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Fine-scale analysis of urban flooding reduction from green infrastructure: An ecosystem services approach for the management of water flows

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ABSTRACT

Climate change is expected to modify the timing and amount of precipitation in the future, increasing the demand for effective adaptation at the local scale, especially to mitigate the impacts of extreme events, expected to increase in frequency and magnitude. Green infrastructure (GI) can provide a crucial water regulating ecosystem service, helping communities to adapt to the increased stormwater runoff and associated flood risks expected from climate change. This paper presents a new planning tool that utilizes remote sensing and census data to model the supply and demand for urban flood reduction services through GI. A high-resolution urban digital model is used to distinguish between permeable and impermeable areas at fine (e.g. 25 cm) spatial scale. Flood reduction capacity was modeled using two indices: i) the amount of runoff reduced by existing GI, and ii) the runoff reduction coefficient. We also analyzed the flood reduction demand using a vulnerability index. The tool is demonstrated in a historical urban center of the Northern Italy, with different scenarios used to identify priority areas of intervention. The results show that the flood reduction capacity is unevenly distributed throughout the study area. Public and private surfaces contribute different amounts of runoff with different flood reduction potentials. In eight of nine urban study areas, private properties generate more runoff than public properties under the worst scenario conditions. The study identified two priority areas of intervention, based on their mismatch between supply and demand of GI's water regulating services.

1. Introduction

Because of the proliferation of impervious surfaces, urban regions are extremely vulnerable to the effects of climate change on precipitation, and less resilient than rural settlements to a wide range of climate-related disturbances (Ashley et al., 2005; Huong and Pathirana, 2013). Climatic change is expected to exacerbate precipitation patterns in future (Schröter et al., 2005), increasing the demand for a suite of water-related services (Zheng et al., 2016).

Because the impacts of climate change are experienced locally (Carter et al., 2015), many cities are developing mitigation and adaptation strategies to reduce their vulnerability (Musco et al., 2016; Rangarajan et al., 2015; Rosenzweig et al., 2011; Zidar et al., 2017a). Effective local adaptation strategies are needed specifically to mitigate the consequences of extreme events, which are predicted to increase in frequency and magnitude (IPCC, 2014) in the years to come.

A paradigm shift is needed, to replace the outdated resistance-based approach (e.g. requiring the construction of new hard infrastructure) with an ecosystem-based approach (Ojea, 2015) that seeks to restore, enhance, or create ecosystem services within the urban matrix. The latter would promote the conservation and restoration of natural systems specifically for the benefits they provide to humans, e.g. ecosystem services (ES) (Temmerman et al., 2013).

Green infrastructure (GI) has been defined as 'all natural, semi-natural and artificial networks of multifunctional ecological systems within, around, and between urban areas, at all spatial scales' (Tzoulas et al., 2007). This definition includes a wide range of ecosystem types, which provide many different bundles of ES. Among these, several regulating services are particularly relevant in urban contexts including climate regulation, air quality regulation, water flow regulation, water purification (Haase et al., 2014).

Water regulation refers to the control of surface water flows so as to maintain normal levels in the watershed (De Groot et al., 2002). In the urban context, water regulation often refers to the control of stormwater runoff and associated flooding (Gómez-Baggethun et al., 2010; McPhearson et al., 2014), which can cause severe damage to public and

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private assets and negatively impact the quality of life and human safety (Hammond et al., 2015). Because it was typically designed to convey historical "design storms", conventional urban drainage infrastructure is often ineffective at managing runoff during the extreme events attributed to climate change (Ashley et al., 2005). In this context, GI is gaining increased attention by both researchers and urban planners (de Sousa et al., 2016a,b, 2012; Haase et al., 2014; Mason and Montalto, 2014; Rangarajan et al., 2015) because it can be used to retrofit water regulating services into urban landscapes that are currently inadequately serviced by existing drainage systems. The approach is often synergistic with other municipal efforts to restore ecosystems heavily impacted by previous and ongoing phases of urbanization (Haaland and van den Bosch, 2015).

An increasing number of studies have described the ES that can potentially be delivered by urban GI (Endreny et al., 2017; Pappalardo et al., 2017; Pulighe et al., 2016; Wang et al., 2014) but very few tools have been put forth to enable their incorporation in urban decision-making processes (e.g. Kabisch, 2015; Nikodinoska et al., 2018). A joint analysis of ES supply and demand could be used to inform decision-making processes around ES delivery (Burkhard et al., 2012; Gissi and Garramone, 2018). The supply of ES is defined as the capacity of a particular planning area or ecosystem to provide ES (Burkhard et al., 2012), while the demand for ES is defined as those ES that are recognized or desired by beneficiaries or end users in the study area (Wolff et al., 2015).

Such an approach would help to transfer the ES concept from theory to practice, one of the most important contemporary challenges in ES science (Gissi et al., 2015; Gissi and Garramone, 2018). Though different methods for mapping ES provision capacity (i.e. ecological functions) are presented in literature, e.g. direct measures, proxy indicators and models (Egoh et al., 2012), rarely are these combined in a contextual analysis of ES demand (Wolff et al., 2015). Once recent exception is Zidar et al. (2017b) who used a map of seven ecosystem service gaps, e.g. geographic regions no longer capable of providing the ES most needed by the residents of Camden, New Jersey, as a planning tool for siting and designing multifunctional GI.

Assessment of ES demand differs according the purpose of the analysis. In another context, the targets fixed by energy plans can be used to quantify the demand for bioenergy provision by incorporating ES trade-off analysis (Gissi et al., 2018, 2016). Wolff et al. (2015) classify demand types in four typologies: risk reduction, preferences and values, direct use or consumption of goods and services. Among these, the need for risk reduction can be used for assess demand of flood mitigation (Liquete et al., 2013; Nedkov and Burkhard, 2012).

By identifying priority areas for ES management and protection, ES can be incorporated into a wide range of local efforts to adapt to climate change. For example, Snäll et al. (2016) demonstrated that spatial conservation prioritization could represent a suitable tool for GI design, allowing cost-effective allocation of conservation efforts. Verhagen et al. (2017) mapped capacity and demand for five ES at European level. They found that ignoring ES demand led to the siting of interventions in remote regions where the ES benefits to society were small.

This paper presents a new planning tool that utilizes remote sensing and census data to model the supply and demand for urban flood reduction services through GI. The study focuses on flood reduction ES provided by GI, defined as the capacity of urban GI to absorb urban stormwater to reduce the risk of flooding. We define urban GI as all the pervious green spaces within the urban study area, on both private and public properties. First, we introduce the method for mapping the supply of flood reduction services from existing urban GI. A high-resolution urban digital model was used to distinguish between permeable and impermeable areas at fine scale, with a precision of 25 cm. Next, we classified the pervious areas based on their soils, vegetation, construction materials, and land cover coverage, utilizing the SCS (Soil Conservation Service) Curve Number (CN) method (USDA - Soil Conservation Service, 1972) to quantify runoff generation at the catchment scale. Regions generating more runoff are assumed to generate greater flood risk. Because the analysis is carried out at the catchment, and not the watershed scale, watershed slopes are ignored. Flood reduction capacity is evaluated using two indices: i) the amount of runoff reduced by green spaces (Δv) (Zhang et al., 2012), and ii) the runoff reduction coefficient (Cr). Secondly, we analyzed the demand for flooding reduction through the computation of a Vulnerability Index (VI), which represents the vulnerability of local population and buildings to urban flooding. The method was applied to the historical urban center of Dolo, a highly urbanized area in Northern Italy. The analysis was replicated for 24 scenarios of rain events, emerging from the combination of three factors: i) precipitation depth, ii) antecedent moisture condition of soils and iii) conditions of initial abstraction. Finally, we matched the flooding reduction capacity of urban GI with the respective demand for such service, in order to identify priority areas of intervention where to urgently mitigate potential flooding events.

2. Methods

2.1. Study area

The study area comprises the historical urban center of the Municipality of Dolo (coordinates 45°25′29.57″N 12°04′32.92″E), located inside the Metropolitan Area of Venice, Italy. The municipality of Dolo covers 24.8 km^2 and has a total population of approximately 15,000 inhabitants, of which 4226 live inside the historical urban center (1.67 km^2). It is located within the watershed of the Venice lagoon.

The climate of the study area is classified as B1 (Humid) according to the Thornthwaite classification (Feddema, 2005), with an average temperature is 13.2 °C. Mean rainfall ranges from 600 and 1100 mm yr^{-1}, with an annual average of 912 mm. The mean annual reference evapotranspiration is 730 mm (Aschonitis et al., 2017). Historically, the wettest month is May (94.4 mm), while the driest is January (49.9 mm). The hydraulic soil group of this area is classified as B type according to the USDA-NRCS classification (NRCS, 1986). Soils belonging to this category typically have between 10% and 20% clay and 50% to 90% sand with a loamy sand or sandy loam texture (USDA, 2009).

The historical urban center of Dolo is frequently subjected to urban flooding events because of an inadequately sized urban drainage system and large amount of impervious surfaces (Municipality of Dolo, 2012). Evidence of the effects of climate change has been detected and studied by Bixio (2009). A 60-year analysis (1956–2010) of precipitation patterns in the Venice lagoon drainage basin (where Dolo is situated) reveals an intensification of events rainfall accompanied by simultaneous reduction in annual precipitation totals. In September 2007, several high-intensity, short duration rainfall events generated runoff in excess of the conveyance capacity of the local drainage infrastructure, generating extreme flood damage (Municipality of Dolo, 2012).

2.2. High-resolution urban digital model

A high-resolution urban digital model of all of the pervious and impervious elements, both public and private, within the historical urban center of Dolo and their relative heights was generated from a variety of data sets. Soil maps were generated by processing spatial data obtained from LIDAR (Light Detention and Ranging) survey using ArcGis 10.3 (ESRI). An aerial survey commissioned by the Metropolitan City of Venice Administration in 2014 produced 4000 high-resolution images. Then, a 3D digital model of the area was created with the Dense Image Matching technique (Hirschmüller, 2008). Raster images -DSM (Digital Surface Model) and DTM (Digital Terrain Model) were generated with a precision of 25 cm (Pixel 0.25 m). The DSM reports the altimetric data of all natural and anthropogenic elements (namely impervious) in a specific area, while the DTM reports the morphology of