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Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?

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Abstract

During the last two decades, a large amount of research has been published in German on the reduction of rainwater runoff for different types of roof greening. This paper analyzes the original measurements reported in 18 publications. Rainfall–runoff relationships for an annual and seasonal time scale were obtained from the analysis of the available 628 data records. The derived empirical models allowed us to assess the surface runoff from various types of roofs, when roof characteristics and the annual or seasonal precipitation are given. The annual rainfall–runoff relationship for green roofs is strongly determined by the depth of the substrate layer. The retention of rainwater on green roofs is lower in winter than in summer. The application of the derived annual relationship for the region of Brussels showed that extensive roof greening on just 10% of the buildings would already results in a runoff reduction of 2.7% for the region and of 54% for the individual buildings. Green roofs can therefore be a useful tool for reducing urban rainfall runoff. Yet in order to provide a greater effect on overall runoff they should be accompanied by other means of runoff reduction and/or water retention.

Keywords: Green roof; Roof greening; Water retention; Urban hydrology; Runoff; Germany; Models; Vegetative roofs; Ecoroof

1. Introduction

In developed countries, the level of urbanization is still rising and expected to reach 83% in 2030 (United Nations, 2002; Antrop, 2004). Cropland, grassland and forests are displaced by the impervious surfaces of streets, driveways and buildings greatly intensifying storm water runoff, diminishing groundwater recharge and enhancing stream channel and river erosion (cf. Stone, 2004). This ongoing urbanization involves an unsustainable use of natural systems and creates numerous problems both within and outside cities. One of the major environmental problems of urbanization is that the urban hydrological system has to cope with a highly fluctuating amount of surface runoff water which may become extremely high during periods of rainfall and remains low during the rest of the time (cf. White, 2002). Climate change may further increase these fluctuations. In particular, the flood risk will

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further increase (e.g. Environment Agency, 2002; Villarreal et al., 2004). Tools for reducing the high runoff during rainfall and to increase retention include storage reservoirs and ponds where water can be temporary stored (Ferguson, 1998; White, 2002) and green areas where water can infiltrate and evaporate. However, this means a redesign of the urban hydrological system so that it again plays a more active and positive role in the natural hydrological cycle. The creation of more green areas is also an answer to the recent calls for a more ecological and greener urbanization (cf. Onmura et al., 2001; White, 2002; Van Herzele and Wiedemann, 2003; Dunnett and Kingsbury, 2004). Unfortunately, the high amount of impervious surfaces (Blume, 1998; Ferguson, 1998) and the high land prices make the creation of green areas in urban regions very expensive if not impossible. Given the huge amount of unused roof area (about 40–50% of the impermeable surfaces in urban areas (cf. Dunnett and Kingsbury, 2004)), green roofs – also known as rooftop gardens or vegetative roofs or even ecoroofs – may be an interesting alternative. Thanks to their water storing capacity, green roofs may significantly reduce the runoff peak of the most rainfall events. The reduction consists in: (i) delaying the initial time of runoff due to the absorption of water in the green roof system; (ii) reducing the total runoff by retaining part of the rainfall; (iii) distributing the runoff over a long time period through a relative slow release of the excess water that is temporary stored in the pores of the substrate. Fig. 1 illustrates the reduction in peak runoff from a green roof, as observed in Belgium during a rainstorm. Green roofs may also have an impact on the heat island effect of urban areas through increasing evapotranspiration of water (Ernst and Weigerding, 1985; Von Stülpnagel et al., 1990; Bass et al., 2002) and may reduce the energy cost for cooling and/or heating of buildings (Takakura et al., 2000; Niachou et al., 2001). The heat island effect, which results in higher air temperatures and lower air humidity compared to that in the surrounding areas, is considered to reduce the living quality in the cities (Niachou et al., 2001).

In some highly urbanized societies like Japan, Singapore, Germany and Belgium the advantages of green roofs have already resulted in incentives from the government to encourage or even impose the use of green roofs (see Osmundson, 1999; Wong et al., 2003; Dunnett and Kingsbury, 2004).

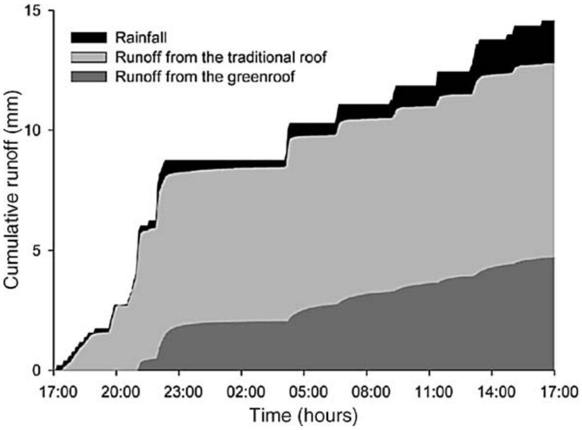

Fig. 1. Typical cumulative runoff from a non-greened roof and an extensive green roof as observed in Leuven (Belgium) during the 24 h period of a 14.6 mm rain shower (April 2003, 5 p.m.–5 p.m. on the next day). Both roofs had a slope of 20°.

Green roofs basically consist of a vegetation layer, a substrate layer (where water is retained and in which the vegetation is anchored) and a drainage layer (to evacuate excess water) (see, e.g. Mentens et al., 2003). Based on the depth of the substrate layer two main types of green roof are usually distinguished in Europe (Krupka, 1992; Kolb and Schwarz, 1999):

- Extensive green roofs with a substrate layer with a maximum depth of about 150 mm. *Sedum* species usually make up the major part of the vegetation. This type may also be installed on sloped surfaces. The slope angle can be as high as 45°.
- Intensive green roofs with a substrate layer with a depth of more than 150 mm. Grasses, perennial herbs and shrubs make up the main constituents of the vegetation. Intensive green roofs are typically installed on roofs with a slope of less than 10° and, depending on design and access, they may be used as roof gardens.

Since the first mentioning of the water retaining capacity of green roofs in the German literature in 1985 (Ernst and Weigerding, 1985), several European scientists have studied the relationship between precipitation, roof properties and runoff. The studied time period and roof characteristics vary widely in the consulted literature. In the last couple of years, two papers (Kolb, 1998; Mann, 2000) summarized part of the existing literature. However, the authors did not re-analyze the data to derive empirical models of the rainfall–runoff relationship for green roofs. The latter may be useful for prediction purposes and in urban planning. This paper aims at quantifying the potential of green roofs in reducing the surface water runoff. Therefore, a review of the available European literature was conducted to establish empirical relations between runoff, rainfall and roof characteristics and this for various time scales (annual, seasonal and rain storm event). As an example, the derived models were then applied to Brussels to quantify the potential runoff reduction by roof greening for the city region, the inner city and individual buildings. Furthermore, some conclusions for urban planning were drawn.

2. Material and methods

A literature review was undertaken to collect as much data as possible on measurements of runoff from green roofs. Most of the research has been done in Germany, so the core of the literature data comes from Germany. For some aspects, also data from the surrounding countries have been used (e.g. Fig. 1). As such comparable climatic conditions could be assumed. The main source of information was the German journal “Dach + Grün”. Original measurements were reported in 18 publications (Table 1) from which we collected 628 records in a database. To extend the data set as much as possible, data were extracted from graphs if the exact numbers were not given. Each record consists of two parts. The first part covers the roof properties (substrate type: non-covered, gravel, green roof; substrate depth (mm); number of layers; slope (%); slope length (mm)). The second part relates to the precipitation and corresponding runoff at one or more of three time scales: annual, seasonal and rainstorm events. The following precipitation characteristics have been included: intensity (mm h^{-1}); time span of rainstorm (min); total runoff during time span of rainstorm (mm); total amount (mm); peak runoff (mm).

In the literature reviewed, data on annual and seasonal runoff were obtained from field measurements, whereas runoff data from rainstorm events were the result of controlled experiments. According to German guidelines (Lösken, 2002), a rainstorm is defined as a rainfall of 300 l s^{-1} ha^{-1} during 15 min, being 27 mm in 15 min. Peak runoff during a rainstorm event is defined as the amount of runoff during the last 5 min of the rainfall (W. Kolb, personal communication). This

Table 1
Summary with some basic characteristics of reviewed publications on water retention from green roofs

Author (year)	No. of roofs	Substrate (mm)	Roof slope (%)	Location	Yearly precipitation (mm)	No. of years	Seasonal data	Rainstorm intensity (mm h^{-1})
Kaufmann (1999)	8	100	2	Burgdorf	920–1347	4	Yes	80–130
Kolb (1987)	3	60–120	0	n.r.	–	–	–	208–222
Kolb (1998)	13	0–500	0–58	n.r.	–	–	–	11–350
Kolb (1999a)	12	100	2–84	n.r.	–	–	–	150–300
Kolb (1999b)	36	90	2–84	n.r.	–	–	–	100–300
Kolb (2002)	9	0–100	2	n.r.	–	–	–	200–300
Kolb (2003)	6	20–100	27	n.r.	–	–	–	300
Liesecke (1989)	8	30–180	3	Hannover	644	3	–	27.8
Liesecke (1993)	24	70–180	2	Hannover	554–628	5	Yes	–
Liesecke (1994)	7	0–120	2	n.r.	–	–	–	300
Liesecke (1998)	18	0–380	2	Hannover	644	–	Yes	300
Liesecke (1999)	8	0–120	0–9	Tornesch	712–918	3	–	300
Liesecke (2002)	10	100	2	Hannover	533–657	4	Yes	–
Mann (2000)	2	150	2–27	Marsberg and Heilbron	–	–	–	–
Mann (2001)	1	100	2	Tübingen	–	–	–	–
Mann (2002)	16	100	0–2	Throughout Germany	587–930	–	–	–
Mann and Henneberg (1998)	7	0–350	0–27	Unknown	–	–	–	–
Mann et al. (2000)	22	0–350	0–27	Krauchenwies-Göggingen	670	1	Yes	–

n.r., not relevant for the time level on which measurements were made; these references refer to experimental work; –, not available.

runoff divided by the rainfall during 5 min gives the percentage of runoff.

Analysis of variance (ANOVA) was used to identify the significant factors in the data set (Neter et al., 1996). Linear regression was performed separately for every time scale. Due to the large amount of independent variables and the amount of missing data, the ANOVA could not always be applied with all variables and in such a case several approaches were taken like using only the assumed, most important variables or taking subsets of the data set. In order to make sure that the used statistical methods were valid, the assumptions of the linear model were checked: normality of the error terms was checked using the Kolmogorov–Smirnov and the Shapiro–Wilk tests, while the equality of variance was checked visually on a plot of predicted values versus residuals. Where the requirement of normality was not met, second-degree factors were calculated and added in the ANOVA. This was always sufficient to normalize the data, so transformations were not necessary. These second-degree factors were first standardized to avoid problems with multicollinearity. All statistical analyses were done using the statistical software package SPSS 11.0.

To illustrate the effect of green roofs on the runoff reduction in an urban environment, an example is presented for Brussels (Brussels Capital Region, Belgium) for which detailed land cover data are available (Gryseels, 1998). The macroclimate is largely comparable to the German climate. The mean annual rainfall of 821 mm for Brussels fits well in the range for which the rainfall–runoff relationship was established (Table 3). The city region is a relatively green urban area with a lot of gardens, parks and forests, which cover about 50% of the total area. Buildings occupy only 26% of the total area. However, the built-up area strongly differs between the city centre, where greenery is sparse and buildings occupy about 60% of the area, and the outer limits of the region (southeast) where the Zoniën forest is located (Fig. 5). Annual runoff of the various land cover types varies widely from 0% for water surfaces, forests and public parks, 10% for agriculture and other green zones, 15% for privately owned green, 25% for recreational zones and 90% for roads, parking areas and buildings (cf. Kuttler, 1998; Dunnett and Kingsbury, 2004). Using the percentages of runoff for the several land cover types, the area of the different land cover classes and the mean annual rainfall the total annual runoff was estimated at 61.4×10^9 l. To estimate the potential reduction of the runoff by greening the roofs, the following assumptions were made:

- 10% of the buildings may have an extensive green roof. This percentage is quite realistic if one considers that this is less than the current percentage green roofs out of all new roofs in Germany (Köhler, 2003).
- A substrate layer of only 100 mm is assumed. This type of extensive green roof can be installed on almost all roof slopes.

3. Results

3.1. Annual runoff

An overview of the annual runoff from roofs (Table 2) presented in the existing literature clearly demonstrates that the runoff is mainly determined by the roof type and may be as high as 91% for a traditional non-greened roof and as low as 15% for an intensive green roof (see also Fig. 2). The annual precipitation, type of roof, number of layers and depth

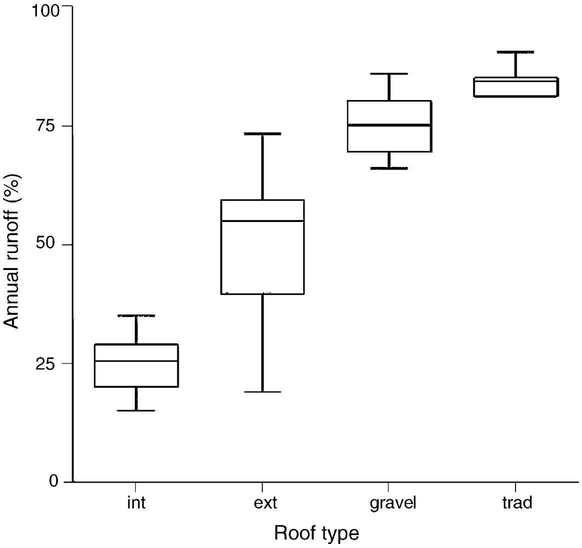

Fig. 2. Annual runoff for various roof types as a percentage of the total annual rainfall; respectively, for intensive green roofs (“int”, $n = 11$), extensive green roofs (“ext”, $n = 121$), gravel-covered roofs (“gravel”, $n = 8$) and non-greened roofs (“trad”, $n = 5$). The box plots show the total range of the data (after removal of outliers), the 25 and 75% percentiles and the median.

Table 2
Substrate layer depth (mm) and runoff (% of total annual precipitation) characteristics of the literature data set on an annual level

	Intensive green roof ($n = 11$)	Extensive green roof ($n = 121$)	Gravel-covered roof ($n = 8$)	Non-greened roof ($n = 5$)
Substrate layer Depth (mm)				
Minimum	150	30	50	/
Maximum	350	140	50	/
Median	150	100	50	/
Average	210	100	50	/
Runoff (%)				
Minimum	15	19	68	62
Maximum	35	73	86	91
Median	25	55	75	85
Average	25	50	76	81

Table 3
Regression equations and proportion of the total variation explained by the regression (R^2) of the annual surface runoff (RO) on the yearly precipitation (P) for various roof types for a given rainfall range

Roof type	Rainfall range (mm)	Runoff (RO, mm year^{-1})–rainfall (P, mm) relationship	R^2	N
Non-greened roof	670–918	$\mathrm{RO} = 0.81P$	0.99	5
Roof with 5 cm of gravel	644–1347	$\mathrm{RO} = 0.77P$	0.99	8
Green roof	554–1347	$\mathrm{RO} = 693 - 1.15P + 0.001P^2 - 0.8 \times \mathrm{S}$	0.78	125

S equals the depth of the substrate layer (mm). The latter varied between 30 and 380 mm.

of the substrate layers are significantly correlated with the yearly runoff ($p < 0.05$), while the age of the green roof, slope angle and length are not significantly correlated with the yearly runoff ($p > 0.05$) (Table 3). The regression equations of annual runoff on rainfall and other variables, as determined from the collected data set, are presented in Table 3; for non-greened roofs, runoff is solely determined by precipitation; for green roofs the depth of the substrate layer is also needed. Fig. 3 shows the relationships for the two conventional, non-living roof types and two green roofs having different substrate depths (50 and 350 mm).

3.2. *Seasonal runoff*

In the reviewed literature, seasons were differently interpreted. As these could not be combined separate analyses were necessary.

Where two seasons (winter (1 October–30 March) and summer (1 April–30 September), cf. Kaufmann, 1999) had been distinguished in the data set, data on a 5 cm gravel roof and a green roof with 100 mm of substrate could be analyzed. Both roof types had a slope of 2%. Pairwise comparisons of the percentage of runoff during the two periods showed that the runoff was significantly higher during winter. This was both the case for the gravel roof (86% winter runoff versus 70% summer runoff) and the green roofs (80% winter runoff versus 52% summer runoff). Re-

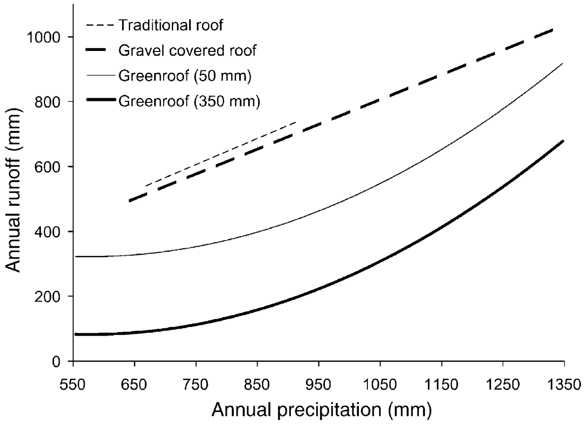

Fig. 3. Relationships between the annual runoff and annual rainfall for various roof types, as estimated from the equations presented in Table 3. The relationship for green roofs is illustrated for a substrate depth of 50 mm and one of 350 mm.

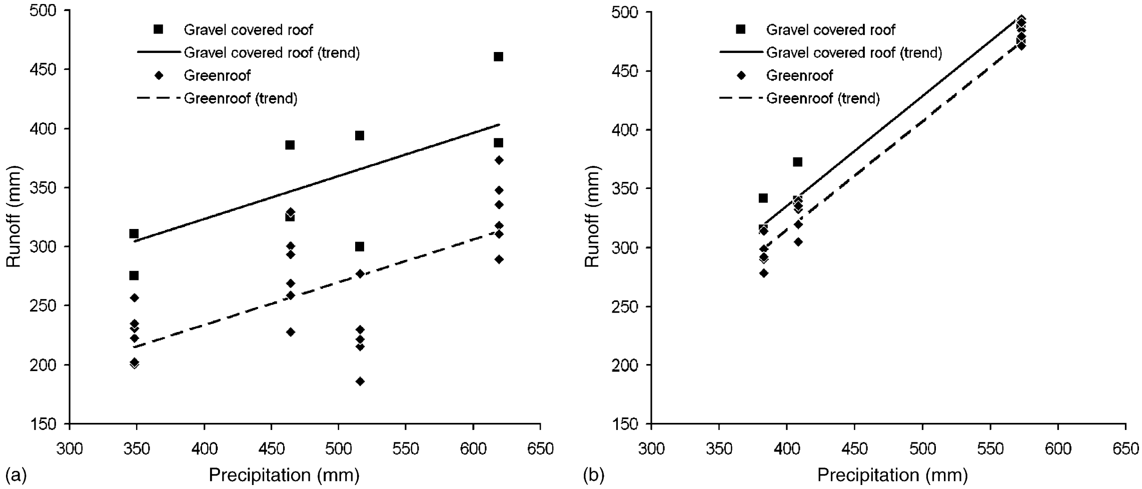

Fig. 4. The relationships of precipitation and runoff on a gravel-covered and a green roof during: (a) summer (regression equation, $RO = 89 + 0.36P + 89G$; $R^2 = 0.64$; $n = 32$) and (b) winter (regression equation, $RO = -61 + 0.94P + 22G$; $R^2 = 0.97$; $n = 24$). RO: seasonal runoff (mm season^{-1}); P: precipitation (mm); $G = 1$ for a roof covered with 50 mm gravel and 0 for a green roof with 100 mm substrate depth.

lationships between rainfall and runoff are shown in Fig. 4.

Where three seasons (warm (1 May–30 September), cold (16 November–15 March) and the combined in-between seasons (16 March–30 April and 1 October–15 November)) had been distinguished in the literature data set (cf. Liesecke, 1993, 1998, 2002), only measurements on green roofs with a slope of 2% could be analyzed. The depth of the substrate varied between 30 and 180 mm. For the in-between and the cold period, no relationship could be found between runoff and substrate depth. During the warm period, one additional centimeter of substrate resulted in 2.5 mm less runoff ($p < 0.05$). However, the proportion of the total variation explained by the multiple regression (R^2) was low (0.157). Substrate depth was divided into several groups that were used as the factor in ANOVA with the percentage of runoff as the dependent variable. The best grouping proved to be a division in three groups (<50, 50–150, >150 mm), whereby the first and third groups have a significantly different percentage of runoff during the warm period (runoff for the three groups is 38, 30 and 20%, respectively, whereby 38% is significantly different from 20% ($p < 0.05$)). Pairwise comparisons between the different seasons were made for the second group (50–150 mm), as measurements for this group were only available for the three seasons. The percentage runoff was significantly different between all seasons ($p < 0.05$). Runoff is 30% for the warm season, 51% for the cool and 67% for the cold season.

3.3. Rainstorm event

For conventional, non-living roofs the literature data were limited to roofs with a slope of 2%. The results showed that 96% of the rainfall runs off from such a roof ($R^2 = 1.00$ and $n = 18$).

Due to data limitations, it was not possible to establish relationships between the roof parameters and runoff during rainstorm events.

3.4. Simulation of the potential runoff reduction for Brussels

Using the equation for green roofs in Table 3 for a mean annual rainfall of 821 mm and assuming that 10% of all buildings get roof greening (100 mm substrate), runoff reduction would be as large as 1.7×10^9 l, i.e. 2.7% of the total estimated runoff (without green roofs) for the city (Table 4). The city centre itself (and in general other more densely built-up areas) had a larger percentage of potential runoff reduction (3.5%) since for the assumed conditions the annual runoff reduction from single buildings is 54% (only 42% versus 90% of total rainfall is lost as surface runoff).

Table 4
Estimated annual runoff reduction in Brussels (Belgium) under the assumption that 10% of the roofs have an extensive green roof with a soil depth of 10 cm

Region	Runoff reduction (%)
Capital region	2.7
City centre	3.5
All buildings	5.4
Single building	54

Total mean annual runoff is estimated at 61.4 × 10^9 l.

4. Discussion

4.1. General (valid for both annual and seasonal time level)

Non-covered and gravel-covered roofs have a much higher runoff than green roofs (cf. Figs. 1 and 2; Table 2). Intensive green roofs, thanks to the storage capacity of their thick substrate layer, are more effective in reducing the runoff than extensive green roofs (Table 2; Fig. 2).

Although the equations (Table 3; Fig. 4) have a high coefficient of determination (R^2), their use is restricted to the specified rainfall range, which is typical for the Western and Central European climatic conditions. An extrapolation to other regions with a different climate may result in wrong estimates due to the importance of the rainfall distribution, intensity and evaporating power of the atmosphere.

4.2. Annual runoff

The rainfall–runoff relationship is linear for non-covered and gravel-covered roofs but includes a quadratic factor (see Table 3) in the case of green roofs. This is because higher annual precipitations interfere with a higher amount of extreme events, for which retention is lower (Madsen et al., 1998). The latter are less retained by green roofs than low intensity rainstorms. On non-living roofs the runoff reduction is so small that the effect of higher precipitation intensities does not affect the rainfall–runoff relationship. Yet for these conventional roofs (both non-covered and gravel-covered) the number of observations in the green roof literature is much smaller than for greened roofs. This is especially the case for non-covered roofs where the number of observations was only five. However, the range for these data was a lot smaller and no second variable had to be taken into account. Therefore, it was acceptable to apply the linear regression analysis.

4.3. Seasonal runoff

The seasonal variation of the rainfall plays a clear role in the retention of runoff. This also follows from the work of Kaufmann (1999), Liesecke (1989,1993) and Villarreal et al. (2004). Warm seasons result in higher evapotranspiration; therefore, the water retaining capacity regenerates faster and the surface runoff from green roofs is smaller for the following rainstorm (cf. Villarreal et al., 2004). As can be seen from Fig. 4, the amount of data on which this regression analysis is based is limited to only a few seasons, resulting in only a limited number of precipitation levels. However, the number of replicates per precipitation level is large enough to justify the use of regression analysis.

4.4. “Rainstorm” runoff

Valid relationships for a rainstorm time scale could not be derived. Since these relationships are also required to study the full effect of green roofs on urban hydrology, either a lot more measurements under various weather conditions are needed and/or a runoff model for green roofs is required. Data are currently being collected at an experimental set-up in Leuven (Belgium). A runoff model is under construction at the KULeuven. This model will make it possible to simulate the runoff from various types of green roofs and for various time scales.

4.5. Estimate of the potential runoff reduction for Brussels

The simulation demonstrates that the use of extensive green roofs, even on only 10% of all roofs in a relatively green urbanized region, already reduces the annual runoff by 2.7%. This reduction is not distributed equally over the entire region because the amount of built-up area varies widely and decreases from the city centre to the outskirts (Fig. 5). The reduction in runoff accomplished by green roofs in the city centre is higher than in the suburbanized areas (Table 4). More green roofs and using green roofs with a deeper substrate

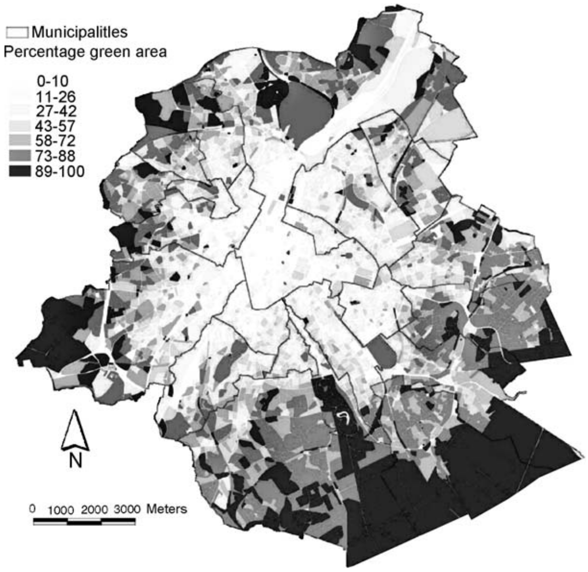

Fig. 5. Percentage of green land cover types in the Brussels Capital Region (adapted from: BIM-IBGE, 2002).

layer would further enhance the effect. It should be noted that the depth of the substrate layer cannot be extended without consequences, while extensive green roofs are virtually maintenance free, the intensive green roofs usually need extra watering during dry periods (during normal periods the larger substrate layer can support a vegetation which requires more water but this vegetation is less resilient to water shortages) and furthermore, they pose construction adjustments to account for the extra load (cf. Krupka, 1992).

5. Conclusions: green roofs a tool for solving runoff reduction?

As an ever-growing percentage of the world's population lives in cities, the displacement of open land by impervious surface of streets, driveways and buildings will intensify rainfall runoff. This will not only increase the risk of flooding but will also threat water resources through pollutants transported from impervious surfaces. Soil surface sealing also influences regional climate and air quality (cf. Environment Agency, 2002; Stone, 2004; Sukopp, 2004). Tools for reducing the high runoff during rainfall and to increase retention include storage reservoirs and ponds, where water can be temporary stored, and green areas, where water can infiltrate and evaporate. One of the benefits of green roofs is their role in rainfall water management. From our review of the literature, it is clear that rainfall-retention capability on a yearly basis (Table 2) may range from 75% for intensive green roofs (median substrate depth: 150 mm) to 45% for extensive green roofs (median substrate depth: 100 mm). The magnitude of the retention depends on the structure of the green roof (the amount of layers and their corresponding depths), the climatic conditions and the amount of precipitation. Quantitative relationships between annual rainfall and annual surface runoff could be obtained from an analysis of the collected literature data (Table 3).

From the analysis on a seasonal level, it was shown that the retention is significantly lower in winter than in summer (Fig. 4). This results from differences in evapotranspiration and in rainfall distribution.

Data on the time level of a rainstorm event are currently insufficient for statistical analysis. Clearly, much more research is needed here. The peak runoff reduction at such small time scale could have an effect on the design of sewage systems.

Under a modest scenario of 10% of Brussels' roofs to be greened with an extensive green roof (100 mm substrate depth), the runoff reduction can easily be 2.7%. Although this looks rather small, we should be aware that the benefits of green roofs are many and varied, as was found using an integrated cost-benefit analysis of green roofs in Toronto (Peck, 2003).

Villarreal et al. (2004) assessed the effect of disconnecting impervious areas from a combined sewer in favour of a new open rainfall management (including open channels, ponds and green roofs) in Augustenborg, an inner city high density housing suburb of Malmö (Sweden). They found that it not only improved storm water management in the area, but also the performance of the combined sewer system that serves the surrounding area. They further found that while green roofs are effective at reducing overall flow volumes, they were not so good at reducing storm flow peaks. All this agrees well with our experience. They also pointed to an important advantage of green roofs over ponds and open channel systems: green roofs do make use of previously unused space and thus, do not limit the demands of the people for "open space" on the ground.

However, it is clear that roof greening alone will never fully solve the urban runoff problem and it needs to be combined with other runoff reduction measures (e.g. storage reservoirs in urban green or under infrastructure, rainwater cisterns, an increase of green areas). Models integrating all these on various time scales are clearly needed if we really want to predict runoff for more efficiently!

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