, S. M.; BEGUERÍA, S.; LÓPEZ-MORENO, J. I. A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. **Journal of Climate**, v. 23, n. 7, p. 1696–1718, 2010. Available at: <https://journals.ametsoc.org/view/journals/clim/23/7/2009jcli2909.1.xml>. Access: 8 may. 2025.

VILLAR, P. C.; HIRATA, R. Groundwater Governance and the Construction of Legal Indicators for Brazilian States. **Ambiente & Sociedade**, v. 25, p. e00371, 2022. Available at: <https://www.scielo.br/j/asoc/a/MyJxyZZwMjRQm3Hmh7GnVKs/?lang=en>. Access: 15 oct. 2024.

VONK, M. A. **SPEI: A simple Python package to calculate and visualize drought indices**. Zenodo, 2024. Available at: <https://zenodo.org/records/10816741>. Access: 8 may. 2025.

XIANG, X.; LI, Q.; KHAN, S.; KHALAF, O. I. Urban water resource management for sustainable environment planning using artificial intelligence techniques.

Environmental Impact Assessment Review, v. 86, p. 106515, 2021. Available at: <<https://www.sciencedirect.com/science/article/pii/S0195925520307939>>. Access: 24 nov. 2024.

YANG, J.; LIU, H.; TANG, Z.; PEETERS, L.; YE, M. Visualization of Aqueous Geochemical Data Using Python and WQChartPy. **Groundwater**, v. 60, n. 4, p. 555–564, 2022. Available at:

<<https://onlinelibrary.wiley.com/doi/abs/10.1111/gwat.13185>>. Access: 17 dec. 2024.

ZHAO, T. et al. Artificial intelligence for geoscience: Progress, challenges, and perspectives. **The Innovation**, v. 5, n. 5, 2024. Available at:

<[https://www.cell.com/the-innovation/abstract/S2666-6758\(24\)00129-2](https://www.cell.com/the-innovation/abstract/S2666-6758(24)00129-2)>. Access: 24 nov. 2024.

ZHAO, G.; GAO, H.; LI, Y.; TANG, Q.; WOOLWAY, R. I.; MERDER, J.; ROSA, L.; MICHALAK, A. M. Decoupling of surface water storage from precipitation in global drylands due to anthropogenic activity. **Nature Water**, v. 3, n. 1, p. 80–88, 2025.

Available at: <<https://www.nature.com/articles/s44221-024-00367-7>>. Access: 27 may. 2025.

ZIPPER, S. C.; FARMER, W. H.; BROOKFIELD, A.; AJAMI, H.; REEVES, H. W.; WARDROPPER, C.; HAMMOND, J. C.; GLEESON, T.; DEINES, J. M. Quantifying Streamflow Depletion from Groundwater Pumping: A Practical Review of Past and Emerging Approaches for Water Management. **JAWRA Journal of the American Water Resources Association**, v. 58, n. 2, p. 289–312, 2022. Available at:

<<https://onlinelibrary.wiley.com/doi/abs/10.1111/1752-1688.12998>>. Access: 15 oct. 2024.