

**Universidade de Évora - Escola de Ciências e Tecnologia**

**Mestrado em Biologia da Conservação**

Dissertação

**Restauro Ecológico de Galerias Ripícolas em Sistemas  
Produtivos do Alentejo: Desafios e Soluções num Contexto  
de Escassez Hídrica**

Gabriela Santos Gomes

Orientador(es) | Paula Matono  
Carla Pinto Cruz

Évora 2025

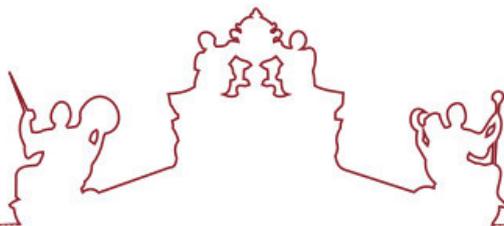
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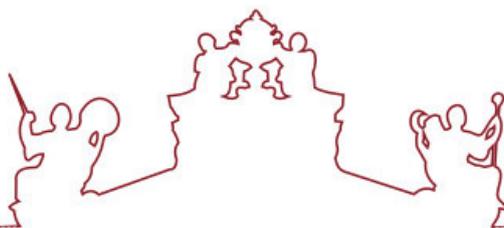
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# Índice

|                                                 |    |
|-------------------------------------------------|----|
| Resumo .....                                    | 2  |
| Abstract .....                                  | 3  |
| Enquadramento Geral .....                       | 4  |
| Artigo Científico .....                         | 8  |
| Abstract.....                                   | 8  |
| 1. Introduction .....                           | 9  |
| 2. Conceptual & Policy Background .....         | 11 |
| 3. Case Study: Enxoé watershed, Portugal.....   | 12 |
| 3.1 Study area .....                            | 12 |
| 3.2 Ecological characterization .....           | 14 |
| 3.3 Setting objectives .....                    | 17 |
| 4. Framework for Climate-Smart Restoration..... | 19 |
| 4.1 Key strategies description .....            | 19 |
| 4.2 Decision Support Tools (DSTs).....          | 20 |
| 5. Discussion.....                              | 23 |
| 6. Conclusions .....                            | 25 |
| 7. References.....                              | 27 |
| 8. Annexes .....                                | 35 |
| Considerações Finais .....                      | 37 |
| Referências .....                               | 39 |

# **Restauro Ecológico de Galerias Ripícolas em Sistemas Produtivos do Alentejo: Desafios e Soluções num Contexto de Escassez Hídrica**

## **Resumo**

Os cursos temporários mediterrânicos encontram-se cada vez mais ameaçados pelas alterações climáticas e intensificação agrícola. Contudo, continuam sub-representados na prática e política de restauro ecológico. Esta dissertação propõe um modelo de planeamento adaptado a estes ecossistemas, integrando quatro estratégias-chave para o restauro: (1) caracterização ecológica; (2) identificação de geosséries; (3) definição do ecossistema de referência e objetivos; (4) restauro adaptativo e *climate-smart*. O caso de estudo da bacia hidrográfica do Enxóe, no sul de Portugal, constituiu a base para o desenvolvimento deste modelo e criação de duas ferramentas de suporte à decisão, demonstrando o valor ecológico da intermitência, destacando o papel da vegetação ripícola e reforçando a sua importância para os agroecossistemas face à escassez hídrica. Aplicada à fase de pré-implementação, esta abordagem demonstra que o planeamento é essencial para uma gestão adaptativa e destaca os cursos temporários como infraestruturas naturais essenciais para a resiliência climática e desenvolvimento agrícola sustentável.

**Palavras-chave:** rios temporários mediterrânicos; resiliência climática; vegetação ripícola.

# **Ecological Restoration of Riparian Galleries in Alentejo Production Systems: Challenges and Solutions in a Context of Water Scarcity**

## **Abstract**

Mediterranean temporary rivers are increasingly threatened by climate change and agricultural intensification. However, they remain underrepresented in ecological restoration practices and policies. This dissertation proposes a planning framework tailored to these ecosystems, integrating four key strategies for restoration: (1) ecological characterization; (2) geoseries identification; (3) reference ecosystem and objective setting; (4) adaptive and climate-smart restoration. The case study of the Enxoé River Basin, in southern Portugal, was the basis for the development of this framework and the creation of two decision support tools, demonstrating the ecological value of intermittency, highlighting the role of riparian vegetation, and reinforcing its importance for agroecosystems in the face of water scarcity. Applied to the pre-implementation phase, this approach shows that planning is essential for adaptive management and highlights temporary rivers as vital natural infrastructures for climate resilience and sustainable agricultural development.

**Keywords:** Mediterranean temporary rivers; climate resilience; riparian vegetation

## Enquadramento Geral

Os rios temporários mediterrânicos são ecossistemas de elevado valor ecológico e funcional, embora frequentemente desvalorizados na gestão e na política ambiental (Nikolaidis et al., 2013). Estes sistemas, também designados como rios intermitentes ou efémeros, são característicos das regiões áridas e semiáridas do sul da Europa e distinguem-se por um regime hidrológico alternado entre fases com e sem caudal, condicionado pela sazonalidade climática (Acuña et al., 2017; Tooth, 2000). A sua intermitência, muitas vezes percecionada como uma limitação, constitui na realidade uma das principais fontes da sua resiliência ecológica (Leigh et al., 2016). No entanto, encontram-se hoje entre os ecossistemas mais ameaçados pelas alterações climáticas e intensificação agrícola (Lorenz et al., 2023).

A variabilidade hidrológica natural dos rios temporários influencia fortemente o gradiente de vegetação ripícola e a estrutura das comunidades associadas (Sánchez-Montoya et al., 2022). As galerias ripícolas constituem, assim, ecótonos de elevada variabilidade espacial e temporal, dependentes das condições geomorfológicas, bioclimáticas e do uso do solo (Riis et al., 2020). Esta plasticidade ecológica torna-as elementos-chave para a adaptação às alterações climáticas (Capon et al., 2013). A vegetação ripícola assegura múltiplas funções ecológicas e serviços de ecossistema essenciais: regula o microclima, estabiliza margens, retém sedimentos, filtra poluentes, sequestra carbono e mantém a conectividade ecológica, permitindo a coexistência de espécies aquáticas e terrestres (Stubbington et al., 2020). Nos sistemas agrícolas, desempenha ainda um papel relevante ao suportar serviços como a polinização, dispersão de sementes e controlo biológico de pragas (Kaletová et al., 2019). Desta forma, a vegetação é um fator determinante não só da hidromorfologia dos rios, como também é um importante indicador das pressões antrópicas exercidas sobre o ecossistema, sendo por isso uma componente-chave na avaliação e monitorização do estado ecológico dos rios (Del Tánago et al., 2021). No entanto, apesar da sua importância, estes ecossistemas permanecem frequentemente subvalorizados, sobretudo durante as fases secas, sendo muitas vezes considerados áreas de baixo valor biológico, estético e produtivo (Steward et al., 2012).

A bacia do Mediterrâneo, que se estende desde a Península Ibérica até ao Médio Oriente e ao Norte de África, é atualmente considerada um dos principais hotspots de biodiversidade do planeta, destacando-se pela elevada diversidade de espécies endémicas, incluindo cerca de 13 000 espécies de plantas (4,3% do total mundial) e 235 espécies de vertebrados (0,9%) (Myers et al., 2000). É também uma das regiões mais vulneráveis às alterações climáticas, registando uma taxa de aquecimento 20% superior à média global, com previsões que apontam para aumentos até 50% durante o verão e até 100% em áreas terrestres do norte da bacia (Lionello & Scarascia, 2018). O aumento da temperatura, associado à redução significativa da precipitação e à intensificação de fenómenos extremos, como secas e cheias, tem agravado a escassez hídrica e afetado

profundamente a dinâmica dos ecossistemas terrestres e aquáticos (Tramblay et al., 2020). Em 2022, estimou-se que cerca de 41% da população europeia foi afetada pela escassez de água, número que se prevê aumentar nas próximas décadas (European Environmental Agency, 2025).

A agricultura é um dos setores com maior impacto nos recursos hídricos, na Europa é responsável por cerca de 59% do consumo total de água, grande parte perdida por evaporação ou absorvida pelas culturas (European Environmental Agency, 2024). Embora o número de explorações agrícolas tenha diminuído, a superfície agrícola utilizada (SAU) e o seu valor económico têm aumentado, o que traduz uma intensificação dos sistemas produtivos, particularmente no sul da Europa, com destaque para culturas de elevado valor económico e de grande exigência hídrica, como olivais, amendoais e vinhas (Eurostat, 2023). Esta transição para modelos intensivos e superintensivos implica maior mecanização, uso intensivo de agroquímicos e consumo elevado de água, o que conduz à degradação dos solos, perda de conectividade ecológica e redução da resiliência dos ecossistemas perante o stress climático (Cerdà et al., 2021; Jie et al., 2002). Face a este cenário, impõe-se a necessidade de abordagens integradas e multidisciplinares para a gestão dos ecossistemas mediterrânicos, que conciliem a conservação da biodiversidade com a sustentabilidade económica e social, promovendo o equilíbrio entre a produtividade agrícola e a conservação ambiental.

Neste cenário, o restauro ecológico surge como uma ferramenta fundamental para mitigar impactos e recuperar a funcionalidade dos rios temporários mediterrânicos. Define-se como o conjunto de ações que visam a recuperação substancial de um ecossistema, devolvendo-lhe estrutura, função e resiliência, de acordo com um modelo de referência apropriado (Gann et al., 2019). No contexto mediterrânico, esta tarefa exige uma abordagem que reconheça o valor ecológico da intermitência e integre simultaneamente as dimensões políticas e socioeconómicas a diferentes escalas (europeia, nacional e local). Assim, o restauro das galerias ripícolas não deve ser visto como uma restrição à produção agrícola, mas como um investimento estratégico e uma oportunidade para a sustentabilidade produtiva e ecológica das paisagens.

No plano político europeu, de forma geral, verifica-se um avanço progressivo no reconhecimento da importância do restauro ecológico e da gestão sustentável dos recursos hídricos. A Diretiva-Quadro da Água (2000/60/CE) estabeleceu a meta de alcançar o “bom estado ecológico e químico” das massas de água dos Estados Membros, embora apenas 37% das massas de água superficiais da Europa tenham cumprido esse objetivo em 2021 (European Environmental Agency, 2024; European Parliament & Council, 2000). Mais recentemente, a Estratégia de Biodiversidade para 2030 e a Lei do Restauro da Natureza vieram reforçar esse compromisso definindo metas vinculativas para restaurar ecossistemas e habitats degradados, e promover a reabilitação hidromorfológica e a remoção de barreiras fluviais com o objetivo de atingir pelo menos 25 000 km de rios de curso livre (European Commission, 2020; European Parliament & Council, 2024). De igual modo, a Estratégia Europeia para a Resiliência Hídrica define como metas o restauro e proteção do

ciclo da água (incluindo a adoção de práticas *water-smart*), a construção de uma economia inteligente para a gestão dos recursos hídricos, e a garantia de disponibilidade deste recurso para a população e capacitar os cidadãos para a resiliência hídrica (European Commission, 2025a). Em Portugal, a operacionalização destas metas europeias tem avançado, nomeadamente, através do Plano Nacional de Restauro da Natureza (PNRN), que, apesar de ainda se encontrar em delineamento, dá particular ênfase ao restauro de habitats degradados e à conservação da biodiversidade com metas específicas que incorporam os rios e a sua conectividade (Presidência do Conselho de Ministros, Economia, Ambiente e Energia e Agricultura e Pescas, 2024).

Apesar deste enquadramento, a aplicação prática continua fortemente orientada para rios permanentes, sem uma definição operacional clara de “rio temporário” (Nikolaidis et al., 2013). Esta lacuna conduz frequentemente à adoção de práticas de gestão inadequadas que ignoram a temporalidade natural destes sistemas (Larned et al., 2010). Ainda assim, diversos projetos demonstram o potencial do restauro adaptado a condições locais, como: o LIFE Riparia-Ter em Espanha, focado no controlo de espécies invasoras e plantação de espécies nativas; o LIFE Saramugo em Portugal, com o objetivo de conservar a espécie *Anaocypris hispanica* e o seu habitat; e o projeto português de Valorização e Adaptação do Ribeiro de Aveiras às Alterações Climáticas, que aplicou técnicas de bioengenharia para estabilizar margens e reduzir os efeitos de cheias (Câmara Municipal de Azambuja, 2020; Matono et al., 2019; Oficina técnica LIFE + Natura Riparia-Ter, 2013). Para além destes exemplos, destacam-se ainda o projeto RIVEAL, que avalia os serviços de ecossistema prestados pelas galerias ripícolas e projeta a sua evolução sob diferentes cenários climáticos e de gestão em Portugal, e o MERLIN, que promove a renaturalização de ecossistemas de água doce através da aplicação e expansão de soluções baseadas na natureza em vários contextos europeus (Aguiar et al., 2022; MERLIN Consortium, 2023).

Estes exemplos demonstram que o restauro, quando adaptado às condições locais, pode aliar benefícios ecológicos e socioeconómicos. Contudo, a integração dos diferentes atores desde o início dos projetos — autarquias, associações, comunidades locais e agricultores — é essencial para o sucesso das intervenções (Gornish et al., 2024). Neste sentido, a Política Agrícola Comum (PAC) desempenha um papel determinante ao condicionar subsídios a práticas sustentáveis e apoiar os agricultores através de incentivos e financiamentos específicos (European Commission, 2025b).

Deste modo, é evidente que, embora os rios temporários mediterrâneos enfrentem pressões crescentes, são precisamente estes ecossistemas que oferecem soluções naturais para reforçar a resiliência climática e sustentabilidade agrícola. Apesar do aumento da literatura sobre restauro ecológico e políticas ambientais europeias, persiste uma lacuna na integração e na aplicação prática desse conhecimento no contexto dos ecossistemas temporários (Leigh et al., 2016). A informação disponível encontra-se frequentemente dispersa e orientada para sistemas permanentes, o que limita a sua transposição para realidades semiáridas, como o sul da Península Ibérica (Munné et al., 2021). Assim, torna-se essencial realizar uma revisão crítica e sistematização aplicada do conhecimento

existente, de forma a construir um modelo de planeamento adaptado às condições ecológicas, climáticas e socioeconómicas da região.

É neste contexto que se insere o trabalho desenvolvido nesta dissertação. O objetivo central consiste em propor um modelo de planeamento para o restauro em rios temporários, especificamente em contextos agrícolas mediterrânicos. O trabalho emerge da análise do caso de estudo da bacia hidrográfica do rio Enxoé, realizado no âmbito do contrato Interadministrativo de Cooperação celebrado entre a Agência Portuguesa do Ambiente (APA) e a Universidade de Évora para os estudos de reabilitação de cursos de água na região hidrográfica do Guadiana em clima de escassez hídrica, integrado no Programa Operacional Regional do Alentejo 2014-2020.

Em alternativa às orientações de restauro convencionais, centradas na monitorização pós-implementação — frequentemente limitada pela ausência de dados ou pela falta de conhecimento ecológico consolidado (Stubbington et al., 2017) —, a proposta apresentada privilegia o planeamento prévio como etapa essencial para uma gestão adaptativa eficaz. Pretende operacionalizar o conhecimento ecológico e político existente em orientações práticas antes da execução das intervenções, assegurando que estas possam ser ajustadas de forma dinâmica aos contextos ecológicos, climáticos e sociopolíticos, mesmo na ausência de séries de monitorização longas.

Em suma, o trabalho desenvolvido pretende potenciar a operacionalização de planos de restauro da natureza para cumprir as metas europeias ao apresentar uma ferramenta técnico-científica de apoio à decisão, adaptada à realidade dos rios temporários mediterrânicos. O modelo propõe quatro *Key Strategies for Climate-Smart Restoration* e oferece uma abordagem escalável e replicável para a gestão e restauro destes ecossistemas com base no caso de estudo do rio Enxoé.

## Artigo Científico

# Climate Resilience by Design: A Framework for Scalable Restoration of Temporary Rivers in Mediterranean Agroecosystems

### Abstract

As climate change intensifies and temperatures rise, Mediterranean agroecosystems are becoming increasingly vulnerable to water scarcity and habitat degradation, reinforcing the need to restore freshwater systems to sustain essential ecosystem services. In semi-arid regions, temporary rivers play a central ecological role yet are often degraded and undervalued, particularly during dry phases, as agricultural intensification and water demands increase.

To address these challenges, we propose an evidence-based planning framework that positions ecological restoration as a primary mechanism for building climate resilience in Mediterranean rivers. Based on the analysis of the Enxoé watershed case study, a temporary sub-basin of the Guadiana River in southern Portugal, the framework is structured around four key strategies for climate-smart restoration: (1) ecological characterization, (2) geoseries identification, (3) reference ecosystem and objective setting, and (4) adaptive and climate-smart restoration. Enxoé field surveys and spatial analyses provided the empirical basis for these strategies and two decision-support tools were produced to help translate diagnostic insights into tailored restoration actions.

The strategies are supported through a legal and governance contextualization that links ecological conditions to European policy instruments, such as the EU Nature Restoration Law, the Water Framework Directive, and the Common Agricultural Policy. Together, they translate ecological and socioeconomical evaluations into a replicable and adaptive framework that supports evidence-based restoration planning and improves the interface between science, governance, and practice. By explicitly framing restoration as a climate-adaptation tool, it supports a structured pathway to scale nature-based solutions and enhance the resilience and sustainability of Mediterranean agroecosystems.

Keywords: riparian vegetation; restoration planning; climate-smart strategies; nature-based solutions; nature restoration law.

#### Implications for practice:

- Integrate temporary river restoration into agricultural management to strengthen climate resilience in Mediterranean regions;
- Apply a structured, evidence-based approach to plan site-specific and scalable actions;
- Align restoration planning with EU policy instruments, to facilitate implementation through policy coherence and funding access.

## 1. Introduction

Throughout history, Mediterranean landscapes have been shaped by a delicate balance between climate, water, soil, and agriculture. For centuries, farmers across the region have adapted to the seasonal variability of rainfall and flow regimes, relying on rivers and streams to sustain their crops and livestock (Blondel, 2006). However, this historical balance is under increasing pressure. The Mediterranean Basin is one of the fastest-warming regions in the world, warming approximately 20% faster than the global average, and is experiencing longer droughts, shifting precipitation patterns, and severe water scarcity (Intergovernmental Panel on Climate Change, 2023; Lionello & Scarascia, 2018; Trambly et al., 2020).

Agriculture, the most water-demanding sector, represents about 59% of total water abstraction in the European Union (European Environmental Agency, 2024). Although the number of agricultural holdings has declined over the last few years, the overall utilized agricultural area (UAA) and its economic value have both increased, reflecting the trends toward intensification, especially in southern Europe (Eurostat, 2023). These dynamics have led to land-use homogenization, soil erosion, biodiversity loss, and growing pressure on water resources (Cerdà et al., 2021; Sharma et al., 2011). Together, the effects of climate change and land-use intensification now threaten the long-term sustainability of agroecosystems, which heavily depend on water availability and ecosystem services to maintain productivity and resilience.

Among freshwater systems, temporary rivers (covering intermittent and ephemeral streams) are one of the most ecologically distinctive yet undervalued ecosystems. They are characterized by alternating flow conditions (flowing, non-flowing, and dry phases) resulting from climate and geomorphological variability (Gallart et al., 2012; Leopold & Miller, 1956). In Mediterranean regions, they dominate arid and semi-arid catchments, supporting unique communities adapted to hydrological extremes, even though they remain among the least studied aquatic systems (Skoulikidis et al., 2017; Tooth, 2000). Despite their ecological and hydrological importance, temporary rivers remain poorly represented in management frameworks and are frequently misclassified and degraded due to inappropriate management interventions (Nikolaidis et al., 2013; Sánchez-Montoya et al., 2022). During dry phases, they are frequently perceived as degraded or unproductive areas, which leads to neglect or mismanagement (Cottet et al., 2023; Steward et al., 2012). In many cases, they are managed as perennial rivers, where flow is artificially maintained through releases from reservoirs or wastewater discharges, or even converted to agricultural land during dry periods (Acuña et al., 2017). Such practices disrupt the natural hydrological variability that underpins their ecological identity, resilience, and biodiversity, compromising their capacity for ecological recovery after drought (Larned et al., 2010; Stubbington et al., 2020).

From an ecological perspective, riparian corridors along river margins play a crucial role in sustaining both biodiversity and agricultural resilience. Riparian vegetation mitigates agricultural

impacts by filtering nutrients and sediments, stabilizing soils, regulating temperature, and buffering extreme hydrological fluctuations (Corbacho et al., 2003; Popescu et al., 2021). These corridors also act as ecological connectors, allowing species to disperse across fragmented landscapes and providing refuge during droughts and low-flow periods. Beyond their ecological functions, they deliver critical ecosystem services, such as carbon sequestration, flood mitigation, pollination, pest control, and fire resistance, which are increasingly recognized as essential for climate adaptation and sustainable agriculture (Riis et al., 2020). However, riparian systems are heavily degraded and fragmented ecosystems that are affected by land use changes, overgrazing, channel modification, and invasive species proliferation, which lead to simplified vegetation structures, loss of native biodiversity, and declining service provision (Fernández García et al., 2021; Naiman et al., 2005; Stella et al., 2013). Addressing these challenges requires an urgent transition toward restoration approaches that integrate ecological understanding, hydrological variability, and socio-political contexts, particularly in agricultural landscapes, as they face competing demands for water and land (Capon et al., 2013; Rivaes et al., 2013).

Ecological restoration is increasingly recognized as an essential tool that, when complemented with other conservation efforts and nature-based solutions (NBS), can reconcile agriculture with water resilience (European Commission, 2025a; Gann et al., 2019). The restoration of riparian corridors in temporary rivers should not be perceived as a land-use constraint but rather as a strategic investment in climate-resilient production systems, since it provides a pathway to balance ecological integrity and economic viability through evidence-based adaptive management (Keesstra et al., 2018). Although multiple European Union policy instruments now converge toward these goals, most initiatives and assessment criteria remain biased toward perennial systems, overlooking the ecological complexity and temporal variability of temporary rivers (Nikolaidis et al., 2013). In the Iberian Peninsula, where temporary rivers dominate southern basins, this gap presents both a challenge and an opportunity to design scalable models that simultaneously address different dimensions (Lorenzo-Lacruz et al., 2013).

In this study, we aim to address that gap by developing a planning framework for ecological restoration of temporary rivers, using the case study of the Enxoé watershed, a sub-basin of the transboundary Guadiana River in southern Portugal, as the basis. Through its analysis, we identify four Key Strategies for Climate-Smart Restoration: (1) ecological characterization, (2) geoseries identification, (3) reference ecosystem and objective setting, and (4) adaptive and climate-smart restoration. Rather than presenting a theoretical or conceptual model, this approach, built on a data-driven diagnostic framework, enables us to translate field-based evidence and conceptual and policy contextualization into a replicable, scalable framework for restoring temporary rivers in agricultural regions increasingly affected by water scarcity.

## 2. Conceptual & Policy Background

Despite accounting for over 50% of the global river network, temporary rivers remain among the least studied and most threatened freshwater ecosystems (Datry et al., 2017; Lemm et al., 2021; Vörösmarty et al., 2010). Their flow intermittence supports dynamic ecological processes: flowing periods sustain aquatic biota such as macroinvertebrates, amphibians, and fish, while dry phases allow terrestrial colonization, seed dispersal, and nutrient cycling through microbial and plant activity (Datry et al., 2014). The alternation of these phases underpins a dynamic equilibrium that is central to their resilience to climatic extremes (Capon et al., 2013; Rivaes et al., 2013). This intrinsic variability makes temporary rivers particularly vulnerable to human-induced pressures. Hydrological alterations, excessive water abstraction, nutrient enrichment, and channel modification have drastically reduced their capacity to maintain ecological functions (Cottet et al., 2023). Even small dams or reservoirs can interrupt longitudinal and lateral connectivity, transforming once-diverse riparian corridors into simplified, degraded systems dominated by invasive species. As ecotones between aquatic and terrestrial systems, riparian corridors are critical for hydrological regulation and ecological buffering, and their degradation directly weakens the resilience of both freshwater and adjacent terrestrial ecosystems.

Restoration efforts for temporary rivers have often failed because most methodologies were originally designed for perennial rivers. Techniques developed under continuous-flow assumptions often prove inadequate where hydrological intermittence, sediment dynamics, and agricultural dominance demand adaptive, context-specific approaches (Larned et al., 2010; Nikolaidis et al., 2013). This highlights the need for planning frameworks that explicitly incorporate temporal variability, spatial heterogeneity, and socio-economic constraints (Capon et al., 2013; Gann et al., 2019). Our study relies on this conceptual gap, aligning with the *Society for Ecological Restoration (SER) International Principles and Standards*, which emphasize that restoration must be process-oriented, reference-informed, and adaptive (Gann et al., 2019).

Over the past two decades, European policies have progressively integrated and acknowledged the importance of river restoration and sustainable water management. The EU Water Framework Directive (WFD) established a unified strategy aimed at achieving the “good ecological and chemical status” of all water bodies within 15 years of the directive's adoption or 2015 (European Parliament & Council, 2000). However, only about 37% of Europe’s surface waters currently meet this goal, largely because assessment indicators strongly rely on continuous-flow conditions, which are unsuitable for temporary systems (European Environmental Agency, 2024; Matono et al., 2012). The EU Biodiversity Strategy for 2030 reinforced restoration targets, setting an ambitious goal to reconnect at least 25 000 km of free-flowing rivers by removing artificial barriers and rehabilitating riparian habitats (European Commission, 2020). The EU Nature Restoration Law introduces binding restoration targets for degraded ecosystems, including riverine habitats, with explicit goals to improve ecological

connectivity and climate resilience (European Parliament & Council, 2024). Complementarily, the EU Water Resilience Initiative focuses on protecting and restoring the water cycle, building a *water-smart* economy, raising climate resilience awareness, and enhancing adaptation capacity across Member States (European Commission, 2025a).

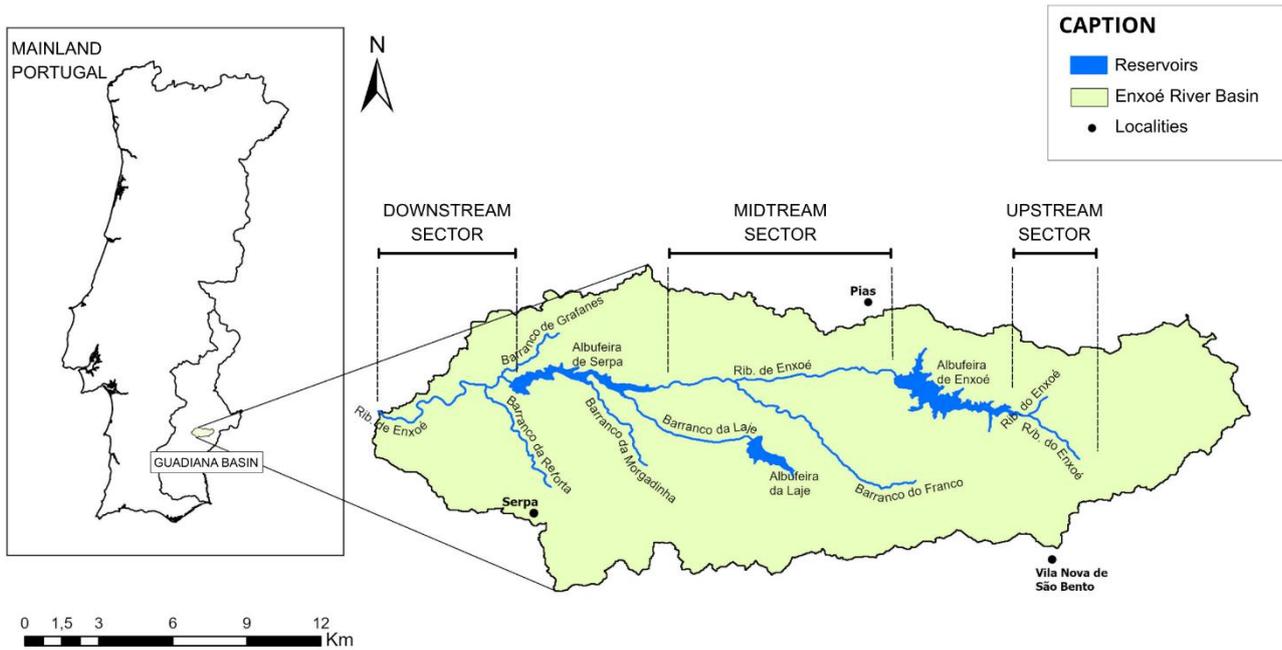
At the Iberian scale, transboundary cooperation between Portugal and Spain under the Albufeira Convention has been pivotal for integrated river basin management (Presidência da República, 1999). The Guadiana River Basin, where the Enxoé sub-basin is located, exemplifies the potential and challenges of cross-border governance. While basin plans integrate WFD principles, their implementation often varies between national jurisdictions, highlighting the need for harmonized ecological criteria and data sharing (García-Ruiz et al., 2013; Lorenzo-Lacruz et al., 2013). In Portugal, the Water Law (Law No. 58/2005) and subsequent River Basin Management Plans (RBMPs) operationalize WFD objectives, integrating measures for riparian restoration and promoting sustainable land-use practices through agro-environmental schemes and subsidies under the Common Agricultural Policy (CAP) (European Commission, 2025b; República Portuguesa, 2005).

Collectively, these policies and governance mechanisms underscore that temporary rivers represent strategic targets for achieving Europe's water, land, and biodiversity objectives. However, practical implementation remains limited, especially in data-scarce, agriculturally dominated catchments, where a lack of tailored methodologies hampers progress. The Enxoé case study directly addresses this by integrating ecological, political, and socio-economic elements into a replicable framework that operationalizes EU and national restoration goals.

### **3. Case Study: Enxoé watershed, Portugal**

#### **3.1 Study area**

The Enxoé watershed is a temporary river basin located in southern Portugal within the Alentejo region (Figure 1). It belongs to the Guadiana River Basin, one of the largest transboundary watersheds on the Iberian Peninsula. Covering approximately 236 km<sup>2</sup>, the Enxoé sub-basin is an important local water source that contributes to downstream hydrological dynamics.



**Figure 1.** Map of the location of the Enxoé river basin (Guadiana basin, southern Portugal), identifying the main watercourses, reservoirs, localities, and defined river sectors.

The region has a semi-arid Mediterranean climate, characterized by hot, dry summers and mild, wet winters. Precipitation varies, with strong interannual variability and concentrated rainfall events between October and March. Average annual temperatures range between 16 and 17°C, with summer maxima frequently exceeding 30°C (Instituto Português do Mar e da Atmosfera, 2024). The marked seasonality results in a highly intermittent flow regime, with streamflow mainly occurring during the wet season, while in summer, the river reduces to ephemeral surface water and prolonged dry reaches interspersed with isolated pools.

The basin's topography is characterized by gentle slopes (6–12%), with elevations ranging from 100 to 400 m above sea level. The underlying geology consists mainly of schists, greywackes, and metavolcanic formations from the South Portuguese Zone, overlain by Quaternary deposits in alluvial areas. Soils are generally shallow, predominantly leptosols and cambisols, with low organic matter content and limited water-holding capacity, conditions that intensify erosive processes during intense rainfall (Direção-Geral do Território, 2022).

The landscape matrix is characteristic of Mediterranean dryland, the Montado (Dehesa) agrosilvopastoral system dominated by *Quercus rotundifolia* Lam. (holm oak) and *Quercus suber* L. (cork oak), punctuated by shrub-dominated patches of *Cistus ladanifer* L. (gum rockrose), *Rosmarinus officinalis* L. (rosemary), and *Genista* sp. (cape broom). Agricultural land use is widespread, comprising a mosaic of intensive and super-intensive olive groves and pastoral areas. The riparian corridor includes native species such as *Fraxinus angustifolia* Vahl (ash), *Tamarix africana* Poir. (tamarisk), *Salix atrocinerea* Brot. (willow), and *Flueggea tinctoria* (L.) G.L.Webster (tamujo).

However, these green corridors are increasingly fragmented, and the plant communities are being replaced by invasive species, particularly the exotic *Arundo donax* L. (giant reed) and the native yet expansive *Rubus ulmifolius* Schott (wild blackberry).

The Enxoé displays a strong longitudinal gradient of intermittency, with upstream reaches often drying completely during summer, while midstream and downstream sectors often retain residual pools. This spatial variability shapes ecological gradients and defines restoration priorities, as the time of surface water persistence directly influences vegetation structure, soil–water interactions, and overall habitat condition.

In summary, the Enxoé watershed represents a typical Mediterranean temporary river system shaped by agricultural intensification, hydrological regulation, and climatic extremes. Its high desertification risk, combined with a landscape mosaic of natural habitats and diverse production systems, further underscores its representativeness in the region. These features make it an ideal reference landscape for developing a replicable restoration planning framework.

## **3.2 Ecological characterization**

### 3.2.1. Diagnostic approach

The ecological characterization aimed to establish a baseline understanding of the structure, composition, and condition of the river corridor as the primary input for the restoration planning model. The assessment combined floristic and hydromorphological data collected through field surveys, complemented by GIS-based analysis that integrated topographic, geological, and land-use datasets (Direção-Geral do Território, 2022) with climatic information from IPMA (Instituto Português do Mar e da Atmosfera, 2023).

Fieldwork was conducted between April and May 2023, comprising 13 representative reaches of approximately 100 m each, distributed along the longitudinal profile of the main river: upstream, midstream, and downstream sectors (Figure 1). The reaches were selected to sample the entire range of natural plant community types (habitats) and to capture the diversity of ecological conditions across the basin.

Floristic surveys were conducted along reach-length transects stratified by the principal hydrogeomorphic gradient (geoseries), distinguishing three main zones: streambed, lower bank, and upper bank. Within each zone, all characteristic riparian plant species were recorded, and their percentage cover within the reach was estimated. In each vegetation belt, all characteristic riparian plant species were recorded, together with their estimated percentage cover within the sampled reach. The vertical structure of the vegetation was also evaluated by determining the relative proportion of herbaceous, shrub, and tree strata, and the percentage of canopy shading over the channel was estimated visually. Complementarily, the continuity of the riparian corridor was assessed

and classified into five categories, reflecting the degree of structural connectivity: continuous, semi-continuous, interrupted, sparse, and absent. Additionally, the Riparian Forest Quality Index (QBR) was used to assess the integrity of the riparian vegetation (Munné et al., 1998).

Environmental characterization included the assessment of hydromorphological and water quality parameters (Annex 1). For each reach, land use in the riparian buffer, channel dimensions, substrate composition, bank slope and stability, and flow conditions were recorded through field measurements and visual assessment. Physicochemical water parameters (temperature, conductivity, dissolved oxygen, and pH) were measured in situ, along with visual observations of transparency, color, and potential indicators of degradation (e.g., aquatic weeds, algal growth, or sediment accumulation). In addition, cross-sectional profiles were drawn for each reach, and the Geomorphological Quality Index (GQC) was applied to evaluate the overall physical habitat condition (Ferreira et al., 2011).

Finally, anthropogenic pressures were recorded following the criteria of the FAME Consortium (2004). Evaluation was carried out at both the reach and fluvial sector scales to capture cumulative impacts along the Enxoé stream. Recorded variables included: surrounding land use and cover, influence of urban areas, riparian vegetation condition, fluvial connectivity, sediment load, hydrological regime modification, water acidification and toxicity, morphological condition, organic contamination and nutrient enrichment, influence of lentic or artificial water bodies, and water abstraction.

### 3.2.2. River sector evaluation

The ecological characterization revealed a clear longitudinal gradient in ecological condition along the Enxoé river, reflecting cumulative pressures and variations in hydrology, geomorphology, and vegetation structure.

- Upstream sector:

The river corridor exhibited the greatest degree of ecological degradation, including substantial loss of natural structure. Riparian vegetation was largely absent or highly fragmented, dominated by the invasive alien *A. donax* and the native *R. ulmifolius*, accompanied by ruderal and nitrophilous herbaceous species, and isolated individuals of *T. africana*, *S. atrocinnerea*, and *Populus* sp. (poplar). The tree layer and canopy cover were sparse, leading to high water temperatures and poor water quality. Several areas exhibited signs of eutrophication, consistent with nutrient enrichment from agricultural runoff. Channel banks were eroded and poorly consolidated, further destabilized by livestock trampling and their direct access to the watercourse, in association with a silted riverbed dominated by fine sediments. The QBR scored as *poor*, reflecting extreme ecological degradation, while the GQC ranged from *poor* to *moderate*, indicating strong morphological alteration and sedimentation associated with intensive olive groves and riparian vegetation loss.

- Midstream sector:

Intermediate conditions, reflecting the partial recovery potential in these reaches. Riparian vegetation was semi-continuous, though locally degraded and fragmented, consisting mainly of shrub-dominated communities of *Nerium oleander* L. (oleander), *T. africana*, and *F. tinctoria*, with dense nuclei of *A. donax*, abundant lianas, and a scattered tree cover of *S. atrocinerea* and *Populus* sp. Hydromorphological conditions were intermediate, with confined channels, steeper slopes, and ongoing bank erosion due to livestock trampling and the absence of riparian vegetation in several areas. Flow regulation between the Enxoé and Serpa reservoirs resulted in reduced flow and hydrological connectivity, and limited sediment transport, producing nutrient-enriched pools. QBR values ranged from *poor* to *good*, and GQC scores were predominantly *moderate*, which indicates significant hydromorphological modification.

- Downstream sector:

Well-preserved reaches with the highest potential for natural ecological recovery. Riparian vegetation ranged from semi-continuous to continuous, with a well-structured profile and high floristic richness and diversity. All vegetation strata were well represented – trees (*S. atrocinerea*, *Populus* sp., and *F. angustifolia*), shrubs (*T. africana*, *N. oleander*, and *F. tinctoria*), and lianas – providing high canopy cover and habitat complexity. Hydromorphological conditions were substantially better, with alternating riffles and pools, stable or moderately consolidated banks, and a heterogeneous substrate of gravel and cobbles. Permanent flow persists in several reaches, and sedimentation was limited despite localized effects from small transversal structures. Both QBR and GQC scores ranged from *moderate* to *excellent*, indicating higher structural complexity, ecological integrity, hydromorphological diversity, and bank stability.

The evaluation of anthropogenic pressures revealed a cumulative disturbance pattern along the Enxoé. Livestock trampling and overgrazing were the most significant pressures, causing bank destabilization, sediment resuspension, and loss of natural regeneration capacity. Agricultural intensification, driven by the expansion of olive groves across the basin, caused diffuse pollution from fertilizers and agrochemicals, the removal of riparian corridors, and floodplain occupation, which reduced sediment retention and flow regulation during high precipitation events, while increasing pesticide drift. Invasive species proliferation represented the third major driver of degradation, with *A. donax* and *R. ulmifolius* forming dense areas along the channel, suppressing native vegetation, altering hydrological and geomorphic dynamics, and increasing fire risk through the accumulation of biomass that also blocks water flow during flood pulses. Additionally, small transversal structures (small dams and bridges) further disrupted longitudinal connectivity and sediment transport, simplifying channel morphology and reducing habitat diversity.

### 3.3 Setting objectives

This step is essential to translate the outputs of ecological characterization into concrete, measurable, and adaptive restoration goals. Three elements were integrated in this process: (1) the reference ecosystem approach, to ensure ecological realism and dynamic targets for climate adaptation; (2) the legal context, to align planning with multilevel governance instruments; and (3) a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, to assess internal and external factors influencing implementation and involve the socio-economic dimensions.

The identification of reference ecosystems is essential to define restoration needs and spatial scale. It provides a real ecological analogue under similar environmental conditions to the project site, showing what the system would resemble in the absence of degradation, while accounting for both historical and future dynamics (Gann et al., 2019; Giardina et al., 2007; Nelson et al., 2024). In this way, the reference conditions were based on the concept of geoseries (or *curtosséries*), which describe spatial sequences of vegetation communities distributed along environmental gradients associated with hydrology, soil type, and geomorphology (Flor et al., 2021). For temporary rivers, geoseries identification provides a scientific basis for determining which native plant communities are most suited to each reach. The dominant vegetation geoseries identified in the Enxoé watershed were (Espírito-Santo et al., 1999; Pereira, 2013):

- *Saliceto atrocinerneo-australis* S. (willow woodland / salgueiral): arborescent shrubland, dominated by willows (*Salix* spp.), typical of torrential floodplains on siliceous substrate and exposed slopes to strong fluvial dynamics;
- *Typho angustifoliae* – *Phragmiteto australis* S. (reed bed / caniçal): helophytic vegetation commonly found along river banks, often replacing the willow woodland.
- *Rubo* – *Nerieto oleandri* S. (oleander scrub / loendral): hygrophilous association, dominated by oleanders (*Nerium oleander*), characteristic of secondary channels with stony substrate and severe summer drought;
- *Pyro* – *Securinegeto tinctoriae* S. (tamarisk thicket / tamujal): arborescent shrubland adapted to dry alluvial soils, on the riverbed or secondary channels, especially on stony substrate;

These communities illustrate how ecological zonation along the channel can guide planting design, placing flood-tolerant species in lower sections and drought-adapted species in higher banks. The inclusion of shrub and herbaceous layers enhances structural complexity, promotes soil stabilization, and increases habitat heterogeneity.

The legal contextualization derives from the growing emphasis on riparian ecosystem restoration within several policy and legal instruments at different scales. In the case of the Enxoé river, the Water Law (Law nº58/2005, December 29) was identified as one of the most important

national frameworks for water resource management and associated ecosystems, transposing the goals of the EU Water Framework Directive by promoting sustainable water management and establishing River Basin Management Plans (RBMPs) as key planning tools (República Portuguesa, 2005). Therefore, in addition to the European legislation, the adoption of several regional and municipal instruments is also fundamental to designing context-specific and coherent restoration strategies.

Finally, a SWOT analysis was conducted to evaluate internal factors (e.g., interdisciplinary approach, challenges in application) and external factors (e.g., policy alignment, insufficient funding) that could directly or indirectly affect the restoration plan (Bull et al., 2016; Pickton & Wright, 1998). This assessment considered both ecological and socio-economic aspects, including perspectives from various stakeholders. Identified strengths included: the enhancement of riparian ecosystem functions, improvement of water quality, and increased resilience to climate change. Weaknesses mainly involved administrative and technical constraints, particularly the limited implementation capacity and the need for sustained monitoring. Opportunities focused on raising public awareness of river conservation and encouraging policy co-creation, while threats involved climate change impacts, resource use competition, and uncertain long-term financial support.

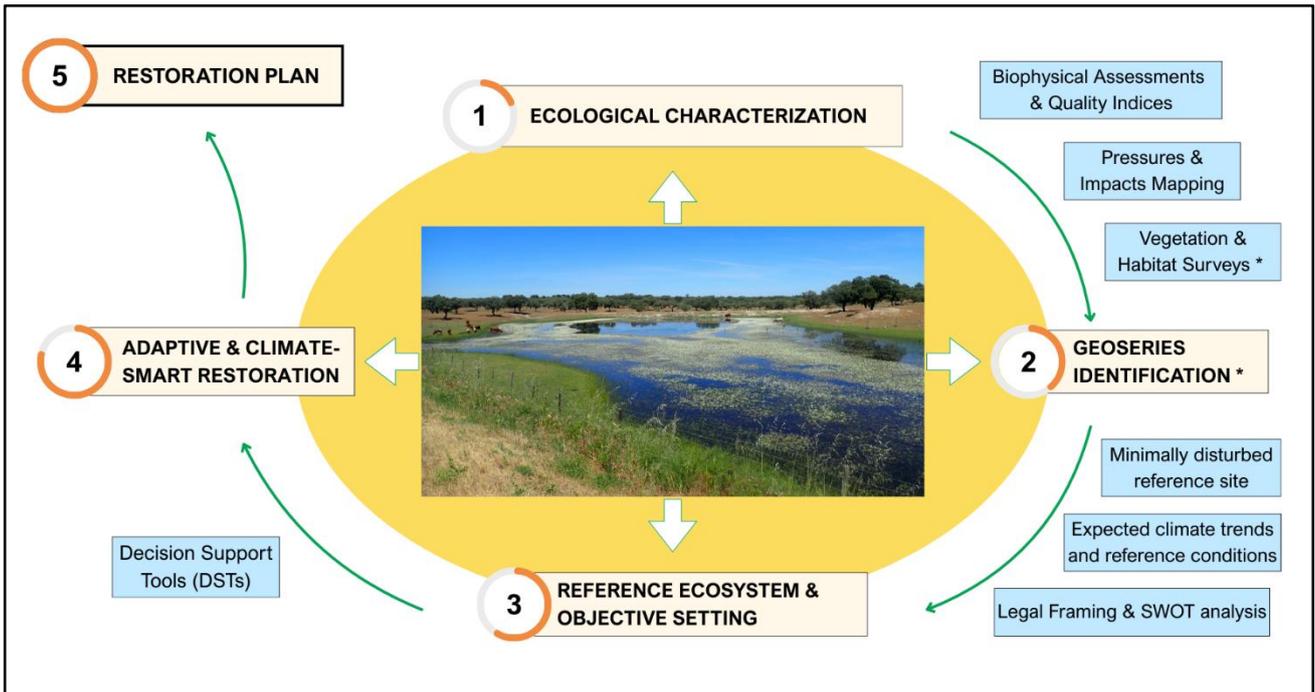
Based on these elements, three main objectives were established for the restoration plan: improve hydromorphological conditions; improve water quality; and enhance the conservation status of riparian vegetation. All three are inherently broad and foundational, reflecting core principles of river restoration that extend beyond this case study. For each objective, corresponding indicators and targets were identified and aligned with both future-oriented ecological conditions and legal frameworks (Table 1).

**Table 1.** Objectives, indicators, and targets defined for the restoration plan of the Enxoé watershed.

| OBJECTIVES                                                 | INDICATORS                                                                        | TARGETS                                                               |
|------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------|
| Improve hydromorphological conditions                      | Monthly ecological flow released from the Enxoé and Serpa dams (hm <sup>3</sup> ) | Comply with established ecological flow values                        |
|                                                            | Hydromorphological quality status, evaluated by indices                           | Achieve at least <i>good</i> hydromorphological quality               |
| Improve water quality                                      | Water quality status                                                              | Achieve at least <i>good</i> water quality                            |
| Enhance the conservation status of the riparian vegetation | Extent of riparian gallery with well-conserved structure (ha)                     | Increase the extent of well-conserved riparian vegetation             |
|                                                            | Area occupied by invasive and exotic species (ha and % cover)                     | Reduce the area and percentage covered by invasive and exotic species |
|                                                            | Riparian gallery conservation status (index-based)                                | Achieve at least a “Good” riparian quality status                     |

## 4. Framework for Climate-Smart Restoration

After analyzing the case study's diagnosis and planning processes, we propose a framework that strengthens the planning stage of ecological restoration, translating local insights into broader methodological guidance that addresses the challenges of restoring temporary rivers in Mediterranean agroecosystems. The framework integrates four transferable and scalable key strategies that, together with two decision support tools developed from Enxoé learnings, outline a roadmap for climate-resilient restoration planning (Figure 2):



**Figure 2.** Proposed model for restoration planning, illustrating the key strategies and their complementary inputs (blue boxes).

### 4.1 Key strategies description

1. Ecological characterization: establishes the ecological baseline through detailed biophysical assessments (including quality value indices), vegetation and habitat surveys, and pressures and impacts mapping – resulting in the identification of ecological and degradation gradients so stakeholders can prioritize areas for intervention and tailor restoration activities to specific local contexts;
2. Geoseries identification: help translate ecological gradients and vegetation surveys into reference conditions that align with spatial vegetation distribution according to hydrology, soil, and geomorphology characteristics.

3. Reference ecosystem and objective setting: defines realistic/ adaptive objectives and future-oriented/ policy-aligned targets, by identifying ecosystems that can serve as benchmarks providing a basis for monitoring and evaluating the success of restoration initiatives over time;
4. Adaptive and climate-smart restoration: integrates decision support tools into the planning process by using previous assessment data to ensure restoration is not only scientifically robust but also socially acceptable and economically viable.

Structured as a sequence of interconnected elements, where each strategy provides the informational basis for the next, the framework ensures that restoration actions are ecologically sound, legally coherent, and socioeconomically feasible. This integrative structure promotes a transparent and iterative planning process that can be adapted to different contexts while maintaining ecological integrity and climate resilience.

#### **4.2 Decision Support Tools (DSTs)**

Based on the information from the case study, two Decision Support Tools (DSTs) were developed to assist in planning adaptive and climate-smart restoration actions:

- Restoration Decision-Support Matrix (Table 2):

By linking pressures and ecological conditions to specific restoration actions, Table 2 ensures that proposed techniques directly address the type and severity of degradation observed at each site. It functions as a hierarchical system for prioritizing problems and categorizing restoration solutions, enabling its application beyond the Enxoé case.

The actions proposed within this tool do not encompass all possible restoration techniques, as additional measures can be found in specialized river restoration manuals and technical guidelines (Fernandes & Freitas, 2011; Fernandes, 2022). Moreover, it is essential to obtain the necessary authorizations and permits from the relevant authorities to ensure compliance with legal, environmental, and administrative requirements.

**Table 2.** Restoration Decision-Support Matrix for ecological restoration projects of river basins in arid and semi-arid catchments. Techniques to be used to solve the respective impacts resulting from a set of pressures identified.

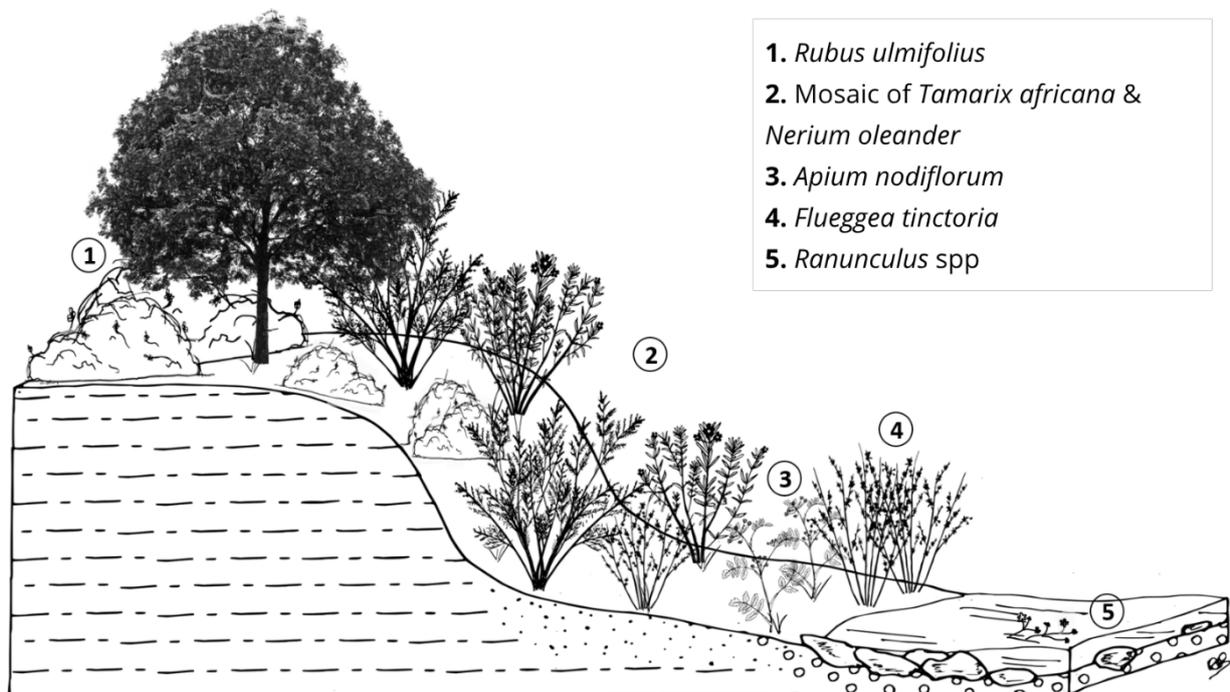
|  Agriculture & Livestock<br> Dams & Structures<br> Point Source Pollution<br> Invasive Alien Species<br> Vegetation Clearing<br> Water Abstraction<br> Sediment Extraction | PRESSURES                                                                         |                                                                                   |                                                                                   |                                                                                     |                                                                                     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |  |  |  |  |  |
| TECHNIQUES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | IMPACTS                                                                           |                                                                                   |                                                                                   |                                                                                     |                                                                                     |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Erosion                                                                           | Habitat Loss                                                                      | Bank Destabilization                                                              | Vegetation Degradation                                                              | Hydrological Alteration                                                             |
| Livestock exclusion/access control to the waterline                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | X                                                                                 | X                                                                                 |                                                                                   | X                                                                                   |                                                                                     |
| Channel and bank cleaning                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                                                                   | X                                                                                 |                                                                                   |                                                                                     | X                                                                                   |
| Bed desiltation/ Dredging                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                                                                   | X                                                                                 |                                                                                   |                                                                                     | X                                                                                   |
| Low weirs                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | X                                                                                 | X                                                                                 |                                                                                   |                                                                                     |                                                                                     |
| Invasive species control                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                                                                   |                                                                                   |                                                                                   | X                                                                                   | X                                                                                   |
| Turf reinforcement mats                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                   |                                                                                   | X                                                                                 | X                                                                                   |                                                                                     |
| Hydroseeding                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | X                                                                                 |                                                                                   | X                                                                                 | X                                                                                   | X                                                                                   |
| Planting                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | X                                                                                 | X                                                                                 | X                                                                                 | X                                                                                   | X                                                                                   |
| Live staking                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | X                                                                                 | X                                                                                 | X                                                                                 | X                                                                                   | X                                                                                   |
| Geotextiles and live geomats                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | X                                                                                 |                                                                                   | X                                                                                 |                                                                                     |                                                                                     |
| Brush layering                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                                   |                                                                                   | X                                                                                 |                                                                                     |                                                                                     |
| Live fascines bundles                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | X                                                                                 |                                                                                   | X                                                                                 | X                                                                                   |                                                                                     |
| Live gabions/ Vegetated gabions                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | X                                                                                 |                                                                                   |                                                                                   | X                                                                                   |                                                                                     |
| Brushwood mattress                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | X                                                                                 |                                                                                   | X                                                                                 |                                                                                     |                                                                                     |
| Vegetation mat or brush mattress                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                   |                                                                                   | X                                                                                 |                                                                                     |                                                                                     |
| Live retaining walls                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                   |                                                                                   | X                                                                                 |                                                                                     |                                                                                     |
| Reinforced earth                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                   |                                                                                   | X                                                                                 |                                                                                     |                                                                                     |
| Live cribwall                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                                   |                                                                                   | X                                                                                 |                                                                                     |                                                                                     |
| Bio-roll/ Coconut fiber roll                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                   |                                                                                   | X                                                                                 |                                                                                     |                                                                                     |
| Micro weirs                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | X                                                                                 |                                                                                   |                                                                                   |                                                                                     |                                                                                     |
| Live riprap                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | X                                                                                 |                                                                                   |                                                                                   |                                                                                     |                                                                                     |
| Flow deflectors                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | X                                                                                 | X                                                                                 |                                                                                   |                                                                                     |                                                                                     |

- Cross-sectional Riparian Vegetation Models:

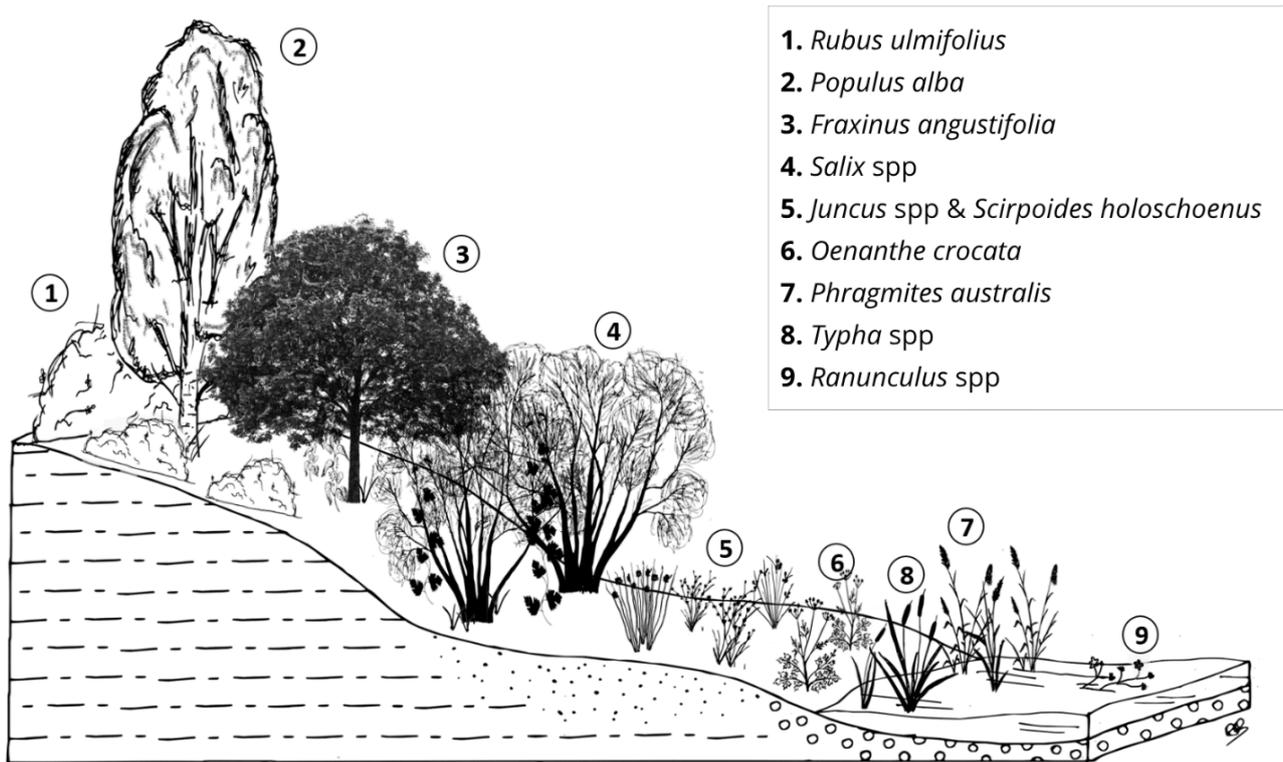
Based on the previous tool evaluation, revegetation (e.g., planting) is clearly one of the central techniques to address multiple impacts. In fact, it is the foundation of long-term ecological resilience, ensuring riparian systems can withstand drought, flooding, and hydrological variability while remaining functional and adaptive.

For this reason, two revegetation models were developed using the concept of riparian geoseries as the guiding ecological structure. Species selection followed the characteristic plant communities of each river sector from Enxoé, considering their natural distribution along the edapho-hydrophilic gradient and their tolerance to future changes in water availability. Annex 2 provides the plant species list supporting this approach, and its application led to the identification of two revegetation types of models, both transversal and broadly applicable to Mediterranean temporary rivers in arid and semi-arid catchments:

- higher flow intermittency, longer and more pronounced dry periods, steep banks, an embedded transverse profile, higher longitudinal slope and hydrodynamic energy, and lower accumulation of fine sediments (Figure 3);
- river stretches with lower flow intermittency, shorter and less intense dry periods, a flattened transverse profile, reduced longitudinal slope and hydrodynamic energy, and greater accumulation of fine sediments (Figure 4).



**Figure 3.** Cross-sectional profile and ecological succession of native species to be used in the ecological restoration of river stretches with an embedded profile, more pronounced drought, and greater hydrodynamics. Illustration by Raquel Barreto



**Figure 4.** Cross-sectional profile and ecological succession of species to be used in the ecological restoration of river stretches with a flattened profile, less pronounced drought, and reduced hydrodynamics. Illustration by Raquel Barreto

## 5. Discussion

The Enxoé watershed illustrates how temporary Mediterranean rivers retain significant ecological and strategic value for climate adaptation and resilience, despite their degradation. The persistence of native riparian patches and the geomorphological diversity along the Enxoé river show that hydrological intermittency, often regarded as a limitation, is, in fact, a key ecological feature that sustains resilience and biodiversity under increasing hydrological stress. These results align with conclusions from other Mediterranean studies that highlight the adaptive value of intermittency in maintaining ecosystem functionality (Bogan et al., 2017; Gianuca et al., 2024; Schilling et al., 2021).

From an ecological perspective, this study supports the conservation of temporary rivers, in line with recent European policies that increasingly recognize the critical role of river ecosystems in climate adaptation and sustainable water management (European Commission, 2025b). As demonstrated by Castellano et al. (2022), restored and mature riparian areas can show comparable taxonomic composition and vegetation richness while enhancing regulating and supporting ecosystem services. This suggests that targeted restoration efforts can yield significant ecological benefits, reinforcing the importance of maintaining and improving the ecosystem integrity of temporary rivers.

The developed Decision Support Tools (DSTs) offer a practical structure for translating these insights into actionable restoration measures. By linking diagnosed pressures and impacts to appropriate restoration techniques, the Restoration Decision-Support Matrix provides a flexible and adaptive tool that can be tailored to local contexts, particularly valuable in Mediterranean regions, where data scarcity and limited monitoring often constrain effective restoration planning and implementation (Stubbington et al., 2017). The decision-tree format facilitates evidence-based prioritization and informed decision-making, enabling stakeholders to select interventions that address the most pressing ecological concerns while considering the socio-economic contexts. However, the selection and application of the techniques require careful technical evaluation, considering not only the objectives but also the associated costs, feasibility, and potential constraints (Teiga, 2014). Priority should be given to the minimum level of intervention necessary to restore ecosystem functionality and enhance natural self-regeneration capacity, thereby reducing disturbance and costs, while maximizing restoration effectiveness. In fact, action prioritization should reflect the degree of degradation and the ecological function of each river sector.

On the other hand, the two cross-sectional riparian revegetation models provide operational guidance for practitioners, enabling adaptive selection and spatial distribution of plant species according to the geomorphological and hydrological setting of each river reach. Under projected Mediterranean-climate scenarios, characterized by higher temperatures and longer dry seasons (Intergovernmental Panel on Climate Change, 2023), the success of restoration efforts will depend on selecting plant communities capable of adapting to water scarcity and irregular hydrological regimes. The models thus demonstrate how ecological and climate projections can be integrated into restoration design, transforming static planting schemes into adaptive and ecologically resilient schemes.

The four key strategies — basin characterization, geoseries identification, reference ecosystem and objectives setting, and adaptive and climate-smart restoration — form a structured model, bridging the gap between ecological diagnosis and implementation. Quantitative indicators such as the Riparian Forest Quality Index and the Geomorphological Quality Index ensured objective prioritization, while the geoseries identification aligned revegetation schemes with local hydrological and geomorphological gradients. This integrated approach responds to one of the main challenges in Mediterranean restoration practice: the lack of tailored tools that account for hydrological variability and the absence of long-term monitoring data (Borg Galea et al., 2019).

Despite the growing recognition, progress in adaptation planning and restoration remains constrained by limited resources, insufficient technical capacity, weak political commitment, and dependence on external funding (Aguiar et al., 2018). By aligning restoration targets with major policy instruments, our analysis strengthens coherence between local actions and European goals for biodiversity recovery, ecological connectivity, and water resilience. In the case of Enxoé, it also highlights the value of transboundary management under the Albufeira Convention, fostering

cooperation between Portugal and Spain through data exchange, methodological harmonization, and improved water management practices (Sondermann & de Oliveira, 2021).

In regions such as the Alentejo, where agriculture dominates, the engagement of local communities, farmers, and landowners is crucial to ensure ecological success and social acceptance (Santos et al., 2025). Participatory approaches and incentive mechanisms under the Common Agricultural Policy can facilitate the integration of nature-based solutions into agricultural practices (Pistocchi, 2022). Effective implementation, therefore, requires multi-actor participation, promoting co-management and long-term maintenance of restoration actions. Involving local stakeholders enhances social acceptance while delivering tangible co-benefits such as reduced erosion, improved soil fertility, and enhanced ecosystem services. Similar approaches have proven effective in other Mediterranean restoration projects and should be adopted to ensure continuity beyond the initial implementation phase (Gornish et al., 2024).

Overall, the Enxoé case study demonstrates the ecological and strategic value of temporary rivers and shows how a structured, scalable framework can guide their restoration and management. By identifying key strategies to be integrated during the planning phase, this study helps bridge gaps between European and national policies, socially limiting perceptions of temporary rivers, and implementation processes that are often hindered by limited monitoring and data. In doing so, it transforms site-specific insights into transferable methodological guidance for other arid and semi-arid basins. Furthermore, it contributes to operationalizing the EU Nature Restoration Law, providing a technical and scientific tool for adaptive, climate-resilient restoration planning. Moving forward, it is essential to continue developing innovative approaches that address the unique ecological characteristics of temporary rivers, ensuring their long-term sustainability and the vital ecosystem services on which Mediterranean societies depend.

## **6. Conclusions**

The rising challenges posed by increasing temperatures, prolonged water scarcity, and agricultural intensification make it imperative to re-evaluate how we manage and restore freshwater ecosystems. Our findings highlight the role of temporary rivers, often overlooked in policy and practice, in supporting climate adaptation and sustainable agriculture across the Mediterranean basin. The Enxoé case study demonstrates that a structured, evidence-based restoration planning framework can strengthen the resilience of riparian habitats and the agroecosystems they support, offering a practical bridge between theory and practice under intensifying climatic and anthropogenic pressures.

The restoration of Mediterranean watercourses must explicitly address their temporary flow regime and associated ecological processes, while integrating land use, vegetation dynamics, biological invasions, and extreme events such as droughts, floods, and wildfires. The framework and

DSTs proposed here offer clear criteria for diagnosing degradation, selecting appropriate measures, and navigating technical and legislative requirements across scales, providing a replicable model for other basins with similar hydrological and socio-economic contexts.

While this study advances an evidence-based, climate-smart framework for restoration planning, further research and long-term monitoring are necessary to evaluate its effectiveness and inform adaptive management. A climate-smart, locally tailored approach that integrates ecological, political, and socio-economic dimensions remains crucial to address the root causes of degradation. For this reason, the framework presented here can help reinforce ecological integrity, promote sustainable land management, and strengthen the long-term resilience of both natural and human systems in the face of climate change.

## 7. References

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## 8. Annexes

**Annex 1** – Parameters, evaluation criteria, and measurement methods used in the hydromorphological surveys applied in the ecological characterization of the Enxoé watershed.

|                                  | PARAMETER                                | EVALUATION                                                                                             | MEASUREMENT          |
|----------------------------------|------------------------------------------|--------------------------------------------------------------------------------------------------------|----------------------|
| <b>Hydromorphological Survey</b> | Land use                                 | Identification of land use in the surrounding area within 10 m and 50 m buffers                        | Visual estimate      |
|                                  | Average channel width                    | Mean value of several transects                                                                        | Measuring tape       |
|                                  | Substrate types                          | Classification: sand, gravel, cobbles, boulders, exposed rock                                          | Visual estimate      |
|                                  | Bank slope                               | Mean of several points along each margin                                                               | GPS                  |
|                                  | Bank stability                           | Classification: stable, moderately consolidated, eroded                                                | Visual estimate      |
|                                  | Mean water depth                         | Mean of various points                                                                                 | Graduated rod        |
|                                  | Flow velocity                            | Classification: absent, low, moderate, high                                                            | Flow meter           |
|                                  | Basic physicochemical parameters         | Temperature (°C), electrical conductivity ( $\mu\text{S}/\text{cm}$ ), dissolved oxygen (mg/L), and pH | Multiparameter probe |
|                                  | Water transparency and color             | Classification: clear, turbid, highly turbid                                                           | Visual estimate      |
|                                  | Alterations in water                     | Record of smell, dark sediment, or surface foam                                                        | Visual estimate      |
|                                  | Indicators of degradation in the channel | Record of aquatic weeds, nitrophilous plants, filamentous algae, and woody debris                      | Visual estimate      |

**Annex 2** – Plant species list proposed for ecological restoration, based on the characteristic plant communities of each river sector from Enxoé, indicating the species suitable for each of the types of water availability.

| Species                                                                    | Water availability             |                                   |
|----------------------------------------------------------------------------|--------------------------------|-----------------------------------|
|                                                                            | Less drought and hydrodynamics | Greater drought and hydrodynamics |
| <i>Apium nodiflorum</i> (L.) Lag.                                          | X                              |                                   |
| <i>Bryonia dioica</i> Jacq.                                                | X                              |                                   |
| <i>Crataegus monogyna</i> Jacq                                             | X                              |                                   |
| <i>Cyperus longus</i> L.                                                   | X                              | X                                 |
| <i>Erica lusitanica</i> Rudolphi                                           |                                | X                                 |
| <i>Flueggea tinctoria</i> (L.) G.L. Webster                                |                                | X                                 |
| <i>Fraxinus angustifolia</i> Vahl                                          | X                              | X                                 |
| <i>Galium aparine</i> L.                                                   | X                              |                                   |
| <i>Hedera hibernica</i> (G.Kirchn.) Bean                                   | X                              |                                   |
| <i>Iris pseudacorus</i> L.                                                 |                                | X                                 |
| <i>Juncus acutus</i> L.                                                    | X                              | X                                 |
| <i>Juncus acutiflorus</i> Hoffm.                                           | X                              | X                                 |
| <i>Juncus articulatus</i> L.                                               | X                              | X                                 |
| <i>Juncus effusus</i> L.                                                   | X                              | X                                 |
| <i>Lonicera periclymenum</i> subs. <i>hispanica</i> (Boiss. & Reut.) Nyman | X                              |                                   |
| <i>Lythrum junceum</i> Banks & Sol.                                        | X                              | X                                 |
| <i>Lythrum salicaria</i> L.                                                | X                              | X                                 |
| <i>Mentha pulegium</i> L.                                                  | X                              | X                                 |
| <i>Mentha suaveolens</i> Ehrh.                                             | X                              | X                                 |
| <i>Nerium oleander</i> L.                                                  | X                              | X                                 |
| <i>Oenanthe crocata</i> L.                                                 | X                              | X                                 |
| <i>Osyris alba</i> L.                                                      |                                | X                                 |
| <i>Phragmites australis</i> (Cav.) Trin ex. Steud.                         | X                              | X                                 |
| <i>Populus alba</i> L.                                                     | X                              |                                   |
| <i>Pyrus bourgaeana</i> Decne.                                             | X                              | X                                 |
| <i>Rosa canina</i> L.                                                      | X                              | X                                 |
| <i>Rubia peregrina</i> L.                                                  | X                              | X                                 |
| <i>Rubus ulmifolius</i> Schott                                             | X                              | X                                 |
| <i>Salix salviifolia</i> subsp. <i>australis</i> Brot.                     | X                              |                                   |
| <i>Scirpoides holoschoenus</i> (L.) Soják                                  |                                | X                                 |
| <i>Smilax aspera</i> L.                                                    |                                | X                                 |
| <i>Tamarix africana</i> Poir                                               |                                | X                                 |
| <i>Tamus communis</i> L.                                                   | X                              | X                                 |
| <i>Typha domingensis</i> Pers.                                             | X                              | X                                 |
| <i>Vitis vinifera</i> (C.C.Gmel.) Hegi                                     | X                              | X                                 |

## Considerações Finais

O trabalho desenvolvido nesta dissertação reforça o papel dos cursos de água temporários do Mediterrâneo como infraestruturas ecológicas essenciais para a resiliência climática e a sustentabilidade dos sistemas agrícolas (Borg Galea et al., 2019). Com base no caso de estudo da bacia do Enxoé, foi desenvolvido um modelo de planeamento que demonstra como o restauro ecológico, orientado por análises integradas e ajustado às especificidades locais, pode gerar benefícios ecológicos e produtivos. A ferramenta proposta traduz o conhecimento científico e o enquadramento político em orientações práticas, respondendo a uma das principais lacunas na prática do restauro ecológico: a distância entre o planeamento e a implementação.

No entanto, apesar do crescente reconhecimento político a nível europeu, refletido em instrumentos como a Lei do Restauro da Natureza e a Diretiva-Quadro da Água, persistem dificuldades estruturais, nomeadamente recursos limitados, capacidade técnica insuficiente, fraco compromisso político e dependência de financiamento externo (Aguiar et al., 2018). Segundo Rodríguez-González et al. (2022), a gestão eficaz dos ecossistemas ribeirinhos, como os analisados neste trabalho, enfrenta múltiplos desafios: (i) necessidade de interdisciplinaridade, integrando conhecimento sobre diferentes ecossistemas (aquáticos, terrestres e ribeirinhos); (ii) valorização social e política da vegetação ripícola; (iii) melhoria do conhecimento científico sobre o funcionamento destes sistemas; (iv) consideração da variabilidade espacial e do contexto local; (v) integração das dimensões socioeconómicas e antecipação dos efeitos das alterações climáticas e de outras pressões emergentes, como a intensificação agrícola; (vi) uniformização dos métodos de monitorização e partilha de dados; e (vii) validação de boas práticas de gestão. Estes desafios reforçam a urgência de uma abordagem integrada, preditiva e aplicada, capaz de apoiar o restauro ecológico e a gestão sustentável da água em cenários de alterações climáticas e intensificação agrícola.

Neste sentido, o modelo desenvolvido integra quatro eixos estratégicos complementares entre si — (1) caracterização ecológica, (2) identificação de geosséries, (3) definição do ecossistema de referência e objetivos, e (4) restauro adaptativo e *climate-smart* — que articulam de forma coerente os principais desafios ao restauro dos rios temporários. Adicionalmente, foram ainda desenvolvidas 2 ferramentas de apoio à decisão com vista à sua utilização em futuros estudos de forma a auxiliar a identificação, priorização e organização das ações de restauro de acordo com o estado ecológico, tipo de uso de solo e vegetação. Esta estrutura permite ajustar intervenções a diferentes contextos, conciliando o rigor técnico-científico com a aplicabilidade prática. Os resultados do Enxoé demonstram ainda o papel essencial das galerias ripícolas e da vegetação associada, não apenas como elementos de estabilidade física e paisagística, mas como componentes funcionais dos agroecossistemas, responsáveis pela prestação de serviços de ecossistema. O restauro das

margens fluviais reforça, assim, a capacidade adaptativa das paisagens agrícolas face a secas prolongadas e temperaturas extremas.

Em suma, a presente dissertação propõe um enquadramento aplicável a regiões áridas e semiáridas, onde a intermitência deve ser entendida como característica natural e funcional, e não como limitação de gestão. A integração entre dados de campo, análise espacial e enquadramento político evidencia a importância de abordagens interdisciplinares e multiescalares no planeamento e demonstra ainda o valor da cooperação transfronteiriça na gestão de bacias partilhadas ao promover a harmonização de metodologias, a partilha de dados e o uso eficiente dos recursos hídricos. Esta colaboração representa um passo decisivo para consolidar uma governação hídrica mais integrada, adaptativa e resiliente à escala da paisagem mediterrânica.

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