Assessment of NBS Impact on Pluvial Flood Regulation Within Urban Areas: A Case Study in Coimbra, Portugal

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Abstract The majority of the world population is living in urban areas. As cities expand, soil sealing increases the vulnerability of urban areas to pluvial floods, and the consequent impacts on social and economic domains. Flood mitigation typically relies on grey infrastructures, but the implementation of Nature-Based Solutions (NBS) can be critical to cope with increasing flood hazard driven by urbanization and climate change. By mimicking natural hydrological processes, NBS enhance water retention, infiltration and evapotranspiration through greening, leading to lower runoff and flood hazard. The effectiveness of NBS on flood mitigation is affected by several factors including the type of NBS and the biophysical characteristics of the area. Nevertheless, a relatively limited number of studies have monitored the impact of NBS, and thus the lack of knowledge is still a barrier to the widespread implementation of this approach. This chapter assesses the impact of a Green Infrastructure (GI) located in Coimbra (Portugal), which performs as a NBS for runoff management and flood hazard mitigation. The study applies the widely used Curve Number method to estimate runoff within the *Quinta de São Jerónimo* study site, driven by rainfall events of 2-, 5-, 10- and 20-years recurrence, based on Intensity–Duration–Frequency precipitation curves. The results show that the implemented NBS can retain runoff produced by 20-years flood, decreasing the flood peak and flood hazard in downstream urban areas. This efficiency is achieved by combining blue, green and grey elements, and proved useful to enhance urban resilience. Furthermore, the green and blue elements of the NBS provide additional ecosystem services, including environmental, social and economic benefits (co-benefits), relevant for human well-being in urban areas.

Keywords Co-benefits, Green infrastructure, Nature-based solutions, Pluvial floods, Runoff management, Urban areas

1 Introduction

Urban areas encompass over half of the world's population [1] and are expected to embrace 70% of the population by 2050 [2]. Urbanization enhances soil sealing with impervious materials (e.g. concrete, asphalt or buildings). In 2006, sealed soils covered 2.3% of the European Union [3]. Sealing is one of the main problems associated with sustainable urban development [4], given, for example, the potential impacts on the hydrological cycle [5]. Expanding impervious surfaces reduce evapotranspiration (although few studies show small increases [6, 7]), decrease infiltration rates, and increase stormwater runoff, thus enhancing the susceptibility to floods [5, 8–10].

To mitigate flood hazard driven by urbanization, hydrologic flows are generally shifted to a complex series of drains, pipes, and other grey infrastructures, designed to facilitate the centralized collection of stormwater and quickly divert it away from the urban areas [11]. These traditional systems often produce unintended consequences, such as changes in the hydrological behaviour and increase pollutant concentrations [12, 13], which affect the urban water quality [14]. Nevertheless, even with these drainage systems, high-intensity rains may trigger low-grade flooding of streets, homes, and basements, causing economic losses, adverse physical and mental problems, and amplification of social inequalities [15]. Changes in precipitation patterns associated with more extreme events (e.g. intensity and frequency of rainfall) driven by climate change, coupled with urbanization trends, will exacerbate cities' vulnerability to flooding [16]. Since grey infrastructures are typically dimensioned for specific volumes of water, often not considering realistic urbanization rates or the impact of climate change, additional solutions are required to enhance urban adaptation and resilience [17].

Over the last decades, urban water drainage management options changed substantially, moving from an approach primarily focused on grey infrastructures to a multifunctional one, based on engineered green/ecological systems which mimic the natural hydrological cycle [18]. This nature-based solutions (NBS) approach aims to restore pre-development flow-regimes within urban catchments and address the degradation of urban water quality [19].

Green Infrastructures (GIs), defined as "*a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services*" [20], are at the very heart of NBS approach [21]. GI aims to increase the cover of permeable surfaces to maximize infiltration and water storage capacity of the soil, retain surface runoff near its source, and slow water transfer downslope. This will delay flood peaks and alleviate urban drainage systems [14, 22, 23]. In this context, GI can be understood as an operationalization of NBS [24]. Urban GI includes diverse types of green and blue spaces, such as public parks, community gardens, bioswales, dry ponds and wetlands [25–27]. In the literature and practice, however, a wide range of terms referred to similar GI applications have been applied, such as Sustainable Drainage Systems, Low Impact Development, and Sponge Cities [21, 28, 29]. These NBS range from solutions with low human intervention to solutions involving the creation of new ecosystems [30], as well as solutions considering a combination of green and grey infrastructures (hybrid solutions) [24, 30, 31].

NBS for stormwater management have been studied extensively by engineers and urban planners [15], and have become popular in several countries to mitigate urban floods [32]. Numerical hydrologic and hydrodynamic models have been widely used to select and design stormwater management strategies, such as the Storm Water Management Model [33], and the Model for Urban Stormwater Improvement Conceptualization (MUSIC) [34]. However, these useful tools for planning purposes often lack the details needed to consider site-specific aspects [35]. Field studies have shown that NBS performance can be highly dependent on their design, implementation aspects, and local biophysical aspects, including the intensity and duration of rainfall events [36].

NBS proved to be effective in managing runoff [37] and efficient in substituting grey infrastructures such as dikes or levees [30, 38, 39]. They are effective and flexible strategies to tackle climate change and enhance urban resilience [40–42], and often less cost-effective when compared to grey options [43]. Although literature provides evidence on the positive impacts of NBS on water management, most studies are based on qualitative assessments [44]. Thus, the lack of evidence-based knowledge of NBS effectiveness, developed upon monitoring data from implemented solutions, represents one of the major barriers for a wider implementation of this approach [14]. Nevertheless, NBS is an effective way to increase the greening in urban environments and to provide a wide range of ecosystem services (co-benefits are driven by several ecological, social and economic functions), relevant to promote the well-being of residents [27, 45, 46]. These co-benefits must be taken into consideration when assessing NBS effectiveness [21].

This chapter aims to assess the impact of an NBS on stormwater regulation and mitigation of pluvial floods in urban areas. The NBS investigated includes green and blue elements, coupled with grey elements, designed and implemented as a mandatory requirement for the approval of an extensive urbanization project implemented in Coimbra, Portugal, where pluvial floods are recurrent. The effectiveness of the NBS on flood mitigation is based on the comparison of runoff estimates for several recurrent floods (2, 5, 10 and 20 years) and the water retention capacity of the NBS, using widely accepted methods. In addition, this study explores the co-benefits provided by the NBS, in order to provide a holistic evaluation of the NBS approach used by local authorities to enhance urban resilience.

2 Flood Management in Coimbra and Green Infrastructures

2.1 Location and Characterization of the Urban Areas

Coimbra is the largest city in the Portuguese Centre region (Fig. 1a). The municipality of Coimbra (319 km^2) accommodates a population of 143,397 inhabitants [47]. The urban perimeter (Fig. 1b), including all urban and urbanizable spaces, covers 16% of the municipality surface area and comprises over 64% of its population [48]. Coimbra's urban consolidated area (Fig. 1b), designated as city core and considering stabilized urban soils and infrastructures (Regulating Decree 9/2009), however, extends over 13 km^2 and settle 44,534 inhabitants [49].

The origins of Coimbra city date back to the pre-Roman period, and until nowadays, it records a significant urbanization trend, driven by a massive increase in the population (Fig. 1c), which lead to extensive surface sealing. In 2018, the urban land use covered 22% of the municipality, while agriculture, forest and water

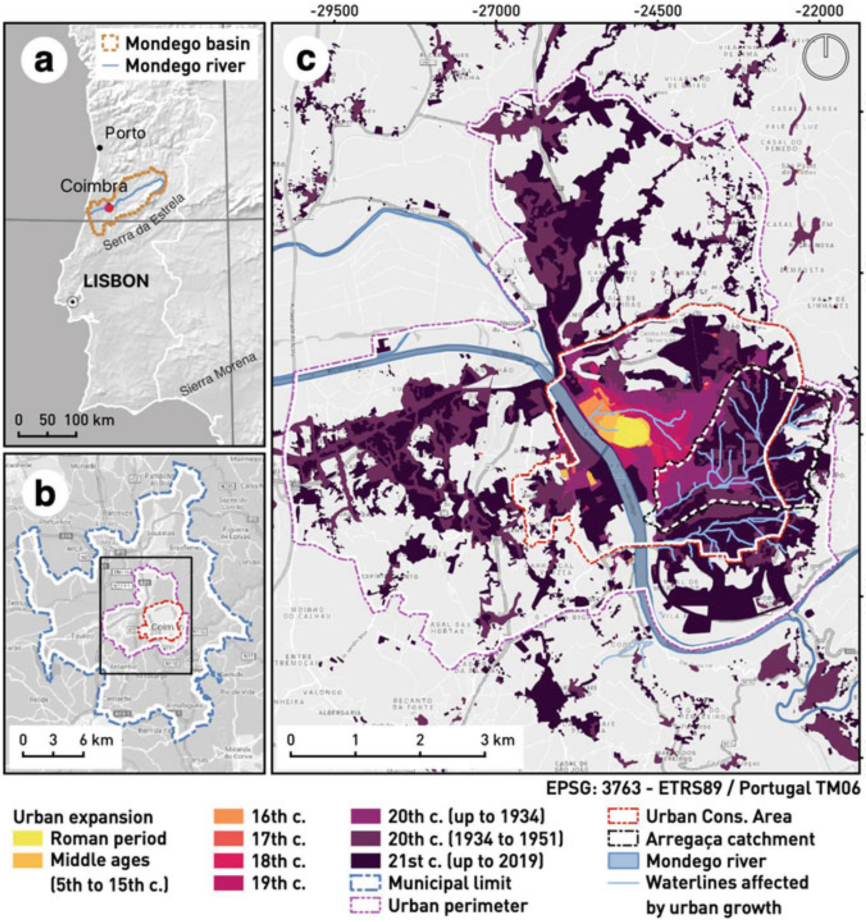

Fig. 1 Location of Coimbra in the central region of Portugal (**a**), extent of the urban perimeter and urban consolidated areas within Coimbra municipality (**b**), and expansion of the urban areas since the Roman period (**c**)

occupied 32%, 39% and 1%, respectively [50]. In the urban perimeter of Coimbra several GI extend over 2,567 ha, including a wide variety of GI from which arable land and forests are dominant (Table 1). Although the extent of GI has been decreasing over the last 15 years (from 53.4% in 2006 to 51.1% in 2018), as a result of urbanization, the green urban areas, and sports and leisure facilities were expanded from 5.0% to 5.3% and 1.1% to 1.2% from 2006 to 2018, respectively [50]. This increase was driven by an effort performed by local authorities to achieve a greener and more sustainable city. According with these aims, the approval of urbanization projects over the last years required the inclusion of GI elements.

Table 1 Changes in the area (ha) occupied by all types of GI (based on Urban Atlas land use classes) and their surface cover within the urban perimeter of Coimbra city (in % of the total urban area), between 2006 and 2018 [50]

	Land use				
	2006		2018		
GI types	(ha)	(%)	(ha)	(%)	% of change
Green urban areas	249.6	5.0	265.3	5.3	6.3
Sports and leisure facilities	55.6	1.1	58.1	1.2	4.4
Arable land (annual crops)	1,450.8	28.9	809.1	16.1	−8.0
Permanent crops			31.9	0.6	
Pastures			212.1	4.2	
Herbaceous vegetation associations			281.1	5.6	
Forests	793.5	15.8	776.7	15.5	−2.1
Water	132.7	2.6	132.7	2.6	0.0
Total	2,682.3	53.4	2,566.9	51.1	−4.3

2.2 *Water Management and Floods*

Coimbra expanded from the margins of the Mondego river (227 km), which drains the second largest basin (approximately 6,645 km^2) entirely in the Portuguese territory (Fig. 1a) [51]. Coimbra has a Mediterranean hot summer climate (Csa, according to Köppen-Geiger classification), with average annual temperature of 16°C and average annual rainfall of 922 mm, recorded between 1941 and 2000. The average annual flow of Mondego was 108 m^3/s [52]. The highest flow recorded in Coimbra reached 2,457 m^3/s, in January 1962, corresponding to a return period between 25 (2,131 m^3/s) and 100 years (2,756 m^3/s), which led to severe floods in the city [53]. Coimbra and the Mondego lowlands have a long history of floods [51, 54, 55], triggered by heavy winter rainfalls and favoured by the large size and marked orography of the river basin. These characteristics lead to peak flows reached in a few hours after extreme rainfall onsets [52].

At the end of the eighteenth century, the Mondego river was largely artificialized, namely in the section crossing Coimbra city and in the downslope alluvial plain [51, 52], to reduce the impacts of the river floods. Despite the intervention, the measures implemented were not sufficient to mitigate floods, and during the twentieth century several management plans based on grey infrastructures were implemented. The most extensive measures were the three dams constructed upstream Coimbra city, a weir bridge in the river stretch crossing the city, and five large dikes with one being located immediately upstream the city. Despite these infrastructures, periodic floods still affect Coimbra and settlements placed in the river floodplain, leading to major economic losses in urban infrastructures and agriculture fields [52].

Although riverside floods are quite relevant given their magnitude, pluvial floods across the city have been more frequent and intense over the last decades, due to progressive soil sealing and increasing frequency of short but intense rainfalls. Pluvial floods have been increasingly noticed due to overflowing of the grey

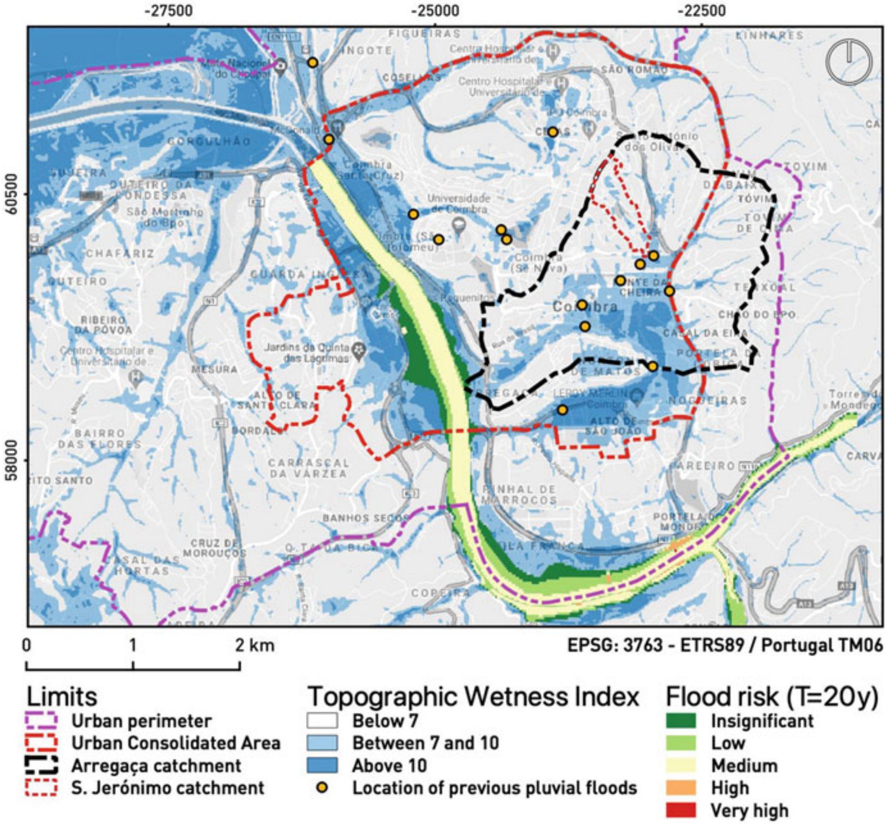

Fig. 2 Location of major pluvial floods recorded since 2006 in the urban perimeter and urban consolidated area of Coimbra, and identification of the flood-prone areas estimated using the Topographic Wetness Index, and the flood risk areas for the 20 years return period identified in the Directive 2007/60/EC

stormwater drainage systems, and/or lack of maintenance of the urban drainage systems (e.g. gutters bridged with litter and sediments). Since 2006, at least 10 large pluvial flood episodes were recorded in the city, with major constrains for vehicular traffic within the main roads and avenues, inundation of private and commercial buildings, and causing occasional shallow landslides. Most of these floods were observed in winter, but also during spring and late summer. These floods tend to affect specific areas of the city, usually located in flood-prone areas (Fig. 2).

The flood-prone areas identified in Fig. 2 were assessed using the Topographic Wetness Index (TWI), calculated in QGIS (3.14) using the SAGA algorithm, based on a Digital Elevation Model (DEM) with 10 m resolution provided by the Portuguese Directorate General for Territory. This method has been widely used as a proxy to identify flood-prone areas [56]. It was applied to identify flood susceptible areas within the city, since the official flood risk maps prepared to fulfill the European Floods Directive (Directive 2007/60/EC) only identify critical areas near the Mondego river, associated to fluvial floods (Fig. 2).

Since water management approaches based on grey infrastructures are not sufficient to prevent floods, local authorities have been implementing additional measures based on NBS over the last decades. Thus, several GI have been implemented or adapted to perform as NBS for flood mitigation. The NBS approach used include the installation of (1) alluvial woods in all the areas susceptible to 20-year return floods, (2) an urban park in the area adjacent to the flood-prone urban perimeter, (3) conservation of the vegetation on Mondego river margins (still under implementation) and (4) GI for recent urbanization projects [57]. *Quinta de São Jerónimo* GI is one example of the latter strategy, comprising a small infrastructure developed to fulfill legal criteria for the implementation of a new urbanization project.

3 Case Study of *Quinta de São Jerónimo* GI

3.1 Location and Biophysical Characterization

Quinta de São Jerónimo is located on the eastern part of Coimbra city and comprises a small sub-catchment within the Arregaça catchment (Fig. 2). With an area of 420 ha and 20,900 inhabitants (INE, 2011), Arregaça covers an important part of the Coimbra urban consolidated area and includes some areas under relatively high flood susceptibility, and where pluvial floods have been recorded over the last years (Fig. 2). *São Jerónimo* catchment covers 3.8% of the Arregaça catchment and is placed in a narrow and steep valley, with slopes up to 45%, ranging from 164 m a.s.l. in the northern part to 69 m a.s.l. in the southeast area. *São Jerónimo* catchment is not prone to local floods but rather contributes to downslope floods in the urban area. One of the most recurring flood sites identified over the last years is located immediately downslope *São Jerónimo* catchment (Fig. 2).

São Jerónimo catchment was subject to a strong urbanization in 1999, driven by the implementation of *Quinta de São Jerónimo* project. This urbanization project, involving the construction of 21 individual housing lots, 30 collective housing lots and 6 lots for private equipment, led to the extent of the impervious surface in *São Jerónimo* catchment from 37.4% in 1995 to 65.2% in 2018, at the expense of forest areas (Fig. 3). This urbanization project, developed as a residential area for high social strata (which became the most expensive residential area in Coimbra), also included the implementation of *Quinta de São Jerónimo* GI (mandatory for the approval of the urbanization project). This GI extends over 5.6 ha and comprises extensive green areas, walking routes, a tennis club with sports fields, a lake, a swimming pool, an amphitheatre, a bar, an old chapel with an atrium, a few management infrastructures and a parking area. Although it is a public garden, it has a condominium function and is managed by owners and residents of *Quinta de São Jerónimo*, through a cooperation agreement for the management of green spaces and collective use.

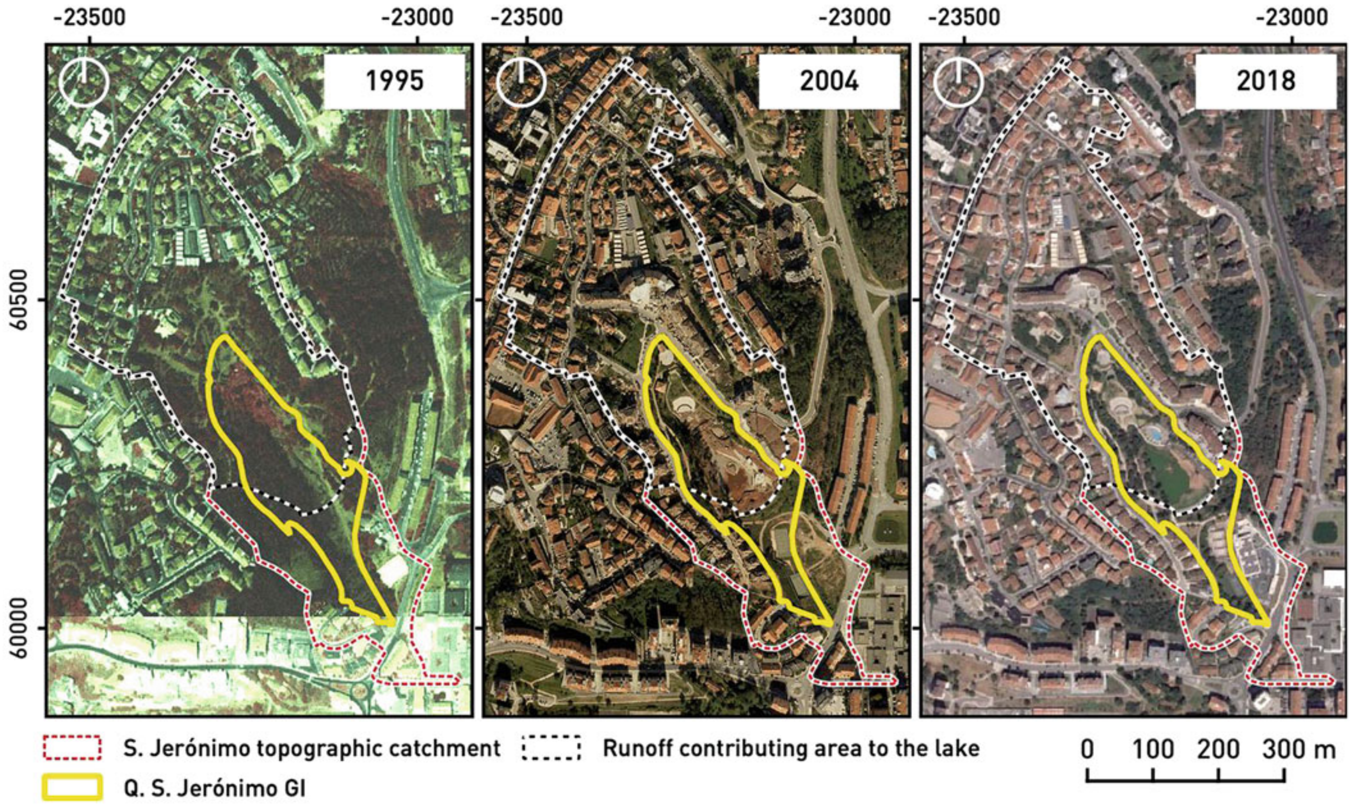

Fig. 3 Land use changes in *São Jerónimo* catchment driven by the implementation of *Quinta de São Jerónimo* urbanization project, which includes the *Quinta de São Jerónimo* green infrastructure, for the years 1995, 2004 and 2018

Quinta de São Jerónimo GI, although designed to provide an attractive and beautiful landscape, was also conceived to retain stormwater runoff and slow down its transfer to downslope areas. Thus, it has been claimed by municipal authorities as an NBS for flood mitigation. However, the water management system within this GI combines natural water storage principles with a grey engineered infrastructure, being classified as a hybrid NBS [24, 31]. Stormwater runoff from the catchment is collected and piped to the GI which includes ~2.4 ha of green areas, a small retention basin in the amphitheatre area with a water storage capacity of 75 m^3, a lake with ~0.3 ha, and a sequence of five settling ponds with a total capacity of 24 m^3 located upslope the lake to retain sediments and pollutants (Fig. 4).

The small retention basin receives stormwater runoff generated from the 700 m^2 amphitheatre (Fig. 5a) sealed surface and the surrounding area, and slows its release to the first settling pond by reduced discharge controlled through a small outlet (Fig. 5b). The first settling pond receives stormwater runoff from *Quinta de São Jerónimo* and transfers the runoff through the sequence of ponds until the lake. The bottom of the lake was sealed with concrete, and a spillway structure was installed to provide a slow release of incoming stormwater runoff to the downslope Arregaça drainage system (Fig. 4). The lake structure and the spillway system provide an additional storage capacity apart from the usual water level.

3.2 *The Role of* Quinta de São Jerónimo *GI on Flood Mitigation*

3.2.1 Methodology

Field surveys were performed to develop a topographic assessment of the lake and the surrounding area, in order to calculate the water storage capacity at typical water level, at the spillway level (when runoff is piped into the urban drainage system), and the maximum water storage capacity considering the flooding of part of the green area (Fig. 4).

Within *São Jerónimo* catchment, an artificial drainage system was installed to convey and pipe surface runoff from sealed surfaces. Although field surveys were developed to investigate the real contributing area of the catchment supplying runoff to *Quinta de São Jerónimo* GI, the lack of detailed information about the subsurface drainage system (despite the contacts established with local water authorities) was a major constrain for the study. Thus, the estimates of the stormwater runoff to *Quinta de São Jerónimo* GI considered the contribution of all the topographic catchment upslope the lake. Since runoff measurements are not performed in the study site, runoff estimates were based on Curve Number (CN) method developed by the Soil Conservation Service [58]:

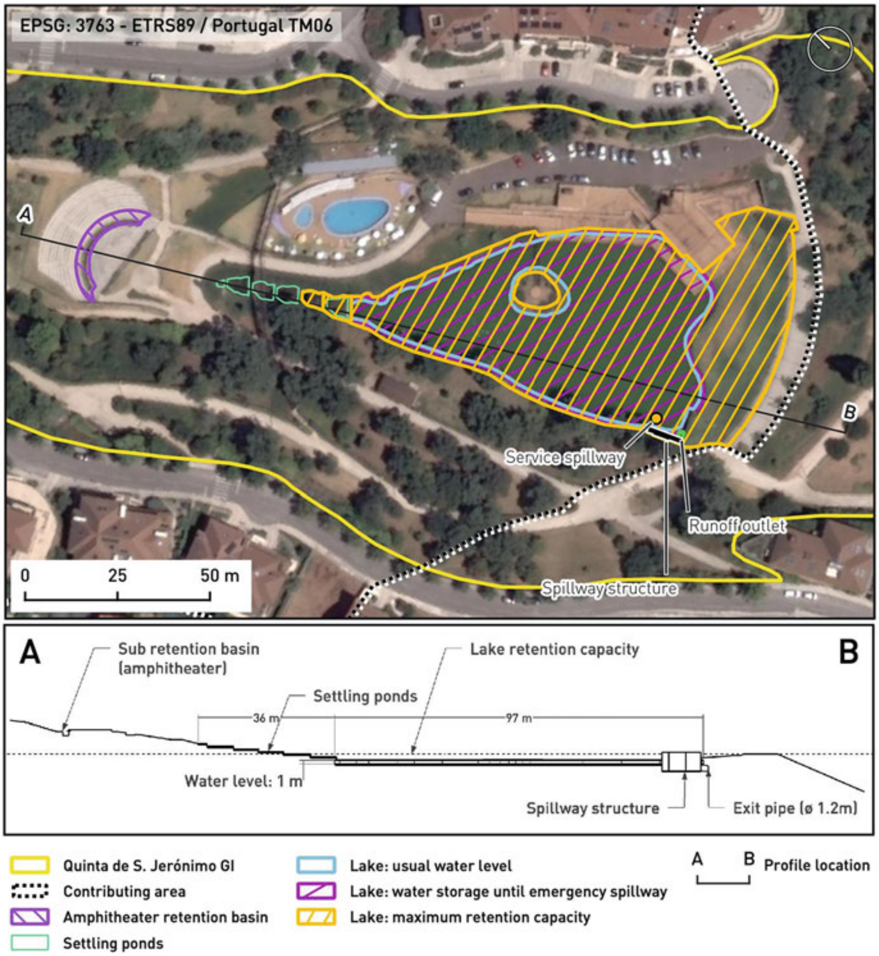

Fig. 4 Detailed view of Quinta de São Jerónimo GI, and the stormwater management system including a retention basin, a sequence of five ponds and a lake with typical water level and maximum water storage capacity, controlled by the spillway. The A-B profile of the GI provides a lateral view with details on the spatial relationship between all the water management devices

$$Q = \frac{\left[P - 0.2 \times \left(\frac{1000}{CN} - 10\right)\right]^2}{\left[P + 0.8 \times \left(\frac{1000}{CN} - 10\right)\right]} \tag{1}$$

where Q = runoff (mm), P = rainfall (mm), CN = Runoff Curve Number.

Since the topographic catchment includes several land-uses, a weighted Curve Number was calculated as follows:

Fig. 5 View of the Amphitheatre in the foreground, with a small water retention volume (**a**), and the reduced outlet connecting to the settling ponds (**b**)

Table 2 Runoff Curve Numbers for different land-uses and hydrological soil groups (A: soils with low runoff potential; B: soils with moderate infiltration rates when thoroughly wetted; C: soils with slow infiltration rates when thoroughly wetted; and D: soils with high runoff potential) [42]

	Hydrologic soil group			
Land cover	A	B	C	D
Impervious surface	98	98	98	98
Forested pervious area	30	55	70	77
Non-forested pervious area	49	69	79	84
Open water[a]	n/a	n/a	n/a	n/a

[a] Areas of open water are not included in the calculation of stormwater runoff

$$CNw = \frac{\Sigma(CNi \times Ai)}{At} \tag{2}$$

where CNw = weighted Runoff Curve Number, CNi = Runoff Curve Number for the land use i, Ai = area of the land use i (m^2), At = Total area of the study site (m^2).

Land use types and associated areas were extracted from the Urban Atlas [50]. The CN values were obtained from Table 2, based on the Soil Conservation Service values [58] and adapted from Tsegaya et al. [42]. The hydrological soil group considered for *São Jerónimo* topographic catchment was C, due to the relatively fine-textured soils, their slow infiltration rate and the shallow soil depth assessed during field visits.

The rainfall (P) used in Eq. (1) to estimate catchment runoff was based on rainfall intensity [59], calculated from the Intensity–Duration–Frequency (IDF) curves of Coimbra (Table 3), using Eqs. 3, 4 and 5. P and Q (from Eq. 1) were calculated for the return periods of 2, 5, 10 and 20 years. Stormwater runoff (mm) estimates were then converted into volume (m^3) by multiplying for the topographic contributing area.

$$P = h = t \times I \tag{3}$$

Table 3 IDF curves developed for Coimbra, for durations between 5 to 30 min [60] and 30 min to 6 h [61], for different return periods

	Return period (years)							
	2		5		10		20	
Duration	a	b	a	b	a	b	a	b
5–30 min	202.72	−0.577	259.26	−0.562	290.68	−0.549	317.74	−0.538
30 min–6 h	280.69	−0.653	374.38	−0.647	436.65	−0.644	496.49	−0.643

$$I = \frac{h}{t} \tag{4}$$

$$I = at^b \tag{5}$$

where I = rainfall intensity (mm/min), h = height of rainfall (mm), t = duration of rainfall (min), a and b = parameters from the Intensity–Duration–Frequency curves.

This methodology was also applied to estimate the surface runoff from Arregaça catchment, to understand the magnitude of *São Jerónimo* runoff within the larger urban catchment. In this case, the calculation of CN was performed considering the hydrological group B instead of C, given the higher soil permeability in Arregaça than *São Jerónimo* catchment.

3.2.2 Water Storage Capacity of the Lake

The spillway determines the water level and the storage capacity of the lake, and provides a controlled release of flows into the downslope drainage system of Arregaça catchment, during large rainfall events. The spillway structure is made of concrete and comprises a service spillway, an auxiliary spillway and an emergency spillway, associated with three distinct water levels in the lake, triggered by storm events, which produce increasing runoff excess (Fig. 6). The service spillway controls the normal water level. The auxiliary spillway comprises a lateral grid, placed 0.22 m above the service spillway, and provides an additional water storage capacity, besides which the runoff discharges to the downslope drainage system. The emergency spillway, comprising a larger upper grid in the overall spillway structure, is activated when the water exceeds 0.62 m above the normal water level in the lake. The maximum water level capacity of the retention basin is reached at 1.66 m above the normal water level. Under the highest water levels, the three types of spillways are functioning simultaneously, but all the runoff discharge is controlled by a single exit pipe.

The lake usually accommodates 2,995 m^3 of water. Thus, the storage capacity to retain additional runoff during the storms is provided by the spillway structure and the local topographic settings. The 0.22 m between normal water level (controlled by the service spillway) and the bottom of the auxiliary spillway provides an additional

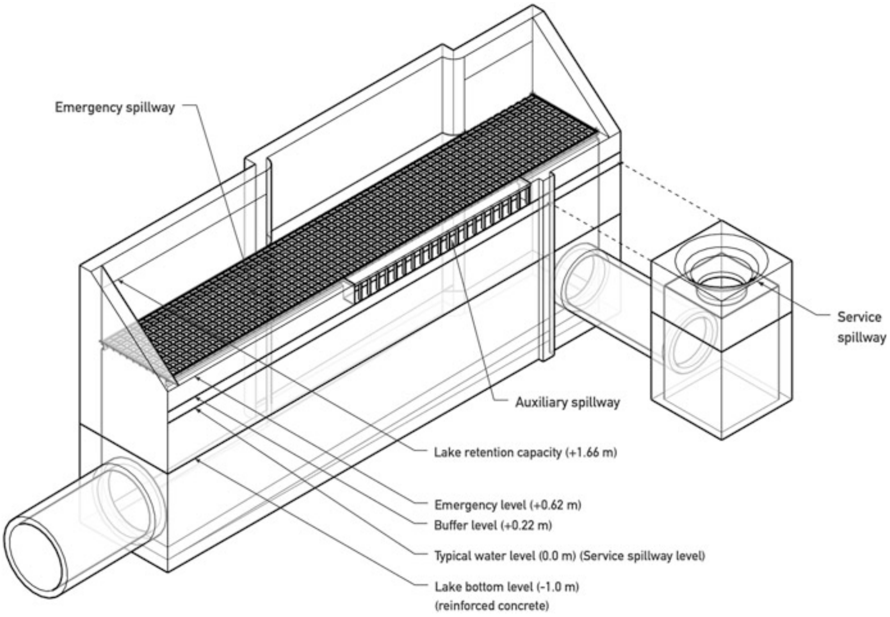

Fig. 6 Schematic representation of the spillway structure installed in *Quinta de São Jerónimo* GI lake, controlling the water storage capacity within the NBS

water storage of 667 m^3, before the auxiliary spillway is activated. This volume represents 22% of the total water storage capacity. After reaching the auxiliary spillway, which increases runoff discharge into the downslope drainage system, an extra storage capacity of 1,240 m^3 is provided (up to 0.62 m above normal water level), just before reaching the emergency spillway. Both volumes of water (1,907 m^3) are kept inside the normal lake boundaries. After surpassing the 0.62 m water level, where the emergency spillway provides extra runoff discharge volume, an additional capacity of 4,120 m^3 is provided through the water volume that overflows to a grass-covered embankment located in the south part of the lake (Table 4). A total retention volume of 6,027 m^3 is ensured (not including normal water volume), after which runoff will flow to *Quinta de São Jerónimo* GI downslope area and, if not infiltrated and/or retained, will contribute to downslope urban floods. If the GIs water storage capacity includes the capacity provided by the upslope retention basin located in the amphitheatre (75 m^3), the total storage of the blue infrastructure is 6,102 m^3, which represents 2 times the normal volume of the water in the lake.

3.2.3 Performance of the Blue Structures to Mitigate Downslope Floods

The performance of the NBS to mitigate downslope floods was based on comparing the water storage capacity and the potential stormwater runoff generated in the

Table 4 Typical water storage capacity of the lake and additional storage capacities affected by the spillway structure (see details on Fig. 6)

Water level	Water storage capacity (m^3)	Description
Typical water level (service spillway level)	*2,995*	Typical volume stored in the lake (maintained by the service spillway)
Buffer level (+0.22 m)	667	Retention capacity provided until the water level reaches the auxiliary spillway, located 22 cm above the service spillway. Water volume is kept inside the lake borders
Emergency level (+0.62 m)	1,240	Retention capacity provided before the water level reaches the emergency spillway, located 62 cm above the service spillway. Auxiliary spillway device in use. Water volume is kept within the lake
Lake retention capacity (+1.66 m)	4,120	Maximum retention capacity provided when the water level reaches 1.66 m above normal water level. All three spillway components in use. This water storage considers the overflow of the lake and flooding of the grass embankment
Total retention volume	***6,027***	Represents the maximum storage capacity of the lake, excluding the typical volume stored in the lake

Table 5 Land cover types and weighted CN values for *São Jerónimo* and *Arregaça* topographic catchments

	São Jerónimo			Arregaça		
	Area			Area		
Land cover type	(m^2)	(%)	CNw	(m^2)	%	CNw
Impervious areas	103,342	66.7	89.5	2,279,822	54.2	81.2
Forest pervious areas	36,927	23.8		708,857	16.9	
Non-forest pervious areas	14,762	9.5		1,215,175	28.9	
Total area	158,157	–	–	4,203,854	–	–

contributing topographic catchment, estimated from the CN method (Table 5). The stormwater runoff results for the different rainfall durations and return periods analysed are presented in Table 6. Comparing the runoff estimated for *São Jerónimo* topographic catchment (assuming that all the runoff reaches the blue infrastructures of *Quinta de São Jerónim*o GI) with the total storage capacity of the GI (6,102 m^3), it is possible to understand that this GI can accommodate runoff from rainfall events up to 60 min, associated with return periods up to 20 years. However, if only the capacity of the blue structure is considered (amphitheatre and lake), without letting part of the green area (grass embankment) to be overflowed (1,315 m^3), the GI would cope only with runoff from rainfall events up to 10 min, associated with return periods of 2 years, and events up to 5 min and return periods of 5 years.

The high runoff volume stored in the GI (0.62 m above normal water level) is not effectively retained in the NBS but rather partially released at control rate by the spillway, which slows the water outflow into the downslope drainage system.

Table 6 Rainfall intensity and runoff volume estimated for *São Jerónimo* and *Arregaça* topographic catchments, for rainfalls of different duration and return periods

	Rainfall intensity (mm/h)				Runoff (m^3)							
					São Jerónimo				Arregaça			
Rainfall duration (min)	2 year	5 year	10 year	20 year	2 year	5 year	10 year	20 year	2 year	5 year	10 year	20 year
5	80.1	104.9	120.1	133.7	845	1,160	1,354	1,527	19,004	27,188	32,286	36,861
10	53.7	71.1	82.1	92.1	1,191	1,635	1,918	2,174	28,005	39,744	47,281	54,109
15	42.5	56.6	65.7	74.0	1,447	1,990	2,342	2,662	34,762	49,185	58,606	67,193
30	30.5	41.5	48.9	55.7	2,156	3,006	3,577	4,110	53,632	76,437	91,833	106,202
60	19.4	26.5	31.3	35.7	2,795	3,895	4,635	5,321	70,780	100,391	120,392	138,934

Although runoff generated in *São Jerónimo* catchment represents only 4% of the Arregaça catchment runoff, *Quinta de São Jerónimo* GI provides a relevant storage capacity and delay in the peak discharge, which may alleviate the flood risk downslope.

The results showed that combining blue and green infrastructures was relevant to maximize the runoff storage capacity of GI, and that NBS can provide a relevant complement to runoff management with conventional grey infrastructures, maximizing the mitigation of downslope pluvial floods. These findings support the increasing evidence that incorporating GI in urban design can alleviate flood risk due to their effectiveness in managing urban floods, reducing peak flow rates, and controlling the total volume of stormwater runoff [14, 62]. Furthermore, this case study demonstrates the relevance of GI to manage stormwater near its origin, as reported by previous authors [42].

Even though *Quinta de São Jerónimo* GI was fully operational in 2006, storm events recorded during that year in June and October (both with rainfall equivalent to 60 min duration and return periods of 20 years) led to floods in the urban area placed immediately downslope (Fig. 2). Thus, albeit *Quinta de São Jerónimo* GI can support water management in Arregaça, additional NBS measures are required to mitigate runoff within the extensive urban area of Arregaça catchment. The current water management system in Arregaça, mainly depending on grey infrastructures, has proved insufficient to prevent floods and NBS can provide an important complement to enhance urban resilience.

3.3 Co-benefits of Quinta de São Jerónimo

As stressed by some authors, the evaluation of NBS should not focus only on water management aspects, but also include additional benefits provided to the society [11, 21]. Similar to other NBS, *Quinta de São Jerónimo* GI supports local stormwater management but also provides multiple secondary benefits (co-benefits) far beyond that of flood protection, relevant for people and the environment, through direct and indirect use of ecosystem services delivered by the green and blue components.

Quinta de São Jerónimo GI has a green area of 13,452 m^2, with a wide variety of trees, shrubs and herbaceous species, and a blue component including a lake of approximately 3,000 m^2, and some springs and water tanks. These green and blue areas provide habitat for several plants (e.g. at least 25 different trees) and animals (e.g. small birds, ducks and fishes), some of them with high conservation value (e.g. *Quercus rubra* and *Quercus ilex*). Besides the relevant ecological benefit, improving biodiversity and ecological resilience, this GI provides some food items since it includes an edible garden with a few fruit trees (e.g. oranges and lemons) and aromatic plants. Several studies highlight the impact of GI on improving biodiversity, namely through the provision of wildlife habitat [63], but also timber and food items [46]. Few authors argue that urban gardens can decrease the overall urban

Fig. 7 Overview of *Quinta de São Jerónimo* green infrastructure (GI); (**a**) view to the south part, with the retention lake (south-centre part of the GI) and tank (in the northern part), the amphitheatre (in the centre) and edible gardens; (**b**) example of a tree with slab providing botanical information; (**c**) view to the north of the GI, showing few deposition ponds in the foreground, the amphitheatre on the midground, and the upper limit of the GI with the old chapel and fountains

footprint, and decrease the reliance of urban dwellers on external provision services [64].

The impact of *Quinta de São Jerónimo GI* on water regulation is beyond that of stormwater volume storage. It includes water evapotranspiration and infiltration by the green areas, and a small contribution for water quality regulation driven by reduced erosion (favoured by vegetation cover), filtration of contaminants through the soil and sediment retention in the tanks and lakes. The relevance of green areas, namely woody vegetation, rainfall interception, increased evapotranspiration, and infiltration in urban areas, has been widely identified [42, 65]. *Quinta de São Jerónimo* GI offers additional regulating ecosystem services such as temperature regulation through shading and evaporative cooling, which mitigates heat-island effect and reduces the energy used in buildings [11]. It also provides airborne particulate filtration and improves air quality [66], noise reduction [67], biological carbon capture and storage [68], and thus climate change mitigation [14]. These co-benefits can occur even if not considered or maximized in the original design of the GI [14]. However, some authors argue that the magnitude of GI benefits on regulation of ecosystem services and biodiversity is affected by the connectivity between green and blue spaces and should be assessed at a larger scale such as regional and national [27].

Quinta de São Jerónimo GI plays a major role in cultural services, allowing the residents to reconnect to nature and improve their well-being [64]. This GI promotes a healthier lifestyle by supporting physical activities, such as walking and sports practices, enhanced by the presence of multi-sport infrastructures, including tennis field and swimming pool [67]. *Quinta de São Jerónimo* GI has a high aesthetic value (Fig. 7a) and provides education and recreation opportunities. This GI includes a wide variety of trees, with several of them placed nearby the walking routes, providing botanical information through slabs with the species common and Latin names and their origin (Fig. 7b). It also comprised an aromatic plant zone with a wide variety of species, identified with high education value slabs.

Furthermore, *Quinta de São Jerónimo* GI supports social networks, improving social benefits such as cohesion and entertainment. This is enhanced by available supporting infrastructures, including bar and restaurant, and an amphitheatre (Fig. 7c) where some cultural events are organized (e.g. music festivals). In contrast, grey infrastructure lacks involvement and engagement with community initiatives [14]. This GI also includes a small heritage chapel and a viewpoint for part of Coimbra city. Recreational settings are used by residents living in close proximity and visitors that come to *Quinta de São Jerónimo* GI for relaxation and socialization purposes. These cultural services have been widely reported in other GI implemented in urban areas [14, 69]. Green spaces reduce stress, anxiety, depression, and increase the level of happiness and life satisfaction [68].

Additionally, *Quinta de São Jerónimo* GI provides economic benefits by supporting the local economy by promoting the bar, restaurant, swimming pool, and sports fields. The maintenance of GI and existent infrastructures provides work opportunities in the private sector, called by previous researchers as collar jobs [70].

Although this chapter does not aim to perform an economic valuation of the investigated GI, some authors stress the relevance of cost-benefit analysis to assess GI projects developed for water management purposes [11]. These analyses are commonly restricted to the cost of measures to increase safety and reduce expected damages. Thus, grey options typically appear as the only economically viable strategy for flood mitigation [11]. However, Vincent et al. [71] demonstrated that GI's economic feasibility is substantially improved if multiple benefits are considered. The monetary valuation of co-benefits would help decision-makers when choosing among different solutions [72]. However, the costs and benefits of GI change when green and blue infrastructures are combined with grey solutions [11], such as the *Quinta de São Jerónimo* GI. A mix of green, blue and grey infrastructures have been identified as the best strategy to enhance urban resilience since they complement each other to provide several benefits in limited urban spaces [35], and green components have higher adaptability and resistibility to deal with the uncertain future [17].

4 Final Considerations

Coimbra is a city historically vulnerable to floods. Over the last years, however, increasing urbanization and frequency of short but intense rainfalls have led to a relatively higher number of pluvial floods, raising concerns about the insufficiency of the water management system, largely based on grey infrastructures. These problems raised awareness among local authorities, which started to consider NBS approach to mitigate flood hazard. Some NBS were already implemented across the city, and it became mandatory that large urbanization projects include Green Infrastructures to get the approval from the authorities.

Quinta de São Jerónimo GI is an example of NBS implemented to mitigate the impacts of an urbanization project, involving the construction of 57 lots of individual and collective houses and private equipment. The NBS includes blue and green elements, such as ponds, a lake and grassed areas, integrated with a grey infrastructure (spillway) which controls the runoff storage capacity of the semi-natural elements. Based on a simple methodology used worldwide to estimate runoff generated within the *São Jerónimo* topographic catchment (CN method), and the calculation of the water storage capacity of the NBS from the topographic characteristics, this study demonstrates the effectiveness of the NBS to mitigate floods. The relatively small scale NBS has the capacity to cope with runoff driven by rainfalls with recurrence up to 20 years, providing runoff storage near to its source (sealed surfaces within urban development), and a slow release of runoff which delays the peak flow into downslope urban areas. These findings demonstrate that incorporating GI in urban design can be an important strategy to manage urban floods and alleviate flood risk.

The investigated GI comprises an appropriate strategy to cope with runoff from the relatively small urban area, which is important to mitigate downslope floods, frequently recorded in nearby urban areas. This NBS, however, is not enough to prevent downslope floods in urban areas of the Arregaça catchment, as noticed with the 2006 urban floods. These floods were triggered by runoff provided from an extensive urban area, with only 4% being supplied by *São Jerónimo* sub-catchment. Therefore, a network of NBS should be considered to complement the current urban drainage system, and effectively mitigate floods and enhance urban resilience in large cities. This is especially important under climate change context, where extreme precipitation events are expected to be more frequent and severe.

The implementation of NBS in urban areas also provides additional ecosystem services, including regulation, provisioning and cultural services, particularly relevant in urban areas given the limited access to green areas, triggered by the limited available space in the cities. Thus, planning and implementing NBS for stormwater management should also consider the additional co-benefits, important for the environment and human well-being.

The strategy of the authorities to include GI as a mandatory element for new urbanization projects is interesting to support the implementation of NBS. However, it may lead to ad-hoc planning strategies, and less than optimal outcomes regarding flood mitigation. Despite there is an interest and an effort to implement NBS, previous studies show that the lack of a coherent approach can hinder the effectiveness of implemented NBS, or even its proper implementation [29, 38].

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References

1. UN DESA (2018) Revision 2018 world urbanization prospects. United Nations Department of Economics and Social Affairs. https://www.un.org/development/desa/publications/2018-revision-of-world-urbanization-prospects.html. Accessed 2 Jul 2020
2. United Nations, Department of Economic and Social Affairs, Population Division (2014) World urbanization prospects: the 2014 revision, highlights (ST/ESA/SER.A/352)
3. Prokop G, Jobstmann H, Schönbauer A (2011) Report on best practices for limiting soil sealing and mitigating its effects. Study contracted by the European Commission, DG Environment. Technical Report-2011–50. www.ec.europa.eu/environment/archives/soil/pdf/sealing/Soil%20sealing%20-%20Final%20Report. Accessed 10 Jul 2020
4. Artmann M (2016) Urban gray vs. urban green vs. soil protection — development of a systemic solution to soil sealing management on the example of Germany. Environ Imp Assess Rev 59:27–42
5. Sun N, Limburg KE, Hong B (2019) Chapter 6 – The urban hydrological system. In: Hall MHP, Balogh SB (eds.) Understanding urban ecology. https://doi.org/10.1007/978-3-030-11259-2_6
6. Wang Z, Xie P, Lai C, Chen X, Wu X, Zeng Z, Li J (2017) Spatiotemporal variability of reference evapotranspiration and contributing climatic factors in China during 1961–2013. J Hydrol 544:97–108
7. Strohbach MW, Doring AO, Mock M, Sedrez M, Mumm O, Schneider AK, Weber S, Schroder B (2019) The "hidden urbanization": trends of impervious surface in low-density housing developments and resulting impacts on the water balance. Front Environ Sci 7:29
8. Ferreira CSS, Walsh RPD, Nunes JPC, Steenhuis TS, Nunes M, de Lima JLMP, Coelho COA, Ferreira AJD (2016) Impact of urban development on streamflow regime of a Portuguese peri-urban Mediterranean catchment. J Soils Sediments 16:2580–2593
9. Kalantari Z, Ferreira CSS, Walsh RPD, Ferreira AJD, Destouni G (2017) Urbanization development under climate change: hydrological responses in a peri-urban Mediterranean catchment. Land Degrad Dev 28(7):2207–2221
10. Abebe Y, Kabir G, Tesfamariam S (2018) Assessing urban areas vulnerability to pluvial flooding using GIS applications and Bayesian belief network model. J Clean Prod 174:1629–1641
11. Alves A, Gersonius B, Kapelan Z, Vojinovic Z, Sanchez A (2019) Assessing the co-benefits of green-blue-grey infrastructure for sustainable urban flood risk management. J Environ Manag 239:244–254
12. Ferreira CSS, Walsh RPD, Costa ML, Coelho COA, Ferreira AJD (2016) Dynamics of surface water quality driven by distinct urbanization patterns and storms in a Portuguese peri-urban catchment. J Soils Sediments 16:2606–2621
13. Ferreira CSS, Walsh RPD, Steenhuis TS, Ferreira AJD (2018) Effect of Peri-urban development and lithology on streamflow in a Mediterranean catchment. Landsc Degradat Dev 29:1141–1153
14. Li L, Collins AM, Cheshmehzangi A, Shun FK (2020) Identifying enablers and barriers to the implementation of the Green Infrastructure for urban flood management: A comparative analysis of the UK and China. UFUG: 126770
15. Venkataramanan V, Packman A, Peters D, Lopez D, McCuskey DJ, McDonald RI, Miller WM, Young SL (2019) A systematic review of the human health and social wellbeing outcomes of green infrastructure for stormwater and flood management. J Environ Manag 246:868–880
16. Sota CD, Ruffato-Ferreira VJ, Ruiz-García L, Alvarez S (2019) Urban green infrastructure as a strategy of climate change mitigation. A case study in northern Spain. UFUG 40:145–151
17. Dong X, Guo H, Zeng X (2017) Enhancing future resilience in urban drainage system: green versus grey infrastructure. Water Res 124:280–289
18. European Commission (2015) HORIZON 2020 – work programme 2016–2017: 12. Climate Action, Environment, Resource Efficiency and Raw Materials. 2016 1349 of 9 March 2016. Accessed via European Commission Decision C (23-05-2018). http://ec.europa.eu/research/

participants/data/ref/h2020/wp/2016_2017/main/h2020-wp1617-leit-space_v1.1_en.pdf. Accessed 12 Jul 2020

19. Kalantari Z, Ferreira CSS, Page J, Romain G, Olsson J, Destouni G (2019) Meeting sustainable development challenges in growing cities: coupled social-ecological systems modeling of land use and water changes. J Environ Manag 245:471–480. https://doi.org/10.1002/ldr.3264
20. European Commission (2013) Green Infrastructure (GI)—Enhancing Europes Natural Capital. Com, 2013. 249 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions, Brussels (23-05-2018). http://ec.europa.eu/environment/nature/ecosystems/docs/green_infrastructures/1_EN_ACT_part1_v5.pdf. Accessed 12 Jul 2020
21. Jato-Espino D, Sañudo-Fontaneda LA, Andrés-Valeri VC (2018) Green infrastructure: cost-effective nature-based solutions for safeguarding the environment and protecting human health and well-being. In: Hussain C (ed) Handbook of environmental materials management. Springer, Cham. https://doi.org/10.1007/978-3-319-58538-3_46-1
22. Alçada e Silva C (2017) Alterações climáticas, precipitação e água em zonas urbanas. Dissertation, University of Coimbra
23. Gunnel K, Mulligan M, Francis RA, Hole DG (2019) Evaluating natural infrastructure for flood management within the watersheds of selected global cities. Sci Total Environ 670:411–424
24. Kumar P, Debele SA, Sahani J, Aragão L, Barisani F, Basu B, Bucchignani E, Charizopoulos N, Di Sabatino S, Domeneghetti A, Sorolla EA, Finér L, Gallotti G, Juch S, Leo LS, Loupis M, Mickovski SB, Panga D, Pavlova I, Pilla F, Löchner PA, Renaud FG, Rutzinger M, Sarkar Basu A, Aminur Rahman Shah M, Soini K, Stefanopoulou M, Toth E, Ukonmaanaho L, Vranic S, Zieher T (2020) Towards an operationalisation of nature-based solutions for natural hazards. Sci Total Environ 731:138855
25. Haase D (2015) Reflections about blue ecosystem services in cities. Swage 5:77–83
26. Koc CB, Osmond P, Peters A (2016) A green infrastructure typology matrix to support urban microclimate studies. PRO 169:183–190
27. Ronchi S, Arcidiacono A, Pogliani L (2020) Integrating green infrastructure into spatial planning regulations to improve the performance of urban ecosystems. Insights from an Italian case study. Sustain Cities Soc 53:101907
28. Ballard BW, Kellagher R, Martin P, Jefferies C, Bray R, Shaffer P (2007) The SUDS manual. CIRIA- Construction Industry Research and Information Association, London
29. Kuller M, Bach PM, Roberts S, Browne D, Deletic A (2019) A planning-support tool for spatial suitability assessment of green urban stormwater infrastructure. Sci Total Environ 686:856–868
30. Martín EG, Costa MM, Máñez KS (2020) An operationalized classification of nature based solutions for water-related hazards: from theory to practice. Ecol Econ 167:106460
31. Grimm N, Cook EM, Hale RL, Iwaniec DM (2016) A broader framing of ecosystem services in cities: benefits and challenges of built, natural, or hybrid system function. In: Seto KC-Y, Solecki W, Griffith C (eds) The Routledge handbook of urbanization and global environmental change1st edn. Routledge, Taylor & Francis Group, New York
32. Alexander K, Hettiarachchi S, Ou Y, Sharma A (2019) Can integrated green spaces and storage facilities absorb the increased risk of flooding due to climate change in developed urban environments? J Hydrol 579:124201
33. Rossman LA (2015) Storm water management model user's manual version 5.1. EPA, Cincinnati
34. Wong THF, Fletcher TD, Duncan HP, Coleman JR, Jenkins GA, Siriwardena L (2002) Model for urban stormwater improvement conceptualisation (MUSIC) (version 1.00). CRC for Catchment Hydrology, Melbourne
35. Alves A, Vojinovic Z, Kapelan Z, Sanchez A, Gersonius B (2020) Exploring trade-offs among the multiple benefits of green-blue-grey infrastructure for urban flood mitigation. Sci Total Environ 703:134980

36. Massoudieh A, Maghrebi M, Kamrani B, Nietch C, Tryby M, Aflaki S, Panguluri S (2017) A flexible modeling framework for hydraulic and water quality performance assessment of stormwater green infrastructure. Environ Model Softw 92:57–73
37. Sorensen J, Emilsson T (2019) Evaluating flood risk reduction by urban blue-green infrastructure using insurance data. J Water Res Plan Manag:145–142. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001037
38. Schäffler A, Swilling M (2013) Valuing green infrastructure in an urban environment under pressure – the Johannesburg case. Ecol Econ 86:246–257
39. Liquete C, Udias A, Conte G, Grizzetti B, Masi F (2016) Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits. Ecol Ser 22:392–401
40. Demuzere M, Orru K, Heidrich O, Olazabal E, Geneletti D, Orru H, Bhave AG, Mittal N, Feliu E, Faehnle M (2014) Mitigating and adapting to climate change: multifunctional and multi-scale assessment of green urban infrastructure. J Environ Manag 146:107–115
41. Stessens P, Khan AZ, Huysmans M, Canters F (2017) Analysing urban green space accessibility and quality: a GIS-based model as spatial decision support for urban ecosystem services in Brussels. Ecol Ser 28:328–340
42. Tsegaye S, Singleton TL, Koeser AK, Lamb DS, Landry SM, Lu S, Barber JB, Hilbert DR, Hamilton KO, Northop RJ, Ghebremichael K (2019) Transitioning from gray to green (G2G) – a green infrastructure planning tool for the urban forest. UFUG 40:204–214
43. Kalantari Z, Ferreira CSS, Deal B, Destouni G (2019) Nature-based solutions for meeting environmental and socio-economic challenges in land management and development (Editorial). Land Degradation and Development, pp 1–4
44. Raymond CM, Berry P, Breil, M, Nita, MR, Kabisch, N, de Bel, M, Enzi, V, Frantzeskaki, N, Geneletti, D, Cardinaletti, M, Lovinger, L, Basnou, C, Monteiro, A, Robrecht, H, Sgrigna, G, Munari, L, Calfapietra, C (2017) An impact evaluation framework to support planning and evaluation of nature-based solutions projects. Report prepared by the EKLIPSE expert working group on nature-based solutions to promote climate resilience in urban areas. Centre for Ecology & Hydrology, Wallingford
45. Kabisch N, Strohbach M, Haase D, Kronenberg J (2016) Urban green space availability in European cities. Ecol Indic 70:586–596
46. Leitão IA, Ferreira CSS, Ferreira AJD (2019) Assessing long-term changes in potential ecosystem services of a peri-urbanizing Mediterranean catchment. Sci Total Environ 660:993–1003
47. INE (2011) General population census per NUTS. https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_publicacoes. Accessed 12 May 2020
48. INE (2020) Resident population per NUTS (estimates). https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_publicacoes. Accessed 12 May 2020
49. INE (2011) General population census per statistical unit. https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_publicacoes. Accessed 12 May 2020
50. European Union, Copernicus Land Monitoring Service (2020) European Environment Agency (EEA) https://land.copernicus.eu/local/urban-atlas/urban-atlas-2018. Accessed 20 Apr 2020
51. Lourenço L, Velez F, Cunha PP, Lima IP, Tavares A (2017) Flood risk in the lower Mondego. Guidebook of the study trip No 3. In: IV international congress on risks. 23rd–26th May. RISCOS, Chã do Freixo, Portugal
52. Cardielos JP, Lobo R, Peixoto P, Mota E, Duxbury N, Caiado P (2016) Mondego O Surdo Murmúrio do Rio. In: A água como património: experiências de requalificação das cidades com água e das paisagens fluviais. Coimbra University Press. pp 95–112
53. APA (2011) Plano de Gestão de Bacia Hidrográfica – Região Hidrográfica do Vouga, Mondego e Liz (RH4). Lisboa
54. Martins AF (1940) O esforço do Homem na Bacia do Mondego. Ensaio Geográfico. Coimbra
55. Tavares AO, Barros L, Santos PP, Zêzere JL (2013) Desastres naturais de origem hidro-geomorfológica no Baixo Mondego no Período 1961-2010. Territorium 20:65–76

56. García-Rivero AE, Olivera J, Sallinas E, Yuli RA, Bulege W (2017) Use of hydrogeomorphic indexes in SAGA-GIS for the characterization of flooded areas in Madre de Dios, Peru. Int J Appl Eng Res 12(19):9078–9086
57. APA (2016) Plano de Gestão dos Riscos de Inundações - Região Hidrográfica 4 - Vouga, Mondego e Lis - Zonas Críticas: Coimbra, Estuário do Mondego, Águeda, Ria de Aveiro e Pombal. APA, Lisboa
58. United States Department of Agriculture (USDA) (1986) Urban hydrology for small watersheds, 2nd ed. TR-55, Washington
59. Ramke H-G (2018) Collection of surface runoff and drainage of landfill top cover systems. In: Cossu R, Stegmann R (eds) Solid waste landfilling, concepts, processes, technologies. Elsevier, Amsterdam, pp 374–416
60. Matos MR, Silva MH (1986) Estudos de precipitação com aplicação no projeto de sistemas de drenagem pluvial. Curvas intensidade-duração frequência da precipitação em Portugal. In: Encontro Nacional de Saneamento Básico/86. Laboratório Nacional de Engenharia Civil, Lisboa
61. Brandão C, Pinto da Costa J, Rodrigues R (2001) Análise de fenómenos extremos precipitações intensas em Portugal Continental. INAG, Lisboa
62. Zhang T, Xiao Y, Liang D, Tang H, Yuan S, Luan B (2020) Rainfall runoff and dissolved pollutant transport processes over idealized urban catchments. Front Earth Sci 16
63. Goddard MA, Dougill AJ, Benton TG (2010) Scaling up from gardens: biodiversity conservation in urban environments. Trends Ecol Evol 25(2):90–98
64. Calderón-Contreras R, Quiroz-Rosas LE (2017) Analysing scale, quality and diversity of green infrastructure and the provision of urban ecosystem services: a case from Mexico City. Ecol Ser 23:127–137
65. Ferreira CSS, Walsh RPD, Shakesby RA, Keizer JJ, Soares D, González-Pelayo O, Coelho COA, Ferreira AJD (2016) Differences in overland flow, hydrophobicity and soil moisture dynamics between Mediterranean woodland types in a peri-urban catchment in Portugal. J Hydrol 533:473–485
66. Setala H, Viipola V, Rantalainen AL, Pennanen A, Yli-Pelkonen V (2013) Does urban vegetation mitigate air pollution in northern conditions? Environ Pollut 183:104–112
67. Chen S, Wang Y, Ni Z, Zhang X, Xia B (2020) Benefits of the ecosystem services provided by urban green infrastructures: differences between perception and measurements. UFUG, p 126774
68. Navarrete-Hernandez P, Laffan K (2019) A greener urban environment: designing green infrastructure interventions to promote citizens' subjective wellbeing. Landsc Urban Plann 191:103618
69. Zuniga-Teran AA, Gerlak AK, Mayer B, Evans TP, Lansey KE (2020) Urban resilience and green infrastructure systems: towards a multidimensional evaluation. Curr Opin Environ Sustain 44:42–47
70. King A, Shackleton M (2020) Maintenance of public and private urban green infrastructure provides significant employment in Eastern Cape towns, South Africa. UFUG 126740
71. Vincent SU, Radhakrishnan M, Hayde L, Pathiran A (2017) Enhancing the economic value of large investments in sustainable drainage systems (SuDS) through inclusion of ecosystems services benefits. Water 9:841
72. Chenoweth J, Anderson AR, Kumar P, Hunt WF, Chimbwandira SJ, Moore TLC (2018) The interrelationship of green infrastructure and natural capital. Landsc Use Pollut 75:137–144