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Rainwater harvesting in catchments for agro-forestry uses: A study focused on the balance between sustainability values and storage capacity

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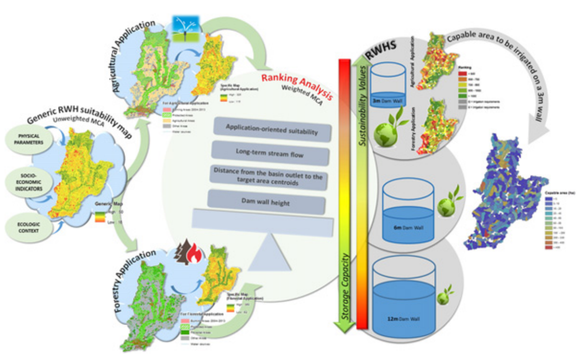
HIGHLIGHTS

- Improved rainwater harvesting suitability model is presented.
- The harvested rainwater is to be used in irrigation or wildfire combat.
- The model differs from others because it uses dam wall height as evaluation parameter.
- The use of small height dam walls can greatly limit irrigable area.
- More engineered dams are more suited for larger-scale agro-forestry uses.

GRAPHICAL ABSTRACT



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ABSTRACT

Rainwater harvesting (RWH) is used to support small-scale agriculture and handle seasonal water availability, especially in regions where populations are scattered or the costs to develop surface or groundwater resources are high. However, questions may arise as whether this technique can support larger-scale irrigation projects and in complement help the struggle against wildfires in agro-forested watersheds. The issue is relevant because harvested rainwater in catchments is usually accumulated in small-capacity reservoirs created by small-height dams. In this study, a RWH site allocation method was improved from a previous model, by introducing the dam wall height as evaluation parameter. The studied watershed (Sabor River basin) is mostly located in the Northeast of Portugal. This is a rural watershed where agriculture and forestry uses are dominant and where ecologically relevant regions (e.g., Montezinho natural park) need to be protected from wildfires. The study aimed at ranking 384 rainfall collection sub-catchments as regards installation of RWH sites for crop irrigation and forest fire combat. The height parameter was set to 3 m because this value is a reference to detention basins that hold sustainability values (e.g., landscape integration, environmental protection), but the irrigation capacity under these settings was smaller than 10 ha in 50% of cases, while continuous arable lands in the Sabor basin cover on average 222 ha. Besides, the number of sub-catchments capable to irrigate the average arable land was solely 7. When the dam wall height increased to 6 and 12 m, the irrigation capacity increased to 46 and 124 sub-catchments, respectively, meaning that more engineered dams may not always ensure all sustainability values but warrant much better storage. The limiting parameter was the dam wall height because 217 sub-catchments were found to drain enough water for irrigation and capable to store it if proper dam wall heights were used.

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1. Introduction

The access to clean and potable water is a fundamental human right. Water is essential for all life forms and a foundation for the socio-economic development, being used in many different ways such as in the agricultural, domestic, industrial, power generation and recreation uses. It is also a fundamental part of the ecosystem on which reproduction of biodiversity depends (FAO, 2003; Sivanappan, 2006). Rainwater is the most directly accessible water supply source. Rainwater harvesting (RWH) comprises the collection, treatment and storage of rainwater for future use, as either principal or supplementary water source (Fewkes, 2006). Rainwater can be stored in the soil or behind manufactured dams, as well as in tanks or containers, for productive use like drinking water, water for livestock and for irrigation. It can also be redirected to recharge aquifers (Isioye et al., 2012). This method of water storage has a long history and has been used by ancient civilizations worldwide to support agriculture and to cope with seasonal water availability (Fewkes, 2006; UNEP, 2014). The mitigation of rainfall variability in time and space plays a central role in rainwater harvesting, but other advantages can also be mentioned such as improvement of water retention in the landscape, the low-cost provision of water for basic human needs and other small-scale productive activities, or the decentralized control of storm water runoff (Bellu et al., 2016; Kahinda et al., 2008, 2007; Mesbah et al., 2016; Palla et al., 2011, 2012; Rockström and Barron, 2007). Besides the operational advantages, RWH and storage is an accessible option in areas with dispersed populations or where the exploration costs of other water resources are high (Mati et al., 2006).

There is an ample variety of rainwater harvesting techniques, while the choice for a specific solution greatly depends on the application (UNEP, 2014). Agro-forestry uses often resort to the so-called field RWH where the rainfall collection area is a watershed. Field systems can distinguish between in-field RWH (IRWH) or ex-field RWH (XRWH) variants (Kahinda et al., 2008). IRWH systems have the target area inside and XRWH outside the rainfall collection watershed. The practice of field RWH (both IRWH and XRWH) is frequently concerned with ecological sustainability values, namely through the aesthetic landscape enhancement, sustainable drainage and environmental protection (Kahinda et al., 2008; Kahinda and Taigbenu, 2011; Terêncio et al., 2017). Standing on this paradigm, water managers will tend to follow concepts and attend building requirements of sustainable flood retention basins in the conception and installation of field RWH systems (Robinson et al., 2010; Scholz, 2007; Scholz and Sadowski, 2009; Scholz and Yang, 2010; Yang et al., 2011). The question to pose is if these systems are capable to store enough water when a fixed volume of this resource is required to supply the application, for example the irrigation of a crop area with pre-defined dimension. A common building restriction of field RWH systems is the dam wall height. To naturally or easily cope with the aforementioned ecological sustainability values, dam wall heights must not exceed $\approx$3 m (Yang et al., 2011). In general, the harvested rainwater stored in the reservoir created by a 3 m-high wall is limited and may not fully accomplish the irrigation requirements. Thus, the balance between ecological sustainability and storage capacity requires that suitability models of field RWH systems use the dam wall height as application constraint. It is worth mentioning that installation of more engineered dams may become essential for development of an irrigation project, but they should preserve sustainability values anyway. In these cases, the design and construction guidelines of a dam should cope with this condition.

The Food and Agriculture Organization has published a list of factors commonly used in models to identify proper RWH sites, which includes climatic, hydrological, topographical, agronomic, edaphic and socioeconomic variables (FAO, 2003). This list is a reference but cannot be used universally because specific factors are meant to predefined purposes. For example, if the purpose is to find sites to supply rainfed agriculture (present case), factors like distance from rainfall collection and application areas or the aforementioned dam wall height are very important. But if the intention is to improve groundwater recharge, then site selection factors must include topographic, altimetric or geologic indicators (Pacheco, 2015; Pacheco and Van der Weijden, 2014a, 2014b). In the last decades, a number of techniques have been developed to assess site suitability based on specific variables (Mati et al., 2006; Mbilinyi et al., 2007; Mou et al., 1999; Patrick, 1997; Prinz et al., 1998; Senay and Verdin, 2004; Terêncio et al., 2017). Kahinda et al. (2008, 2009) developed a GIS-based comprehensive model, which combines physical, ecological and socio-economic attributes, to assess the suitability of a given area to field RWH in South Africa. Although fairly complete, the Kahinda model does not consider constraints such as dam wall height. Recently, Terêncio et al. (2017) incorporated the dam wall height as variable in a site allocation model, but as output from the modeling run instead of a predefined constraint. Thus, the main purpose of this study is to generalize the use of dam wall height as evaluation parameter. To accomplish this goal, the following tasks need to be completed: (1) To apply the model by Terêncio et al. (2017) in a predefined watershed using specific irrigation settings (irrigation area, corresponding volume of harvested rainwater). This model distinguishes a planning workflow (focused on catchment characteristics) from an application workflow (focused on application constraints). In the end, a number of sub-catchments are ranked according to their rainfed irrigation and wildfire combat suitability; (2) To use the dam wall height as predefined application constraint, assuming values between 3 and 12 m; (3) To map storage capacity of RWH dam reservoirs based on the various heights, making the proper interpretation as regards irrigation competence; (4) To map the dimension of irrigation projects in the studied watershed, capable of being supplied from a RWH system with 3 m-high dam wall. This task will be focused on rainfall collection sub-catchments unable to supply the predefined irrigation requirements; (5) To discuss the ecological impacts resulting from the installation of more engineered structures. The use of the dam wall height as iterative input parameter allowed exposing how low cost naturally sustainable dams compare with more costly and less sustainable structures as regards storage capacity and ecological impacts, an achievement not reported before to our best knowledge.

2. Materials and methods

2.1. Study area

The Sabor River is an Iberian water course located in the Trás-os-Montes and Alto Douro (Portugal) and Castile-Leon (Spain) regions, being one of the most important tributaries of Douro River (Fig. 1). The Sabor watershed drains an area of approximately 3297 km^2, largely concentrated in the Portuguese territory (2742 km^2) (APA and ARHNorte, 2012; Gaspar et al., 2016; Silva, 2010). The main water course runs from northeast to southwest along narrow beds and banks bordered by steep hillsides in most of its catchment. The headwaters rise to an altitude of approximately 1600 m·a.s.l, being located in Zamora province (Spain). The river crosses the border in the area of the Montesinho Natural Park and flows along 120 km until it reaches the mouth in Torre de Moncorvo, at an altitude of 97 m (CIMPOR, 2017; Gaspar et al., 2015).

Geology is characterized by alternating igneous and metamorphic rocks (Silva et al., 1989), as well as strong local neotectonic activity (Gaspar et al., 2016; Pereira and Azevedo, 1995). The lithologic inventory is very diverse, comprising autochthonous and parautochthonous Palaeozoic metasediments (quartzites, phyllites), allochthonous mafic and ultramafic rocks (amphibolites, serpentinites, flaser gabbros), and

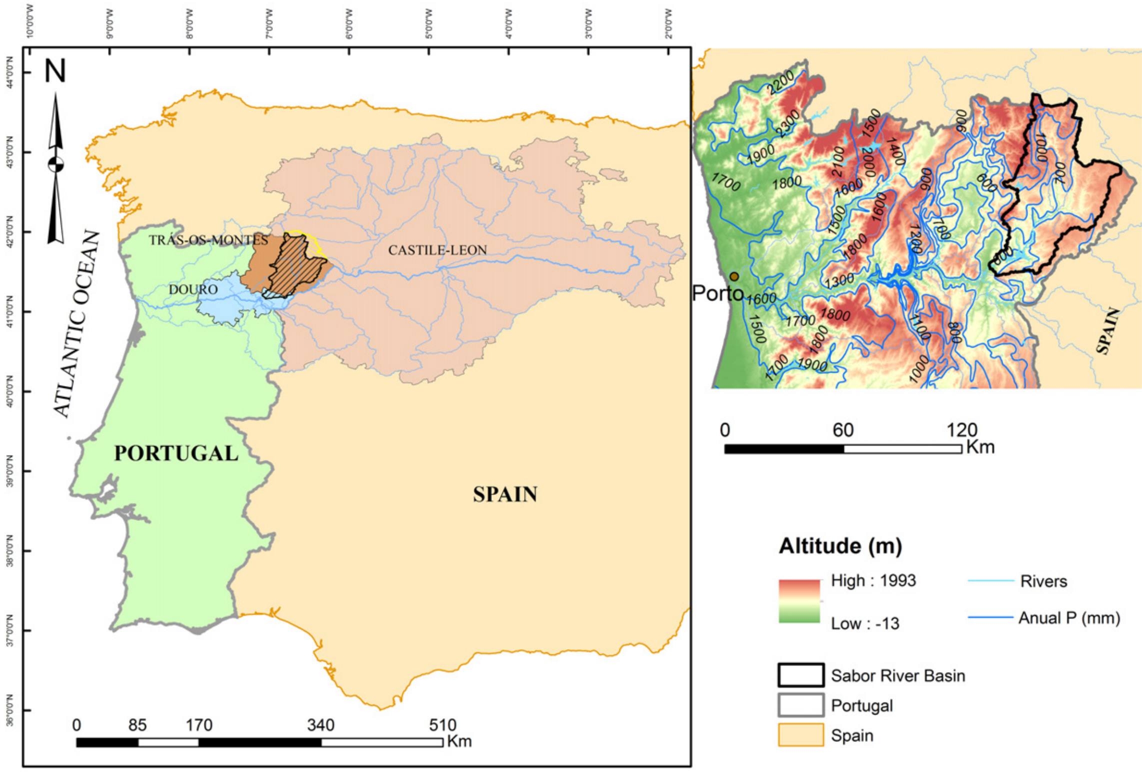

Fig. 1. Location, topography, drainage network and precipitation contours in the vicinity of the study area (Sabor River basin, Portugal).

Hercynian granites. Leptosols predominate in the entire Sabor river basin, namely the umbric leptosols (Agroconsultores e Coba, 1991; FAO, 2003).

The Mediterranean climate prevails in the Sabor River watershed. Temperature (T) ranges from 1 °C in winter to 27.6 °C in summer (Gonçalves, 1985). Precipitation (P) approaches 730 $mm \cdot yr^{-1}$ (SNIRH, 2017), while potential evapotranspiration (ETP) reaches 718 $mm \cdot yr^{-1}$, ranging from 14 mm in January to 128 mm in July (APA and ARHNorte, 2012). These data refer to the climatological norms of 1961–1990 (T) and 1981–2010 (P, ETP), respectively. In general, precipitation increases towards the Northeast direction (Fig. 1) following the increase in altitude (Nunes, 2015). The largest stream flows are concentrated in autumn and winter months. From July to September, the flows decrease substantially, even to zero in the driest years (APA and ARHNorte, 2012; Nunes, 2015).

The 2012 Corine Land Cover survey published by the European Environmental Agency (https://www.eea.europa.eu) identified 43.2% of forests and shrubs, 56.2% of agricultural areas, 0.46% of artificial surfaces, and 0.14% of water bodies. On average, irrigation of crop land consumes 6733 m^3 of water per hectare per year (INE, 2011). The Sabor river basin crosses several municipalities of Trás-os-Montes and Alto Douro region, namely Bragança, Alfandega da Fé, Macedo de Cavaleiros, Miranda do Douro, Mogadouro, Vimioso and Torre de Moncorvo. However, the population density is not very high. The 2011 demographic census revealed an average density of 27 $inhabitants \cdot km^{-2}$ within the Portuguese sector of Sabor River basin (INE, 2017).

A large area (≈40%; please see Fig. 3 below) of Sabor River catchment is legally classified as Nature Network 2000, here represented by various Community Importance Sites (CIS), Protected Areas (PA) and Special Protection Zones (SPZ). In these sensitive areas, human activities should be adapted to cope with the protection of important habitats and species (ICNF, 2017). The Sabor Valley is further classified as Important Bird Area by Bird Life International (Melo et al., 2010). The Sabor River has recently (2013) been dammed near the mouth with the purpose of hydropower generation (http://snirh.apambiente.pt/). This dam affects the Nature Network Site called "Rios Sabor e Maçãs", which has been classified as SCI and SPZ (PTZPE0037) under the Birds and Habitats Directives, because the site shelters various habitats as well as animal and plant species of Community interest.

2.2. Framework model

The framework model of Terêncio et al. (2017) is composed of two workflows: the planning workflow and the allocation workflow. This study makes no changes to the planning workflow but introduces a number of improvements to the allocation workflow. The next subsections comprise a brief description of both workflows, becoming more detailed where the allocation workflow was improved.

2.2.1. Planning workflow

The planning workflow (Fig. 2a) creates maps for a set of relevant physical parameters, socio-economic indicators and ecological contexts, as listed in Table 1. The physical parameters characterize the catchment for water resources availability and storage capacity, based on annual rainfall volumes, runoff coefficients (curve number), soil texture classes and soil profile depths. The socio-economic indicators set up the potential demand on water for irrigation, based on the spatial distribution of land uses (e.g., crop lands) and population density, while depicting the quality of available surface water (e.g., expressed as Chemical Oxygen Demand – COD – and Biochemical Oxygen Demand – BOD_5). The ecologic contexts describe the catchment's vulnerability to hazards that can affect agro-forestry uses, such as wildfires (expressed as wildfire risk) or soil erosion (expressed as terrain slope), and characterize the watershed for sensitive areas such as stream banks or legally protected regions (e.g., natural parks). The obtained maps are combined in a so-called non-weighted Multi Criteria Analysis (MCA) to produce a generic suitability map for the installation of RWH infrastructures. The weighting of parameters frequently operated in MCA models is not

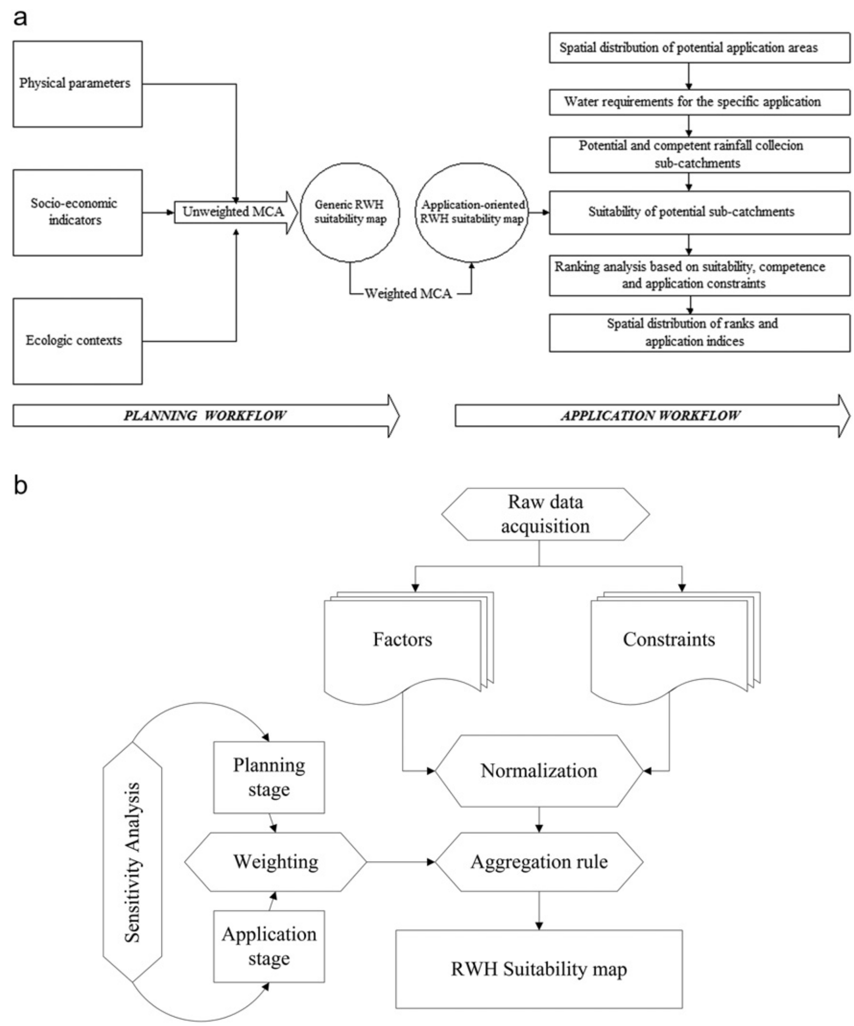

Fig. 2. a – Rainwater harvesting (RWH) suitability model, comprising the planning and allocation workflows. The details on the model are provided in the text. Adapted from Terêncio et al. (2017). b – Flowchart describing the spatial Multi Criteria algorithm embedded in the RWH suitability model (Fig. 2a).
Adapted from Terêncio et al. (2017).

implemented at this stage, because weights may differ according to the application.

2.2.2. Allocation workflow

Having finished the planning workflow, one executes the allocation workflow (Fig. 2a) to identify the best places to install RWH systems in the studied watershed. In the Terêncio et al.'s (2017) version of this algorithm, the first step towards accomplishing this task was to define a specific irrigation project and its fundamental settings: geographic location, spatial incidence (i.e., area to be irrigated – a, ha), rainfall collection catchment and specific water requirements (v, $m^3 \cdot ha^{-1} \cdot yr^{-1}$), which set up the project's water demand ($V_0 = v \times a$, $m^3 \cdot yr^{-1}$). In the improved algorithm (present study), the analysis is extended to all potentially irrigated areas (arable land) with a spatial incidence wider than a predefined threshold (e.g., $a \geq$ average arable land area). Put another way, while the Terêncio et al. (2017) work produced a suitability map for an entire watershed but an allocation map for a single site (the project area), the present work generates suitability and allocation maps for the entire studied area generalizing the previous work. The value of v is not changed because Terêncio et al. (2017) adopted an average water requirement, applicable as proxy to any type of crop. An additional improvement to the allocation workflow was the planning of forestry uses (e.g., wildfire combat) in compliment to the irrigation use. The basic idea was to define rainfall collection sites based on the irrigation requirements and then see how these sites cope with the forestry use.

Having defined a potential use for harvested rainwater, the weights of physical, socio-economic and ecological variables are adjusted to the application specificities, assuming values between 1 and 5 (Table 1). In case the application is irrigation (as in Terêncio et al., 2017) then the weights of socio-economic parameters (e.g., Agriculture areas) and some of their indicators (e.g., Annual crops) are maximized (equated to 5) to ensure proximity between these areas and the optimal RWH sites. If otherwise the intended use is forestry, then the maximized variables are the ecological contexts as whole and some of their indicators (e.g., wildfire risk). Subsequently to the weighting, the MCA algorithm is rerun to update the generic suitability map into an application-oriented version.

Besides defining the application-oriented suitability, the allocation workflow seeks for all sub-catchments within the studied watershed potentially capable of feeding the RWH systems with V_0 every year. This search is based on engineering formulae, which set up a relationship between V_0 and sub-catchment area (A_0). Sub-catchments with area $A \geq A_0$ are considered potentially competent. Validation of competence is attained by comparison of V_0 with long-term river flows ($V_d = Q \times A$, where Q is the sub-catchment mean river flow usually expressed in $mm \cdot yr^{-1}$ and obtained from stream flow records). In case $V_d \geq V_0$, the sub-catchment is considered competent.

A last improvement to the allocation workflow is related to changes in the so called ranking analysis. This step ranks the scores of suitability, Q and two application constraints. These partial ranks vary between 1

Table 1
Parameterization of Multi Criteria Analysis (MCA): explicative factors, assembled by groups and divided into classes with predefined suitability scores; Boolean constraints, scored as "no data"; weights of factors and groups of factors (values inside brackets), as adopted in the agriculture (boldface values) and forestry (italic values) applications.

Attribute	Class number	Measurement unit	Score	RWH suitability
Physical parameters (**3**, *3*)				
Rainfall (**1**, *1*)	1	mm·yr^{-1}	0–100	1
	2		100–200	2
	3		200–400	5
	4		400–600	4
	5		600–800	3
	6		800–1000	3
	7		>1000	1
Curve number (**1**, *1*)	1	Dimensionless	0–20	5
	2		20–40	4
	3		40–60	3
	4		60–80	2
	5		80–100	1
Soil texture (**1**, *1*)	1	% clay	0–6	1
	2		6.1–15	4
	3		15.1–25	5
Soil depth (**1**, *1*)	1	m	>0.75	5
	2		0.4–0.75	4
	3		0.3–0.4	3
	4		0.2–0.3	2
	5		<0.2	1
Socio–economic indicators (**5**, *1*)				
Population density (**3**, *1*)	1	inhabitants·ha^{-1}	0.065524–0.216527	1
	2		0.216528–0.882593	2
	3		0.882594–3.820569	3
	4		3.820570–16.779809	4
	5		16.779810–73.942251	5
Agriculture areas (**5**, *1*)	1	Dimensionless	Annual crop	5
	2		Pastures	4
	3		Permanent crops	3
	4		Heterogeneous	1
	5		Other	No data
Water quality (**1**, *1*)	1	mg·L^{-1} (BOD)	<1	5
	2		1–1.8	4
	3		1.8–2.6	3
	4		2.6–3.4	2
	5		>3.4	1
	1	mg·L^{-1} (COD)	<2.4	5
	2		2.4–11	4
	3		11.0–13.0	3
	4		13.0–21. 0	2
	5		>21	1
Ecological contexts (**1**, *5*)				
Wildfire risk (**1**, *5*)	1	Dimensionless	Low	1
	2		Low–moderate	2
	3		Moderate	3
	4		High	4
	5		Very high	5
	6		Urban	No data
	7		Hydrography	No data
Protected areas (**1**, *5*)	1	Dimensionless	Outside	1
	2		Inside	5
Stream banks (**1**, *1*)	1	Dimensionless	Outside	1
	2		Inside	5
Terrain slope (**1**, *1*)	1	%	0–5%	5
	2		5%–10%	4
	3		10%–15%	3
	4		15%–30%	2
	5		>30%	1

and m, where m is the number of sub-catchments. For variables suitability and Q the ranks increase proportionally to the variable scores. For the application constraints, a detailed explanation is provided below. The overall rank is the sum of partial ranks. The first application constraint is the distance from the sub-catchment outlet to the application area (D), because it influences water transport costs. The second constraint is the dam wall height (H) because it influences building costs, landscape integration and storage capacity. In the Terêncio et al. (2017) work, the application workflow ranked the potentially capable sub-catchments according D by assigning higher scores to shorter distances. In that work, the application area had a precise location inside the studied watershed and the suited rainfall collection sub-catchments were all candidates to irrigate that area. In the present study, application areas are distributed all over the watershed while rainfall collection sub-catchments can irrigate by gravity flow a number of n areas located downstream. The larger the n the larger is the sub-catchment rank, because larger n values may reduce water transportation costs via scale economy effects. In order to account for the combined influence of D and n scores in water transportation costs, the allocation workflow in this study replaced D by a normalized D, equated to $Dn = D / n$ (m). In this context, potentially capable sub-catchments that are close to numerous application areas will be given the highest Dn ranks. The rationale behind Dn holds for the use of RWH systems in agriculture, because economic sustainability of these systems is favored through crop irrigation by gravity flow. For the use in wildfire combat, the D parameter is adequate (regardless the altitude relationship between rainfall collection and application areas), if assuming that water for fire extinction is mostly thrown from airplanes. In the Terêncio et al. (2017) work, the value of H represented the minimum dam wall height required to store V_0 in the RWH system. Put another way, H was a model output in that study. In the present work, the dam wall height changed from output to input assuming predefined values: 3 m, 6 m and 12 m. The first value represents a low-cost infrastructure that can be easily integrated in the landscape. Besides, the ecological disturbance in and around the dam and the associate lake is expected minimal. When a network of these structures is distributed across the watershed, it can create a pleasant green mosaic landscape, but the overall storage capacity will be small. The higher H values represent progressively larger-cost infrastructures with poorer integration ability and potentially large ecological implications, but that can store larger volumes of water. To handle the balance between building costs/landscape integration and storage capacity, the H ratio has been defined, which replaced the H value of Terêncio et al. (2017) in this study. The H ratio is calculated for each predefined dam wall height as the quotient between the volume of harvested water stored behind the dam wall (V_s) and the volume required for irrigation (V_0). The RWH sites with $H = V_s / V_0 \geq 1$ are capable to supply all the required water, while sites with $H < 1$ are not. It is expected that green mosaic landscapes (network of RWH sites storing harvested rainwater behind a 3 m-high dam wall) comprise a large number of sites with $H < 1$. For those landscapes, the allocation workflow provides information on the maximum irrigable area.

2.3. Model development

The planning workflow is a spatial MCA to be operated by GIS software. The procedure involves the execution of five tasks (Siqueira et al., 2017; Valle Junior et al., 2014, 2015): (*a*) *Raw data acquisition*. Explicative factors and Boolean constraints (in short called attributes) are defined and scored, and then a thematic map is drawn to illustrate the spatial distribution of attribute scores; (*b*) *Normalization*. To become comparable, attributes are recast to a common scale; (*c*) *Weighting*. Considering the contribution to the study goal, explicative factors are given a comparative importance (weight); (*d*) *Aggregation*. A global suitability index based on weighted factors and Boolean constraints is computed for each point in the target region using an aggregation rule; (*e*) *Sensitivity analysis*. This task is frequently used to overcome the ambiguity of factor weighting.

The inventory of attributes for the current MCA is summarized in Table 1. It comprises the physical parameters, socio-economic indicators and ecological contexts described in Section 2.2. The explicative factors encompass the scored attributes while the Boolean constraints are depicted as "no data" in Table 1 and refer to regions where the MCA model will not be applied. Explicative factors may be numeric (e.g., curve numbers) or qualitative (e.g., crop types) classes. Regardless the case, classes are given normalized ratings that vary from 1 to 5. Ratings are proportional to RWH suitability. The overall suitability index is calculated by the following aggregation rule:

$$\text{RWH Suitability} = \sum_{i=1}^{m} w_i^g \left[\sum_{j=1}^{p} w_j^f F_{j,i} \right] \prod_{k=1}^{q} C_k \quad (1)$$

where superscripts f and g represent specific factors (e.g., population density) or groups of factors (e.g., the socio-economic indicators), respectively, $F_{j,i}$ is the normalized score of factor j in group i, w_{jf} and w_{ig} are the weights of factor j and group i, C_k is the Boolean score of constraint k, which is set to 1 if regions are to be included in the analysis and 0 otherwise, and finally m, p and q, in that order, are the number of groups (3, representing the sets of physical, socio-economic and ecologic variables), factors (4 for the physical parameters, 3 for the socio-economic indicators and 4 for the ecological contexts) and constraints (related to class 5 of factor "Agricultural areas" and to classes 6 and 7 of factor "Wildfire risk"). At the planning stage, which means before setting up an application for the RWH systems, the values of w_{jf} and w_{ig} are equated to 1 because there is no a priori reason to raise or drop the importance of a particular factor or group of factors. At the succeeding allocation stage, w_{jf} and w_{ig} are optimized for the specific application.

The spatial incidence (A_0) and associated water demand (V_0) for irrigation use are defined by the water resources planner. Having defined a representative value for both variables, planners will use the allocation workflow (Fig. 2a) to delineate rainfall collection catchments with $A \geq A_0$ capable of delivering V_0 to application areas. The combination of V_0 and A_0 into a common equation, so the value of A_0 can be estimated on the basis of a pre-defined V_0, has been proposed by the so-called Dutch method and used by Terêncio et al. (2017) to develop the allocation workflow. The Dutch method relates V_0 (m^3) with A_0 (ha) as follows:

$$V_0 = \left(-\frac{b \times q_s}{1+b} \right) \times \left(\frac{60 \times q_s}{a \times (1+b)} \right)^{\frac{1}{b}} \times C \times A_0 \times 10 \quad (2a)$$

where a and b are constants appearing in Intensity-Duration-Frequency (IDF) curves (e.g., De Paola et al., 2014; Elsebaie, 2012), q_s (mm/min) is the so-called specific discharge and C (dimensionless) is the sub-catchment's mean runoff coefficient. In keeping with the Dutch method, specific discharge is equated to:

$$q_s = \frac{6q}{C \times A_0} \quad (2b)$$

where q (m^3/s) is the outflow rate allowed by the RWH system (ecological flow). Replacing Eq. (2b) in Eq. (2a) and rearranging, one arrives to the equation for calculating A_0:

$$A_0 = \frac{1}{C} \times \left(-\frac{6b \times q}{1+b} \right)^b \times \left(\frac{360q}{a \times (1+b)} \right) \times \left(\frac{10}{V_0} \right)^b \quad (3)$$

As calculated by Eq. (3), A_0 is the minimum area a basin needs to cover so the storage volume V_0 is delivered to the RWH system. There will be a number of these sub-catchments distributed across the studied watershed. To select a best sub-catchment, the planner will rank the potentially capable sub-catchments according to suitability based on the project-oriented map and to application constraints as discussed above.

2.4. Database preparation

The attribute and final suitability maps are prepared in the ArcMap version 10 computer program (ESRI, 2010), a well-known GIS. The use of GIS packages facilitates the processing, overlay and combination of multi scale and multi type spatial data, projected on a multitude of coordinate systems, the reason why became mandatory in thematic surveys or projects focused on collection and interpretation of spatial data (Fonseca et al., 2016; Pacheco and Van der Weijden, 2012a, 2012b; Pacheco et al., 2013, 2014, 2015; Sanches Fernandes et al., 2012, 2015; Santos et al., 2014). In total, the number of attributes to be used as input data for the spatial MCA is 12 (Table 1). The required geographical and alphanumeric data were downloaded from a number of institutional databases, described in Table 2 along with the purpose of their use in the MCA model. The table also contains references to data ownership and to the institutional website's Uniform Resource Locator. The spatial data for all explicative factors but chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5) could be downloaded from the holder's website as polygon shapefiles or raster files. The vector maps were converted to raster format and the raster files processed in a Map Algebra tool of ArcMap for normalization (task b of MCA) and production of suitability maps. For COD and BOD_5 the spatial data could be downloaded as point shapefiles. In these cases, variables were interpolated within the Sabor River basin using the *Topo to Raster* tool of ArcMap, prior to be processed in the Map Algebra tool.

3. Results

3.1. Planning workflow

In this study, the planning and allocation workflows were applied to the Sabor River basin considering two complementary uses for the harvested rainwater: agriculture and forestry. The basin was selected because of its rural occupation and ecological relevance. Fig. 3 highlights the predominance of arable land (3a) and forests (3b) in the watershed, besides bringing attention to the spatial incidence of legally protected sites and burned areas of last decade. The spatial distribution of RWH suitability factors is displayed in Fig. 4 while the generic suitability map is portrayed in Fig. 5a. The maximum range of generic suitability is 2–60 (Table 1). In the Sabor River basin the range is 18–50, not far from the maximum. The most capable areas are located in the upstream sub-catchments and near the stream banks where suitability is generally above the average. The application-oriented suitability maps are illustrated in Fig. 5b,c. They were derived from application of Eq. (1) to the suitability factors (Fig. 4), considering the selected application weights (Table 1). For the planning of crop irrigation, the socio-economic indicators were given the largest comparative weight (5), followed by the physical parameters (3) and the ecological contexts (1). The socio-economic attributes "agricultural areas" and "population density" were also qualified with large weights (5 and 3, respectively). The relative importance of socio-economic indicators and ecological contexts switched when the purpose was to help planning wildfire combat in the catchment. In this case, the ecological contexts received the largest weight (5), being followed by the physical parameters (3) and the socio-economic indicators (1). Besides, the ecologically important attributes "wildfire risk" and "protected areas" were ascribed the weights 5 and 3, respectively. The remaining variables in both applications kept the generic weight $w = 1$. Suitability in Fig. 5b ranges from 115 to 325 while in Fig. 5c ranges from 82 to 360. In Fig. 5c, it is clear the similarity among patterns of highly suitable areas and the limits of legally protected areas. This result highlights the prioritization given by the allocation workflow to the protection of ecologically relevant sites against fire.

3.2. Application settings

The volume of water required to irrigate a hectare of crop land in one year is on average $v = 6733\ m^3 \cdot ha^{-1} \cdot yr^{-1}$ (INE, 2011). In this study, the allocation workflow tested the possibility to irrigate crops with harvested rainwater assuming a spatial incidence $a = 222$ ha per irrigation project, where 222 ha is the average area of continuous arable land in the Sabor River. The volume to harvest each year is therefore $V_0 = v \times a = 1{,}494{,}726\ m^3 \cdot ha^{-1} \cdot yr^{-1}$. In order to discharge V_0, rainfall

Table 2
Summary of datasets used in the Multi Criteria Analysis (MCA). The purpose of MCA is to plan best locations for the installation of rainwater harvesting (RWH) systems in rural watersheds. The table columns include references to data types, uses in the MCA data ownership and Internet availability. Websites were assessed in January 2017. Symbol description (institution names in Portuguese): APA – Agência Portuguesa do Ambiente; SNIRH – Sistema Nacional de Informação em Recursos Hídricos; DGT – Direção Geral do Território; INE – Instituto Nacional de Estatística; ICNF – Instituto da Conservação da Natureza e das Florestas.

Variable	Description	Unit	Use	Owner institution (name or acronym)	URL of internet website
Rainfall	Long–term rainfall contours	$mm\cdot yr^{-1}$	Physical explicative factor	APA	https://www.apambiente.pt
Curve number (CN)	Empirical parameter used in hydrology for predicting direct runoff or infiltration from rainfall excess	Dimensionless	Ditto	SNIRH	http://geo.snirh.pt/AtlasAgua/
Soil texture	Percentage of clay in the topsoil	%	Ditto	European Soil Portal	http://eusoils.jrc.ec.europa.eu/
Soil depth	Total soil depth. Calculated by adding the thicknesses of topsoil and subsoil horizons	m	Ditto	European Soil Portal	http://eusoils.jrc.ec.europa.eu/
Population density	Population density	$inhabitants\cdot ha^{-1}$	Socio–economic explicative factor	DGT INE	http://www.dgterritorio.pt/ http://censos.ine.pt/
Agriculture areas	Area occupied by agriculture. Obtained from a CORINE Land Cover map	m^2	Ditto	DGT	http://www.dgterritorio.pt/
Water quality	Average concentration of chemical (COD) and biochemical (BOD_5) oxygen demands in surface water	$mg\cdot L^{-1}$	Ditto	SNIRH	http://snirh.apambiente.pt/
Wildfire risk	Wildfire risk estimated by a multi–criteria analysis involving biophysical and socio–economic parameters: cover vegetation, hillside slope and aspect, road network and population density	Dimensionless	Ecological explicative factor	ICNF	http://www.icnf.pt/
Protected areas	Legally protected areas, by Portuguese and European legislation	Dimensionless	Ditto	ICNF	http://www.icnf.pt/
Stream banks	Water lines obtained from analysis of a Digital Elevation Model	Dimensionless	Ditto	DGT	http://www.dgterritorio.pt/
Terrain slope	Hillside slopes obtained from analysis of a Digital Elevation Model (DEM)	%		DGT	http://www.dgterritorio.pt/

collection sub-catchments need to drain an area larger than $A_0 =$ 314,48 ha (cf. Eq. (3)), if parameter C is set to 0.7 (the average runoff coefficient of Sabor River basin; Fig. 4b), parameters a and b are set to appropriate regional values ($a = 338{,}48$; $b = -0.630$; Matos and Silva, 1986) and parameter q (the ecologic flow) is arbitrarily set to 0.01 $m^3\cdot s^{-1}$ (315,360 $m^3\cdot yr^{-1}$, approximately 12% of the total

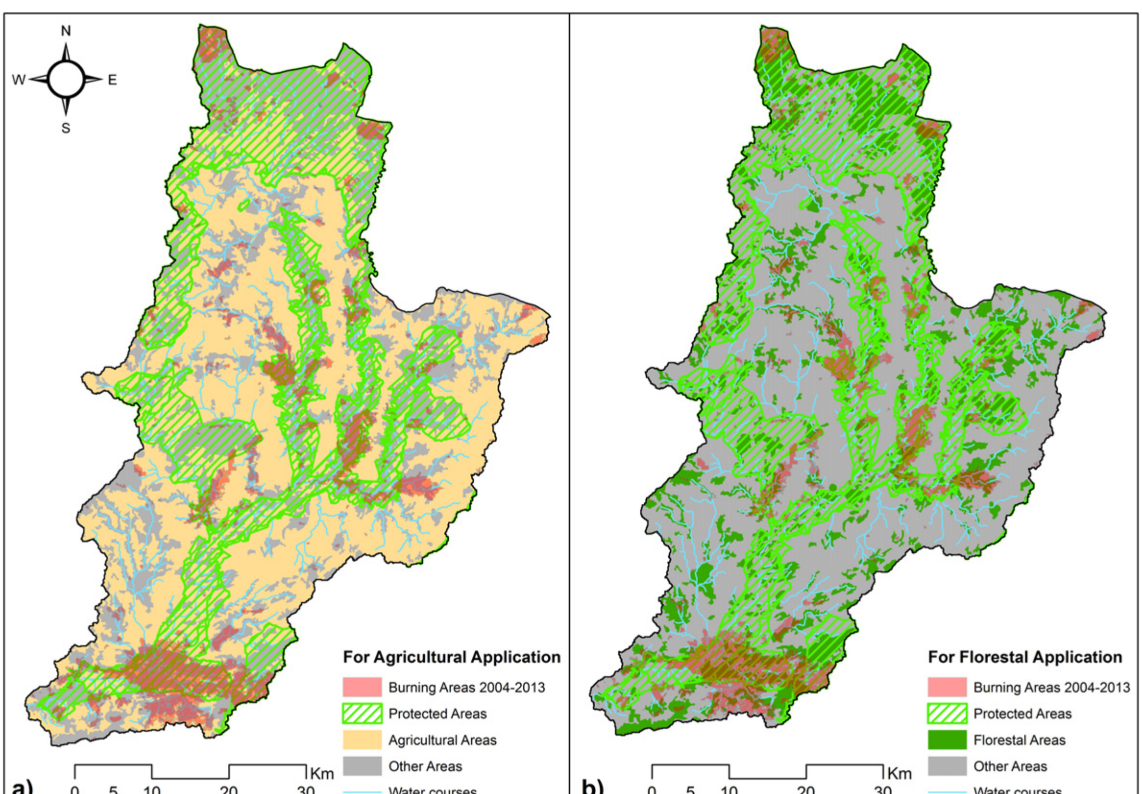

Fig. 3. Spatial incidence of arable land (3a), forests (3b), legally protected areas and burned areas (3a, 3b) in the Sabor River basin.

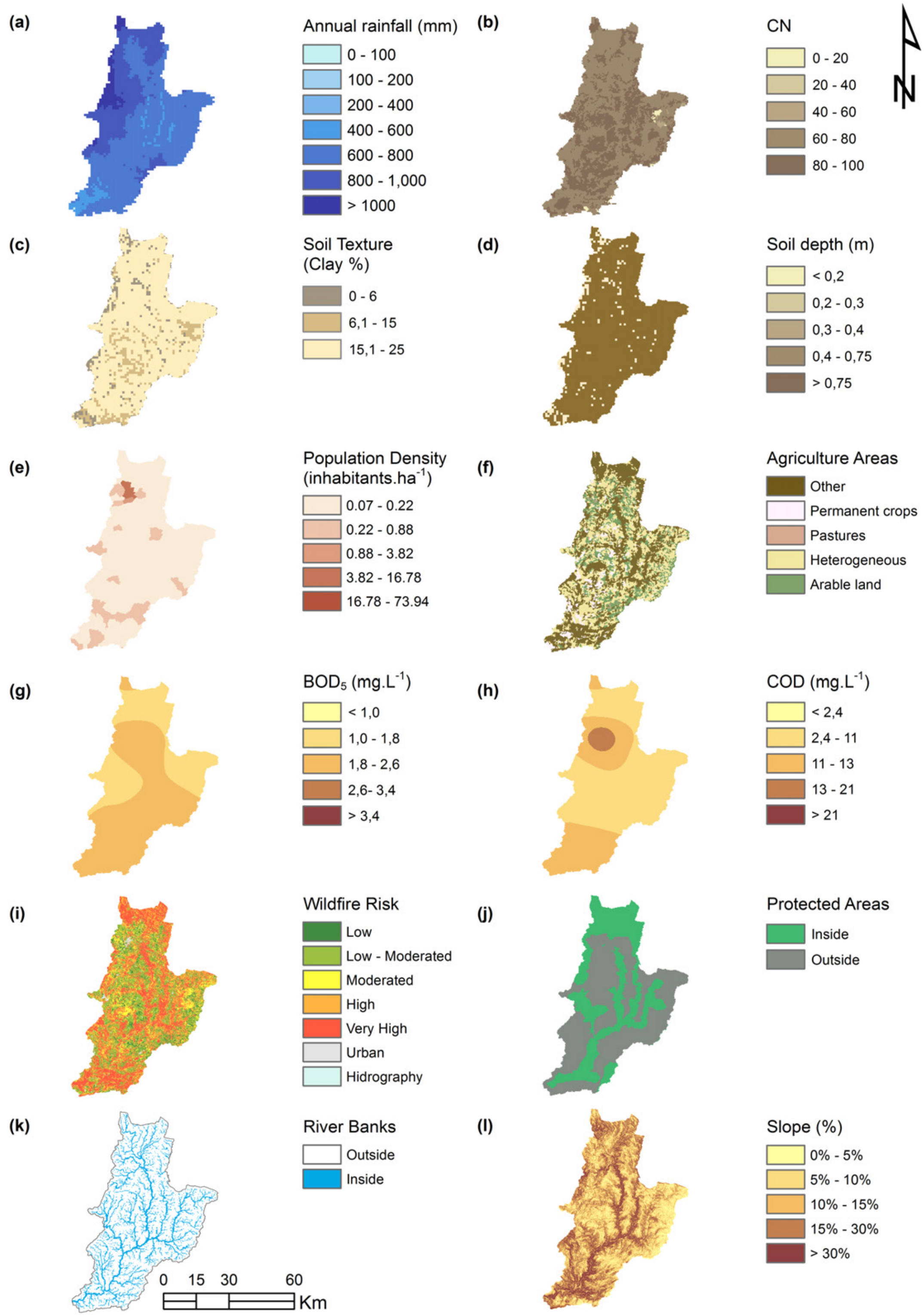

Fig. 4. Spatial distribution of suitability attributes, used in the planning workflow of Fig. 2a.

harvested water). For these application settings, the number of potential rainfall collection sub-catchments is 384. These settings were transposed to the forestry use because this is considered by the allocation workflow a complementary use for harvested rainwater. On the other hand, it is difficult to define, and hence quantify, what are the water requirements for wildfire combat. The 384 potential rainfall collection sub-catchments with $A \geq A_0$ were identified and drawn using the ArcHydro software (ESRI, 2012), a watershed delineation tool embedded in ArcMap (ESRI, 2010). The corresponding boundaries are illustrated in all maps of Fig. 6. The average values of explicative factor in each sub-catchment are listed in the Supplementary material.

3.3. Allocation workflow

The suitability to use stored rainwater for crop irrigation varies from 150 to 260 (Fig. 6a.1), while for wildfire combat it varies from 153 to

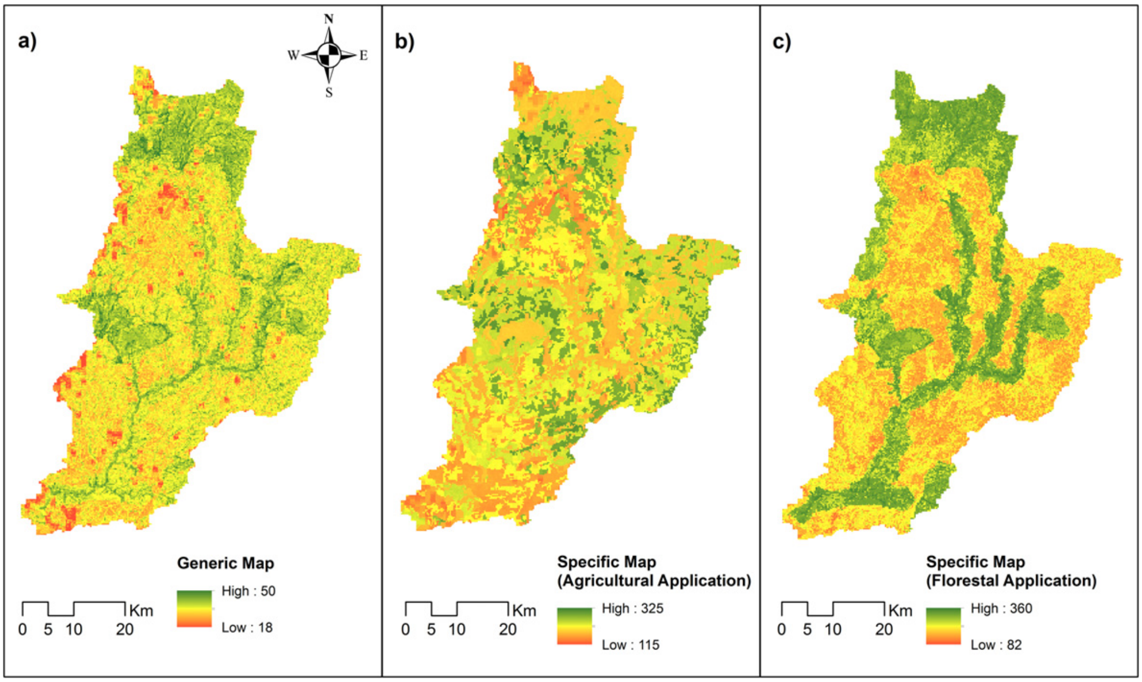

Fig. 5. RWH suitability maps as determined from the unity (*a* – generic map) and application-dependent (*b* – irrigation; *c* – wildfire combat) weights used in the spatial Multi Criteria Analysis (Fig. 2b).

316 (Fig. 6a.2). Long-term stream flow contours downloaded from the SNIRH website (URL in Table 2) show that annual discharges in the sub-catchments range from $V_d = 0.4–16.3$ $Mm^3 \cdot yr^{-1}$ (Fig. 6b). So, although the rainfall zoning embedded in parameters *a* and *b* of Eq. (3) has defined 384 sub-catchments as potentially capable to sustain irrigation and wildfire compact applications with sufficient rainwater (i.e., $V_0 = 1.49$ Mm^3 yr^{-1}), the cross validation of rainfall zoning with long-term river flows reduced this number to 217 competent sub-catchments ($V_d > V_0$; 56.5%). The *D*n ratio increases towards downstream, from 16 m to 73 m (Fig. 6c.1). When the arable land is relatively well distributed across the watershed (present case; Fig. 3a), the average distance (*D*) from a rainfall collection sub-catchment to the irrigation areas located downstream increases from the upland to the lowland sub-catchments. This is also true for the number (*n*) of crop land areas irrigable by that sub-catchment. If both increases were linear, the *D*n ratio would stay relatively constant, but that is not the case (Fig.

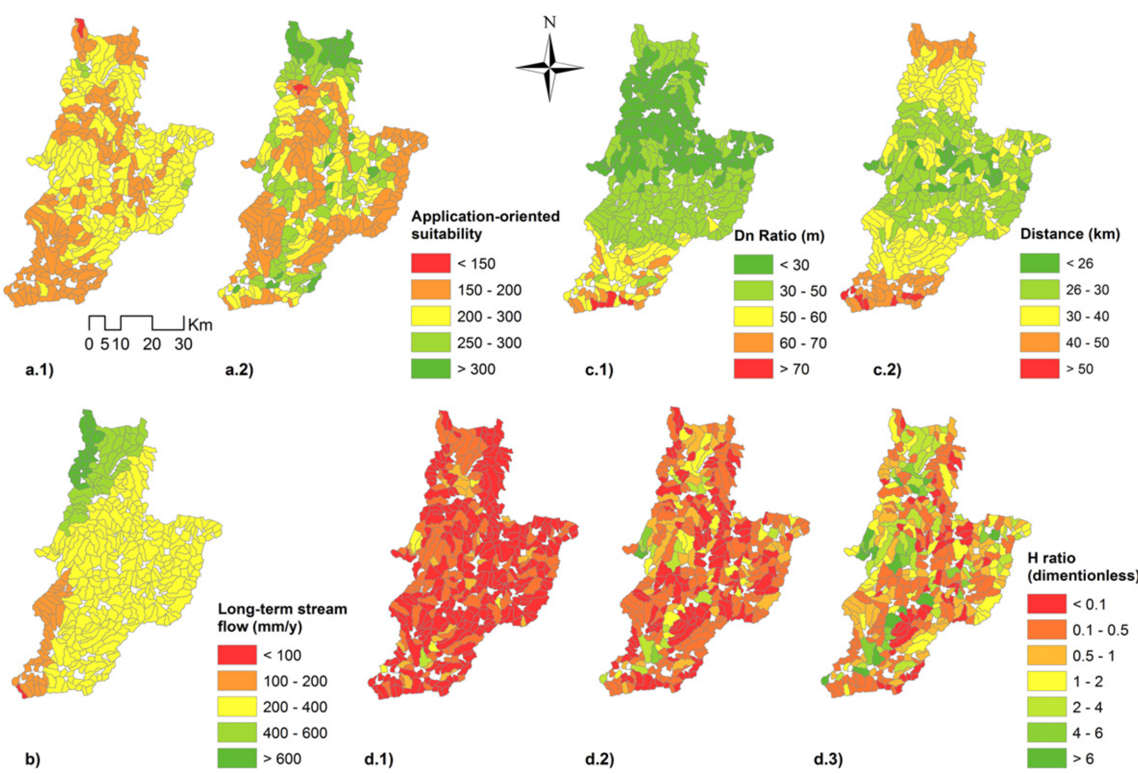

Fig. 6. Spatial distribution of application-oriented suitability (6a), long-term stream flow (6b), and allocation parameters (6c, 6d), averaged within 384 sub-catchments.

6d.1). The increase of D/n quotient towards downstream suggests a non-linear variation for D and n with higher increase rates ascribed to the nominator (D). The average distance from rainfall collection sub-catchments to forest stands ranges from 25.1 to 53.3 km (Fig. 6c.2), increasing from the central towards the most peripheral sub-catchments, as expected for a watershed where the forested areas are also relatively well distributed. The capacity to store V_0 in the RWH system (i.e., in the reservoir created behind the dam wall) was tested for three alternative dam wall heights: 3, 6 and 12 m. The capacity was indicated by the so-called H ratio defined previously as V_s/V_0, where V_s is the reservoir's storage capacity. The ranges of H ratios are (Fig. 6d.1–3): for 3 m wall – $H = 0.0$–2.1 (average 0.1); for 6 m wall – $H = 0.0$–6.7 (average 0.2); for 12 m wall – $H = 0.0$–15.1 (average 0.6). For the 3 m wall (Fig. 6d.1), only 7 sub-catchments (1.8%) are fully capable to supply the water requirements, while for 6 m and 12 walls (Fig. 6d.2 and d.3) the numbers rise to 46 (12.1%) and 124 (32.3%) sub-catchments, respectively.

The ranking of subcatchments based on the application-oriented suitability and constraints "long-term stream flow", "Dn ratio" ("distance" for the forest application) and "H ratio" are summarized in Fig. 7. The discrete ranks of all 384 sub-catchments are listed in the Supplementary material considering the irrigation and wildfire applications as well as the three dam wall heights. As higher the rank as more capable is the sub-catchment. The ranks are overlaid by line patterns where $Q \times A = V_d > V_0$ and (or) $H = V_s/V_0 > 1$. It is clear that only a few sub-catchments are able to comply with the predefined irrigation requirements, especially when the use of a 3 m-high wall is considered. In order to investigate the irrigation capacity of 3 m-high RWH sites in the Sabor River basin, the allocation workflow calculated the maximum irrigable area of each rainfall collection sub-catchment. The results are illustrated in Figs. 8a (spatial distribution) and 8b (histogram). The histogram reveals that 1/3 of potentially capable sub-catchments is competent to irrigate an area smaller than 5 ha and 1/2 and area smaller than 10 ha. The supply of irrigation projects with this kind of RWH site necessarily implies that farming activities in the catchment are carried out in keeping with the maximum allowance of water retention in the dam reservoir. This should be considered even more in a climate change context that predicts a reduction of the water available. Allowing activities to grow beyond this threshold inevitably leads to the construction of infrastructures with limited natural ecological sustainability. In these cases, sustainability can still be accomplished if design and construction guidelines pay attention to ecological values or the project attend other components of sustainability (e.g., social sustainability). In either case, they may become a social and economic necessity.

4. Discussion

4.1. Modeling results and comparison with previous studies

The generic map (Fig. 5a) shows an increase of RWH suitability in the upstream direction and at the headwaters of watercourses. This pattern changed to a relatively homogeneous distribution of suitable areas (Fig. 5b) when irrigation was defined as application resulting in larger weights for the socio-economic parameters and related explicative factors "land use", "population density" and "water quality". The pattern changed again when the application was redefined to wildfire combat and greater weights were ascribed to the ecologic contexts and associated explicative factors "wildfire risk" or "legally protected sites". Now, the highest suitability scores were distributed around sensitive areas (Fig. 5c). The high sensitivity of RWH suitability assessments to application settings highlight the importance of setting up a clear objective for the use of harvested rainwater before making any decision on the allocation of irrigation, wildfire combat or other projects. In this context, we need to say that Jha et al. (2014) or Singh et al. (2017) probably selected the runoff coefficient, terrain slope and drainage density as suitability parameters because their RWH model aimed to couple harvesting potential with enhanced (artificial) aquifer recharge. And it is worth recalling a concluding statement of Adham et al. (2016a) in their recent

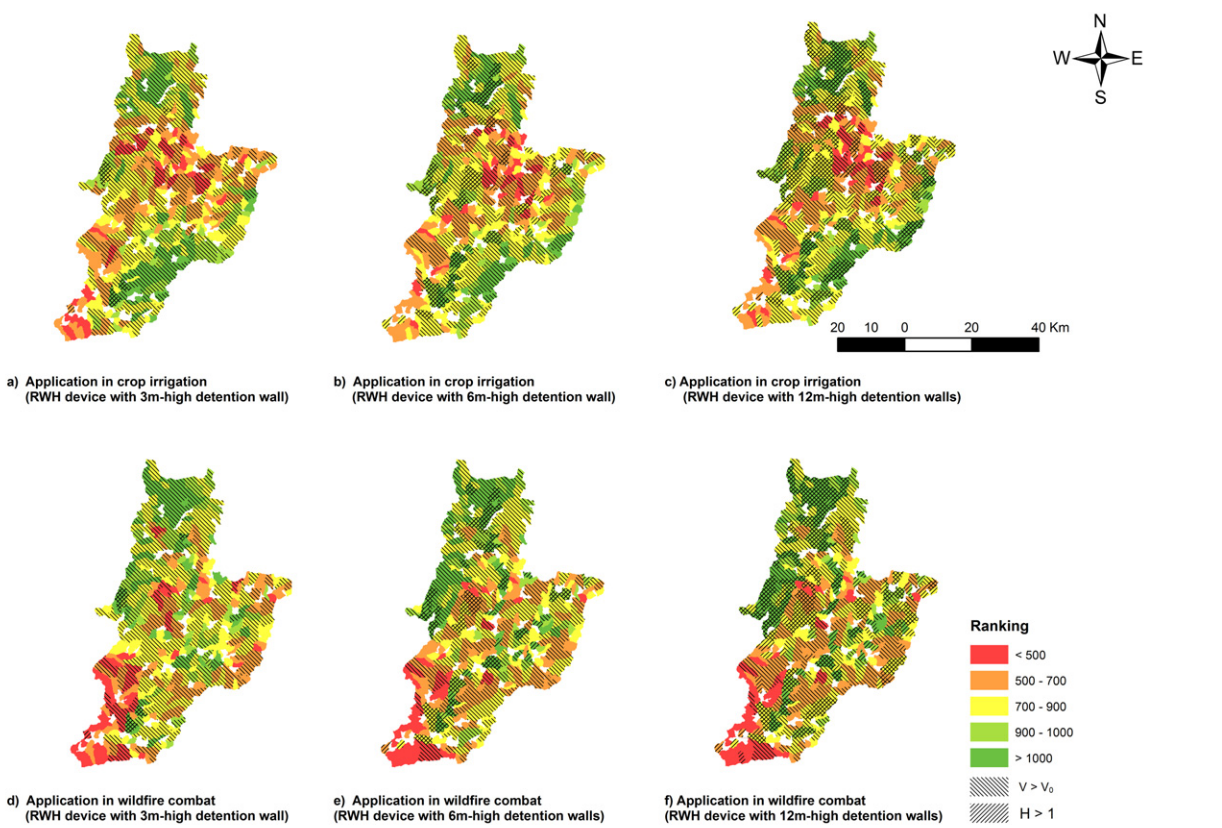

Fig. 7. Results of ranking analysis, considering the building of 3, 6 and 12 meter high dam walls and the application of harvested rainwater in irrigation and wildfire combat.

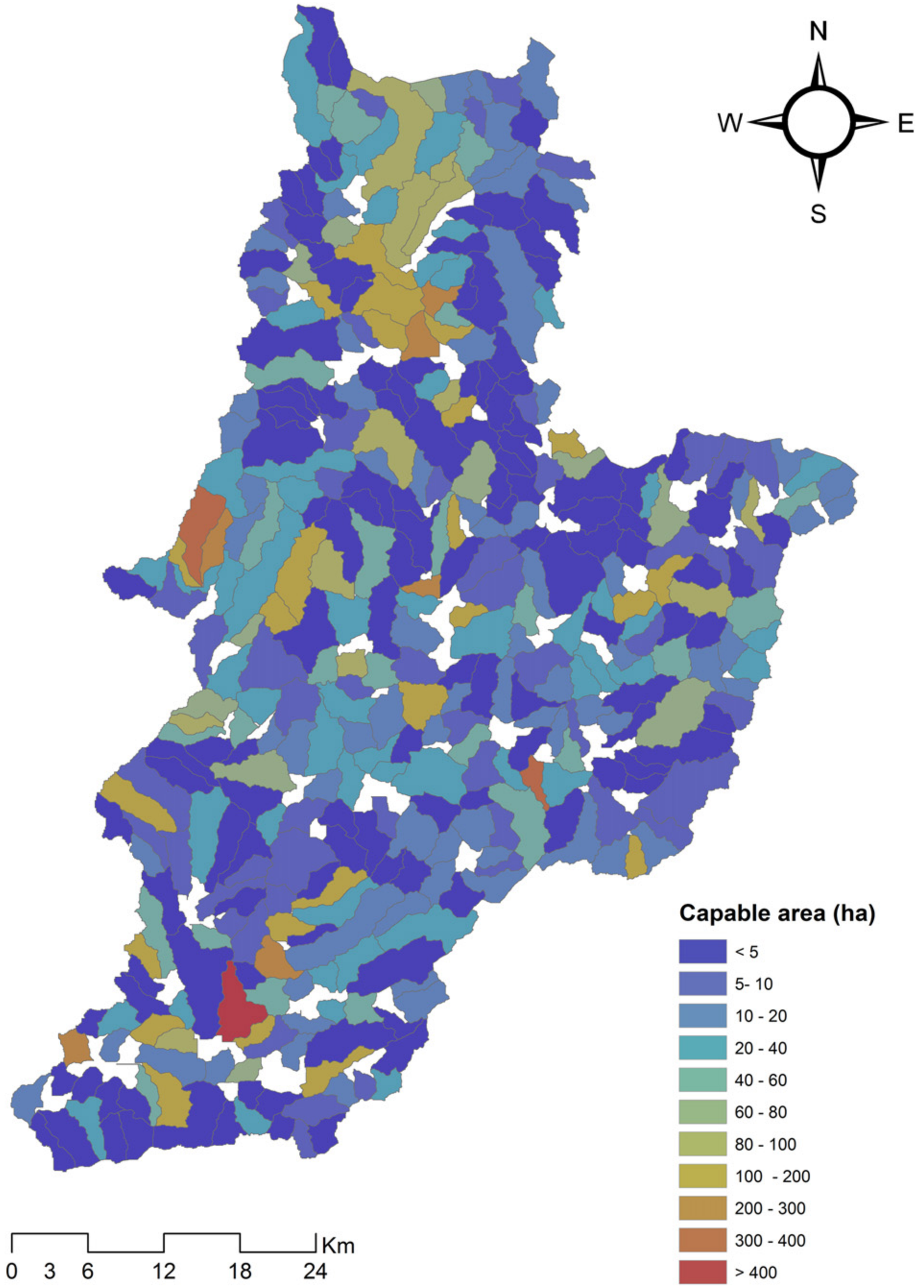

Fig. 8. a – Spatial distribution of irrigable areas supplied by a 3 meter high dam reservoir. b – Histogram of irrigable areas supplied by a 3 meter high dam reservoir.

review paper on the identification of suitable sites for rainwater harvesting structures: "determining the most helpful method for selecting suitable RWH sites is a great challenge". To our view, the challenge can be overcome if RWH modelers (re)design their algorithms through replacement of static suitability parameters and associated weights by flexible counterparts, a feature accommodated in just a few studies (e.g., Mbilinyi et al., 2007). In that context, the flexibility of Terêncio et al.'s (2017) model to deal with application-oriented weights is a strong point in favor of their method.

Besides suitability (Fig. 6a), the allocation workflow defines long-term stream flow, distance between rainfall collection and application areas, *D*n ratio and *H* ratio as relevant selection constraints. The spatial distribution of these variables is illustrated in Fig. 6b–d. Long term stream flows (Fig. 6b) are used to check the competence of potentially capable sub-catchments as regards water availability. This check is mandatory because Eq. (3) defines the area of a catchment potentially capable to generate the irrigation requirements (V_0), based on regional-scale climate parameters (*a* and *b* constants), but cannot ensure actual supply at local scale. The discharge volumes ($V_d = Q \times A$) estimated for the 384 potentially capable sub-catchments corroborate the need to validate competence, because the number of competent sub-catchments ($V_d > V_0$) was just 56.5% of the total. Only a few studies have investigated the effectiveness of catching and storing water and the utility of RWH within the existing farm management (Adham et al., 2016b). The model by Adham and co-workers was designed to improve water availability for different RWH systems based on crop water requirements and rainfall-runoff relationship, being pioneer in that respect. The present study follows that track by indexing RWH suitability to long-term stream flows. The *D*n ratio represents the mean distance from a potentially capable sub-catchment and an area irrigable by that catchment, using gravity flow. The smaller the *D*n the less expensive are the average water transportation costs. In the Sabor River basin, the smallest *D*n values are ascribed to the upstream sub-catchments (Fig. 6c.1). Thus, in the planning of rainfed irrigation at catchment

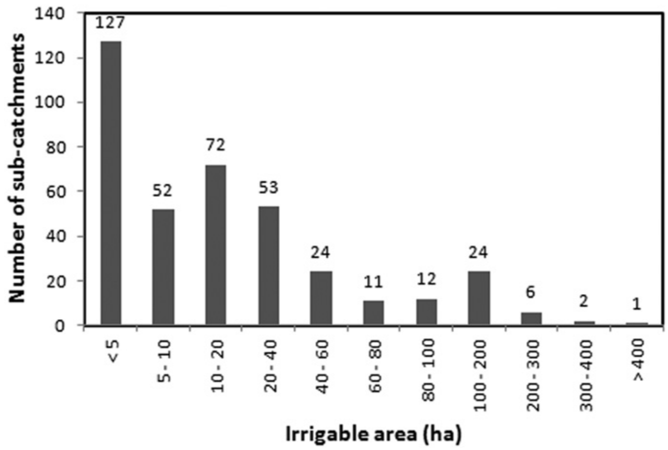

Fig. 8 (*continued*).

scale these sub-catchments should be viewed as best candidates to rainfall collection. The use of *D*n as proxy to water transportation costs is not necessarily right when the purpose of rainwater harvesting is wildfire combat, because water is frequently transported to the burning areas by airplane and hence the topographic (altitude) relationship between source and application areas in these cases is irrelevant. For that reason, in the allocation of RWH sites to assist wildfire extinction the workflow uses the mean distance between potentially capable sub-catchments and forest stands. This distance increases from the centre to the periphery of Sabor basin (Fig. 6c.2), as expected, highlighting the importance of central sub-catchments in this application. For a complementary use of harvested rainwater (i.e., irrigation and wildfire combat), the central sub-catchments are also the best candidates to install the RWH sites, because they are characterized by small *D*n and *D* values (please compare Fig. 6c.1 and c.2). The *H* ratio is probably the most relevant constraint in the planning of rainwater harvesting for irrigation, because it compares RWH sites as regards storage capacity, potential construction costs and ecological sustainability values (landscape integration, sustainable drainage, environmental protection). The spatial distribution of *H* ratios is illustrated in Fig. 6d.1–3. The higher the *H* value the larger the storage capacity. When $H > 1$, the harvested rainwater exceeds the irrigation requirements, but if $H < 1$ the RWH system is unable to supply enough water for the predefined needs. Fig. 6d were drawn for three dam wall heights: 3 m (6d.1), 6 m (6d.2) and 12 m (6d.3). The lower walls are low-cost infrastructures that can be easily integrated in the landscape, but their storage capacity is limited. The higher walls can accumulate much larger volumes of water but their building requirements raise construction costs while reducing landscape assimilation. The results for the 3 m wall reveal that $H > 1$ for just **7** (1.8%) sub-catchments, while this number rises to 46 (12%) and 124 (32.3%) for the 6 and 12 meter walls, respectively. Besides, the number of sub-catchments with $H < 0.1$ decreases from 261 (68%) to 49 (12.8%) when the wall height increases from 3 m to 12 m. With so many rainfall collection areas unable to cope with $H \geq 1$, when the option is to install a RWH system with 3 m-high dam wall, it is unlikely that water resource planners can regularly consider the development of rainfed agriculture based on these systems. Facing these results, the option for more engineered infrastructures may be viewed as opportunity.

The ranking of sub-catchments based on the application-oriented suitability, long-term stream flows, distance parameters and dam wall heights (Fig. 7) generally associates the highest ranks (green sub-catchments) to $V_d / V_0 > 1$ (line patterns inclined to the left). Thus, the highly ranked sub-catchments can potentially supply enough water to rainfed irrigation. However, to effectively supply the harvested rainwater, the condition $V_d / V_0 > 1$ must be complemented with the condition of $V_s / V_0 = H > 1$ (line patterns inclined to the left), generating green sub-catchments overlaid by cross line patterns. Ranking of potentially capable sub-catchments based on yield (V_d) and storage (V_s) have been considered in a study by Petheram et al. (2017), but the authors indexed the ranks to construction costs (yield/cost and storage/cost ratios) while in the present study the rank was indexed to the irrigation needs (V_d / V_0 and V_s / V_0). When looking at Fig. 7a, it is clear that 3 m–high dam walls fail to cope with these requisites, with few exceptions. Fig. 8b strengthens this conclusion because 1/3 of rainfall collection areas can irrigate no >5 ha of arable land if the RWH system installed on their outlets is built with a 3 m-high wall. The more engineered solutions (Fig. 7b, c) raise the number of cross lined sub-catchments, while some of them are highly ranked (green). Overall, the green cross lined sub-catchments are the top rainfall collection areas within the Sabor River basin. Although the use of harvested rainwater in wildfire combat is not constrained by the $V_d / V_0 > 1$ or $V_s / V_0 = H > 1$ conditions, because it is viewed as complement to the use in irrigation, the green cross lined subcatchments in Fig. 7d–f are also likely to be the top rainfall collection areas for this application.

4.2. Sustainability

In the context of flood attenuation, Yang et al. (2011) defined a sustainable flood retention basin as an impoundment or integrated wetland "capable of being maintained at a steady level without exhausting natural resources, harming the environment and causing severe ecological damage". This definition can be transposed to conventional field RWH sites since they are also contributors to flood attenuation and attend the aforementioned characteristics, besides complying with their other uses (e.g., irrigation of cropland). For the parameterization of water impoundments (six types), the work of Yang attributed a central role to the dam wall height (*H*), because the value $H \leq 3$ m was linked to low-engineered structures (on average < 30% elements) mostly destined to sustainable drainage, aesthetic landscape, recreation and environmental protection (types 3 to 6), in brief to hold ecological sustainability values, while the value $H \gg 3$ m was associated with high-engineered structures (on average > 70% elements) destined to drinking water supply or hydraulic purposes (types 1 and 2). In the Sabor River basin, irrigation projects extending to 5 ha of arable land or less can be supplied with harvested rainwater stored behind 3 m-high dam walls (Fig. 8a,b), which means by ecologically sustainable RWH sites. Ecological sustainability is an invaluable social asset, which is important to preserve at all cost. Thus, in cases where the claim for food production requires the irrigation of larger areas, hydraulic engineers are ought to think more about how to better construct, operate and maintain larger dams and reduce their negative impacts, as well noted by Chen et al. (2016). Besides, authorities, planners and the society need to adhere to best management practices as to attenuate contaminant exports towards the aquatic media upstream the dams, namely leachates of farmland fertilizers or poorly treated domestic and industrial effluents. In this context, a recent study performed on a problematic dam proposed a solution based on collector pipes controlled by auto mechanical gates, to reduce sediment and heavy metal storage in the reservoir and enhance lake water quality (Al-Nasrawi et al., 2016). Another study reported the recovery of water quality and biodiversity in a polluted dam lake in Spain (Camargo, 2017), following the implementation of mitigation measures upstream the infrastructure such as the improvement of an industrial waste water treatment plant with better lime and limestone reactors to retain more efficiently fluoride ions as insoluble calcium fluoride.

Besides attending improved construction guidelines and the implementation of best management practices at catchment scale, construction of medium size dams to be used as RWH devices must be decided in the context of other components of sustainability, namely the social component. Current frameworks indicate that assessments of the social impact of dams should start by simultaneously considering the dimensions of space, time and value as well as the components infrastructure, livelihood and community, and refer both the positive and the negative impacts (Kirchherr and Charles, 2016). The assessment of social impacts is of great importance before the construction of large dams but it also matters to the construction of medium size dams. In a study about the social sustainability of a large dam in Malaysia (Andre, 2012), the participants in a questionnaire (mostly indigenous people affected by the project) indicated the protection of environment as issue to attend, but assumed that a sound social sustainability could be achieved if the issues of landlessness, self-sufficiency, compensation and transportation could be amicably resolved. It was recognized, however, that the elements of social sustainability that are important to one community or hydrological water catchment area, are often unique to that community, and cannot always be translated or transferred to another area. Indeed, in another similar study in Cambodia the environmental impacts and the changes to livelihoods were the most important concerns of the affected population (Siciliano et al., 2015). In the present study, the option for more engineered dams considers the construction of medium size structures with dam wall heights not exceeding 12 m. The social impacts of these projects should not be negative because this type of dam creates small lakes that do not interfere significantly with key social issues such as resettlement, landlessness or change to livelihoods or styles. Besides, the complementary use of these dams in wildfire combat represents a positive ecological impact, considering the coverage of Sabor River basin by protected areas. However, some negative ecological impacts must also be expected, related to habitat fragmentation, disturbance of hydrologic regime or water quality deterioration. As noted above, the options to take can be twofold: do not construct or better construct. As also noted, better construction needs to be accompanied by sustainable management of catchments eventually operated through spatial decision support systems (Sanches Fernandes et al., 2011, 2014), that help reducing nutrient and heavy metal exports towards the aquatic media and preserve good quality water in dam lakes. Measures such as the improvement of domestic and industrial waste water, implementation of best management practices in agricultural areas (use of green manure, minimum tillage, retaining harvest residues on topsoils), or the replanting of riparian vegetation along the water courses, are some examples of sustainable management referred to in many catchment studies (e.g., Ferreira et al., 2017; Santos et al., 2015a, 2015b; Valera et al., 2016), but unfortunately not always implemented in the field.

5. Conclusions

The use of rainwater harvesting (RWH) to supply irrigation projects in the Sabor River basin (Portugal) is strongly limited to irrigation areas smaller than 10 ha, if the option is for small height ($H = 3$ m) dam walls. This is because the storage capacity of associated reservoirs is rather limited, a circumstance that also affects complementary uses of harvested rainwater such as wildfire combat. The value of 10 ha was estimated by a RWH site allocation method developed by Terêncio et al. (2017), improved in this study through consideration of H in the algorithm. The Sabor River basin drains an area of approximately 3297 km^2 and the site allocation model delineated 217 sub-catchments capable to deliver enough water to irrigate an average arable land, which in the Sabor basin corresponds to 222 ha. However, given the storage constraint imposed by the dam wall height only 7 of these basins can accumulate the proper amount of water, estimated in $V \geq 1.49$ Mm^3 yr^{-1}. In case the dam wall height increases to 6 m the number rises to 46 sub-catchments with $V \geq 1.49$ Mm^3 yr^{-1} and if $H = 12$ m the number rises to 124. The model sensitivity to H should be an alert to planners of sustainable RWH sites. Although dams with $H \leq 3$ m hold values of ecological sustainability (e.g., landscape integration, environmental protection) they may fail to supply enough resource to the predefined application, a circumstance less applicable to the more engineered dams with 6 m $\leq H \leq$ 12 m or higher. In brief, the study in the Sabor River basin clearly demonstrated the suitability of sustainable rainwater harvesting to support domestic or small community agriculture, or to assist the struggle against small forest fires. It also showed the limitation of using these low- cost infrastructures in the planning of general agro-forestry uses at catchment scale.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.09.198.

References

Adham, A., Riksen, M., Ouessar, M., Ritsema, C., 2016a. Identification of suitable sites for rainwater harvesting structures in arid and semi-arid regions: a review. Int. Soil Water Conserv. Res. 4:108–120. https://doi.org/10.1016/j.iswcr.2016.03.001.

Adham, A., Wesseling, J.G., Riksen, M., Ouessar, M., Ritsema, C., 2016b. A water harvesting model for optimizing rainwater harvesting in the wadi Oum Zessar watershed, Tunisia. Agric. Water Manag. 176, 191–202.

Agroconsultores e Coba, 1991. Carta dos solos, do uso actual da terra e da aptidão da terra do nordeste de Portugal. UTAD/PDRITM, Vila Real.

Al-Nasrawi, A.K.M., Jones, B.G., Alyazichi, Y.M., Hamylton, S.M., Jameel, M.T., Hammadi, A.F., 2016. Civil-GIS incorporated approach for water resource management in a developed catchment for urban-geomorphic sustainability: Tallowa Dam, southeastern Australia. Int. Soil Water Conserv. Res. 4, 304–313.

Andre, E., 2012. Beyond hydrology in the sustainability assessment of dams: a planners perspective – the Sarawak experience. J. Hydrol. 412–413, 246–255.

APA, ARHNorte, 2012. Relatório de Base - Parte 2 (Caracterização e diagnóstico da região hidrográfica). Plano Gestão da Região Hidrográfica do Douro PGRH3. 376.

Bellu, A., Sanches Fernandes, L.F., Cortes, R.M.V., Pacheco, F.A.L., 2016. A framework model for the dimensioning and allocation of a detention basin system: the case of a flood-prone mountainous watershed. J. Hydrol. 533:567–580. https://doi.org/10.1016/j.jhydrol.2015.12.043.

Camargo, J.A., 2017. Multimetric assessment of macroinvertebrate responses to mitigation measures in a dammed and polluted river of Central Spain. Ecol. Indic. 83, 356–367.

Chen, J., Shi, H., Sivakumar, B., Peart, M.R., 2016. Population, water, food, energy and dams. Renew. Sust. Energ. Rev. 56, 18–28.

CIMPOR, 2017. Aproveitamento Hidroeletrico do Baixo Sabor [WWW document]. http://www.cimpor-portugal.pt/artigo.aspx?lang=pt&id_object=1247&name=Aproveitamento-Hidroeletrico-do-Baixo-Sabor, Accessed date: 15 February 2017.

De Paola, F., Giugni, M., Topa, M., Bucchignani, E., 2014. Intensity-duration-frequency (IDF) rainfall curves, for data series and climate projection in African cities. Spring 3:133. https://doi.org/10.1186/2193-1801-3-133.

Elsebaie, I.H., 2012. Developing rainfall intensity–duration–frequency relationship for two regions in Saudi Arabia. J. King Saud Univ. - Eng. Sci. 24:131–140. https://doi.org/10.1016/j.jksues.2011.06.001.

ESRI, 2010. ArcMap (version 10).

ESRI, 2012. ArcHydro Tools for ArcGIS 10 – Tutorial.

FAO, 2003. Land and Water Digital Media Series, 26. Training Course on RWH (CDROM), Planning of Water Harvesting Schemes, Unit 22. Food and Agriculture Organization of the United Nations Rome, FAO.

Ferreira, A.R.L., Sanches Fernandes, L.F., Cortes, R.M.V., Pacheco, F.A.L., 2017. Assessing anthropogenic impacts on riverine ecosystems using nested partial least squares regression. Sci. Total Environ. 583, 466–477.

Fewkes, A., 2006. The technology, design and utility of rainwater catchment systems. In: Butler, D., Memon, F.A. (Eds.), Water Demand Management. IWA Publishing, London.

Fonseca, A.R., Sanches Fernandes, L.F., Fontainhas-Fernandes, A., Monteiro, S.M., Pacheco, F.A.L., 2016. From catchment to fish: impact of anthropogenic pressures on gill histopathology. Sci. Total Environ. 550:972–986. https://doi.org/10.1016/j.scitotenv.2016.01.199.

Gaspar, R., Ferreira, J., Carrondo, J., Silva, M.J., 2015. The use of quartz during the Upper Paleolithic and Early Mesolithic in Sabor valley (NW Iberia): the Foz do Medal case. Quat. Int. 424:98–112. https://doi.org/10.1016/j.quaint.2015.10.095.

Gaspar, R., Ferreira, J., Carrondo, J., Silva, M.J., García-Vadillo, F.J., 2016. Open-air Gravettian lithic assemblages from Northeast Portugal: the Foz do Medal site (Sabor valley). Quat. Int. 406:44–64. https://doi.org/10.1016/j.quaint.2015.12.054.

Gonçalves, D.A., 1985. Contribuição para o Estudo do clima da Bacia Superior do Rio Sabor. Influência da Circulação Geral e Regional na Estrutura de Baixa Atmosfera. Universidade de Trás-os-Montes e Alto Douro, Vila Real.

ICNF, 2017. Rede Nacional de Áreas Protegidas [WWW document]. Inst. da Conserv. da Nat. e das Florestashttp://www.icnf.pt/portal.

INE, 2011. O uso da água na agricultura. 1. Inst. Nac. Estatística:p. 95. https://doi.org/10.1017/CBO9781107415324.004.

INE, 2017. Base de dados online do site do Instituto Nacional de Estatística, Lisboa, [WWW Document]. Inst. Nac. Estatística.

Isioye, O.A., Shebe, M.W., Momoh, U., Bako, C., 2012. A Multi Criteria Decision Support System (Mdss) for Identifying Rainwater Harvesting Site (S) in Zaria, Kaduna State, Nigeria. 1 pp. 53–71.

Jha, M.K., Chowdary, V.M., Kulkarni, Y., Mal, B.C., 2014. Rainwater harvesting planning using geospatial techniques and multicriteria decision analysis. Resour. Conserv. Recycl. 83, 96–111.

Kahinda, J.M., Taigbenu, A.E., 2011. Rainwater harvesting in South Africa: challenges and opportunities. Phys. Chem. Earth 36:968–976. https://doi.org/10.1016/j.pce.2011.08.011.

Kahinda, J.M., Taigbenu, A.E., Boroto, J.R., 2007. Domestic rainwater harvesting to improve water supply in rural South Africa. Phys. Chem. Earth Parts A/B/C 32:1050–1057. https://doi.org/10.1016/j.pce.2007.07.007.

Kahinda, J. Marc, Lillie, E.S.B., Taigbenu, A.E., Taute, M., Boroto, R.J., 2008. Developing suitability maps for rainwater harvesting in South Africa. Phys. Chem. Earth 33:788–799. https://doi.org/10.1016/j.pce.2008.06.047.

Kahinda, J.M., Taigbenu, A.E., Sejamoholo, B.B.P., Lillie, E.S.B., Boroto, R.J., 2009. A GIS-based decision support system for rainwater harvesting (RHADESS). Phys. Chem. Earth 34:767–775. https://doi.org/10.1016/j.pce.2009.06.011.

Kirchherr, J., Charles, K.J., 2016. The social impacts of dams: a new framework for scholarly analysis. Environ. Impact Assess. Rev. 60, 99–114.

Mati, et al., 2006. Mapping the Potential of Rainwater Harvesting Technologies in Africa. A GIS Overview on Development Domains for the Continent and Ten Selected Countries. Technical Manual No. 6. World Agroforestry Center (ICRAF). Netherlands Ministry of Foreign Affairs, N.

Matos, R., Silva, M., 1986. Estudos de precipitação com aplicação no projecto de sistemas de drenagem pluvial. Curvas Intensidade-Duração-Frequência da Precipitação em Portugal. ITH 24 LNEC, Lisbon.

Mbilinyi, B.P., Tumbo, S.D., Mahoo, H.F., Mkiramwinyi, F.O., 2007. GIS-based decision support system for identifying potential sites for rainwater harvesting. Phys. Chem. Earth Parts A/B/C 32:1074–1081. https://doi.org/10.1016/j.pce.2007.07.014.

Melo, J.J. De, Chainho, P., Fráguas, B., Santos, P.T., Patacho, D., 2010. A barragem do Baixo Sabor: um caso de má aplicação da avaliação de impactes ambientais. CNAI'10 | 4ª Conferência Nacional de Avaliação de Impactes | 20 a 22 Out'10, Vila Real.

Mesbah, S.H., Mohammadnia, M., Kowsar, S.A., 2016. Long-term improvement of agricultural vegetation by floodwater spreading in the Gareh Bygone Plain, Iran. In the pursuit of human security, is artificial recharge of groundwater more lucrative than selling oil? Hydrogeol. J. 24:303–317. https://doi.org/10.1007/s10040-015-1354-y.

Mou, H., Wang, H., Kung, H., 1999. Division Study of Rainwater Utilization in China 9th International Rainwater Catchment System Conference, Brazil.

Nunes, A., 2015. Recursos Hídricos Na Bacia Do Rio Sabor: Evolução Recente E Relações Com Mudanças Sócio-Ambientais. Actas do 6º Congr. Ibérico sobre Gestão e Planif. da Água 10.

Pacheco, F.A.L., 2015. Regional groundwater flow in hard rocks. Sci. Total Environ. 506–507:182–195. https://doi.org/10.1016/j.scitotenv.2014.11.008.

Pacheco, F.A.L., Van der Weijden, C.H., 2012a. Weathering of plagioclase across variable flow and solute transport regimes. J. Hydrol. 420–421:46–58. https://doi.org/10.1016/j.jhydrol.2011.11.044.

Pacheco, F.A.L., Van der Weijden, C.H., 2012b. Integrating topography, hydrology and rock structure in weathering rate models of spring watersheds. J. Hydrol. 428–429:32–50. https://doi.org/10.1016/j.jhydrol.2012.01.019.

Pacheco, F.A.L., Van der Weijden, C.H., 2014a. Modeling rock weathering in small watersheds. J. Hydrol. 513:13–27. https://doi.org/10.1016/j.jhydrol.2014.03.036.

Pacheco, F.A.L., Van der Weijden, C.H., 2014b. Role of hydraulic diffusivity in the decrease of weathering rates over time. J. Hydrol. 512:87–106. https://doi.org/10.1016/j.jhydrol.2014.02.041.

Pacheco, F.A.L., Landim, P.M.B., Szocs, T., 2013. Anthropogenic impacts on mineral weathering: a statistical perspective. Appl. Geochem. 36:34–48. https://doi.org/10.1016/j.apgeochem.2013.06.012.

Pacheco, F.A.L., Varandas, S.G.P., Sanches Fernandes, L.F., Valle Junior, R.F., 2014. Soil losses in rural watersheds with environmental land use conflicts. Sci. Total Environ. 485–486C, 110–120.

Pacheco, F.A.L., Santos, R.M.B., Sanches Fernandes, L.F., Pereira, M.G., Cortes, R.M.V., 2015. Controls and forecasts of nitrate yields in forested watersheds: a view over mainland Portugal. Sci. Total Environ. 537:421–440. https://doi.org/10.1016/j.scitotenv.2015.07.127.

Palla, A., Gnecco, I., Lanza, L.G., 2011. Non-dimensional design parameters and performance assessment of rainwater harvesting systems. J. Hydrol. 401:65–76. https://doi.org/10.1016/j.jhydrol.2011.02.009.

Palla, A., Gnecco, I., Lanza, L.G., La Barbera, P., 2012. Performance analysis of domestic rainwater harvesting systems under various European climate zones. Resour. Conserv. Recycl. 62:71–80. https://doi.org/10.1016/j.resconrec.2012.02.006.

Patrick, E., 1997. Assessing water harvesting suitability. In: FAO, R.S.a.W.R.P.o.t.I.W (Ed.), Food and Agriculture Organization of the United Nations, Rome, Italy.

Pereira, D., Azevedo, T., 1995. Evolução quaternoaria do Graben da Vilariça (Tras-os-Montes, NE Portugal). Cad. do Lab. Xeolooxico Laxe. pp. 123–137.

Petheram, C., Gallant, J., Read, A., 2017. An automated and rapid method for identifying dam wall locations and estimating reservoir yield over large areas. Environ. Model. Softw. 92, 189–201.

Prinz, D., Oweis, T., Oberle, A., 1998. Rainwater harvesting for dry land agriculture – developing a methodology based on remote sensing and GIS. Proceedings, XIII International Congress Agricultural Engineering, ANAFID, Rabat, Morocco.

Robinson, M., Scholz, M., Bastien, N., Carfrae, J., 2010. Classification of different sustainable flood retention basin types. J. Environ. Sci. 22:898–903. https://doi.org/10.1016/S1001-0742(09)60195-9.

Rockström, J., Barron, J., 2007. Water productivity in rainfed systems: overview of challenges and analysis of opportunities in water scarcity prone savannahs. Irrig. Sci. 25:299–311. https://doi.org/10.1007/s00271-007-0062-3.

Sanches Fernandes, L.F., Santos, C., Pereira, A., Moura, J., 2011. Model of management and decision support systems in the distribution of water for consumption: case study in North Portugal. Eur. J. Environ. Civ. Eng. 15, 411–426.

Sanches Fernandes, L.F., Seixas, F., Oliveira, P., Leitao, S., Moura, J., 2012. Climate change impacts on nitrogen in a hydrographical basin in the northeast of Portugal. Fresenius Environ. Bull. 21, 3643–3650.

Sanches Fernandes, L.F., Marques, M.J., Oliveira, P.C., Moura, J.P., 2014. Decision support systems in water resources in the demarcated region of Douro — case study in Pinhão River Basin, Portugal. Water Environ. J. 28, 350–357.

Sanches Fernandes, L.F., Terêncio, D.P.S., Pacheco, F.A.L., 2015. Rainwater harvesting systems for low demanding applications. Sci. Total Environ. 529:91–100. https://doi.org/10.1016/j.scitotenv.2015.05.061.

Santos, R.M.B., Sanches Fernandes, L.F., Moura, J.P., Pereira, M.G., Pacheco, F.A.L., 2014. The impact of climate change, human interference, scale and modeling uncertainties on the estimation of aquifer properties and river flow components. J. Hydrol. 519: 1297–1314. https://doi.org/10.1016/j.jhydrol.2014.09.001.

Santos, R.M.B., Sanches Fernandes, L.F., Pereira, M.G., Cortes, R.M.V., Pacheco, F.A.L., 2015a. A framework model for investigating the export of phosphorus to surface waters in forested watersheds: implications to management. Sci. Total Environ. 536:295–305. https://doi.org/10.1016/j.scitotenv.2015.07.058.

Santos, R.M.B., Sanches Fernandes, L.F., Varandas, S.G.P., Pereira, M.G., Sousa, R., Teixeira, A., Lopes-Lima, M., Cortes, R.M.V., Pacheco, F.A.L., 2015b. Impacts of climate change and land-use scenarios on *Margaritifera margaritifera*, an environmental indicator and endangered species. Sci. Total Environ. 511:477–488. https://doi.org/10.1016/j.scitotenv.2014.12.090.

Scholz, M., 2007. Classification methodology for sustainable flood retention basins. Landsc. Urban Plan. 81:246–256. https://doi.org/10.1016/j.landurbplan.2007.01.010.

Scholz, M., Sadowski, A.J., 2009. Conceptual classification model for sustainable flood retention basins. J. Environ. Manag. 90:624–633. https://doi.org/10.1016/j.jenvman.2007.12.018.

Scholz, M., Yang, Q., 2010. Guidance on variables characterising water bodies including sustainable flood retention basins. Landsc. Urban Plan. 98:190–199. https://doi.org/10.1016/j.landurbplan.2010.08.002.

Senay, G., Verdin, J., 2004. Developing index maps of water-harvest potential in Africa. Appl. Eng. Agric. 20, 789–799.

Siciliano, G., Urban, F., Kim, S., Lonn, P.D., 2015. Hydropower,social priorities and the rural–urban development divide: The case of large dams in Cambodia. Energ Policy 86, 273–285.

Silva, L., 2010. Avaliação da Qualidade Ecológica de Sistemas Lóticos da Bacia Hidrográfica do Rio Sabor (Bacia do Douro) Avaliação da Qualidade Ecológica de Sistemas Lóticos da Bacia Hidrográfica do Rio Sabor (Bacia do Douro).

Silva, A., Rebelo, J., Ribeiro, M., 1989. Notícia explicativa da Folha 11C e Torre de Moncorvo. Serviços Geol. Port. Lisboa.

Singh, L.K., Jha, M.K., Chowdary, V.M., 2017. Multi-criteria analysis and GIS modeling for identifying prospective water harvesting and artificial recharge sites for sustainable water supply. J. Clean. Prod. 142, 1436–1456.

Siqueira, H.E., Pissarra, T.C.T., do Valle Junior, R.F., Fernandes, L.F.S., Pacheco, F.A.L., 2017. A multi criteria analog model for assessing the vulnerability of rural catchments to road spills of hazardous substances. Environ. Impact Assess. Rev. 64:26–36. https://doi.org/10.1016/j.eiar.2017.02.002.

Sivanappan, R.K., 2006. Rain water harvesting, conservation and management strategies for urban and rural sectors. Rainwater Harvest. Water Manag, pp. 1–170.

SNIRH, 2017. SNIRH – Sistema Nacional de Informação de Recursos Hidricos [WWW Document].

Terêncio, D.P.S., Fernandes, L.F.S., Cortes, R.M.V., Pacheco, F.A.L., 2017. Improved framework model to allocate optimal rainwater harvesting sites in small watersheds for agro-forestry uses. J. Hydrol. 550:318–330. https://doi.org/10.1016/j.jhydrol.2017.05.003.

UNEP, 2014. Green Infrastructure Guide for Water Management: Ecosystem-based Management Approaches for Water-related Infrastructure Projects.

Valera, C., Valle Junior, R.F., Varandas, S.G.P., Sanches Fernandes, L.F., Pacheco, F.A.L., 2016. The role of environmental land use conflicts in soil fertility: a study on the Uberaba River basin, Brazil. Sci. Total Environ. 562, 463–473.

Valle Junior, R.F., Varandas, S.G.P., Sanches Fernandes, L.F., Pacheco, F.A.L., 2014. Environmental land use conflicts: a threat to soil conservation. Land Use Policy 41:172–185. https://doi.org/10.1016/j.landusepol.2014.05.012.

Valle Junior, R.F., Varandas, S.G.P., Sanches Fernandes, L.F., Pacheco, F.A.L., 2015. Multi criteria analysis for the monitoring of aquifer vulnerability: a scientific tool in environmental policy. Environ. Sci. Pol. 48:250–264. https://doi.org/10.1016/j.envsci.2015.01.010.

Yang, Q., Shao, J., Scholz, M., Plant, C., 2011. Feature selection methods for characterizing and classifying adaptive sustainable flood retention basins. Water Res. 45:993–1004. https://doi.org/10.1016/j.watres.2010.10.006.