Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.21551

99 (2017) 4–9
December

Design, calculations and performance evaluation of rain gardens in an urban neighborhood of Thessaloniki, Greece

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Received 25 November 2016; Accepted 22 March 2017

ABSTRACT

Rain gardens are engineered gardens, designed to harness the natural ability of vegetation and soils to store and treat storm water. This paper deals with site selection, design and performance evaluation of rain gardens, using an urban neighborhood of Thessaloniki, Greece, as case study. The neighborhood is close to the city centre and suffers from street and sidewalk inundation during rain events of medium intensity. Selection of eight rain garden sites, based on qualitative criteria, is discussed and further supported by preliminary calculations, regarding local sewer efficiency and rain runoff. Moreover, design of certain technical features is discussed, taking into account large street slopes, typical of the study area.

Keywords: Rain garden; Inflow structure; Sewer network; Urban rainwater management; Thessaloniki

1. Introduction

Urbanization has a negative impact upon water resources, increasing the flood risks and the need for an integrated flood risk management [1,2]. Integrated urban rain water management combines the classic approach, namely that of fast diversion of rainwater from urban areas (through a pipe system), with low environmental impact techniques (or sustainable drainage systems), such as rain gardens, green roofs, and permeable pavements and sidewalks, which aim at: (a) reduction of the total outflowing amount of water, (b) reduction of peak outflows, (c) utilization of rain water in secondary uses that do not require high-quality water, (d) improvement of the urban environment and (e) improvement of the quality of outflowing water and, essentially, reduction of damage, or nuisance, caused by insufficient sewer networks. In this paper, application of rain gardens in a neighborhood of Thessaloniki, the second largest city in Greece, is discussed.

2. Brief description of rain gardens

Rain gardens appeared, or rather were described and scientifically analyzed for the first time during the 1990s in the United States. They are the most important method of ecological rainwater management for urban and suburban areas. The main parts of a typical rain garden are the following [3–5]:

- The ponding area: It is a natural or artificial ground depression. In rather flat areas, it is constructed simply by soil excavation. In sloping ground, excavation material can be used to construct an earth berm at the downslope side. Surfaces with large slope are not that suitable for rain garden construction.
- Inflow structure that directs rainwater from downspouts or impermeable areas (streets, sidewalks) to the ponding area.
- Outflow structure that allows water to exit the rain garden, when the ponding area is full. This structure is

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Presented at the conference on Efficient and Sustainable Water Systems Management toward Worth Living Development, 2nd EWaS 2016, Chania, Greece, June 1–4, 2016.

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necessary in order to reduce erosion risk and to direct outflowing water towards the local sewer network, or another, properly selected, place.

Plants (preferably native ones) that can tolerate periodic inundation are also an integral part of rain gardens, since they contribute to (a) upgrading the local urban landscape and (b) retention of certain pollutants, which results in improvement of rain runoff quality [6–8].

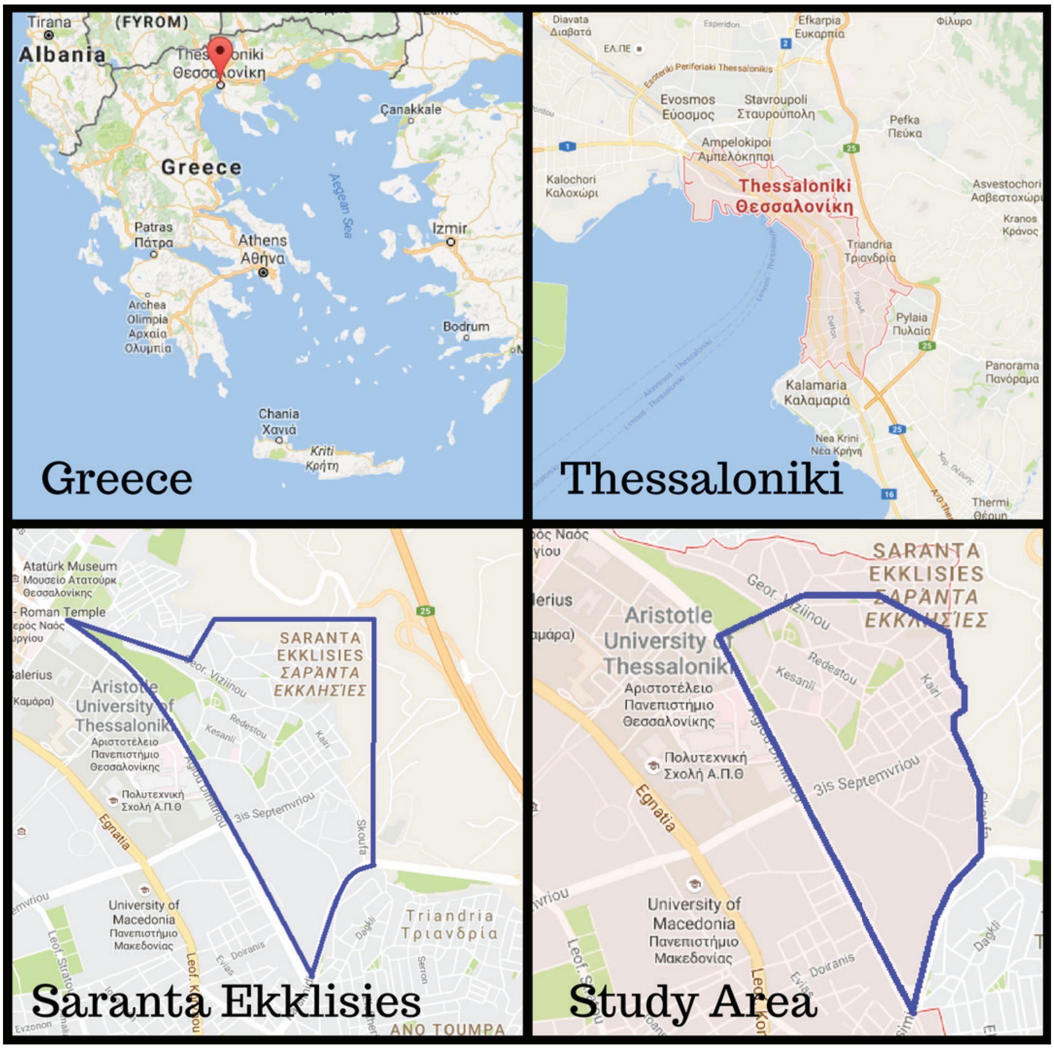
3. The area of interest

The area, which has served as case study in this paper, is depicted in Fig. 1 (which is based on Google maps). It is located in Thessaloniki, the second largest city of Greece, at a short distance from its centre. It covers the largest part of the neighborhood of Saranta Ekklisies, namely an area of approximately 450,000 m^2. Thessaloniki metropolitan area is not prone to major floods. Many of its neighborhoods, though, including the study area, suffer from damages, caused by medium rain events, in particular where ground slope changes abruptly.

The neighborhood of Saranta Ekklisies has been initially developed in the 1920s, with one- and two-storied houses, in order to host Greek refugees from Eastern Thrace. It has been redeveloped mainly after 1980, when old small houses were replaced by larger, mainly three-storied ones and the population increased accordingly. Still, it has not merged with the city centre, from which it is separated by a small grove and the main campus of Aristotle University of Thessaloniki.

One of the neighborhood assets is that there are more green spaces, compared with the city centre. Another characteristic is sloping ground surface, which is both an asset and a drawback. With regard to rainwater management, it is clearly a drawback, since it results in quick rain runoff concentration to lower spots with small slope. A prominent example is the Agiou Dimitriou Street, which separates Saranta Ekklisies from the University campus and a major hospital. On the other hand, existence of more green spaces is definitely an asset, from the aforementioned point of view.

Regarding sewer infrastructure, the area is served by the Water Supply & Sewerage Co. of Thessaloniki S.A. (EYATH S.A.). A drawback, common with most of the city centre, is that the inlets to the storm water sewer system are not adequate.



Greece

Thessaloniki

Saranta Ekklisies

Study Area

Fig. 1. The study area in Thessaloniki, Greece (based on Google maps).

As a result, rain runoff takes place mostly on the impermeable street and sidewalk surfaces, even during and after rain events of medium intensity. Construction of rain gardens in Saranta Ekklisies could contribute greatly in alleviating this problem, as discussed by Katsifarakis et al. [9,10]. Selection of rain garden sites in less than half of the current study area has been investigated in a previous work of the authors of this paper [11]. The findings have been incorporated in this work as well.

4. Selection of rain garden sites in the study area

Selection of sites that are suitable for rain garden construction is a challenging task in densely built areas. Our approach has been based both on map inspection and on field survey during rain events. Selection criteria included the following:

- Expected efficiency, with regard to current rain runoff problems, the local car traffic load, the pedestrian flows and the local sewer network.
- Land ownership – we have restricted site selection search to public and municipal plots only.
- The relative location of the selected sites and their distribution over the study area.
- Observance of the required smallest distance between rain gardens and adjacent buildings.
- Anticipated cost and efficiency of required inflow structures.

Based on the aforementioned criteria, the following sites have been selected in the study area:

- Location K1: This site is a park, which is sloping towards Agiou Dimitriou Street and located next to its junction with St. Kyriakidi Street. This junction is shown in the photo of Fig. 2, after a short, yet intense, rain event. All streets around the park are transformed to shallow streams during such events and the sewer system fails, at least locally. Additional reasons, besides severity of street and sidewalk inundation, that support selection of this site, are heavy traffic load along both streets and vicinity to a major hospital. The proposed rain garden area is approximately equal to 2,400 m^2.
- Location K2 (at the junction of Raidestou and Anaktoriou Streets): This site is a small park next to a street with large slope, which transfers considerable amounts of rainwater during rain events. Its area is equal to 33 m^2 and its selection contributes to a more even distribution of rain gardens in the study area.
- Locations K3, K4 and K5 have been selected, due to their vicinity to a private hospital and Student Dormitories A and C, which are the highest buildings in the study area. K3 is a small park, located between the entrance of the hospital and the entrance of Dormitory C, park K4 is next to the entrance of Dormitory A and K5 is close to its eastern side, along a street with large slope. The proposed rain gardens' area is approximately equal to 270, 360 and 1,540 m^2, respectively. Sites K1 to K5 are marked with red color on the map of Fig. 3, while the dormitories and the private hospital are marked with green.
- Location K6 (opposite of the Student Dormitory A on Levanti Street): This site is a small park opposite of the rain garden K5. The proposed rain garden area is equal to 250 m^2. Together with site K5, it will alleviate the problem at the junction of Levanti and St. Kyriakidi streets, which bears a heavy traffic load.
- Location K7 is part of the bed of a stream portion, which has survived urbanization. Its current hydraulic function is quite restricted, so its bed is suitable for rain garden construction [9]. The reasons for selecting this site are (a) Tritis Septemvriou Street, running along the stream bed, has a large slope and it is transformed to a shallow stream during medium intensity rain events, as it receives runoff of other streets, as well, (b) car traffic is very heavy close to its junction with Agiou Dimitriou Street and (c) inlets to the sewer network are too few. The proposed rain garden area is equal to 5,500 m^2. Sites K6 and K7 are marked with red color on the map of Fig. 4.
- Location K8, shown on the map of Fig. 5, is a green space, rather inaccessible to the public, between the Kaftanzogleion Sport Center and Katsimidou Street. This street runs all the way from Thessaloniki ring road to Agiou Dimitriou Street (and further, towards the sea). It has large slope and very heavy car traffic. For these reasons, alleviation of rain runoff problem is quite important. Moreover, diverting rain runoff to the proposed rain garden site may contribute to the recharge of the local shallow aquifer, used for irrigation of sport installations.

Fig. 2. Junction of Agiou Dimitriou and St. Kyriakidi Streets during a short, intense rain event.

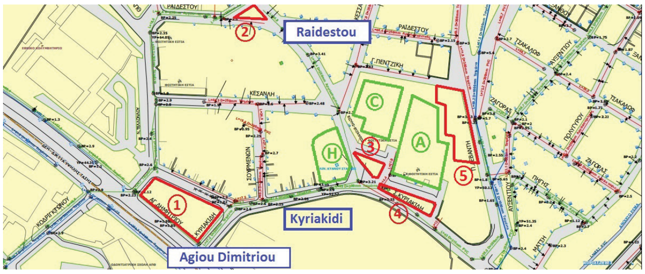


Fig. 3. Map showing selected rain garden sites K1 to K6 (based on EYATH map).

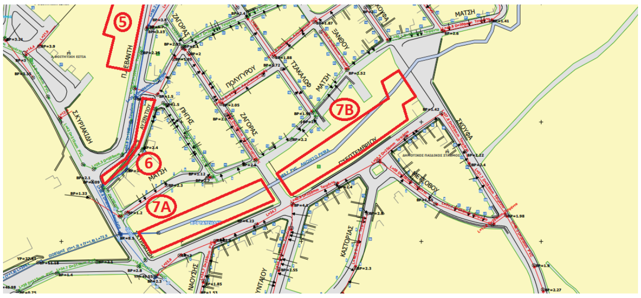


Fig. 4. Map showing selected rain garden sites K6 and K7 (based on EYATH map).

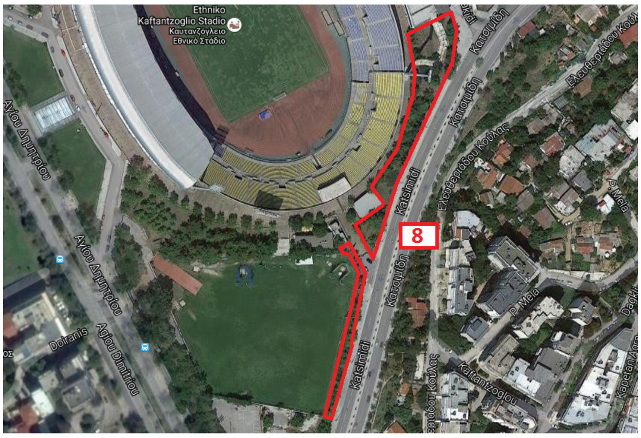


Fig. 5. Map showing selected rain garden site K8 (based on Google maps).

Efficient combinations of flood mitigation with aquifer replenishment have been reported both in urban and rural areas [12]. The proposed rain garden area is approximately equal to 1,200 m^2.

5. Indicative calculations of local sewer network and rain garden efficiency

Rain gardens are not substitutes to sewer networks, but rather complementary with them. Their incorporation into urban rainwater management systems may even lead to net financial benefit, due to possible decrease in sewer network expansion and maintenance cost, and in the operation cost of sewage treatment facilities [13]. In a way, selection of rain garden sites is related to the inefficiencies of local sewer network system.

EYATH S.A. provided us with maps, partially shown in Figs. 3 and 4. They include details on the local network, which consists of storm water sewers (blue color), sanitary sewers (red color) and combined flow sewers (green color). Our calculations focus on three pipes, serving the two most problematic areas, namely the junctions of Agiou Dimitriou Street with St. Kyriakidi Street and Tritis Septemvriou Street, which are shown in Fig. 6.

To estimate the local sewer system efficiency and the rain garden storage capacity, we take into account a 2-year return period R_p, namely the extreme rain event that may occur with a 50% probability each year. The reason for choosing a rather small R_p value is that the consequences of rain garden failure to retain rain runoff are not very important. In order to calculate the rain runoff quantities, the diagram of Fig. 7, given in [14], was used. The x-axis of the diagram indicates the duration of the rainfall, while the y-axis shows its intensity. The different curves represent the extreme rainfall that is likely to happen once every 2, 5, 10, 20 and 50 years.

Fig. 6. Junctions of Agiou Dimitriou with St. Kyriakidi and Tritis Septemvriou streets (based on Google maps).

First, we checked whether the two combined flow pipes (1A and 1B) at Agiou Dimitriou Street at point P1, and the combined flow pipe 2 at point P2, can carry the peak rain runoff of the area that is served by each of them. Their diameters are equal to D_{1A} = 500 mm, D_{1B} = 300 mm and D_2 = 400 mm, while their longitudinal slopes (they do not run along the small-slope Agiou Dimitriou Street) are equal to I_{1A} = 1.2%, I_{1B} =1.6% and I_2 = 1.2%, respectively.

Due to large street slopes, runoff concentration is of the order of few minutes only. From the diagram of Fig. 7, the rain intensity i is equal to 50 mm/h, for duration equal to 20 min, while the rain runoff coefficient can be considered equal to 0.8. The areas that are supposed to be drained by pipes 1A, 1B and 2 are equal to 24,500, 65,500 and 9,400 m^2, respectively. Then, if the runoff were completely collected by the sewer system, the flow rates that should be carried by the three pipes would be equal to 0.27, 0.73 and 0.10 m^3/s, respectively. For pipe 2, this might be an underestimate, since rain runoff that should be collected by other pipes, may end up flooding Tritis Septemvriou Street.

The maximum flow rate $Q_{\max}$, that can be carried by a circular pipe under free surface flow conditions is achieved when the flow depth is equal to 0.94D (where D is the inner diameter of the pipe). To calculate it, we used the Manning's formula, as follows:

$$Q = \frac{1}{n} \times A \times R_h^{2/3} \times I^{1/2} \tag{1}$$

where n is the Manning's coefficient (taken equal to 0.02 s/m$^{1/3}$), A is the pipe cross-section and R_h the hydraulic radius. It leads to the following results:

$Q_{\text{max1A}} = 0.29$ m^3/s, $Q_{\text{max1B}} = 0.085$ m^3/s and $Q_{\text{max2}} = 0.16$ m^3/s.

The aforementioned calculations are summarized in Table 1, together with the features of the pipes.

Regarding the pipes at point P1 we can conclude that pipe 1A is sufficient, however, pipe 1B is only able to carry a portion of the rain runoff. Then, rain gardens should alleviate mainly the burden of pipe 1B. The choice of rain garden sites K1 to K5 takes into account this criterion as well.

Regarding the pipe at point P2, we can conclude that its carrying capacity is sufficient. Thus, we can draw the conclusion that the problem at P2 is due to insufficient inlets of the sewer system, and to the large street slopes that lead rain runoff to it.

To arrive at a preliminary estimate of the rain runoff volume that can be retained by the proposed rain gardens, we take into account a typical cross-section, as shown in Fig. 8. In this case, the storage capacity of the rain garden depends on the following three terms: (a) the effective porosity of the gravel layer, (b) the effective porosity of the soil layer and (c) the difference between the upper level of the rain garden berm (or that of the surface of inflowing water) and the level of the soil surface.

We consider that (a) the width of gravel layer is $b_3 = 0.25$ m, while its effective porosity equals 0.30, (b) the width of the soil layer is $b_2 = 0.40$ m and its effective porosity equal to 0.20 and (c) the difference between the level of soil surface and the level of rain garden's berm is $b_1 = 0.15$ m.

Then, the water volume S_K that can be stored by each square meter of the typical rain garden is given as follows:

$$S_K = 0.25\times 0.3 + 0.4\times 0.2 + 0.15 = 0.305\ \text{m}^3/\text{m}^2 \qquad (2)$$

This value could be used for preliminary calculations, for all the selected rain garden sites, except for K7, namely the stream bed. Then, calculation of the total rain runoff volume that could be stored in each of the proposed rain gardens is straightforward. Results are summarized in Table 2, where the value for K7 is a lower limit.

The total rain runoff volume (Vol) from an area S can be calculated as follows:

$$\text{Vol} = S \times i \times T \times f \qquad (3)$$

where i is the rain intensity, T the duration of the rain and f a runoff coefficient.

According to the diagram of Fig. 7, the intensity of the extreme rain event that lasts for 2 h is 20 mm/h, for a return period of 2 years. For $f = 0.85$, it follows from Eq. (3) that the total rain runoff volume for the areas that are drained by pipes 1A, 1B and 2 is equal to 830, 2,200, and 320 m^3, respectively.

Rain garden K1 can serve the runoff areas of pipe 1A and of 1B, while K2 to K6 that of pipe 1B. The area of pipe 2 is served by K7, while K8 is not related to the two investigated junctions.

It follows, then, that the proposed rain gardens would be able to mitigate substantially the rain runoff problem in the study area. Moreover, a preliminary estimate shows that construction of rain gardens is a cost-efficient solution, since substantial improvement of the existing sewer network requires replacement of pipe B and construction of more inlets, along all 3 pipes. On the other hand, rain garden construction could be less than 50 Euros per square meter (plus the cost of inflow structures) and could be combined with rehabilitation of green areas (in particular part B of K7). Moreover, one of the small rain gardens (like K3) could be constructed first, to allow for accurate cost estimates and efficiency monitoring [15]. Actually, site monitoring should start at least 1 year before the rain garden construction, for comparison reasons.

6. Design of technical features

Due to the large street slopes of the study area, inflow and outflow structures of the proposed rain gardens deserve

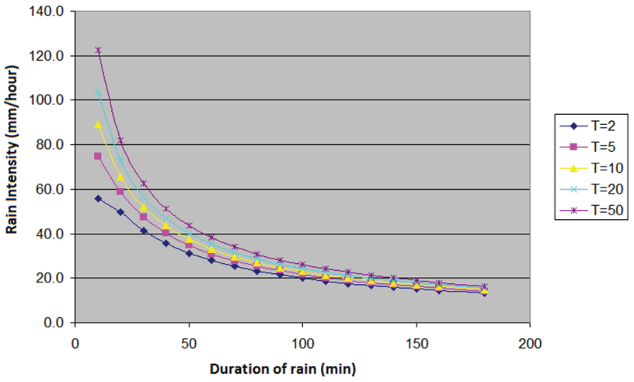


Fig. 7. Intensity–duration–frequency curves for Thessaloniki area for different return periods T [14].

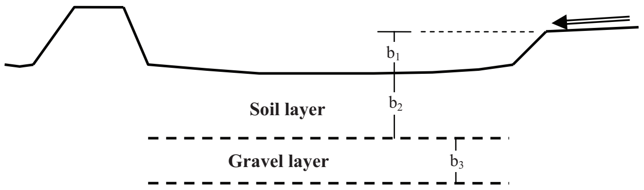


Fig. 8. Sketch for the calculation of rain garden storage capacity (vertical cross-section) [9].

Table 1
Summary of hydraulic and hydrologic calculations

Pipe no	Pipe diam. D (mm)	Pipe slope I	Q_{max} carried m^3/s (Eq. 1)	Drained area (m^2)	Q for 2-year return period
1A	500	1.2%	0.290	24,500	0.27
1B	300	1.6%	0.085	65,500	0.73
2	400	1.2%	0.160	9,400	0.10

Table 2
Approximate storage capacity of proposed rain garden sites

Site	Volume (m^3)
K1	736.0
K2	10.0
K3	83.0
K4	110.0
K5	470.0
K6	76.0
K7	1,700.0
K8	365.0

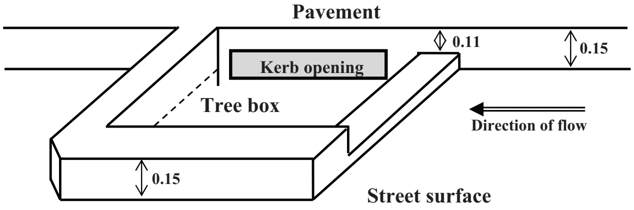


Fig. 9. Inlet structure combining curb opening and tree box.

special attention, as simple kerb cuts or openings might not be sufficient to divert rain runoff to the adjacent rain gardens.

One option is to combine kerb openings with tree boxes as shown in Fig. 9. The small threshold along tree box inlet aims at diverting very small flows from the rain garden towards the sewer system. The reason is twofold: (a) these low flows cause no nuisance and (b) they may carry rather heavy pollution load, which should end up at the sewer treatment facility. These inlet structures can be adjusted to most of the proposed rain garden sites.

At the upper part (part B) of site K7 in particular, where the stream bed is substantially lower than the street surface, a downspout should be used along the concrete wall, which retains the street and its sidewalk.

Regarding outflow structures, site K1 deserves special care. The border of this inclined park with Agiou Dimitriou sidewalk is a concrete berm, with a maximum height of 0.55 m. Most of the rain garden surface should be lowered by 0.10–0.20 m and an additional low berm should be constructed along part of St. Kyriakidi Street. Moreover, a conduit should be fixed along the berm's edge, in order to collect excess rainwater and to channel it, through a short downspout, to the sewer network.

7. Summary and conclusions

In this paper, we have presented a case study, regarding use of rain gardens in an urban area suffering from mild damages during medium intensity rain events. Selection of eight sites has been discussed first, together with the respective qualitative criteria. Initial selection has been followed by preliminary calculations on the local sewer network efficiency and the anticipated rain runoff peak and total volume. Results have shown that rain garden construction at the selected sites can alleviate street and sidewalk inundation problems in the study area. Finally, some design details of inflow and outflow structures along streets with large slopes have been presented, which might be useful in studies of other urban contexts.

Acknowledgments

Sewer network maps were provided by Thessaloniki Water Supply & Sewerage Co. S.A (EYATH S.A.). Its contribution and in particular that of Mr. I. Kavouras, is gratefully acknowledged.

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