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Multicriteria Approach to Define Adequate areas for the Implementation of Ecosystem-based Adaptation Strategies

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ABSTRACT:
This concept was developed in the framework of a task of the C2IMPRESS Horizon Europe Project focused on disaster-resilient societies. It deals with the use of an Ecosystem-based Adaptation (EbA) approach to increase groundwater resources. The objective is to create conditions for sediment and water retention and storage. By contributing to mitigating water scarcity, if necessary using treated wastewater, this approach simultaneously develops local ecosystems and helps prevent wildfires. The main rationale is to use in-channel Managed Aquifer Recharge (MAR) methods, making use of natural topographical and geological features coupled with the potential upstream natural erosion and sedimentation processes to generate storage capabilities in areas where aquifers do not occur. To define the best areas, a multicriteria system is defined and an analytic hierarchy process (AHP) is applied to weight the relative importance of each criterion. The following criteria were defined, based on the objective and available information: Slope, Geology, Land Use, and Sediment generation potential. Use of treated wastewater as an alternate water resource (AWR) for infiltration is also considered. The methodology is applied to the Alva watershed located in Centre Portugal, where maps were produced to classify each criterion and AHP was used to produce the final maps.

Keywords: Drought resilience, flooding resilience, Analytic Hierarchy Process, Ecosystem-based Adaptation, Managed Aquifer Recharge

1. Introduction

The C2IMPRESS project (Co-creative improved understanding and awareness of multi-hazard risks for disaster resilient society, www.c2impress.com) is funded by the European Union through the Horizon Europe Programme. It aims to develop an innovative set of products that contribute to a more resilient society in the face of risks due to extreme weather events under different climate change scenarios.

There are four case study areas (CSA): Egaleo (Greece), Mallorca (Balearic Islands, Spain), Ordu (Turkey) and Centro Region (Portugal). In each of those study areas, different hazards are being studied, i.e., heat waves, wildfires, river floods, wave overtopping, and coastal floods. The Portuguese CSA, Centro Region, addresses several hazards in five different sub-areas: river flooding in Mondego river, wave overtopping and coastal flooding in Aveiro and Figueira da Foz areas, and its impact on ship mooring and manoeuvring in Aveiro and Figueira da Foz harbours, droughts in Alva River basin (a

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subbasin in Mondego river), impact of wildfires on surface water flow and groundwater flow and quality in Alva River basin, and also on Leirosa-Monte Real aquifer system.

Ecosystem-based Adaptation (EbA) is defined as "the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change." (CBD, 2009). This definition also includes the "sustainable management, conservation and restoration of ecosystems, as part of an overall adaptation strategy that takes into account the multiple social, economic and cultural co-benefits for local communities" (UNEP & UNDP, 2012). The last publication also states that EbA embraces the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. Watershed management is one of the EbA targets when considering revegetation or afforestation to control erosion and regulate water flow, thus attenuating flooding (Doswald and Osti, 2011).

This paper deals with climate change adaptation strategies, namely droughts, in Alva River basin (Figure 1), a 707.6 km2 watershed located in central Portugal. The region shows high temperatures and low precipitation values during Summer, being particularly vulnerable to water scarcity (CIBSE, 2019). Climate change projections for this area show an increase in temperatures and the decrease of precipitation for both RCP4.5 and RCP8.5 ensembles models scenarios until the year 2070 (Loureiro et al., 2017, CIBSE, 2019). These changes are likely to exacerbate the frequency and intensity of extreme events such as wildfires (Pausas & Keeley, 2021), as higher temperatures and reduced precipitation contribute to drier vegetation and prolonged drought conditions, creating more favourable environments for ignition and spread. The Alba River basin situation reflects patterns observed across other affected Mediterranean regions, underscoring this study's broader relevance. According to the IPCC Sixth Assessment Report, hydroclimatic trends indicate that the Mediterranean is predominantly vulnerable to the impacts of warming, notably prolonged and stronger heat waves, and increased drought in an already dry climate (Ali et al., 2022).

One measure to combat water scarcity is increasing groundwater resources. This may be achieved building sand dam reservoirs (aquifers) with locally generated sediments where natural, such as surface runoff, or alternative water resources (AWR), such as treated wastewater, can be retained and stored. The sand reservoir may be regarded as an EbA solution where water storage, infiltration conditions and vegetation growth are possible, allowing also the development of some economic activity (agriculture). The whole scheme may be also seen as a Managed Aquifer Recharge (MAR) solution (Zhang et al., 2020). These in-channel structures use the natural features of the terrain, such as the stream valley topographic profiles and the underlying geological features, allowing for the creation of wet conditions in dry areas or during drought periods, allowing to lower the risk of forest fires, so frequent in this region of Portugal (e.g., CTI, 2022). Sand dams have shown to also increase the amount of vegetated land cover as a result of the increased soil moisture (Ryan and Elsner, 2016), with potential impacts on ecosystem preservation (Dile et al., 2016), therefore supporting mitigating climate change impacts (Ritchie et al., 2021) with low initial investment costs (Castelli et al., 2022).

Finding the adequate location to create the conditions to raise these reservoirs using EbA solutions is the purpose of this article.

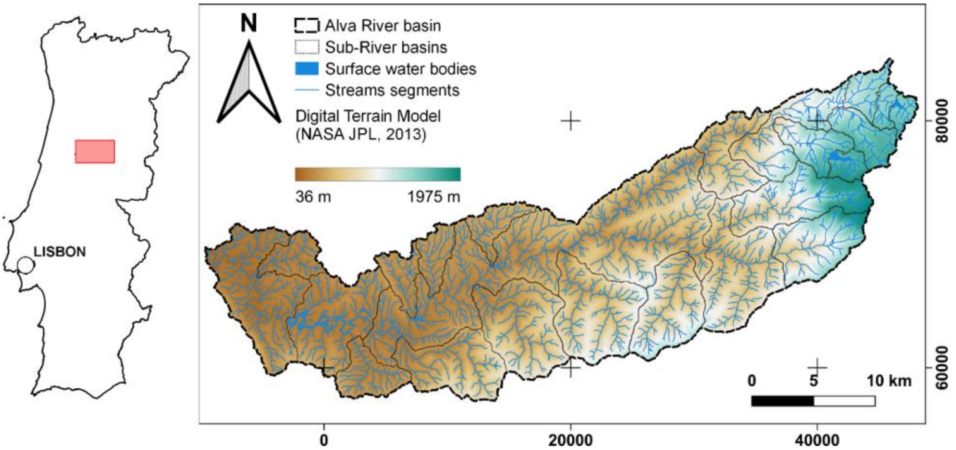

Figure 1: *Location and topography of the Alva River basin in central Portugal (coordinates in meters, EPSG 3763)*

2. Methodology

2.1 Criteria

A multicriteria decision analysis (MCDA) was performed using a set of properties which influence the development of sand dams. To develop a useful and applicable methodology, relevant information should be easily available. The considered set of properties is shown in Table 1, where an explanation of their contribution or importance to define the most suited places is provided. The classification of each criterion and corresponding standardisation, developed specifically for this analysis, is provided in the next subsections.

Table 1: Criteria and rationale used in the MCDA

Criterion	Rationale
Slope	The lower the slope, the more suitable the area is for locating the sand dam aquifer. A cutoff value was used above which the criterion assumes the minimum score.
Geology	This criterion regards both geology and overlying soil. The more impermeable, the better, as it allows water to remain stored.
Land Use	This is related with the physical space available to implement the solution. As more space is available, the more suitable is the area.
Sediment generation potential	The more prone an area is to generate sediments, the more suitable it is for implementing sand dam aquifers.

2.1.1 Slope

Slope is computed using the Digital Terrain Model provided by NASA JPL (2013) with an approximate resolution of 30 m. The standardisation of slope uses a slope cutoff value above which the criterion assumes the lower value of 0.1. Between 0 % slope and the cutoff slope value, defined as 5 % following the MCDA implementation presented by Bonilla Valverde et al. (2016), the suitability standardisation function for slope criterion is given Equation 1, presented in Figure 2.

$$\text{Standard slope} = 1+[(\%\ \text{slope})/(\%\ \text{cutoff value}) * (0.1-1)] \qquad \text{(Equation 1)}$$

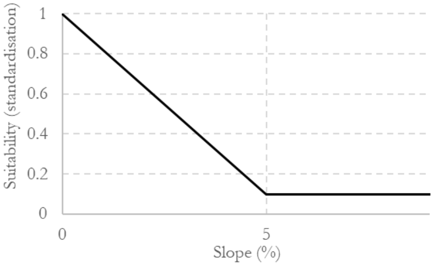

***Figure 2**: Standardisation function for slope criterion*

2.1.2 Geology

The legend of the geological formations represented in the Geology Map of Portugal at scale 1:500 000 (SGP, 1992) was classified in terms of general permeability characteristics. The classification is presented in a standardised form in Table 2.

Table 2: Standardisation of the Geology criterion based on the legend of the Geology Map of Portugal at scale 1:500 000

Geology code	Description	Standardisation
QUARTZ	Quartz and carbonated quartz	0.9
C1A	Western edge of the Lower Cretaceous: Torres Vedras sandstone; Almargem sandstone; Carrascal sandstone; Sandstones of Palhaça and Requeixo	0.3
OSG	Sanguinheira Group: sandstones and pelites	0.4
CBI	Undifferentiated	0.8
delt_l	Microdiorites, microandesites, lamprophyres and dolerites	0.8
OCA	Cácemes Group: ardoiferous schists, siltstones and sandstones	0.6
Q	Terraces, Sands and Gravels	0.1
g_22a	Quartzdiorites and biotite granodiorites	0.7
Q*	Glacial deposits of Gerês and Estrela	0.3
C1G	Buçaco Sandstones	0.4
OQABS	Armorican Quartzite Formation (Southwest Edge): Quartzites, conglomerates and schists	0.6
g_23d	Moscovitic-biotitic granites	0.8
PB	Gravel pits of the Beira Baixa Plateau	0.2
FI_N	Arkoses of Coja, Nave de Haver and Longroiva	0.5
g_13	Undifferentiated two-mica granite	0.7
g_23b	Porphyroid monzonitic granites	0.7
MF	Folques conglomerates and Vidoal lutites	0.6
g_22b	Granites and granodiorites	0.7
CBR	Fine-grained turbidites (Rosmaninhal Formation)	0.8
CBA	Almaceda Formation: turbidites	0.8

2.1.3 Land use

Land use has been previously used by Martins et al. (2024) in another application of a MCDA for a different general purpose. However, the used rationale (the more physical space available the more suitable) remains, and the same standardisation process applies. Table 3 presents the relations between the CORINE Land Cover 2018 map classes (EEA, 2020) and the standardised values.

Table 3: Standardisation of the land use criterion based on Corine Land Cover map class (Code_18)

Code_18	CORINE land cover 2018 class description	Standardisation
112	Discontinuous urban fabric	0.5
121	Industrial or commercial units	0
124	Airports	0.3
211	Non-irrigated arable land	0.6
212	Permanently irrigated land	0.6
221	Vineyards	0.5
223	Olive groves	0.5
231	Pastures	0.7
241	Annual crops associated with permanent crops	0.6
242	Complex cultivation patterns	0.6
243	Land principally occupied by agriculture, with significant areas of natural vegetation	0.6
311	Broad-leaved forest	0.5
312	Coniferous forest	0.5
313	Mixed forest	0.6
322	Moors and heathland	0
324	Transitional woodland-shrub	0.9
332	Bare rocks	1
333	Sparsely vegetated areas	0.9
334	Burnt areas	0.3
511	Water courses	0
512	Water bodies	0

2.1.4 Sediment generation potential

The sediment generation potential is computed using the Universal Soil Loss Equation (USLE). The use of USLE is common in Portugal at multiple scales and strongly related with the impact of wildfires and farming practices (see Meneses, 2014; Coutinho et al., 2015; Ferreira & Ferreira, 2019; Roque et al., 2023). For the case of the study area, plenty of published official information is currently available, namely several technical recommendations and manuals, allowing for a straightforward implementation.

USLE has known limitations, as discussed by Benavidez et al. (2018) and Kinnell (2019). It may not fully encompass the complexities of the rainfall-soil erosion but its implementation in watershed scale may provide a first-step information for identifying areas that require the use of soil conservation practices. The quality of this method's results is highly dependent on the quality of the base information (Kinnell, 2010) and granting that the parametrization of USLE components may be complex, other models (e.g., Revised USLE v2, WEPP), providing a more complete characterization of the erosion processes and dynamics, can require increased efforts to assemble without necessarily producing more reliable results (Tiwari et al., 2000).

The USLE, based on the works of Wischmeier and Smith (1978), represents the average annual soil loss (A) [$\text{ton.ha}^{-1}.\text{year}^{-1}$], calculated by the following formula:

$$A = 2.24 * R * K * (LS) * C * P \qquad \text{(Equation 2)}$$

In which R represents the Rainfall erosivity factor [American ton.feet.acre^{-1}.year^{-1}], K is the Soil erodibility factor [ton.h.MJ^{-1}.mm^{-1}], (LS) is the Topographic Steepness factor [-], C is the Land Cover Management factor [-] and P is the Erosion Control Practices factor [-].

R is directly available for the Portuguese continental territory from the Water Atlas published by APA (2010).

K was determined using as base information the soil chart at 1:100 000 scale for the northern Portuguese regions (DGADR, 2021) and for which the Soil erodibility factor values are defined by Geometral and Agroconsultores (2004a, b). The K values presented on Table 4 were assigned by relating the soil occurrences with the tables presented in Geometral and Agroconsultores (2004b).

Table 4: Classification of the soil erodibility factor (K) based on the subdominant soil classes

Subdominant soils classes (SSDOM) defined in Geometral and Agroconsultores (2004a)	K
UM.lep.hu; UM.len.hu; LP.um; LP.dy	0
UM.lep.hu; UM.len.hu; LP.um	0
CM.sk.dy; UM.hu.(sk,ha); CM.fv.dy; RG.dy.ha	0.01
RG.len.dy; RG.lep.dy; RG.dy.ha; UM.pa.hu	0.01
RG.dy.ha; LV.dy.ha	0.016
RG.ai.dy; RG.lep.dy; LP.dy; UM.hu.ha	0.016
LP.dy; LP.li; RG.len.dy; RG.dy.ha	0.016
RG.lep.(sk,dy); CM.sk.dy; RG.len.(dy,sk); UM.len.hu	0.011
LP.dy; UM.hu.sk; UM.len.hu; LP.um	0.011
CM.dy.(cr,ha); LV.sk.dy; RG.lep.dy	0.09
RG.dy.ha; FL.sk	0.005
UM.hu.(ha,sk); AT.pa.rg; CM.sk.dy; CM.fv.dy	0.005
RG.len.dy	0.005
AT.pa.rg	0.005
LP.um; LP.li; UM.len.hu; UM.hu.sk	0.012
CM.sk.dy; CM.len.dy; AT.pa.rg	0.013
CM.dy.(cr,ha); CM.sk.dy; RG.len.dy	0.013

LS factor computation relied on the procedures provided by Reis and Pena (2020) for the Portuguese territory. Uses as the main base layer the Digital Terrain Model provided by NASA JPL (2013) with an approximate resolution of 30 m.

C was characterised based on the CORINE Land Cover 2018 map (EEA, 2020) and the tables presented in Pimenta (1999) that relate the map legend with the C factor (Table 5). The description of each land use class code was presented in Table 3.

P factor was set equal to 1 (P = 1) as recommended by CNT (2025) for the situations in which no detailed information exists but, most of all, from the observation that this factor tends to create unrealistic results in the computation of soil erosion potential.

After the computation of the Universal Soil Loss (A) using Equation 2, and following the classifications defined for soil loss of other works (Fang and Fan, 2020, Panagos et al., 2020, Golijanin et al., 2022, Tesema et al., 2024), the results were standardised as shown in Table 6.

Table 5: Classification of Land Cover Management factor (C) based on Corine Land Cover map class (Code_18)

Code_18	C	Code_18	C	Code_18	C
112	0.01	231	0.02	322	0.05
121	0.01	241	0.4	324	0.05
124	0.01	242	0.2	332	0.05
211	0.4	243	0.3	333	0.05
212	0.2	311	0.1	334	0.05
221	0.2	312	0.1	511	0.005
223	0.1	313	0.1	512	0.005

Table 6: Standardisation of the Sediment generation potential criterion

Value of A (soil loss) [ton.ha^{-1}.year^{-1}]	Description	Recommendation	Standardisation
0	Null	None	0
0-2	Very low (natural)	Ideal situation, no need to act	0.2
2-5	Low (acceptable)	Monitor, may not require additional measures	0.4
5-10	Moderate	Take basic conservation measures	0.6
10-20	High	Implement urgent conservation practices	0.8
>20	Very high	High risk of degradation, reevaluate the land use	1.0

2.2 Analytic hierarchy process

An analytic hierarchy process (AHP) method using pairwise comparison was applied to weight the relative importance of each criterion. The description of this methodology can be found for instance in Saaty (1987), or Martins et al. (2024). Synthetically, it consists in comparing all the possible pairs of criteria and stating the relative importance of one criterion over the other. This can be achieved using a scale from 1 to 9 where, in the range limits, 1 reflects that both criteria have similar importance, and 9 means the first criterion is of extreme importance in relation to the second criterion. Increasing intermediate values reflect the intensification of the relative importance of the first criterion compared to the second one. Exemplifying, if criteria 1 has strong importance over criteria 2, a value of 5 is assigned. The reciprocal value would be applied for the opposite comparison: criteria 2 has an importance of 1/5 compared to criteria 1. A detailed explanation can be found in Saaty (1980, as cited in Vanier et al., 2006).

Three sets of pairwise comparisons were carried out by the authors of this paper. Each author produced a square matrix, and for each matrix the parameter's weights were computed. The evaluation of the individually produced matrixes was followed by brief meetings between the authors to understand (1) potential lack of understanding of specific criteria, (2) a clear understanding of the problem to be addressed, which is fundamental to provided proper criteria weighting, and (3) discuss potential biased results. The average criteria weight was also calculated. For the pairwise comparison to be accepted a maximum consistency ratio (CR) of 0.1 is advisable (cf. Saaty, 1987). Otherwise, the pairwise comparison procedure reveals inconsistencies and should be revisited.

2.3 Exclusion areas

Exclusion areas represent zones where sand dam reservoirs should not be implemented due to physical and/or legal restrictions. First, these areas should be in the valleys. Secondly, these valleys should be located on the heads of small rivers or creeks, so that the status of the hydromorphological elements supporting the biological elements for the surface water, as required by the Water Framework Directive (OJEC, 2000), is fulfilled (most importantly the river continuity). Additionally, wellhead protection areas were treated as exclusion zones, as any MAR intervention within the River basin may be seen by the water authority as disrupting natural recharge processes, potentially affecting both the quality and quantity of water at the well.

To select the adequate areas, only the 1st order water courses (using the Strahler stream order classification), meaning the most upstream rivers, were considered, and a 100 m buffer (50 m distance for each stream bank) was contemplated along these water courses. The water courses and the Strahler classification is available at SNIAmb (2006).

2.4 Final Score

To obtain the final values for the computation of the most suitable places for the location of the sand dam reservoirs, considering the non-excluded areas defined in 2.3, the computed weights (W) presented in Table 8 are multiplied by the standardised values of the criteria (S) characterised using the procedures outlined in section 2.1:

$$\text{Final score of suitability} = W_{Slo} \,.\, S_{Slo} + W_{Geo} \,.\, S_{Geo} + W_{LU} \,.\, S_{LU} + W_{SGP} \,.\, S_{SGP}$$

(Equation 3)

To define the more appropriate areas, a minimum threshold value of 0.6 was considered. All areas presenting a Final score equal or greater than this threshold are considered adequate to implement the sand dam reservoirs.

3. Results

The results of the classification and standardisation of each criterion are represented in Figure 3.

The pairwise comparison was performed by the three authors (Table 7). It can be observed the assignment of different weights. The consistency ratio (CR) demonstrates the adequacy of the comparison.

Figure 4 presents the selected stream buffers where at least a part of its area presents a final score of suitability above the chosen threshold value of 0.6. The same figure represents the portion of the buffer above that threshold (for instance, 0.5 means 50 % of the area of that buffer presents a final score of suitability of 0.6 or above – the maximum is 1).

Table 8 summarises the results obtained using the weights provided by each author and using the average of the weights, expressed in terms of the total area of the buffers, which is 76.03 km^2, representing approximately 11% of the Alva River basin area.

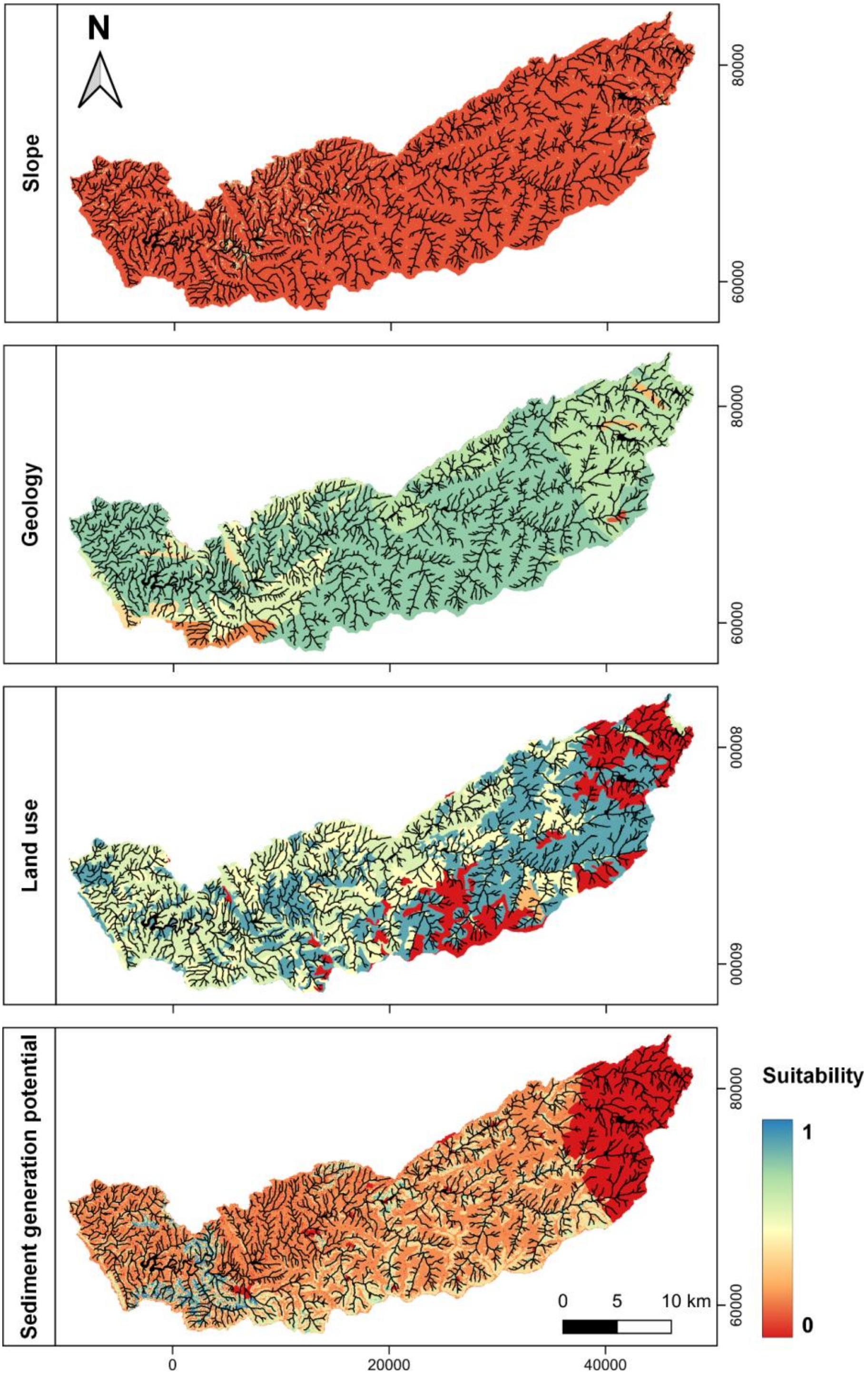

Figure 3: *Standardized maps for the criteria considered in the MCDA*

Table 7: Pairwise comparison matrices and computation of the weight of each parameter

	Author A					Author B					Author C					Authors' average
	Slo	Geo	LU	SGP	**W A**	Slo	Geo	LU	SGP	**W B**	Slo	Geo	LU	SGP	**W C**	**W av**
Slo	1	1	2	1/3	**20%**	1	2	5	1/3	**28%**	1	1	3	1/5	**16%**	**21%**
Geo	1	1	3	1	**29%**	1/2	1	3	1/2	**19%**	1	1	5	1/3	**21%**	**23%**
LU	1/2	1/3	1	1/5	**9%**	1/5	1/3	1	1/5	**7%**	1/3	1/4	1	1/7	**6%**	**7%**
SGP	3	1	5	1	**42%**	3	2	5	1	**47%**	5	3	7	1	**57%**	**49%**
CR					**0.04**					**0.06**					**0.04**	

Slo = slope, Geo = geology, LU = land use, SGP = sediment generation potential, CR = consistency ratio, W = weight (authors A, B, C), W av = weight average

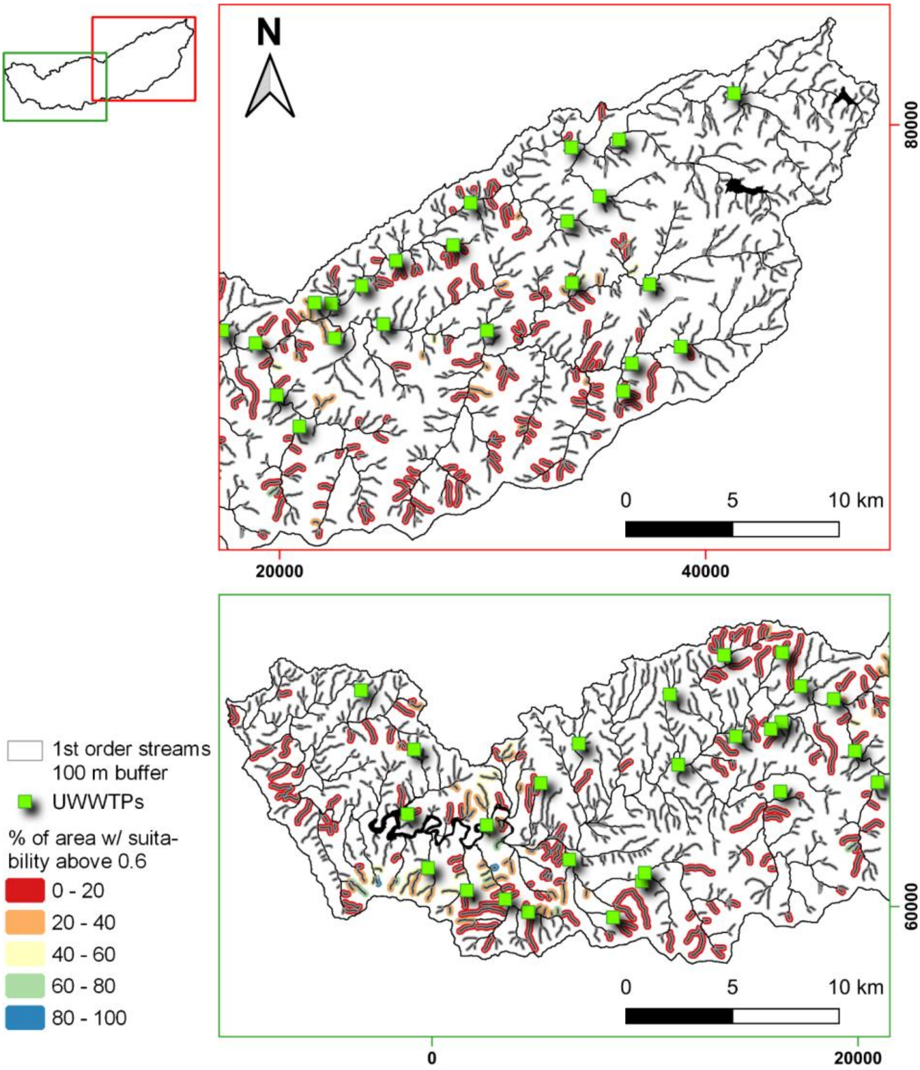

Figure 4*: Identification of the percentage of the area per buffer where the Final score of suitability is above the threshold value of 0.6*

Table 8: Percentage of the stream buffer area where the Final score of suitability is above the threshold of 0.6

	Author A	Author B	Author C	Authors' average
% of the stream buffer area with Final suitability score equal or higher than 0.6	4.00	2.24	4.73	2.96

Besides creating natural conditions to increase sediment and water storage, one of the objectives was to use treated urban wastewater as an alternative water resource to increase storage. In that sense the results obtained and represented in Figure 4 were also interpreted in terms of conditions to store that source of water. A major condition is that the Urban Wastewater Treatment Plant (UWWTP) has at least secondary treatment process and is located in or close to the selected areas. In total, Alva River basin has 45 UWWTP. It is observed that only 4 UWWTP are located in the considered 100 m buffer zones, which represent only 1.2 % of the stream buffer areas classified as suitable (any percentage of area with a suitability classification of 0.6 or above). Expanding the search area to a 500 m buffer zone along the stream (i.e., 250 m from each stream bank) results in the inclusion of 15 UWWTPs within the defined suitable buffers. It is important to note that in this preliminary analysis no clear information is provided regarding the volumes and the quality of the treated urban wastewater, which can ultimately deem the UWWTP as non-adequate as source for EbA.

4. Conclusions

The presented sand dam reservoir scheme is regarded as an EbA enabling MAR to face future situations of climate change. Climate models for the area predict a general reduction in the amount of precipitation, more concentrated precipitation episodes in time, and rising temperatures. These EbA are sediment reservoirs resulting from local erosion processes. They allow water storage, enable vegetation growth and biodiversity, promote the development of some economic activity (agriculture), therefore improving ecosystem services to support adaptation to climate change. Augmenting water storage increases resilience of local communities to drought periods and contributes to reduce floodings downstream in wet periods. Besides, it allows the use of treated wastewater, as an alternative water resource (AWR).

As the construction of dams may be seen as a counter effective measure particularly under the *free-flowing rivers* targets defined by EU Nature Restoration Regulation (European Parliament, 2024), that break the continuity of a river, the construction of small artificial weirs, even if with natural materials, is deemed only for the first order watercourses, meaning that only the uppermost parts of the streams are contained, thus ensuring the continuity throughout most part of the river.

The need to make use of significant areas of land is often the greatest challenge in river EbA projects. Communities can be opposed to changes in land, either due to loss of land or through perceived security issues (Doswald and Osti, 2011). However, in the studied case, the land use may not be a major obstacle, as the involved areas are relatively small and there is a benefit that reverts to the communities, creating new forms of water storage and ecosystems that rely on them. Moreover, creating wetter zones can reduce the vulnerability of this highly exposed area to wildfires.

During the development of this study, the conduction of the pairwise comparison showed that the three authors understood the situation under analysis differently, obliging them to talk and to make clearer what was at stake. This showed that, before conducting an analytic hierarchy process (AHP), a clear statement of the objective of the study and an explanation of the considered criteria is required, otherwise contradictory results may be obtained. To reduce subjectivity, further developments of this methodology may include the consultation of an increased number of experts with knowledge of the local challenges and specificities. This has been already done in previous works (for instance Martins et al., 2024).

As a result of this study, it was possible to have a preliminary assessment of what would be the most suitable areas for the implementation of the sand dams in the Alva River basin, developing EbA solutions and, if possible, also using treated urban wastewater as an AWR. Addressing the use of this source of water in EbA will require overcoming regulatory barriers, as in Portugal no clear guidelines and qualitative thresholds are yet in place. The use of this resource raises concerns in the Water Authority strongly related with emerging organic contaminants. Therefore, contamination risk concerns are being addressed in other EU-funded projects (e.g., MARCLAIMED project), not only by putting in place the necessary technologies and monitoring capabilities for safeguard quality and safety, but also to increase awareness of the benefits of making use of AWR, particularly in foreseeable context of future increased stress induced over the conventional water sources.

This work also represents a first step for promoting EbA solutions as a complementary process for water resources management at watershed level, in line with both EU climate adaptation goals and restoration strategies. Future implementation will require detailed impact assessment studies to quantify and evaluate the potential social benefits, estimate costs, characterise retained water volumes and establish expected biodiversity improvements at local scale.

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