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Monetary value of urban green space as an ecosystem service provider: a case study of urban runoff management in Finland

Sveta Silvennoinen[a], Maija Taka[b], Vesa Yli-Pelkonen[c], Harri Koivusalo[b], Markku Ollikainen[d], Heikki Setälä[a]

[a] Dept. of Environmental Sciences, University of Helsinki, Niemenkatu 73, FI-15140 Lahti, Finland

[b] Dept. of Built Environment, Aalto University, P.O.Box 15200, FI-00076 Aalto, Finland

[c] Dept. of Environmental Sciences, P.O.Box 65, FI-00014 University of Helsinki, Finland

[d] Dept. of Economics and Management, P.O.Box 27, FI-00014 University of Helsinki, Finland

email: sveta.silvennoinen@gmail.com, maija.taka@aalto.fi, vesa.yli-pelkonen@helsinki.fi, harri.koivusalo@aalto.fi, markku.ollikainen@helsinki.fi, heikki.setala@helsinki.fi

Corresponding author: Vesa Yli-Pelkonen

Abstract

The predicted increase in the number of urban flood events can result in substantial monetary losses to society. These costs may be alleviated by preserving ecosystem services, such as urban runoff management. We studied the monetary value of this ecosystem service by applying the replacement cost method in six catchments with varying land-use intensities in two cities in Finland. The economic analysis was based on metric data of urban runoff generation, provided by automatic monitoring stations in the catchments. A hydrological model was applied to estimate evaporation from impervious surfaces, and to simulate runoff in the catchments. Our results suggest that leaving green space unconstructed results in significant monetary savings. The cost of managing runoff correlated with land-use intensity. The ecosystem service value (ESV) was generally higher in catchments with high land-use intensity, low proportion of green space, and high costs of runoff management. Depending on the degree of imperviousness, the ESV ranged from 90 000 – 270 000 € ha^{-1}. Further, our results suggest that estimates of runoff generation and evaporation are key hydrological factors for assessing ESV. Our study demonstrates how the combination of field data and hydrological and monetary analyses can support regional planning in cold climates.

1. Introduction

Intensive land use is associated with drastic changes in vegetation cover and soil sealing, causing severe anomalies in the hydrological cycle (Schueler 1994; Douglas 2011; Illgen 2011). Urban catchments - with highly disturbed soils - are characterized by high proportions of impervious surfaces resulting in increased surface runoff, decreased infiltration and evapotranspiration (ET), and the presence of dense and efficient drainage systems (Booth & Jackson 1997; Burton & Pitt 2002; Burian & Pomeroy 2010). These changes in the hydrological cycle are manifested in increased frequencies and severities of urban flood events (Booth 1991; Burton & Pitt 2002; Kotola 2003; Ogden *et al*. 2011), which are, specifically at high latitudes, predicted to become more frequent due to an increase in precipitation associated with climate change (Lehner *et al.* 2006; IPCC 2007; Aaltonen *et al.* 2008; Perrels *et al.* 2008, 2010). Furthermore, untreated urban runoff – i.e. stormwater – is an important pathway for pollutants in urbanized catchments (Bäckström *et al.* 2002) and is an important source of the impairment of surface and ground water resources (Pitt *et al.* 1999; Burton & Pitt 2002; Allan 2004; Goonetilleke *et al.* 2005). There is growing concern that the increased volume and reduced quality of stormwater will result in increased monetary losses to society (Aaltonen *et al.* 2008; Bélanger 2008; Perrels *et al.* 2008, 2010). To reduce urban runoff, urban green space and the ecosystem services (ES) it provides has been suggested as a feasible alternative to conventional stormwater management (e.g. Burian & Pomeroy 2010; Liu *et al*. 2014).

The ecosystem services (ES) framework has become increasingly common in urban land-use and green-area planning, as urban ecosystems provide multiple ES, that are of great importance to the well-being of urban inhabitants. Furthermore, urban ES often provide justification for preserving the urban green infrastructure at substantial quantity and quality in urban planning and development. Urban runoff management (sometimes also called "flood protection", depending on the context), as studied in this paper, is categorised in regulation and maintenance services in the ES framework and is maintained by vegetation and soil associated with permeable surfaces (CICES, 2017). The simple use of ES framework is not, however, always unproblematic – for instance, due to a lack of empirical studies showing the actual magnitude of benefits (including monetary) to urban inhabitants or society. This is also the case with urban runoff management, as studies estimating the monetary value of urban soils in terms of storing rainwater, and thus mitigating urban runoff generation, are virtually non-existent.

Urban green infrastructure, such as trees, lawns and green roofs, are known to mitigate runoff problems through water harvesting and enhancing infiltration and evapotranspiration (Bélanger 2008; Burian & Pomeroy 2010; Liu *et al*. 2014). For example, Elmqvist *et al*. (2015) reported annual evapotranspiration of 1000 m^3 ha^{-1} in urban parks in Sacramento Ca, USA, and Peper *et al*. (2007) estimated that city street trees in New York, USA have an annual interception of 3.4 million m^3. However, despite the various benefits by urban green space, its continuous replacement with housing and other impervious surfaces makes the provision of ES vulnerable, and creates a trade-off situation between ecosystem services and city consolidation policies (Eigenbrod *et al*. 2011; Elmqvist *et al*. 2015).

From an economic point of view, diminishing urban green areas and thus the deterioration of urban runoff management and other ES have traditionally resulted not only in a significant loss of citizens' welfare, but also in direct monetary losses due to increased investments on expensive technical solutions replacing the services carried out by urban green space (Bélanger 2008; van Zoest & Hopman 2014; Elmqvist *et al.* 2015). However, for instance in the USA and Western Europe, the conversion of urban green areas to built-up i.e. – grey areas – is becoming less common, as the multiple benefits of green areas to urban inhabitants are being realised.

Nevertheless, the incorporation of ecological processes into urban planning, for example through increasing the proportion of permeable surfaces in urban areas, has proven to be challenging, since investment decisions in many countries are traditionally based on financial analyses that do not account for the benefits of ES (van Zoest & Hopman 2014). However, a growing number of studies report substantial monetary benefits associated with ES provided by urban green space, e.g. related to urban runoff management (see Elmqvist *et al*. 2015). The reported economic values, mostly derived from methods that indirectly estimate stormwater reduction capacity via, e.g. canopy interception models, range from 0.34 € m^{-3} (Vargas 2009) up to 200 € m^{-3} (American Forests 2002).

The aims of this study were to (1) determine the economic value of the ecosystem service that urban green space can provide in terms of urban runoff management, in six urban catchments with different land-use intensities in the cities of Helsinki and Lahti, southern Finland; (2) assess how the estimated ecosystem service value (ESV) will change in the time span of 40 years, when climate change impacts the urban runoff volume and the costs of a conventional stormwater system; and (3) drawing on these analyses of ESV, examine whether it is economically beneficial to use urban vegetated areas for runoff management instead of relying only on conventional pipe-based drainage.

The monetary value of the ecosystem service is defined in this paper as the net savings in technological solutions (conventional pipe-based drainage) when urban runoff is managed with the same service provided by green space.

This study was conducted at high latitudes, which introduce unique setting for ecosystem services. The four distinct seasons – with a prolonged cold season and soil frost – together with compact urban settlements, require carefully designed runoff management solutions. However, planning of such solutions is hindered by a lack of urban runoff data across seasons. The study sites, belonging to a Long-Term Socio-Ecological Research (LTSER) network (Setälä *et al.* 2010), have been intensively studied in terms of urban hydrology (Taka 2012; Krebs *et al*. 2013, 2014; Valtanen *et al*. 2013, 2014). Based on our previous research on urban runoff (Krebs *et al*. 2013, 2014; Valtanen *et al*. 2013), we hypothesized that: i) preserving urban green areas results in substantial monetary savings for society via the ecosystem service of urban runoff management; and ii) ESV is higher at high land-use intensity, where costs of managing runoff are predicted to be higher. Importantly, unlike previous studies, the value calculations here are based on a combination of rarely-available urban empirical hydrological data and model results. By using microscale urban runoff data as an input into the ESV evaluation, we aimed to identify the prospects of using urban green space to manage seasonal urban runoff volumes. As our approach is based on these data, it can be utilized in similar urban regions with no accurate time series data of runoff available. Thus, the current study aims at providing a cost-effective and quantitative model to serve land-use planning and management, and related decision-making.

2. Material and methods

2.1. Study catchments

The study was conducted in the cities of Helsinki (60°10’N, 24°56’E; population of 635 000), and Lahti (60°59’N, 25°39’E; population of 120 000) in southern Finland. The six study catchments are classified into three land-use intensity categories (hereafter High, Intermediate and Low), thus representing different degrees of sealed surfaces and population densities (Fig. 1). They form part of the international LTSER network. These catchments were chosen to represent urban land cover with varying intensity, and they all have separate sewer systems, which discharge runoff to the receiving surface water systems without any treatment. Finally, they are closely located within the city and relatively similar in size.

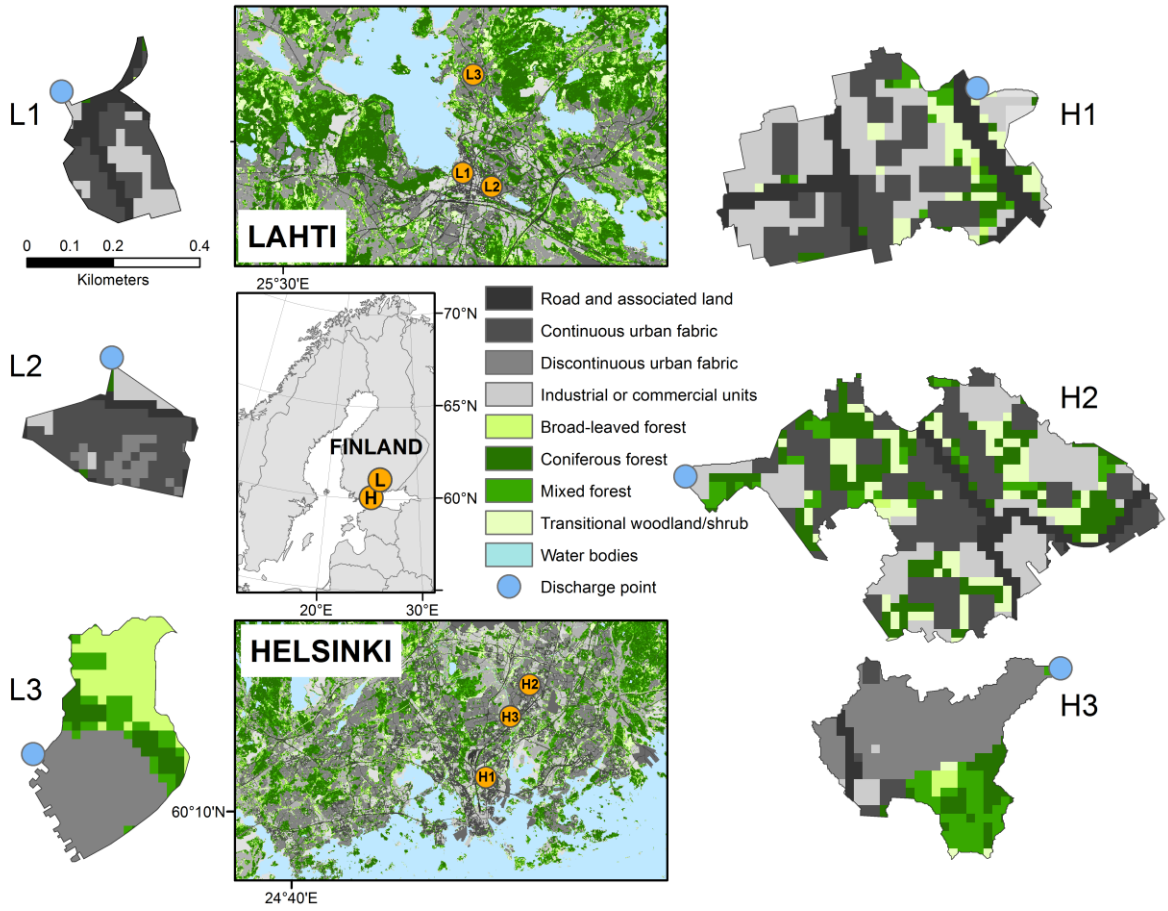


Figure 1. Location of the study catchments with diverging land-use intensity (high to low) in Lahti (L), where L1 = High catchment, L2 = Intermediate catchment, L3 = Low catchment and in Helsinki (H), where H1 = High catchment, H2 = Intermediate catchment, H3 = Low catchment. The land-cover classification is based on CORINE classification (FEI 2015). Note that the catchments are presented at the same scale.

The main characteristics of the six urban catchments are presented in Table 1. High catchments (L1, H1) represent urban core areas with a high impervious fraction, intensive land-use, high traffic volume, with fragmented green spaces that mainly located in public park areas and residential yards. The Intermediate catchments (L2, H2) represent urban/suburban areas, while the Low catchments (L3, H3) are situated in suburban/residential areas characterized by single-family houses. In the Intermediate and Low catchments, the percentage of pervious areas is clearly higher than in the High catchments, and typical green spaces are urban forests, parks, residential yards and gardens. The catchments in Helsinki and Lahti differ in bio-geographical characteristics and local topography, and population densities of the High and Intermediate catchments of Lahti are considerably higher compared with Helsinki (Table 1). When looking only at the impervious

fractions of the catchments, the classification is relational, i.e., the urban density classes 1-3 reflect the relative TIA differences within each study area.

Table 1. Main characteristics of the studied catchments (adopted from Setälä *et al*. 2010; Taka 2012; Valtanen *et al*. 2013; Krebs *et al*. 2014; Lundberg, 2011). TIA = Total Impervious Area. Drainage density is the total pipeline density in relation to catchment area.

Land-use intensity	High		Intermediate		Low	
City	Lahti	Helsinki	Lahti	Helsinki	Lahti	Helsinki
Catchment size (ha)	6.1	24.1	6.5	38.4	12.6	14.5
Population density (inhab. km^{-2})	10 800	4 200	7 100	5 500	1 400	2 400
TIA (%)	89	68	62	36	19	35
Length of pipe system (km)	2.6	4.4	3.2	4.5	1.6	1.5
Drainage density (km km^{-2})	42.8	18.4	49.7	11.8	13.1	10.2
Share of managed green spaces	0.34	0.35	0.24	0.3	0.1	0.1

2.2. Data collection

Runoff measurements were conducted in Lahti from December 2008 to August 2010, and in Helsinki from December 2010 to November 2014. Runoff was monitored at a measurement station located at the catchment discharge outlet, equipped with a runoff probe (ultrasonic flow sensor Nivus PCM4) placed into a stormwater pipe. Flow rate (l s^{-1}) and precipitation (mm) were measured continuously at 1-min intervals throughout the study periods (intervals were increased to 2 or 3 min during the freezing winter periods) and recordings at each station were stored using data loggers (Campbell CRX10) (see Valtanen *et al*. 2013). Additional precipitation data, including snowfall, were obtained from the Finnish Meteorological Institute (FMI), which operated a station recording precipitation at 10-min intervals, 2-6 km from the studied catchments (see Valtanen *et al*. 2013). In Helsinki, precipitation was measured at the FMI's Kumpula weather station, located 1-4 km from the studied catchments (see Taka 2012). All spatial data for the catchments were calculated using MapInfo. In Lahti (L1-L3), estimated drainage density consists of the main collector stormwater pipes and pipes located on private estates, including pipe connections from roof drains to the network. Open ditches were excluded. In Helsinki (H1-H3), the data represent only main collector pipes.

Economic data consists of estimates on construction costs of pipelines, their annual operation and maintenance (O&M) costs, and construction costs of impervious surfaces. For green space, the data contains estimates of the investment (48 €/m^2) and managing (0.5 €/m^2) costs of the green infrastructure. The data were collected through numerous personal interviews, e-mail correspondences, and unit cost reports. Data were provided by local water and environmental service and technical maintenance companies, and city officials of Lahti and Helsinki (see Tables 2 and 5 and References for details). Due to the overall lack of precise calculations and statistical data that is typical of this data type, only values considered as *best estimates* were usually available. Although using best-estimate values acquired from experts, brings some limitations to the applicability of the values, and consequent calculations in other urban areas, we are confident that these best-estimate values represent the real cost-situation in the studied urban areas. Since it was not possible to calculate precise costs for different catchments, estimations of cost variation between three different types of areas (High, Intermediate and Low land-use intensity) were made, with the exception of O&M costs, which were only available at the city-scale. Due to the high variation in land costs between the catchments, land costs were not included in the calculations. The high variation in land costs is not usually linked to ecosystem services, but to complexity of land-price formation in urban areas. This depends on factors such as housing prices, urban business opportunities, location and the quality of the surrounding urban environment (e.g. the share of green space). Construction costs of the pipeline system for urban runoff management cover material and related work. The most important variable affecting the price of stormwater pipes is pipe diameter, which is determined by site characteristics, location and land-use intensity. The data gathered provide costs for small and large pipe diameters, which are 300 – 400 mm (small) and ca. 1000 mm (large) in Lahti; and ≤ 500 mm (small) and ≥ 600 mm (large) in Helsinki. Construction cost was approximated based on average pipe diameter in the catchment. The use of pipe cost for diameters of 300 – 400 mm in L1 was deemed acceptable, as the cost in city centre is not constant, and can achieve up to 1000 € m^{-1} depending on the characteristics of the site (Hiltunen 2011). All related costs are presented in Table 2.

Maintenance of the existing stormwater pipes in Helsinki costs ca. 2 million €/a, or 1 €/m/a, assuming that there are ca. 2000 km of stormwater pipelines in Helsinki (Heinonen 2012). In addition, Helsinki accomplishes other maintenance work related to the entire system, totalling 130 000 € in 2012 (Heikkilä 2013). For simplicity, this sum was proportioned to the total length of pipes, resulting in operational costs of 0.065 €/m/a. The estimation of O&M costs for the city of Lahti was about 1 €/m/a (Heikkonen 2013). Costs concerning the removal of sand comprise about 11 €/inlet/a

in Helsinki according to cleaning statistics of 2012 (Heikkilä 2013), and ca. 33 €/inlet/a in Lahti (Uski 2013). The number of inlets is calculated in compliance with design instructions, which is ca. one inlet per 650 m^2 of impervious surface (AFLRA 2012).

Table 2. Construction and operation and management (O&M) costs of a conventional stormwater system. The data were collected through personal interviews (Hiltunen 2011; Lehtonen 2011; Heinonen 2012; Hyvärinen 2012; Heikkilä 2013; Heikkonen 2013; Uski 2013). L1 and H1 refer to High catchments, L2 and H2 to Intermediate catchments, L3 and H3 to Low catchments in Lahti and Helsinki, respectively.

Land-use intensity	High		Intermediate		Low	
City	L1	H1	L2	H2	L3	H3
Average pipe diameter (mm)	110-400	300-500	110-600	300-800	225-500	300-400
Approximated construction cost (€ m^{-1})	600	800	300	800	200	400
Total annual O&M cost (1000 €)	5.3	7.5	5.2	7.2	2.8	2.4
Construction cost (1000 € ha^{-1} of impervious surface)	289	216	241	262	138	117

2.3. Analysis of ecological data

The analysis of the eco-hydrological data was conducted based on measured and modelled runoff values for both annual and seasonal (warm) periods. Annual characteristics were calculated using long-term runoff-precipitation ratios (precipitation-weighted means). For the warm period (June-November), runoff coefficients in Lahti were defined as 'direct precipitation-induced runoff event divided by total precipitation during the event', and in Helsinki as 'runoff-precipitation ratios'. As runoff-precipitation ratios may have been biased due to sudden gaps in data, event-scale runoff coefficients (i.e. runoff (mm) / precipitation (mm)) were used instead. This dimensionless variable indicates the conversion rate of rainfall into runoff. Runoff coefficients for impervious areas (runoff-precipitation ratio for impervious areas only) were derived for all catchments using the hydrological model detailed below. Applied mean annual precipitation was 633 mm (warm period 403 mm) in Lahti and 642 mm (warm period 396 mm) in Helsinki (Kersalo & Pirinen 2009).

The Drainmod-type hydrological model was utilized for evapotranspiration estimations (Koivusalo & Kokkonen 2003). The model simulates precipitation-runoff processes, including evaporation (evapotranspiration), and can be parameterised for different surface types. The modelling approach was based on the vertical one-dimensional representation of a soil column and its water content. The water balance of soil was defined in terms of air volume in the soil, as in pervious areas infiltration can enter the soil domain whenever there is empty air pore space in the soil, and both evapotranspiration and drainage from soil can increase the air volume in soil column. In contrast, in impervious areas the infiltration capacity at the soil surface can be adjusted to reduce or block infiltration. If water is not infiltrated, it will generate surface runoff, which is delayed before it is discharged out of the system using a linear store. Drainage (using the *Hooghoudt equation*) is activated whenever the simulated water table level of the soil column is above a prescribed drainage depth (Skaggs 1980).

The model was supplied with the degree-day snowmelt model (Koskela *et al.* 2012) to support annual daily simulations during cold seasons. The input data consisted of daily air temperature, precipitation and potential evapotranspiration (PET), calculated according to the reference crop evaporation equation (Shuttleworth 1993). Weather data were obtained from the aforementioned FMI weather stations in Helsinki (Kumpula) and Lahti (Laune). Missing values were replaced with data from a nearby station, or with zeros (in the case of missing precipitation records). The model was set to simulate a period of 5 years from 2007 to 2011 in all catchments. In order to minimize the impact of initial values (air volume of the soil) on model results, a warm-up period of one year (2007) was executed before running the simulations for the study period. The model was calibrated against the observed warm period and annual runoff coefficients of the Lahti catchments, where the quality of the runoff data was earlier assessed by Valtanen *et al*. (2014). Snow model parameters were the same for pervious and impervious surfaces. Surface runoff retention was assumed to be minimal, with the retention parameter of the linear store being 0.95. Urban areas were assumed to be covered by impervious surfaces, i.e. without any vegetation. Imperviousness was defined as EIA (*effective impervious area*, i.e. impervious area directly connected to pipelines) instead of TIA (*total impervious area*), and determined by application of the linear regression equation of Sillanpää (2013). After calibration, the model was used to simulate runoff for the catchments. The hydrological model produced an estimate of evaporation from water on impervious surfaces, where evapotranspiration from the soil was assumed to be negligible.

2.4. Analysis of the economic data

For ESV evaluation relating to runoff management services in urban areas, the replacement cost method was considered the most appropriate valuation method. It represents the indirect valuation approach, where the cost of a close substitute is used as a measure of value of the replaced non-priced environmental good or service (Bockstael *et al.* 2000; Hanley & Barbier 2009). The analysis was conducted by isolating specific processes produced by the ecosystem (urban runoff management service provided by urban green space), and by assessing the cost of the best available technologically-produced substitute (man-made stormwater conveyance system) for the ecosystem service.

Consider first the current state of pipelines and weather. The amount of rain falling on impervious surfaces (P_i) was used to estimate the cost (C_c) of controlling runoff per volume of stormwater (€ m^{-3}), applying the same approach as PPA (2008) in equation (1), where the investment cost, $C_{grey,}$ is divided by the precipitation to produce a unit cost. The runoff managed by urban green space (m^3) is denoted by I in equation (2), where A is the catchment area (ha), φ is the runoff coefficient or total runoff-precipitation ratio, E_i is the share of evaporation from precipitation in impervious surfaces (%), and P is annual precipitation (m^3/ha).

Drawing on equations (1) and (2), the monetary value of the ecosystem service (ESV, € ha^{-1}) is determined in equation (3) as the cost-saving (net of infrastructure costs, C_g, of green space), due to the volume of runoff managed by urban green space (A_p is the pervious surface area (ha)). In addition, evaporation from impervious surfaces was excluded. Hence, ESV measures the cost-saving based on construction and annual costs of pipelines and net of those of the green space. It includes neither the price of land nor other benefits of green space (such as recreation or climate services). By using the revealed preference argument for the existing green space, the benefits are regarded higher than land prices, so that it is possible to apply equation (3) in this context.

$$C_c = C_{grey}/P_i \tag{1}$$

$$I = \left(PA(1-\varphi)\right) - (E_i P_i)/100 \tag{2}$$

$$ESV = (C_c - C_g)I/A_p \tag{3}$$

ESV in equation (3) was calculated based on both modelled and measured runoff values. To avoid overestimation of the ESV, the measured data-based ESV was replaced with modelled ratios for L1 for the entire year, and for H1 for both examined periods, presenting the combined ESV. To improve comparability with other studies, we approximated the annual avoided costs. Despite the technical life-span of a conventional stormwater system being 50 – 100 years, the system requires inspection as early as 20 – 40 years after construction due to land-use and climate-induced changes (AFLRA 2012), which can lead to upgrading or replacement of parts of the system. Equation (4) gives the total construction costs (C_{total}) as a sum of the investment and the present value of projected annual O&M costs of a 40-year time span. The present value is the current equivalent value of the costs paid over the whole time span (Boardman *et al.* 2006).

$$C_{total} = (C_{grey} + \sum_{t=1}^{40} C_{omt}(1+i)^{-(t-1)})/P_i \quad (4)$$

In equation (4), C_{total} is the total cost of controlling runoff, C_{om} is the annual O&M cost, i is the discount rate (3%), and t is an index over the time span of 40 years. The annual control cost (€ m^{-3}) of urban runoff and annual avoided costs (€ ha^{-1}) can be obtained from the total cost of controlling runoff by dividing it by the assumed total life span of 40 years.

Following Nurmi *et al*. (2013), we assumed that O&M costs will: i) stay the same for the first 10 years; ii) double during the next ten years due to doubling demands for repair, and increase by an additional 10% due to resizing needs; and iii) triple during the last 20 years due to the growing demand for repair, and increase by an additional 20% due to resizing needs.

3. Results

3.1. The volume of runoff managed by urban green space

Both measured and modelled runoff coefficients varied widely across land-use intensity categories and seasons. In Helsinki, annual runoff ratios were higher than warm period ratios in all catchments in both modelled and measured results (Table 3). Surprisingly, the measured runoff ratio in H1 was low for both the warm period and for the whole year. In contrast, the model resulted, in each case, in higher values compared to the measured values, with the biggest difference for H1. While the model estimates a positive trend between total impervious area (TIA) and runoff ratios, it was not

present in the measured ratios.

Table 3. Seasonal runoff coefficients (i.e. total runoff-precipitation ratio) for the studied urban catchments in Lahti (L1-L3) and Helsinki (H1-H3). Data are based on runoff measurements by Taka (2012) and Valtanen *et al*. (2013), and the model results of this study.

Catchment	Warm period		Whole year	
	Measured	Modelled	Measured	Modelled
L1	0.74	0.69	0.54	0.75
L2	0.44	0.46	0.50	0.55
L3	0.10	0.10	0.33	0.22
H1	0.15	0.54	0.18	0.61
H2	0.24	0.28	0.25	0.38
H3	0.13	0.27	0.18	0.38

In Lahti, both modelled and measured data show positive co-variation between TIA and runoff. At both L2 and L3, runoff coefficients during the warm period were lower than the measured runoff ratios for the entire year. This was in agreement with the model. In contrast, the measured warm period runoff coefficient in L1 was higher compared to the runoff ratio for the entire year (Table 3).

The modelled proportions of evaporation from impervious areas, irrespective of catchment type, were estimated to be similar in both cities (13%, 524 m^3/ha/a in Lahti; and 14%, 554 m^3/ha/a in Helsinki) during the warm period. During the entire year, 12% (760 m^3/ha/a) of precipitation falling on impervious surfaces evaporated in Lahti, and 13% (835 m^3/ha/a) in Helsinki. Taking into account these proportions, the amount of runoff managed by urban green space was calculated (Table 4). Our results show that the lower the TIA, the higher the proportion of precipitation infiltrated into pervious surfaces, with the exception of H2 in Helsinki, if applying measured runoff values.

Table 4. Runoff volume (m^3) and the proportion of precipitation (%) managed by urban green space. Results of the warm period are reported first, followed by the annual results (e.g., warm period / annual). L1 and H1 refer to High catchments, L2 and H2 to Intermediate catchments, L3 and H3 to Low catchments in Lahti and Helsinki, respectively.

Land-use intensity	High	Intermediate	Low

City	L1	H1	L2	H2	L3	H3
Runoff volume measured (1000 m^3)	3.5 / 13.6	72.2 / 113.4	12.6 / 17.9	107.8 / 173.1	44.4 / 51.6	47.2 / 72.2
Runoff volume modelled (1000 m^3)	4.8 / 5.5	34.9 / 46.8	12.0 / 15.5	101.7 / 141.1	44.4 / 60.4	39.2 / 53.6
% of precipitation, measured	14 / 35	75 / 73	48 / 44	71 / 70	88 / 65	82 / 77
% of precipitation, modelled	19 / 14	36 / 30	46 / 38	67 / 57	88 / 76	68 / 57

3.2. The cost of urban runoff management

The cost of controlling urban runoff (€ m^{-3}) correlated positively with land-use intensity, resulting in higher costs in catchments of higher land-use intensity (see Table 5 and see equation 1). The only exception was H2 (Helsinki), where the cost of controlling runoff was higher compared to H1.

Table 5. The cost (€ m^{-3}) of controlling runoff in the three land-use intensity types in Lahti and Helsinki (Data from Hiltunen 2011; Lehtonen 2011; Heinonen 2012; Heikkilä 2013; Heikkonen 2013; Uski 2013; Takainen 2017; Rapal Oy 2012). Results of the warm period are reported first, followed by the annual results (e.g., warm period / annual). L1 and H1 refer to High catchments, L2 and H2 to Intermediate catchments, L3 and H3 to Low catchments in Lahti and Helsinki, respectively.

Land-use intensity	High		Intermediate		Low	
City	L1	H1	L2	H2	L3	H3
Cost of controlling runoff by infrastructure	71.7 / 45.6	54.7 / 33.7	59.7 / 38.0	66.1 / 40.8	34.2 / 21.8	29.6 / 18.2
Cost of controlling runoff by green space	20.5 / 13.0	21.4 / 13.2	14.4 / 9.2	18.4 / 11.3	6.0 / 3.8	6.1 / 3.8
Annual cost of controlling runoff by infrastructure	2.1 / 1.3	1.5 / 0.9	1.9 / 1.2	1.8 / 1.1	1.2 / 0.8	0.9 / 0.6

3.3. Ecosystem service value (ESV)

The estimates of ESV based on measured runoff values and equation (3) were somewhat high, ranging from 0.1 M€ to 0.3 M€ in Helsinki and from 0.1 to 0.7 M€ in Lahti (Table 6). ESV

correlated positively with land-use intensity in each case. ESV based on modelled runoff resulted in the same relationships, with the exception of H2 (Helsinki), which had higher ESV compared to H1. With the exception of L1 (measured runoff), ESV was always higher during the warm period compared to the entire year, thus emphasizing the higher evapotranspiration potential during the warm season. We therefore argue that the use of both measured and modelled runoff data would result in the best approximation of ESV (Table 7).

Table 6. ESV (1000 € pervious-ha^{-1}) calculated using measured and modelled runoff values in the three land-use intensity types in Lahti and Helsinki. Results of the warm period are reported first, followed by the annual results (e.g., warm period / annual). L1 and H1 refer to High catchments, L2 and H2 to Intermediate catchments, L3 and H3 to Low catchments in Lahti and Helsinki, respectively.

Land-use intensity	High		Intermediate		Low	
City	L1	H1	L2	H2	L3	H3
ESV, measured runoff	271 / 663	310 / 301	230 / 209	210 / 208	123 / 91	117 / 111
ESV, modelled runoff	364 / 269	150 / 124	221 / 180	198 / 169	123 / 106	97 / 82

Table 7. ESV (1000 € pervious-ha^{-1}) and annual savings calculated, using measured runoff values, replaced with modelled ratios for L1 for the entire year and for H1 for both examined periods (combined ESV) in the three land-use intensity types in Lahti and Helsinki. Results of the warm period are reported first, followed by the annual results (e.g., warm period / annual). L1 and H1 refer to High catchments, L2 and H2 to Intermediate catchments, L3 and H3 to Low catchments in Lahti and Helsinki, respectively.

Land-use intensity	High		Intermediate		Low	
City	L1	H1	L2	H2	L3	H3
ESV, combined	271 / 269	150 / 124	230 / 209	210 / 208	123 / 91	117 / 111
40 a. total ESV	313 / 311	155 / 128	299 / 272	221 / 219	184 / 136	142 / 134
Annual savings	7.8 / 7.8	3.9 / 3.2	7.5 / 6.8	5.5 / 5.5	4.6 / 3.4	3.6 / 3.4

Accounting for the increased O&M costs relating to conventional stormwater systems led to an increased ESV of urban green space with time. In 40 years, ESV will grow by 3, 6, and 21% (for H1, H2, and H3, respectively) and by 16, 30, and 50% (for L1, L2, and L3, respectively). Annual

savings related to urban green space, when calculated on a per hectare basis and assuming a total span of 40 years for the current substitute, show the same trend as ESV (Table 7).

4. Discussion

4.1. Ecosystem Service Value (ESV)

Our study aims to explore whether preserving green space in cities leads to savings for the society, and whether it can provide an alternative to traditional urban runoff management. The analysis is based on rarely-available time-series data of urban runoff, enriched with a hydrological model, to make an extension of traditional model results to ESV evaluation. Overall, our findings support the hypotheses that: i) urban green space reduces runoff, thus providing a valuable ecosystem service of urban runoff management with substantial economic benefits for the society; and ii) ESV is higher at high land-use intensity with an increasing proportion of impervious area, and conventional grey infrastructure thus becomes more expensive. Our findings are in accordance with the proposition of Schueler (1997) that the cost for urban runoff management is a direct function of the amount of impervious cover. Construction costs of stormwater management systems range from 117 000 to 216 000 € ha^{-1} in Helsinki and from 138 000 to 289 000 € ha^{-1} in Lahti – considerably higher than the 4000 – 100 000 € ha^{-1} reported by Schueler (1997). It is important to note, however, that these values were not adjusted for inflation for comparison to Schueler's (1997) values, which may partly cause the observed differences in cost, in addition to contextual differences (e.g. climate, geography, location). Likewise, the cost of controlling runoff by infrastructure is clearly dependent on land-use intensity; in both cities, cost during the warm period increases from ca. 30 (whole year 20) € m^{-3} in the Low catchments to ca. 60 (whole year 40) € m^{-3} in the High catchments, with the exception of H2.

Our findings from boreal/hemi-boreal cities complement previous studies and demonstrate how undeveloped urban green areas result in significant monetary savings. Similarly to costs of controlling runoff, ESV correlates with land-use intensity. Regardless of the study period, higher land-use intensity relates to higher ESV. ESV ranged from ca. 270 000 € ha^{-1} to 120 000 (whole year 90 000) € ha^{-1} in Lahti, and from ca. 150 000 (whole year 120 000) € ha^{-1} to ca. 120 000 (whole year 110 000) € ha^{-1} in Helsinki, with H2 again being the exception (ca. 200 000 € ha^{-1}). Likewise, the amount of runoff managed by urban green space correlated negatively with TIA.

ESV varies greatly depending on the valuation method used, the calculation of runoff reduction, the type of cost data (annual costs of stormwater quality management vs. single infrastructure investment), and the accuracy of ESV estimation (Table 8). Furthermore, other valuation studies have predominantly been conducted under warmer climate conditions, which makes comparisons challenging.

Table 8. A comparison of ESV from different studies across the globe. Values (€) were approximated using historical exchange rates (Xe 2016), applying the first day of publication year, except in Zhang *et al.* (2012) where values from 2009 were used and Jim & Chen (2009) where values from 2004 were used.

City or state	**Reported ecosystem service**	**Urban runoff reduction (m^3)**	**ESV €/m^3, €/ ha** (if available)	**Valuation method applied**	**Reference**
Beijing, China	Rainwater-runoff reduction	154 million m^3	0.9 €/m^3 2 300 €/ha	Runoff coefficients based on soil infiltration rates, unit prices of stormwater reservoir, avoided cost of runoff purification (costs of reclaimed water)	Zhang *et al*. 2012
Campus forest, Tucson, Arizona, USA	Stormwater benefits	10 900 m^3	0.98 €/m^3	The i-Tree software (canopy interception model); annual savings in municipal infrastructure and maintenance expenses	UACATBA 2012
Campus forest, San Diego, USA	Stormwater runoff reduction	530 000 m^3	0.34 €/m^3	The i-Tree STRATUM hydrology model and stormwater treatment costs	Vargas 2009
Forest in Albuquerque, NM, USA	Avoided stormwater runoff	1.5 million m^3	1.7 €/m^3 73 €/ha	The i-Tree software (canopy interception model)	Davey Resource Group 2014
New York municipal forest, USA	Stormwater runoff reduction	3.4 million m^3	8 €/m^3 6 000 €/ha	Numerical simulation model (annual rainfall interception by trees, throughfall and stem flow) and stormwater management control costs	Peper *et al*. 2007
Modesto municipal forest, California, USA	Stormwater runoff reduction	292 000 m^3	1.8 €/ m^3	A numerical interception model (rainfall intercepted by trees, throughfall and stem flow), expenditures on stormwater quality and flood control program	McPherson *et al*. 1999
Washington DC Metropolitan Area, USA	Stormwater runoff reduction	27 million m^3	200 €/m^3 70 400 €/ha	The CITYGreen software with modelled runoff, avoided cost for storage of stormwater in retention ponds (30-year construction cycle)	American Forests 2002
Forest in Montgomery, Ala., USA	Stormwater runoff reduction	6.4 million m^3	56 € per m^3, 26 500 €/ha	CITYgreen software with modelled runoff and local 20-year construction cycle costs	American Forests 2004
Forest in Albuquerque, NM, USA	Stormwater runoff reduction	570 000 m^3	155 € per m^3, 32 500 €/ha	CITYgreen software with modelled runoff and local construction costs	American Forests 2009
The greenbelt in Hangzhou city, China	Water regulation	4.38 million m^3	10 €/m^3	The CITYGreen software with empirical model	Zhang *et al*. 2006, rep. by Jim & Chen 2009
Philadelphia (PA), USA	Stormwater retention value	14 million m^3	(1) 0.3 €/m^3; 1 200 €/ha; (2) 24 €/m^3 100 850 €/ha	Runoff calculated by the model, annual budget for water treatment (1) and one-time capital costs associated with constructing the system to handle single	PPA 2008

				large storms (2)	
Upper Cahaba Watershed in Trussville, Alabama, USA	Stormwater quantity	not reported	16 €/m^3 (low-density areas) 54 €/m^3 (high-density areas)	WinSLAMM model (hydrology simulation based on comparison of no runoff control with various implementations of stormwater controls), one-time capital costs associated with constructing stormwater controls	McKinney 2009

Many previous studies have used annual urban runoff management costs (e.g. PPA 2008; Vargas 2009), or a combination of treatment and construction costs (e.g. McPherson *et al.* 1999; Zhang *et al.* 2012) as a basis for ecosystem service benefit calculations. Nevertheless, our study reveals surprisingly similar values for annual benefits, despite the very different approach: the estimated annual cost of controlling runoff is ca. 1.1 € m^{-3} for High catchments, and ca. 0.7 € m^{-3} for Low catchments, which leads to approx. 3 000 – 8 000 € ha^{-1} annual savings in High catchments and 3 500 € ha^{-1} in Low catchments, if the total life cycle of a substitute is assumed to be 40 years. However, we expect that the ESV revealed here is more compatible with studies where construction costs are applied. For instance, studies reported by American Forests (2002, 2004, 2009) applied the CITYgreen model, resulting in a cost of controlling runoff compatible to, or exceeding those of the current study, while the ESV expressed as € ha^{-1} is still much lower. The ESV proposed by PPA (2008) – when one-time construction costs are considered – and McKinney (2009) is closest to the ESV calculated in our research.

In general, our findings highlight how leaving pervious areas unconstructed results in greater savings in more intensive land-use areas. This is further supported by the decreasing cost-effectiveness of conventional stormwater systems in catchments of higher land-use intensity. As the ESV in our research reflects the avoided infrastructure costs, these savings will grow with time, due to the increasing avoided annual O&M costs of conventional stormwater systems (Table 7).

Preserving urban green areas can result in even greater monetary benefits than described above. Whereas our research concentrated only on urban runoff volume, benefits from improved water quality comprise the largest share of overall benefits (Braden & Ando 2011). Furthermore, green spaces comprise both direct use and indirect use values. Direct use values include benefits related to the protection of habitats and preserving site biodiversity (Angold *et al*. 2006; McKinney 2008; Klaus 2013), enhanced recreational opportunities and aesthetic values (Casado-Arzuaga *et al*. 2014). Indirect use values include energy savings and reducing temperature extremes (Rosenfeld *et al*. 1998; Akbari 2002; Gill *et al.* 2007), carbon sequestration (McPherson 1998; Akbari 2002; Nowak & Crane 2002), contribution to groundwater recharge (Zhang *et al*. 2015), increased property value

(Payton *et al*. 2008) and health benefits (Maas *et al.* 2006; Gidlöf-Gunnarsson & Öhrström 2007). In addition, various other costs, although not taken into consideration in our study, accrue when an area gets sealed. These costs can be significant: for example maintenance and repaving costs of streets in 2011 were in average ca. 44 000 € ha^{-1} in Helsinki and 14 000 € ha^{-1} in Lahti (Rapal Oy 2012). One-time recognition of these costs further increases the ecosystem value of urban green space by 5 – 40%, assuming the entire green space becomes paved.

Overall, urban green spaces effectively perform the functions of conventional stormwater and runoff management approaches, as the EPA (2014) among many others have noted. Construction and management costs of such urban green spaces depend on the type and location of the green area. Despite continuing anthropogenic disturbances to urban green space, the preservation of urban green space appears to result in higher monetary benefits at higher land-use intensity. Although this may challenge the common trend aimed at densifying city infrastructure, preserving pervious areas in the city may serve as a proactive policy when developing sustainable cities. The economic significance of urban green space provides a rationale for the preservation of ecosystem services, especially taking into account their high potential in climate change adaptation (van Zoest & Hopman 2014), as well as the increasing need for the resizing and renovation of older conventional stormwater systems in the near future (Aaltonen *et al.* 2008; Nurmi *et al*. 2013).

4.2. Factors affecting the reliability of our ESV calculations

ESV was calculated as a direct function of the cost of controlling runoff, which, in turn, depends on catchment drainage density, structure of the drainage system, pipe diameter and TIA (see eq. 1, 2, 3). In our study, ESV was influenced by site-specific characteristics of the infrastructure, such as pipe diameter (L1, H2), and higher than expected drainage density (in L2). Similarly, the configuration of the entire stormwater pipe system and disposition of the collector pipe may affect pipe size and cost. As these factors may impact the correlation between TIA (%) and drainage density (km km^{-2}) (see Table 1), it is likely that ESV is also sensitive to these factors.

Seasonal variation in precipitation patterns controlled runoff values, thus affecting the subsequent ESV (Tables 4, 5, 6, 7). All studied catchments received more than 50% of their annual precipitation during the warm period. In L1, more than 60% of measured annual runoff occurred during the warm period (Valtanen *et al.* 2013), which may explain the higher runoff coefficient (0.74) during the warm period compared to the annual runoff ratio (0.54). In the Helsinki catchments, the importance of spring runoff (Taka 2012) was manifested by higher annual runoff

compared to runoff during the warm period. However, evapotranspiration was higher during the warm period, enabling all catchments to manage a higher proportion of the total precipitation (Table 4). This corroborates findings by Sillanpää (2013), who reported higher evapotranspiration losses during the warm period compared to the cold period. Reduced infiltration due to frozen soils and suppressed evapotranspiration demand during the cold period posed a slight but straightforward negative effect on ESV for the whole year in all catchments. As such, the unexpectedly low runoff measured during the entire year in L1 could be due to factors such as snow removal, leading to an overestimation of ESV for the year. This suggests that when catchments at the city core are concerned, the modelling approach may give more reliable predictions of ESV in cold climates.

Similarly, the surprisingly low runoff ratios measured in H1 indicate the vast capacity of pervious surfaces in managing urban runoff, especially during the warm period. However, the modelled results imply that urban cores with low proportions of pervious surfaces and with highly dispersed and efficiently managed green spaces are unlikely to have high runoff infiltration or evaporation capacities. Furthermore, the probe measuring runoff flow in H1 was occasionally covered with suspended material, which influenced the flow results. Moreover, it cannot be ruled out that a proportion of runoff escaped from this catchment outside the studied discharge point. The amount of remaining water managed by green space might also be overestimated due to snow ploughing. In cold regions, the local hydrology is commonly affected by the collection and transportation of snow out of the catchment. Since the influence of snow removal is challenging to estimate, it was excluded from the analysis.

Evapotranspiration is significant when considering water and heat balances of urban areas (Grimmond & Oke 1999). However, evaporation from impervious surfaces is frequently ignored in ESV calculations; the proportion of rainwater retained in surface depressions and evaporating afterwards can be notable and decrease runoff (Douglas 2011). Here, our model-derived results imply that evaporation from impervious areas was up to 835 m^3/ha/a, influencing the urban water balance and the ecosystem service value of urban green space. For example, including evaporation in our model calculations decreases ESV in L1 by ca. 40% and in H1 by ca. 20%.

The studied warm period (June - November) differs slightly from the growing season (April-October) in southern Finland, when radiation and evaporation are at their highest. This may explain the comparatively low values of evaporation, and the small difference in evaporation between the warm and annual periods. Evaporation values were based on Shuttleworth's (1993) reference crop

evaporation equation, which was scaled down during model calibration, and refers to the uncertainty of using the reference crop evaporation equation developed for latitudes further south than Finland (see Turunen *et al*. 2015). The model simplified the actual processes occurring at the catchments, and only considered pervious and impervious areas as lumped entities. However, despite these simplifications, we assume that the calibration against measured warm period runoff coefficients of the Lahti catchments provided sufficiently accurate estimates of evaporation.

As with any research attempting to combine ecological and economic datasets, our analysis is prone to simplifications that may affect the interpretability of the final results. However, by applying the replacement-cost method, we attempted to meet conditions that would ensure reliable value estimations, as proposed by Shabman & Batie (1978). As such, our study presents a valid attempt to evaluate the relationship between the amount of retained runoff, green space in urban settings, and subsequent ESV. However, additional information is needed before more detailed estimates of the monetary benefits of urban green space can be given. Moreover, improved methods to estimate evaporation rates from various urban surfaces are needed, together with a cost-benefit analysis to facilitate the justification of the investment decisions allocated to urban runoff management (McPherson 1992; Pataki *et al*. 2011). Although in this paper we have addressed urban green space in general, it would be beneficial to refine the value estimations to consider urban runoff management solutions provided by different types of green spaces, such as semi-natural and multifunctional green areas (e.g. rain gardens or retention basins). For instance, in Finland, semi-natural runoff management solutions would perhaps be cheaper in new housing areas, when some remaining nature within the area can be saved and used for runoff management. However, such solutions are often difficult to implement in older constructed areas, where retrofitting would be needed. Ultimately, we emphasize the importance of multidisciplinary studies in fully understanding the interdependencies of various sociological, ecological and economic factors that determine the real value of the ecosystem service of urban runoff management, as suggested by Troy *et al*. (2015).

5. Conclusions

The numerical approach to monetary value of urban green space provides a simple method by which the many services and disservices of these spaces can be evaluated. Our study used the replacement-cost ecosystem service valuation method to facilitate decision-making by highlighting

appropriate and environmentally favourable urban planning strategies. Results clearly show that urban green space of different sizes provides monetarily-measurable ecosystem services related to urban runoff management. Furthermore, we indicated that the preservation of green space results in significantly higher savings in catchments of higher land-use intensity compared to areas of lower land-use intensity. The ecosystem service value proved to be higher during the warm period, reflecting the larger evapotranspiration demand during warmer periods. Conosequently, this study proposes that the effects of evaporation from impervious surfaces influence ecosystem services, and thereby merits more attention. Finally, the study provides a concrete example of how to combine field data with computational hydrologic and monetary analyses to support decision making in urban planning under cold climatic conditions.

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