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Planning Landscape with Water Infiltration. Empirical Model to Assess Maximum Infiltration Areas in Mediterranean Landscapes

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Abstract Water infiltration is a natural process of landscape. The areas with high capacity to infiltrate are especially important in landscape planning, whose protection is crucial for the continuity of water flow, maximizing the recharge of aquifers, minimizing flooding risks and reduce soil erosion. The different interpretations of the criteria for the delimitation water infiltration areas, its imprecise legal nature and the progressive incentive for sustainable water and management policies, have created the need for an integrative and ecological based methodology that suppresses this gap at the landscape planning level. The aim of this research was to create a GIS model, based on ecological principles, that contributes to the delimitation of the maximum infiltration areas. The mapping of water-related systems guarantees the inclusion and protection of the hydrological cycle in the landscape planning. The application of the model in Almada Municipality, from Lisbon Metropolitan Area, allows the integration of the maximum infiltration areas in planning, municipal management and urban design. Almada is part of the recharge area of Tagus River aquifer. With the application of the proposed model, we concluded that 54 % of the municipality has maximum infiltration areas and 38 % of those are already impervious due to construction works. Finally, we concluded that this method should be applied in an early stage of planning, at several scales, leading to the definition of potential soil uses and priority intervention measures according with its ecological suitability.

Keywords Maximum infiltration · Water flow · Landscape planning · Model · Geographic information system · Lisbon metropolitan area (Portugal)

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1 Introduction

The concept of landscape can be defined as a complex system (Magalhães et al. 2007), which is described as a relation between an input, a process and its output, that is, there is a flow of information, energy and matter through it (Chadwick 1978). Landscape planning's main goal is to maintain or create ecological flow continuity and interactions between the components that form landscapes. The ecological flow is the natural movement of water, air, soil, nutrients and living organisms in the landscape. This goal covers all planning scales and will provide landscape stability as a dynamic system (Pena and Abreu 2012). The equilibrium between the use of landscape by man and landscape integrity and resilience is then provided. The identification of landscape structures, such as ecological networks (Jongman 1995; Magalhães 2001; Cook 2002) or, more recently designated, green infrastructures (Naumann et al. 2011), will ensure the flow continuity, keeping the natural ecosystem functioning. The continuity of natural spaces is thus a critical factor in maintaining a sustainable ecosystem (Levin et al. 2007), both in rural or urban areas. The latter needing particularly urgent action due to the intensity of land use transformation (Colding 2007).

One of the ecological flows that are part of the landscape system is water flow. In the European Water Frame Directive (WFD 2000) it is considered that, for environmental protection, there is a need to take into account the natural flow conditions of water within the hydrological cycle, leading to the resilience of water resources system (Liu et al. 2012). Studies on spatial planning have been developed in a way to support the implementation of the Water Frame Directive (Volk et al. 2007). Water is related to many planning problems in natural and altered environments (Dunne and Leopold 1978) and is the primary element of the ongoing interactions in nature, being present, directly or indirectly, in all human activities (Fabos 1979). Beyond a resource widely used by the humanity, water has an essential function in nature: in the rocks weathering and modeling land relief, as a soil genesis and soil erosion factor, as well as a trigger for the soil enrichment in nutrients and plants and animals existence (Tricart 1978).

Water importance has been progressively translated into several political and thematic national and international frameworks over the past 20 years. Water is considered a natural environmental component (Law n. ° 11/87 1987), the natural capital of a city (Aalborg 1994) and as a goal of the decade (UN 2003) and the millennium (UN 2000). The integrated planning of water resources (Decree-Law n.° 45/94 1994; GWP 2000), European Strategy for Sustainable Development (EC 2001), National Strategy for Sustainable Development (RCM n° 109/207 2007), the importance of their management (CSD 1992) and its consideration in urban areas (EC 1990; EC 2005), has been a constant concern of the legislation produced.

The accurate landscape planning has to consider the water conservation. These approach to landscape planning will also have major advantages in providing ecosystem services (Alcamo (coord) 2003; Van Leeuwen et al. 2012; Kolinjivadia et al. 2014), and it is currently related to the thematic of Nature Base Solutions (EC 2015). The mapping of water-related systems, such as water lines, headwater areas, wet systems and maximum infiltration areas, guarantees the inclusion and protection of the hydrological cycle in the landscape planning. This work is focused on the definition of a precise methodology and tool to map maximum infiltration areas, being a useful tool for landscape and land use planners and related sciences.

The maximum infiltration areas are those with larger capacities for the infiltration of water. These areas are important in their function of maintaining the water flow continuity, decreasing run-off and soil erosion, and contribute to the increase of fresh water by ground water supply. The infiltration rate is influenced by vegetation cover, properties of the soil (porosity and hydraulic conductivity) and soil moisture (Chow et al. 1988), but rainfall characteristics (rainfall intensity, quantity, raindrop dimension) and land use are also determinant (Dunne and Leopold 1978). Marsh (1986) adds a factor that also influences infiltration: slope position. The geological substratum also has a crucial role in the water infiltration capacity. The main geological features to be considered are: the rock type, its fracturation degree, texture and structure as well as the type and degree of weathering (Abreu and Pena 2007).

Water flow calculations (Martinez et al. 2011) or laboratory methodologies have been developed to calculate and measure soil permeability in a given location (Beaudet-Vidal et al. 1998; Mao et al. 2016). However, for landscape planning, those surveys would be too expensive, the scale of planning is greater and it would be necessary to have numerous analyses. Despite some work that have been made to evaluate the aquifers vulnerability by the interpretation of some hydrogeological characteristics (Aller et al. 1987; Brito et al. 2006; Lathamani et al. 2015) the linkage to landscape planning and managing was not yet accomplished. Therefore, there is a lack of methodology to determine spatially, on a municipal scale, in a Geographic Information System (GIS), the areas of maximum infiltration. In this context, the aim of this work is to propose a Maximum Infiltration Model (MIM), which will allow spatial determination of these areas, considering the ecological processes involved. The model construction is tested and calibrated with baseline data from known permeability sites in Sintra municipality (Lisbon Metropolitan Area (LMA), Portugal). The case study where MIM is applied and validated is the Almada municipality (LMA, Portugal).

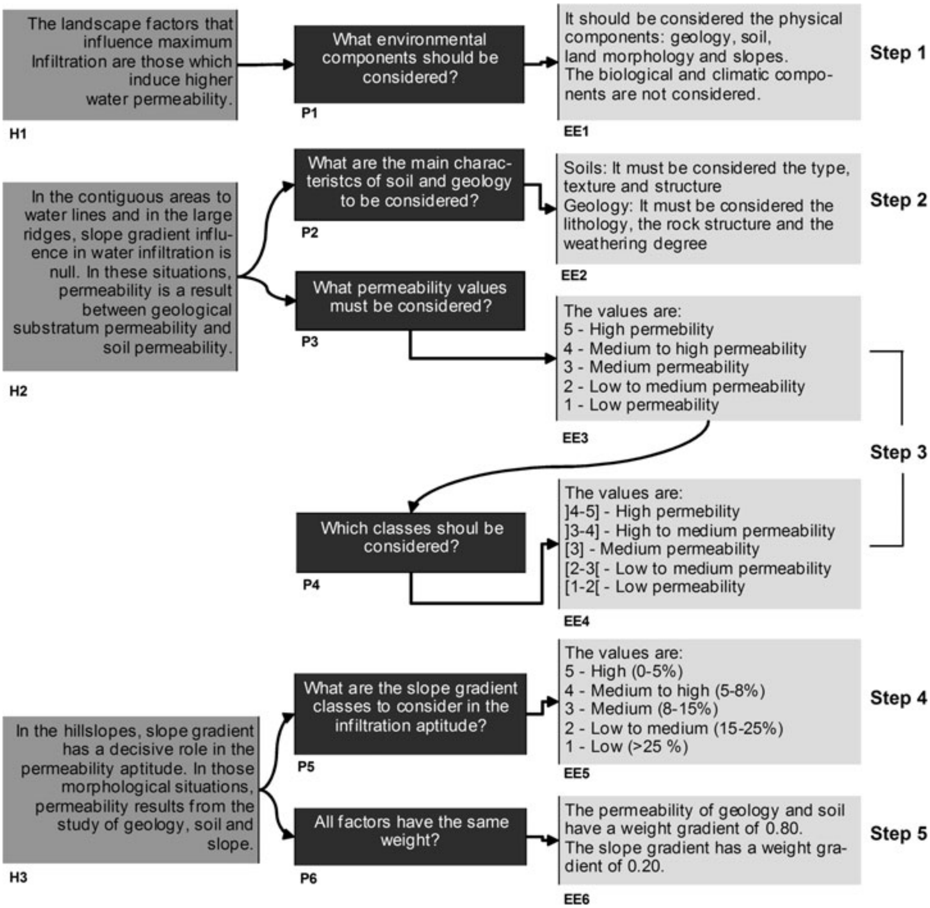
2 Methodological Approach

The construction of a model involves a structure, a sequence of instruction and a simplification of realty with generalized characteristics and relationships (Chorley and Haggett 1967). For the achievement of a MIM, the hypothetical-deductive method which allows testing hypotheses and error elimination was considered. The goal is to simplify reality with the best possible accuracy.

The response to a particular problem arises from the formulation of hypotheses (H), problems (P) and error elimination (EE). The Maximum Infiltration Model construction is based on three hypotheses: (H1) the landscape factors that influence maximum infiltration are those, which induce higher water permeability; (H2) in the contiguous areas of streams and the large hilltops, slope influence in water infiltration is null; in these situations, permeability is a result of geological substratum permeability and soil permeability; (H3) in the hillslopes, slope gradient has a decisive role in the permeability aptitude. In these morphological situations, permeability results from the study of geology, soil and slope.

The EE was made through experimentation using a GIS with ArcGIS software from ESRI, and data collected from literature. The EE leads to the measurement of parameters that influence permeability and contributes to building the model.

A schematic representation of the procedure for constructing the model is presented in Fig. 1. For each hypothesis (H) the approach with the problem (P) and error elimination (EE) description are explained.


H1
The landscape factors that influence maximum Infiltration are those which induce higher water permeability.

P1
What environmental components should be considered?

EE1
It should be considered the physical components: geology, soil, land morphology and slopes. The biological and climatic components are not considered.

Step 1

H2
In the contiguous areas to water lines and in the large ridges, slope gradient influence in water infiltration is null. In these situations, permeability is a result between geological substratum permeability and soil permeability.

P2
What are the main characteristcs of soil and geology to be considered?

EE2
Soils: It must be considered the type, texture and structure
Geology: It must be considered the lithology, the rock structure and the weathering degree

Step 2

P3
What permeability values must be considered?

EE3
The values are:
5 - High permebility
4 - Medium to high permeability
3 - Medium permeability
2 - Low to medium permeability
1 - Low permeability

Step 3

P4
Which classes shoul be considered?

EE4
The values are:
]4-5] - High permebility
]3-4] - High to medium permeability
[3] - Medium permeability
[2-3[- Low to medium permeability
[1-2[- Low permeability

H3
In the hillslopes, slope gradient has a decisive role in the permeability aptitude. In those morphological situations, permeability results from the study of geology, soil and slope.

P5
What are the slope gradient classes to consider in the infiltration aptitude?

EE5
The values are:
5 - High (0-5%)
4 - Medium to high (5-8%)
3 - Medium (8-15%)
2 - Low to medium (15-25%)
1 - Low (>25 %)

Step 4

P6
All factors have the same weight?

EE6
The permeability of geology and soil have a weight gradient of 0.80.
The slope gradient has a weight gradient of 0.20.

Step 5

Fig. 1 Model construction procedure

2.1 Data Acquisition

In order to test some hypotheses, baseline data from known permeability sites was used, namely two aquifers: Vale de Lobos and Pisões-Atrozela. Both of them are located on the Sintra municipality (Fig. 2a). The Vale de Lobos aquifer is porous, multilayered and recharged directly, unconfined and confined, and can reach 115 m thick (PROTAML 2001). It is located between 38°47′47″ and 38°50′4″ North and 9°13′59″ and 9°18′25″ West in the Carregueira hill. The Pisões-Atrozela aquifer is located in the foothills of the Serra de Sintra. It is recharged directly. However, it is highly influenced by the numerous veins of the magmatic rocks of the Serra de Sintra that may provide zones of intense fracturing and weathering with interesting hydrogeological behaviour (Ramalho et al. 1993). The aquifer can reach 940 m thick. The Pisões-Atrozela aquifer is located between 38°44′49″ and 38°48′15″ North and 9°19′51″West and 9°23′55″ West.

Geologic and soil cartography are used for the model construction at the following scale: 1:50000 (JML/INETI/FCT-UNL 2005) and 1:25000 (IHERA 2000), respectively.

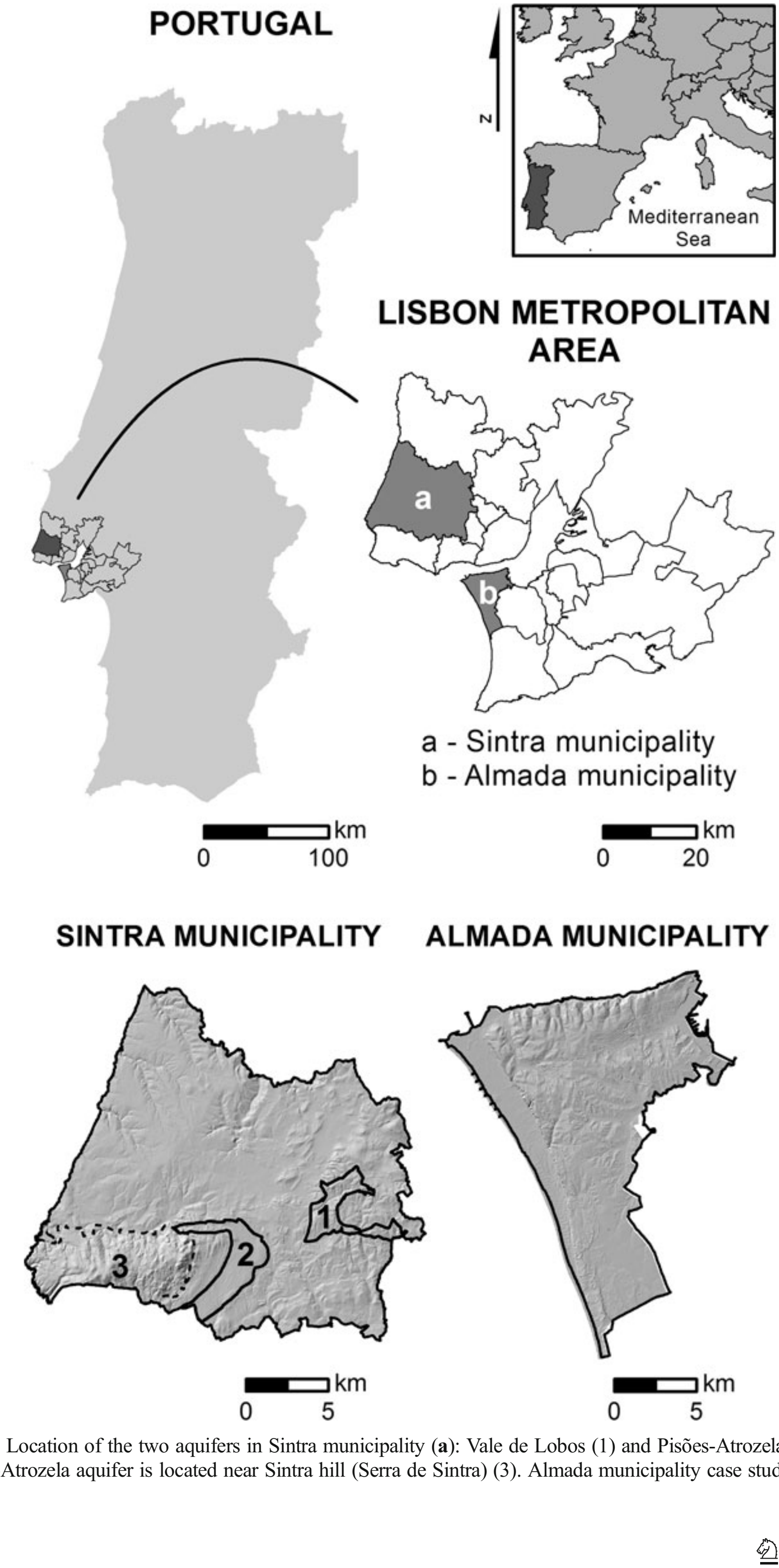


Fig. 2 Location of the two aquifers in Sintra municipality (**a**): Vale de Lobos (1) and Pisões-Atrozela (2). The Pisões-Atrozela aquifer is located near Sintra hill (Serra de Sintra) (3). Almada municipality case study (**b**)

After model construction, it was applied to a study area (Almada municipality) from LMA (Fig. 2b). Almada municipality is located between 38°32′58″ and 38°41′58″ North and 9°7′44″ and 9°15′53″ West, south of Tagus River. The geologic cartography of Almada was at a scale of 1:50000 (Zbysewski 1963) and the soil cartography at a scale of 1:25000 (SROA/CNROA 1969).

2.2 Model Construction

The following subsection designations are the different steps of model construction procedure from Fig. 1, each representing the hypothesis (H), the problem (P) and the error elimination (EE).

2.2.1 Step 1: H1 – P1 – EE1

The environmental components to be considered in the MIM are the physical factors, such as the geological substratum, soils, land morphology and slopes. These factors contribute to higher or lower infiltration rates. Vegetation cover is not considered in the model because it is a factor that can be quickly and easily modified. However, vegetation cover (type and density) is of great importance in the permeability maximization. For this reason, it must be considered in landscape planning. Climatic conditions are not considered in the model construction because at the municipality level of planning, the climatic variation is not significant.

The permeability that results from the application of the MIM is entitled potential permeability (PP). The term potential is used considering that the permeability is the result of the representation of the main parameters that contribute, to a greater or lesser extent, to the permeability of the substrata in a given territory, reflecting the capability to transmit water.

2.2.2 Step 2: H2 – P2 – EE2

The main characteristics of the geological substratum to be evaluated when considering its influence on permeability and maximum infiltration are: rock type, structure, texture and weathering degree (Soliman et al. 1998; Hiscock 2005). For the soil contribution to the permeability and the maximum infiltration evaluation, the main characteristics taken into account are: soil type (according to soil classification system), thickness and texture. The evaluation of soil and geological substratum permeability is carried out through cartography interpretation, complemented with field work.

2.2.3 Step 3: H2 – P3– EE3 and H2-P4-EE4

In the model construction, values corresponding to the permeability degree of a given geological formation or type of soil are assigned. Five permeability classes that allow the evaluation of the permeability of a specific site are considered: [1] low; [2] low to medium; [3] medium; [4] medium to high and [5] high. The use of these values allows the simplification of the model and facilitates its use. However, by assigning a value to the permeability for the different soil types and geological formations there is a need to define the classes that better represent the water infiltration behaviour, when the information is overlapped for GIS processing. For this purpose, it was used the aquifer of Vale de Lobos as a well-known system. Three different approaches, named as first, second and third exercises, were tested in a GIS to define each permeability class. In the Vale de Lobos area the geology (formations of sandstones, limestone and marls of Cretaceous and Jurassic periods) is favourable to water infiltration with classes that fit into the "high permeability" and "high to medium permeability" (Fig. 3a). The soils, mostly classified as Entisols non humic (Portuguese classification) (Fig. 3b), also have properties, which promote water infiltration.

In the first exercise, the five classes of permeability correspond to the mathematical rules of round numbers to the nearest integer. In the second exercise, only the extreme situations (high or low permeability) and the medium value of permeability are considered to have integer values, the other permeability classes have an open interval. In the third exercise, only the medium class of permeability (3) is an integer. To the other classes the assigned value are the

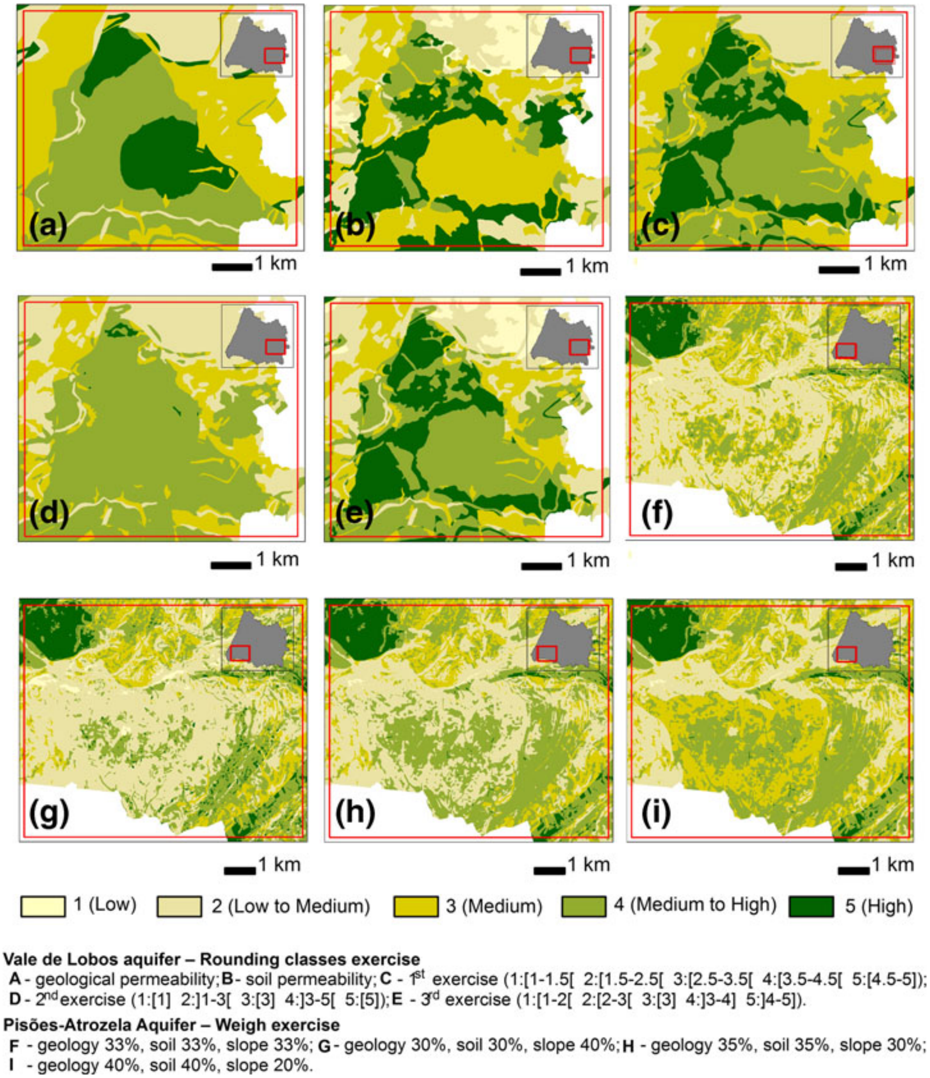


Fig. 3 *Vale de Lobos aquifer*– Rounding classes exercise (**a**, **b**, **c**, **d**, **e**) and *Pisões-Atrozela Aquifer* – Weigh exercise (**f**, **g**, **h**, **i**)

lower or the higher class of the range where the obtained value (from the overlapping of geology and soil) lies (e.g. for “medium to high” permeability class, represented by 4, the class ranges from 3 (open interval value) to 4 (closed interval value)).

In the first exercise, there is a reduction in the number of cases to be assigned to classes 1 and 5 (Fig. 3c). In the second exercise (Fig. 3d) it is concluded that there is an oversimplification of the results, with a tendency to decrease the value of the permeability of the study area. The classes 2 and 4 are favoured since they cover a wider range of hypotheses.

The results of the third exercise (Fig. 3e), show a more balanced allocation of the classes “low” (1) and “high” (5) than the results obtained for the other two exercises.

2.2.4 Step 4: H3 – P5 – EE5

Slopes influence the capacity for water infiltration in the substrata and consequently on the maximum infiltration capacity evaluation of a site. Lower slopes lead to high infiltration capacity, depending on soil and geology, while in higher slopes the infiltration will be reduced due to the greater intensity of run-off.

Five classes of slopes are considered (McHarg 1969; Magalhães 2001) with five types of infiltration capacity according to each slope class: [1] low (>25 %); [2] low to medium (15–25 %); [3] medium (8–15 %); [4] medium to high (5–8 %); [5] high (0–5 %).

The threshold of 5 % is considered for the majority of the authors as the value to define the flat areas, where infiltration is promoted. The threshold of 8 % corresponds to areas where run-off do not prevent infiltration, although the average run-off can be fast. The threshold of 15 % results in a fast run-off that can determine soil erosion. The 25 % threshold is in sensitive areas, where soil erosion is felt with high intensity, so infiltration is lowest.

2.2.5 Step 5: H3 – P6 – EE6

Considering slope as a factor to determine MIM, there is a need to understand the weight of slope in the water infiltration assessment.

The Pisões-Atrozela aquifer was chosen as a baseline scenario to assess the weight of slope in the water infiltration in a given area. This aquifer is located in the foothills of Sintra hill (Serra de Sintra). The magmatic massif of Sintra is cut by numerous veins of magmatic rocks (microgranites, microsienites, rhyolites, microdiorites, dolerites, etc.) that may provide zones of intense fracturing and weathering with interesting hydrogeological behaviour (Ramalho et al. 1993). The fractures in the magmatic rocks of the massif, mainly granites and sienites as well as their weathering products are also factors to be considered. Consequently, the Sintra hill geology plays a significant role in the recharging of the Pisões-Atrozela aquifer. The permeability factors ascribed to the geology, soil and slope were tested considering different weights in order to decide the best weight to describe the Pizões-Atrozela aquifer. The weights tested translate: equal influence of all factors (Fig. 3f); high influence of slope in reducing infiltration (Fig. 3g); slight increase of geology and soil factors when compared with slope (Fig. 3h); and lower influence of slope in the permeability assessment (Fig. 3i).

The best solution will be the one that translates the higher values of permeability in the Sintra hill. Nevertheless, it is not expected to have the greatest classes of permeability, due to the steep slopes occurring in the area. Through the analysis of the different scenarios, it is concluded that the solution considering 40 % for geology, 40 % for soil and 20 % for slope (Fig. 3i) will be the one that best represents the importance and contribution of the Sintra hill for the recharge of Pizões-Atrozela aquifer. In Fig. 3i it is clear that the “medium to high” and the “medium” are the dominant classes for the potential permeability. The other tested solutions indicated a large representation of “low to medium” classes of potential permeability.

2.3 Maximum Infiltration Model (MIM)

The conditions for the model construction are established after the error elimination. The model in Fig. 4a allows subsequent application in GIS.

Maximum Infiltration areas is applied in the three ecological land morphological positions: contiguous areas of streams (wet systems); large hilltops; hill slopes.

In the first two land morphology positions, slope degree does not influence permeability, unlike the hill slopes where the slope degree influences permeability and infiltration.

In contiguous areas of the streams and in large hilltops, the PP corresponds to the permeability ascribed to the geology and soil with equal weights. In the hill slope, the PP corresponds to 80 % of the permeability of geology and soils, and 20 % of the slope ability to enhance infiltration. Maximum infiltration areas are those whose permeability is “high” (5).

Summarizing, in contiguous areas of streams (wet systems) and large hilltops, the PP can be assessed by the Eq. 1:

$$PP = 0.5Pg + 0.5Ps \tag{1}$$

In the hill slope situation the PP can be assessed by the Eq. 2:

$$PP = 0.8(0.5Pg + 0.5Ps) + 0.2Ainf \tag{2}$$

Where:

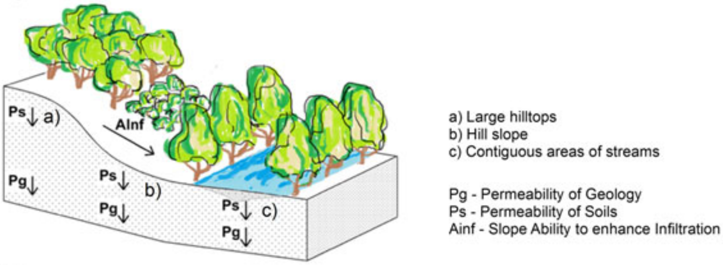
PP	Potential Permeability
Pg	Permeability of Geology
Ps	Permeability of Soils
Ainf	Slope Ability to enhance Infiltration

The defined conceptual model was transposed into a cartographic model (Fig. 4b). This allowed the construction of a GIS. The base maps (geology, soil and slope) and the different land morphology types were considered in this GIS software, and the main operations are also represented in the cartographic model. The model can be converted in an easy reading matrix (Fig. 4c).

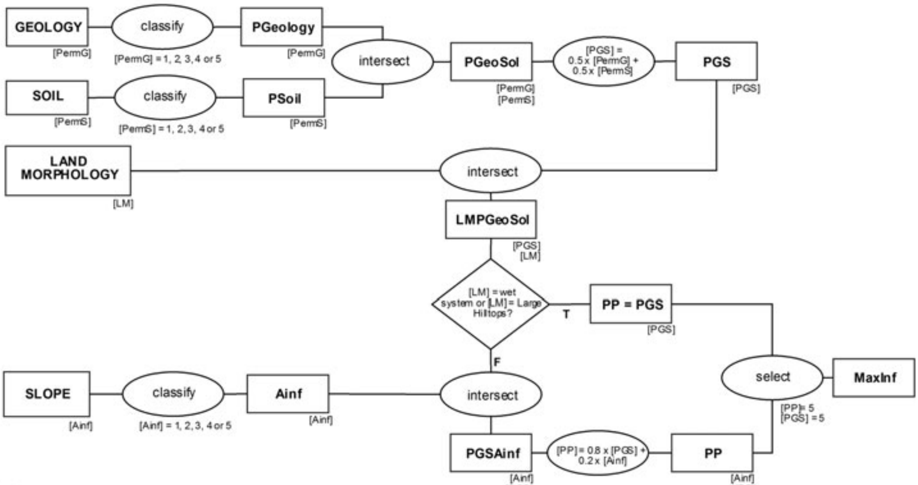
Geology and soil maps were classified from one to five according to the permeability of each geology and soil type. This classification was made in the attribute fields [Pg] and [Ps] from each shapefile (geology.shp and soil.shp). Both sets of information were intersected and gave origin to PGeoSol.shp. A weighted average between geology permeability ([PermG]) and soil permeability ([PermS]) was calculated, originating from the PGS (permeability of Geology and Soil) shapefile. The result was intersected with land morphology. According to the conceptual MIM explained above, it was shown that in wet systems (contiguous areas of streams) and large hilltops the slope does not influence the final permeability, and the PP equals PGS. In hillslope the PP is a result of the permeability of geology and soil (PGS) and also of the slope ability to enhance infiltration (AInf) – originating PGSAinf.

The maximum infiltration areas are those whose attribute from the [PP] field is “5” (High permeability).

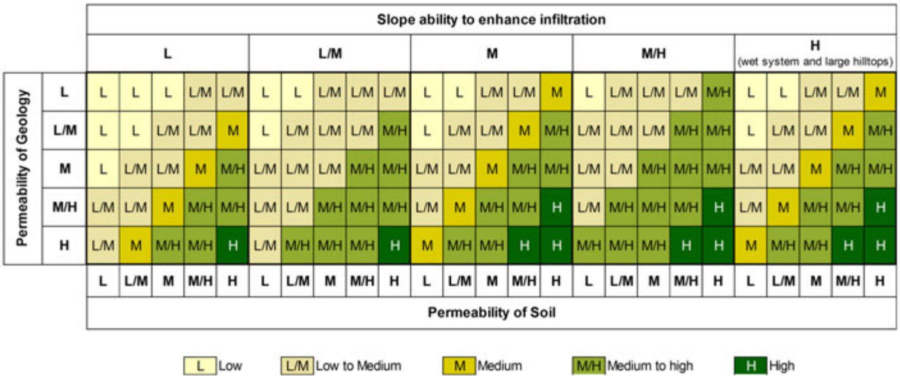
(a) Conceptual Model of MIM



(b) Cartographic Model of MIM



(c) Matrix of Potential Permeabiliy



		Slope ability to enhance infiltration																								
		L					L/M					M					M/H					H (wet system and large hilltops)				
Permeability of Geology	L	L	L	L	L/M	L/M	L	L	L/M	L/M	L/M	L	L	L/M	L/M	M	L	L/M	L/M	L/M	M/H	L	L	L/M	L/M	M
	L/M	L	L	L/M	L/M	M	L	L/M	L/M	L/M	M/H	L	L/M	L/M	M	M/H	L/M	L/M	L/M	M/H	M/H	L	L/M	L/M	M	M/H
	M	L	L/M	L/M	M	M/H	L/M	L/M	L/M	M/H	M/H	L/M	L/M	M	M/H	M/H	L/M	L/M	M/H	M/H	M/H	L/M	L/M	M	M/H	M/H
	M/H	L/M	L/M	M	M/H	M/H	L/M	L/M	M/H	M/H	M/H	L/M	M	M/H	M/H	H	L/M	M/H	M/H	M/H	H	L/M	M	M/H	M/H	H
	H	L/M	M	M/H	M/H	H	L/M	M/H	M/H	M/H	H	M	M/H	M/H	H	H	M/H	M/H	M/H	H	H	M	M/H	M/H	H	H
		L	L/M	M	M/H	H	L	L/M	M	M/H	H	L	L/M	M	M/H	H	L	L/M	M	M/H	H	L	L/M	M	M/H	H
		Permeability of Soil																								

L Low L/M Low to Medium M Medium M/H Medium to high H High

Fig. 4 Maximum Infiltration Model: (**a**) Conceptual Model; (**b**) Cartographic Model of Maximum Infiltration; (**c**) Matrix

3 Results - Model (MIM) Application (Almada municipality)

The MIM application to the Almada municipality (AM) needs a previous study and interpretation of the physical landscape components. According to the MIM procedure, this study includes geology (Zbysewski 1963), soil (SROA/CNROA 1969), slope and land morphology (Cunha 2008).

The geology of AM is composed of Cenozoic formations dating from the Neogene and Quaternary Periods. Due to its lithological composition, texture, structure and weathering degree of the rocks, the majority of formations favour water infiltration. The geologic setting of AM can be divided into four main units: Holocene formations, composed of alluvium, sands, dunes and foothill deposits, along the sea coast, river valleys and cliffs; Pleistocene, consisting of conglomerates mainly composed of quartz and quartzite pebbles; Pliocene, formed by a complex of sands, yellowish or reddish sandstone more or less argillaceous and conglomeratic beds and more or less coarse sands (Zbysewski 1963); Miocene, represented by marine and continental sediments forming a monocline structure oriented south-southeast and also a narrow band in the northern section of the Caparica fossil cliff.

The permeability of the geological formations is evaluated considering their characteristics complemented in some cases by field work. In the AM, the geological formations and their respective assigned permeability classes are listed in Table 1. About 59 % of the geologic formations of Almada are included in the high permeability class, 23 % in the class 4 (medium to high) and 18 % of the total municipality area correspond to the other classes.

Soils in the AM are mostly Fluvisols, developed on alluvium materials with sandy texture and located along the main water lines, and Arenosols consisting mostly of sand, in the coastal zone and south part of the studied area. Colluvium materials located on footslopes originated Colluviosols. There is also a large area of Cambisols on the north of the study area. In the central zone, and also occupying a large area, there are Arenosols and some Podzol soils. The soil permeability is presented in Table 2. The high classes of permeability are assigned to soils with sandy texture, comprising about 24 % of the municipal area. The values ranging between “medium” and “medium to high” classes covers 48 % of the municipal area. In the areas mapped as social areas (water or urban areas) and outcrops, it was assigned the permeability value of the geology.

For the MIM methodology application, the slopes were classified according to the best classes for calculating the suitability for infiltration. About 30 % of the total area has a wavy relief, prevailing slopes between 5 and 16 %. The south areas of Almada, along the coast line, as well as the main wider valleys, corresponding to ≈48 % of the total area under study, present a smooth morphology with low slope values, showing high ability to enhance infiltration. By contrast, in the north part of Almada there are steep slopes along the cliffs and along the Caparica fossil cliff, covering 17 % of the municipal area.

After the assignment of the geological permeability, soil permeability and slope ability to enhance infiltration, the Eqs. 1 and 2 were applied according to the different land morphology types. The results (Fig. 5a and b) show that the areas classified with classes having high permeability (maximum infiltration areas) represent a wide area of about 54 % of the total municipality area. Around 30 % of total municipal area has “medium to high” and the remaining 16 % correspond to the other permeability classes.

The MIM result obtained for the AM was compared with the current regional map of strategic areas for protection and recharge of aquifers (SAPRA) defined by the Lisbon and Tagus Valley Regional Coordination and Development Commission (CCDR-LVT) (Ramos et al. 2010). The methodology, applied at a regional scale, estimates the effective recharge rate from a weighted average of three parameters: net recharge, topography, and lithology and vadose zone structure. Ramos et al. (2010) used the DRASTIC ratings (Aller et al. 1987) for net recharge and topography, and also considered a rate to the lithology and vadose zone

Table 1 Geological formations in Almada municipality and their permeability interpretation expressed as classes of permeability: (5) high; (4) medium to high; (3) medium; (2) low to medium; (1) low

Stratigraphic chart			Formations	Permeability class	Area (ha)	Percentage of total case study area
Erathem era	System period	Series epoch				
Cenozoic	Quaternary	Holocene	Alluvium	5	434.5	6.2
			Dune sands	5	418.3	6.0
			Beach sands	5	115.7	1.6
			Dunes	5	1367.3	19.5
			Foothill deposits	3	59.2	0.8
		Pleistocene	“Belverde” conglomerate	5	1837.0	26.1
	Neogene	Pliocene	“Santa Marta” sands	4	846.3	12.0
		Miocene	Sandstone with *Fabellipecten tenuisulcatus* at “Braço de Prata” and areolas with *Chlamys macrotis* at “Cabo Ruivo”	4	478.8	6.8
			Siliceous sands and clayed, sandy limestone with *Schizaster scillae* at “Grilos” and limestone with *Pycnodonta squarrosa* at “Marvila”	3	153.4	2.2
			Blue clay at “Xabregas”	3	312.8	4.4
			Sands at “Vale de Chelas” and limestone with *Anomia choffati* at “Quinta das conchas”	3	313.9	4.5
			Limestone with *Chlamys scrabiuscula* at “Musgueira”	4	38.4	0.5
			Sands with *Placuna miocenica*	4	188.7	2.7
			Limestone with *Chlamys scrabrella* at “Casal Vistoso”	4	25.5	0.4
			Sands at “Quinta do Bacalhau”	3	67.3	1.0
			Blue clay at “Forno do Tijolo”	2	95.5	1.4
			Sandy limestones at “Entrecampos” (“Banco Real”)	4	16.1	0.2
			Sands with *Chlamys pseudo-pandorae* at “Estefânia”	4	3.9	0.1
–	–	–	Landfill	2	256.6	3.6

structure interpretation. According to Table 3, about 77 % of the SAPRA intersect the delimited maximum infiltration areas (Fig. 5c). For the other 23 % of the areas, the dominant potential permeability class (medium to high), cover 18.5 % of the SAPRA defined by the CCDR-LVT (Ramos et al. 2010).

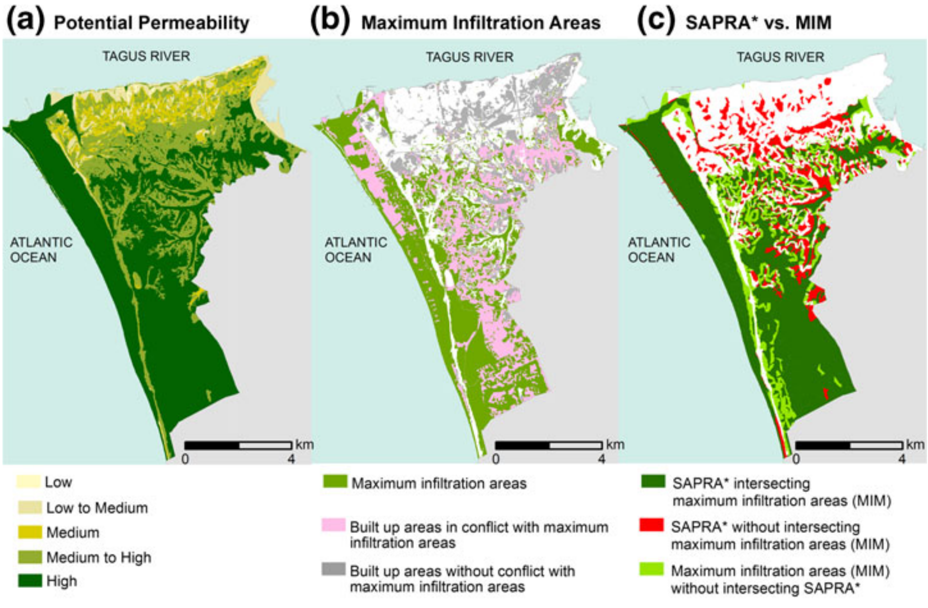
4 Discussion

The Almada municipality is part of Tagus-Sado Basin Aquifer. This aquifer is recharged directly by rain water and has a transmissivity between 100 and 3000 m^2/day (Almeida et al.

Table 2 Soils and their respective permeability classes of the Almada municipality

Soil taxonomy		Permeability (range) classification in study area	Area (ha)	Percentage of total case study area
Portuguese classification (SROA)	FAO classification			
Regossolos	Arenosols	4 /5	1296.0	18.4
Solos Litólicos	Cambisols	3 / 4	1776.1	25.3
Solos Calcários	Cambisols Calcaric	3 / 4	1093.6	15.6
Solos de Baixas	Colluvic Regosols	3 / 4	488.7	7.0
Aluviossolos	Fluvisols	2 / 3	261.4	3.7
Podzois Hidromórficos	Gleyic Podzols	2	5.3	0.1
Solos Hidromórficos	Gleysols	2	11.3	0.2
Litossolos	Leptosols	4	35.5	0.5
Podzois não Hidromórficos	Podzols	4 / 5	391.5	5.6
Solos Halomorficos	Soloncharks	1	1.3	0.02
Outcrops	–	–	74.7	1.1
Social Areas (urban or water)	–	–	1593.7	22.7

2000). To provide hydrological cycle flow continuity and contribute to the maximization of the recharge and water quality of the aquifer, the land use cover and management practices are determinant. According to Liu et al. (2004), changes in land use influence the hydrologic processes. However, the impact of land use change on the subsurface components of the hydrologic cycle is less well recognized (He et al. 2009). The rapid urban growth leads to the



* SAPRA - regional map of strategic areas for protection and recharge of aquifers (CCDR-LVT, Ramos et al. 2010)

Fig. 5 Classes of Potential Permeability (**a**), Maximum Infiltration Areas (**b**) and comparison between SAPRA (CCDR-LVT, Ramos et al. 2010) and MIM results of the Almada municipality

Table 3 Comparison between regional model SAPRA (CCDR-LVT) and MIM model for Almada municipality

Strategic areas for protection and recharge of aquifers (SAPRA) (CCDR-LVT) vs. Maximum Infiltraton Areas (MIM)		Area (ha)		Percentage of total SAPRA	
SAPRA (CCDR-LVT) intersecting maximum infiltration areas (MIM)		2837.1		77.4	
SAPRA (CCDR-LVT) without intersecting maximum infiltrationan areas (MIM)	with low Potential Permeability	828.9	0.9	22.6	0.0
	with low to medium Potential Permeability		29.5		0.8
	with medium Potential Permeability		120.5		3.3
	with medium to high Potential Permeability		677.9		18.5

increase of soil sealing and, consequently, the groundwater recharge decreases. The integration of the maximum infiltration areas in landscape planning is the first step in protecting ground water.

The urban development of AM has not been planned taking into account the importance and the preservation of the areas of water recharge and has grown faster and unplanned since the seventies, after the Tagus bridge construction. As a consequence ≈38 % of the total of the maximum infiltration areas are already built-up, having a high impermeable rate (Fig. 5b). The other 62 % still have conditions for the right landscape planning with land uses and practices that are suitable for maximum infiltration protection and enhancement: woodlands, riparian woodlands, riparian galleries, parks, natural and semi-natural vegetation conservation, terrace agriculture and good agriculture practices.

The determination of the infiltration rate can be accomplished with direct or indirect methodologies. The direct methodologies are used when the target is the infiltration rate itself, such as the use of a water budget to estimate infiltration, runoff, evapotranspiration and recharge with field experiments and soil samples study (Chen et al. 2005). The indirect methodology is used, when it is possible to evaluate the infiltration rate through the study of other variables, such as run-off calculations using runoff curve number methods (Patil et al. 2008). The MIM model is an indirect method to estimate infiltration, and can be a helpful tool for the application to other studies (Benito et al. 2010) and policies, such as water framework directives and integrated water resources management (Ross 2014).

The differences obtained by the comparison between MIM and SAPRA are due to the differences in methodology and scale of analysis. The MIM is at local scale whereas SAPRA is at regional scale with lesser detail. There are 13.5 % of the AM with maximum infiltration areas mapped by MIM, which are not considered in the SAPRA. In these particular case, all components have “high” permeable geological formations, and soils with characteristics ranging between “medium to high” and “high” permeability. About 46 % of those areas are located in the flattened areas, without slope influence. These areas provide good water infiltration and should be considered as strategic for protection and recharge of aquifers at municipal scale. Similarly, these differences come from the differences in the scale of analysis.

Despite being a qualitative model, without field survey analysis, the MIM is a model providing satisfactory results, which represents the reality of a territory. In fact, 77 % of the SAPRA areas (CCDR-LVT; Ramos et al. 2010) are coincident with those obtained with the MIM application. With this model, it is possible to map areas presenting higher permeability, without undertaking expensive soil analysis. The MIM follows the requirements considered by Chorley and Haggett (1967) for a suitable model, especially the possibility of replication/application to other areas. The main fragility of the methodology is the dependence on the interpreter's sensitivity and scientific knowledge, but a transdisciplinary team in geology/geomorphology, soil science, land use and landscape planning can reduce the constraints.

There are other indirect methodologies, unsatisfying in accomplishing the infiltration rate, such as the *Soil Conservation Service* curve-number-run-off method that only considers soil and land use (Zhan and Huang 2004), leaving aside geology and slope, which are fundamental physical bases of the territory.

The land use has a significant role in the maximization and minimization of the infiltration rates (Harden and Scruggs 2003). In MIM model, the land use is not considered because it is a component that could be under pressure and can easily be changed, unlike geology, soil and land morphology. The delimitation of MIMs is made in a particular context of landscape planning to evaluate the best land uses to be planned.

According to Marsh (1986) there are three strategies to achieve on site management of rain water. These strategies can be summerized: to store the excess water in site; return the excess water to the ground; plan the development without increasing runoff significantly. The MIM allows to implement those three strategies, by mapping maximum infiltration areas. This strategy can also be implemented in urban planning. The Maximum Infiltration Model can also be useful at higher planning scales.

5 Summary and Conclusions

The guiding principle of landscape planning should be the continuity of natural flows of energy and matter in a landscape. For this it is crucial to delimit structures with spatial coherence, incorporating notions of carrying capacity, ecological integrity and natural continuity, and consistency over time; the predominant processes in landscape lead to its dynamic stability. By maintaining the continuity of natural water flows the risk of erosion and floods are minimized, and aquifer recharge is maximized.

To apply the proposed model (MIM) it is necessary to evaluate the physical landscape factors of each area under study. This evaluation will provide the necessary background for the outcome to be as accurate as possible and easy to apply, and still be used in GIS. The model itself, when applied to a given area, requires landscape factors to be evaluated by technical experts, which should be able to interpret the landscape characteristics and assign a qualitative value for the permeability of the substrata. This model should be continuously improved also considering other parameters involved in the infiltration processes, such as the climate conditions.

The MIM can also be a contribution to the landscape planning in urban areas through the identification of sensitive areas where water has conditions to infiltration. These sensitive areas are suitable to be planned as urban green areas, being part of the Nature Based Solutions.

The model application to Almada municipality reveals that ≈38 % of the maximum infiltration areas are already impervious and the remaining 62 % should have a land cover favouring the water infiltration. The preferred land uses to accomplish these requirements should be, depending on the area, woodlands, riparian galleries, best agricultural practices, soil protection and the possibility to set parks and gardens in urban areas.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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