

UNIVERSIDADE ESTADUAL PAULISTA – UNESP

CÂMPUS DE JABOTICABAL

**VULNERABILIDADE AMBIENTAL E DISPONIBILIDADE
HÍDRICA DA BACIA RIO PARAÍBA DO SUL (CORREDOR
SUDESTE DA MATA ATLÂNTICA BRASILEIRA)**

Gislaine Costa de Mendonça
Bióloga

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**VULNERABILIDADE AMBIENTAL E DISPONIBILIDADE HÍDRICA DA BACIA RIO
PARAÍBA DO SUL (CORREDOR SUDESTE DA MATA ATLÂNTICA BRASILEIRA)**

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GISLAINE COSTA DE MENDONÇA - nascida em 18 de maio de 1988 no município de Matão – São Paulo. Bióloga graduada em Ciências Biológicas pela Universidade de Araraquara – UNIARA no ano de 2013. Mestra em Aquicultura (Biologia Aquática) pelo Centro de Aquicultura da Unesp - Caunesp, em 2018. Iniciou em 2020 o Doutorado junto ao Programa de Pós-Graduação em Agronomia na área de Ciência do Solo na Faculdade de Ciências Agrárias e Veterinárias da Universidade Estadual Paulista, Júlio de Mesquita Filho (FCAV/Unesp). Atua desde de 2012 em avaliações ambientais relacionadas aos recursos hídricos (qualidade, bioindicadores, bacias hidrográficas), e em 2018 ingressou no monitoramento do uso e cobertura do solo (diagnóstico, planejamento, política, governança), com recentes contribuições em investigações de emissão de carbono. É Pesquisadora Associada ao Grupo de Pesquisa em Política de Uso do Solo – PolUS e desenvolve projetos de pesquisa, ensino e extensão junto ao Laboratório de Geomática – Departamento de Engenharia e Ciências Exatas da FCAV/Unesp. Consolidou se como pesquisadora na área de modelagem de paisagem, com ênfase nos serviços hidrológicos em agroecossistemas e pela aplicação de geotecnologias (geoprocessamento, sensoriamento remoto, linguagem de programação). Especialista no desenvolvimento de metodologias de delimitação de áreas prioritárias, com foco na recuperação ambiental e implantação de sistemas agroflorestais, produzindo trabalhos como suporte à decisão de projetos e políticas públicas voltados aos serviços ambientais e resiliência climática.

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“O meio ambiente não é o espaço em que vivemos, mas o espaço do qual vivemos”
[Ana Primavesi, 1997. In: Agroecologia. Ecosfera, Tecnosfera e Agricultura]

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VULNERABILIDADE AMBIENTAL E DISPONIBILIDADE HÍDRICA DA BACIA RIO PARAÍBA DO SUL (CORREDOR SUDESTE DA MATA ATLÂNTICA BRASILEIRA)

RESUMO - O estudo da pressão em ecossistemas naturais é importante para determinar métricas que identifiquem o impacto de uma atividade antropogênica sobre o meio e a disponibilidade dos serviços ecossistêmicos. Esta pesquisa tem como objetivo verificar a vulnerabilidade ambiental, os conflitos de uso do solo e calcular a disponibilidade hídrica da Bacia do Rio Paraíba do Sul, no Corredor Sudeste da Mata Atlântica Brasileira, como suporte a identificação de áreas prioritárias para a implementação de planos de manejo específico e recomposição florestal. O aporte teórico-metodológico desta pesquisa será desenvolvido por técnicas de sensoriamento remoto, sistema de informação geográfica e levantamento de dados de geologia, solo, topografia, uso e cobertura natural do solo, vazão e clima. Também será realizada a divisão hidrogeológica da bacia hidrográfica a partir da modelagem hidrológica, para a determinação das variáveis de paisagem (uso do solo), clima (precipitação, temperatura do ar, radiação solar, velocidade do vento e umidade relativa do ar), geomorfologia e a topografia em escala de sub-bacias. E estimativa a disponibilidade hídrica nas sub-bacias será calculadas a partir das descargas líquidas nos exutórios dos cursos de água de cada sub-bacias de estudo. A partir do processo estatístico de álgebra de mapas e análise hierárquica de processos serão realizadas comparações pareadas dos fatores para criar uma matriz de razão que irão determinar a vulnerabilidade ambiental e os conflitos de uso do solo nas sub-bacias. As variáveis serão comparadas para definir sua importância relativa, para a hierarquização de áreas prioritárias e para determinar métricas que possam ser utilizadas como sistema de suporte na elaboração de um plano de reflorestamento e manejo na Bacia do Vale do Paraíba.

“Palavras-chave:” agroecossistema, bacias hidrográficas, conservação de água e solo, modelagem da paisagem, serviços ambientais

ENVIRONMENTAL VULNERABILITY AND WATER AVAILABILITY OF THE PARAÍBA DO SUL RIVER BASIN (SOUTHEAST CORRIDOR OF THE BRAZILIAN ATLANTIC FOREST)

ABSTRACT – The study of pressure on natural ecosystems is important to determine details that identify the impact of an anthropogenic activity on the environment and the availability of ecosystem services. This research aims to verify the environmental vulnerability, land use conflicts and calculate the water availability of the Paraíba do Sul River Basin, in the Southeast Corridor of the Brazilian Atlantic Forest, as a support to the identification of priority areas for the implementation of plans of specific management and forest recomposition. The theoretical-methodological contribution of this research will be developed by remote sensing techniques, geographic information system and data collection of geology, soil, topography, land use and natural cover, flow and climate. The hydrogeological division of the watershed will also be carried out based on hydrological modeling, for the determination of landscape variables (land use), climate (precipitation, air temperature, solar radiation, wind speed and relative humidity), geomorphology and topography at sub-basin scale. The estimate of water availability in the sub-basins will be calculated from the liquid discharges in the outlets of the watercourses of each sub-basins under study. From the statistical process of map algebra and hierarchical analysis of processes, paired comparisons of the factors will be carried out to create a ratio matrix that will determine the environmental vulnerability and land use conflicts in the sub-basins. The variables will be compared to define their relative importance, to rank priority areas and to determine metrics that can be used as a support system in the elaboration of a reforestation and management plan in the Vale do Paraíba Basin.

“Keywords:” agroecosystems, environmental services, landscape modelling, soil and water conservation, watersheds

CAPÍTULO 1 - Considerações gerais

1. Introdução

O equilíbrio entre o desenvolvimento socioeconômico e a gestão sustentável dos recursos naturais é um dos grandes desafios da ciência. À medida que aumenta a urgência de equilibrar e alcançar simultaneamente os Objetivos de Desenvolvimento Sustentável - ODS (<https://sdgs.un.org/goals>), são necessárias estudos robusto e estratégias eficazes para promover o uso do solo, da água e dos serviços de biodiversidade e regulação atmosférica, sem comprometer a conservação dos ecossistemas naturais; pois disto também depende a segurança alimentar e hídrica, a resiliência e sustentabilidade dos sistemas (FAO, 2017; Chen et al., 2022).

Em bacias hidrográficas inseridas em agroecossistemas, as interações complexas entre os componentes do ecossistema (bióticos e abióticos) e os modelos atuais de uso da terra têm sobrecarregado a capacidade de manutenção e provisão de SE, levando à degradação destes sistemas (Foley et al., 2005; Chazdon et al., 2019). Isto representa um desafio adicional para a restauração da paisagem e recuperação ambiental, pois também requer assegurar que as funções socioeconômicas dos ecossistemas sejam mantidas, favorecendo além de práticas agrícolas conservacionistas, a adoção de sistemas de produção mais sustentáveis do ponto de vista de integração ecológica, com agroflorestas, entre outros modelos de agricultura regenerativa (Kanter et al., 2018; de Mendonça et al., 2022).

As iniciativas de restauração ecológica e reflorestamento em arranjos agroflorestais e bio diversos ganham força no cenário mundial para a regeneração de paisagens agropecuárias (Laurett et al., 2021), e integram o quadro de Soluções Baseadas na Natureza (SBN) para a proteção, gestão sustentável e restauração do ecossistema natural. Adicionalmente, estes sistemas alcançam novas perspectivas e patamares no âmbito das normativas e incentivos à prestação dos serviços ambientais e em políticas públicas para recuperação da vegetação nativa nos programas de Pagamento por Serviços Ambientais (PSA) (Brancaion et al., 2019).

Nos últimos anos, as políticas ambientais e os investimentos associados à restauração da Mata Atlântica direcionaram a Bacia do Rio Paraíba do Sul (PSRB) a

restaurar e conservar seus recursos naturais visando o uso sustentável da terra, a conservação da vegetação nativa e a recuperação florestal dentro de das propriedades privadas, e com isto a compensação socioeconômica em pagamentos por serviços ambientais (SEMIL, 2023). Neste cenário, a ciência do solo desempenha um papel crítico na conservação das as bacias hidrográficas, ao propor soluções que promovem práticas agrícolas mais sustentáveis e assim contribuir para a qualidade dos ecossistemas terrestres e aquáticos e conseqüentemente, a segurança hídrica e a sustentabilidade dos meios de produção.

Deste modo, o desenvolvimento deste projeto de pesquisa explorou fundamentos e metodologias de investigação para compreender e estabelecer critérios para a recuperação e a conservação de bacias hidrográficas em agroecossistemas. A modelação da fragilidade da paisagem, da dinâmica do uso e ocupação do solo, da disponibilidade hídrica superficial e dos padrões agrometeorológicos, foi aplicada com o intuito de avançar na compressão do nexo solo-água e promover a conservação dos serviços ecossistêmicos providos a nível da água na Bacia Hidrográfica do Rio Paraíba do Sul. Portanto, os métodos e resultados aqui relatados também apresentam tendências locais em provisão dos serviços hidrológicos, do potencial de exposição de degradação do solo relacionadas a conversão do uso da terra para apoiar estratégias de resiliência climática e as metas de restauração de paisagens e recuperação da Mata Atlântica.

1.1. Objetivo geral da pesquisa

Investigar a vulnerabilidade ambiental e a disponibilidade hídrica na porção paulista da Bacia Hidrográfica do Rio Paraíba do Sul como suporte aos planos de ação e de iniciativas de manejo e conservação da bacia, à implementação de sistemas de produção mais sustentáveis e ao desenvolvimento de métricas (avaliação e valoração); subsidiar programas de pagamentos por serviços ambientais relacionados a provisão de água e conservação do solo e alavancar a recuperação da Mata Atlântica dentro de propriedades privadas.

1.2. Objetivos específicos

- Realizar a setorização hidrológica para otimizar a gestão e a governança da grande bacia a partir da delimitação de unidades de resposta hidrológica (UH); estimar os fluxos superficiais de vazão para investigar as contribuições específicas de cada UH para disponibilidade hídrica superficial na grande bacia;
- Estimar o balanço hídrico climatológico como indicador de disponibilidade hídrica regional; aplicar e comparar o desempenho de algoritmos de aprendizado de máquinas (*Machine Learning*) e de rede neural artificial (*Artificial Neural Network*) na predição de Evapotranspiração Potencial (ETp) para automatizar as avaliações de serviços hidrológicos;
- Integrar a avaliação da vulnerabilidade ambiental da bacia a um sistema espacial multicritério de apoio à decisão para identificar áreas prioritárias em termos de abastecimento de água e degradação do solo e otimizar ações estratégicas de restauração da paisagem e produção conservacionistas; propor métricas e indicadores para a implementação, valoração e escalonamento de planos de ação para o pagamento por serviços ambientais.

1.3. Abordagem da pesquisa

As questões centrais, a metodologia desenvolvida e os principais resultados desta pesquisa contribuem para as investigações no âmbito do Projeto [GEF/FAPESP \(2018/17044-4\)](#), que avalia ao manejo agroflorestal e cultivo de espécies nativas no Vale do Paraíba em atendimento a chamada liderada pelo Fundo Global para o Meio Ambiente (GEF), o Ministério da Ciência e Tecnologia do governo brasileiro, a Secretaria de Infraestrutura e Meio Ambiente do Estado de São Paulo (SEMIL / SP) e a Agência de Financiamento da Pesquisa do Estado de São Paulo (FAPESP).

O trabalho também atua como um Sistema de Suporte à Decisão (DSS) ao fornecer projeções e insights para orientar políticas públicas de incentivo

socioeconômico para pagamentos por serviços ambientais e restauração da paisagem propõe elucidar as demandas no âmbito das políticas públicas em desenvolvimento e futuras: i) Onde intensificar esforços e alocar recursos; Quais as métricas de valoração e monitoramento. Deste modo, a tese foi estruturada em cinco seções – capítulos, que apresentam as contribuições da tese doutoral para os pontos centrais desta pesquisa, com ênfase na avaliação da vulnerabilidade ambiental e disponibilidade hídrica na Bacia Hidrográfica do Rio Paraíba do Sul:

Capítulo 1 – Considerações gerais: Retrata a contextualização, objetivos, abordagem e referencial teórico da pesquisa.

Capítulo 2 – Disponibilidade hídrica superficial da Bacia Hidrográfica do Rio Paraíba do Sul: Apresenta o estudo da hierarquização de bacias críticas e dos fluxos hidrológicos superficiais;

Capítulo 3 - ETpML Previsão de evapotranspiração potencial através de algoritmos de aprendizado de máquina para otimizar avaliações de serviços hidrológicos: Diagnostica a disponibilidade hídrica regional e aplicação de algoritmo de aprendizado de máquinas e rede neural para automatizar a estimativa de evapotranspiração potencial.

Capítulo 4 - Um sistema espacial multicritério de apoio à decisão para otimizar pagamentos para programas de serviços ecossistêmicos visando a restauração da paisagem: Estabelece a identificação de áreas prioritárias em termos de abastecimento de água e degradação do solo e proposição de métricas.

Capítulo 5 – Considerações Finais: Retrata os principais achados da pesquisa e recomendações para a gestão da Bacia Hidrográfica do Rio Paraíba do Sul.

2. Referencial Teórico

2.1. Vulnerabilidade Ambiental em bacias hidrográficas

Estudos globais em ciências do solo destacam abordagens de modelagem ambiental integrada para solucionar questões ambientais complexas, como a conservação da água e do solo à escala de bacias hidrográficas. A área de drenagem sustenta habitats e seres vivos, e fornece uma unidade territorial complexa para investigar fenômenos e processos (naturais e antrópicos), no intuito de melhor compreender as interações e impactos da ocupação humana sobre a manutenção e provisão de múltiplos serviços ecossistêmicos (provisão, regulação e suporte (Chen et al., 2022; de Mendonça et al., 2022). Esta abordagem também fornece um arcabouço robusto e métricas eficientes para fomentar políticas de manejo sustentável.

A análise geoespacial da vulnerabilidade ambiental nas bacias hidrográficas investiga a fragilidade do sistema e a suscetibilidade dessas áreas a impactos e mudanças ambientais negativos, naturais ou pela ação humana pelo uso insustentável dos recursos. Uma extensa literatura relata avaliações de bacias hidrográficas para monitorar as condições ambientais e como a vulnerabilidade natural e os conflitos ambientais de uso do solo, impactam a incerteza donexo água-terra-alimentos e comprometem a provisão de serviços nas agroecossistemas (Pena et al., 2020; Rodríguez-Merino et al., 2020, Chigbu et al., 2022).

Estas abordagens frequentemente combinam a avaliação de múltiplos fatores, como a degradação do solo em função das condições biofísicas naturais da paisagem e dos padrões de uso da terra, entre outros processos ambientais. Uma estrutura de Análise de Decisão Multicritério (MDC) acoplada a Sistemas de Informação Geográfica (SIG) possibilita integrar e ponderar diferentes fatores com base em critérios específicos, permitindo análises espaciais detalhadas da vulnerabilidade ambiental em diversas abordagens (Craig et al., 2020; de Mendonça et al., 2023). Com isto é possível identificar áreas críticas e mais sensíveis, para orientar a tomada de decisões e otimizar iniciativas de restauração da paisagem e de conservação da água e do solo.

2.1.1. Vulnerabilidade natural

A avaliação espacial da vulnerabilidade natural reflete a importância das condições do ambiente e da erosão natural nas bacias e é fundamental para se conduzir de forma bem-sucedida a implementação das melhores práticas de gestão e conservação. Para operar mudanças no uso da terra é preciso adaptar-se aos tipos litológicos e de solo, bem como às características de relevo e cobertura da terra. Adicionalmente, nas áreas vulneráveis, as perdas de solo e a qualidade da água é particularmente sensível às mudanças no uso da terra (Pacheco et al., 2018; Pacheco e Sanches Fernandes, 2016). Os serviços hidrológicos e de suporte do solo são consideravelmente comprometidos, enquanto os serviços hidrológicos (apoio, regulação, fornecimento) e seus impactos no fluxo de água e na qualidade da água como um serviço prestado de áreas a montante para jusante ao longo das bacias hidrográficas (Pacheco 2020; Simedo et al., 2020; Tribouillois et al., 2022).

A vulnerabilidade natural determina o risco intrínseco à erosão do solo em função de características ambientais em uma unidade de paisagem. A metodologia para determinação da vulnerabilidade natural é baseada nos estudos de Crepani et al. (2001) adaptada por Pissarra et al. (2021) para agroecossistemas, e consiste em uma análise espacial multicritério baseada em múltiplos fatores ambientais e antropogênico, que caracterizam os riscos de perda natural e exposição da terra. Onde vulnerabilidade natural (dado secundário) deriva da distribuição espacial de três fatores ambientais (dados primários): geologia, solo, relevo e, um fator antropogênico: a cobertura da terra. Por meio de álgebra de mapas, equacionado pela média aritmética de todos os fatores, tem-se o valor de índice para a suscetibilidade à erosão e, portanto, a vulnerabilidade à perda de solo no sistema.

2.1.2. Conflito ambiental de uso da terra

Diante da percepção de alteração nos sistemas naturais advindos dos efeitos da degradação ambiental, o conflito ambiental de uso da terra, é caracterizado pelo desvio entre os usos reais e os usos naturais da terra, e tem sido amplamente estudado pelas graves consequências ambientais que esses conflitos são

responsáveis (Valle – Júnior et al., 2014). Uma consequência imediata é a erosão amplificada do solo, que tem sido documentada em bacias hidrográficas de topografia escarpada que, apesar de susceptíveis à erosão, estão a ser ocupadas por usos agrícolas acima da capacidade suporte (Valle – Júnior et al., 2015; Pacheco, Sanches, 2016; Costa et al., 2020). No geral, os conflitos ambientais de uso da terra são considerados uma das principais causas da degradação da terra nos agroecossistemas, um desequilíbrio entre as funções ambientais e socioeconômicas.

O conceito de conflito ambiental pelo uso da terra abrange duas situações específicas: uso da terra acima da capacidade, ou uso subestimado, levando à baixa produtividade e degradação do solo. Na unidade de bacias hidrográficas, a determinação da capacidade de uso do solo é determinada por indicadores da dissecação do terreno, como índice rugosidade; que evoluiu em sua aplicação pelo surgimento dos sistemas de informação geográfica (GIS). Portanto, diferente da avaliação de vulnerabilidade natural, que expõe o risco de degradação, a análise de conflito ambiental do uso do solo, indica regiões potencialmente em processo de degradação, um retrato atual das condições do solo para orientar técnicas conjuntas de conservação do solo.

2.2. Avaliação da disponibilidade hídrica

Os serviços e benefícios providos pelos ecossistemas aquáticos e terrestres dentro de uma bacia hidrográfica desempenham um papel crucial na disponibilidade e fornecimento de água (quantidade e qualidade) para os múltiplos usos. Compreender a dinâmica da água na unidade territorial de bacias hidrográficas requer uma avaliação conjunta das diversas interações e processos hidrológicos que ocorrem na paisagem, incluindo aspectos climáticos e antrópicos. Uma visão completa dos sistemas hidrológicos inclui a combinação de múltiplas abordagens em hidrologia, como suporte a tomada de decisão sobre a gestão dos recursos hídricos. Este entendimento também é fundamental para o desenvolvimento de ações estratégicas, o estabelecimento de critérios de conservação do solo e da água e garantir a segurança hídrica nas bacias (Pacheco, 2020; Laurett et al., 2021).

Em sua complexidade, a bacia hidrográfica é uma entidade hidrológica natural que tem como resposta à precipitação, um dinamismo sistêmico e cíclico (deflúvio,

infiltração, evapotranspiração) (Pissarra et al., 2004, 2010; Attanasio, 2004) que regula o Balanço Hídrico (entrada e saída de água) e resulta na disponibilidade de água no sistema (no solo, aquíferos, rios, lagos, vegetação, atmosfera). A Disponibilidade Hídrica resultante nas bacias hidrográficas (água produzida e armazenada) é condicionada a variabilidade espaço – temporal; incluindo os efeitos das características geomorfológicas da bacia, configuração espacial e componentes da paisagem (bióticos e abióticos) (Harlin, 1984; Magalhães et al., 2022; Saha et al., 2022).

2.2.1. Balanço Hídrico

A análise do balanço hídrico é uma ferramenta essencial para avaliar a disponibilidade e o uso da água em uma determinada região, pois contabiliza a diferença entre as entradas e saídas de água durante um período de tempo específico, expresso em volume por unidade de tempo. O balanço hídrico nas bacias o que inclui além das entradas pela precipitação pluvial (P), as contribuições de água de rios e infiltração de água no solo; como saída ou perda de água para a atmosfera é contabilizado a evaporação (E), que é a perda de água da superfície terrestre (solo) e aquáticas (rios e lagos), e pela transpiração das plantas (evapotranspiração) (Thornthwaite, 1948; Sun et al., 2019).

Concomitante, parte da água que chega ao solo pode infiltrar e percolar para camadas mais profundas do perfil, permanecendo armazenada na parte porosa (sistemas subterrâneos e em reservatórios), ou escoar superficial e/ou lateralmente, incluindo a extração de água (Melton, 1957; Abdulkareem et al., 2018). As informações de armazenamento de água solo possibilitam também a avaliação da recarga de aquíferos subterrâneos e de armazenamento reservatórios, com extensas aplicações nas práticas e projeções agrícolas.

O extrato final do balanço hídrico fornece métricas quali e quantitativas sobre o estado atual da região, e subsídios para projeções e estimativas de disponibilidade hídrica ao identificar as características hidrológicas da bacia e variações sazonais. Adicionalmente, um Balanço Hídrico Climatológico, que considera médias anuais e condições climáticas de longo prazo, possibilita avaliar a disponibilidade hídrica ao

longo de décadas, importantes para o planejamento de infraestruturas hídricas, bem como identificar tendências em resposta às mudanças climáticas para sistemas mais resilientes (Valeriano et al., 2022; Pluntke et al., 2023).

O balanço hídrico climatológico investiga a variação de armazenamento de água no solo e a quantidade de água armazenada em um dado intervalo de tempo, fornecendo um extrato da disponibilidade hídrica regional, fundamental para determinar períodos de déficit e excedente hídrico e realizar uma gestão mais sustentável dos serviços hidrológicos (Gowri et al., 2021; Wilson et al., 2022). Considerando a modelagem de agroecossistemas, ecossistemas que sustentam os sistemas de produção agrícola, esta é uma avaliação integrada à escala de bacia que permite avaliar padrões climáticos e estimar o potencial hidrológico para os sistemas de cultivo (irrigados ou não) visando a sustentabilidade e a segurança hídrica nas bacias.

2.2.2. Disponibilidade Hídrica

Por sua vez, a disponibilidade hídrica refere-se à quantidade de água que está disponível para uso em uma determinada região em um determinado período de tempo, geralmente expressa em metros cúbicos por ano (m^3/ano) ou litros por segundo (l/s). Na hidrologia, a disponibilidade hídrica é avaliada em dois níveis principais: a **Disponibilidade Superficial**, caracterizada pela água prontamente disponível em rios, lagos, reservatórios e outras superfícies aquáticas para os usos múltiplos; e a **Disponibilidade Subterrânea**, que representa a água armazenada nos aquíferos subterrâneos, acessada apenas por fontes ou poços. Por fim, a **Disponibilidade Real**, que é a quantidade de água realmente disponível para uso considerando as limitações naturais e antrópicas (sazonalidade das chuvas, a poluição da água e a sobre-exploração), e as **Demandas** existentes, determinam a estrutura base de gestão e governança dos recursos hídricos (ANA, 2020).

A disponibilidade hídrica de uma bacia hidrográfica é comumente avaliada, na sua etapa inicial, pelos fluxos superficiais a partir das descargas líquidas médias observadas nos cursos de água, produto entre o volume de água produzida e consumida. A disponibilidade hídrica superficial é caracterizada por uma vazão

mínima de referência, que para fins de gestão, representa a provisão de água a ser considerada no Balanço Hídrico Quantitativo, uma relação entre a oferta e a demandas consuntivas estimadas. Assim, o volume de água disponível anualmente é utilizado como base para comparações em relação à demanda hídrica atual e projetada. Projeções em segurança hídrica usam como parâmetro a demanda hídrica social 1000 m³/hab/ano, de acordo com as projeções da Organização das Nações Unidas (ONU).

No Brasil, a Agência Nacional de Águas e Saneamento Básico (ANA, 2015) estabelece como vazão referência a média mínima da vazão de sete dias consecutivos em um período de retorno de dez anos, a Q_{7.10}. Isto representa a vazão mínima a ser mantida em um curso d'água durante um período de 7 dias, em pelo menos 10% do ano, um limiar ecológico e sanitário, para equilibrar as demandas humanas por água e a proteção dos ecossistemas aquáticos, uma garantia de que o curso d'água tenha água suficiente para sustentar a vida.

Em São Paulo, a vazão de referência é definida no Plano de Bacias Hidrográficas ou, na ausência deste, pela Lei Estadual nº 9.034 de 1994, que também preconiza a Q_{7.10} como vazão de referência e considera crítica quando a soma das vazões captadas em uma determinada bacia hidrográfica, ou em parte desta, é superior a 50% da respectiva vazão de referência. A disponibilidade hídrica observada na Q_{7.10} também é utilizado para orientar a outorga de direitos de uso da água e a definição de metas para sustentabilidade dos usos múltiplos da água no Brasil, como abastecimento público e irrigação.

Investigações da disponibilidade hídrica nas bacias podem ser aplicadas para suprir demandas pontuais e específicas, bem como orientar planos de gestão e estabelecer políticas públicas de desenvolvimento e dispositivos para a governança dos recursos hídricos e do uso sustentável do solo. Contudo, não recomenda se uma avaliação isolada, visto que os sistemas terrestres e aquáticos estão fortemente relacionados, a exemplo, os processos de degradação do solo e assoreamento de cursos d'água e reservatórios naturais de água que impactam diretamente na disponibilidade hídrica (quantidade e qualidade) (Pan et al., 2020).

Adicionalmente as interações superfície - atmosfera promovem processos hidrológicos à nível de solo e clima, representando risco de escassez hídrica e

impactos severos sobre a manutenção de múltiplos serviços ecossistêmicos fundamentais ao desenvolvimento socioeconômico, sobretudo o sucesso da produtividade agrícola. Outros estudos realizados sobre a disponibilidade hídrica em agroecossistemas evidenciam os impactos dos padrões de uso da terra sobre a modificação no conteúdo de água armazenado no solo de bacias agrícolas (Simedo et al. 2020; Lopes et al., 2020). Alterações no clima, temperatura e regime das chuvas, também influenciam as respostas hidrológicas e o balanço hídrico nas bacias hidrográficas (Liu et al., 2018; Li et al. 2021).

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CAPÍTULO 2- Disponibilidade hídrica superficial da Bacia Rio Paraíba do Sul

Resumo - Os processos hidrológicos nas bacias hidrográficas são constantemente influenciados por fatores naturais e antrópicos. Diante das interações e processos nestes sistemas, os objetivos e aporte teórico-metodológico deste capítulo investigam a disponibilidade hídrica à escala de sub-bacias na porção paulista da grande Bacia do Rio Paraíba do Sul. Devido à complexidade biofísica nas bacias hidrográficas, a subdivisão de subunidades possibilita um diagnóstico específico das contribuições de cada sub-bacia. A divisão da área foi efetuada no modelo hidrológico *Soil and Water Assessment Tool*. A investigação da disponibilidade hídrica foi realizada pela avaliação dos fluxos superficiais (vazões), utilizando a metodologia proposta no estudo de “Regionalização da Água no Estado de São Paulo”, modelos probabilísticos e determinísticos desenvolvido pelo Departamento de Água e Energia Elétrica do Estado de São Paulo (DAAE) e automatizada em plataforma digital. O delineamento das unidades experimentais caracterizou 23 sub-bacias agrupada em duas categorias, sub-bacia e compartimentos hidrológicos. Isto possibilita a identificação de áreas de manejo específicos para o estabelecimento de estratégias de recuperação ambiental e o desenvolvimento de métricas mais eficientes que suportem os processos de tomada de decisão e os instrumentos de políticas públicas com vistas a gestão e governança dos recursos hídricos. O índice de vazão específica médio foi determinado pela razão entre a vazão média em uma dada seção de medição e a respectiva área de drenagem, em que é possível identificar uma tendência de redução da vazão específica de montante para jusante, conforme o aumento do tamanho da bacia e o comprimento do rio. Espera-se que estes indicadores de disponibilidade hídrica na unidade territorial de sub-bacias possam servir como parâmetros no sistema de suporte à decisão aos programas de pagamento por serviços ambientais (valoração e implementação) na região.

Palavras-chave: gestão de recursos hídricos, modelagem hidrológica; segurança hídrica; serviços hidrológicos; sistema de suporte à decisão; vazão de referência

1. Introdução

O ecossistema fornece uma gama de benefícios de sustentação da vida que são essenciais para o desenvolvimento e bem-estar humano (MEA, 2005). A disponibilidade hídrica que rege o abastecimento de água potável, entre os múltiplos usos, é o serviço ecossistêmico mais valioso e crucial para a sobrevivência e o desenvolvimento da sociedade humana (Boithias et al., 2014; Huq et al., 2019). A degradação dos habitats naturais, ocasionada pela intensa modificação da paisagem e uso insustentável dos recursos, resulta na interrupção gradativa das funções do ecossistema (provisão, regulação, suporte) (Steffen, 2015; Yohanes et al., 2021). O desenvolvimento de práticas agrícolas sem adaptação em bacias hidrográficas estratégicas intensifica a degradação do solo e da água em quantidade e qualidade (Pacheco, Sanches Fernandes, 2016; Pacheco 2020). Com isto, a manutenção dos serviços relacionados aos recursos hídricos e a disponibilidade hídrica é particularmente afetado, por comprometer e perturbar os processos hidrológicos (Shi et al., 2020; Li, et al 2021).

Como em diversas regiões tropicais, a Mata Atlântica brasileira foi degradada ao longo da história pelas ações humanas e expansão das terras agrícolas sobre a cobertura de vegetação nativa (Metzger, 2009, Andrade et al., 2020). Conseqüentemente, a perda de cobertura florestal contribuiu ao longo do tempo, para o declínio dos serviços hidrológicos, entre outros serviços relacionados a regulação dos fluxos hidrológicos e climáticos na região (Alvarenga et al. 2016). Considerando a complexidade da conservação da água e do solo, incluindo metas de resiliência climática, nos últimos anos, as políticas ambientais e os investimentos associados à restauração da Mata Atlântica direcionaram a Bacia do Rio Paraíba do Sul (PSRB) como alvo de ações de conservação do bioma. Um dos instrumentos de política utilizados são esquemas de pagamentos por serviços ambientais (PSA), como incentivo a adoção de práticas e usos da terra que conservem e/ou melhorem os serviços ecossistêmicos (SEMIL, 2021).

Contudo, apesar de promoverem a produção de água e a conservação do solo, as abordagens existentes para as modalidades de PSA vigentes não possuem métricas específicas para avaliar ou valorar, junto aos esquemas, a capacidade e a relevância local das bacias hidrográficas para produção de água, bem como a

hierarquização de regiões estratégicas para manejo e sustentabilidade do sistema. Assim, a fim de contribuir para a valoração dos serviços de provisão de água, esta proposta pretende investigar a dinâmica das vazões em sub-bacias, como indicador da disponibilidade hídrica superficial na porção paulista da Bacia do Rio Paraíba do Sul - Corredor Sudeste da Mata Atlântica Brasileira, com vistas a projeção da produção de água como serviço prestado na bacia.

1.1. Objetivos

1.1.1. Objetivo Geral

Avaliar a disponibilidade hídrica na bacia hidrográfica do Rio Paraíba do Sul - Corredor Sudeste da Mata Atlântica Brasileira como suporte a elaboração de métricas de avaliação e valoração de serviços ambientais hídricos.

1.1.2. Objetivos Específicos

i) Realizar a divisão hidrológica (sub-bacias) da bacia hidrográfica do Rio Paraíba do Sul - Corredor Sudeste da Mata Atlântica Brasileira, à montante da Represa do Funil para otimizar a gestão e governança dos recursos hídricos;

ii) Determinar os fluxos superficiais em cada unidade hidrológica a nível de sub-bacia e identificar os padrões da disponibilidade hídrica superficial na porção paulista da Bacia do Rio Paraíba do Sul - Corredor Sudeste da Mata Atlântica Brasileira.

2. Material e Métodos

2.1. Área de estudo

Esta proposta tem como área de aplicação a porção paulista da Bacia Hidrográfica do Rio Paraíba do Sul (BHRPS) no Corredor Sudeste da Mata Atlântica Brasileira, Estado de São Paulo (Figura 1). A região é estratégica para o projeto “Conexão da Mata Atlântica”, que implementou diferentes modalidades de programas para o pagamento por serviços ambientais, ao longo de toda a BHRPS e no Vale do

Paraíba. A área também é contemplada no Projeto FAPESP - Processo: 2018/17044-4 ao qual esta proposta está vinculada e pretende contribuir para o direcionamento e efetividade dos manejos agroflorestais na bacia.

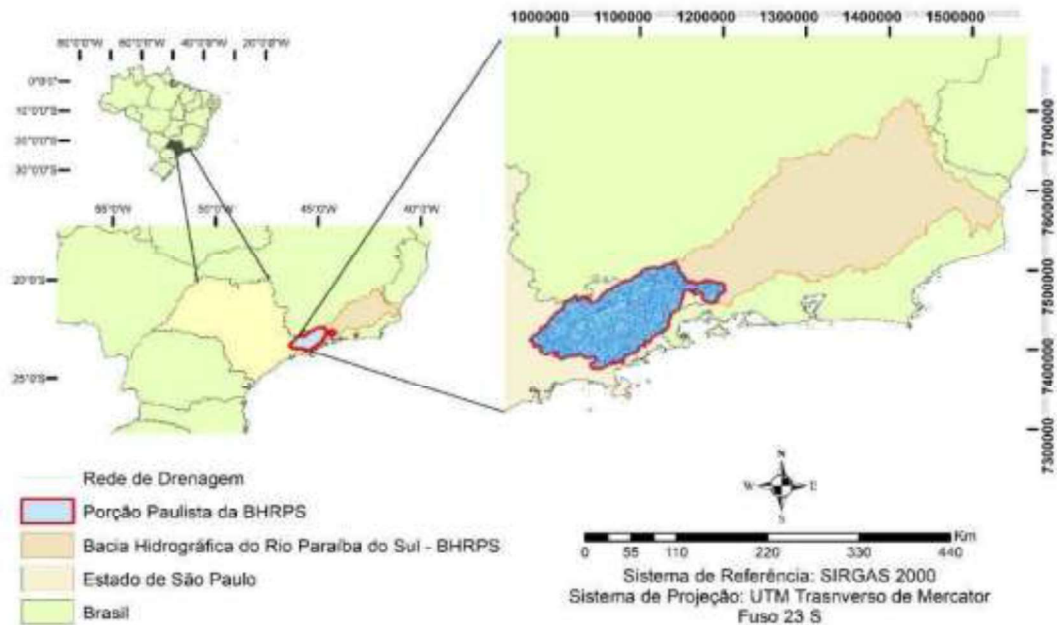


Figura 1. Localização geográfica da Bacia Hidrográfica do Paraíba do Sul, Corredor Sudeste da Mata Atlântica Brasileira, com destaque a área de estudo na porção paulista no Estado de São Paulo, Brasil.

A região está localizada à montante da Represa do Funil na Bacia Hidrográfica do Rio Paraíba do Sul, no Corredor Sudeste da Mata Atlântica Brasileira, Estado de São Paulo. A área compreende a porção contígua aos 38 municípios que constituem a Unidade de Gerenciamento de Recursos Hídricos- 02, Paraíba do Sul (ANA, 2020), entre as coordenadas Longitudes 290.159,83 m E e 338.603,71 m E, e Latitudes 7.753.489,00 m S e 7.361.362,45 m N, Fuso 23K. A BHRPS abriga uma das partes mais industrializadas do Brasil, incluindo agropecuárias e, é uma área de alta importância para a produção de águas em uma das regiões mais desenvolvidas do país, com inúmeros tributários e afluentes.

A vegetação remanescente apresenta 3.846 km² de vegetação natural de domínio fitogeográficos Mata Atlântica, (IBGE, 2016). O clima é classificado por Köppen como subtropical quente, com temperatura média anual oscilando entre 18°C

e 24°C, com máximas precipitações de 2250 mm/ano (Alvares, et al., 2013). Geomorfologicamente, as unidades morfoestruturais são denominadas de Cinturão Orogênico do Atlântico e Bacias Sedimentares Cenozóicas. As formas do relevo são de escarpas, morros altos, altos e alongados e morros baixos, com predomínio de Cambissolos, Litossolos, Afloramentos rochosos, Litólicos e Latossolo Vermelho Amarelo (Ross; Moriz, 2011). O uso e cobertura predominante é a pastagem (49%), seguida pela vegetação natural (28%) e áreas agrícolas, incluindo culturas perenes e anuais (18%), o que ressalta a necessidade de investigações multidisciplinares para o direcionamento dos planos de reflorestamento e dos programas de Pagamentos por Serviços Ambientais na região. Nesta proposta, a área de estudo será delimitada em sub-bacias menores a partir da sub-divisão hidrológica para caracterização e simulação comparativa das respostas hidrológicas do ambiente, conformando métricas e padrões de manejo específicos em cada sub-bacia.

2.2. Delineamento hidrológico

O delineamento hidrológico de toda a BHRPS, das sub-bacias e da rede de drenagem será realizada com base na metodologia proposta por Pissarra et al. (2013), pela subdivisão de compartimentos hidrológicos (CH) a partir do processamento de um Modelo Digital de Elevação (MDE) no modelo hidrológico *Soil and Water Assessment Tool* (SWAT), ferramenta “ArcSWAT” (ArcSWAT; <https://swat.tamu.edu/software/arcswat>).

O dado de entrada de MDE consiste em informações de superfície topográfica a partir da amplitude altimétrica de uma cena em formato de imagem raster. O MDE a ser utilizado nesta proposta tem resolução espacial em células de grade de 12,5 × 12,5m, com base em imagens orbitais do Satélite Avançado de Observação Terrestre (ALOS), Sensor Radar de Abertura Sintética *Phased Array* banda L (PALSAR), disponibilizado pela *Alaska Satellite Facility* (ASF) (<https://search.asf.alaska.edu>).

Cada CH foi caracterizado por um ponto de foz e subdividido em sub-bacias e sub-compartimentos hidrológicos, caracterizados pelas linhas de drenagem e divisores topográficos. As áreas consideradas como sub-bacias apresentam no seu interior um rio principal que inicia em uma nascente e desagua no ponto de foz; já os sub-compartimentos apresentam no seu interior uma secção da linha de drenagem do

rio principal, não contendo o ponto da nascente. Estas unidades espaciais permitem uma investigação mais efetiva das propriedades geomorfológicas e a melhor descrição da disponibilidade hídrica na bacia. (Neitsch et al., 2011). O fluxograma da metodologia consta na Figura 2.

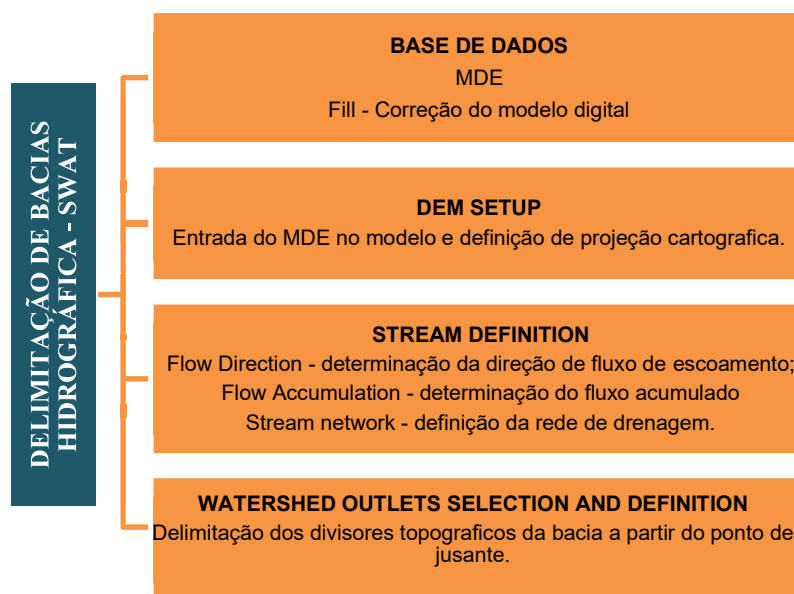


Figura 2. Fluxograma da metodologia de delimitação de bacia hidrográfica pelo método automático no SWAT.

2.3. Disponibilidade hídrica superficial

A determinação da disponibilidade hídrica das sub-bacias foi determinado a partir da estimativa dos fluxos de entrada de água na bacia com base na metodologia de “Regionalização da Água no Estado de São Paulo”, um método para estimativa de disponibilidade hídrica baseado em modelos probabilísticos e determinísticos desenvolvido pelo Departamento de Água e Energia Elétrica do Estado de São Paulo (DAAE, 1994) e automatizada no software SIGRH2001 disponibilizado em plataforma digital página do DAAE (<http://www.daee.sp.gov.br>). No software a modelagem hidrológica foi aplicada a partir da entrada das coordenadas geográficas do centróide de cada sub-bacia.

No método adotado no “Estudo de Regionalização de Variáveis Hidrológicas”, desenvolvido pelo DAAE (1994) e trabalhos de Vilella; Mattos, (1975), os fluxos de

vazão específicos são obtidos pela relação linear entre a área de drenagem e o total médio precipitado (P , em mm anuais) na bacia hidrográfica, de acordo com parâmetros da reta de regressão de acordo (a e b) em função da região hidrográfica.

Conforme a Figura 3, considerando a regionalização hidrográfica para o Estado de São Paulo, que agrupa áreas homogêneas com variáveis hidrológicas semelhantes de acordo com os Parâmetros Regionais do Estado de São Paulo (DAAE, 1994), foram adotados valores de a e b constantes para a Bacia Hidrográfica do Paraíba do Sul: Região N ($a = -26,23$ e $b = 0,0278$). Quanto ao parâmetro $C7,m$: Região Z ($C7,m = 0,85$), considerando o período de retorno de 10 anos (0,889).

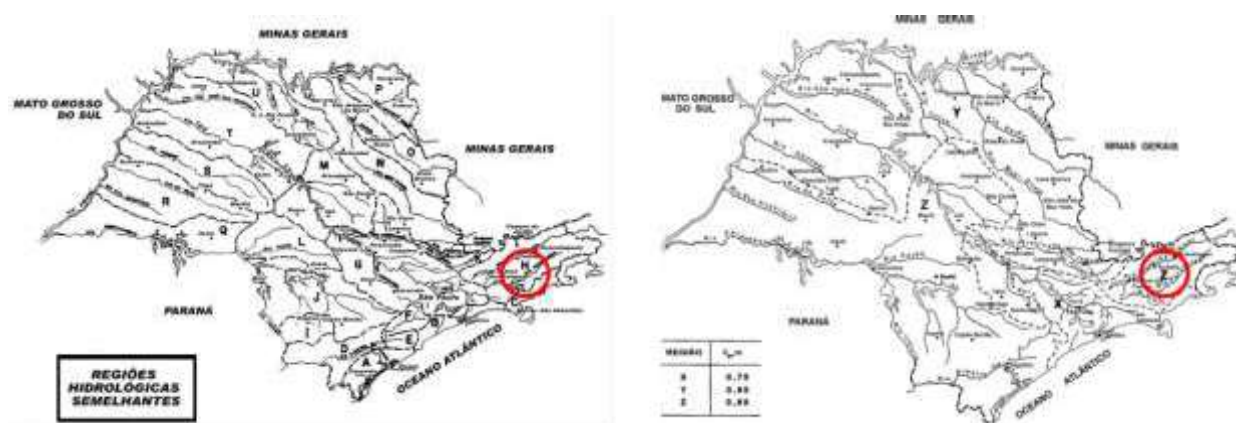


Figura 3. Regiões hidrológicas semelhantes do Estado de São Paulo e Regiões hidrológicas semelhantes quanto ao parâmetro $C7,m$ (DAAE, 1994).

A descarga média plurianual, numa dada seção de um curso d'água são obtidas pela relação linear da vazão (Q), com o total anual médio precipitado na bacia hidrográfica (P):

$$Q = a + b \cdot P$$

Onde: Q = vazão; P = total anual médio precipitado na bacia hidrográfica; e a , b = parâmetros da reta de regressão de acordo com a região hidrológica.

O cálculo da regressão entre a chuva média anual (mm/ano) e a vazão média plurianual (L/s/km²) utiliza o mapa de isoietas para as bacias hidrográficas do Estado de São Paulo. A precipitação média anual (P) de cada microbacia é calculada pela

média ponderada da precipitação, interpolada entre as bacias hidrográficas consecutivas (P_i^*), e a área de drenagem (A_i) das mesmas:

$$\bar{P} = \frac{\sum (A_i \cdot P_i^*)}{\sum A_i}$$

* De acordo com a plataforma, os dados de precipitação são coletados a partir de Posto Metrológico mais próximo a bacia hidrográfica do Rio Paraíba do Sul. As vazões fornecidas na plataforma seguem a metodologia do DAEE (1994).

2.4. Análise dos resultados

Uma análise de cluster hierárquica baseada em distâncias euclidianas e o método de Ward (1963) foi usada para buscar uma avaliação global das interações das sub-bacias e os fluxos hidrológicos.

3. RESULTADOS E DISCUSSÃO

A elaboração do diagnóstico e caracterização ambiental da bacia hidrográfica do Rio Paraíba do Sul (BHRPS) foi conduzido como base às investigações da vulnerabilidade ambiental e disponibilidade hídrica, fornecendo informações fundamentais para as avaliações e projeções no contexto da bacia.

Delineamento hidrológico

A área de drenagem da BHRPS oficial no Estado de São Paulo é de 13.900 km². A área de estudo está contida na região a jusante da Represa do Funil, totalizando 12.605 km². Como a área do Estado é de 247.706 km², a unidade da BHRPS representa aproximadamente 5,6% da área total do estado e a unidade de investigação 5,1%.

O delineamento das unidades experimentais foi realizado conforme Figura 4A. O alinhamento que perfaz a rede de drenagem principal (Rio Paraíba do Sul) é formado pelos pontos de menores altitudes do sistema aberto, tem início no ponto de foz (Represa do Funil – menor altitude) e segue até o ponto de nascente principal

(maior altitude do sistema de drenagem do rio), e forma a calha do rio principal com afluentes e sub-afluentes. A BHRPS é limitada por um alinhamento que contém os pontos de maiores altitudes do sistema caracterizado pelo divisor topográfico (limite) (Figura 4A).

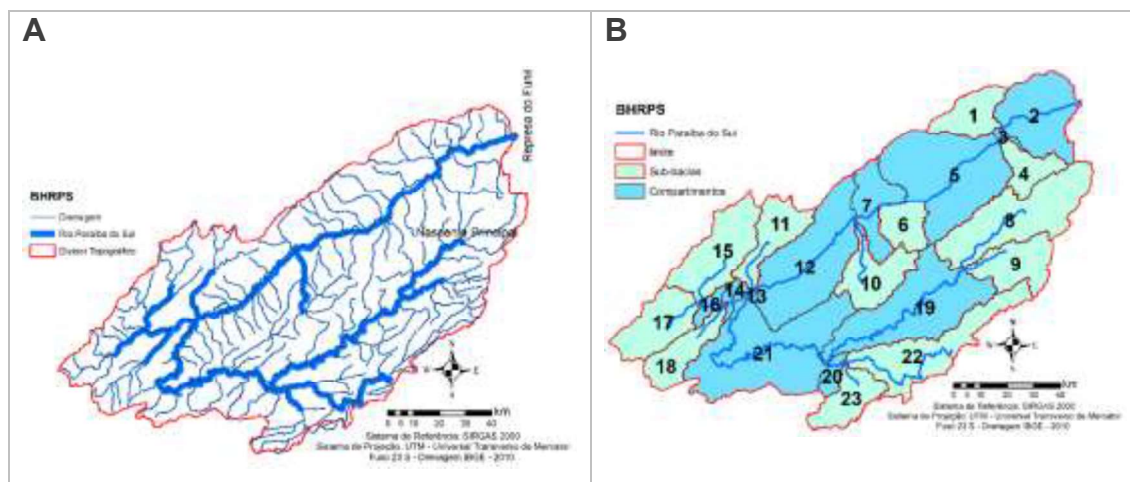


Figura 4. Sub-bacias e pontos de monitoramento da BHRPS – SP.

O delineamento das unidades experimentais foi idealizado em dois espaços geográficos para o desenvolvimento da investigação, caracterizado por compartimentos hidrológicos (CH): doze sub-bacias: 1, 4, 6, 8, 9, 10, 11, 15, 17, 18, 22 e 23 e onze sub-compartimentos hidrológicos: 2, 3, 5, 7, 12, 13, 14, 16, 19, 20 e 21 (Figura 4B).

As doze áreas consideradas como sub-bacias (Figura 4B) apresentam no seu interior um rio principal que é caracterizado por uma linha de drenagem que tem início no ponto de nascente e término no ponto de foz (Ponto de Monitoramento), isto é, o ponto de confluência com outra rede de drenagem. Esta linha de drenagem principal apresenta seus afluentes e subafluentes. Esta região é delimitada por uma linha caracterizada geograficamente pelos valores de maiores altitudes, conformando a linha do divisor topográfico (limite). Esta área é uma unidade hidrológica independente e conforma uma região onde as águas oriundas do ciclo hidrológico desaguam apresenta um efeito direto da relação infiltração/deflúvio. Segundo Costa et al. (2020), os CHs são regiões que contêm as redes de drenagem que interagem entre si e

armazenam as águas que contribuem para a vazão do rio e compõem o sistema de drenagem superficial que irá desaguar suas águas no ponto de foz daquela região.

As onze áreas consideradas como compartimentos (Figura 4B) apresentam no seu interior uma secção da linha de drenagem do rio principal (rio Paraíba do Sul), não contendo o ponto da nascente deste rio no seu interior. Essa região recebe água de seus afluentes e subafluentes na região delimitada pelo divisor topográfico (limite), entretanto, a produção de água não tem origem nesta superfície hidrológica, e a água oriunda da precipitação não apresenta efeito direto na relação infiltração/deflúvio, uma vez que o compartimento recebe águas de nascentes de outras redes de drenagem em seu interior.

O que separa cada unidade experimental caracterizada por sub-bacias e/ou compartimentos, são os divisores de água, que são estruturas do relevo, como morros, serras, chapadas ou picos, que definem o padrão de drenagem das águas da chuva ou nascentes, ou seja, determinam por meio da topografia para onde essas águas escoarão. As águas de cada unidade de análise (sub-bacias e compartimentos) escoam no sentido em direção à porção mais baixa da área topográfica (Represa do Funil), seguindo o padrão do relevo. Essas áreas são elementos naturais de extrema importância para o ecossistema. Cada unidade apresenta territórios com diferentes funções sociais, econômicas e ecológicas e as regiões especificadas são responsáveis pela manutenção do Bioma Mata Atlântica, além de dar base para o desenvolvimento das atividades socioeconômicas ligadas ao setor primário da economia, como a pecuária e a agricultura.

A área considerada pertence a região de drenagem do Estado de São Paulo a montante da Represa de Água do Funil, onde localiza-se a Usina Hidrelétrica de Funil construída no rio Paraíba do Sul, no local conhecido como “Salto do Funil”, na divisa entre o Estado de São Paulo e Estado do Rio de Janeiro, na cidade de Resende. Sua operação teve início em 1969 e, um ano e meio depois, a usina já fornecia ao sistema elétrico de FURNAS com capacidade total: 216 MW (ANA 2011, 2014). Um aspecto que evidencia a importância desta usina é sua barragem que, ao possibilitar a regularização do volume de sua vazante, reduz a frequência e a intensidade das cheias que ocorrem nas cidades a jusante.

A espacialização das áreas consta na Figura 4B e os principais dados das

características físicas estão demonstrados na Tabela 1. A BHPS apresenta uma área total de 1.260km². A menor área consta do compartimento 13 e a maior compartimento 21.

Tabela 1. Características físicas das sub-bacias e dos compartimentos da BHRPS – SP.

Sub-bacias	Área (ha)	Declividade Média (%)	Latitude	Longitude	Altitude Média (m)	Altitude Mínima (m)	Altitude Máxima (m)	Perímetro (m)
1	34198,22	32,01	-22,56	-45,10	903,44	511	2401	128199.5
2	73065,68	27,59	-22,56	-44,85	785,92	462	2791	179277.1
3	3217,31	20,36	-22,64	-44,97	601,46	510	762	55061.5
4	26092,37	27,75	-22,74	-44,89	884,03	517	1925	133432.1
5	130496,07	19,77	-22,77	-45,19	744,84	515	2005	246468.8
6	27854,12	15,08	-22,93	-45,34	677,68	524	1485	107387.9
7	39377,40	16,04	-22,87	-45,45	721,28	521	1984	194618.2
8	101904,32	24,61	-22,90	-44,93	1097,6	768	2055	273523.9
9	46421,30	24,17	-23,07	-44,93	1031,5	768	1682	165779.3
10	47790,85	24,08	-23,10	-45,45	744,32	531	1473	201575.2
11	41418,02	30,08	-22,97	-45,82	847,83	551	1737	181477.2
12	115391,23	13,41	-23,05	-45,69	653,57	528	1919	250214.9
13	1087,76	5,85	-23,17	-45,90	570,09	550	636	22119.8
14	7792,23	16,08	-23,17	-45,97	607,90	549	788	75100.1
15	68680,00	28,72	-23,02	-46,02	857,46	584	2022	192358.7
16	8593,60	20,62	-23,20	-46,06	667,39	559	839	85743.8
17	52385,84	20,28	-23,27	-46,25	756,61	597	1424	154600.5
18	37081,32	15,65	-23,36	-46,16	678,24	559	1156	157633.0
19	118238,97	24,74	-23,21	-45,31	905,02	631	1648	294097.6
20	10090,08	21,08	-23,44	-45,61	772,44	629	1202	73554.1

21	149627,19	20,48	-23,36	-45,84	720,35	529	1207	330072. 0
22	83556,18	26,91	-23,35	-45,25	958,47	683	1662	322223. 0
23	36198,63	24,11	-23,52	-45,55	800,48	685	1279	148178. 6
Área total	1260558,69							1260,6 km²

Disponibilidade hídrica superficial

A vazão média de longo período estimada para as bacias interestaduais, é de 9.812 m³/s, enquanto que a do Estado de São Paulo é 3.140 m³/s, ou seja, 32% da vazão das bacias interestaduais. As informações acerca da disponibilidade dos recursos hídricos espacializados nas unidades experimentais do trabalho na BHRPS no estado de São Paulo, a montante da Represa do Funil, a partir da série histórica de precipitações na determinação das vazões Q_{7,10}, Q_m, Q₉₈, Q₉₅ e Q₉₀ e da divisão geográfica dos compartimentos e sub-bacias com os pontos de monitoramento, constam na Tabela 2 e nas Figuras 5 - A, B, C, D, E e F.

Tabela 2. Valores estatísticos de vazão – Q₉₀, Q₉₅, Q₉₈, Q_{7,10}, Q_m (m³/s).

	Q ₉₀	Q ₉₅	Q ₉₈	Q _{7,10}	Q _m
Maior	1303,00	1100,00	910,00	750,00	3200,00
Menor	10,00	9,04	8,16	6,76	16,72
Média	378,78	326,92	281,42	233,30	793,75
DP	339,69	294,10	254,32	210,83	765,74
CV	111,51	111,16	110,65	110,65	103,66
Mediana	266,95	228,87	183,74	152,32	592,87

A disponibilidade hídrica das águas superficiais pode ser de domínio federal, enquanto que os rios que possuem nascente e foz no mesmo Estado são estaduais. A água superficial é distribuída entre unidades políticas vizinhas de acordo com os fatores como área de drenagem contida em cada unidade, elementos climáticos, utilizações estabelecidas no passado e no presente, necessidades econômicas e sociais, população, custo envolvidos e outros.

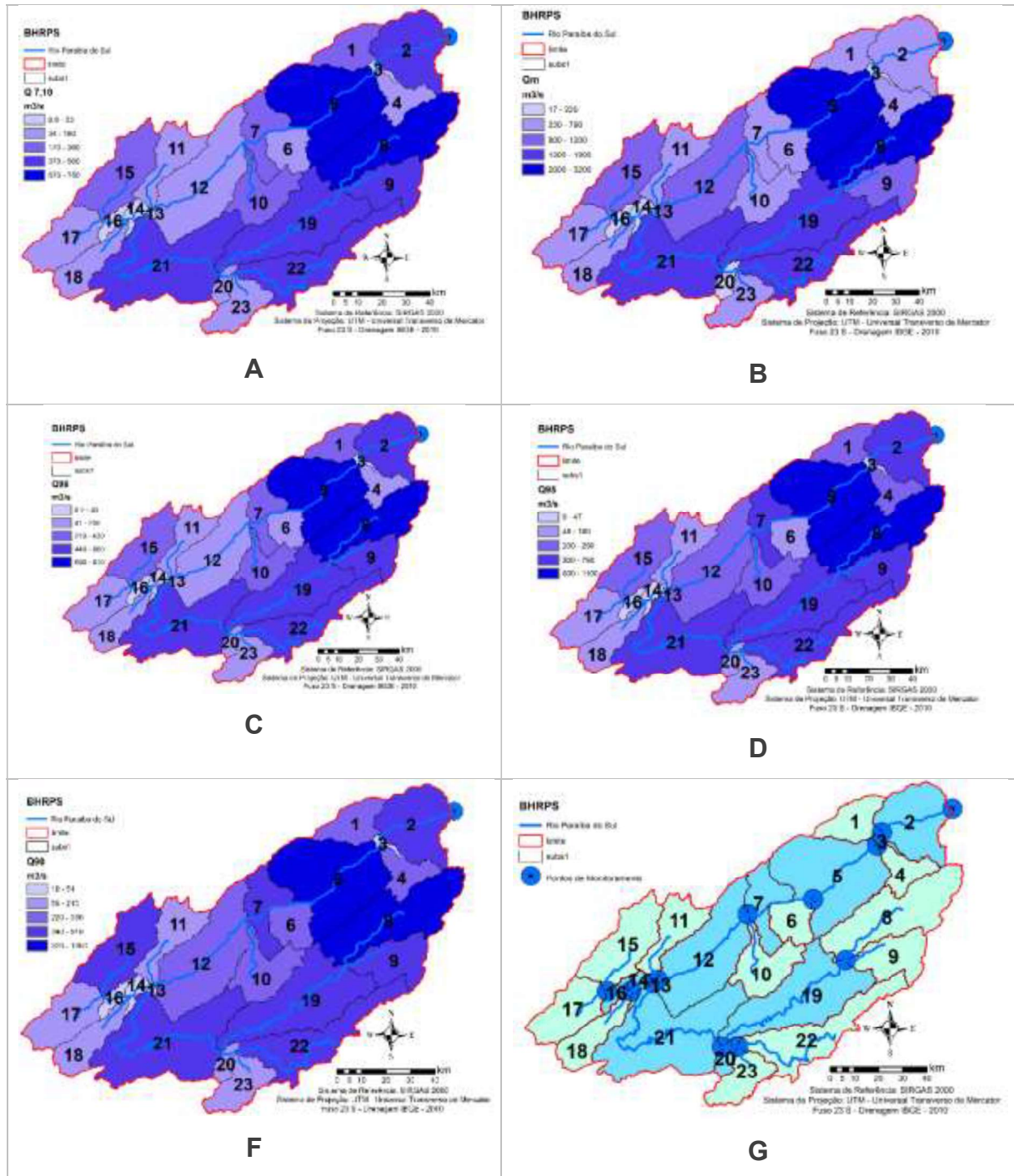


Figura 5. Valores da vazão na BHRPS – SP.

Os valores de Q7,10, que correspondem à vazão mínima com sete dias consecutivos de duração no tempo de retorno de dez anos, indicam que a cada dez anos, em média, há o risco de ocorrer em sete dias seguidos vazão mínima de 6,8 a

750m³/s, com valor médio de 233,30 m³/s (Tabela 2, Figura 5A). A vazão de referência (Q_m) que leva em conta a regularização assegurada por reservatórios mais as contribuições mínimas das áreas das bacias não controladas, é estimada entre os valores de 17 m³/s– 3200 m³/s (Tabela 2, Figura 5B). Segundo ANA (2005), na área total da BHRPS o valor é de 2.105 m³/s, o que estaria, em 100 anos de período de retorno, em níveis críticos de escassez de água. Na análise teórica do máximo potencial possível de ser explorado considera-se a vazão média de longo período (Q_m), ou seja, a permanência de água no sistema da BHRPS para o escoamento total, por razões de ordem econômica, equivale ao potencial de água e deve ser reduzido na prática para cerca de 70% da vazão média (Tucci, 1998; Tucci, 2002).

Os valores que indicam que as vazões são maiores ou iguais a ela durante 98%, 95% e 90% do tempo variaram entre Q₉₈ (8,2m³/s – 910m³/s), Q₉₅ (9m³/s – 1100m³/s) e Q₉₀ (10m³/s – 1303m³/s), apresentando o valor médio de 281,42m³/s, 326,92m³/s e 378,78m³/s, respectivamente (Tabela 2 e Figuras 5C, 5D, 5E), representam a probabilidade de 98%, 95% e 90% de as vazões serem igualadas ou superadas no tempo, respectivamente. A vazão para a percentagem de permanência do tempo é de extrema importância para verificar a vazão de referência e para classificar um rio que terá a vazão atendida pelo menos 95% do tempo. Adicionalmente, pode-se estabelecer que o rio deva ter pelo menos a classe inferior a esta para as vazões entre 95% e 100%, garantindo assim, certos condicionantes do rio. Segundo Tucci (2002), a classe em que o oxigênio dissolvido é ≥ 5 mg/L, na classe inferior a condição é de 3 mg/L, o que garantiria vida aquática mesmo nos cenários mais críticos.

Na curva de permanência de vazão (Figura 6), observa-se a percentagem de tempo que uma dada vazão é igualada no período de 100 anos.

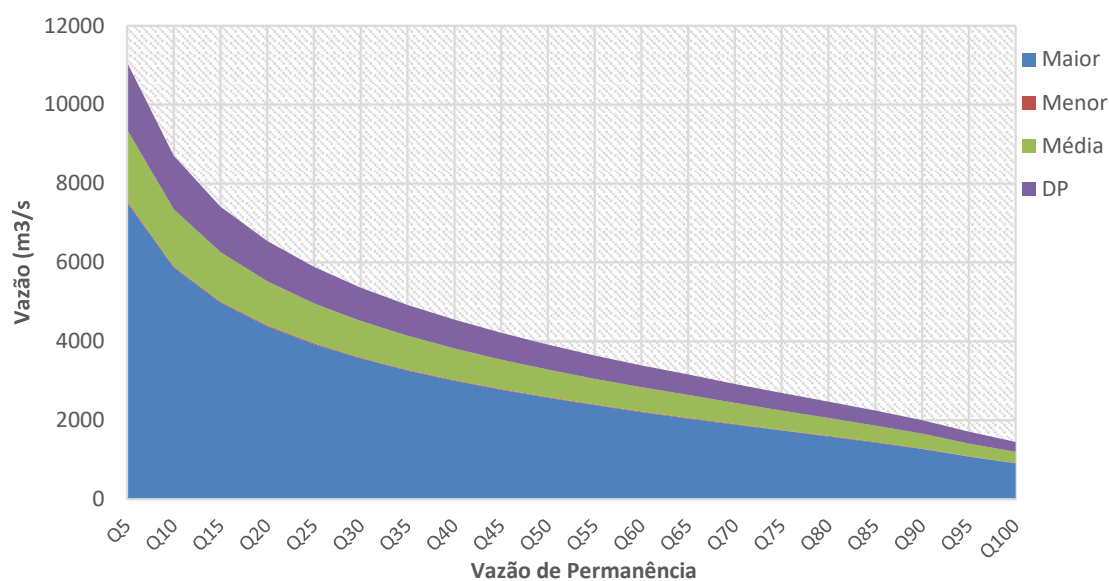


Figura 6. Curva de permanência de vazão (m³/s) ao longo dos 100 anos.

A curva de permanência de vazões é uma tradicional função hidrológica e por isso as vazões Q90, Q95 e Q98 dela extraídas têm enfoque hidrológico. Segundo Vilella; Matos (1975) e Tucci (2002), a vazão de referência é estabelecida para um valor de vazão que representa o limite superior de utilização da água em um curso d'água e é, também, um dos entraves à implementação de um sistema de outorga. Depende da garantia de atendimento à demanda necessária que se considera para os usos a serem instalados em determinada bacia. As vazões mínimas aplicadas como referência são vazões de elevada permanência no tempo, calculadas de forma estatística (ANA, 2015).

Os valores da vazão e o mapeamento das vazões específicas da BHRPS (Tabela 2, Figura 5) fornecem uma visualização da distribuição espacial das vazões e permite verificar a estimativa da vazão específica desejada em cada compartimento e sub-bacias. As regiões de sub-bacias mais carentes de água são as sub-bacias 11, 17, 18, 20 e 23. Assim, deve-se fazer um estudo regionalizado para obter informações, mais específicas destas áreas nos períodos de estiagem (vazão específica mínima), nas áreas sujeitas às maiores enchentes (vazão específica máxima) e na disponibilidade de água da bacia (vazão específica média de longo período).

As vazões mínimas, como a de sete dias de duração e período de retorno de 10 anos (Q7,10), e as obtidas da curva de permanência para 98, 95 e 90 por cento de

probabilidade (Q98, Q95 e Q90) são valores característicos do comportamento da estiagem em uma bacia hidrográfica, enquanto a vazão média de longo período (Qm), corresponde a síntese de todas as vazões ao longo do tempo. A vazão Q7,10 média (233,30 m³/s) apresenta um enfoque estatístico, e é considerada como variável aleatória à qual se aplica técnicas estatísticas para avaliar sua probabilidade de ocorrência. Corresponde a um valor que, em média, a cada 10 anos, será igualado ou inferiorizado pelo escoamento médio de estiagem do rio em quaisquer 7 dias consecutivos (Tucci, Mendes, 2006; Tundisi, 2003).

Estas três modalidades de vazões são utilizadas em vários Estados brasileiros como "vazão de referência", para definição de critérios de outorga de direito de uso de água. Por exemplo, nos Estados de Minas Gerais, São Paulo, Rio de Janeiro, Espírito Santo e Paraná utilizam a vazão Q7,10 (Tucci, 2002). De acordo com a Lei Estadual nº 9.034 de 1994, quando a soma das vazões captadas em uma determinada bacia hidrográfica, ou em parte desta, superar 50% (cinquenta por cento) da respectiva vazão de referência, a mesma será considerada crítica e haverá gerenciamento especial que levará em conta a disponibilidade hídrica a partir das descargas líquidas calculadas nos exutórios (Pontos de Monitoramento) dos cursos de água de cada sub-bacia.

Nos valores de vazão que indicam que as vazões são maiores ou iguais a ela durante a percentagem do tempo para a vazão de referência, a classe do rio é atendida pelo menos à aquela percentagem do tempo. Adicionalmente, pode-se estabelecer que o rio deva ter pelo menos a classe inferior a esta para as vazões entre 95% e 100%, garantindo assim, certos condicionantes do rio (ANA, 2015; Tucci, 2002; Vilella, Matos, 1975). A maior importância para o gerenciamento dos recursos hídricos é a de garantir uma vazão que deva ser mantida no rio. Na comparação dos volumes de água disponíveis é necessário verificar a demanda social estabelecida pela ONU (1000 m³/hab ano) para avaliação da disponibilidade hídrica mundial (global e por país) e nacional (por estado). A bacia apresenta disponibilidade hídrica suficiente para abastecer os reservatórios e a avaliação dos efeitos das medidas de adaptação na alocação ótima de recursos hídricos sob condições variadas de disponibilidade de água deve ser monitorada (Liu et al., 2018).

Para compatibilizar valores das sub-bacias que apresentam as nascentes do

rio principal em suas áreas e por terem dimensões diferentes, foi obtida a informação espacial da vazão específica, definida como sendo a vazão dividida pela área de drenagem de cada uma das doze sub-bacias (Figura 7). O índice de vazão específica médio foi determinado pela razão entre a vazão média em uma dada seção de medição e a respectiva área de drenagem (Tucci, 2002). De acordo com este autor, existe uma tendência de redução da vazão específica de montante para jusante, conforme o aumento do tamanho da bacia e o comprimento do rio.

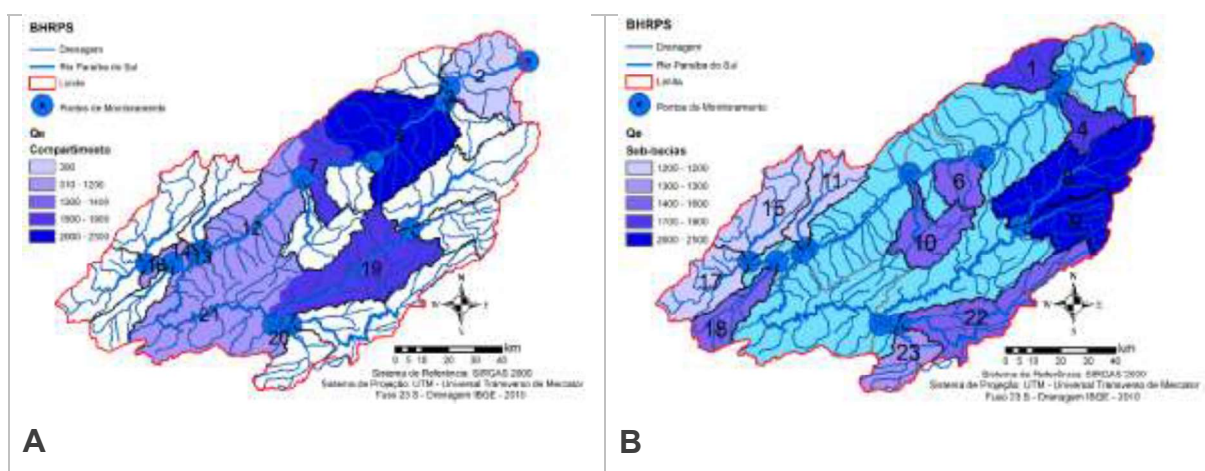


Figura 7. Vazão específica (Q_e ; $L \cdot s^{-1} \cdot km^{-2}$) dos onze compartimentos (A) e das doze sub-bacias (B) da BHRPS – SP.

A apresentação dos dados obtidos para o zoneamento hidrológico foi feita através da análise espacial de cada sub-bacia considerando a posição de cada uma delas no Rio Paraíba do Sul. O zoneamento, a partir da vazão específica (Figura 7), pode ser utilizado como uma técnica para melhorar o entendimento e qualidade dos dados hidrológicos, tendo em vista que é obtida para a área de influência em cada unidade experimental, tais como as sub-bacias e compartimentos da BHRPS em km^2 . Tucci (2002) relata em seu trabalho que ocorre uma tendência de redução da vazão específica conforme o aumento do tamanho da bacia e o comprimento do rio. Dessa forma assegura que as cabeceiras (regiões das sub-bacias) costumam apresentar maiores precipitações e declividade, isso reflete no efeito de armazenamento de água no sistema da bacia a jusante de um rio nas áreas de cabeceiras.

A vazão específica é a vazão média distribuída pela área de drenagem de cada

unidade experimental para que se possa compatibilizar valores da vazão nas regiões de dimensões diferentes no interior da BHRPS. Neste sentido, a BHRPS apresenta as sub-bacias 8 e 9 com Q_e de maiores valores. Como a Q_e diminui conforme aumenta o tamanho da bacia hidrográfica, estudos utilizando os valores fluviométricos devem ser desenvolvidos na área.

Na análise multivariada das vazões (Q_m ; $Q_{7,10}$; Q_{98} ; Q_{95} e Q_{90}) por sub-bacias é possível identificar o agrupamento de dois grupos bem distintos (Figura 8). O agrupamento pode estar relacionado aos maiores volumes de água, produzido ou confluído em cada unidade territorial, já que são observadas bacias de cabeceira (8, 9 e 22) e compartimentos hidrológicos (2, 5, 19, 21) no mesmo grupo.

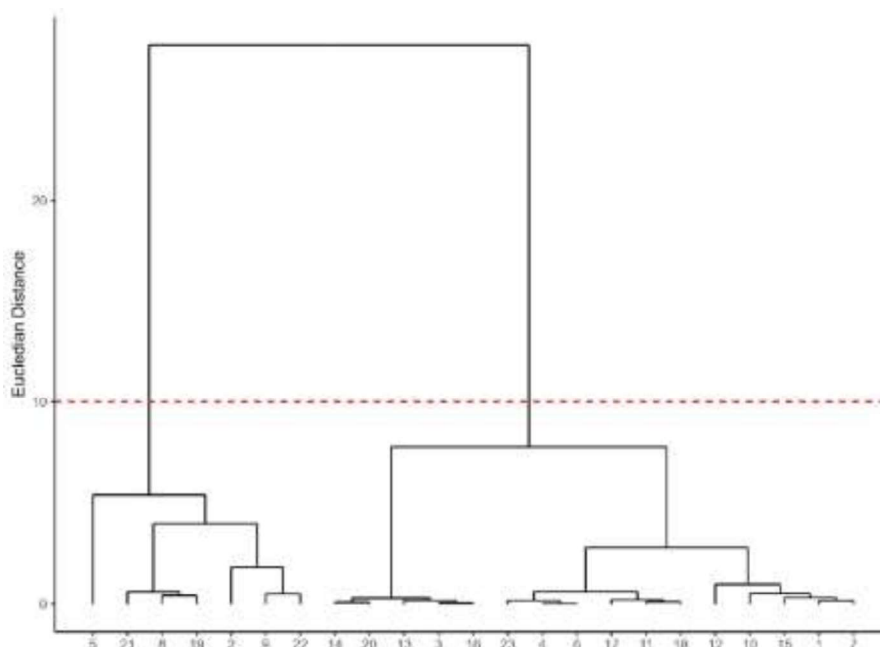


Figura 8. Agrupamento hierárquico dos compartimentos hidrológicos agregados por usos da terra, declividade e tipo de solo.

Os valores determinados se constituem em um importante instrumento da Política Nacional dos Recursos Hídricos do Brasil (BRASIL, 1997), bem como em políticas internacionais, corroborando com os trabalhos de Fu et al. (2018); Geussens et al. (2019) e Ghaley et al. (2014) na definição de métricas para serviços ecossistêmicos e por fornecer a estimativa estatística da disponibilidade hídrica dos

ecossistemas hidrológicos das sub-bacias e dos compartimentos da BHRPS. A investigação das vazões e dos processos envolvidos é importante no intuito de proporcionar subsídios que fundamentam a tomada de decisões e auxiliam no planejamento e manejo do uso racional dos recursos hídricos, permitindo adequar os fatores socioeconômicos aos ecológicos (FAO, 2017; FAO, 2020), respeitando-se a sazonalidade dos corpos hídricos, de forma a não interferir de maneira negativa na hidrodinâmica da BHRPS.

O recurso hídrico superficial se constitui da origem do escoamento básico dos rios e o aquífero confinado representa uma área de reserva de água nas rochas. Entretanto, nem todas as formações geológicas possuem características hidroquímicas e hidrodinâmicas (Sreekanth et al., 2018; Martins et al., 2019) que permitam a exploração econômica de águas subterrâneas através de poços tubulares profundos, para médias e grandes vazões. Uma política consequente para o aproveitamento das águas deve partir da premissa fundamental de que a água subterrânea é um recurso estratégico e sua exaustão e degradação podem acarretar consequências irreversíveis. Os estudos das vazões superficiais e podem subsidiar projetos de conservação e restauração e definir as métricas de valoração e projetar cálculo para gerar os incentivos econômicos, permitindo aos produtores rurais que ocupam a bacia a condução mais adequada das atividades de conservação e proteção aos recursos hídricos em áreas prioritárias. A otimização espacial contribui para o direcionamento da alocação de recursos e ações de restauração em bacias hidrográficas e com isto melhorar a conservação de múltiplos serviços ecossistêmicos, a resiliência socioeconômica e climática (Chazdon et al., 2020; Aryal et al., 2023; de Mendonça et al., 2022).

No geral destacamos como usuários da bacia: população urbana e rural; indústrias; Cidades; Grupos e organizações diversas pelo uso da água para diversos fins. potenciais provedores de serviços ambientais: Produtores Rurais.

Considerando o âmbito do Projeto Conexão Mata Atlântica - “Recuperação de Serviços de Clima e Biodiversidade no Corredor Sudeste da Mata Atlântica Brasileira” – (<https://www.infraestruturameioambiente.sp.gov.br/conexao>), que tem como objetivo aumentar a proteção da biodiversidade e da água e combater mudanças climáticas; projetamos que o engajamento e benefícios socioeconômicos contemplem

em torno as 337 propriedades rurais cadastradas no projeto. Com isto é possível integrar informações socio –econômica para promover as atividades de conservação da água e do solo, pela restauração da vegetação nativa e adoção de sistemas produtivos mais sustentáveis em terras privadas.

Assim, o pagamento por serviços ambientais (PSA) considerando as sub-bacias com mais disponibilidade hídrica pode promover áreas de Proteção Hídrica e distribuir incentivos econômicos aos produtores aderentes a exemplo de Pissarra et al. 2021. O Produtor de Água poderá ser reconhecido como protetor das áreas prioritárias para a produção de água para bens e serviços. A partir deste serviço ecossistêmico, os ambientes naturais serão reconhecidos pela sociedade e o produtor irá ser pago pela produção de água (Maes et al., 2016; Burkhard et al., 2012).

4. CONCLUSÃO

Nos padrões geográficos e temporais, de acordo com os resultados apresentados, conclui-se que é necessário conhecer a disponibilidade hídrica ao longo do tempo para elaborar um plano de gestão de regulação da água e do solo mais eficiente em uma bacia hidrográfica. As estimativas das vazões das regiões dos compartimentos hidrológicos fornecem informações importantes para a tomada de decisão no processo de outorga dos recursos hídricos e as métricas outorgáveis podem ser utilizadas conforme a disponibilidade hídrica para os períodos sazonais definidos no estudo. A compreensão da dinâmica hidrogeomorfológica da área de estudo possibilitará a elaboração de prognósticos para uma gestão mais eficiente do uso sustentável da água e conservação do solo na bacia hidrográfica.

Os mapas temáticos da disponibilidade hídrica das sub-bacias na ótica de valor econômico, social e ecológico podem auxiliar na elaboração de métricas para esquemas de determinação dos serviços ecossistêmicos para a produção agrícola e para a conservação ambiental, que irão servir a sociedade como um todo. Os incentivos econômicos a serem atribuídos a partir da classificação dos valores das métricas hidrológicas podem ser considerados os bens ecossistêmicos produzidos em cada sub-bacia. A partir do cálculo da porcentagem de produção hídrica em cada unidade e do uso do solo, considerando o ecossistema natural, pode-se verificar as

áreas mais propícias para tornar áreas de compensação para investimentos ambientais. Assim, as métricas definidas neste trabalho podem auxiliar o formato da legislação voltada para as atividades demandadas, no pagamento por serviço ambiental – produtor de água, a partir da abordagem quantitativa.

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CAPÍTULO 3: ETpML: Previsão de evapotranspiração potencial através de algoritmos de aprendizado de máquina para otimizar avaliações de serviços hidrológicos¹

RESUMO - As ligações de evapotranspiração potencial (ETp) desempenham um papel fundamental na modelagem ambiental; no entanto, a falta de um conjunto complexo de dados meteorológicos limita a sua previsão e aplicações à escala da bacia hidrográfica. O ETpML apresenta um framework de programação que visa automatizar a previsão de ETp a partir de uma base de dados reduzida e, conseqüentemente, alavancar avanços na avaliação de serviços hidrológicos. O ETpML compreende um kit de ferramentas que permite um fluxo de trabalho complexo: modelar um conjunto de dados meteorológicos híbridos; comparar o desempenho de métodos de aprendizado de máquina (ML) (floresta aleatória, seleção gradual e perceptron multicamadas); aplicando o modelo de melhor ajuste. Aplicações de ETpML para tratar de serviços hidrológicos de bacias hidrográficas mostram melhores resultados em florestas aleatórias, uma precisão de aproximadamente 88% e um erro de cerca de 10%. Nossas descobertas destacaram a reprodutibilidade, viabilidade e previsões precisas do ETpML, dados os períodos críticos detectados e regiões prioritárias para uma melhor gestão das bacias hidrográficas. Este quadro representa uma otimização na modelação de sistemas combinados água-terra-solo-atmosfera, melhora a avaliação dos serviços hidrológicos para apoiar o processo de tomada de decisão sobre os atuais desafios da segurança hídrica e das alterações climáticas.

Palavras-chave: balanço hídrico climatológico; *multi-layer perceptron*; *random forest*; *stepwise forward selection*; disponibilidade de água; gestão de bacias hidrográficas.

¹ Este capítulo corresponde ao artigo científico submetido à revista [Environmental Modelling & Software](#) em 07 de julho de 2023 e encontra-se em avaliação para publicação.

ETpML: Forecasting potential evapotranspiration through machine learning algorithms to optimize hydrological services assessments ¹

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Abstract

Potential evapotranspiration (ET_p) links plays a key role in environmental modeling; however, the lack of complex weather dataset limits its forecasting and applications at watershed scale. ETpML presents a programming framework which aims to automate ET_p prediction from a reduced database, consequently, leverage advances in hydrological services assessment. ETpML comprises a toolkit that enables a complex workflow: modeling a hybrid weather dataset; comparing Machine Learning (ML) methods performance (random forest, stepwise forward selection, and multi-layer perceptron); applying best fitted model. Applications of ETpML to address watershed hydrological services shows best results from random forest, an accuracy ~88% and an error about 10%. Our findings highlighted ETpML reproducibility, feasibility and accurate predictions, given detected critical periods and priority regions for a better watershed management. This framework represents an optimization in modeling

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combined water-land-soil-atmosphere systems, improve hydrological services assessment to support decision-making process on the ongoing water security and climate change challenges.

Keywords: climatological water balance; multi-layer perceptron; random forest; stepwise forward selection; water availability; watershed management.

1. Introduction

Evapotranspiration (ET) is a process of water transport from soil and plant to the atmosphere, returning to it most of the precipitation that occurred at the surface (Pan et al 2020; Jasechko et al., 2013). Because it is both an evaporation (soil) and transpiration (plant) process, its biophysical control mechanisms are complex, either because of the distinct characteristics of soil properties, the heterogeneity of the vegetation, or even the climate (Granata and Nunno, 2021; Chen and Liu, 2020; Lian et al., 2018). Due to these characteristics, evapotranspiration is one of the main components of climatological and hydrological assessments, and has several applications in environmental sciences such as, climatological water balance methodologies, agricultural zoning, irrigation planning hydrological modelling, energy balance, cropping and forest yield, ecosystems production (Zhang et al., 2020a; Ma et al., 2019; de Lima et al, 2021; de Oliveira Aparecido et al., 2021; Valeriano et al., 2022).

Given this complexity, estimating ET is not a simple task, one way to accomplish this is by potential evapotranspiration (ET_p), which is nothing more than the water demand from the atmosphere (Xiang et al., 2020). There are several ET_p models, those related to air temperature (Thornthwaite 1948), radiative transfer (Penman, 1948, Monteith, 1973), and mass transfer (Albrecht, 1950). These models can be applied at different spatial scales, such as at regional scale (Zhang et al., 2020b; Niyogi et al., 2020) reaching global scale (Purdy et al., 2018; Zhang et al, 2019), and at various time scales (Tikhmarine et al, 2019; Liu, 2021; Nassar et al., 2021; Ahmadi et al., 2021), either with in situ observations or via remote sensing (Delogu et al., 2021; Elnashar et al., 2021; Mosre and Suárez, 2021; Chen and Liu, 2020; Sun et al., 2019; Silva et al.,

2019; Cui et al., 2021).

In addition to this variety of models and applications, recent methods involving Machine Learning (ML) are being used to perform ET estimations (Sun et al., 2011; Adeloje et al., 2012; Abdullah et al., 2015; Kisi et al., 2015; Feng et al., 2017; Ferreira et al., 2019; Granata, 2019; Yuan et al., 2020; Tikhamarine et al., 2020; Ahmadi et al., 2021). This advancement is not only with ET, but in all areas of knowledge, due to the greater computational capacity we currently possess (Mjolsness and Decoste, 2001; Al-Turjman and Baali, 2019; Roscher et al., 2020; Yuan et al., 2020; Willard Jared et al., 2022). Although ML methods provides good estimative and is a powerful tool nowadays, some algorithms do not have the same physical basis that empirical models have.

There are several ML algorithms, and they can be classified into supervised and unsupervised, and can also perform classifications or regressions, based on different methods (Liakos et al., 2018; Ray et al., 2019; Linardatos et al., 2020; Yuan et al., 2020; Greener et al., 2022). The modeling strategy of many algorithms consists of two moments, training, which is when the model is fitted, and testing, which consists of applying and evaluating the model. However, a model can be fitted incorrectly or perform worse due to the choice of parameters, making hyperparameter optimization techniques necessary to obtain the best possible model (Bergstra and Bengio, 2012; Yang and Shami 2020; Dong et al., 2021).

Applications of Machine learning (ML) algorithms in biosphere–atmosphere exchange studies have revealed a great potential for estimating reference evapotranspiration (Adeloje et al., 2012; Kar et al., 2021; Katimbo et al., 2023; Wu et al., 2023). However, the use of algorithms at watershed scale and water management is still limited, in part due to the lack of an accurate and complete database and the spatial complexity at watershed scale. Likewise, a better understanding of hydrological services flows and their drivers in watershed systems can be optimized by ETp modeling and water balance components, especially in the absence of long-term local records and limited observations, since these strongly depend on extensive and complex data such as climate, soil parameters, and management data (Azzam et al., 2022; Stapleton et al., 2022).

Considering the ETp importance and its ensembles to hydrological services

assessment, in this study, we look to address this gap through the release of a programming framework for ET_p prediction, ET_pML. ET_pML combines R and Python toolset to optimize the prediction of ET_p, including (1) modeling a reduced database, climatic (temperature and precipitation), geographic (longitude and latitude), and temporal (year and month) parameters; comparing three supervised ML performance for ET_p prediction as described in section 2.5 and (2) estimating ET_p from the best fitted model for apply it to a climatological water balance simulation, which is crucial for hydrological studies. Moreover, using ML modeling and a friendly programming language improves research reproducibility and decision-making support.

ET_pML was applied to estimate the ET_p in the Upper Paraíba do Sul River Basin (UPSR), that consists the upstream portion of the Paraíba do Sul River Basin (PSR) and provides a clear example of hydrological spatial heterogeneity and the hydrological services challenges in agroecosystems. The UPSR drainage area has undergone extensive land use changes (Ovalle et al., 2013), hindering access to high-quality freshwater and the depletion of water resources (ANA, 2021), while increasing the demand for multiples water uses. The great PSR plays an important role in water security in the main Brazilian metropolitan regions (Paiva et al., 2020), and UPSR corresponds its headwater catchment. Besides, the Paraíba Valley has been considered a target goal in payment for environmental services policies and investments associated with the restoration of the Atlantic Forest (SIMA, 2023).

To address hydrological services in UPSR we assumed climatological water balance components, water surplus and water deficit, as an indicator of water availability and water scarcity regarding soil water storage. We developed the ET_pML framework in order to encourage the applicability of ML to optimize ET_p forecast and provide a best performing algorithm to endorse predictive capabilities for watershed management. ET_pML allows project ET_p rates and automating the setup of water-land-soil-atmosphere based models in any watershed. This paper presents a modeling toolkit that also aims to contribute within climate change resilience and water security perceptions on the climate agenda worldwide (de Melo et al., 2023). In this sense, this paper contributes to a hydrological macrosectorial assessment of evapotranspiration and water balance to increase the resilience of ecosystems in watershed level. ET_pML application is innovative compared to similar models of green water evapotranspiration

in two aspects; firstly, ETpML can be trained to estimate potential evapotranspiration using two climatological variables (temperature and precipitation), and it does not require in-depth details crop typology, soil attribute, water fluxes, topography or irrigation data; secondly, ETpML estimates will provide valuable information in order to support strategic decisions on long-term watershed management and water security, which may further assist policymakers and authorities in developing better adaptation and mitigation strategies. Notably, we provide a case study of applying the ETpML framework to optimize hydrological services assessments in UPSR. However, the developed structure comprises a green water evapotranspiration forecasting based on sensor/reanalysis data and that can be applied to any watershed, according to the region-specific database.

2. Material and methods

2.1. Study Area

The ETpML was carried out at the Upper Paraíba do Sul River Basin (UPSR), which is a macro-sector of the Paraíba do Sul River Basin (PSR), that is located in São Paulo state – Brazil (Figure. 1. A). The study area comprises around 12605.6 km² of Paraíba Valley drainage area, where the river descends from an altitude of around 1800 m to 600 m through narrow valleys carved out of crystalline rocks (Ovalle et al., 2013a). The predominant climatic type in the region is classified as dry-winter subtropical (Cwa; Köppen-Geiger, 1928), with an average annual precipitation of 1350 mm and a yearly average temperature is 21 °C. In the UPSR the irregular rainfall distribution ranges from 2572 mm to 1846 mm and the average annual temperature ranges from 17.9 °C to 20.9 °C in the historical series 1975-2014 (Figure. 1. B, C).

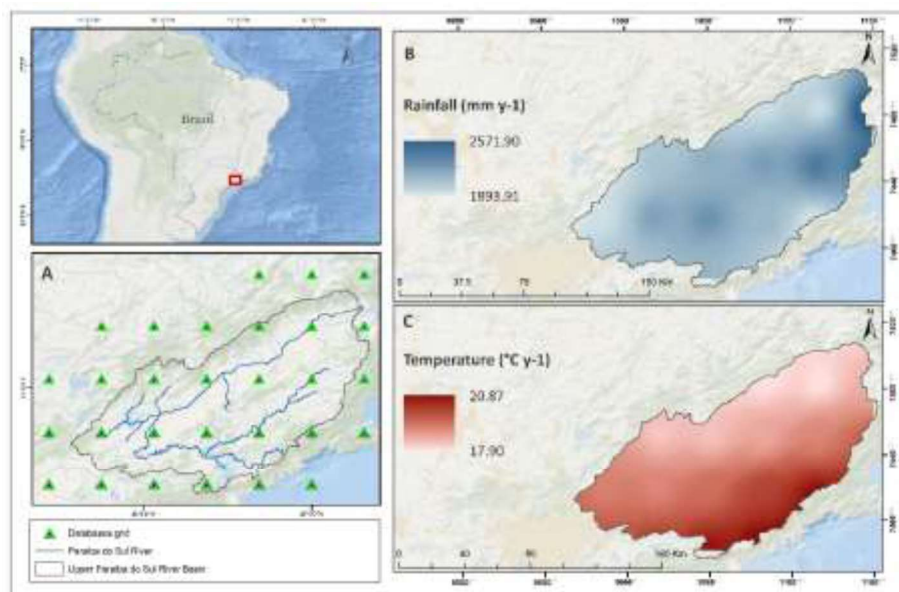


Figure 1. A - Upper Paraiba do Sul River Basin location and meteorological databases grid ; B - Spatial distribution of yearly average rainfall; C - Spatial distribution of yearly mean temperature.

This is an important and strategic watershed for hydrological services, and the main multiple uses of water are distributed among domestic consumption, industry, hydroelectricity generation, agriculture, livestock, and mining. However, it is characterized by high deforestation rates and intense urbanization, since this is the most densely populated area of the entire Paraiba do Sul River Basin (Martins et al., 2023; Moraes-Santos et al., 2021; Paiva et al., 2020). Furthermore, the region hindering access to high-quality freshwater and the depletion of water resources (ANA, 2021), especially during 2013–2014, when the Brazilian southeast had a severe drought and water supply reservoirs of the metropolitan area of São Paulo had the lowest inflows and minimum storage.

The water availability in the Paraiba do Sul River Basin is crucial for water security in southeastern Brazil, and therefore, it is fundamental to optimize the methods and indicators of the watershed water balance. A literature review shows that a few hydrological studies have been developed in the main area of PSR, some emphasize mathematical formulations focusing on water resources management, (Hunt et al., 2022; Marques et al., 2022; Martins et al., 2023; Paiva et al., 2020). However, the solution remains partial in specific assessments, and the water balance between the surface and the atmosphere at the landscape level is not considered, in which ETp

modeling through ML optimization could play an essential role.

2.2. Meteorological databases

2.2.1. Climate Forecast System Reanalysis

Historical series of 35-year meteorological data (1979–2014) were used to characterize the meteorological conditions of the selected study areas (Figure. 1. B, C) and estimate evapotranspiration potential as detailed in section 2.3. We used data from the Climate Forecast System Reanalysis (CFSR), which is a product of a global climate reanalysis based on conventional ground observation data, satellite remote sensing data, and highly advanced technology to represent a global, high-resolution coupled atmosphere-sea ice-ocean-land system (He & Zhao, 2018). The CFSR weather data is generated and provided as gridded data from Global Forecast System at a marginally finer spatial resolution ($0.5^\circ \times 0.5^\circ$ vs. 0.5° vs. 0.66°) (Saha et al., 2010), which can be downloaded easily online (<https://globalweather.tamu.edu/>).

Despite this, CFSR weather data has been extensively used in many studies worldwide and provides an accurate database, as documented by multiple reviews (Amarouche et al., 2021; Auerbach et al., 2016; Chen et al., 2023; Elshinnawy & Antolínez, 2023; Saha et al., 2010; Sharp et al., 2015; Tan et al., 2021; Yu et al., 2019; Zhang et al., 2023). For instance, the meteorological data consisted of daily rainfall, maximum and minimum temperature, as well as wind speed, relative humidity, and solar radiation, collected from 29 grided point in the watershed area (Figure. 1 A). In this work we first access the climatological condition of the study region, after we train and test the algorithms.

2.2.2. NASA POWER

The project Predictions of World Energy Resource (POWER) initiated by NASA aimed to enhance the current renewable energy dataset and create new datasets from new satellite systems (Stackhouse et al., 2020) and has several agroclimatology applications (de Souza Rolim et al., 2020). The global distribution of temperature parameters in the POWER / Agroclimatology file is obtained from NASA's Global Model and Assimilation Office (GMAO), Goddard Earth Observing System global assimilation

models version 4 (GEOS-4: <http://gmao.gsfc.nasa.gov/systems/geos4/>) and version 5 (GEOS-5: <http://gmao.gsfc.nasa.gov/products/>), while precipitation is obtained from the GPCP 1-DD Satellite-Gauge product. This dataset was used as an independent validation set, to accomplish this we use a time series starting from 2015.

2.3. Potential evapotranspiration

Similarly, to the works conducted by de Souza Rolim et al (2020) and de Lima et al. (2021), potential evapotranspiration (ET_p, mm) was calculated monthly for each coordinate, as well as, the climatic ET_p was determinate for the entire watershed, considering the climatic average for the entire space-time series (CFSR base line 1980 – 2014), by the model proposed by Thornthwaite (1948) (Eq. 1). This method depends on the average monthly temperature (T) in degrees Celsius; the number of days of the month (ND), Julian day (JD); latitude (ϕ) in decimal degree; the number of hours of insolation (N; Eq. 4); sunrise time (hn (°); Eq. 5); the solar declination (δ (°); Eq. 6); besides two other parameters calculated from the average temperature, I (Eq. 2) and a (Eq. 3) respectively. Furthermore, the evapotranspiration calculated by this method was used as our observed value for the machine learning approach (see section 2.4). This bring some limitations, since this ET_p is also calculated from an empirical model. However, in situ measurements is very limited in Brazil, therefore the Thornthwaite method is a good approach for our purposes.

$$ET_p = 16 \times \left(\frac{10 \times T}{I}\right)^a \times \frac{N}{12} \times \frac{ND}{30} \quad (\text{Eq. 1})$$

$$I = \sum 0.2 \times T^{1.54} \quad (\text{Eq. 2})$$

$$a = 0.49 + (0.018 \times I) - (7.7 \times 10^{-5} \times I^2) + (6.75 \times 10^{-7} \times I^3) \quad (\text{Eq. 3})$$

$$N = 2 \times \frac{hn}{15} \quad (\text{Eq. 4})$$

$$hn = \arccos[-\tan \phi \times \tan \delta] \times \frac{180}{\pi} \quad (\text{Eq. 5})$$

$$\delta = 23.45 \times \sin\left(\left(\frac{360}{365}\right) \times (JD - 80)\right) \quad (\text{Eq. 6})$$

2.4. *ETpML modeling framework*

From the monthly ETp calculations for each year and each location, we used three different algorithms to estimate the monthly ETp based on precipitation, temperature, longitude, latitude, year, and month data. These three algorithms consist of Random Forest (RF), Stepwise forward selection (SW), and Multi-layer Perceptron (MLP). Since the time scale of our model is monthly, the inputs related to meteorology (precipitation and temperature) has to be evaluate in this scale, with monthly sums of precipitation and monthly mean temperatures to each coordinate. The inputs regarding the year and the month was given as an integer value and the longitude and latitude in decimal degree.

The general strategy for ETp modeling consists of: first randomly splitting the CFSR database into a training set (70% of the CFSR data) and a test set (30% of the CFSR data), the training set was used to parametrize the algorithms and the test set was used to choose the best between them; after as an independent validation set the data acquired from the NASA-POWER platform was used. This was made to access if the model actually captures the behavior of the region and could properly estimate ETp for unseen time series. The NASA-POWER data set was used as validation set because is entirely independent from CSFR, thus reducing bias related to overfit. Optimization algorithms were also used to define the best parameter sets for each of the machine learning models. The following flow chart details the strategy adopted in this work.

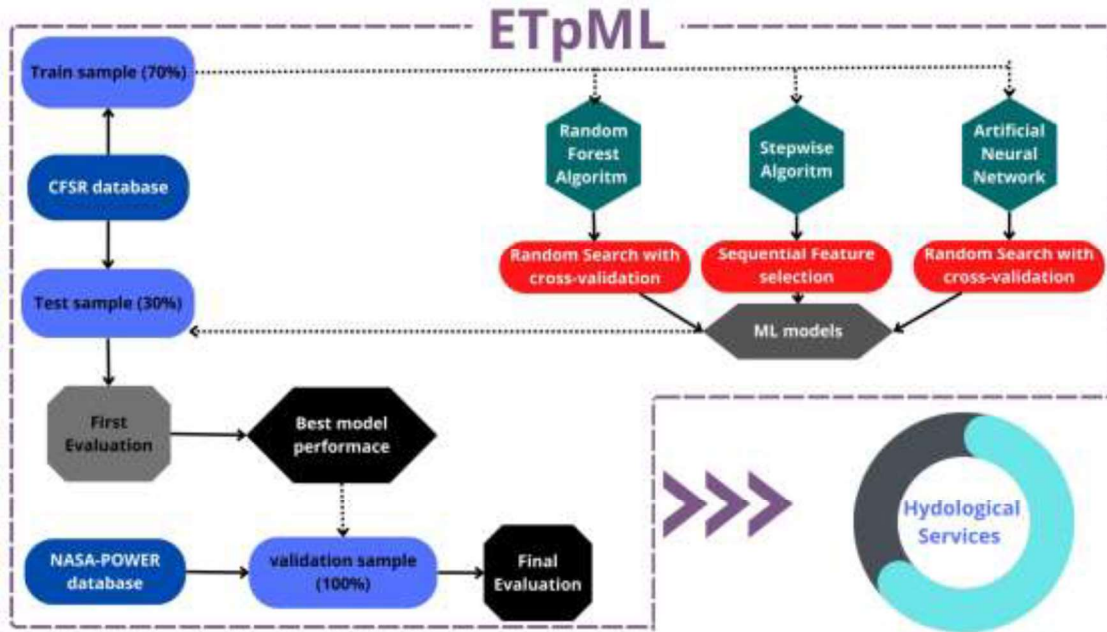


Figure 2. ETpML programming framework proposed to optimize and automate potential evapotranspiration (ET_p) forecast for hydrological services assessment.

In the training section (I), each algorithm received the training set and then went through the optimization process highlighted in red, generating the best model for each of the methods used. After finishing this section, the generated models were used in the testing section (II), each model received the new data set, and then the coefficient of determination (R^2 , Eq. 7), root mean square error (RMSE, Eq. 8), relative root mean square error (RRMSE, Eq. 9) and the mean absolute percentage error (MAPE, Eq. 10) were evaluated, allowing us to select the best among the models. Finally, in the validation section (III), the best model among the tested algorithms received the validation set with new measures, and then the final performance was evaluated.

$$R^2 = 1 - \frac{\sum_{i=1}^n (obs_i - est_i)^2}{\sum_{i=1}^n (obs_i - \overline{obs})^2} \quad (\text{Eq. 7})$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (est_i - obs_i)^2}{n}} \quad (\text{Eq. 8})$$

$$RRMSE(\%) = \sqrt{\frac{\sum_{i=1}^n \left(\frac{est_i - obs_i}{obs_i}\right)^2}{n}} \times 100 \quad (\text{Eq. 9})$$

$$MAPE(\%) = \frac{\sum_{i=1}^n \left(\left| \frac{est_i - obs_i}{obs_i} \right| \times 100 \right)}{n} \quad (\text{Eq 10})$$

Where obs_i = observed value; est_i = estimated value; n = number of observations.

All these metrics accesses different aspects, such as precision and accuracy of the model. The R^2 is a metric that shows how closely the observed value are from the fitted regression line. The RMSE access the standard error of the model in the same unit of the measurement, and the relative RMSE, give how this error represent in percentage. Regarding the MAPE, this metric is also given in percentage error, however this error it's given in the absolute term.

2.4.1. Algorithms

Random Forest (RF): Random Forest is a supervised machine learning model that is not limited to linear models, other advantages of this algorithm are to have low sensitivity to outliers, multicollinearity, and variables at different scales (Douna et al., 2021; Breiman, 2001). Its implementation consists of creating collections of decision trees from bootstrap resampling, which are then combined to perform a prediction (Eq 11). This means that to predict a value, it first creates a prediction for each tree in the forest and then performs the average to obtain the final prediction (Douna et al., 2021; Xu et al., 2018):

$$f(x) = \frac{1}{J} \sum_{j=1}^J h_j(x) \quad (\text{Eq 11})$$

Where $f(x)$ is built from a collection of decision trees $h_j(x)$

Stepwise forward selection (SW): Stepwise is a multilinear regression method (Eq 12), which is sensitive to outliers and multicollinearity (Kalnins, 2018; da Costa et al., 2022). Its basic implementation consists of adding new predictors to the model if it is significant to the model, otherwise the addition to (Zhou and Jiang, 2016):

$$f(x) = \beta_0 + \sum_{i=1}^n \beta_i x_i + \varepsilon \quad (\text{Eq 12})$$

Where β_0 is the linear coefficient, β_i is the fitted i coefficient, x_i is the feature i and ε is the model error.

Multi-layer Perceptron (MLP): MLP is an Artificial Neural Network (ANN) method. Being an ANN, MLP tries to simulate the nervous system of the human brain, some of its features are backpropagation learning. The basic structure of this model is that there is an input layer (predictors), then one or more hidden layer that receives these inputs and performs the computations, and makes the prediction (output layer) (Krogh, 2008; Desai and Shah, 2021). The computation can be divided into two parts, first, the neuron calculates the sum of the weights of the inputs (Eq. 13), then it is activated by an activation function, which can be of the identity type (Eq. 14), logistic (Eq. 15), hyperbolic tangent (Eq. 16) or rectified linear unit function (relu, Eq. 17) within the hidden layer, and finally, the prediction is performed (Eq. 18):

$$S_j = \sum_{i=1}^n w_{ij} I_i + \beta_j \quad (\text{Eq 13})$$

Where S_j is the sum of the weights in neuron j , w_{ij} is the weight connecting feature i with the hidden neuron j , I_i is the feature i and β_j is the bias of neuron j .

$$f_j(x) = x \quad (\text{Eq 14})$$

$$f_j(x) = \frac{1}{1+e^{-x}} \quad (\text{Eq 15})$$

$$f_j(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \quad (\text{Eq 16})$$

$$f_j(x) = \max(0, x) \quad (\text{Eq 17})$$

$$y_k = \beta_k + \sum_{j=1}^n w_{jk} f_j(S_j) \quad (\text{Eq 18})$$

where y_k is the prediction of the neuron in the k th output layer, β_k is the bias in the k th

output layer; w_{jk} is the weight between the hidden neuron j and the neuron in the k output layer and $f_j(S_j)$ is the activation function of the neuron in the hidden layer j .

2.4.2. Optimization

Randomized Search: In this work, we optimized the Random Forest and Multi-layer Perceptron with the Randomized Search method from the scikit learn library (Pedregosa et al., 2011). Basically, this method consists in randomly testing the hyperparameters (Table 1) of a model to find the best combination between them, and has as an advantage over Grid Search a lower computational cost, because it does not test all combinations. Finally, this algorithm is usually more effective than Grid Search because not all parameters are important in the optimization (Bergstra and Bengio, 2012).

Sequential feature selection: Using the sequential feature selection, we did the stepwise selection of the inputs. In general, you can add or remove a feature from a model based on performance. In this work, we used forward selection (Table 1), which consists of starting the model with no features and finding the features that maximize the cross-validation result (Pedregosa et al., 2011).

Table 1. Hyperparameters used for the tested models and parameters of each function used

	parameter	RF	SW	MLP
hyperparameter space	n_estimators/ max_iter	[50,100,150,200,500]	-	[1:1000]
	max_features max_depth	[2,4,6,8] [3,5,7,9]	- -	- -
	activation	-	-	['logistic','tanh', 'identity']
	solver	-	-	['adam','sgd', 'lbfgs']
	learning_rate_ init	-	-	[0:1]
	learning_rate	-	-	['constant', 'adaptive']
	hidden_layer	-	-	[(5,5),(10,10),(10,5,10),(10,10,10)]
	optimization parameter	function	Random Grid	Sequential

	Search	Feature selection	Search
cv	10	10	10
scoring	r2	r2	r2
n_iter/ k_features	20	6	20
forward	-	True	-
random_state	1	1	1

2.5. Climatological water balance

To understand the dynamics of the hydrological service in the UPSR watershed the ETpML setup integrated ET_p prediction according to Thornthwaite (1948) method to forecast the climatological water balance (WB, Figure. 3), also proposed by Thornthwaite and Mather (1955). The water balance is the accounting of water entering (water surplus) and leaving (water deficit) the system. It represents the regional water availability, which is important to determining periods (in this study, months) of water deficit (DEF)/surplus (EXC) and performing more sustainable management of hydrological services (Gowri et al., 2021; Pluntke et al., 2023; Wilson et al., 2022). Considering that in this paper we focus on modeling ET_p to improve hydrological services assessments, it is of interest to quantify the deficit and surplus water obtained from climatological water balance. Thus, we estimate the monthly water deficit (DEF) and surplus (EXC) for each coordinate (de Souza Rolim et al., 2020; de Lima et al., 2021). Finally, we evaluate the WB generated from the observed and estimated ET_p in the validation section (NASA-POWER database).

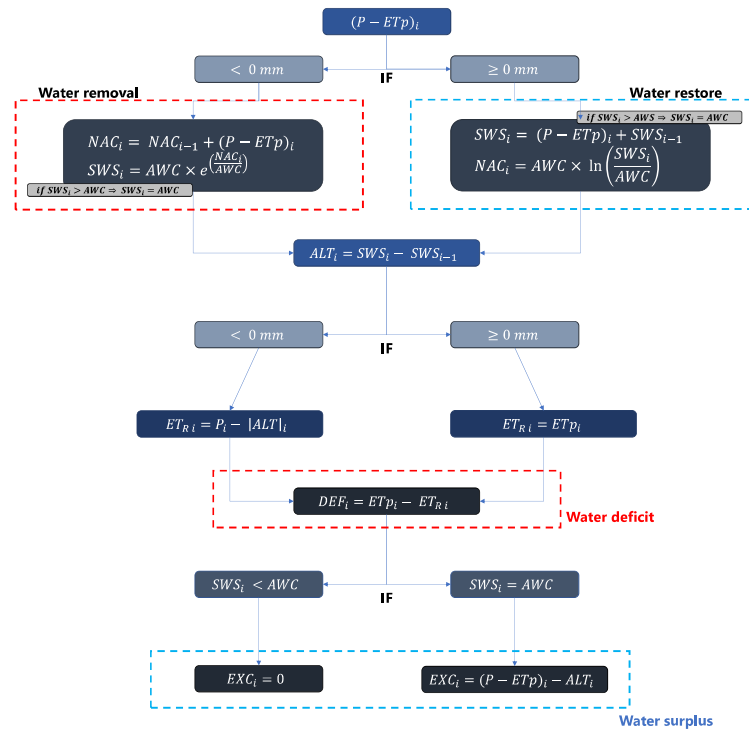


Figure 3. Flowchart of climatological water balance (WB) calculation. Where: P = precipitation; ET_p = Potential Evapotranspiration; NAC = negative accumulation; SWS = soil water storage; AWC = available soil water; ALT = change in soil water storage; ET_R = actual evapotranspiration; DEF = water deficit; EXC = water surplus. (Adapted from de Souza Rolim et al., 2020).

Descriptive statistical analysis was used to describe seasonal variations as well the spatial distribution was generated using the geographic information system (GIS) - ArcMap, by the inverse distance weighted (IDW) interpolation method, 0.25° resolution.

3. Results

3.1. Climatology

Results from the CFSR historical series (1979–2014) describe the yearly average meteorological dynamics at UPSR. The historical average annual rainfall (Figure. 4 a) in the study area is 1984.67 mm rainfall, 166.30 ± 133 mm month⁻¹, with monthly maximums reaching up to 1000 mm month⁻¹. In addition, the highest historical averages are typically observed in January (~360 mm) and December (~310 mm), and

the lowest averages are in June (~53 mm) and July (~58 mm) (Figure. 4 a). For temperature (Figure 4 b), the historical mean is $\sim 19 \pm 2.5$ °C month⁻¹, with January and February being the months with the highest historical means (~ 21.38 °C month⁻¹ for both) and June and July with the lowest mean temperatures (16.2 ± 1.9 °C month⁻¹ and $16.00 \pm .7$ °C month⁻¹, respectively). A brief description of meteorological components by weather stations was provided in the Appendix section (A1), as well as the ET_p . Moreover Figure 1 B and C also provides the spatial distribution of yearly average rainfall and mean temperature at UPRS, respectively.

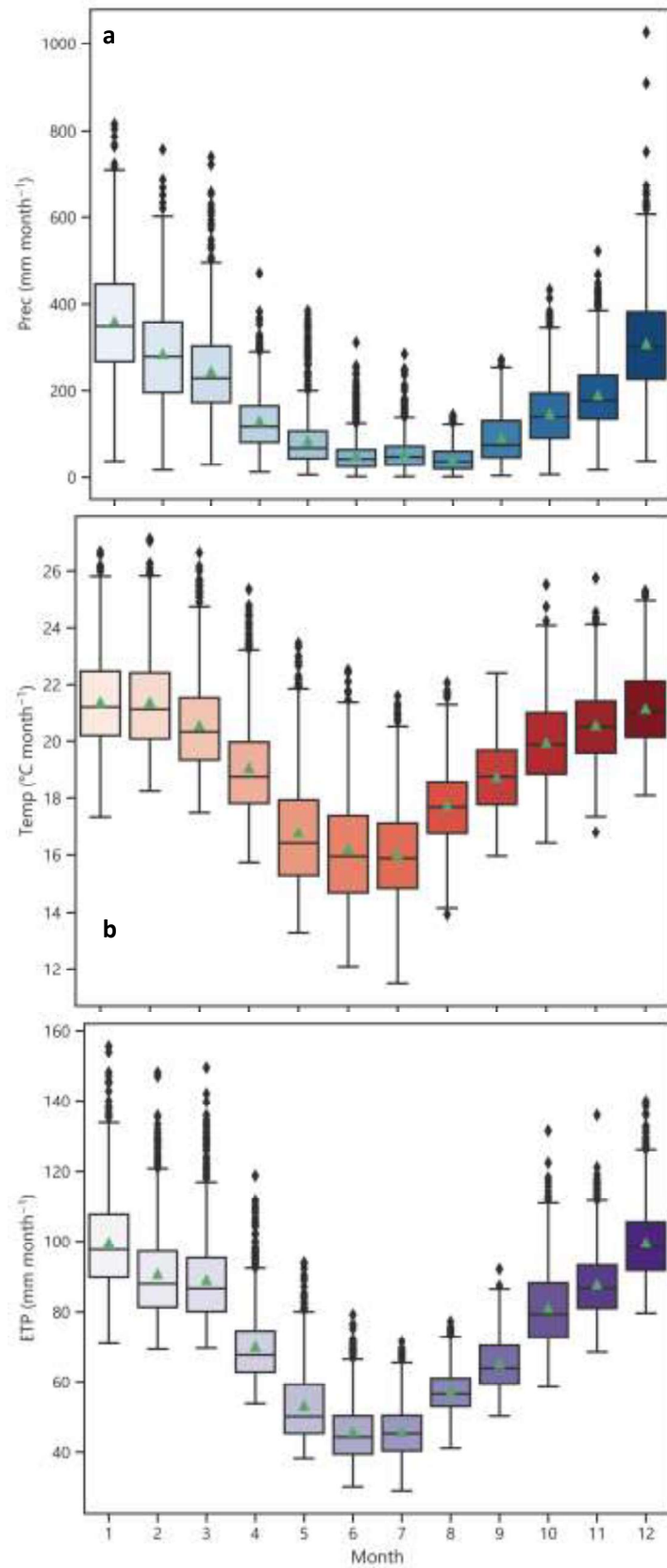


Figure 4. Monthly variation of meteorological components: a – Rainfall (Prec.), b - Mean temperature (Temp.), and Potential evapotranspiration (ET_p).

1 Este capítulo corresponde ao artigo científico submetido à revista [Environmental Modelling & Software](#) em 07 de julho de 2023 e encontra-se em avaliação para publicação.

In the historical series, January and December are the months that present the highest ET_p values ($99.7 \pm 13.77 \text{ mm month}^{-1}$ and $99.6 \pm 10.7 \text{ mm month}^{-1}$, respectively), and that in June and July are observed the lowest evapotranspiration averages ($45.83 \pm 8.68 \text{ mm month}^{-1}$ and $45.82 \pm 13.7.62 \text{ mm month}^{-1}$, respectively) (Figure 4 c). Similarly, water availability decreases between May and August, with August historically showing a deficit of -2 mm, and January a surplus of 260 mm (Figure. 5). A climatological water balance extract by weather stations is also available in the Appendix section (A2).

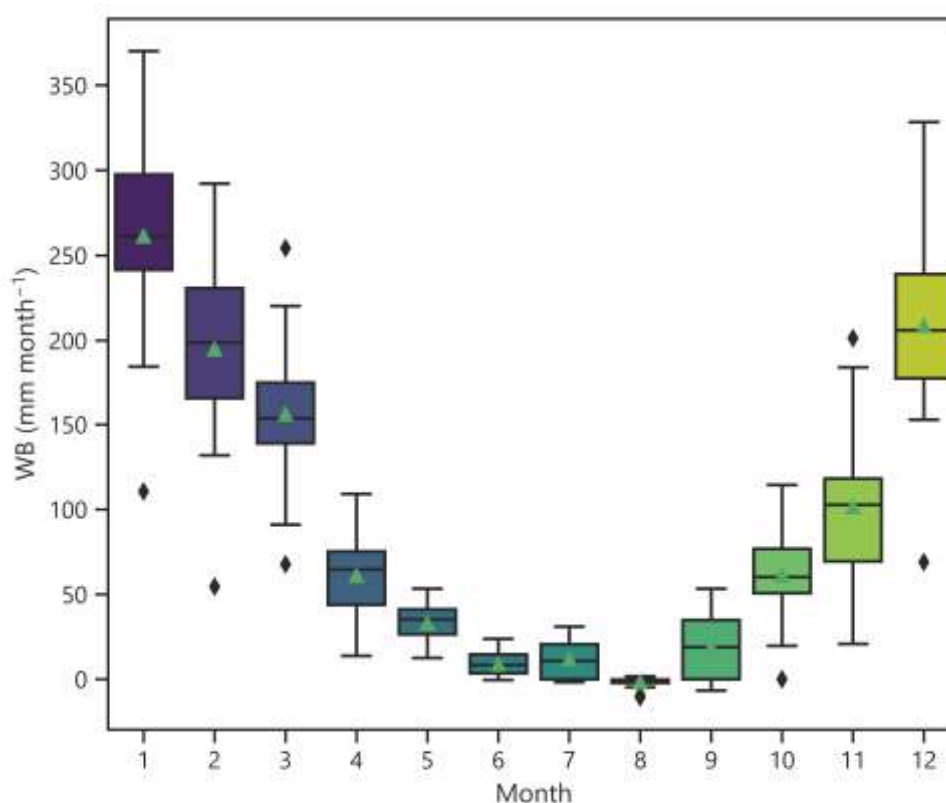


Figure 5. Climatological water balance (WB) in Upper Paraíba do Sul River Basin.

Mapping average hydrological services at UPRS as follows in Figure 6, we identified that the highest water availability at water soil storage level (water surplus $> 100 \text{ mm y}^{-1}$) is concentrated in the regions that correspond to the main spring area and the river mouth. As water scarcity intensifies downstream with a maximum annual water deficit of 32 mm. The highest potential evapotranspiration rates are concentrated in the south of the watershed (Figure 6).

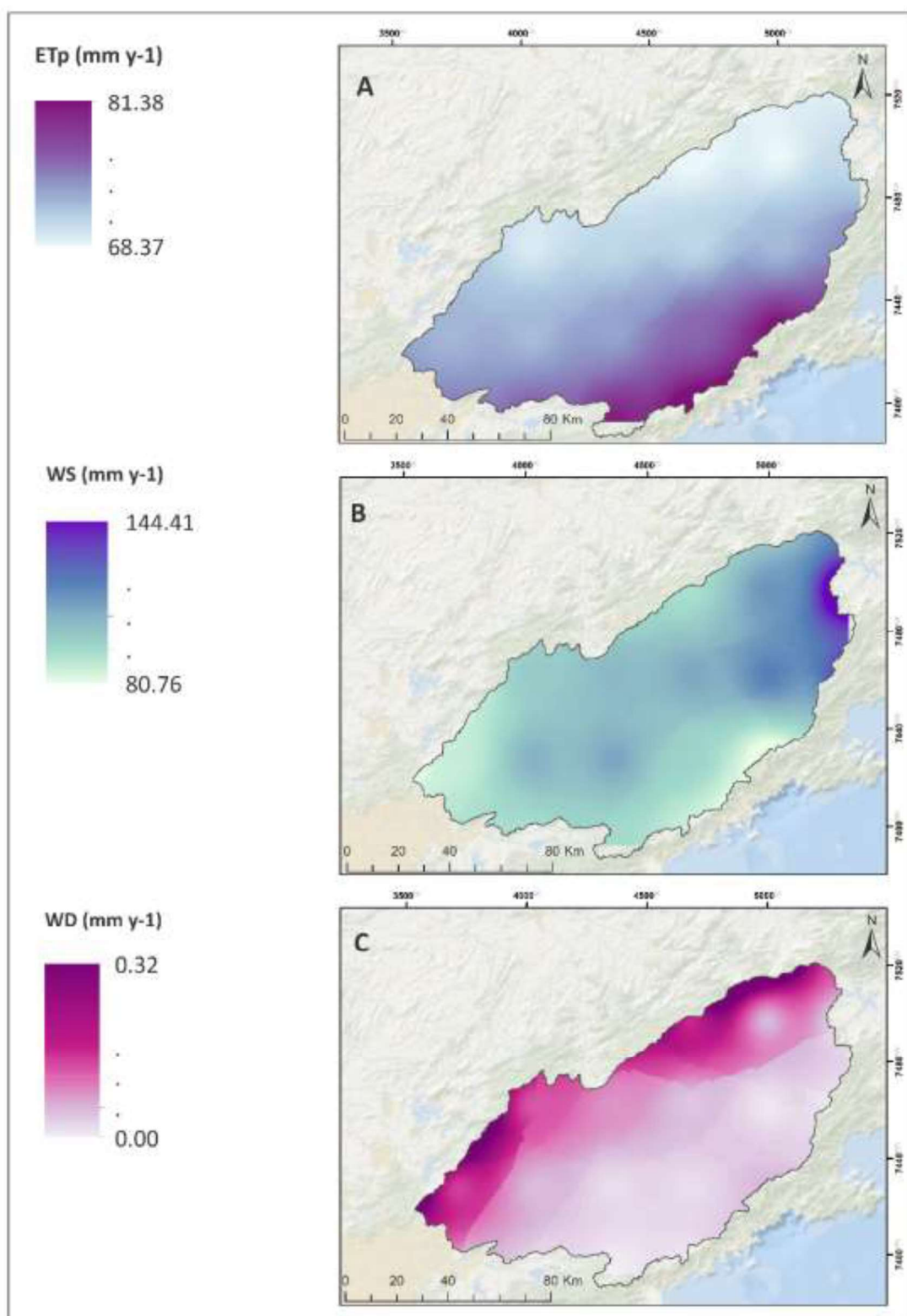


Figure 6. Spatial variation of yearly average: A - Potential evapotranspiration (ET_P), B – Climatological Water surplus (EXC), C – Climatological Water deficit (DEF) in the Upper Paraiba do Sul River Basin.

3.2. *ETpML performance*

The Random Forest model returned as best parameters 500 trees, maximum depth of 9 nodes, and 4 variables, having an average performance (R^2) of 0.987 (Table 2), being the feature of the greatest importance the temperature and the one of least importance the longitude (Figure. 7 a). Regarding SW, the performance between the model with 5 ($R^2 = 0.937$) and 6 ($R^2 = 0.937$) features was not significantly different (Figure 7 b), so we used the model with 5 features (Table 2) and as result the multilinear equation parameterized was $ET_p = 174.3016 - 2.2641 \times longitude + 8.9142 \times latitude + 0.2466 \times month + 3.5571 \times precipitation + 20.261 \times temperature$

Summary statistic for each interaction can be found in Supplementary material, S.T.1. Finally, the MLP, had a performance of 0.92, having been trained with 472 iterations size of the hidden layers being 5x5 activated by an identity function (Table 2) and the lbfgs method to calculate the weights.

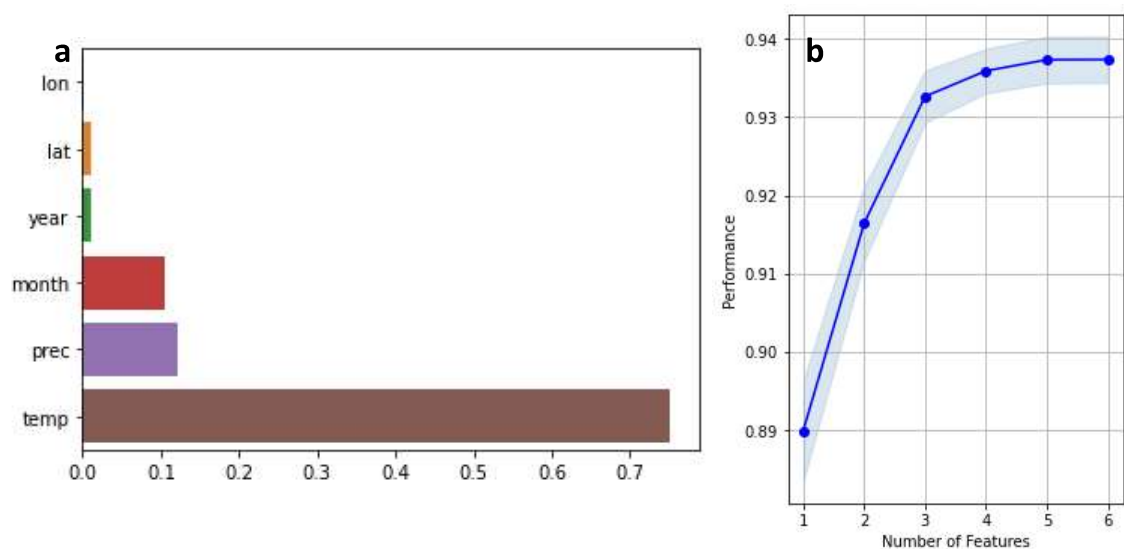
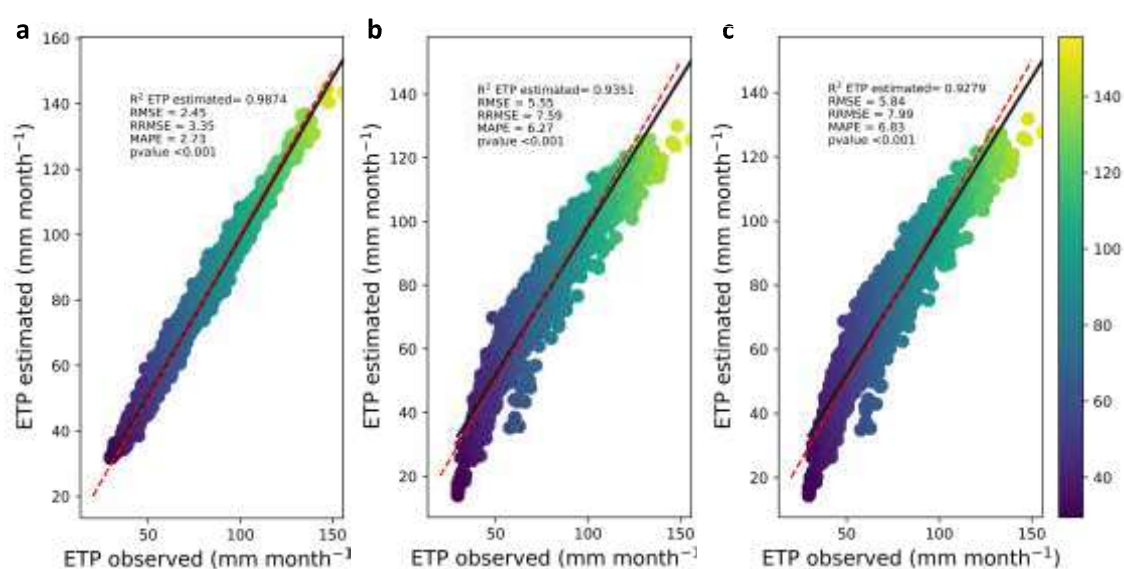


Figure 7. Models' evaluation, a – Random Forest Feature Importance; b- Stepwise forward selection performance.

Table 2. Result of hyperparameter optimization for the models (training)

	RF	SW	MLP
Mean R²	0.991±	0.937 ±	0.928 ±
	0.0001	0.003	0.011
n_estimators/max_iter	500	-	472
max_features/k_features	4	5	-
max_depth	9	-	-
Forward	-	True	-
Activation	-	-	Identity
Solver	-	-	lbfgs
hidden layer	-	-	5 x 5
Alpha	-	-	0.9888
learning_rate_init	-	-	0.2804
learning_rate	-	-	invscaling

After fitting each algorithm used with the training data, the performance of each algorithm on the test set was evaluated using the metrics described in the methodology. The coefficient of determination (R^2) of the model using the Random Forest (RF) method was 0.98 (Figure. 8 a), in Stepwise was 0.935 (Figure. 8 b) and in the neural network was 0.933 (Figure. 8 c). In terms of percent mean absolute error (MAPE), RF performed the best, showing only a 2.7% error, followed by stepwise (MAPE = 6.27%) and multi-layer perceptron (MAPE = 6.42%).

**Figure 8.** Performance comparison of models to ETP_p prediction for test section.

When we evaluated the MAPE, the RF also proved to be superior to the other models considering the RMSE, with its value being ± 2.44 mm month⁻¹, while for the SW and MLP models, these values were ± 5.55 mm month⁻¹ and ± 5.63 mm month⁻¹ respectively. In relative terms (RRMSE) this represents about 3.34% for RF, 7.6% for SW, and for MLP this value is 7.7%. This set of metrics indicates that the Random Forest method was the most generalist, being the one selected for the validation section (Figure. 9).

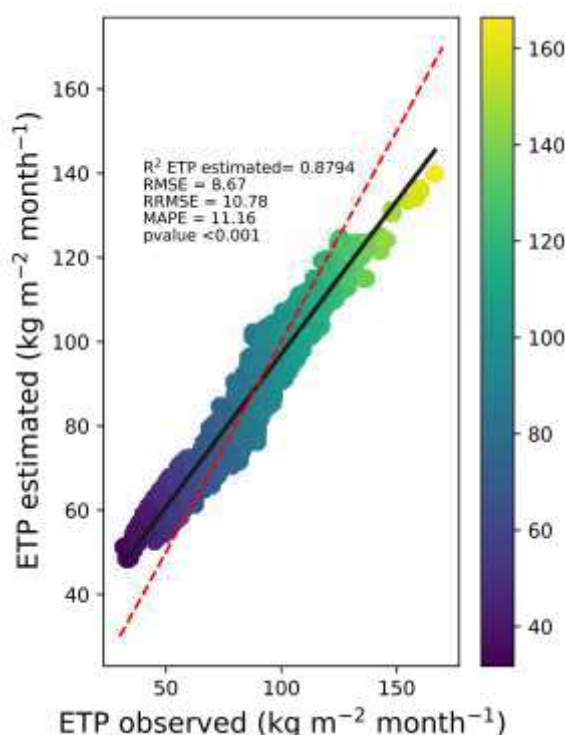


Figure 9. ETpML final adjust, Random Forest model's performance in the validation section.

From the validation of the model with NASA-POWER data, the random forest model has an accuracy (R²) of ~88% in estimating ETp, showing an RMSE of ± 8.7 mm month⁻¹, this represents about 10.8% error from the mean (RRMSE). Finally, the absolute error of the model was ~11.3% (Figure. 9). When using the observed and estimated data from Random Forest to evaluate the water balance it is noted that the model followed the seasonality of the study area, with an approximate error of ± 7.76 mm, slightly overestimating the deficits (April - August) (Figure. 10).

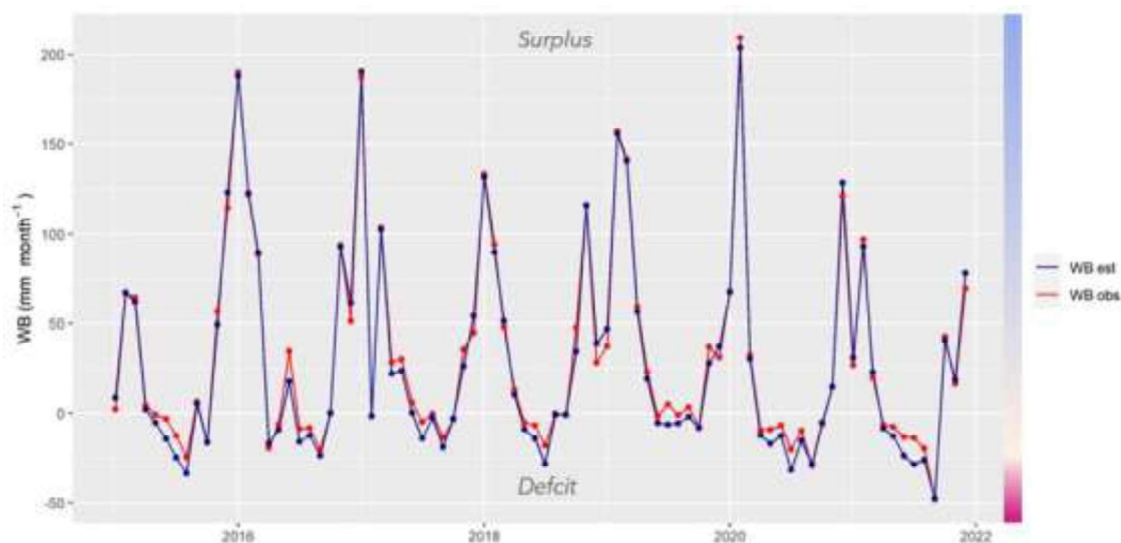


Figure 10. ETpML application in hydrological services assessment through climatological water balance (WB). WB – obs, the red line = water balance generated from observed ET_p ; WB est – blue line = water balance generated from ET_p estimated by Random Forest.

4. Discussion

Meteorological patterns, as precipitation and temperature are the major driving force of spatially distributed models (Shehata et al., 2022; Veetil and Mishra, 2020; Wang et al., 2022). Overall, we can observe that for this region the typical climatological behavior is of high averages at the beginning and end of the year, and low average values in the middle of the year, as observed by Alvares et al. (2013). This is due to the distribution of the seasons in the southern hemisphere and because the typical climate is dry winter (Köppen-Geiger, 1928).

Regarding the highest values observed (Figure 4), from November to March, the climatological pattern is also reflected in the general dynamics of ET_p across the watershed, since temperature and precipitation are the most expressive components in the general estimates of evapotranspiration. For water balance and daily values of evapotranspiration, Targa et al. (2019) also observed well-defined evapotranspiration intervals in the Paraíba Valley region, in which the highest and lowest evapotranspiration values correspond, respectively, in December (86 mm) and June (38 mm). Moreover, long-term climate–hydrological studies in UPS also highlight

seasonal patterns as wet and dry periods, and their effects on water availability, likewise qualitative and quantitative aspects (Ovalle et al., 2013; Pacheco et al., 2017; Souza et al., 2010; Targa et al., 2017).

Despite the complex interplay between several driving forces and the hydrologic response of the catchment, rainfall is contributing to water surplus and water deficit in wet and dry months, while evapotranspiration increases due to higher temperatures. The short period of soil water deficit caused an increase in the ET_p rate during the period of lower rainfall. Differences between rainfall and ET_p in the period suggest that water availability is threatened by water scarcity between June and September. According to Pluntke et al. (2023), depletion of soil water may lead to a collapse of evapotranspiration during droughts even in humid areas.

Likewise, water and soil conservation measures and urban structure adaption in the UPRS must be prioritized and intensified during this period for water security. Integrated hydrologic models and recommendations for landscape restoration, water and soil conservation, and urban resilience to improve hydrological services are also compiled in the literature (Coon & Shuai, 2022; de Mendonça et al., 2022, 2023; Erazo Ramirez et al., 2022; Marianno de Olivera et al., 2023; Pissarra et al., 2021; Roland & Crowley-Ornelas, 2023).

A spatial gradient of ET_p that increases from the southwest to the northeast, upstream to downstream, is consistent with rainfall distribution and mean temperature variation. Nevertheless, seasonal climate variations alone do not explain the observed spatial variability in water availability at the soil storage level. The water balance dynamic in UPRS, and consequently hydrological services, also reflects land use across the watershed, which merges mosaics of native and secondary Atlantic Rainforest, transitioned pasture to livestock production, and urban settlements in its landscape (Devide, 2014; Silva et al., 2016). Land use change, forest and crop management practices, and urban development have the potential to affect the regional hydrologic cycle directly by altering evapotranspiration (Aguilos et al., 2021; Fletcher et al., 2013; J. Liu et al., 2021a; van Opstal et al., 2022; Wang et al., 2021).

Hydrological interactions between soil/land cover/atmosphere and evapotranspiration products have been observed in several studies, including their effects on water balance and availability (da Costa et al., 2023; Jia et al., 2022; Y. Liu

et al., 2013; Scott et al., 2021; Yao & Mallik, 2022). Thus, ETp links to hydrology and water balance have important implications for watershed management and hydrological services provision, since water demand trends increase in UPS (Martins et al., 2023; Paiva et al., 2020).

Therefore, the intention here is not to detail water balance components, but rather to highlight the potential of ETpML to reduce tradeoffs in trends and improve hydrological services assessments (Amani & Shafizadeh-Moghadam, 2023). The accurate estimation of evapotranspiration (ET) is crucial for the efficient management of water resources, understanding hydrological and ecological processes. Furthermore, long-term measurements of local evapotranspiration through the methodology developed in this paper has the potential to explore and understand the effects of climate change, land surface changes, and climate-induced land surface disturbances across the watersheds inserted in the multifunctional context of agroecosystems, here notably the UPSR.

Regarding the ETpML structure training, it is noted that the variable that had greater importance in the construction of the model by Random Forest was the temperature, and this is related to the theoretical reference model, which uses temperature as one of the parameters (Thornthwaite, 1948). Regarding Multi-Layer Perceptron, one of its disadvantages is that it is a black box model, that is, it seeks the best result but the user loses the interpretability of the importance of the variables used for that model (Zihni et al., 2020; Yeh and Cheng, 2010).

Random Forest was the model that showed the best performance in the training and testing session. Since this model is not sensitive to outliers or multicollinearity and is not limited to linear models, it is common for its performance to be better than linear models (Breiman, 2001; Krkač et al., 2020; Douna et al., 2021; Xie et al., 2021). Furthermore, in the literature, we also found cases where Random Forest performed better than other artificial neural networks (Granata et al., 2020; Dias et al., 2021; Al-Mukhtar, 2021). Complementary to this, the fact that it does not lose the interpretability of the importance of the variables, is a contributing factor for Random Forest.

However, stepwise performing slightly better than MLP was a surprising result, this may be related to a possible overfit of the model by stepwise (Kalnins 2018; da Costa et al., 2022). It can also be linked to the fact that MLP is sensitive to non-standard

variables such as the case of coordinates and temporal variables, moreover, MLP is a method where many parameters must be optimized which makes it more complex to train compared to Random Forest and Stepwise (Pedregosa et al., 2011; Liu et al., 2021b)

Thus, Random Forest was the most generalist model during the training and testing sections, meaning, it was able to learn and estimate with the lowest bias among the models evaluated, even when subjected to data not seen before. When subjected to the validation data, the performance of the RF model reduces, however, its performance is still high, being similar to other studies (Xu et al., 2018; Saggi and Jain, 2019; Yang et al. 2021). However, one should consider that in the validation section, the data used are from another database, meaning that the acquisition methodologies of the bases are different leading to observational differences that can influence the result (Stackhouse et al., 2020) and mainly, the model receives data from a time series never seen before, meaning that the model was able to learn and adjust the behavior of the region and predict with a high accuracy data from seven years beyond the trained period, demonstrating its predictive ability.

An appropriate modeling algorithm reduces the trade-off between model interpretability and model accuracy. Nevertheless, extreme drought events could be better prevented when applying the ETpML in planning projections of the UPRS, since RF overvalues water balance in ± 7.76 mm, with an excellent estimation power ($\sim 88\%$). Similarly, Essenfelder & Giupponi (2020), used an ML approach to estimate water availability in a watershed and they observed an R^2 around 0.8 with an error of approximately 20% on a monthly scale. We remember that in the recent past the Brazilian southeast faced a serious water crisis, and the biggest reservoir located in the UPRS that feeds a complex water supply, Paraibuna reservoir (~ 224 km²; 4.74×10^9 m³), reached its lowest level in 2015 with only 1.09% of effective volume (ANA, 2015).

ETpML applications enables optimize and automate potential evapotranspiration prediction from a reduced database for any environmental modeling, and this paper provides an example of hydrological services assessment at watershed scale. This represents an improvement in capacity to manage water resources and avoid severe situations that compromise water security. In other

studies, machine learning methods, including random forest and artificial neural networks, have been used to estimate local ET_p in several time scales (Ferreira et al., 2019; Granata, 2019; Granata et al., 2020; Feng et al., 2019; Douna et al., 2019; Dias et al., 2021). Considering long-term watershed management demands and ET_pML performance, this suggest that our approach can be applied in other regions. However, the results could be different, even regarding the best algorithm. This is due because the framework intent to optimize the models to local variability and each local can have a unique model, providing the best possible estimative to a region, this is particularly helpful to policymakers and stakeholders for planning purposes.

5. Conclusion

A programing framework as ET_pML provides a toolset for optimizing water-surface-atmosphere systems modeling. The workflow presented an accurate ET_p forecasting and an essential background trough hydrological service assessment at watershed scale. Mapping hydrological services shows seasonal variation in ET_p prediction, that was driven by the amount and seasonality of rainfall and average temperature. This is consistent with climatic patterns in the Paraíba do Sul River Basin, characterized by high values at the beginning and end of the year, and lower averages in the middle year. Likewise, water balance components followed the average annual ET_p rate and affect water availability in the watershed, tending to increase water deficit in the north and water surplus amount in the east. This is a potential trend that threats water security and suggests a critical period and priority regions for better watershed management and hydrological services provision.

Into ET_pML setup, machine learning models (Random Forest, Stepwise forward selection, Multi-layer Perceptron) performed well; however, the random forest model showed the best results in predicting potential evapotranspiration, especially regarding the associated error. When the Random Forest model was submitted to a completely new data set, the performance remained high, with an accuracy of almost 90% and an error of approximately 10%. This indicates that this model is effective for ET_p predictions, even when subjected to data from different sources and with a different time series than the trained one. Furthermore, the Random Forest is a user-friendly

machine learning model that does not lose the interpretability of the variables, unlike black box models, and allows sharing common frames to apply and compare analysis.

Overall, results indicate the reproducibility and feasibility of including ETpML in order to optimize ET_p forecasting and the Random Forest based model. We also demonstrate the application of a modeling framework using a hybrid ensemble of remote sensing and reanalysis of observed weather data for forecasting climatological water balance projections that will support climate change risks mitigation and adaptation into the decision-making process for water-sensitive applications.

Acknowledgments

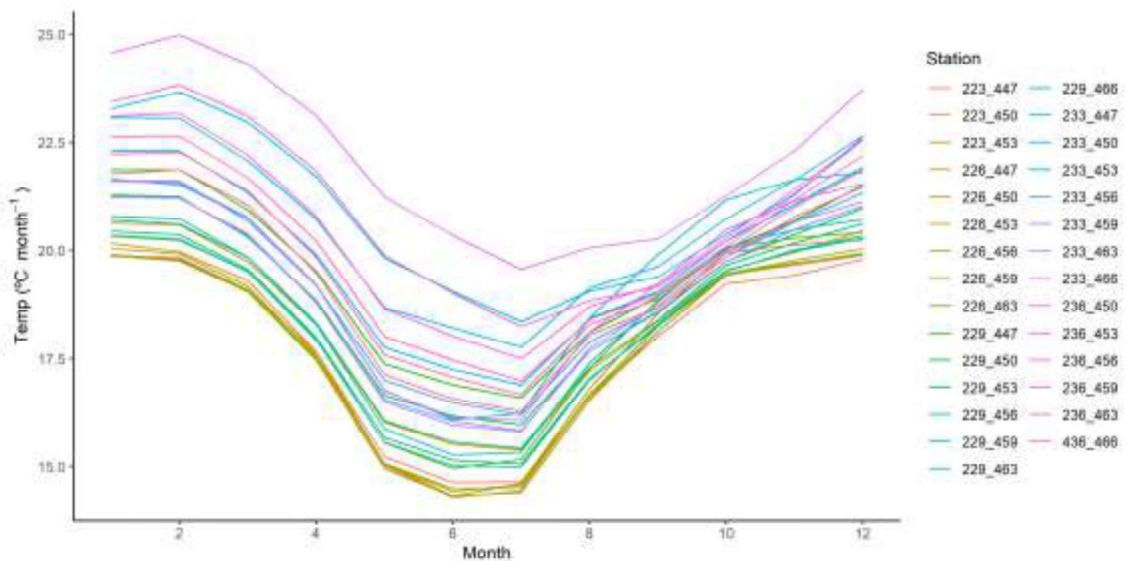
This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), PhD fellowship Proc. nº 88887.493039/2020-00 and internationalization fellowship CAPES/PRINT Proc. nº 88887.685328/2022-00. This publication comprises Gislaine Costa de Mendonça's PhD research within the Graduate Program in Agronomy (Soil Science) at the School of Agricultural and Veterinarian Sciences (FCAV) - São Paulo State University (Unesp); and also contributes to execute PhD sandwich working plan approved by CAPES/PRINT program, held at the University of Trás-os-Montes and Alto Douro. We also thankfull for the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) by the funding conceded to T.C.T. Pissarra, under the project Proc. nº405976/2021-6. Additional funding and support were provided by The Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) Proc. nº: 2018/17044-4 to M.T.V.N. Abdo. For the author integrated in the CQVR, the research was supported by the Portuguese National Funds of FCT – Fundação para Ciência e Tecnologia, projects UIDB/00616/2020 and UIDP/00616/2020, and Brazilian funds of CAPES - Fundação Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, scholarship Proc. no. 88887.716753/2022-00, PRINT – Programa Institucional de Internacionalização – CAPES/PRINT - Edital nº 41/2017. As regards this author, the publication also contributes to execute the working plan approved by the post-doc program in Agronomy (soil science) of Universidade Estadual Paulista Júlio Mesquita Filho (UNESP, campus Jaboticabal) to which the author Fernando A.L. Pacheco is affiliated

during the January – June 2023 period.

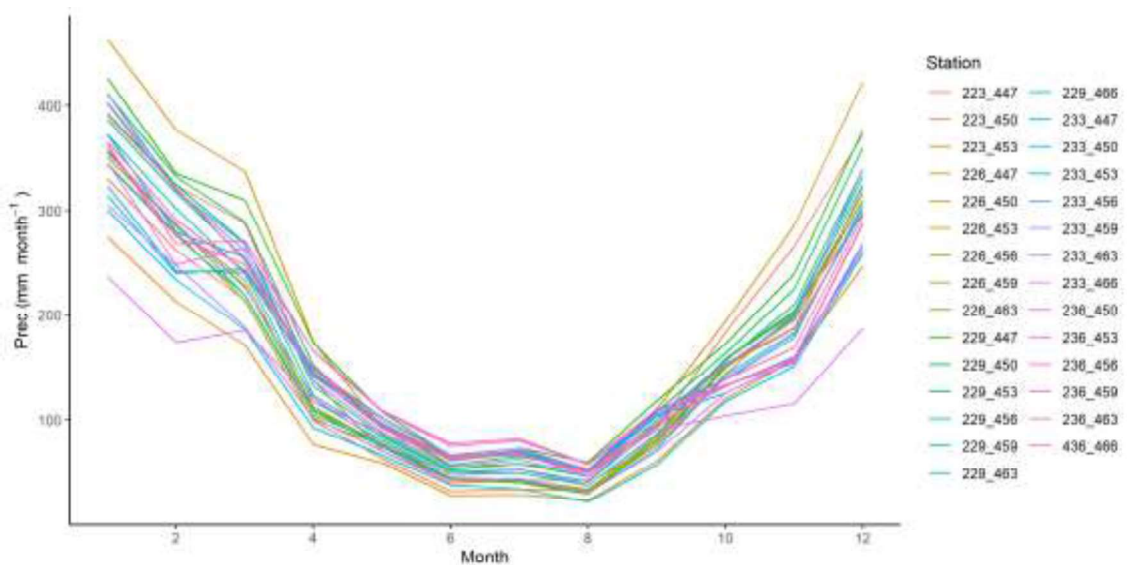
Appendix

A.1. Monthly variation of meteorological components and potential evapotranspiration for the weather stations in Upper Paraíba do Sul River Basin.

Mean temperature

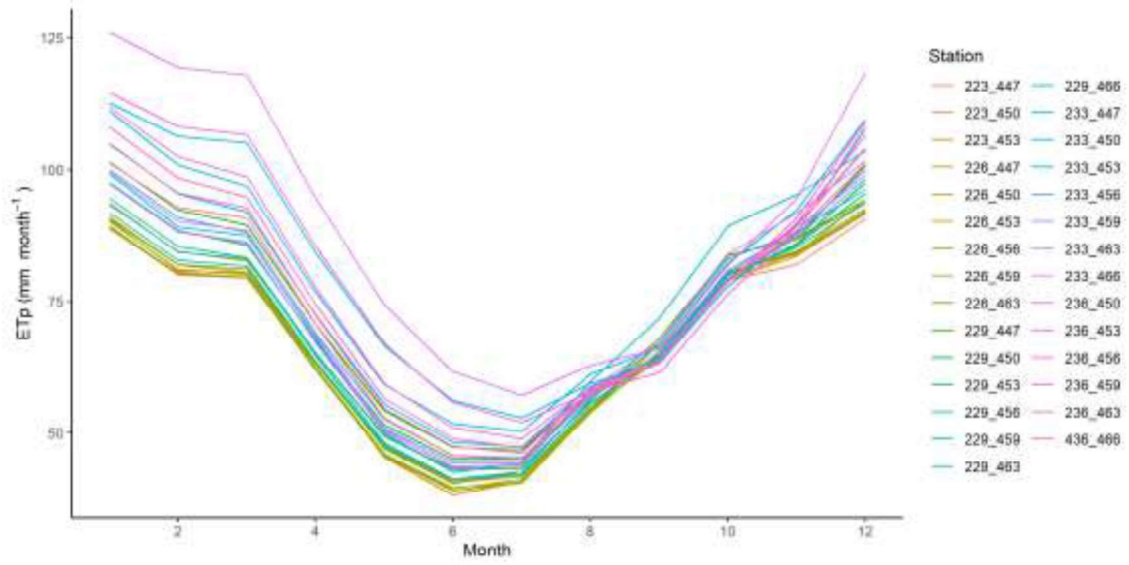


Rainfall

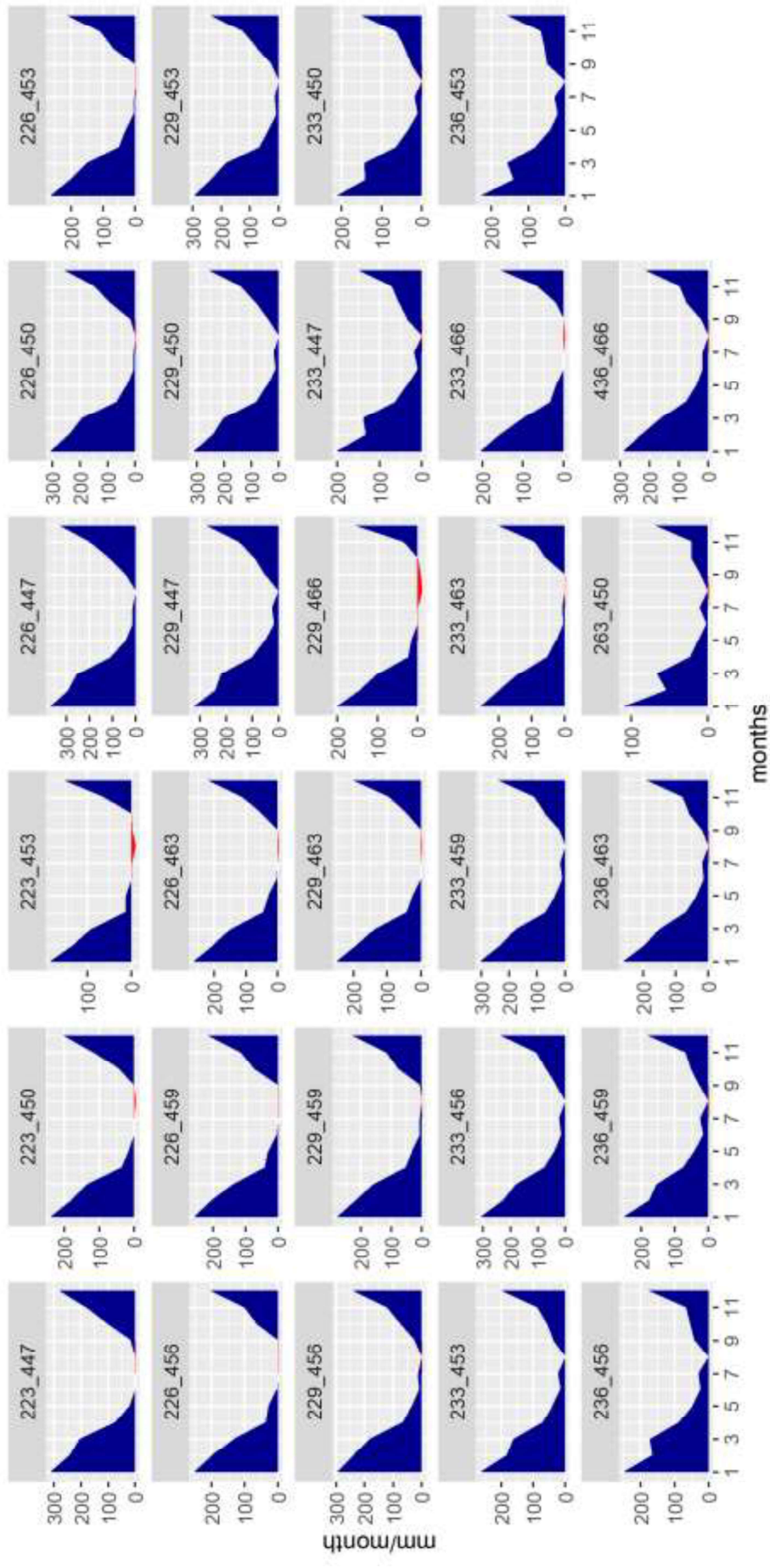


Potential evapotranspiration

1 Este capítulo corresponde ao artigo científico submetido à revista [Environmental Modelling & Software](#) em 07 de julho de 2023 e encontra-se em avaliação para publicação.



A.2. Average climatological water balance (water surplus, water deficit) by weather stations in Upper Paraíba do Sul River Basin.



1 Este capítulo corresponde ao artigo científico submetido à revista [Environmental Modelling & Software](#) em 07 de julho de 2023 e encontra-se em avaliação para publicação.

Supplementary material

S.T.1. Feature selection summary statistic for stepwise model

feature_idx	(5,)	(4, 5)	(1, 4, 5)	(0, 1, 4, 5)	(0, 1, 3, 4, 5)	(0, 1, 2, 3, 4, 5)
	[0.89265214	[0.92095988	[0.93344747	[0.935231	[0.93614294	[0.9361801
	0.90026739	0.92633645	0.93916941	0.94118188	0.94246137	0.94253883
	0.89708657	0.91881416	0.93430682	0.93690784	0.9383878	0.93839268
	0.88411694	0.91443745	0.93367148	0.93868058	0.94136435	0.94137747
cv_scores	0.88831087	0.91092375	0.92791158	0.9318079	0.93378701	0.93379677
	0.89454392	0.91709192	0.93348343	0.93503216	0.93662682	0.93632248
	0.89435566	0.9192558	0.93409774	0.93760025	0.93893633	0.93901177
	0.88440215	0.91390574	0.93339437	0.93730419	0.93828548	0.93830665
	0.88125089	0.91179916	0.92992564	0.93339073	0.93459403	0.93470584
	0.88199233]	0.91070677]	0.92701648]	0.93202563]	0.93275247]	0.93298395]
avg_score	0.889897885	0.916423107	0.93264244	0.935916216	0.937333861	0.937361654
feature_names	((('temp',),)	((('prec',),	('lat', ('prec',),	('lon', 'lat',	('lon', 'lat',	('lon', 'lat', 'year',
		('temp',))	('temp',))	('prec',),	('month', ('prec',),	('month', ('prec',),
				('temp',))	('temp',))	('temp',))
ci_bound	0.004765281	0.003543493	0.002484289	0.002110649	0.002229557	0.002215862
std_dev	0.006416047	0.004771013	0.003344884	0.00284181	0.00300191	0.002983471
std_err	0.002138682	0.001590338	0.001114961	0.00094727	0.001000637	0.00099449

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CAPÍTULO 4: PSA – Bacias: Um sistema espacial multicritério de apoio à decisão para otimizar pagamentos para programas de serviços ecossistêmicos visando a restauração da paisagem ¹

RESUMO - Em todo o mundo, o pagamento por serviços ambientais lidera uma série de iniciativas que proporcionam um caminho viável para reduzir as compensações entre a restauração da posse de terra nas agroecossistemas. Para preencher lacunas espaciais nos instrumentos de comando-controle, desenvolvemos o PSA – Bacias, uma estrutura baseada em bacias hidrográficas que visa identificar áreas prioritárias para otimizar os programas ambientais e socioeconômicos em andamento do Projeto Conexão Mata Atlântica em toda a Bacia do Rio Paraíba do Sul. As áreas prioritárias foram delimitadas com base numa análise de decisão multicritério em software GIS, combinando componentes-chave (gestão de bacias hidrográficas; vulnerabilidade da paisagem; disponibilidade de água; degradação da terra), que representam fatores cruciais para melhorar a restauração da paisagem e os serviços ecossistêmicos através das agroflorestas. Foram criados três cenários de áreas prioritárias para identificar onde os benefícios podem ser maximizados: i) conservação de múltiplos serviços ecossistêmicos; ii) prestação de serviços hidrológicos; iii) neutralidade da degradação do solo. A projeção dos cenários priorizou 2.798 km² ao longo das bacias hidrográficas e sub-bacias mais críticas, expondo um elevado nível de degradação da terra e riscos para os serviços hidrológicos. Além disso, cerca de 50% das propriedades rurais privadas cadastradas nos programas estão distribuídas em áreas de média prioridade, o que representa um alerta para redirecionamento de metas e intensifica os esforços na alocação de recursos (implementação/monitoramento). PES – Os produtos e conhecimentos de captação forneceram uma estrutura de apoio e um coeficiente de ajustamento para otimizar os pagamentos para programas de serviços ambientais, no sentido da restauração da paisagem e da conservação dos serviços ecossistêmicos.

Palavras-chave: agroecossistema; agroflorestas; neutralidade da degradação do solo; disponibilidade hídrica; gestão de bacias hidrográficas.

¹ Este capítulo corresponde ao artigo científico para submissão à revista [Ecosystem Services](#)

PES - Catchment: A spatial multicriteria decision support system to optimize payments for ecosystem services programs targeting landscape restoration ¹

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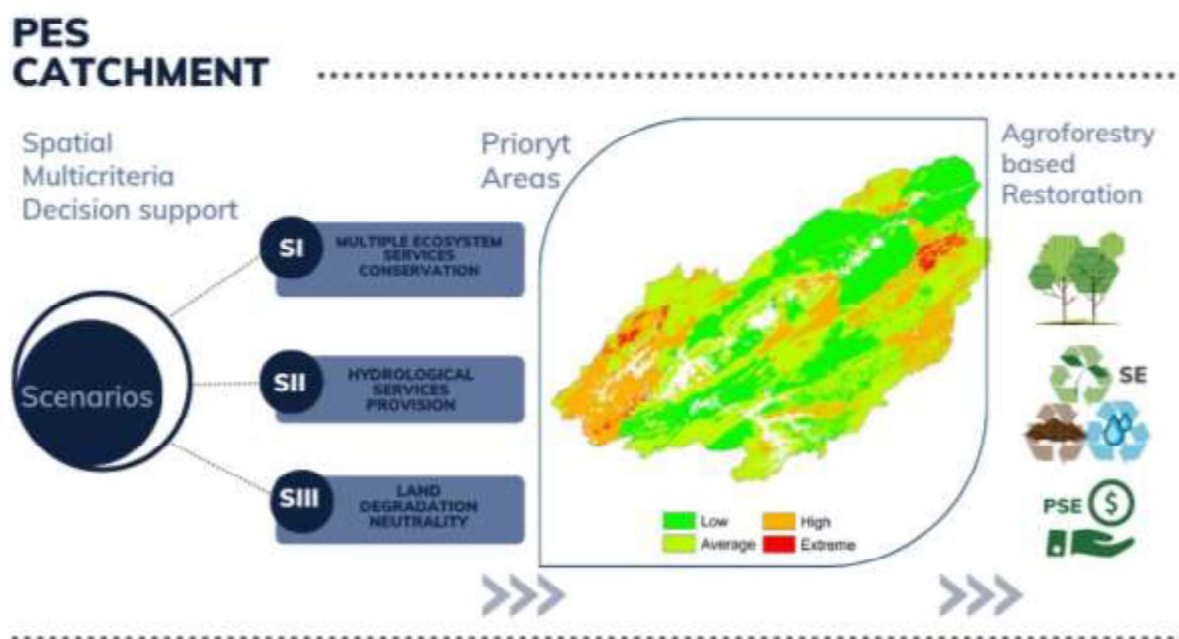
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Highlight

- Spatial targeting provided control points to allocate resources, monitoring and evaluating payments for environmental services instruments;
- Watershed-based prioritizing areas is an efficient approach to optimizing Conexão Mata Atlântica Project environmental & socio-economic initiatives;
- PES – Catchment can contribute to upscaling agroforestry-based-restoration and drive land degradation neutrality in vulnerable watersheds;

Graphical abstract



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Abstract

Worldwide, payment for environmental services lead a series of initiatives that provide a viable route to reduce tenure-restoration tradeoffs within agroecosystems. To fill spatial gaps in command-control instruments, we developed the PES-Catchment, a watershed-based framework that aims to identify priority areas for optimizing the Conexão Mata Atlântica Project's ongoing environmental and socio-economic programs across the Paraíba do Sul River Basin. Priority areas were delimited based on a multicriteria decision analysis in GIS software by combining key components (watershed management; landscape vulnerability; water availability; land degradation), that represents crucial drivers to improve landscape restoration and ecosystem services through agroforestry. Three scenarios of priority areas were created in order to identify where the benefits can be maximized: i) multiple ecosystem services conservation; ii) hydrological services provision; iii) land degradation neutrality. Scenarios projection prioritized 2798 km² along the most critical catchments and sub-basins, exposing a high level of land degradation and risks to hydrological services. Furthermore, around 50% of the private rural properties registered in the programs are distributed in areas of medium priority, which represent an alert to redirect targets and intensifies the efforts in resource allocation (implementing/monitoring). PES – Catchment products and insights provided a support structure and an adjustment coefficient to optimize payments for environmental services programs, towards to landscape restoration and ecosystems services conservation.

Keywords: agroecosystem; agroforestry; land degradation neutrality; water availability; watershed management.

1. Introduction

Towards in sustainable agroforestry-based landscape restoration requires a spatial optimization and targeting of the resource allocation and restoration actions across watersheds to improve multiple ecosystem services conservation, socio-economic and climate resilience (Abdo et al., 2016; Ahammad et al., 2023; Aryal et al., 2023; Chazdon et al., 2020; de Mendonça et al., 2022; Ntawuruhunga et al., 2023; Siqueira et al., 2020). High-level nature-based-solutions (NbS) to promote land use conversion in watersheds, water, and food security, as well as co-benefits for biodiversity among several ecosystem services (water supply, regulation of water quality, protection of the soil, mitigation of extreme events) have been addressed through land use policies and investments (UN-Water, 2018; Guo et al., 2020; Kang et al., 2023; Zhang et al., 2022).

Command and control instruments such as Payments for Environmental

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Services (PES) lead a series of initiatives that provide a viable and efficient route, if well targeted, to reduce tenure-restoration tradeoffs within agroecosystems. Following the “user pays” and “provider gets” principles, PES schemes seeking to support environmental socio - economics transactions, that takes place on the condition that either Ecosystem Services (ES) are provided or land is used in a way to secure those ES. Thereby landowners (providers) are compensated by adopting sustainable land-use and forest-management techniques that improve crucial ES for benefits and human well-being (users).

Worldwide, public or private agreements to financing specific PES to compensate the impact of productive systems. This represents an investment of up to US\$ 24.7 billion annually, totaling 387 programs in 62 countries (Salzman et al., 2018). In Brazil, well-done examples of PES have been implemented and conducted in favor of ecological restoration and smallholders' livelihoods, and Agroforestry System (AFS) emerges as a conciliatory alternative to forest ecosystem conservation and combats land degradation. In particular, the Atlantic Forest is already quite threatened and requires ambitious goals for restoring native vegetation to protect and restore its ecosystem services (Alves-Pinto et al., 2017; Aza et al., 2021; Guedes Pinto et al., 2023; Ruggiero et al., 2019).

In recent years, environmental policies and external investments associated with the restoration of the Atlantic Forest have directed the Paraíba do Sul River Basin (PSB) to restore/conservate its natural resources. These initiatives have been leveraging within “Conexão Mata Atlântica (CMA)” project - Atlantic Forest Connection, which assembly efforts of the Brazilian federal government, state governments of São Paulo, Rio de Janeiro and Minas Gerais among several sectors to increase biodiversity protection, water conservation and combat climate changes in the biome (MCTI, 2023; Devide et al., 2022).

Specifically in São Paulo state, the CMA project is held in the Paraíba Valley through PES models that encourage best agricultural conservation practices, land use conversion to agroforestry in order to change the landscape matrix in detriment of small holders' economic activities and ecosystem services provision (SIMA, 2023). The positive impacts of CMA - PES experiences are evident at governance level and the assessment of long-term benefits for ecosystem services and biodiversity still ongoing;

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while temporally discontinuation and spatial lack are still major limitations and may compromise their effectiveness.

As a result, there is also limitations to integrate strategic regions to upscaling PES implementation and landscape restoration. Particularly, watershed-based approach deliver a feasible decision toolbox that expose priorities to a wide range of stakeholders to improving environmental & socio-economic conditions and to make informed decisions based on quantified potential outcomes. In fragile landscapes, hydrological and soil supporting services are considerably acquired, and the PES structures gain from considering watersheds systematic to maintain a maximum ecosystem services as possible.

An extensive literature reports catchment assessments to monitoring and valuating hydrological services (support, regulation, provision), and its impacts on water flow and water quality as a service provided from upstream to downstream areas along watersheds (Gebremariam et al., 2014; Ovalle et al., 2013; Pacheco et al., 2017; Pissarra et al., 2021; Pluntke et al., 2023; Simedo et al., 2020; Tribouillois et al., 2022). Environmental conditions, such as the natural vulnerability and environmental land or land use conflicts impact on the water-land-food nexus uncertainty and comprise PES provision in agroecosystem, as they increase operating costs (Chigbu et al., 2022; Borrelli et al., 2017; Pacheco, 2020; Pacheco et al., 2018; Pena et al., 2020).

However, current PES approaches underway still do not consider the specific contributions of targeting basins to agroforestry-based restoration and ES conservation increases. Furthermore CMA-PES modalities also do not add a complete inventory of land-use conversion costs and implementation of best management practices into the assessment framework.

To fill potential spatial gaps in PES implementation (valuation, command-control, and monitoring), we developed a multicriteria hierarchy framework to support decision-making process of PES related to watershed ecosystem services in Paraiba do Sul Valley, the “PES -Catchment”. A proposal to modeling spatial targets to upscaling landscape restoration through agroforestry systems and improve the effectiveness of PES instruments within the Conexão Mata Atlântica. The PES - Catchment points out the watershed as a basic territorial management unit and focuses on hydrological services and land degradation. Thus, this proposal aims to identify

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priority areas in order to implement a water-soil-based PES program.

Priority areas are delimited where there is a greater risk to the maintenance of ES and therefore, where benefits can be maximized, primarily in two aspects: water provision and soil conservation. Which includes projecting scenarios and estimating socio-economics compensation to adherents (participant producers). For this purpose, three scenarios of priority areas were created by exploring representatives' attributes related to landscape vulnerability and water provision, in order to improve i) multiple ecosystem services conservation; ii) hydrological services provision; iii) land degradation neutrality; and answers the following question: 1) where are critical areas concerning water supply and soil degradation and therefore potentially priority areas? and 2) are current PES initiatives addressing these areas within the action plan?

The projected scenarios and the selection of focal rural properties already enrolled in CMA's PES programs provide a framework of the spatial range, to support evaluations combining several land information and align current strategies and future initiatives. We emphasize that our results do not refute the advances of PES, but rather, add perceptions and propositions in support of decision-makers for strategic planning, implementing, and valuating public and private PES. Sustainable watershed-based prioritizing areas are an alternative to allocate restoration areas and drive land degradation neutrality. Therefore, PES - Catchment insights intend to endorse Conexão Mata Atlântica program, among other stakeholders related to watershed management and land use policies.

The increasing complexity of multifunctional aspects of the agroecosystem within Atlantic Forest, among other agricultural landscapes worldwide, requires a multidisciplinary investigation to guide ecological restoration. However, spatial distribution is still one of the major limitations of the PES in force in Brazil. Given that, this proposal aims to optimize the identification of priority areas to support PES strategies and agroforest-based restoration, regarding the Conexão Mata Atlântica's lacks.

2. Material and methods

2.1. Study Area

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This proposal was applied to the pilot area PSBsp, which consists in a São Paulo portion of Paraíba do Sul River Basin (PSB), Figure 1. The great PSB drains one of the most developed regions of Brazil, covering part of the State of São Paulo in the region known as Vale do Paraíba Paulista (VPP) - 13,900 km², part of the State of Minas Gerais in Zona da Mata Mineira - 20,700 km², and half of the Rio de Janeiro state - 20,900 km². In all this extension there are 180 municipalities, 36 of which are partially inserted in the basin. The water availability in the PSB is crucial for water security in southeastern Brazil, that responsible for supplying over 4,922,779 inhabitants and support multiple uses of water among domestic consumption, industry, hydroelectricity generation, agriculture, livestock, and mining (IBGE 2000, ANA, 2023; Martins et al., 2023; Moraes-Santos et al., 2021; Paiva et al., 2020).

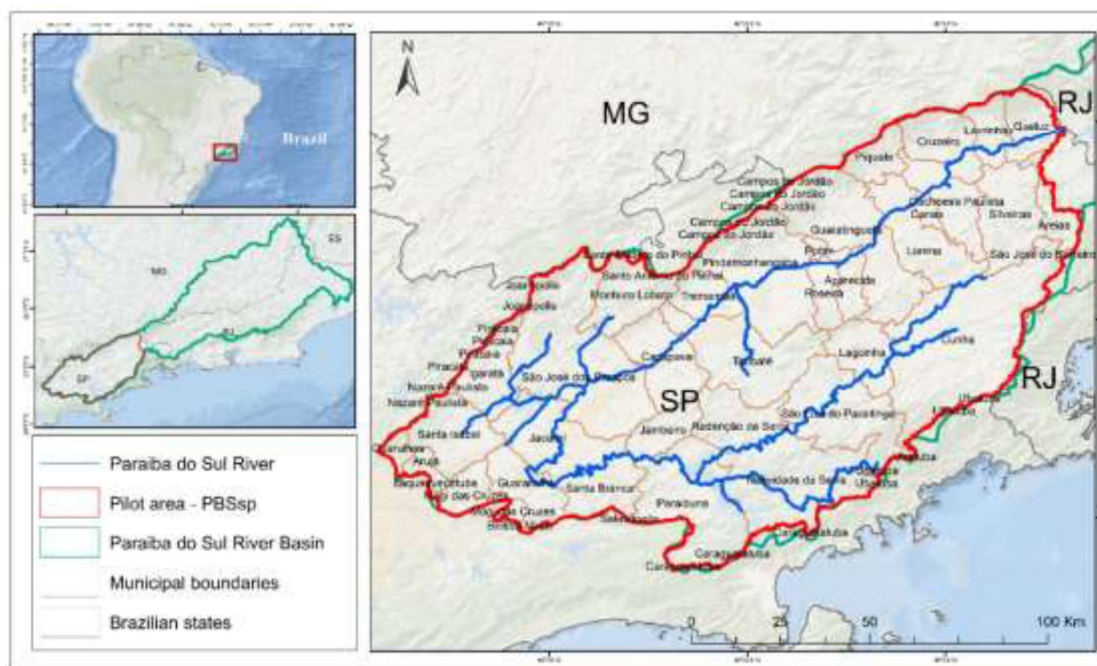


Figure 1. Location of the great Paraíba do Sul River Basin (PSB); Paraíba do Sul River main hydrographic network (PSB); and the study area - Paraíba do Sul River Basin in São Paulo State (PSBsp); Brazilian administrative boundaries for State and city.

The pilot area PSBsp corresponds to the upper macro-sector of the great PSB and comprises around 12605.6 km² across the VPP drainage area. Livestock and pasture predominate (49%) constituting the majority of smallholders' livelihoods; followed by agricultural areas cover that covers 18%, including perennial and annual

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crops. Forest cover represents around 30%, vegetation reminiscent of the Atlantic Forest characterized by high deforestation rates and intense urbanization since this is the most densely populated area of the entire Paraíba do Sul River Basin (Martins et al., 2023; Moraes-Santos et al., 2021; Paiva et al., 2020), Appendix section A1. Therefore, this region plays a strategic role for a more sustainable watershed management and land uses.

Reduce conflicts between ecosystem and socio-economic functions is the main goal PES programs, such as the Conexão Mata Atlântica project, that is committed to ecosystem conservation while promoting NbS economic systems. Specifically in São Paulo state, the CMA project is held in the Paraíba Valley through PES model that encourage best agricultural conservation practices and land use conversion to agroforestry or more sustainable productive system to improve ecosystem services provision and landscape restoration.

CMA - PES recognizes the contribution of farmers and landowners in providing environment services/benefits, by taking care of their land, adopting actions to conserve native forests, recover degraded areas and implement sustainable production practices. Currently, adhered approximately by 640 rural landowners, covering three main axes: 1) investigation, management, and monitoring (biodiversity and carbon); 2) ecological restoration in the Paraíba River basin; 3) sustainability of areas protected by law and actions to change the landscape matrix in detriment of small holders' economic activities in conservation buffer zones (SIMA, 2023).

2.2. Modeling conceptual approach

We elaborate PES - Catchment as a tool suite supported by Multi-Criteria Decision Analysis (MCDA) to stand out the spatial optimization for alternative priority areas scenarios. The spatial modeling of scenarios components (watershed management; landscape vulnerability; water availability; land degradation) interfaces with Geographic Information System (GIS) by aggregating key factors (hydrological delineation; lithologic fragility, soil erosion susceptibility; hydrological services flow; environmental land use conflict). Furthermore, landscape and hydrological models are useful to support ecosystem services restoration (Mao et al., 2019; Possantti et al.,

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2023; Siles et al., 2019).

To rank several alternatives, a set criterion (components/factors) was established by participatory technique, conducted at the Paraiba do Sul Valley through articulating and consulting specialists, decision makers, local agroforestry networks, OCIPs, and local rural producers within the project scope "Evaluation of growth and production of native forest species and crops using 3-PG and YieldSafe models" (GEEF/FAPES 2018/17044-4).

Selected attributes correspond to crucial drivers in response to landscape restoration, soil and water conservation, forest recovery, and livelihood farming through agroforestry systems. These criteria have been extensively investigated in several previous studies, presented in different spatiotemporal combinations to summarize the multiple functional aspects in agroecosystems, such as land use, socioeconomic safeguarding, and biophysical conditions, including in the Atlantic Forest context (Carvalho de Melo et al., 2021; Correa et al., 2016; Fletcher et al., 2013; Haggar et al., 2019; Lemos et al., 2023; Lopes et al., 2021; Marques et al., 2022; Ota et al., 2020; Pena et al., 2020; Possantti et al., 2023; Reverte et al., 2020; Souza et al., 2010).

Hereupon, three scenarios of priority areas were created aiming to propose alternatives to allocate restoration areas and optimizing PES strategies, according to the assumptions of i) multiple ecosystem services conservation; ii) hydrological services provision; iii) land degradation neutrality.

2.2.1. Modeling components

Watershed management (Wm): In the approach presented here, the Wm component ensures that the priority areas established maximize the benefits and management of the PES at the watershed scale, extrapolating the integrated management beyond the boundaries of municipalities. More integrative and multisectoral management raises the chances of management initiatives in watersheds and consequently ensures that ecological functions are sustained in drainage areas (Pacheco, 2018; Poongodi & Venkateswaran, 2018; Sukristiyanti et al., 2018; Mani et al., 2022). Due to the biophysical complexity of watersheds, the sub-division in

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territorial units enables better spatial diagnosis of impact factors and their effects on the environment (Obeidat et al., 2021). By establishing the hydrological delineation as a criterion in the identification of specific management areas for the establishment of environmental recovery strategies through agroforestry and PES systems, we promote assertive monitoring and develop more efficient metrics that support decision-making processes and public policy instruments. In this proposal, we define as experimental plots hydrological response units (HU), to provide a sectoral extract of the PSBsp and account for the specific contribution of these drainage subareas to the integrated management of the watershed and thus assign the degree of prioritization in the PES - Catchment planning.

Landscape vulnerability (Lv): Lv component is a function of landscape exposure, also understood as fragility, sensitivity, or potential impact, given by combining key environmental conditions that are applied worldwide to assess risk from natural and man-made disasters, such as geological pedological formation. With this we establish within the MCDA framework which areas are most at risk of soil loss or degradation, and within the scenario projection this information provides a base layer for successfully conducting land use conversions, implementing best production practices, and managing PES. In vulnerable areas, soil losses and water supply are particularly sensitive, and operational costs become higher at the expense of more stable areas (Pacheco et al., 2014; Pacheco and Sanches Fernandes, 2016). A regional assessment of lithologic fragility and soil erosion susceptibility provides the landscape vulnerability as a control measure to prioritizing environmental management (higher vulnerability, higher priority for conservation/recovery), and establish a consequential link between ES users and providers, i.e, incomes from the service provided should be higher in vulnerable areas.

Water availability (Wa): In this methodology, water availability considers the minimum flow rates applied as a reference to ensure compliance with the multiple uses of water in the Watershed. These are flows of high permanence over time, calculated statistically for each hydro-unit, to verify the service provided in water supply and the sustainability of water demand. Several studies have explored the relationship

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between the flows of hydrological services and the inflow and outflow of water, flow in volume (Flow - Q). Additionally, reference flows are widely used indicators in water resources management and serve as a basis for water use conceptions in permanent or temporary rivers. To account for an efficient indicator within the MCDA framework and the projection of scenarios we established the flow rate $Q_{7,10}$ as a proxy for water availability. The $Q_{7,10}$ flow rate can be understood as the annual value of the average of 7 consecutive daily flows that can be repeated, on average, only once every ten years, that is, a return period of 10 years (Von Sperling, 2007). Thus, this approach prioritizes restoration actions in basins with lower production, and consequently greater incentive through the PES in the regions most sensitive to water scarcity, without disregarding other key regions for the maintenance of hydrological services.

Land degradation (Ld): Land degradation is an imbalance of environmental (biophysical) and socio-economic (property incomes and rights) conditions of land led by deforestation and unsustainable land use. Given that, the theoretical-methodological contribution of this research considered environment land use conflict metrics as an effective indicator of potentially degraded areas in PBSsp. Across agroecosystems the land use of watersheds is dominated by agriculture, livestock, and forest remains, and often, current land use is not consistent with potential land use or capacity, thus configuring the “environmental land use conflict”. Environmental land use conflict is well known as the deviation between actual land uses and potential land uses regarding land capacity, and its consequences for environmental balance and sustainability of soil and water ecosystem services have been widely studied (Pacheco 2020). New assumptions in the implementation and valuation of PES are introduced to improve the effectiveness of Conexão Mata Atlântica, since environmental land use conflict also increases the effective costs of management and conservation practices (Borrelli et al., 2017; Pissarra et al., 2021), a pertinent point of view in towards land degradation neutrality. The data processing and methodological approach of each component is described in Section 2.3.

2.2.2. Scenarios

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SI - Multiple ecosystem services conservation

Decision support for the implementation of payments for environmental services programs related to water and soil in PBS is fundamental to ensure the control of provisioning, regulating, and supporting ecosystem services in the Southeast Corridor of Atlantic Forest biome (SCAF), including socio-environmental and climate resilience. The SI scenario projection examines the increasing resource scarcity and multi-ecosystem services management by comprising a balanced combination of the key components. Here we establish an equivalence of importance between water availability and land degradation, as the interactions between land uses and watershed hydrological processes are important for multiple ecosystem services.

SII - Hydrological services provision

One of the fronts that PES - Catchment intends to strengthen within the CMA is to maximize incentives for services rendered in favor of water provision, in quality and quantity. The SII scenario prioritizes the implementation of PES in areas where water availability may be compromised according to the minimum flows observed. In addition, key sub-basins for maintaining up-downstream hydrological flows are highlighted. For this simulation the highest weights are assigned to the components water availability and watershed management, i.e., the final product of this map indicates priority areas for field interventions focused on the conservation of springs combined with soil conservation practices, implementation of agroforestry as a catalyst in recharge areas and/or containment zones on the slopes of the basin.

SIII - Land degradation neutrality

The effective inclusion of PES schemes in ecosystem services protection is a key challenge for future environmental governance. In an attempt to improve agroecosystem restoration and the current PES strategies in Paraiba do Sul Valley, we understand that it is necessary to compute the degree of fragility and degradation in the valuation-command-control frameworks. Therefore, it is in these scenarios that we emphasize the components of landscape vulnerability and land degradation with the highest coefficients. Environmental conditions in susceptible landscapes and the use of productive practices above the carrying capacity contribute to inflating operating

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costs of restoration and land use conversion. The SIII approach is an alternative for prioritizing strategic areas to drive land degradation neutrality.

2.3. Spatial framework development

The spatial modeling for prioritizing areas consists of combining all four components alternately concerning the relative importance of each component for each scenario, given the previous prepositions already justified as summarized in Figure 2. For this, workflow consists of applying the PES -Catchment to the PSBsp area assuming a logical sequence: 1st) factors geodataset processing – acquisition, treatment, analysis, geofencing, processing, transformation and classification; 2nd) weighting and reclassification of each factor and their respective modeling component is performed as described in section 2.3.1 and section 2.3.2; 3rd) after the previous determination, the factors compose the georeferenced information layer of each component (raster or shapefile), which are coupled to the mathematical structure of the model (section 2.3.3) to project each priority scenario according to the relative weights; 4th) a sensitivity analysis is developed from the counterfactual scenario of the focal properties already registered in the current PES programs (section 2.3.4). Complementing, an estimate for economic compensation is provided according to the priority areas generated in this proposal.

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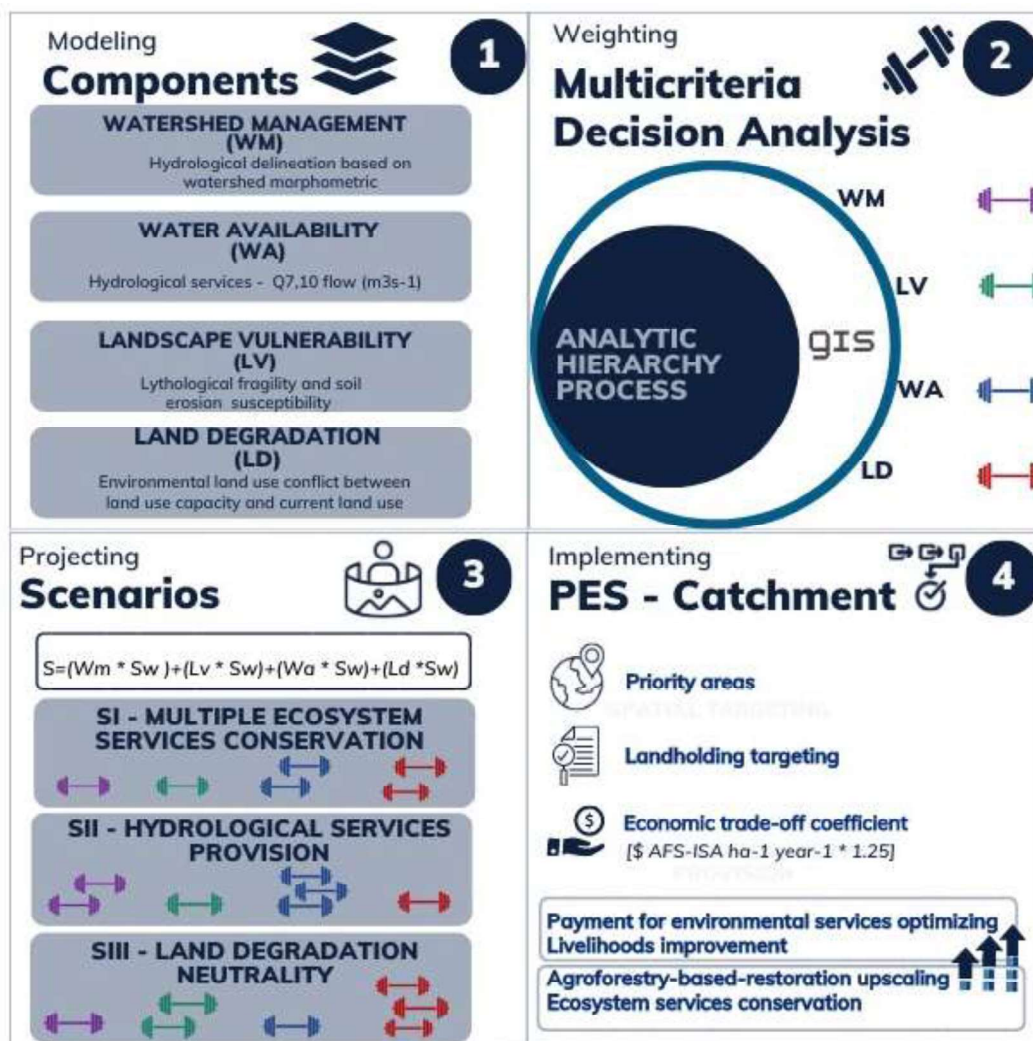


Figure 2. PES - Catchment flowchart. Spatial modeling for prioritizing areas, projecting scenarios to improve payments for environmental services programs.

2.3.1. Dataset processing: Factors and components

PES - Catchment is implemented in GIS environment, here specifically, we use the ArcGIS/ArcMap software, however, its processing can be performed by other geoprocessing toolkits. Each set of input information (factors) is processed to generate primary maps of each component, used in the simulation of the scenarios according to the algebra described in section 2.3.3. Each factor, was obtained through different sources, and constitute geospatial information of primary or secondary data, depending on the format in which it was obtained, they are processed or converted from shape file format to GeoTIFF, since the map algebra method implies the

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overlapping of raster files. After processing, each factor is submitted to the image reclassification process, which consists in changing the values of each pixel to the weights obtained in the MCDA ranking, according to the methodology described in the next section.

This step is applied to all factors so that they are assigned the relative weight of the specific classes of their category and subsequently considered in the respective components and the map algebra for scenario generation. In this proposal, all factors were obtained from the delimitation of the PSBsp upstream of the Funil Dam, in the Southeast Corridor of the Brazilian Atlantic Forest, in the state of São Paulo, processed with the same spatial resolution (30 m) and projected in the Cartesian coordinate system, Datum SIRGAS 2000, Universal Transverse Mercator, zone 23S. It should be noted that the geoprocessing tooling may change depending on the package to be replicated, so we provide a general processing guideline. Each input database (factor) and the composition of the corresponding output information sets (components) are described below.

Watershed management (Wm): The Wm component consists of the hydrological delineation of the Paraíba do Sul River basin, and considers the overlap, neighborhood, and connectivity of data to verify the functions and responses of the watershed. The hydrological delineation was carried out based on the methodological propositions of morphometric analysis and hydrological zoning from relief information and altimetric amplitude obtained in Digital Elevation Models (DEM) (Pissarra et. al. 2013). The delimitation of the study area - PBSsp was made from the main mouth point (Funil outlet), which marks the entrance of the Paraíba do Sul River in the Funil Reservoir in São Paulo state and characterizes the extent of water contribution upstream. The division of HU was characterized by monitoring outlets, which are secondary points according to the basin hierarchy. For subsequent weighting of the criteria and specificities of each factor concerning MDC, the HUs were classified into two categories: i) catchments, presenting in their interior a main river that starts at a spring and flows into the mouth point and therefore, a greater hydrological interaction ii) sub-basins present in their interior only a section of the drainage line of the main river, not containing the spring point, thus assuming a lower impact than catchments,

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however, fundamental for the maintenance of hydrological services. These criteria allow us to attribute the specific relevance of these spatial units for a more effective investigation of geomorphological properties and the best description of water availability (Neitsch et al., 2011).

* ALOS DEM (12.5 m resolution), downloaded from the Alaska Satellite Facility (ASF; <https://search.asf.alaska.edu>) Distributed Active Archive Center (DAAC) was used to delimit hydrological division, extract drainage networks, in addition to providing general altitude and slope descriptions.

Landscape vulnerability (lv): The landscape vulnerability component expresses the biophysics conditions that potentially expose the landscape surface to land degradation process as soil loss and sediment runoff, consequently making these regions more sensitive to the impacts of management and use. This approach has been well-tried in several studies, and proven to be related to watershed geomorphology. To extrapolate these applications and advance the spatial management and effectiveness of PES programs, we adapted the methodologies proposed by Pissara et al (2022) and de Mendonça et al. (2023), which consists of a multi-criteria spatial analysis implemented in GIS software, based on multiple environmental and anthropogenic factors to characterize the risks of natural land loss and exposure derived from the spatial distribution of three environmental factors, geology, soil, and relief, and one anthropogenic factor, land cover. However, to avoid the collinearity of the slope and land use factors, which here already integrate the land degradation component, we highlight the aspects of lithologic fragility and soil erosion susceptibility as key factors to express the environmental fragility of the PSBsp, generating a common baseline axis for the projection of the priority areas in the 3 scenarios. Together, these factors constitute the landscape vulnerability component, which is aggregated to the MDCA framework for the projection of the prioritization scenarios as proposed and detailed in section 2.3.3. In this way, each factor (lithologic fragility and soil erosion susceptibility) corresponds to a map (raster image) and represents an information layer and spatial distribution of this attribute classified in the range: vulnerable - stable. The attribution of weights to the classes of each factor is

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determined according to the degree of fragility that the category represents for the landscape, be it the lithological type or the soil type. Thus, the highest ratings are assigned to categories that represent the greatest potential risk of exposure to the landscape (vulnerable), while lower weights configure the low vulnerability of the system (stable). The specific weights of the classes of each factor and the importance of the Lv component were determined according to the mathematical treatment described in section 2.3.2. Additionally, the source of obtaining each factor is described below:

* Lithologic fragility was obtained from the lithological types, taken from the Geological Map of the State of São Paulo, developed by the Brazilian Geological Survey Service (CPRM), at a scale of 1: 750,000, available at (<https://geosgb.cprm.gov.br/geosgb/downloads.html>);

* Soil erosion susceptibility used the information about the soil types of the region extracted from the Soil Map of the State of São Paulo, at a scale of 1: 100,000, available on the website of the Instituto Florestal (IF) (www.iforestal.sp.gov.br);

Water availability (Wa): The water availability was evaluated from the net discharges calculated at the outlets of the water courses of each HU in the $Q_{7,10}$ flow values. The then hydrological services flow (HSflow) was estimated from the methodology of "Regionalization of Water in the State of São Paulo", a method for estimating water availability based on probabilistic and deterministic models developed by the Department of Water and Power of the State of São Paulo (DAAE). This study is based on the analysis of historical series of precipitation and discharges observed in 444 pluviometric stations and 219 fluviometric stations distributed in the state of São Paulo. The deterministic method was automated in the SIGRH2001 software and made available on the DAAE website (<http://www.daae.sp.gov.br/>), that provides estimating the flow rates $Q_{7,10}$, Q_{98} , Q_{95} , Q_{90} , and Q_m . The hydrological modeling was applied starting with the input of the geographic coordinates of the centroid of each HU and the respective total area information (km^2). Then the model provides as output the estimates of the flow rate values $Q_{7,10}$, used in the preparation of the Wa component.

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A polygon shapefile describes the basin and HU boundaries, as well as the corresponding table attribute. Subsequently, by conversion tools in GIS, the shapefile and its attribute are used to produce a raster map of the HSflow, which is classified and weighted according to management priority, i.e., here the highest weight is assigned to the HUs with the lowest hydrological flow.

Land degradation (Ld): To determine the land degradation component we applied the environmental land use conflict analysis across de PSBsp. The land uses conflict map has created the analysis of the deviation between Land capability (UP) and Actual use (UA) (Valle Junior et al, 2013, 2014). The Land capability is a method that uses the roughness coefficient (RN) morphometric parameter, the relationship between the total length of the drainage network over a given area: Drainage density (Dd) Horton, 1945 and Slope (S); $RN = Dd \times S$, Strahler, 1952), extracted from ALOS DEM. Ruggedness number (RN) is an environmental parameter that directs potential soil use in terms of soil capability (Guidolini et al., 2020). The values of the RN for each sub-basin are classified by Natural Breaks (Jenks) method into 4 land capability classes (Costa et al., 2019, 2023). To define the conflict areas, map algebra is executed with the actual land use class (UA) and Land capability class (UP) assigned weights, agriculture weight 1, pasture weight 2, forestry/silviculture weight 3, and natural forestry weight 4 (Equation 1).

$$\text{Environmental Land Use Conflict (C)} = \text{Weight UP}_i - \text{Weight UA}_j, \quad \text{Eq. (1)}$$

Where n is the number of classes (4). The algebra analyses the negative and zero results, which are classified as regions without Land Use Conflict, and positive results (1, 2, 3) are the levels of conflict. The Conflict class 1 area can be represented by regions where the deviation of an immediately higher class occurs, while the conflict Class 2 or Class 3 with greater deviations (Valle Junior et al, 2013, 2014).

The algebra analyses the negative and zero results, which are classified as regions without Land Use Conflict, and positive results (1, 2, 3) are the levels of conflict. The Conflict class 1 area can be represented by regions where the deviation of an immediately higher class occurs, while the conflict Class 2 or Class 3 with greater

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deviations. Thus, in the MDCA analysis, the highest values are assigned to the classes with the greatest conflict, as we understand that it is in these areas that efforts should be concentrated, both for the implementation of the PES restoration actions and for monitoring.

* Actual land use class (UA) was extracted from MapBiomias product: Land Cover and Land Use Maps (<https://mapbiomas.org/>) scenes 2020, collection 06, 30m resolution; subsequently classified according to the above methodology: agriculture, pasture forestry/silviculture and natural forestry.

2.3.2. Multicriteria Decision Analysis

In this proposal, the decision-making process is supported by the Analytic Hierarchy Process (AHP), which uses a multi-level hierarchical structure of objectives, criteria, subcriteria, and alternatives (Saaty, 1980; Piantanakulchai and Saengkhaio, 2003; Raharjo and Endah, 2006; Briozo and Musetti, 2015; ANAC, 2023). That leads to a pairwise judgment (among criteria) by decision makers - Participatory Technique and synthesizes the priorities of PES - Catchment to optimize landscape restoration and PES implementation. The Multicriteria Decision Analysis was conducted according to the following instructions:

First, the rating for each criterion was defined, then to build the reciprocal matrix (A , Eq.2) we used the difference between the rates of criteria (Δ_{ij}). If the difference between the values equals 0, this implies that both criteria have equal weights, i.e. they will assume the value of 1 in the matrix, as an example see table:

$$A = \begin{bmatrix} 1 & \Delta_{ij} & \dots & \Delta_{in} \\ 1/\Delta_{ji} & 1 & \dots & \Delta_{mn} \\ \dots & \dots & 1 & \Delta_{mn} \\ 1/\Delta_{ni} & 1/\Delta_{nm} & 1/\Delta_{nm} & 1 \end{bmatrix} \quad (\text{Eq.2})$$

Where Δ_{ij} = difference between the criteria, i = line 1 to m^{th} and j = column 1 to n^{th} .

Then we normalize the matrix A (Eq.4) by the sum in each column (Eq 3) and calculate the mean local priority (MLP) vector as the average of each row (Eq 5). From

the MLP vector, the matrix of relative weights was calculated (Eq 6) by multiplying the MLP vector by matrix A

$$S_j = \sum_{i=1}^m a_{ij} \quad (\text{Eq.3})$$

Where S_j is the sum for each column, a_{ij} is the element of column j , and line i from the A matrix. Which $i = 1$ to m^{th} and $j = 1$ to n^{th}

$$A^{norm} = \begin{bmatrix} a_{ij}/S_1 & \dots & a_{im}/S_j \\ \dots & \dots & \dots \\ a_{mj}/S_1 & \dots & a_{nm}/S_j \end{bmatrix} \quad (\text{Eq. 4})$$

Where a_{ij} is the element of column j and line i from the A matrix and S_j is the sum of column j . Which $i = 1$ to m^{th} and $j = 1$ to n^{th}

$$p_i = \frac{\sum_{j=1}^n a_{ij}^{norm}}{k} \quad (\text{Eq.5})$$

Where p_i is the mean local priority for each line, a_{ij}^{norm} if the element of column j and line i from the A^{norm} matrix and k is the number of elements in line i . Which $i = 1$ to m^{th} and $j = 1$ to n^{th}

$$A^r = \begin{bmatrix} a_{ij} \times p_1 & \dots & a_{im} \times p_i \\ \dots & \dots & \dots \\ a_{nj} \times p_1 & \dots & a_{nm} \times p_i \end{bmatrix} \quad (\text{Eq.6})$$

Where a_{ij} is the element of column j and line i from the A matrix, and p_i is the mean local priority for line i . Which $i = 1$ to m^{th} and $j = 1$ to n^{th}

Finally the largest eigenvalue (λ_{max}) value was calculated (Eq.7) and then we calculated the consistency index (CI) and finally the consistency ratio (CR), equations 8 and 9 respectively.

$$\lambda_{max} = \frac{\left(\sum_{i=1}^m \left(\frac{\sum_{j=1}^n a_{ij}^r}{p_i} \right) \right)}{m} \quad (\text{Eq. 7})$$

Where a_{ij}^r is the element of column j and line i from the A^r matrix, and p_i is the mean local priority for line i . Which $i = 1$ to m^{th} and $j = 1$ to n^{th}

$$CI = \frac{\lambda_{max} - r}{r - 1} \quad (\text{Eq.8})$$

Where CI is the consistency index, λ_{max} is the largest eigenvalue and r is the number of criteria

$$CR = \frac{CI}{RCI} \quad (\text{Eq. 9})$$

Where CR is the consistency ratio, CI is the consistency index and RCI is the random consistency ratio given by Saaty (1980) for a r number of criteria.

2.3.3. Scenarios modeling

Once the factor classes ratings and key components weights have been validated, algebraic operations and functions in GIS software process the corresponding maps, reclassify the parameters multiplied by the AHP mean local priority weights (p_i), and combine the components creating a final map for priority area scenarios through the general equation:

$$S = (W_m \times S_w) + (L_v \times S_w) + (W_a \times S_w) + (L_d \times S_w) \quad \text{Eq. (10)}$$

S scenario; W_m watershed management; L_v landscape vulnerability; W_a water availability; L_d land degradation; S_w component relative weight according to AHP per scenario.

2.3.4. Local sensitivity analysis

Validation of the scenarios consists of cross-tabulation of rural properties already registered in PES programs in the Atlantic Forest Cone in superposition to the three proposed scenarios. Collection of secondary data from public agency: Infrastructure and Environment Secretariat of São Paulo State – SIMA, provided a contractual measure to establish an extract of the order of the current schemes and provide insights to align future initiatives. Here we superimpose the vector file of the rural properties registered in the PES from 2018 to 2020, against the maps of each scenario (raster file) through the Spatial Analyst Tools: Zonal/ Zonal Statistics as Table". In this procedure, we obtain information on the area and number of rural parcels per scenario and the respective priority classes. Descriptive statistics demonstrate the

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location and land dispersion concerning the priority areas proposed in the PES - Catchment.

3. Results

The PES - Catchment model was applied to 12297.34 km² of the Paraíba do Sul watershed in Sao Paulo state. Our proposal assumed the watershed as the main territorial unit for the prioritization of the areas of action of the Conexão Mata Atlântica, in the advantage of the targeting of PES instruments, both in the implementation of NbS initiatives (agroforestry and soil and water conservation practices), in the valuation of environmental services provided and control points for monitoring and evaluation of program activities. The modeling emerges from the integrated watershed assessment considering the vulnerability of the system and the conservation of ecosystem services related to water and soil.

Watershed management component is defined by the hydrological delineation, which consists of the sub-division of experimental units in the PSBsp (Figure 3). The basin is delimited by a line characterized geographically by the highest altitude values in the system, the topographic divider. In sequence, the alignment that makes up the main drainage network (Paraíba do Sul River) is formed by the points of the lowest altitude of the open system, starting at the point of mouth (Funil outlet, which corresponds to the outlet at the Funil reservoir - lowest altitude) and continues up to the point of main springs (highest altitude of the river drainage system), forming the main river channel with tributaries and sub-tributaries.

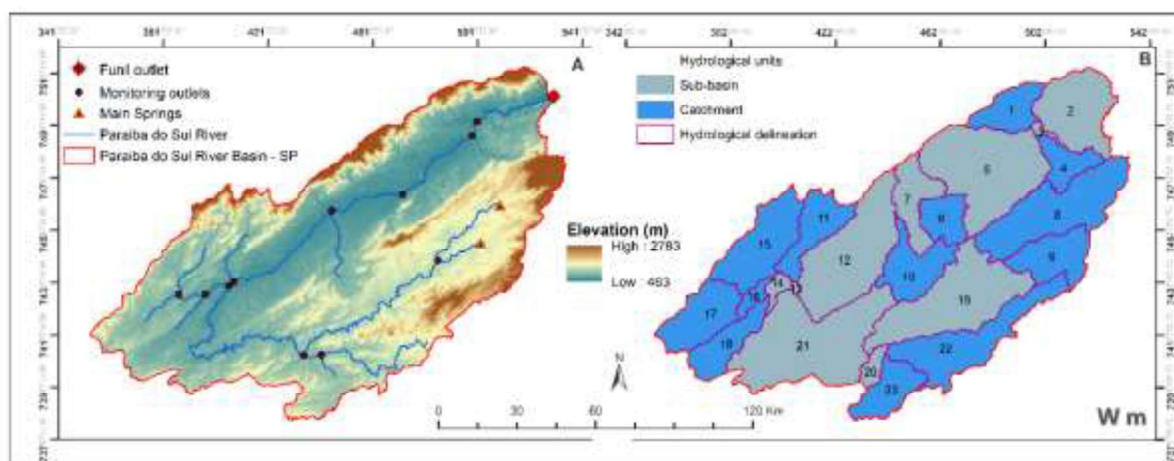


Figure 3. Watershed management component (Wm) through hydrological delineation. A - Terrain elevation (m), main springs, main drainage network, monitoring outlets; B- Hydrological response units, sub-basin, catchment.

Hydrological delineation was conceived in two geographical spaces for the development of the research, characterized by hydrological units (HU): twelve catchments: 1, 4, 6, 8, 9, 10, 11, 15, 17, 18, 22 and 23; and eleven sub-basin: 2, 3, 5, 7, 12, 13, 14, 16, 19, 20 and 21. The smallest area is in compartment 13 and the largest is in compartment 21. What delimits each HU are the water dividers, and relief structures that define the drainage pattern of rainwater or springs, such as hills, mountains, plateaus, or peaks. The waters from each analysis unit flow towards the lowest portion of the topographic area (Funil reservoir), following the relief pattern. However, the relevance of each HU for the interclass weighting of the Wm component considers the potential contribution of these territorial units to the management of water resources in the basin.

The twelve areas considered as catchment present within them a main river that is characterized by a drainage line that begins at the point of source and ends at the point of mouth (monitoring outlet), that is, the point of confluence with another drainage network, its tributaries, and sub-tributaries. This area is an independent hydrological unit and forms a region where the waters from the hydrological cycle flow out, presenting a direct effect on the runoff/ infiltration ratio, and therefore a greater contribution to the storage and runoff system.

The eleven areas considered as sub-basin present in their interior only a

section of the drainage line of the main river (Paraíba do Sul River), and do not contain springs in their interior, and the water originating from precipitation does not present a direct effect on the runoff/ infiltration relation and, therefore, its relative weight relative to catchment will be lower, but not zero. The main biophysical characteristics of the HUs can be found in Supplementary materials SMI; while the weights of the Hydrological delineation factor (W_m component) in the MDC framework can be found in Appendix section, A2.

Concerning Landscape vulnerability, the established soil and geology factors (criteria and categories) allowed a relative and empirical assessment of the fragility and morphodynamic instability of the basic territorial units, assigning a vulnerability gradient according to the impact of the specific classes of each factor for erosive phenomena and landscape evolution.

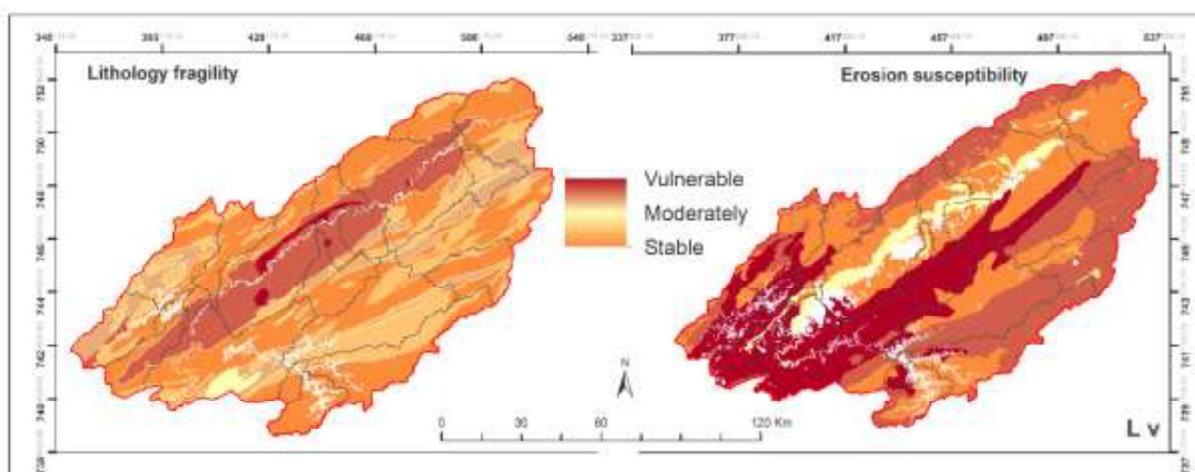


Figure 4. Landscape vulnerability component (Lv) exposed by the fragility of the rocks and soil erosion susceptibility.

The lithological fragility map was generated based on the grouping of the main geological formations found in the area. The groups were arranged according to the lithological types and origin of the rocks, which also guided the pairwise comparison, that for this factor within the land vulnerability component, the weights of each class were a function of the degree of fragility/stability of the rocks, as per Appendix section A2. The ordering and weighting of the ratings of the lithologic classes followed from highest to lowest fragility (degree of cohesion of the rocks). The six main lithological

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groups are: 6 - Dolomite limestone; 5 - Sandstone, Claystone, Conglomerate, Sand deposit; 4 - Metasandstone, Shist, Metarhythmite; 3- Granodiorite, Tonalite; 2- Biotite, Granite, Monzogranite, Quartz monzodiorite, Tiguaite; 1 - Gneiss Migmatite, Myolite, paragneiss. In the whole area occurs the predominance of rock types gneiss migmatite, myolite, and paragneiss, approximately 45 %, which corresponds to a lower degree of vulnerability in most of the territory. The greatest fragility is expressed in the limestone dolomite lithotype, present in less expressiveness, ~1% composes the morphogeology of the basin.

The risks of land exposure due to soil susceptibility to erosive processes showed a high degree of vulnerability throughout the PSBsp. In the region there is a predominance of ferrasols (34%), cambisols (31%) and acrisols (28%). In less expressiveness regions in gleysols, leptosols, histosols, and plinthosols correspond less than 6%. The classification of soils followed the taxonomy of order, and the assignment of weights within the MDCA framework to the specific factor soil, within the landscape vulnerability component, assigned a higher degree of vulnerability to soil types as a function of erosion potential. The soil factor ratings and soil composition in each HU can also be seen in Appendix section A2 and Supplementary materials SM1, respectively.

Through Water availability components (Figure 5), the information about the availability of specialized water resources in the experimental units comprised upstream of the Funil Reservoir is based on the historical series of $Q_{7.10}$ estimated in each HU. The values of $Q_{7.10}$ correspond to the minimum flow in seven consecutive days of duration in the return time of ten years, indicating that every ten years, on average, there is the risk of occurrence in seven consecutive days of minimum flow of 6.8 to 750 m^3s^{-1} , an average of 233.30 m^3s^{-1} (cv% 0.88) in the whole basin.

Assuming the application of $Q_{7.10}$ as the reference flow rate, i.e. the threshold value for water use and the guarantee of meeting water demand, the mapping of this hydrological ecosystem service provides a specific visualization of the HUs sensitive to water scarcity, or lower potential for water storage and production. The less water-available HUs correspond to sub-basin 3, 13, 14, and 20, considering a $Q_{7.10}$ of less than 50 m^3s^{-1} ; however, catchment 16 also presents a lower flow rate (18 m^3s^{-1}). Overall, the average flow in the sub-basins was 273 m^3s^{-1} , while the average $Q_{7.10}$ in

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the catchments is $\sim 202 \text{ m}^3\text{s}^{-1}$. The flow distributed over the drainage area highlighted UHs 5, 8, 19, and 21 with the greatest effect on water storage in the basin system. The detailing of the flows in each HU is described in the Supplementary materials SM1.

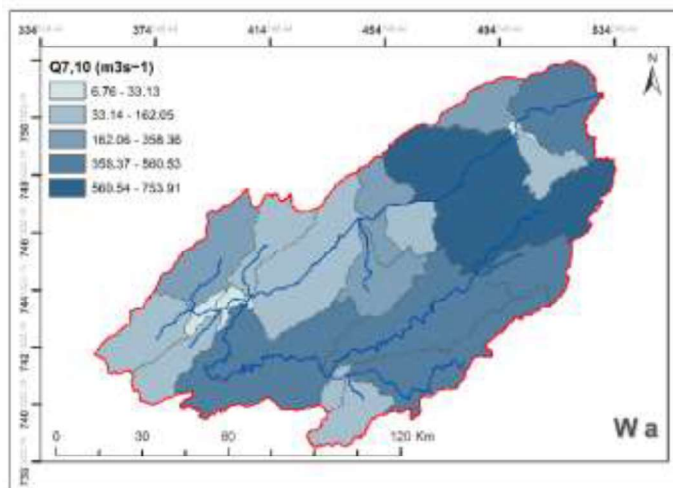


Figure 4. Water availability component (Wa), represented by hydrological services flow - $Q_{7,10} \text{ m}^3\text{s}^{-1}$ at each hydrological response unit.

Land degradation potential is exposed through the land use conflict analysis across the watershed and indicates $\sim 35\%$ PSBsp is under a degree of use conflict, i.e. 2565.45 km^2 of the area presents use conflict level class 1 and $\sim 1813 \text{ km}^2$ are being used 2X more than recommended. However, 65% of the area, which also encompasses the urbanized areas, is occupied within its carrying capacity (Figure 6). In the development of agricultural practices on farms, land use conflict is the challenge that producers need to solve to achieve sustainable land management. In this sense, the weights assigned to the conflict classes are characterized in favor of conservation and recuperation of the areas with greater potential for degradation and can be consulted in Appendix section A2.

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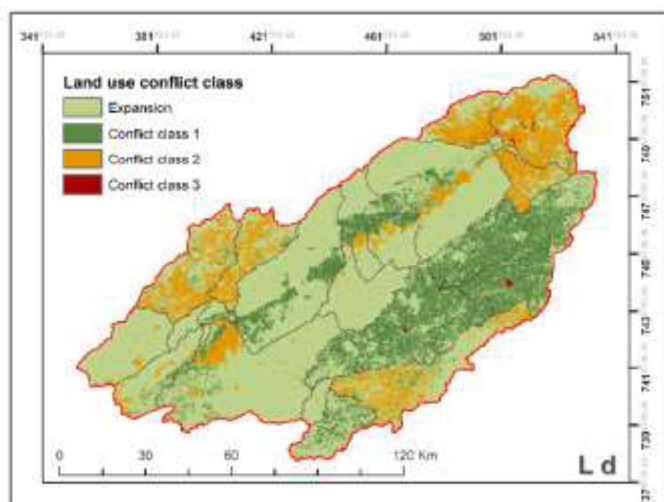


Figure 6. Land degradation component (Ld) from environmental land use conflict classes.

Also, in Appendix section (A1) it is possible to check the biophysical factors that previously composed the environmental land use conflict analysis, as described in section 2.3.1. It should be noted that the land capability map (UP) was generated based on the relief information (slope %) and drainage area (km²), used in the ruggedness number calculation. This step generated an RN map in a range of 10 - 61, later to form the UP layer used in Eq 1, this layer was categorized into 4 classes: 1 - agriculture; 2 - pasture; 3 - forestry/silviculture and 4- natural forestry, following from the lowest RN to the highest, which signals the gradient of risks or limitations of the recommended uses. In this same file, it is also possible to verify the UA layer, which refers to the current land use at the PSBsp, which is also grouped into four classes according to the previous categories to perform the land use conflict calculation. The distribution of environmental land use conflict areas along the HUs, as well as the biophysical characteristics, is provided in the Supplementary materials SM1.

The projection of the scenarios considered an area of interest of approximately 11319 km² since ~ 32% of the PSBsp is cut by rock outcrop and 6% of the region comprises urbanized areas and supply reservoirs. On average the projection of the scenarios indicated that 46% of the total area presents medium priority for the implementation of SAFs within the PES scope. High-priority areas comprise 24% and less than 1% have extreme priority. Additionally, 29% of the evaluated region can be considered to be of lower expressiveness in recovery initiatives (Figure 7, A3).

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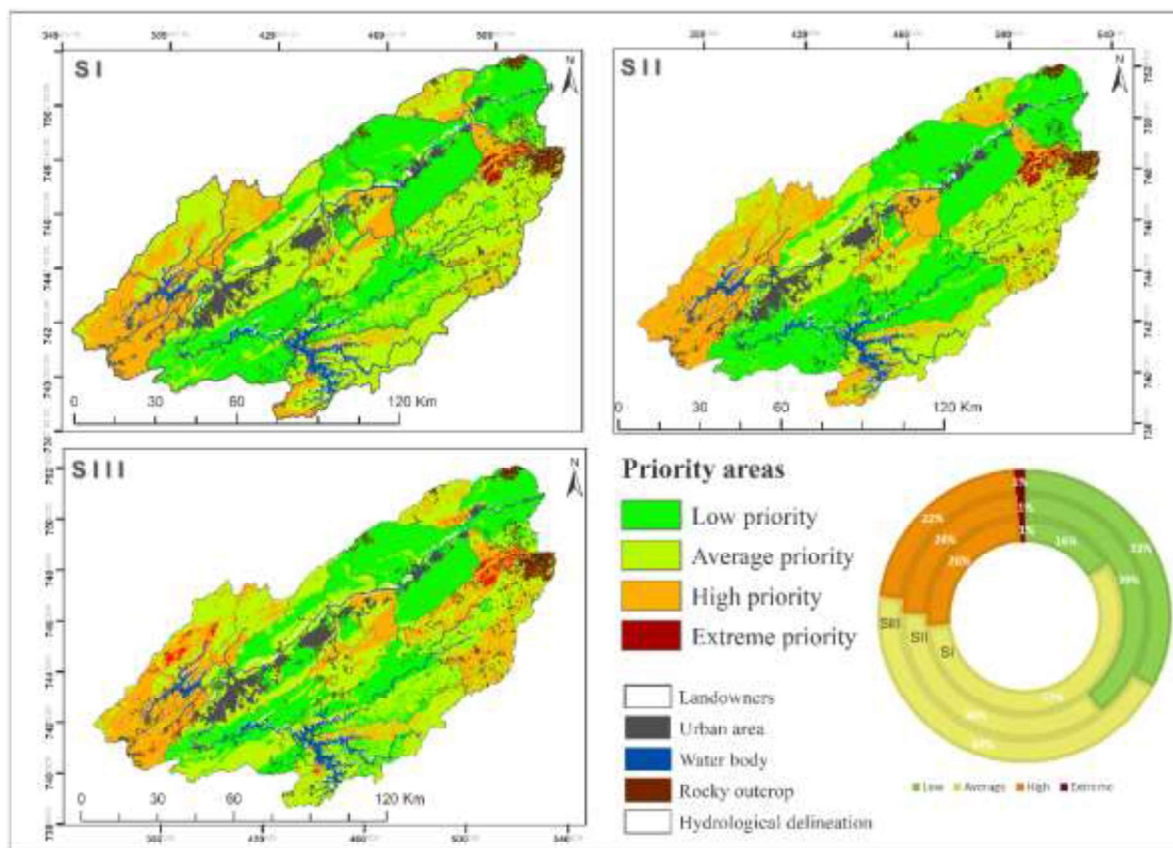


Figure 7. Priority area scenarios for watershed restoration PES: S I - Multiple ecosystem services conservation; S II - Hydrological services provision; S III - Land degradation neutrality.

The performance of the simulations, as well as the ratings assigned to each factor incorporated in the MDCA components, showed a $CI < 0.01$ (Table 1). In the S I the weights of the Water availability and Degraded area components were of equal relevance to the analysis (0.364). Following the established criteria, S II emphasized the components of Water availability (0.512) and Watershed management (0.275). For S III the Degraded area component had the highest weighting in the simulation (0.444).

Table 1. Scenario multicriteria decision analysis: ranking of the mutual importance of component and consistency index. Pairwise comparison according to Saaty (1977).

Component	S I			S II			S III		
	Rank of Importance	Weight	Consistency Index	Rank of Importance	Weight	Consistency Index	Rank of Importance	Weight	Consistency Index
Wm	7	0.182		7	0.275		7	0.222	
Lv	5	0.091		3	0.074		7	0.222	
Wa	9	0.364	0.000	9	0.512	0.004	5	0.111	0.000
Ld	9	0.364		5	0.138		9	0.444	

Wm - Watershed management; **Lv** - Landscape vulnerability; **Wa** - Water availability; **Ld** - Land degradation.

Considering the combination of components and the respective factor weights (interclasses). SI simulation highlighted areas of average priority, approximately 6473 km². Then it identified 2928.91 km² as high priority and 1822.45 km² as low; while only 95.78 km² is recommended as extreme priority. In the SII projection, the Low (4440 km²) and Average (4092 km²) areas had the highest expressivity. In between, the High areas extend over 2681.51 km², and ~ 105 km² points to extreme priority. Hydrological services provision. Land degradation neutrality towards SIII simulation also favored the indication of intermediate zones, 5003.27 for the Average class; followed by 3734.51 with low priority for intervention.

The high-priority areas correspond to 2456.56 km², however, the scenario was the one that projected the largest area in extreme priority condition, 125.38 km². The high and extreme priority areas presented the lowest variability when comparing the three scenarios, presenting a coefficient of variation (CV%) of 0.072 and 0.113 respectively; while the highest variation was observed in the projection of the low CV% class 0.332, followed by 0.189 Average.

Until 2019, the payment for environmental services programs within the scope of the Conexão Mata Atlântica helped protect and restore approximately 20,718 hectares under the Atlantic Forest Biome. In São Paulo state, were benefited more than 700 farmers along 13 municipalities in VPP. Considering official Brazilian farm-size categorization based on fiscal module units - that ranges from 5 to 110 hectares, Law 8.629/1993 (Brazil, 1993), smallholders' livelihoods represent around 80 % of private rural properties enrolled in CMA - PES programs in the Paraíba Valley. Along with medium (17%) and large (3%) rural properties, landholdings are clustered mainly in the HU 2, 4, 8, 9, 10, 19, 20, and 21 (Figure 8).

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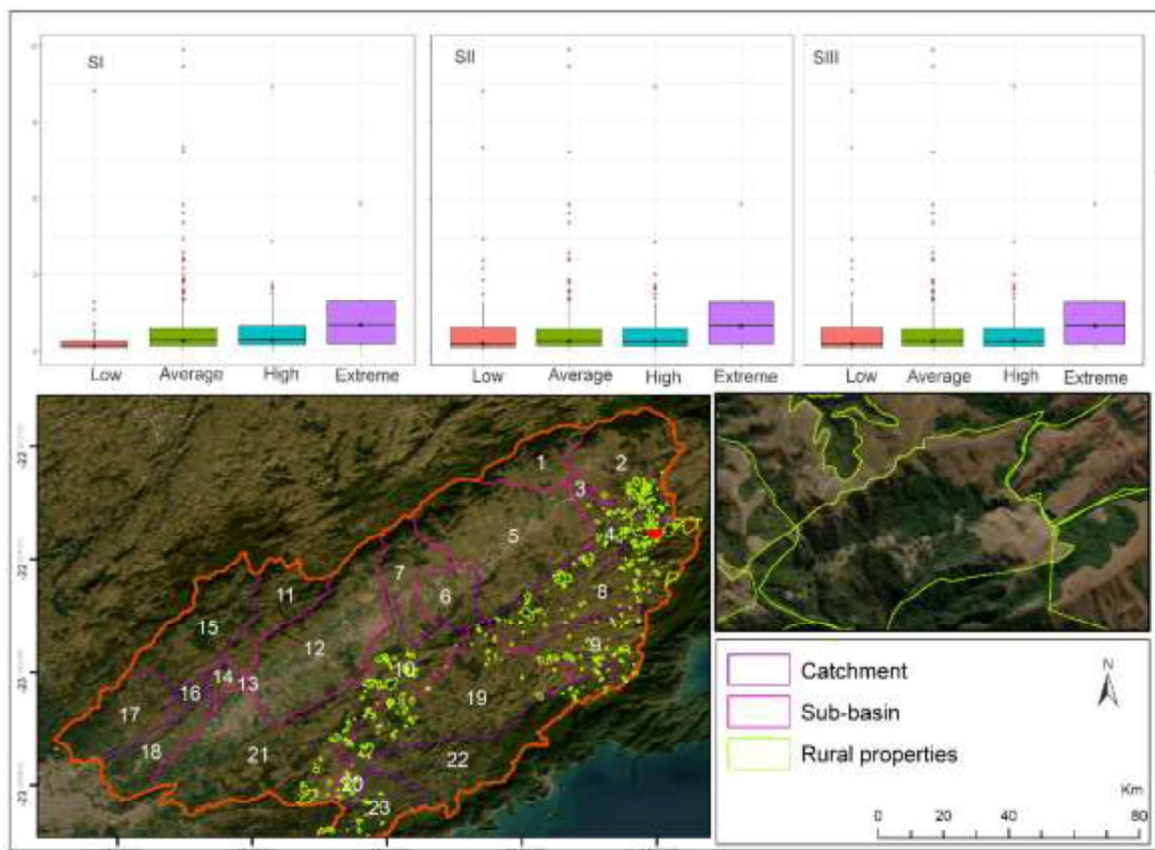


Figure 8. Landholdings distribution, private rural properties area (km²) registered in the CMA - PES programs across the projected priority areas by scenarios; S I - Multiple ecosystem services conservation; S II - Hydrological services provision; S III - Land degradation neutrality.

Regarding the distribution of rural properties across the priority areas generated scenarios, our results indicate that of the 317 projected properties, only 6 are located in extreme priority areas in all scenarios (Figure 8). Together, they add up to an area of 10.2 km², 3.5% of the area owned by local farmers, and less than 1% of the total projected area. Also observed in all scenarios is a concentration of farms in the medium priority areas, ranging from 159 to 179 plots in SIII and SI, respectively, and 170 in SII, an average of 158.67 km². When it comes to the high-priority areas, SIII shows the highest number of farms, 93 (~73 km²), followed by 81 (~68 km²) in SI, and 47 in SII (~45 km²). Here we highlight that the SII scenario simulation leads in the number of rural properties distributed in low-priority areas are about 95 km² in 94 plots, compared to 59 (~56 km²) in SIII and 31 plots in SI (~21 km²).

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A final prototype for mapping priority areas is suggested based on the SI projection, and the grouping of the 23 Hydro-units into 5 Hydro-zones: MC – Paraíba middle course (5,6,7,10,12,21); JB - Jaguari/ Buquira rivers contribution area (11, 14,15, 16, 17, 18); OT – Upstream Funil reservoir area (1, 2, 3); PT - Paraitinga river contribution area (8, 9, 19); PR - Paraibuna river contribution area (20, 22, 23).

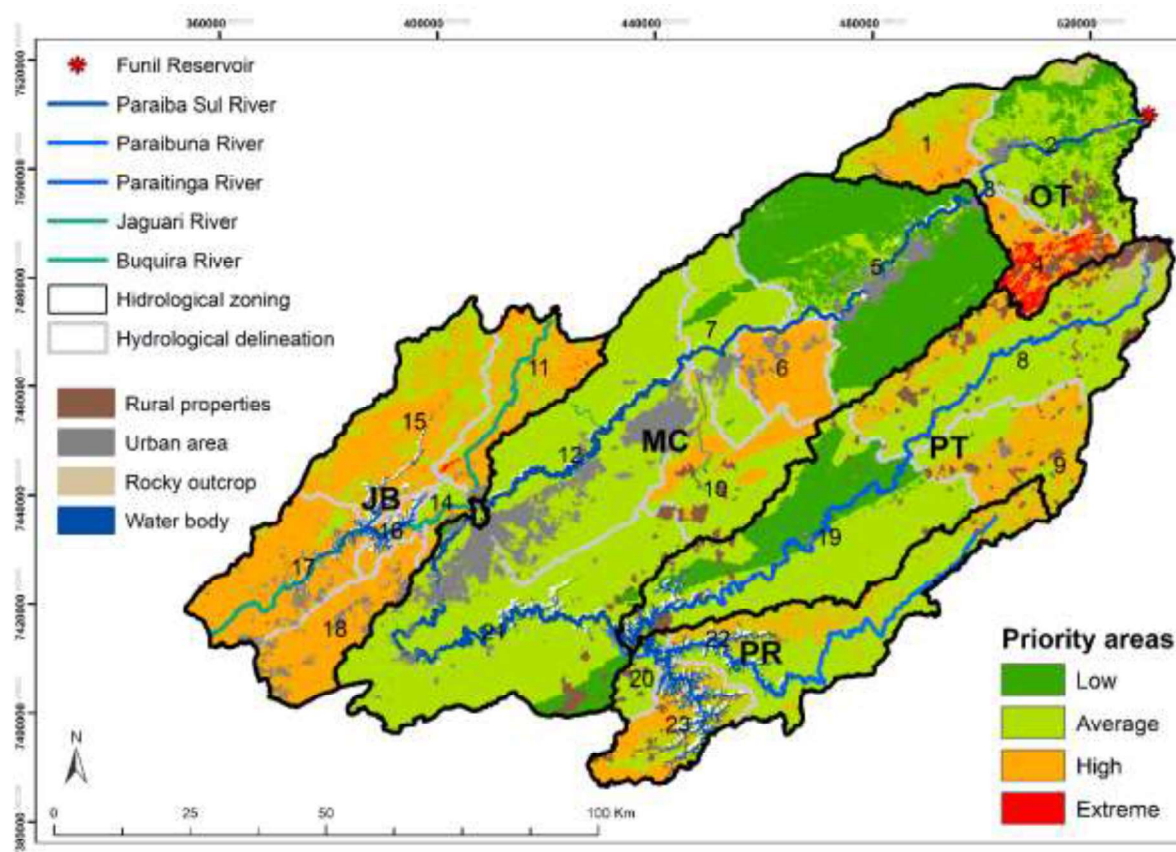


Figure 9. Management product: Priority areas final map to support decision-making according PES- Catchment approach. Hydrological zoning: MC – Paraíba middle course, JB - Jaguari/ Buquira Rivers contribution area, OT – Upstream Funil reservoir, PT - Paraitinga River contribution area; PR - Paraibuna River contribution area S I - Multiple ecosystem services conservation scenario.

Extreme priority areas are concentrated in the hydro-zone OT, sub-basin 4. High priority areas are also common in the catchments of hydro-zones JB, PR, PT, with the exception of catchment n°6 in the Paraíba do Sul middle course. From Low to medium priority regions follow the longitudinal profile from the mouth of the PT hydro-zone

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along the course of the main river.

4. Discussion

In view of agroforestry initiatives and institutional apparatus, efforts to implement, manage, monitor, and measure the performance of payments of environmental services programs are fundamental for the effectiveness and sustainability in the conservation of ecosystem services. The promising results from the Conexão Mata Atlântica project and its guidelines for the implementation of PES schemes are an important strategy to achieve global and national goals for the restoration of native vegetation and to consolidate the productive chains of agroforestry products in the Paraíba do Sul Valley. Within the CMA scope, the PES - Protection modality encouraged the conservation of 100 km² of native vegetation and the ecological restoration of 7.39 km². Also, PSA - Multiple use modality was responsible for promoting best management pasture actions in more than 15 km² and for establishing 75.79 km² of Atlantic Forest conservation and 4.76 km² of managed conservation through ongoing contracts (SIMA, 2023).

By projecting priority scenarios, PES – Catchment contributes to prioritizing the restoration in 2798 km² along the most critical basins and catchments, and therefore water security and ecological restoration in the PSB, meanwhile encouraging agroforestry and more conservationist practices on farms and livelihoods. Considering that Atlantic Forest Restoration Pact aims to restore 15 Mha of degraded lands in the Brazilian Atlantic Forest by 2050 (Calmon et al., 2011), the optimization provided by the PES-Catchment approach could contribute to upscaling agroforestry-based-restoration and monitoring the ongoing projects at CMA, from the flagship PES models - Protection and Multiple Use, to complementary initiatives as Sustainable Value Chain (CVS) and Certification (CERT).

Payment for environmental services is strategic to reduce the rate of biodiversity loss in the Atlantic Forest, which is an important global hotspot (Perrings, et al. 2014; Myers, et al. 2000). The combination of agroecological management and PES programs is essential to ensure ecological restoration in agroecosystems in order to safeguard socioeconomic demands. And the environmental gains promoted by

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agroforestry systems reinforce the importance of incentives provided by specific government regulations. Furthermore, the conversion of intensive systems into agroforestry production systems can reduce the trade-offs between the provision of ecosystem services and human activities, contributing to more robust PES schemes (Pissarra et al., 2021).

The projections provided in the SI scenario, with emphasis on medium-priority regions, demonstrate the conciliatory nature of this approach. The matrix for weighting this scenario considered the complexity and dynamics of water-land-food nexus uncertainty by proposing that the areas be equally prioritized in the advantage of water and soil conservation, such as ecological restoration and economic conditions through agroforestry. As a result, low-priority areas were also suppressed and, if conducted, the alternatives to prioritize areas of action in this scenario offer a path to improve multiple ecosystem services, since a nexus approach has been considered a fundamental and essential vehicle for the practical implementation of PES.

A predominance of medium priority areas over the PBSsp (~5189.31 km²) enables allocate resources and the prospect new signatories in an intermediary spatial and time priority scale. In addition, the concentration of rural properties distributed almost homogeneously in these areas, in the three projected scenarios, shows the progress of initiatives in the region and the engagement of local actors towards the ecological transition, since these regions do not represent a great risk to degradation and that ongoing projects gain strength in areas with diverse agricultural potential, which are less restrictive. However, the lower adherence of landholding in areas of extreme to high priority raises an alert to deepen the understanding of this gap and intensify efforts to cover these areas, from implementation to monitoring.

Vulnerable regions are more sensitive to disturbances and interactions in the environment, on the other hand, it is expected that the services provided through PES actions and agroforestry restoration will also result in greater benefits for ecosystem services. Agroforestry systems represent a great alternative to soil preservation (Kang and Akinnifesi, 2009). Overall, the agroforestry can reduce on average 65% of soil loss compared to conventional systems (Zhu et al., 2020). Béliveau et al. (2017) observed that a short-cycle cropping system had loss more than 40 g m⁻² of total soil loss, meanwhile the agroforestry system lost less than 5 g m⁻² with no significant difference

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from a mature forest. Moreover, soil loss in agroforestry systems can reach 2.69 Mg ha⁻¹year⁻¹, this represents a 37% decrease in soil loss compared to only crop cover, however the forest cover reduced the losses by 63% (Jinger et al., 2022).

Among the scenarios, the SII projected areas with low in greater expressiveness; followed by scenario SIII. This trend may reflect the categorization of basins into two large groups, sub-basin and catchment, by reducing the variability of management units, we mitigate possible anomalies, especially in water production. However, each HU has a specific contribution in the allocation of resources. Independent hydrological units such as catchments form a region where water from the hydrological cycle flows and has a direct effect on the infiltration/outflow ratio, the storage of water in the system and directly contributes to the flow of the river Costa et al. (2020). Therefore, the final product of the SII targets the headwater basins as critical areas for the management of the great Paraíba do Sul River Basin.

The low water flows in these regions represent a high priority for native vegetation conservation practices, the recovery of degraded areas, the conversion of land uses (more regenerative production systems) and the implementation of PES in order to ensure the availability water supply and remunerate, above all, the services provided in the headwater basins. Headwater catchemnts influence water quality and flow conditions of downstream water bodies (Andrade et al., 2020; Simedo et al., 2020). Thus, the activities implemented in these basins can, in addition to being prioritized, be better remunerated, since these benefits can be returned to the water treatment and supply systems and, consequently, to the final consumer. As a good example of socio-economic valuation, Pissarra et al (2021) provide a detailed and efficient inventory of compensation for water production in the 'Agriculture for Clean Water Yield' model, that range from 218.73 US\$/ha/year to 576.5 US\$/ha/year that could be increased by 30% of maximum compensation in vulnerability sectors.

Thus, we assume the relative importance of each territorial subunit, the HU, for an integrated and sustainable management of ecosystem services and the conversion of land use in PBSsp and VPP. Since 2018, PES values are calculated by multiplying the score attributed to conservation practices and land uses within the land property - environmental services index (ISA), by values ranging from R\$ 150.00 to R\$ 1000.00, considering the municipalities covered, the size of the rural module and the resources

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available (SIMA Nº 006/2018; 002/201). The programs cover four territorial units that are fundamental for the conservation of the biome: 1) São Luís do Paraitinga and Natividade da Serra counties; Environmental Protection Area São Francisco Xavier; Buffer Zone of the Bananal Ecological Station and Buffer Zone of the Itairu Nucleus of the Serra do Mar State Park, the largest biological corridor of the Atlantic Forest in Brazil. During 2017 to 2021, it is estimated that landholders receive US\$109.62/ha/year related to the Protection PES program (Lemos et al., 2023).

Despite the developed socioeconomic complexity, paying for specific actions may not be enough to leverage ecological restoration and agricultural transition in the region. Prioritizing PES' areas of action and financing, taking into account the effective costs for recovery and conversion of land use can be a game changer for intensifying agroforestry and ecological restoration initiatives as environmental assets for the producer. In these terms, PES - Catchment suggests coupling to the current CMA valuation system a trade-off coefficient for economic compensation to landowners depending on the priority degree of the region in which rural property is inserted and their associated conversation costs. Landscapes with a high degree of degradation or vulnerability, including the implications and management difficulties imposed by the biophysical characteristics of the land such as slope, soil type, rocky outcrops, among others, can increase the operating costs of soil conservation practices by up to 50%.

The initial implementation of agroforestry systems is up to 1.6 times more expensive than the costs of milk production in family farming [US\$ 7526.00 /ha/year], traditional in the region's livelihoods (IBGE, 2021a; IBGE, 2021b). The mean agroforestry implementation [US\$ 12,919.89/ha/year], and monitoring cost [US\$ 6,459.95/ha/year] are the economic factor measure valuation in PES – Catchment proposal, given US\$ hectare⁻¹ and the conversion rate US\$1.00=R\$3.87, according to Braccalioni et al., (2019) proposal. We assume a project duration of three years, starting by one year of AFS implementation and the second and third year of maintenance, and PES – Catchment also encourages incorporating the opportunity cost of implementing agroforestry systems to replace the predominant agricultural use in each UH.

Therefore, an average adjustment of 25% is suggested in the compensation of environmental services provided through agroforestry to rural producers allocated in

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extreme and high priority regions [R\$ AFS-ISA ha⁻¹ year⁻¹ * 1.25]. This is a way of encouraging the agricultural transition in these hydro-units, where the impact of patterns of land use and occupation are perceived with greater intensity, and consequently, fundamental for the conservation and provision of ecosystem services downstream, a direct link between landowners (producers) and the general population (consumers).

This approach mainly reinforces the incentive to convert from pasture to agroforest (opportunity cost) in the most vulnerable landscapes. Therefore, despite the SAF, at first glance, not being so attractive from an economic and social point of view, it increases the income that landowner receives from PES due to an effective compensation for the improvements achieved.

From a legal point of view, environmental suitability and environmental land deficit, concerning native vegetation conservation in rural properties, can also benefit from prioritizing areas, by favoring restoration combined with a production system - agroforestry. The Brazilian Forest Code - major Brazilian environmental legislation, establishes that the property owner must carry out protection conservation and restoration of native vegetation. Overall, 20% of rural properties total area must be maintained as a Legal Reserve (protection area), where induced restoration, natural regeneration or a combination of both must be carried out until 20% of the property is covered by legally reserved forest area (Nobre et al., 2019). In this approach, we provide a management tool that can identify key regions to enable, regulate and monitor plans for markets, products and forest services in the Atlantic Forest, since, is still incipient forest recomposition with native tree species for commercial purposes (Zakia, 2013).

Prioritizing areas for intervention also complement the PES scheme for crops in the agroforestry system for pre-conversion, i.e., the compensated benefits can also be scaled in time, over the course of execution phases and according to the priority level for watershed management. Decision makers can adopt this regulation measure to ensure the ongoing implementation and maintenance of target practices, as a motivation for farmers embrace SAF conversion. Moreover, active restoration projects can be costly and long-lasting, over 20 years at an average cost ~US\$ 2.1/ha thousand in the Atlantic Forest, and the economic value of naturally regenerating

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forests is often considerably lower than forestry-based-economic systems, as agroforestry (Bracalioni et al. 2019; 2020).

With PES-Catchment compensation and adequate implementation support, landowners could adopt agroforestry as part of their economic incomes to reduce costs while still delivering key environmental benefits and ecosystem services. Incorporating land use conflict as a measure of degraded areas, as in this proposal, it is a main driver for prioritizing strategic areas and reduce tenure-restoration tradeoffs within agricultural landscape. Also, ecosystem services related to soil conservation, as soil organic carbon can increase under agroecosystem compared to degraded pasture and intensive agriculture, however the CO₂ removal by protected areas is higher.

According to the Brazilian Greenhouse Gas Emissions and Removals Estimating System (SEEG, de Azevedo et al., 2018), degraded pasture and intensive agriculture was responsible by 65.7 Mt CO₂ equivalent in 2020, meanwhile agroecosystem remove around 50.6 Mt CO₂ equivalent and the carbon removal by protected areas was around 390 Mt CO₂ equivalent (SEEG, 2021). Furthermore, if Brazil correctly implement the ABC+ plan, until 2030 is estimated that with the implementation of 10 Mha of agroecosystems can lead to a mitigation of 37.9 Mt CO₂ equivalent, and if other practices the mitigation potential could be more than 1000 Mt CO₂ equivalent.

PES-Catchment modeling has limitations regarding incorporating carbon balances, even indirectly benefited by leveraging reforestation activities or conservation of native vegetation, these are not accounted for in this approach. Growing demand for voluntary carbon markets and net zero activities are an important environmental asset and are on the radar of green economic transitions. It is important to point out that for these mechanisms the reward is for the forest standing, that is, the greater the risk of deforestation, the greater the interest in implanting carbon credits in the area to protect the forest. For example, properties close to the conversion unit may not be as attractive to these programs, as well as properties that are in the process of recovery. Forthcoming models simulate growth and crop production of native species to windage of projections scenario, generating data on growth, carbon, biomass and production, they can carry out surveys correlating the studied species and climate change (Abdo, 2021).

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Another important aspect to highlight is that although ecological indices and other landscape metrics, such as connectivity of fragments, play a crucial role in advancing the conservation of biodiversity and functional groups (Jöks et al., 2023; Reis Medeiros et al., 2022; ; Zhao et al., 2023) ; the objective of PES – Catchment is in fact to maximize the benefits associated with water and soil, as they constitute base compartments and support ecosystem services for a multitude of other ecosystem functions. Following the spatial model of de Mendonça et al. (2022), agroforestry can be implemented through buffer zones around forest remnants, to reduce edge effect and improve biological corridors and stepping stones in an agricultural matrix. Diversified farming systems have 26% higher species richness than simplified systems (Sánchez et al., 2022).

When prioritizing areas, a one-way model cannot be suitable for all purposes, it could simply de complexity of environment dimensions that is important to ecological balance. And therefore, we keep the three alternative scenarios to ensure the greatest representation in the decision-making process to change the landscape matrix, advance in agroforestry productive chain and agricultural transition in order the sustainability of agroecosystems. However, the proposed final product is a graphical representation for as a support decision-making tool according to PES- Catchment approach. In this final map it is possible to highlight the areas of greatest conservation urgency as well as macro regions adjacent to the main water bodies in the entire PBSsp. And it strongly indicates the criticality for the recovery of the headwater areas and in the contribution zone upstream of the Funil Reservoir.

The medium and low priority along the Paraíba do Sul River course, especially in the flatter areas, also coincide with the urban agglomerations. This is a particular challenge, Mariano et al., 2022 when proposing important broad-scope public policy targeting the protection of water resources, highlighted the implementation of land use and cover plans that respect land capability, as the potential use of soil. Considering the multifunctionality of cultivated land in peri-urban agriculture areas, agroforestry systems have a positive implication as a productive interface and green solution for adaptation to climate change (Burgess et al. 2022).

Designing, implementing and monitoring PES programs is a challenging undertaken in multiple spheres, identify priority areas it is a tool key to improve any

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environmental & socio-economic strategies, as well implement PES programs either upscaling landscape restoration. In PES – Catchment it is encouraged agroforestry-based restoration actions as an agent of transformation and transition of socio-economic and agricultural matrix, and thereby ensuring that ecosystem services are available for future generations.

5. Conclusion

When prioritizing areas, a one-way model cannot be suitable for all purposes, thus three alternative scenarios provided in PES-Catchment approach addressed crucial dimensions in order to promote multiple ecosystem services conservation (water & soil), landscape restoration and small livelihoods improvement by agroforestry and optimizing payments for environmental services. PES-Catchment highlights watershed as a large-scale interaction of the water-land-tenure-restoration nexus and recognizes the contribution of farmers and landowners in providing environment services/benefits and propose an adjustment coefficient by compensating according to the priority level. Despite the great achievements, landholding distribution of private rural properties registered in Conexão Mata Atlântica PES – programs across the Paraíba do Sul Valley shows a trade-off between the most vulnerable areas and where the PES are actually being carried out, and therefore, it is essential to optimize and intensify efforts to cover these areas, from implementation to monitoring. Headwater basins located in the upstream Funil reservoir region, and at the hydrological contribution areas of Paraitinga, Paraibuna and Jaguari/Buquira rivers are critical to ecosystem services conservation, regarding water availability and soil degradation and, therefore, priority areas for payments for ecosystem services programs and landscape restoration. PES – Catchment products and insights are willing to be validated and adjusted in decision-making process - policies and governance, towards agricultural transition and agroecosystems sustainability.

Acknowledgments

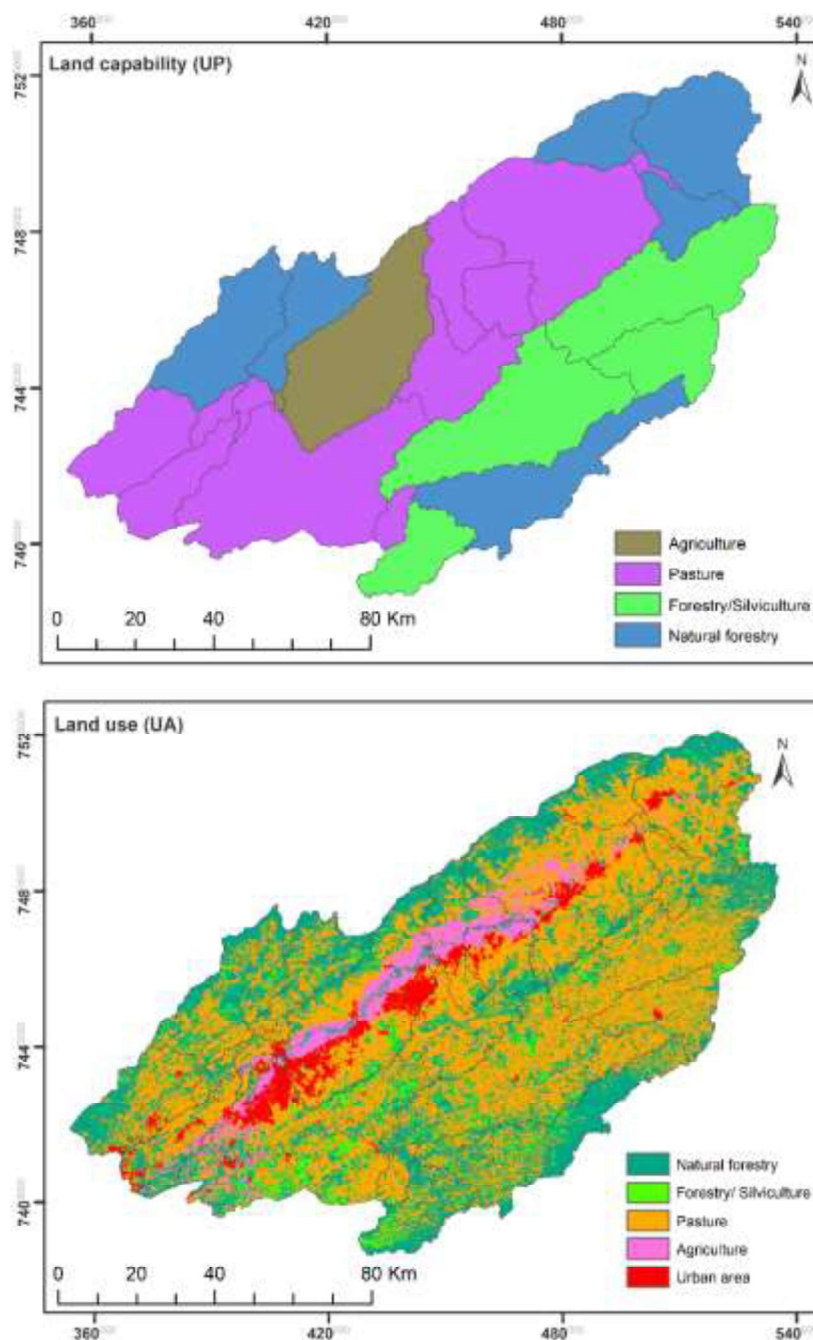
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Appendix

A 1. Land degradation component: Factors that constitutes the environmental land use conflict analysis, (UP) and (UA).



A 2. Factors multicriteria decision analysis: factor class ratings; ranking of the mutual importance of each factor, respective aggregating component and consistency index.

Component	Factor	Class	Ratings Rank of Importance	Weight	Consistency Index
Watershed	Hydrological	Catchment	9	0.857	-

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management	delineation	Sub-basin	3	0.143	
		Dolomite limestone	6	0.315	
		Sandstone, Claystone, Conglomerate, Sand deposit,	5	0.243	
	Geology (Litology type)	Metasandstone, Shist, Metarythmite	4	0.173	0.015
		Granodiorite, Tonalite	3	0.120	
		Biotite, Granite, Monzogranite, Quartz monzodiorite, Tiguaité	2	0.084	
		Gneiss, Migmatite, Myolite, Paragneiss	1	0.064	
Landscape vulnerability					
		Acrisols	9	0.297	
		Cambisols	8	0.231	
		Plinthicsols	7	0.168	
	Soil (orders)	Gleysols	6	0.118	0.013
		Leptsols	5	0.082	
		Histosols	4	0.059	
		Ferralsols	3	0.045	
Water availability	Q 7, 10 (m3s)	6.76 - 33.13	9	0.463	0.009
		33.14 - 162.05	7	0.255	
		162.06 - 358.36	5	0.118	
		358.37 - 560.53	4	0.091	
		560.54 - 753.91	3	0.072	
Land degradation	Land use conflict	Class 3	9	0.627	0.017
		Class 2	5	0.203	
		Class 1	3	0.108	
		Expansion (agriculture/urban)	1	0.061	

A 3. Priority class

	Area (km ²)	SI	SII	SIII	Mean	STD ±	CV%
Priority class	Low	1822.45	4440.20	3734.51	3332.39	1105.87	0.332
	Average	6472.61	4092.04	5003.27	5189.31	980.73	0.189
	High	2928.91	2681.51	2456.56	2688.99	192.91	0.072
	Extreme	95.78	105.94	125.38	109.03	12.28	0.113

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Supplementary Material

Supplementary Materials

SM 1. Main biophysical characteristics of hydrological units.

ID	Hydrological unit	Latitude	Longitude	Area (km ²)	Mean Slope(%)	Mean elevation (m)	Land use				
							Agriculture	Forestry	Pasture	Pasture/Silviculture	Urban area
1	Catchment	-22.56	-45.1	341.98	31.65	903.44	3.67	158.17	172.96	4.41	2.54
2	Sub-basin	-22.56	-44.85	730.66	27.21	785.92	9.91	271.32	408.87	18.58	21.59
3	Sub-basin	-22.64	-44.97	32.17	20.00	601.46	1.35	4.52	25.59	0.36	0.35
4	Catchment	-22.74	-44.89	260.92	27.37	884.03	1.00	89.12	165.74	4.05	1.01
5	Sub-basin	-22.77	-45.19	1304.96	19.52	744.84	113.39	337.79	761.78	21.43	70.45
6	Catchment	-22.93	-45.34	278.54	14.88	677.68	52.53	61.75	127.26	7.66	29.35
7	Sub-basin	-22.87	-45.45	393.77	15.88	721.28	101.85	122.43	142.84	7.25	19.34
8	Catchment	-22.9	-44.93	1019.04	24.26	1097.68	3.60	339.42	631.71	43.48	0.54
9	Catchment	-23.07	-44.93	464.21	23.81	1031.56	2.37	101.21	349.48	6.75	4.21
10	Catchment	-23.1	-45.45	477.91	23.76	744.32	5.69	133.60	311.73	15.11	11.78
11	Catchment	-22.97	-45.82	414.18	29.69	847.83	2.18	210.16	180.55	13.63	7.45
12	Sub-basin	-23.05	-45.69	1153.91	13.23	653.57	207.58	245.44	457.57	39.45	203.73
13	Sub-basin	-23.17	-45.9	10.88	5.78	570.09	2.89	1.47	0.37	0.01	6.14
14	Sub-basin	-23.17	-45.97	77.92	15.80	607.90	12.85	14.32	44.94	0.71	5.10
15	Catchment	-23.02	-46.02	686.80	28.30	857.46	1.16	373.26	282.97	28.69	0.33
16	Catchment	-23.2	-46.06	85.94	20.26	667.39	0.51	34.60	50.36	0.19	0.28
17	Catchment	-23.27	-46.25	523.86	19.93	756.61	1.14	238.05	254.47	9.26	20.60
18	Catchment	-23.36	-46.16	370.81	15.36	678.24	27.77	113.29	186.27	6.31	37.04
19	Sub-basin	-23.21	-45.31	1182.39	24.40	905.02	3.03	376.65	729.55	70.24	2.92
20	Sub-basin	-23.44	-45.61	100.90	20.81	772.44	0.34	29.89	65.36	4.44	0.84
21	Sub-basin	-23.36	-45.84	1496.27	20.15	720.35	115.22	426.22	660.48	162.93	130.94
22	Catchment	-23.35	-45.25	835.56	26.49	958.47	1.32	522.92	266.22	43.64	0.83
23	Catchment	-23.52	-45.55	361.99	23.74	800.48	0.60	225.50	100.62	34.79	0.10

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ID	Soil (km2)										Geology (km2)					
	Acrisols	Cambisols	Gleysols	Ferralsols	Leptsols	Histosols	Plinthosols	Lito_1	Lito_2	Lito_3	Lito_4	Lito_5	Lito_6			
1	190.14	190.14	7.69	138.35	2.03			218.64	73.58			48.12				
2	125.44	125.44	2.35	585.23	0.38			423.22	146.17	122.98		25.73				
3			1.74	30.12				21.07	1.67	1.15		6.14				
4	23.38	148.25	0.28	88.26				21.74	68.64	159.61		10.95				
5	168.29	238.67	133.10	694.62	5.06			521.54	181.15	86.23		486.42	2.27			
6	106.71		43.41	108.47				26.79	26.11	63.04		159.05				
7	36.06	100.17	77.82	163.49	0.26			132.93	6.54	23.25		188.27	33.55			
8	92.97	730.99	1.68	192.54				398.95	427.03	193.05						
9		334.49	7.20	102.74	16.19			307.79	86.93	69.49						
10	375.60		13.75	79.91				282.14	30.55	0.05		77.00	2.29			
11	67.70	89.45	1.07	246.65	3.07			312.78	75.34	2.67		0.30				
12	160.44	133.84	195.43	493.73	2.64			233.55	92.68	8.61		675.42	88.39			
13			4.27	0.04				0.82				9.59				
14	42.04		12.74	22.45				27.38	7.30			42.54				
15	243.94	153.18	0.29	259.18	13.63			240.67	231.85	190.32						
16	62.41		0.66					41.41	15.59			2.02				
17	277.98	115.78	3.32	72.20				93.17	151.43	6.64		54.75				
18	299.43	16.42	27.10	0.02				165.93	28.96			175.93				
19	170.44	589.08	2.12	382.39				404.91	625.85	119.30						
20	45.36	27.66		16.50				72.02	21.04							
21	1062.85	141.98	72.31	91.40		0.89		718.65	159.53	137.39		185.37	252.31			
22	39.78	500.54		251.81	0.80			513.75	288.32							
23	20.97	87.35	0.37	180.10	0.17			296.31	9.24							

* Lito_1- Gneiss, Migmatite, Myolite, Paragneiss; Lito_2- Biotite, Granite, Monzogranite, Quartz monzodiorite, Tiguaite; Lito_3- Granodiorite, Tonalite; Lito_4- Metasandstone, Shist, Metarythmite; Lito_5- Sandstone, Claystone, Conglomerate, Sand deposit; Lito_6- Dolomite limestone.

ID	Conflict class 1	Conflict class 2	Conflict class 3	Agricultural expansion
1	4.38	172.76	3.58	160.75
2	18.34	409.04	9.80	292.76
3	1.34	0.49		30.34
4	4.14	165.65	0.99	90.14
5	112.87	70.64	0.01	1121.17
6	52.71	29.36		196.47
7	101.81	19.30		272.48
8	632.03	3.61	0.54	382.52
9	350.38	2.39	4.21	107.04
10	5.82	11.72		460.36
11	13.59	180.44	2.13	217.63
12	203.60	0.18	0.00	949.84
13	6.06	0.05	0.00	4.76
14	12.83	5.09		60.00
15	28.49	282.93	1.13	373.43
16	0.51	0.36		85.07
17	1.09	20.53		501.61
18	27.40	36.98		306.26
19	729.67	3.00	2.93	446.79
20	0.35	0.86		99.64
21	114.13	131.04		1250.47
22	43.69	265.94	1.28	523.88
23	100.21	0.61	0.10	260.47

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¹ Este capítulo corresponde ao artigo científico para submissão à revista [Ecosystem Services](#)

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CAPÍTULO 5 - Considerações finais

A complexidade multifuncional dos agroecossistemas é um desafio para a expansão das ações estratégicas e políticas públicas em restauração ambiental e manutenção dos serviços de ecossistema. No mesmo sentido, a segurança hídrica nas bacias hidrográficas e a sustentabilidade dos sistemas de produção dependem diretamente do manejo e uso do solo exercido na paisagem, e os programas de pagamentos por serviços ambientais fornecem uma rota viável para reduzir os *trade-offs* de restauração dos ecossistemas dentro das propriedades rurais. Contudo, os mecanismos de compensação socio-econômicos para os prestadores de serviços ambientais em terras privadas ainda carecem de direcionamento e efetividade em seu delineamento (valoração, implementação e monitoramento); incluindo lacunas claras de embasamento técnico e científico quanto a elaboração de critérios e indicadores a serem avaliados.

Para contribuir com o planejamento estratégico e a implantação das políticas públicas de incentivo a manutenção dos serviços ecossistêmicos e desenvolvimento sustentável na Bacia Hidrográfica do Rio Paraíba do Sul, o desenvolvimento deste trabalho e pesquisa entrega um instrumento de suporte a decisão e um protocolo de pagamentos por serviços ambientais com ênfase na conservação do solo e produção de água. A abordagem consistiu na modelagem da vulnerabilidade da paisagem, do fluxo de serviços hidrológicos e de alvos espaciais para otimizar e direcionar as ações de conservação com foco no incentivo aos serviços ambientais adotados em micro-bacias vulneráveis, ou seja, onde os impactos das atividades humanas exercem a maior pressão sobre os SE (provisão, regulação e suporte).

A análise integrada da vulnerabilidade ambiental e da disponibilidade hídrica da bacia hidrográfica descrita ao longo dos capítulos, destacou cinco micro-bacias [3, 13, 14, 16, 20] em estresse hídrico considerando a demanda hídrica per capita inferior a 1000 m³/hab.ano. A modelagem dos fluxos de vazão também fornece métricas e comparativo real do potencial de produção de água nas micro-bacias que também podem ser convertidos em valoração e monitoramento de PSA. Os estudos também evidenciaram bacias críticas a segurança hídrica e de maior vulnerabilidade nas cinco

zonas hidrológicas delimitadas: Setor montante Reservatório do Funil [micro-bacia 1,4, 8]; Setor Jaguari / Buquira [micro-bacia 11, 15, 14, 16, 17 e 18]; Setor Paraitinga [micro-bacia 9]; Setor Paraibuna [micro-bacia 23] e Setor Médio Curso [micro-bacias, 22,23]. Um balanço hídrico climatológico em uma séria climática de 35 anos, evidenciou tendências sazonais de menor disponibilidade hídrica regional à nível de água no solo entre a maio a setembro, com período crítico de déficit hídrico em agosto. E este padrão se agrava nas unidades hidrológicas na vertente esquerda do Rio Paraíba do Sul, onde também ocorre o maior aglomeramento urbano.

Com este estudo, o diagnóstico da vulnerabilidade ambiental da paisagem quanto ao potencial de degradação do solo seja por risco naturais ou uso acima da capacidade de suporte nas micro-bacias, expõe o efeito da fragilidade da terra sobre a prioridade e complexidade operacional para recuperação (contenção de erosão) ou conversão do uso do solo (transição para sistemas de produção mais sustentáveis. E aqui destacamos a principal contribuição deste trabalho para as ações e políticas públicas em curso e futuras, estabelecer a valoração e compensação socioeconômicas aos aderentes (produtores participantes) em função do nível de prioridade (potencial de degradação e criticidade hídrica) em que a propriedade rural se localiza. Assim, o coeficiente de *trade-off* econômico [R\$ AFS-ISA ha-1 year-1 * 1.25] integrado a uma estrutura de PSA, é uma forma de engajar e tornar atrativa a adoção e integração de práticas agrícolas mais sustentáveis pelos produtores, que tendem a ser mais honerosas e complexas, pois elevam os custos operacionais e implicam em maior esforço na implantação e manutenção. A segmentação espacial em áreas prioritárias também pode direcionar os projetos socio -ambientais em escala temporal, delimitando fases de execução conforme a prioridade das áreas, considerando ações emergenciais nas áreas de extrema e alta prioridade, e num segundo momento, nas áreas de prioridade subsequentes.

Por fim, o conffractal entre as áreas prioritárias projetadas e a localização das propriedades rurais atualmente contempladas nas modalidades de PSA no âmbito do projeto “Conexão da Mata Atlântica”, que vem conduzindo ações de conservação e proteção da Mata Atlântica e implementou programas de PSA ao longo de toda a BHRPS e no Vale do Paraíba, é recomendado para o direcionamento futuro de alocação de recursos e esforços cobertos pelo projeto. Adicionalmente, estes insights

podem colaborar para a avaliação da efetividade, desafios e sucesso das ações realizadas durante o projeto.

Nesta abordagem, fornecemos uma ferramenta de gestão que pode identificar regiões-chave para viabilizar, regular e monitorar os programas de PSA na porção paulista da Bacia Hidrográfica do Rio Paraíba do Sul. Todavia, é esperado que esta abordagem possa ser replicada e aplicada a nível municipal e interestadual (Rio de Janeiro, Minas Gerais), para direcionar outras políticas públicas para fortalecimento de cadeias agrícolas sustentáveis, mercado, produtos e serviços florestais, incluindo a exploração cênica da paisagem e turismo rural, bem como alavancar a recuperação da Bacia Hidrográfica do Rio Paraíba do Sul.

Adicionalmente, estudos concomitantes a esta tese, foram desenvolvidos e publicados dois artigos em revistas de alto fator impacto também abordando a modelagem dos agroecossistemas para priorização de áreas, com ênfase na conservação de fragmentos florestais e implementação de sistemas agroflorestais na restauração da paisagem em regiões florestas estacionais semidecíduais, ecótipo de transição Mata Atlântica e Cerrado:

i) **de Mendonça, G. C.**, da Costa, L. M., Abdo, M. T. V. N., Costa, R. C. A., Parras, R., de Oliveira, L. C. M., ... & Pacheco, F. A. L. (2023). Multicriteria spatial model to prioritize degraded areas for landscape restoration through agroforestry. *MethodsX*, 102052. <https://doi.org/10.1016/j.mex.2023.102052>

ii) **de Mendonça, G.C.**; Costa, R.C.A; Parras, R; de Oliveira, L.C.M; Abdo, M.T.V.N.; Pacheco, F.A.L.; Pissarra, T.C.T. Spatial indicator of priority areas for the implementation of agroforestry systems: An optimization strategy for agricultural landscapes restoration. *Science of The Total Environment*, 839: 156185. <https://doi.org/10.1016/j.scitotenv.2022.156185>

Isto reforça os ganhos esperados a partir da aplicação e divulgação dos produtos gerados por esta tese e ressalta a importância da continuidade espacial e temporal destes estudos na Bacia Hidrográfica do Rio Paraíba do Sul e da replicabilidade em agroecossistemas diversos, considerando as agendas e metas nacionais e globais de conservação e desenvolvimento sustentável.