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# URBANIZATION DEVELOPMENT UNDER CLIMATE CHANGE: HYDROLOGICAL RESPONSES IN A PERI-URBAN MEDITERRANEAN CATCHMENT

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## ABSTRACT

Relatively few studies have so far investigated the hydrological impacts of urbanization in Mediterranean catchments, and particularly in peri-urban catchments experiencing relatively rapid and large changes in their land-use mosaic. This study uses data-based model simulations to investigate such impacts, with the Ribeira dos Covões catchment in Portugal as a concrete Mediterranean peri-urban catchment example. We distinguish the impacts of urbanization from those of climatic change on the water flux partitioning and connectivity in the catchment over the period 1958–2013. Decrease in precipitation over this period has primarily driven decreases in annual runoff and actual evapotranspiration, while the urbanization development has primarily changed the relative flux partitioning and connectivity pattern in the catchment. The relative contribution of overland flow to annual and seasonal runoff has increased, keeping the absolute overland flow more or less intact, while the baseflow contribution to the stream network has decreased. Methodologically, the present simulation approach provides a relevant means for distinguishing main drivers of change in hydrological flux partitioning and connectivity under concurrent urbanization and climatic changes. © 2017 The Authors. Land Degradation & Development Published by John Wiley & Sons Ltd.

KEY WORDS: urbanization; climate change; land-use change; hydrological connectivity; peri-urban catchment

## INTRODUCTION

Hydrological characteristics in many river basins around the world are changing with various human-related developments in the landscape (Jaramillo & Destouni, 2014), such as changes in land-use and water-use for food and energy production (Destouni *et al.*, 2013; Jaramillo & Destouni, 2015). Currently, 80% of the world's gross domestic product (GDP) comes from urban areas (United Nations, UN, 2015), containing 54% of the population (World Health Organization, WHO, 2015). However, urbanization continues to spread into peri-urban areas (Oyeyinka, 2008; PU-GEC, 2009), which are transition zones between urban and rural areas, characterized by a wide range of population density, from at least 40 to 20,000 inhabitants per km<sup>2</sup> (Piorr *et al.*, 2015). Although most urban areas across the world are now growing relatively slowly (0.5–0.6% per year), the development of the built environment of peri-urban areas is growing at four times this rate, and this trend is expected to continue (Piorr *et al.*, 2015).

Urbanization involves conversion of previous into impervious surfaces, such as buildings, pavement roads

and car parks. Such changes may further alter hydrological fluxes and their implied water balance (Shuster *et al.*, 2005; Fletcher *et al.*, 2013). Numerous studies since the 1960s focusing on the hydrological impacts of urbanization have identified the following: (i) reduced evapotranspiration due to vegetation removal (Carlson & Arthur, 2000); (ii) reductions in infiltration following surface sealing and soil compaction (Carlson & Arthur, 2000; Hebrard *et al.*, 2006); (iii) increased overland flow and streamflow (O'Driscoll *et al.*, 2010; Fletcher *et al.*, 2013; Miller *et al.*, 2014; Ferreira *et al.*, in press) associated with higher flood hazard (Rose & Peters, 2001); (iv) reductions in groundwater recharge and water table with a corresponding decline in stream baseflow (Hammer, 1972; Wang *et al.*, 2011); and (v) precipitation changes associated with “heat island” effects (Jauregui & Romales, 1996).

Even though various research studies show consistent impacts of urbanization on hydrology, the magnitudes of change vary greatly. Differences in biophysical catchment characteristics, such as climate, geology, lithology and soil properties, affect hydrological processes and may to some degree explain the variability of hydrological response magnitude to urbanization (Boyd *et al.*, 1993; Konrad *et al.*, 2005). Furthermore, other land and water management developments (Jarsjö *et al.*, 2012; Destouni *et al.*, 2013; Kalantari *et al.*, 2014a, 2014b; Jaramillo & Destouni, 2015), in addition to urbanization patterns (Pappas *et al.*,

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2008; Zhang & Shuster, 2014), also lead to runoff and streamflow changes. Runoff variability is further closely linked to the variability of soil-water content, which is a key component of water-storage change that is closely linked with and thus both determines and is determined by current and antecedent weather and climate conditions at the surface as well as by the surface–subsurface flux partitioning and connectivity over entire catchments (Bracken & Croke, 2007; Easton *et al.*, 2007; Destouni & Verrot, 2014; Verrot & Destouni, 2015; Ferreira *et al.*, 2016a).

In the past decade, hydrological connectivity has been widely studied and recognized as a key factor to understand the partitioning of the total input of precipitation among soil-water, groundwater and surface runoff fluxes, and storage changes in surface water and groundwater, and the interactions that determine the hydrological flux connectivity among all these water flux and change components within catchments (Ali & Roy, 2010; Bosson *et al.*, 2012, 2013; Johansson *et al.*, 2015; Parsons *et al.*, 2015; López-Vicente *et al.*, 2016). The questions of water flux and change partitioning, and associated component interactions and flux connectivity in catchments are also essential for understanding the separate and combined impacts of land management and climate change on changes in runoff and waterborne sediment and nutrient transport (Jarsjö *et al.*, 2012; Destouni *et al.*, 2013; Jaramillo & Destouni, 2015; Marchamalo *et al.*, 2015; Keesstra *et al.*, 2016; Masselink *et al.*, 2016).

The hydrological impacts of urbanization may particularly be reflected in peri-urban catchments, which experience changes in flow connectivity due to relatively rapid changes in their heterogeneous land-use mosaic, including a mixture of, e.g. decreasing natural areas, woodland and agriculture along with expanding urban land-uses (Braud *et al.*, 2013). In such catchments, overland flow may occur on both pervious and impervious surfaces, but is prone to be increasingly generated in the latter, expanding urban areas (Ferreira *et al.*, 2015). This particular spatial complexity of peri-urban catchments may be enhanced by temporal soil-moisture variability and change (Destouni & Verrot, 2014); such changes affect the flux partitioning and connectivity patterns and thereby the runoff responses to precipitation changes due to global climate change, e.g. in the Mediterranean region, where soil moisture already exhibits high seasonal variability due to hot dry summers and wet winters (Bracken & Croke, 2007; Easton *et al.*, 2007; Ferreira *et al.*, 2016a).

Relatively few studies have so far investigated the impacts of urbanization on hydrological flux partitioning and connectivity in Mediterranean catchments. This may be due to a limited availability of sufficiently long-term stream flow records that can reveal effects of both climate and land-use changes; see, e.g. the particularly limited data availability in Mediterranean catchments compared to other northern hemisphere catchments studied by Bring *et al.* (2015). Under such data limitations, hydrological models are used as tools to still be able to explore the hydrological

impacts of land-use and climate changes (Asokan *et al.*, 2010; Branger *et al.*, 2013; Isik *et al.*, 2013; Asokan & Destouni, 2014; Jankowsky *et al.*, 2014; Kalantari *et al.*, 2014a, 2014b; Miller *et al.*, 2014; Song *et al.*, 2014); see also reviews by DeFries & Eshleman (2004), Bach *et al.* (2014), Devia *et al.* (2015) and Kalantari *et al.* (2015) of hydrological models used to assess the hydrological impacts of land-use changes.

The present study investigates urbanization impacts on hydrological fluxes and their partitioning and connectivity in a Mediterranean peri-urban catchment as a concrete case study over a long period. The study uses data-based model simulations with the aim to bridge prevailing long-term data gaps in such catchments, particularly in the Mediterranean region. The simulations use the physically based hydrological model MIKE-SHE coupled with the hydraulic model MIKE 11 (Graham & Butts, 2005; Refsgaard *et al.*, 2010; DHI, 2015), applying this to the Ribeira dos Covões catchment. This catchment is located in the periphery of Coimbra, the main city of central Portugal (143,396 inhabitants in 2011, INE, 2012), and a medium-sized European city (EU, 2005). The model application to this changing peri-urban catchment facilitates in-depth analysis of how measured hydro-climatic changes in temperature and precipitation combine with known land-use changes, and particularly urbanization, to affect catchment-scale evapotranspiration and runoff (stormflow and baseflow) fluxes over the period 1958–2013.

## MATERIAL AND METHODS

### *Study Site*

The small Ribeira dos Covões catchment (6.2 km<sup>2</sup>) is somewhat elongated in shape and drains S–N into the large floodplain of the Mondego river through a perennial stream and some upstream ephemeral and intermittent tributaries (Figure 1). The catchment has a humid Mediterranean climate, with an average annual temperature of 15 °C and a mean annual rainfall of 892 mm y<sup>-1</sup> (INMG, 1941–2000). The highest recorded daily rainfall between 1958 and 2013 occurred on 25th October 2006 and was 102 mm day<sup>-1</sup> (return period of 50 years) leading to floods within the catchment. According to older local residents, other such flood events have also occurred around 1936 and 1966.

The geology of the catchment comprises: (i) Cretaceous and Tertiary sandstones, conglomerates and mudstones in the west (56%); (ii) Jurassic dolomitic and marly limestone in the east (41%); and (iii) small areas of Pliocene-Quaternary sandy-conglomerate (colluvium) and alluvial deposits in the main valleys (3%) (Ferreira *et al.*, 2016a). Soils are predominantly deep Fluvisols and Podzols (>3 m and up to 25 m), but with some shallow Leptic Cambisols (<0.4 m) on the steeper limestone slopes (WRB, 2006). Altitude ranges from 34 to 205 m a.s.l., and the average slope is 9°, although the local hillslope gradient reaches 46° in a few locations.

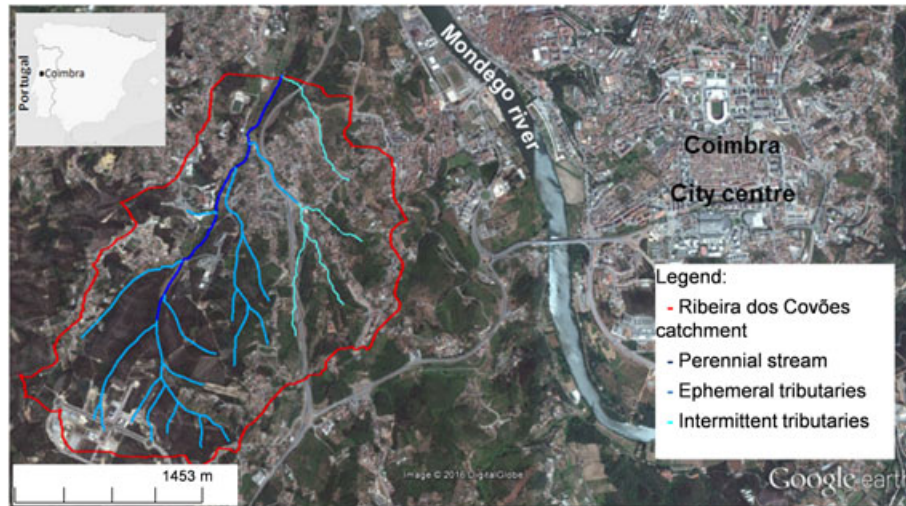


Figure 1. Location of Ribeira dos Covões catchment in Portugal in relation to Coimbra city centre (adapted from Google Earth, 2015). [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Due to its proximity to the Coimbra city centre, the catchment has undergone major land-use changes over the past half-century. Between 1958 and 2012, the agricultural area of mainly olives and arable land declined from 48% to 4%, primarily due to an increase of urban land-use (from 8% to 40%) and of woodland areas (from 44% to 53%), as well as a temporary creation of open spaces (from 0% to 3%) (Figure 2a). Although woodland areas do not exhibit a major increase, the nature of woodland cover also changed, from native species, such as oaks (*Quercus* sp.), to commercial timber plantations, mostly of *Pinus pinaster* L. and *Eucalyptus globulus* L. in the western and headwater parts of the catchment, respectively (Figure 2b). Woodland reached its greatest extent in 2007 (61%), and has since been partially replaced by urban land-use, mostly associated with a major road and an enterprise park construction, along with an expansion of existing urban core areas (Ferreira *et al.*, 2016b).

Urbanization became more pronounced after 1973, as a result of the 1970s Master Plan for urbanization of the Coimbra city. This favoured an increase of residential buildings, consisting mainly of detached houses along major roads, as well as apartment blocks after 1980 (Tavares *et al.*, 2012). In 1993, the approval of a new Master Plan for urban regulation considered the present study catchment as part of the central urban area, leading to establishment of well-defined urban cores in Ribeira dos Covões. This land-use history points at three main land-use phases in the catchment: (i) a rural phase between 1958 and 1973, characterized by a low percentage of urban cover; (ii) a discontinuous urban fabric phase, between 1973 and 1995; and (iii) a more continuous urbanization period after 1995 (Tavares *et al.*, 2012). The gradual increase of urban occupation is also associated with a population rise from 2500 to 26,700 inhabitants (Pato *et al.*, 2015). The construction of an enterprise park, covering about 5% of the catchment area, started in 2008 with deforestation activities and it is still ongoing. After 2013, with the peak

of a national and economic crisis, however, land-use stabilized and only on-going building constructions are currently being finished (Ferreira *et al.*, 2016b). Renewed urbanization increase is further expected after economic recovery, in view of urban projects already approved.

Regarding water management in the catchment, storm runoff from paved surfaces and buildings is in part dispersed in surrounding pervious areas, and in part piped downslope into the stream network and/or nearby abandoned agricultural and woodland areas. A separate sewerage system routes wastewater to a treatment plant located outside the catchment.

### Hydrological Modelling

#### Model overview

The hydrological simulations in this study are carried out with the distributed hydrological model MIKE SHE, which represents the main hydrological components, processes and resulting water flux partitioning and connectivity in the terrestrial part of the hydrological cycle as described in more detail in Supporting Information—Model description. In summary, MIKE SHE is a deterministic, dynamic, physically based and distributed hydrological model that has been described and used in many previous hydrological studies over various parts and climate zones of the world (e.g. Graham & Butts, 2005; Im *et al.*, 2009a, 2009b; Refsgaard *et al.*, 2010; Bosson *et al.*, 2012, 2013; Kalantari *et al.*, 2014a, 2014b, 2015; Johansson *et al.*, 2015; DHI, 2015).

More specifically, MIKE SHE uses physically based differential equations to describe the flow processes and interactions (flux partitioning and connectivity) in and among the main hydrological components. These include streams and other surface water bodies and overland flow at the surface, subsurface unsaturated soil water flow and saturated groundwater flow, as well as vertical land-atmosphere interaction fluxes at the surface. The latter include the driving precipitation from the atmosphere, and its interception and the transpiration of water by vegetation



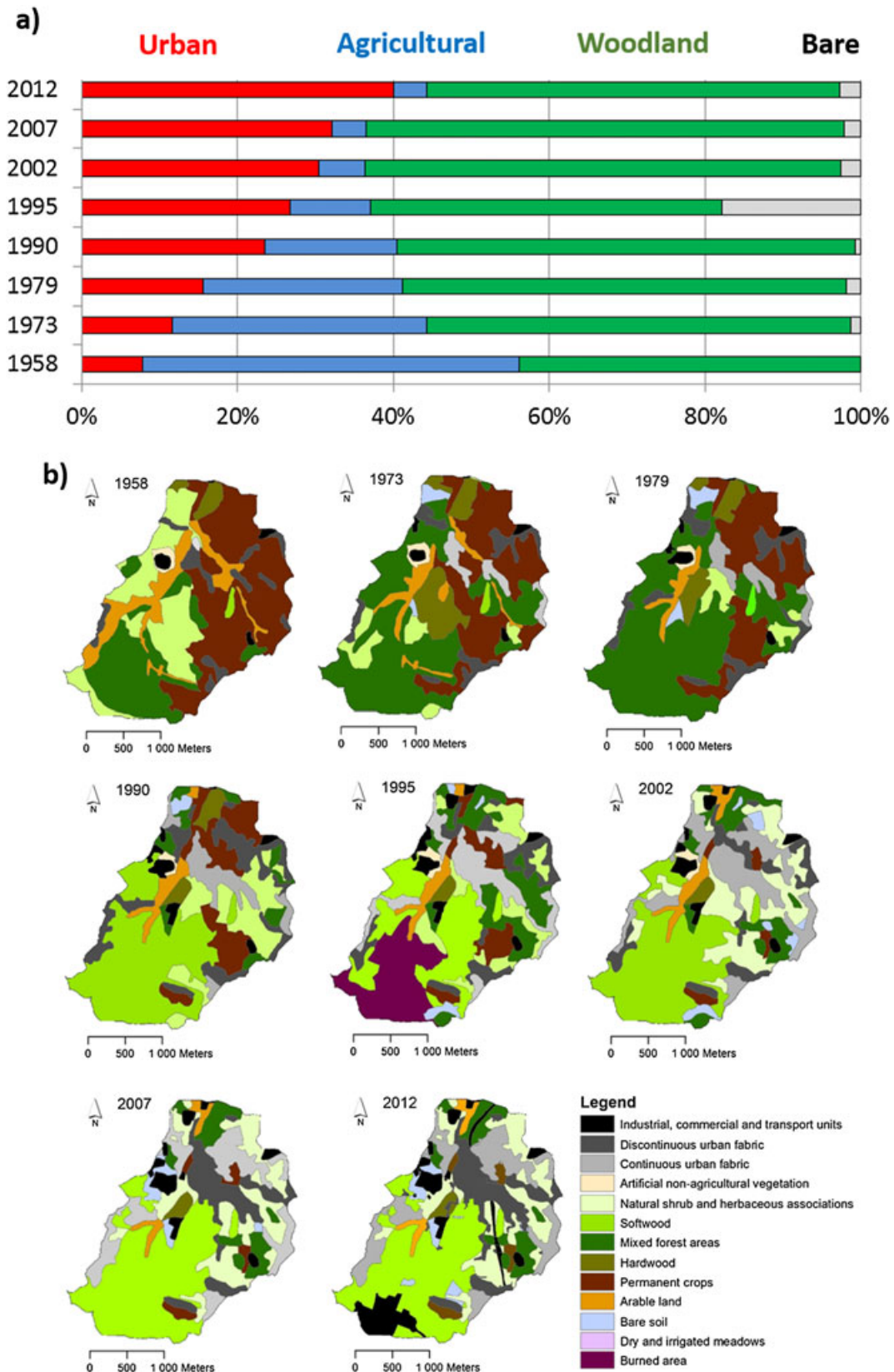


Figure 2. (a) Variation of relative land-use (%) between 1958 and 2012; (b) spatial land-use distribution in different years between 1958 and 2012. The anomalously high percentage of open space seen in panel (a) for year 1995 is due to a forest fire. Land-uses in panel (b) is as previously reported for the Ribeira dos Covões catchment for the different shown years (adapted from Tavares, 2012; Corine Land Cover, 2007, and Google Imagery, 2013). [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

as well as the evaporation of soil water back to the atmosphere.

To handle the representation of all these different hydrological components and their processes, interactions and flux partitioning and connectivity, the hydrological MIKE SHE model is fully coupled with the hydraulic model MIKE 11, the latter specifically for representing channel flow, with exchange-connectivity of water between the two modelling tools taking place throughout each simulation, i.e. the two models are run simultaneously. The coupled MIKE SHE–MIKE 11 model has been already used for water management purposes by local water authorities, responsible among others for the Ribeira dos Covões catchment. For consistency with previous model representations of the hydrology in this catchment, the coupled MIKE SHE–MIKE 11 model is also used in the present study to investigate the combined effect of hydro-climatic and land-use changes on hydrological fluxes in the catchment. The model is used to assess differences between the three representative urbanization stages, including the rural phase (1958–1973), the discontinuous urban phase (1974–1997) and the recent continuous urban period (1998–2013).

#### Input data

The MIKE 11 and MIKE SHE model require several input datasets, as summarized in Table I. The river map and river bed sections are estimated from Google Earth Imagery and topography data (IGP, 2014). Meteorological data are obtained from a weather station belonging to national climatic services (Coimbra/Bencanta), located 0.5 km NW of the study catchment. Daily rainfall and temperature are used, assuming a uniform distribution over the catchment. This assumption is based on the high correlation that has been found by direct comparison between the rainfall data from the weather station and from five new rain gauges installed in 2011, showing no significant spatial variation over the catchment between 2011 and 2013 (Ferreira *et al.*, 2016b). Using daily temperature records, potential evapotranspiration is further estimated as a function of the reference evapotranspiration (i.e. a hypothetical grass crop with no limitation on water availability (Allen *et al.*, 1998; Vázquez, 2003) by means of a crop coefficient approach.

The ArcGIS 10.2.2 software has been used for geospatial referencing in the modelling and mapping, with soil type

determined by a soil map obtained from Ferreira *et al.* (2015), defined to a depth of 4 m, and land-use categorized into 13 types: Continuous urban fabric; Discontinuous urban fabric; Industrial, commercial and transport units; Artificial non-agricultural vegetation (e.g. leisure parks); Arable land; Permanent crops; Dry and irrigated meadows; Hardwood; Softwood; Mixed forest areas; Natural shrub and herbaceous associations, and Bare soil. Land-use changes over the last decades are assessed through maps from 1958, 1973, 1979, 1990, 1995, 2002, 2007 and 2012 (Figure 2b). The maps adapted from Tavares *et al.* (2012) have been designed based on the categories in the Corine Land Cover product (CLC, 1990) and carefully checked for errors. The 2012 map has been prepared using a combination of aerial photographs from Google Imagery and field survey. The information updated for the last map (2012) has been validated based on field visits. Thus, the quality of the data is assured. All these maps have been processed and compared in ArcGIS (Figure 3) and formatted for use in the MIKE SHE model based on the 5-m grid resolutions of the model.

The urban storm drainage system is not included in the model due to the lack of available independent data for doing so. Furthermore, the urban storm runoff is partitioned between flow through pervious soil and piped flow to the stream network and/or to nearby pervious areas. As such, the fast hydrological responses of urban storm runoff may have a major impact on hydrograph shape, but not on catchment-scale water fluxes and their water balance with the daily time resolution of the present study.

#### Model parameterization

Model parameterization (Table II) is determined in accordance with available site information and data (see previous section) and relevant related literature reports. In particular regarding the latter, both the roughness coefficient (Manning  $n$ ), used in the calculation of overland flow, is defined for each land-use feature and river bed roughness coefficient (Manning  $n$ ), used in the calculation of the river flow, were based on values in Chow (1959) and Arcement & Schneider (1989). Furthermore, the crop coefficient ( $K_c$ ), leaf area index (LAI) and root depth (RD) (Bultot *et al.*, 1990; Büttner & Leuschner, 1994; DHI, 2015; Domec *et al.*, 2010; Ferreira *et al.*, 2015; Kelliher *et al.*, 1993 and

Table I. Input data for the MIKE 11 and MIKE SHE model application to the Ribeira dos Covões catchment

Data type	Description	Source
Topography	DEM (5 m) same as MIKE SHE grid size	IGP (2014)
River bed section	Estimated from topography data	IGP (2014)
River map	Location of the river	Google Earth Imagery (2015)
Land-use	Land-use/cover classification maps for the years 1958, 1973, 1979, 1990, 1995, 2002, 2007 and 2012 (scale 1:10,000)	Adapted from Tavares <i>et al.</i> (2012) and Google Earth Imagery (2013)
Soil type	Soil type classification map (scale 1:10,000).	Ferreira <i>et al.</i> , 2015
Streamflow	Daily streamflow from Oct. 2008 to Sept. 2013	Field data (Ferreira <i>et al.</i> , 2006)
Weather	Daily precipitation and daily average temperature from Oct. 1958 to Sept. 2013	IPMA (2016)

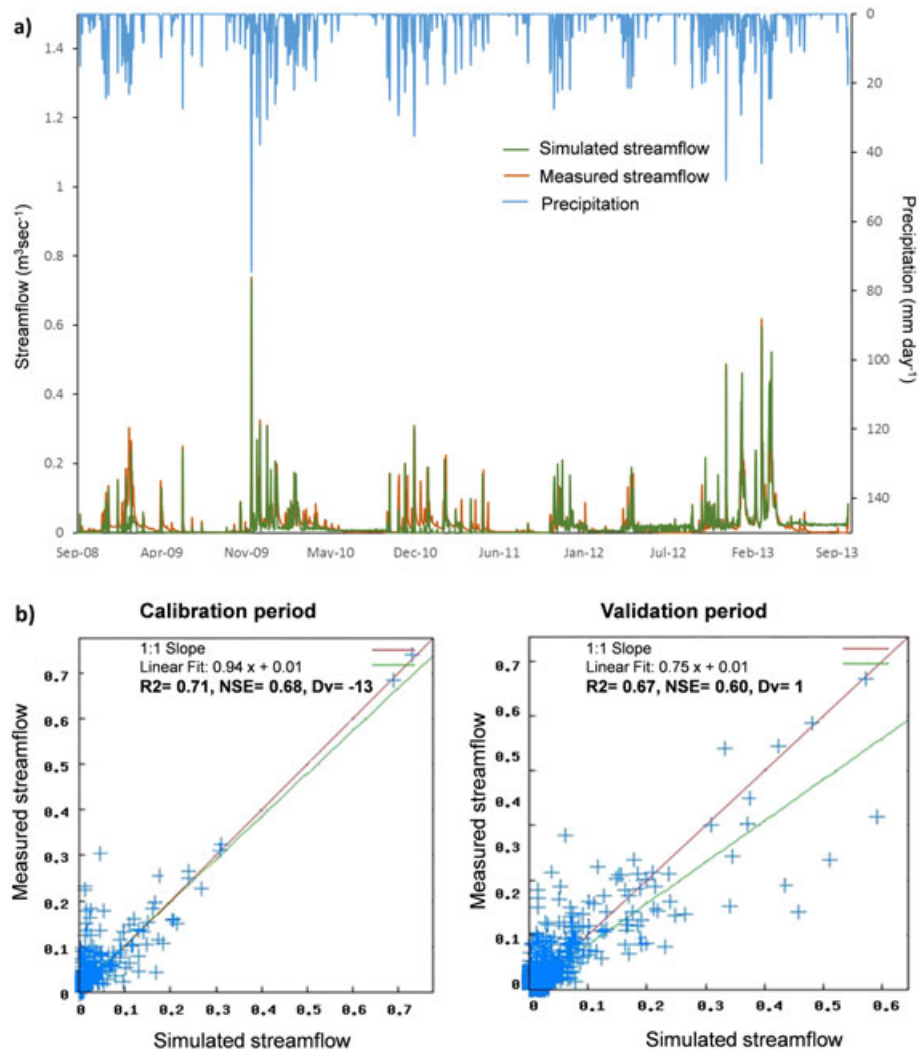


Figure 3. (a) Simulated and measured streamflow ( $\text{M}^3\text{S}^{-1}$ ) during the calibration period (1 October 2008–30 September 2010) and the validation period (1 October 2010–30 September 2013). (b)  $R^2$  represents the coefficient of determination, NSE the Nash–Sutcliffe simulation efficiency and  $D_v$  the relative deviation (percentage bias, given in %) of streamflow volume. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Kalantari *et al.*, 2014a) are derived for different length of growth stages, and relevant soil data (initial values for saturated conductivity of the soil; Table II) are taken from the Ferreira *et al.* (2015) map defined to 4-m depth.

The upper model boundary is the ground surface, as given by the topographical model. The lower boundary in the base setup of the model is at 100-m depth below the surface, equivalent to bedrock depth and in order to avoid significant boundary effects on simulated flow through numerical and corresponding geological layers closer to the surface. Values for the various hydrogeological parameters in the model, such as vertical and horizontal hydraulic conductivity, specific yield and specific storage, are assigned for the different geological layers based on existing general (i.e. not site-specific) relationships. A sensitivity analysis has also been carried out following the procedure of Hävermark (2016) in order to adjust general parameter values to more site-specific ones, and thus improve model parameterization. To improve numerical accuracy, the model time-step (Table II) and numerical

interaction criteria have been controlled to obtain a reasonable compromise between simulation time and numerical stability (DHI, 2015).

#### Model calibration and validation

MIKE SHE has been calibrated against 2 years of daily stream flow data, available for the Ribeira dos Covões catchment from 1 October 2008 to 30 September 2010 (Ferreira *et al.*, 2016b). The calibration has been focused on the most sensitive parameters (Table II), such as the drainage time constant ( $T_c$ ) and soil saturated hydraulic conductivity ( $K_s$ ) (Hävermark, 2016). The  $T_c$  represents a leakage coefficient used to regulate how quickly the water can drain from the catchment (Kalantari *et al.*, 2014a).

With the main sensitive parameters identified, the first calibration step is a simplified tuning of the drainage time constant,  $T_c$ , to calibrate the model with emphasis on getting the greatest daily discharge correct, as recorded on 16 November 2009. In the second and third calibration steps, the flow simulated by MIKE SHE has been calibrated by

Table II. Parameter values used in MIKE 11 and MIKE SHE for 13 land use classes specified in Figure 3

	Model parameter	Land use classes												
		Urban	Arti.	Nat.	Mix.	Hard.	Soft.	Per.	Ara.	Mead.	Infra.	Bare.	Burn.	
Overland flow	Surface roughness coefficient (Manning <i>n</i> ) <sup>a,b</sup>	0.02	0.045	0.05	0.15	0.15	0.15	0.045	0.045	0.035	0.017	0.025	0.03	
	Leaf Area Index (LAI) <sup>c,d,e</sup>	4	4	1	4	1.5	4	4	4	0	0.01	0	0	
	Root depth (RD) (cm) <sup>f,g</sup>	500	1000	800	1200	600	650	100	1000	800	0.01	0	0	
	evapotranspiration	1	1	1	1	1	1	1.2	1	1	1	1	1	
		7					4	200						
		700					1.3							
River flow	Unsaturated zone (UZ)													
Saturated one (SZ)	Horizontal cond. ( $K_h$ ) <sup>h,i</sup>													
	Vertical cond. ( $K_v$ ) <sup>h,i</sup>													
	Specific yield ( $S_y$ ) <sup>h,i</sup>													
	Initial potential head <sup>d</sup>													
	Drain level <sup>d</sup>													
	Time steps													
	Drainage option													
River bed roughness coefficient (Manning <i>n</i> ) <sup>a</sup> Saturated hydraulic conductivity ( $K_s$ ) <sup>h,i</sup>	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	
	Gravel = 0.002													
	Sand = 4.2e - 005													
	Clay = 1e - 008													
	Bedrock = 1e - 010													
	$K_h = 5e - 013$ m/s													
	$K_v = 2.5e - 013$ m/s													
	$S_y = 0.2$													
	Initial potential head = -2.4 m													
	Drain level = -0.8 m relative to the ground													
	Initial time step = 1 day													
	$T_c = 5e - 005$ s <sup>-1</sup>													

<sup>a</sup>Chow (1959).  
<sup>b</sup>Arcement & Schneider (1989).  
<sup>c</sup>Bultot *et al.* (1990).  
<sup>d</sup>DHI (2015).  
<sup>e</sup>Kelliher *et al.* (1993).  
<sup>f</sup>Büttner and Leuschner, 1994.  
<sup>g</sup>Domec *et al.*, 2010.  
<sup>h</sup>Ferreira *et al.*, 2015.  
<sup>i</sup>Kalantari *et al.*, 2014a.  
 Urban. Discontinuous and continuous urban fabric; *Arti.* Artificial non-agricultural vegetated areas; *Nat.* Natural areas with shrubs and herbs; *Mix.* Mixed forest (e.g. oak); *Hard.* Hardwood (e.g. eucalyptus); *Per.* Permanent crops; *Ara.* Arable land; *Mead.* Meadow; *Infra.* Equipment and infrastructures; *Bare.* Bare soil; *Soft.* Softwood (e.g. pine); *Burn.* Burned area).



adjusting  $K_s$  in order to minimize differences between simulated and recorded annual runoff.

After calibration, the model is validated against 3 years of daily stream flow records, available from 1 October 2010 until 30 September 2013. Model performance, defined as the goodness of fit between observed and simulated stream flow, is evaluated for the 5 years of measured data, using the coefficient of determination ( $R^2$ ) (Krause, 2005), the Nash–Sutcliffe efficiency (Nash & Sutcliffe, 1970) and the percent deviation of streamflow volume ( $D_v$ ) also known as the percentage bias (Gupta *et al.*, 2009).

The calibrated and validated model is further run for the three urbanization stages of Tavares *et al.* (2012). (1) For the rural phase (1958–1973), the model is run in two stages: (i) from 1958 to 1965, with the available land-use map of 1958; and (ii) from 1966 to 1973, with the available land-use map from 1973. (2) For the discontinuous urban phase, the model is run in three stages: (i) for 1974–1979, based on the land-use of 1979; (ii) for 1980–1994, based on 1990 land-use map; and (iii) for 1995–1997, with the land-use from 1995. (3) For the most recent continuous urban period, the model is also run in three stages: (i) for 1998–2002, with the land-use from 2002; (ii) for 2003–2010, with the land-use map from 2007; and (iii) for 2010–2013, with the land-use from 2012.

#### Data Analysis

The water-flux output from the MIKE SHE simulations includes area-normalized fluxes (expressed in terms of average water depths, e.g. in unit mm, over the whole catchment area) and associated net balance-implied water storage changes; see also the model, hydrological component and flux-connectivity descriptions and calculation explanations in Supporting Information—Model description. The total evapotranspiration (e.g. in mm) is estimated as follows:

$$AET = E_{\text{canopy}} + E_{\text{OL}} + E_{\text{soil}} + T_{\text{RZ}} \quad (1)$$

Where AET is total actual evapotranspiration;  $E_{\text{canopy}}$  is evaporation from canopy, i.e. interception;  $E_{\text{OL}}$  is evaporation from overland flow (OL);  $E_{\text{soil}}$  is direct evaporation from the soil; and  $T_{\text{RZ}}$  is transpiration by vegetation using water from the root zone.

Furthermore, total runoff is estimated as:

$$\text{Runoff} = \text{OL}_{\text{river}} + \text{SZ}_{\text{drainage}} + \text{SZ}_{\text{river}} \quad (2)$$

Where  $\text{OL}_{\text{river}}$  is the overland flow contribution to the stream network;  $\text{SZ}_{\text{drainage}}$  is the contribution of subsurface flow drainage routed to river through the tile drainage infrastructure from arable land; and  $\text{SZ}_{\text{river}}$  is the flow contribution from the saturated zone (groundwater) to the stream network. The sum of  $\text{SZ}_{\text{drainage}}$  and  $\text{SZ}_{\text{river}}$  is here termed as the total base flow contribution to stream flow. Changes in water storage include changes in both surface water storage and subsurface water storage.

Changes between the different urbanization and land-use stages—rural domain (1958–1973), discontinuous urban

pattern (1973–1995) and urban consolidation (1995–2013)—as well as between observed hydro-climatic data (temperature, precipitation and other water flux variables) are assessed statistically, in terms of box-plot statistical values and differences between these for the months and years in each of the three stage periods. Seasonal changes in the water balance are also investigated in the three stages, based on monthly average hydro-climatic data and simulated mean monthly water flows for the dry summer season (June–August) and the following wet season (September–May).

The statistical significance of the found differences in the investigated hydrological variables between the three urbanization stages are explored by applying Kruskal–Wallis statistical test ( $p < 0.05$ ), given the non-normal data distribution. The least significant difference (LSD) post-hoc test ( $p < 0.05$ ) is also applied in order to further analyse identified significant annual differences. Statistical data analysis is performed using the IBM SPSS Statistics 22 software.

## RESULT AND DISCUSSION

### Model Performance Evaluation

Model results for stream flow show good agreement with the observed stream flow in both the calibration and the independent validation period (Figure 3), with only slightly lower coefficient of determination (0.71 vs 0.67) and Nash–Sutcliffe efficiency (0.68 vs 0.60) in the latter. As should be expected in any modelling study, a perfect fit could not be achieved; however, both indicators are greater than the 0.5 value that is considered a satisfactory model performance for daily stream flow (Moriassi *et al.*, 2007).

The resulting relative deviation of streamflow volume (percentage bias  $D_v$ ) is  $-13\%$  and  $1\%$  in the calibration and the independent validation period, respectively (Figure 3), indicating an error of underestimation (negative value) and overestimation (positive value), respectively, in simulated stream flow results.

### Hydro-Climatic Changes

#### Climate and evapotranspiration changes

Annual average precipitation decreased between the three periods, from  $1041 \text{ mm y}^{-1}$  in 1958–1973 (16% above the long-term average,  $p < 0.05$ ) to  $873 \text{ mm y}^{-1}$  in 1974–1995 and  $845 \text{ mm y}^{-1}$  in 1996–2013 (0.8 and 7% below the long-term average,  $p > 0.05$ ) (Figure 4a). Annual average temperature increased over the same time, with values being significantly lower in 1958–1973 ( $14.9 \text{ }^\circ\text{C}$ ,  $p < 0.05$ ) than in 1974–1995 and 1996–2013 ( $15.6$  and  $15.7 \text{ }^\circ\text{C}$ , respectively,  $p > 0.05$ ) (Figure 4b).

The climatic changes imply significant increase in annual PET (Figure 5a) ( $p < 0.05$ ) due to the temperature increase; in general, increases in PET are largely related to increases in vapour pressure deficit resulting from higher temperature (IPCC, 2007, 2014). Annual actual evapotranspiration, AET, however, has still decreased (Figure 5b) ( $p < 0.05$ ) due to the concurrent precipitation decrease.

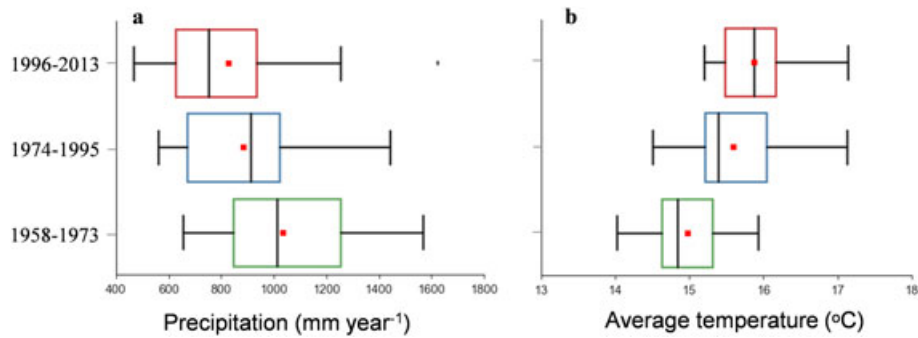


Figure 4. Boxplots for annual (a) precipitation and (b) temperature in the three occupation stages: 1) rural domain (1958–1973); 2) discontinuous urban pattern (1973–1995) and 3) urban consolidation (1995–2013). Boxplots include minimum, first quartile, median, mean (red marker), third quartile and maximum values. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

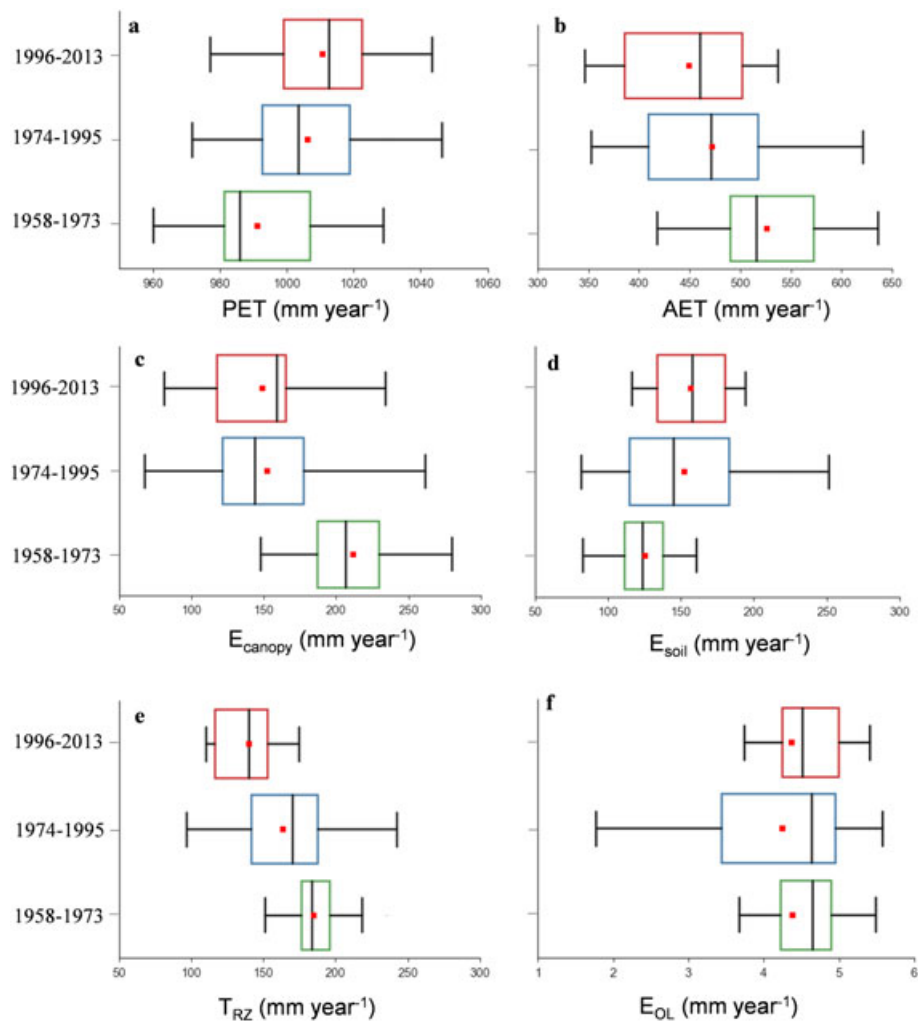


Figure 5. Boxplots for annual (a) potential evapotranspiration (PET) and (b) actual evapotranspiration (AET) in the three occupation stages: 1) rural domain (1958–1973); 2) discontinuous urban pattern (1973–1995) and 3) urban consolidation (1995–2013). AET includes (c) evaporation from canopy (E<sub>canopy</sub>); (d) direct evaporation from soil (E<sub>soil</sub>); (e) transpiration from root zone (T<sub>RZ</sub>) and (f) evaporation from overland flow (E<sub>OL</sub>). Boxplots include minimum, first quartile, median, mean (red marker), third quartile and maximum values. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

The found annual PET increase is from 991 mm y<sup>-1</sup> during the first period ( $p < 0.05$ ) to 1,006 and 1,010 mm y<sup>-1</sup> in the latter development periods ( $p > 0.05$ ). This implies a shift to greater annual average PET than precipitation (885 mm y<sup>-1</sup> in 1974–1995 and 826 mm y<sup>-1</sup> in 1996–2013) in the latter two periods, highlighting a

typical water stress situation reported for the Mediterranean region (Hebrard *et al.*, 2006; Garcia-Ruiz *et al.*, 2011; Paço *et al.*, 2009; Zdruli, 2014). The found decrease in average annual AET (Figure 5b) is from 526 mm y<sup>-1</sup> in the earlier rural domain period ( $p < 0.05$ ) to 474 and 448 mm y<sup>-1</sup> in the two later periods ( $p > 0.05$ ). This change pattern follows

that of precipitation (Figure 4a) and was also noticed during dry and wet conditions (Table III), because the current condition of greater PET than precipitation implies that AET is now constrained by water availability (Beven, 2012).

Apart from the climatic change drivers, land-use changes may also drive AET change (Destouni *et al.*, 2013; Jaramillo & Destouni, 2015). The precise mechanisms for different types of such driver-impact connections between land-use and AET changes remain still mostly as key open questions for further research across disciplines (Jaramillo & Destouni, 2014; Elmhagen *et al.*, 2015). In the present case, one such connection component is the land-use influence of urbanization leading to an overall decrease of vegetation cover, which has in turn decreased the evaporation from the decreased canopy (Figure 5c) and the transpiration of the decreased vegetation from the soil root zone (Figure 5e).

Furthermore, resulting AET changes are to some degree also due to conversion (and not just overall decrease) of vegetation. In the present case, such conversion has occurred from native shrubs, herbaceous vegetation and mixed forest areas (comprising native species, including oak) into fast growing commercial timber plantations of pine (*P. pinaster*) and eucalyptus (*Eucalyptus globulus*) over the discontinuous urbanization period (1974–1995). Evaporation from broadleaved forests (e.g. oak) is then higher than that from conifer stands (e.g. pine) (Komatsu *et al.*, 2007; Baldocchi *et al.*, 2010), reflected in the modelling by a higher crop coefficient for oak ( $K_c$  in Table II).

In general, the model simulations account for land-cover changes and conversions, including the vegetation decrease and species shifts mentioned previously, based on the available land-cover data for the different stage periods.

Calculations of evaporation from canopy are then determined by model parameters for maximum interception storage and potential canopy evaporation, with relevant values assigned for the conditions at each stage period as suggested by Kristensen & Jensen (1975). Furthermore, based on Kristensen & Jensen (1975), the plant transpiration in model simulations is a function of LAI, soil moisture content in the root zone and root distribution function. Considering then, for example, the oak to pine conversion among the various land-use changes occurring in the catchment development, the deeper roots of oak will access soil water more effectively than the more shallow roots of pines, thereby leading to higher transpiration rate and stomatal conductance per unit leaf area in a land-cover stage with more oak than in a land-cover stage with more pine (Paço *et al.*, 2009; Renninger *et al.*, 2015). These vegetation conversions thus contribute to decreased transpiration from the root zone in the Ribeira dos Covões catchment from the rural period (1958–1973) to the urbanization stages (1974–2013) (Figure 5c,  $p < 0.05$ ).

Overall, various data-given climate and land-cover changes thus combine in yielding the resulting net decrease in annual AET (Figure 5b) that is found to have occurred during the urbanization development in the catchment. As parts in this net annual AET decrease, the annual direct evaporation from soil (Figure 5d) has for instance increased while the direct evaporation from annual overland flow (Figure 5f) has more or less remained the same under the combined climatic and land-use changes occurring in the catchment.

In summary over the whole study period, the model results suggest that interception and evaporation from soil represent a greater water loss from the landscape than

Table III. Mean monthly precipitation (P), temperature (T), potential evapotranspiration (PET), actual evapotranspiration (AET) and simulated total runoff (R), runoff coefficient ( $R_{coef}$ ), overland flow ( $OL_{river}$ ), overland flow coefficient ( $OL_{coef}$ ), baseflow and contribution of  $OL_{river}$  to R calculated for the dry summer season (June–August) and the following wet season (September–May) for the three occupation stages: 1) rural (1958–1973); 2) discontinuous urban (1973–1995) and 3) consolidated urban (1995–2013)

	Rural domain	Discontinuous urbanization	Urban consolidation	
T (C)	Wet months	12.7	13.8	13.6
	Dry months	19.0	20.9	21.2
P (mm month <sup>-1</sup> )	Wet months	99.9	91.2	85.9
	Dry months	45.2	38.2	31.0
PET (mm month <sup>-1</sup> )	Wet months	72.2	76.2	75.8
	Dry months	98.7	106.2	106.2
AET (mm month <sup>-1</sup> )	Wet months	46.6	42.2	41.6
	Dry months	27.5	19.8	23.0
R (mm month <sup>-1</sup> )	Wet months	45.2	36.8	34.3
	Dry months	23.7	18.7	18.4
$R_{coef}$ (%)	Wet months	45	41	40
	Dry months	52	49	59
$OL_{river}$ (mm month <sup>-1</sup> )	Wet months	22.9	19.0	18.4
	Dry months	21.4	17.2	17.1
$OL_{coef}$ (%)	Wet months	25	23	23
	Dry months	47	45	55
Baseflow (mm month <sup>-1</sup> )	Wet months	22.3	17.8	15.9
	Dry months	2.3	1.6	1.3
$OL_{river}$ to R (%)	Wet months	55	6	59
	Dry months	85	92	93

transpiration (Figure 5), accounting for 64–68% of mean annual AET. However, whereas evaporation from canopy contributes most to total evaporation during the first, rural period (62% of evaporation in 1958–1973), its contribution has decreased during the subsequent development periods (50% in 1974–1995 and 48% in 1996–2013). In contrast, evaporation from soil has increased in importance with climate change and urbanization, accounting for 51 and 49% in the later continuous and discontinuous urbanization phases, respectively, compared with 36% in the first rural phase ( $p < 0.05$ ). This increase in soil evaporation has been driven in part and in combination by the increased temperature, the increased open area resulting from a forest fire in 1995 and the conversion of permanent crops into urban areas in the catchment, with the latter increasing from 8% in 1958 to 30% in 1995 and 40% in 2012 (Figure 2b). Overall, water losses due to evaporation from overland flow are modelled to be small ( $< 6 \text{ mm y}^{-1}$ ), representing 1% of total evaporation, and relatively constant in time (no significant changes,  $p > 0.05$ ).

#### Runoff and water storage change

Over the entire study period, the modelled annual runoff ranges from  $15 \text{ mm y}^{-1}$  in the driest year of 2007 (with precipitation  $480 \text{ mm y}^{-1}$ ) to  $910 \text{ mm y}^{-1}$  in the wettest year of 2000 (with precipitation  $1,622 \text{ mm y}^{-1}$ ) (Figure 6a). The inter-annual variation of runoff has not changed significantly between the three periods ( $p > 0.05$ ), but average annual runoff has successively decreased from  $508 \text{ mm y}^{-1}$  in 1958–1973, to  $396 \text{ mm y}^{-1}$  in 1974–1995 and  $395 \text{ mm y}^{-1}$  in 1996–2013. This runoff decrease follows that of precipitation, which is consistent with the relative runoff coefficient remaining essentially the same over the three periods (around 45% of precipitation, Figure 6b). Specifically, this constancy implies that the successive climatic precipitation decrease, from the first rural to the last continuous urbanization period (Figure 4a), is partitioned similarly between runoff decrease (according to the constant runoff coefficient) and AET decrease (according to the complementary and thereby also constant evapotranspiration coefficient,

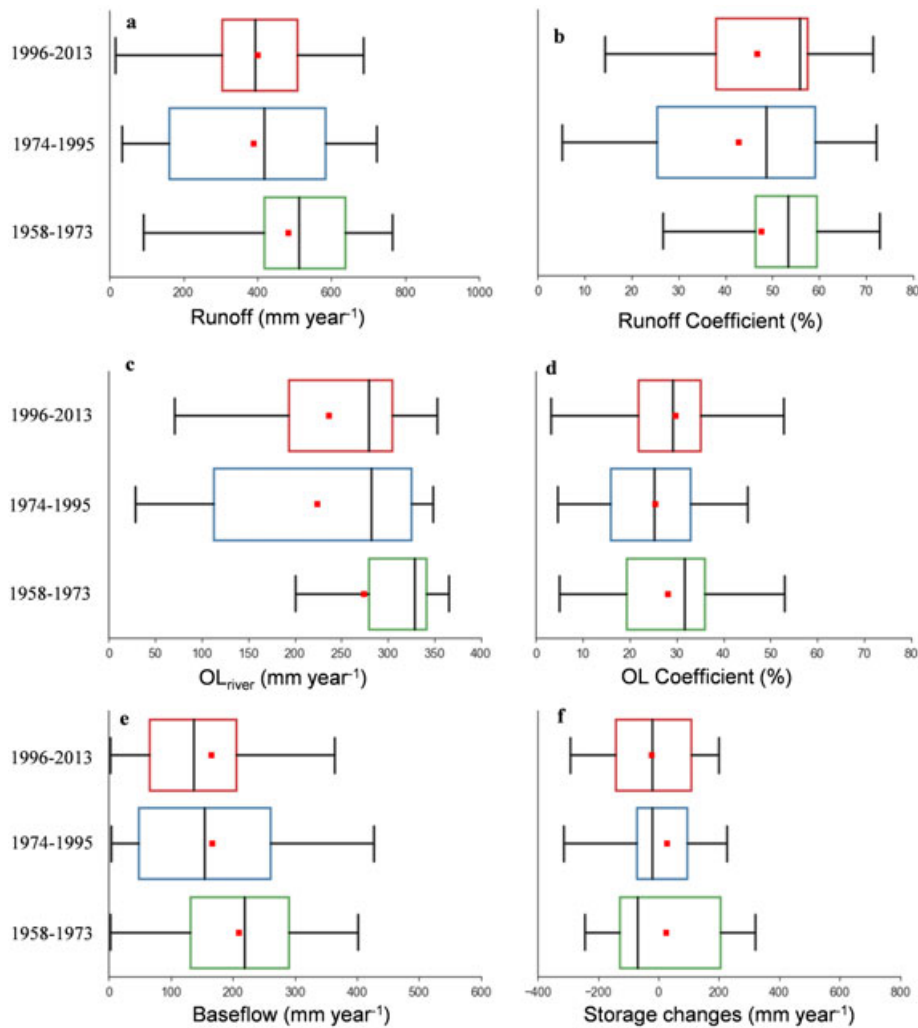


Figure 6. Boxplots for annual (a) runoff, (b) runoff coefficient, (c) overland flow ( $OL_{river}$ ), (d) overland flow coefficient, (e) baseflow and (f) implied water storage change in the three occupation stages: 1) rural domain (1958–1973); 2) discontinuous urban pattern (1973–1995) and 3) urban consolidation (1995–2013). Boxplots include minimum, first quartile, median, mean (red marker), third quartile and maximum values. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



equalling 1 minus the runoff coefficient, i.e. around 55% of precipitation).

The decrease in annual runoff is not primarily due to decrease in annual overland flow. The average annual value of the latter has only decreased relatively slightly, from 274 mm y<sup>-1</sup> to 223 mm y<sup>-1</sup> and then up again to 243 mm y<sup>-1</sup> in the recent urban stage (Figure 6c;  $p > 0.05$ ); furthermore, the relative contribution of annual overland flow to total runoff has increased rather than decreased over the three development periods, from 54 to 62% (Figure 6d,  $p > 0.05$ ). The latter increase is consistent with the also increased seasonal contributions of overland flow to total runoff, from 55 to 59% and from 85 to 93% for the wet and the dry season, respectively (Table III).

The decrease of annual average overland flow under decreased annual precipitation, along with increases in annual and seasonal overland flow coefficients, is due to the increased impervious land cover associated with urbanization. The impact of increased soil sealing on overland flow from the rural to the continuous urbanization period is in relative terms more noticeable in the dry than in the wet season. Specifically, the relative contribution of overland flow to total runoff increases by 4 percentage units in the wet season and by 8 percentage units in the dry season between the two stage periods (Table III). These seasonal results highlight a particularly important impact of soil sealing on water flows in the dry summer season.

The decrease in total runoff over the stage periods corresponds mainly to a decreased contribution from base flow, from 234 to 173 mm y<sup>-1</sup> and later to 152 mm y<sup>-1</sup> (Figure 6e,  $p > 0.05$ ). On annual average, this base flow contribution to total runoff has decreased from 46% in the first period to 38% in the last, urban period. Importantly, under the development of these concurrent climatic, land-use and associated hydrological changes, the annual average storage change in the catchment has remained essentially the same and near-zero (Figure 6f,  $p > 0.05$ ). This storage change finding is consistent with previous data-based results (Jaramillo *et al.*, 2013) and supports fundamental interpretation assumptions (Destouni *et al.*, 2013; Jaramillo & Destouni, 2014, 2015) made for hydrological change assessments in catchments on various scales and in different parts of the world. Seasonally, the base flow decrease is in absolute terms greater for the wet than for the dry season (from 22.3 to 15.9 mm, and from 2.3 to 1.3 mm, respectively), whereas the change in relative terms is greater for the latter, dry season due to its overall small runoff value (Table III).

Given the small size of the catchment, changes over the three development stages may also be noticeable in the catchment hydrograph shape, not least considering the urbanization development in the catchment. However, given the daily time resolution of available rainfall data over most of the study period, the lack of independent data on shorter response times of the storm drainage system, and the focus of the present study on longer-term (than sub-daily) variability and changes in the catchment-scale water balance, the possible changes in fast storm-event responses

and their reflection in hydrograph shape have not been investigated as part of this study. However, changes in rainfall–runoff responses during isolated storm events have been assessed in a previous study for periods in 2008/2009 and 2012/2013 based on 15-min rainfall and streamflow measurements (Ferreira *et al.*, 2016b). Between these times, urban areas expanded from 32 to 40%, leading to faster hydrological response time to storm events (from 60–75 min to 40–45 min), increased overland flow and peak flow, and reduced recession time.

Overall, the climatically driven decrease in precipitation in conjunction with the increasing urbanization development in the peri-urban catchment landscape itself has jointly led to decreased infiltration and further decreased base flow from the subsurface to the stream water network of the catchment. The urbanization development over the same time has particularly increased the relative overland flow coefficient and thereby kept the absolute overland flow component essentially constant in spite of the precipitation decrease in the catchment. These land-use changes represent important flux partitioning and connectivity alterations in the catchment, with a greater share of any effective (precipitation minus evapotranspiration) water input to the catchment now going to overland flow that relatively quickly feeds into the stream network.

## CONCLUSIONS

The changes in hydrological flux partitioning and connectivity occurring in the investigated peri-urban study catchment emerge as driven in combination by the regional climatic change and the urbanization development within the catchment itself. In the Ribeira dos Covões catchment, the main climatic driver of hydrological change has been a decrease in precipitation, leading to decrease in both annual and seasonal runoff and actual evapotranspiration. Even though the decrease in precipitation has been significant, the overland flow exhibits only a minor decrease from the rural to the continuous urbanization period, and the relative contribution of overland flow to total runoff has increased. The impact of urbanization towards increased overland flow has in this transition counteracted the concurrent decrease in precipitation. Thus, based on climate change scenarios that foresee more intense storms, the future flood hazard mitigation in this catchment will be an even greater challenge than under current conditions. Measures to maximize water infiltration and retention in peri-urban catchments therefore still need to be considered and assessed for mitigation of urban flood risks.

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## REFERENCES

- Ali GA, Roy AG. 2010. Shopping for hydrologically representative connectivity metrics in a humid temperate forested catchment. *Water Resources Research* **46**: n/a–n/a. <https://doi.org/10.1029/2010WR009442>.
- Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. Food and Agriculture Organization. ISBN: 92-5-104219-5.
- Arcement Jr GJ, Schneider VR. 1989. Guide for selecting Manning's roughness coefficients for natural channels and flood plains. *U.S. Geological Survey Water-Supply Paper* 2339, 38 pp.
- Asokan S, Destouni G. 2014. Irrigation effects on hydro-climatic change: basin-wise water balance-constrained quantification and cross-regional comparison. *Surveys in Geophysics* **35**: 879–895. <https://doi.org/10.1007/s10712-013-9223-5>.
- Asokan S, Jarsjö J, Destouni G. 2010. Vapor flux by evapotranspiration: effects of changes in climate, land use, and water use. *Journal of Geophysical Research-Atmospheres* **115** D24102. <https://doi.org/10.1029/2010JD014417>.
- Bach PM, Rauch W, Mikkelsen PS, McCarthy DT, Deletic A. 2014. A critical review of integrated urban water modelling—urban drainage and beyond. *Environmental Modelling & Software* **54**: 88–107. <https://doi.org/10.1016/j.envsoft.2013.12.018>.
- Baldocchi DD, Ma S, Rambal S, Misson L, Ourcival JM, Limousin JM et al. 2010. On the differential advantages of evergreenness and deciduousness in mediterranean oak woodlands: a flux perspective. *Ecological applications: a publication of the Ecological Society of America* **20**: 1583–1597. <https://doi.org/10.1890/08-2407>.
- Beven KJ. 2012. *Rainfall–runoff modelling, the primer*, 2nd edn. Wiley-Blackwell; 488. ISBN:978-0-470-71459-1. <https://doi.org/10.1002/9781119951001>.
- Bosson E, Sabel U, Gustafsson LG, Sassner M, Destouni G. 2012. Influences of shifts in climate, landscape, and permafrost on terrestrial hydrology. *Journal of Geophysical Research-Atmospheres* **117** D05120. <https://doi.org/10.1029/2011JD016429>.
- Bosson E, Selroos J-O, Stigsson M, Gustafsson L-G, Destouni G. 2013. Exchange and pathways of deep and shallow groundwater in different climate and permafrost conditions using the Forsmark site, Sweden as an example catchment. *Hydrogeology Journal* **21**: 225–237. <https://doi.org/10.1007/s10040-012-0906-7>.
- Boyd MJ, Bufill MC, Knee RM. 1993. Pervious and impervious runoff in urban catchments. *Hydrological Sciences Journal* **38**: 463–478. <https://doi.org/10.1080/02626669309492699>.
- Bracken LJ, Croke J. 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes* **21**: 1749–1763. <https://doi.org/10.1002/hyp.6313>.
- Branger F, Kermadi S, Jacqueminet C, Michel K, Labbas M, Krause P, Kralisch S, Braud I. 2013. Assessment of the influence of land use data on the water balance components of a peri-urban catchment using a distributed modelling approach. *Journal of Hydrology* **505**: 312–325. <https://doi.org/10.1016/j.jhydrol.2013.09.055>.
- Braud I, Fletcher TD, Andrieu H. 2013. Hydrology of peri-urban catchments: processes and modelling. *Journal of Hydrology* **485**: 1–4. <https://doi.org/10.1016/j.jhydrol.2013.02.045>.
- Bring A, Asokan SM, Jaramillo F, Jarsjö J, Levi L, Pietroń J, Prieto C, Rogberg P, Destouni G. 2015. Implications of freshwater flux data from the CMIP5 multi-model output across a set of northern hemisphere drainage basins. *Earth's Future* **3**: 206–217. <https://doi.org/10.1002/2014EF000296>.
- Bultot F, Dupriez GL, Gellens G. 1990. Simulation of land use changes and impacts on the water balance—case study for Belgium. *Journal of Hydrology* **114**: 327–348. [https://doi.org/10.1016/0022-1694\(90\)90064-5](https://doi.org/10.1016/0022-1694(90)90064-5).
- Büttner V, Leuschner C. 1994. Spatial and temporal patterns of fine root abundance in a mixed oak-beech forest. *Forest Ecology and Management* **70**: 11–21. [https://doi.org/10.1016/0378-1127\(94\)90071-X](https://doi.org/10.1016/0378-1127(94)90071-X).
- Carlson TN, Arthur ST. 2000. The impact of land use – land cover changes due to urbanization on surface microclimate and hydrology: a satellite perspective. *Global and Planetary Change* **25**: 49–65. [https://doi.org/10.1016/S0921-8181\(00\)00021-7](https://doi.org/10.1016/S0921-8181(00)00021-7).
- Chow VT. 1959. *Open channel hydraulics*. McGraw-Hill: New York; 700 pp. ISBN-13: 978-1932846188.
- DeFries R, Eshleman KN. 2004. Land-use change and hydrologic processes: a major focus for the future. *Hydrological Processes* **18**: 2183–2186. <https://doi.org/10.1002/hyp.5584>.
- Destouni G, Verrot L. 2014. Screening long-term variability and change of soil moisture in a changing climate. *Journal of Hydrology* **516**: 131–139. <https://doi.org/10.1016/j.jhydrol.2014.01.059>.
- Destouni G, Jaramillo F, Prieto C. 2013. Hydroclimatic shifts driven by human water use for food and energy production. *Nature Climate Change* **3**: 213–217. <https://doi.org/10.1038/nclimate1719>.
- Devia GK, Ganasri BP, Dwarakish GS. 2015. A review on hydrological models. *Aquati Procedia* **4**: 10011007. <https://doi.org/10.1016/j.aqpro.2015.02.126>.
- DHI 2015. MIKE powered by DHI. Accessed 3 October 2015. <https://www.mikepoweredbydhi.com/>.
- Domec JC, King JS, Noormets A, Treasure E, Gavazzi MJ, Sun G, McNulty SG. 2010. Hydraulic redistribution of soil water by roots affects whole-stand evapotranspiration and net ecosystem carbon exchange. *New Phytologist* **187**: 171–183. <https://doi.org/10.1111/j.1469-8137.2010.03245.x>.
- Easton ZM, Gérard-Marchant P, Walter MT, Petrovic AM, Steenhuis TS. 2007. Hydrologic assessment of an urban variable source watershed in the Northeast United States. *Water Resources Research* **43**: n/a–n/a. <https://doi.org/10.1029/2006WR005076>.
- Elmhagen B, Destouni G, Angerbjörn A, Borgström S, Boyd E, Cousins SAO, Dalén L, Ehrlén J, Ermold M, Hambäck PA, Hedlund J, Hylander K, Jaramillo F, Lagerholm VK, Lyon SW, Moor H, Nykvist B, Pasanen-Mortensen M, Plue J, Prieto C, Van der Velde Y, Lindborg R. 2015. Interacting effects of change in climate, human population, land use, and water use on biodiversity and ecosystem services. *Ecology and Society* **20**: 23. <https://doi.org/10.5751/ES-07145-200123.c>.
- EU 2005. Medium-sized cities in Europe. Ireland: European Foundation for the Improvement of Living and Working Conditions. Available from <http://www.eurofound.europa.eu/pubdocs/1997/53/en/1/ef9753en.pdf> Accessed January 2012.
- Ferreira CSS, Walsh RPD, Steenhuis TS, Shakesby RA, Nunes JPN, Coelho COA, Ferreira AJD. 2015. Spatiotemporal variability of hydrologic soil properties and the implications for overland flow and land management in a peri-urban Mediterranean catchment. *Journal of Hydrology* **525**: 249–263. <https://doi.org/10.1016/j.jhydrol.2015.03.039>.
- Ferreira CSS, Walsh RPD, Shakesby RA, Keizer JJ, Soares D, González-Pelayo O, Coelho COA, Ferreira AJD. 2016a. Differences in overland flow, hydrophobicity and soil moisture dynamics between Mediterranean woodland types in a peri-urban catchment in Portugal. *Journal of Hydrology* **533**: 473–485. <https://doi.org/10.1016/j.jhydrol.2015.12.040>.
- Ferreira CSS, Walsh RPD, Nunes JPC, Steenhuis TS, Nunes M, de Lima JLMP, Coelho COA, Ferreira AJD. 2016b. Impact of urban development on streamflow regime of a Portuguese peri-urban Mediterranean catchment. *Journal of Soils and Sediments* **16**: 2580. <https://doi.org/10.1007/s11368-016-1386-5>.
- Fletcher TD, Andrieu H, Hamel P. 2013. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: a state of the art. *Advances in Water Resources* **51**: 261–279. <https://doi.org/10.1016/j.advwatres.2012.09.001>.
- García-Ruiz JM, López-Moreno JJ, Vicente-Serrano SM, Beguería S. 2011. Mediterranean water resources in a global change scenario. *Earth Science Reviews* **7**: 66. <https://doi.org/10.1016/j.earscirev.2011.01.006>.
- Graham DN, Butts MM. 2005. Flexible, integrated watershed modelling with MIKE SHE. In *Watershed models*, Singh VP, Frevert DK (eds). CRC Press; 245–272 ISBN: 0849336090.
- Gupta HV, Kling H, Yilmaz KK, Martinez GF. 2009. Decomposition of the mean squared error and NSE performance criteria: implications for improving hydrological modelling. *Journal of Hydrology* **377**: 80–91. <https://doi.org/10.1016/j.jhydrol.2009.08.003>.

- Hammer TR. 1972. Stream channel enlargement due to urbanization. *Water Resources Research* **8**: 1530–1540. <https://doi.org/10.1029/WR008i006p01530>.
- Hävermark S. 2016. Modelling the effects of land-use change on a peri-urban catchment in Portugal. *UPTEC W 16005* ISSN 1401-5765.
- Hebrard O, Voltz M, Andrieux P, Moussa R. 2006. Spatio-temporal distribution of surface moisture in a heterogeneously farmed Mediterranean catchment. *Journal of Hydrology* **329**: 110–121. <https://doi.org/10.1016/j.jhydrol.2006.02.012>.
- Im S, Jang C, Kim C, Kim H. 2009a. Assessing the impacts of land use changes on watershed hydrology using MIKE SHE. *Environmental Geology* **57**: 231–239. <https://doi.org/10.1007/s00254-008-1303-3>.
- Im S, Kim H, Kim C. 2009b. Assessing the impacts of land use changes on watershed hydrology using MIKE SHE. *Environmental Geology* **57**: 231–239. <https://doi.org/10.1007/s00254-008-1303-3>.
- INE. 2012. *Censos 2011, XV recenseamento geral da população, V recenseamento geral da habitação*. Resultados Divinitivos: Instituto Nacional de Estatística. 368p (in Portuguese).
- IPCC. 2007. *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge University Press: Cambridge.
- IPCC 2014. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)], IPCC, Geneva, Switzerland, 151 pp.
- Isik S, Kalin L, Schoonover JE, Srivastava P, Lockaby BG. 2013. Modeling effects of changing land use/cover on daily streamflow: an artificial neural network and curve number based hybrid approach. *Journal of Hydrology* **485**: 103–112. <https://doi.org/10.1016/j.jhydrol.2012.08.032>.
- Jankowfsky S, Branger F, Braud I, Rodriguez F, Debionne S, Viallet P. 2014. Assessing anthropogenic influence on the hydrology of small peri-urban catchments: development of the object-oriented PUMMA model by integrating urban and rural hydrological models. *Journal of Hydrology* **517**: 1056–1071. <https://doi.org/10.1016/j.jhydrol.2014.06.034>.
- Jaramillo F, Destouni G. 2014. Developing water change spectra and distinguishing change drivers worldwide. *Geophysical Research Letters* **41**: 8377–8386. <https://doi.org/10.1002/2014GL061848>.
- Jaramillo F, Destouni G. 2015. Local flow regulation and irrigation raise global human water consumption and footprint. *Science* **350**: 1248–1251. <https://doi.org/10.1126/science.aad1010>.
- Jaramillo F, Prieto C, Lyon SW, Destouni G. 2013. Multimethod assessment of evapotranspiration shifts due to non-irrigated agricultural development in Sweden. *Journal of Hydrology* **484**: 55–62. <https://doi.org/10.1016/j.jhydrol.2013.01.010>.
- Jarsjö J, Asokan SM, Prieto C, Bring A, Destouni G. 2012. Hydrological responses to climate change conditioned by historic alterations of land-use and water-use. *Hydrology and Earth System Sciences* **16**: 1335–1347. <https://doi.org/10.5194/hess-16-1335-2012>.
- Jauregui E, Romales E. 1996. Urban effects on convective precipitation in Mexico City. *Atmospheric Environment* **30**: 3383–3389. [https://doi.org/10.1016/1352-2310\(96\)00041-6](https://doi.org/10.1016/1352-2310(96)00041-6).
- Johansson E, Gustafsson L-G, Berglund S, Lindborg T, Selroos J-O, Claesson Liljedahl L, Destouni G. 2015. Data evaluation and numerical modeling of hydrological interactions between active layer, lake and talik in a permafrost catchment, western Greenland. *Journal of Hydrology* **527**: 688–703. <https://doi.org/10.1016/j.jhydrol.2015.05.026>.
- Kalantari Z, Lyon SW, Folkesson L, French HK, Stolte J, Jansson P-E, Sassner M. 2014a. Quantifying the hydrological impact of simulated changes in land use on peak discharge in a small catchment. *Science of the Total Environment* **466–467**: 741–754. <https://doi.org/10.1016/j.scitotenv.2013.07.047>.
- Kalantari Z, Briel A, Lyon SW, Olofsson B, Folkesson L. 2014b. On the utilization of hydrological modelling for road drainage design under climate and land use change. *Science of the Total Environment* **475**: 97–103. <https://doi.org/10.1016/j.scitotenv.2013.12.114>.
- Kalantari Z, Lyon SW, Jansson P-E, Stolte J, French HK, Folkesson L, Sassner M. 2015. Modeller subjectivity and calibration impacts on hydrological model applications: an event-based comparison for a road-adjacent catchment in south-east Norway. *Science of the Total Environment* **502**: 315–329. <https://doi.org/10.1016/j.scitotenv.2014.09.030>.
- Keesstra S, Pereira P, Novara A, Brevik EC, Azorin-Molina C, Parras-Alcántara L, Jordán A, Cerdà A. 2016. Effects of soil management techniques on soil water erosion in apricot orchards. *Science of the Total Environment* **551–552**: 357–366. <https://doi.org/10.1016/j.scitotenv.2016.01.182>.
- Kelliher FM, Leuning R, Schulze ED. 1993. Evaporation and canopy characteristics of coniferous forests and grasslands. *Oecologia* **95**: 153–163. <https://doi.org/10.1007/BF00323485>.
- Komatsu H, Tanaka N, Kume T. 2007. Do coniferous forests evaporate more water than broadleaved forests in Japan? *Journal of Hydrology* **336**: 361–375. <https://doi.org/10.1016/j.jhydrol.2007.01.009>.
- Konrad CP, Booth DB, Burges SJ. 2005. Effects of urban development in the Puget lowland, Washington, on interannual streamflow patterns: consequences for channel form and streambed disturbance. *Water Resources Research* **41**: n/a–n/a. <https://doi.org/10.1029/2005WR004097>.
- Krause P. 2005. Boyle D P, Bäse F. 2005. Comparison of different efficiency criteria for hydrological model assessment. *Advanced Geosciences* **5**: 89–97. <https://doi.org/10.5194/adgeo-5-89-2005>.
- Kristensen KJ, Jensen SE. 1975. A model for estimating actual evapotranspiration from potential evapotranspiration. *Hydrology Research* **6**: 170–188.
- López-Vicente M, Nadal-Romero E, Cammeraat ELH. 2016. Hydrological connectivity does change over 70 years of abandonment and afforestation in the Spanish Pyrenees. *Land Degradation and Development*. <https://doi.org/10.1002/ldr.2531>.
- Marchamalo M, Hooke JM, Sandercock PJ. 2015. Flow and sediment connectivity in semi-arid landscapes in SE Spain: patterns and controls. *Land Degradation and Development* **27**: 1032–1044. <https://doi.org/10.1002/ldr.2352>.
- Masselink RJH, Keesstra SD, Temme AJAM, Seeger M, Giménez R, Casali J. 2016. Modelling discharge and sediment yield at catchment scale using connectivity components. *Land Degradation and Development* **27**: 933–945. <https://doi.org/10.1002/ldr.2512>.
- Miller JD, Kim H, Kjeldsen TR, Packman J, Grebby S, Dearden R. 2014. Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. *Journal of Hydrology* **515**: 59–70. <https://doi.org/10.1016/j.jhydrol.2014.04.011>.
- Moriassi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *American Society of Agricultural and Biological Engineers* **50**: 885–900. <https://doi.org/10.13031/2013.23153>.
- Nash J, Sutcliffe JV. 1970. River flow forecasting through conceptual models, part I—a discussion of principles. *Journal of Hydrology* **10**: 282–290. [https://doi.org/10.1016/0022-1694\(70\)90255-6](https://doi.org/10.1016/0022-1694(70)90255-6).
- O'Driscoll M, Clinton S, Jefferson A, Manda A, McMillan S. 2010. Urbanization effects on watershed hydrology and in-stream processes in the southern United States. *Water* **2**: 605–648. <https://doi.org/10.3390/w2030605>.
- Oyeyinka O. 2008. State of the world's cities: harmonious cities. United Nations Human Settlements Programme (UN-HABITAT).
- Paço TA, David TS, Henriques MO, Pereira JS, Valente F, Banza J, Pereira FL et al. 2009. Evapotranspiration from a Mediterranean evergreen oak savannah: the role of trees and pasture. *Journal of Hydrology* **369**: 98–106. <https://doi.org/10.1016/j.jhydrol.2009.02.011>.
- Pappas EA, Smith DR, Huang C, Shuster WD, Bonta JV. 2008. Impervious surface impacts to runoff and sediment discharge under laboratory rainfall simulation. *Catena* **72**: 146–152. <https://doi.org/10.1016/j.catena.2007.05.001>.
- Parsons AJ, Bracken L, Poepl RE, Wainwright J, Keesstra SD. 2015. Introduction to special issue on connectivity in water and sediment dynamics. *Earth Surface Processes and Landforms* **40**: 1275–1277. <https://doi.org/10.1002/esp.3714>.
- Pato RL, Castro P, Tavares AO. 2015. The relevance of physical forces on land-use change and planning process. *Journal of Environmental Planning and Management* **59**: 607–627. <https://doi.org/10.1080/09640568.2015.1035773>.
- Pierr A, Ravetz J, Tosics I. 2015. Peri-urbanization in Europe—towards European policies to sustain urban–rural futures. Synthesis report: 148 pp. Accessed 3 November. < [http://www.openspace.eea.eu.ac.uk/pdf/appendix/Peri\\_Urbanisation\\_in\\_Europe\\_printversion.pdf](http://www.openspace.eea.eu.ac.uk/pdf/appendix/Peri_Urbanisation_in_Europe_printversion.pdf).
- Refsgaard JC, Storm B, Clausen T. 2010. System Hydrologique Européen (SHE): review and perspectives after 30 years development in distributed physically based hydrological modelling. *Hydrology Research* **41**: 355–377. <https://doi.org/10.2166/nh.2010.009>.



- Renninger HJ, Carlo NJ, Clark KL, Schäfer KVR. 2015. Resource use and efficiency, and stomatal responses to environmental drivers of oak and pine species in an Atlantic coastal plain forest. *Frontiers in Plant Science* **6**: n/a–n/a. <https://doi.org/10.3389/fpls.2015.00297>.
- Rose S, Peters NE. 2001. Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. *Hydrological Processes* **15**: 1441–1457. <https://doi.org/10.1002/hyp.218>.
- Shuster WD, Bonta J, Thurston H, Warnemuende E, Smith DR. 2005. Impacts of impervious surface on watershed hydrology: a review. *Urban Water Journal* **2**: 263–275. <https://doi.org/10.1080/15730620500386529>.
- Song X, Zhang J, Zhan C, Xuan Y, Y, M, Xu C. 2014. Global sensitivity analysis in hydrological modelling: review of concepts, methods, theoretical framework, and applications. *Journal of Hydrology* **523**: 739–757. <https://doi.org/10.1016/j.jhydrol.2015.02.013>.
- Tavares AO, Pato RL, Magalhães MC. 2012. Spatial and temporal land use change and occupation over the last half century in a peri-urban area. *Applied Geography* **34**: 432–444. <https://doi.org/10.1016/j.apgeog.2012.01.009>.
- United Nations (UN). United Nations expert group meeting on population distribution, urbanization, internal migration and development. United Nations Population Division. Accessed 23 September 2015. <[http://sustainabledevelopment.un.org/content/documents/2529P01\\_UNPopDiv.pdf](http://sustainabledevelopment.un.org/content/documents/2529P01_UNPopDiv.pdf)>.
- Vázquez RF. 2003. Effect of potential evapotranspiration estimates on effective parameters and performance of the MIKE SHE-code applied to a medium-size catchment. *Journal of Hydrology* **270**: 309–327. [https://doi.org/10.1016/S0022-1694\(02\)00308-6](https://doi.org/10.1016/S0022-1694(02)00308-6).
- Verrot L, Destouni G. 2015. Screening variability and change of soil moisture under wide-ranging climate conditions: snow dynamics effects. *Ambio* **44**: 6–16. <https://doi.org/10.1007/s13280-014-0583-y>.
- Wang S, Fu B-J, He C-S, Sun G, Gao G-Y. 2011. A comparative analysis of forest cover and catchment water yield relationships in northern China. *Forest Ecology and Management* **262**: 1189–1198. <https://doi.org/10.1016/j.foreco.2011.06.013>.
- World Health Organization (WHO) 2015. Urban population growth. Accessed 13 November 2015. [http://www.who.int/gho/urban\\_health/situation\\_trends/urban\\_population\\_growth\\_text/en/](http://www.who.int/gho/urban_health/situation_trends/urban_population_growth_text/en/).
- Zdruli P. 2014. Land resources of the Mediterranean: status, pressures, trends and impacts on future regional development. *Land Degradation and Development* **25**: 373–384. <https://doi.org/10.1002/ldr.2150>.
- Zhang Y, Shuster W. 2014. Impacts of spatial distribution of impervious areas on runoff response of hillslope catchments: simulation study. *Journal of hydrologic Engineering* **19**: 1089–1100. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000905](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000905).

## SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

### Data S1. Model description