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Original Research

Analysing Bioretention Hydraulics and Runoff Retention through Numerical Modelling Using RECARGA: a Case Study in a Romanian Urban Area

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Abstract

The benefits of bioretention systems are very important to the environment. Because of low knowledge in the field at a national level (in Romania), they are not promoted or implemented. The aim of this research was to develop and promote bioretention systems in Romania, with particular reference to one of the biggest urban developments: Cluj-Napoca. We used the RECARGA to determine effective models of bioretention cell for environmental conditions provided by 4 types of urban sites: commercial, industrial, high-density residential, and low-density residential areas. The bioretention modelling was made for a single event, with and without underdrain. The variables considered in the simulations were: native soil texture, hydrological conductivity, CN, and percentage of impermeable surface. Soil texture was one of the main variables that influenced the model, and is the most important element of control in the design and performance of the bioretention cell. The results also show that hydraulic conductivity has a large effect on the duration of flooding in the bioretention cell. All the details related to a bioretention cell must be carefully studied, and included in the numerical modelling in order to obtain viable bioretention systems.

Keywords: bioretention, hydraulic conductivity, runoff, site, soil

Introduction

Bioretention systems are implemented and studied especially in the context of the urban environment, but lately they are also included in rural and agricultural areas. These sustainable techniques are grouped in a category that is referred to by different terms: sustainable drainage systems (SUDS) in the UK [1-2], low-impact development (LID) or best management practices (BMPs) in the USA and Canada [3], water-sensitive urban design (WSUD) in Australia, natural drainage systems in the U.S. city of Seattle [4], and on-site stormwater management by the Washington State Department of Ecology (USA) [5]. Terminology, although varied, does not necessarily produce confusion regarding the definition and basic characteristics of the categories of sustainable techniques. This type of sustainable system is intended to mimic natural

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hydrological regimes in order to minimize the impact of human activity on surface water drainage discharge, reducing flooding and pollution of waterways and groundwater [6]. There are different measures that vary in design to suit different scenarios. For example, Josimov-Dundjerski (2015) presents one of the sustainable systems based on bioretention for wastewater treatment: the constructed wetland (CW). Due to multiple variables, it is important to choose the correct measure or adapt and develop a new measure [6-7].

Existing research and case studies related to bioretention systems play a crucial role in understanding their mode of operation, the choice of suitable types for different areas and scenarios for reducing the risks arising from incorrect perception [8-12]. Green infrastructure is efficient in controlling the problems caused by the quantity and quality of urban stormwater runoff [13-16]. The sustainable technics based on bioretention are at present researched and implemented on a large scale in various countries worldwide, while in others they are completely ignored. An important step in the application of bioretention systems is determining the model and design according to a given area. The design and modelling tools for these systems have evolved rapidly and encompass a wide range of types that vary in terms of complexity [17-21]. DRAINMOD, stormwater management model (SWMM), WinSLAMM, HydroCAD, HEC-HMS, IDEAL, and WWHM are major computational hydrologic or hydraulic models used to simulate bioretention systems [22-29].

The aim of this research was to develop general rules and effective models for the use of bioretention systems in Romania, with particular reference to one of the biggest urban developments at the national level: Cluj-Napoca. We used the RECARGA model to determine bioretention cell effective models for environmental conditions provided by the studied sites. RECARGA is a hydraulic model for optional event and continuous simulation or design purpose and provides detailed analysis for bioretention hydraulics and runoff retention [21, 22]. This research is useful for sizing the bioretention cell in order to meet the specific performance targets, such as reducing the volume of stormwater runoff and for analysing the potential impact of the variation of design parameters. A secondary objective of this study was to increase scientific and public awareness through targeted analysis of the bioretention cells in the context and environmental conditions in Romania.

Materials and Methods

Study Area

Cluj-Napoca, with an area of 179.5 km², is located in central Transylvania in the Someş Mic Corridor, and is located within three major geographical units: the Transylvanian Plain, the Someş Plateau, and the Apuseni Mountains. It is located specifically at the intersection of parallel 46°46'N with meridian 23°36 'E. Cluj-Napoca is part of the Someş-Tisa basin. The studied sites through the prevailing characteristics fits within these categories: commercial area, industrial area, high-density residential area, and low-density residential area (Fig. 1). The commercial area is located in eastern Cluj-Napoca city (46°45'32.16"N latitude and 23°32'24.78"E longitude), the industrial area is in northeastern Cluj-Napoca (46°47'36.52"N latitude and 23°38'3.72"E longitude), the low-density residential area is in southwestern Cluj-Napoca (46°44'43.81"N latitude and 23°34'10.75"E longitude), and the high-density residential area is to the west (46°45'8.48"N latitude and 23°33'31.37"E longitude) [30].

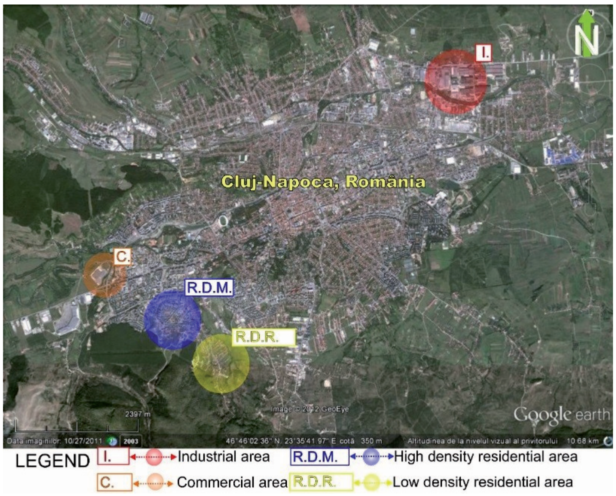


Fig. 1. Map of the studied sites.

Numerical Modelling

For the analysis of bioretention hydraulics and runoff retention in the studied sites we used the RECARGA model developed at the University of Wisconsin-Madison [31-32]. RECARGA is based on continuous modelling or on one event, simulates the hydrological functions of bioretention cells, and was developed using MATLAB computing software and language [33]. RECARGA relies on the Green-Ampt infiltration equation for the initial infiltration in the soil surface and on the van Genuchten relationship for drainage between soil layers [31-32]. The model simulates the continuous movement of water through bioretention cell, records the soil moisture, and water volume for every phase, and synthesizes the results.

From the three types of simulation (continuous, single event, and based on user input) we selected the simulation based on unique event with an excess rainfall (47 mm) in order to evaluate bioretention cell performance under extreme conditions. Some of the variables [34] taken into account to achieve a unique event based on simulations were different for

Table 1. Input data included in the RECARGA model; modelling variables for the 4 sites.

Input data	High-density residential	Low-density residential	Commercial	Industrial
Facility area (m^2)	404.6856	404.6856	404.6856	404.6856
Tributary area (m^2)	4046.85	4046.85	4046.85	4046.85
Percent impervious	56	53	53	83
Pervious CN	98	90	81	93
Regional AVE.ET (cm/day)	0.3302	0.3302	0.3302	0.3302
Simulation type	Single event	Single event	Single event	Single event
Rainfall distribution	Type II	Type II	Type II	Type II
Rainfall depth (cm)	4.70	4.70	4.70	4.70
Output file name	RDM I RDM II	RDR I RDR II	C I C II	I I I II
Depresion zone depth (cm)	15.24	15.24	15.24	15.24
Root layer depth (cm)	60.96	60.96	60.96	60.96
Soil texture in root layer	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam
Storage layer depth (cm)	30	30	30	30
Soil texture in storage layer	Sand	Sand	Sand	Sand
Native soil layer texture	Clay	Silty clay	Sandy loam	Clay
Native soil hydraulic conductivity (cm/hr)	0.2	0.09	5.58	0.42
Underdrain flow rate cm/hr	V_1 - 0	V_1 - 0	V_1 - 0	V_1 - O
	V_2 – 0.43	V_2 – 0.54	V_2 – 0.15	V_2 – 0.215
Target Stay-on (cm)	-	-	-	-

RDM I – High Density Residential Area without underdrain; RDM II – High Density Residential Area with underdrain;
RDR I - Low Density Residential Area without Underdrain; RDR II - Low Density Residential Area with Underdrain;
C I – Commercial area without underdrain; C II – Commercial area with underdrain; I I – Industrial area with underdrain;
I II – Industrial area without underdrain

each site individually (except for evapotranspiration, surface, and rainfall) and concern: native soil texture, hydrological conductivity, CN, evapotranspiration, rainfall, percentage of impermeable surface. For rainfall distribution we selected the Hyetograph (time distribution of rainfall) II; for the simulation we introduced the depth of the precipitation corresponding for a period of 24 hours (mm). Based on the hydrological map of Romania we used the 47 mm (4.7 cm) value.

Average hourly evapotranspiration was Regional AVE.ET is 0.3302 cm/day. Native soil texture of the 4 sites was determined by performing 4 geotechnical drillings. Native soil hydraulic conductivity was determined based on the constant head permeability test and on soil textural classes (Table 1).

For rooting and storage areas we preserved the default values of the RECARGA model: 10 cm/hr, respectively, 15 cm/hr. The underdrain flow required is the result of the division of ponding depth to 24 hours and subtraction of the native soil hydraulic conductivity.

We simulated models for bioretention cells with an area of 404.6856 m^2. Tributary basin area is 4,046.85 m^2. Results on the percentage of impermeability were obtained by assessing areas suitable for bioretention implementation in the four studied sites [30]. The curve number (CN) index has emerged from the consultation of the CN values for hydrological soil groups [35, 36]. The resulting data for each site introduced in the RECARGA model are summarized in Table 1.

We conducted two simulations based on a unique event for each of the 4 areas: with underdrain and without underdrain. Performing 2 simulations for each area is justified by the fact that it is necessary to determine the best options for building the bioretention cells according to the existing conditions. In order to calculate facility area ratio (FAR) in addition to the parameters originally introduced, we introduced one additional parameter: the Target Stayon.

Results and Discussion

The result are summarized in two parts: water balance terms and plant survivability terms [37]. The file also records the relative water content in each

Table 2. Results: plant survivability conditions.

Area/ underdrain	Hours ponded		Number of overflows	Tributary Runoff (cm)		
	Max.	Total		Precipitation cm	Impervious runoff cm	Pervious runoff cm
RDM I	69.5	69.5	1	47	46.65	46.38
RDM II	47.25	47.25	1	47	46.65	46.3836
RDR I	69	69	1	47	46.95	43.775
RDR II	47	47	1	47	46.65	43.775
C I	22.75	22.75	0	47	46.65	40.53
C II	21.25	21.5	0	47	46.65	40.5361
I I	58.25	58.25	1	47	46.65	44.7811
I II	46.25	46.25	1	47	46.65	44.781

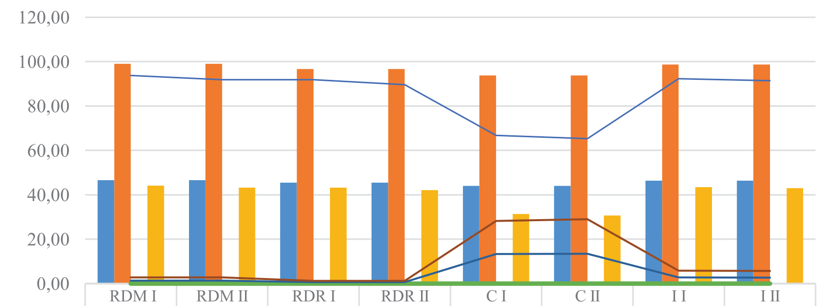
RDM I – High Density Residential Area without underdrain; RDM II – High Density Residential Area with underdrain;
RDR I - Low Density Residential Area without Underdrain; RDR II - Low Density Residential Area with Underdrain;
C I – Commercial area without underdrain; C II – Commercial area with underdrain; I I – Industrial area with underdrain;
I II – Industrial area without underdrain

layer expressed as a fraction of the overall soil volume occupied by water: ThetaRZ (rooting zone), ThetaSZ (storage zone), and ThetaCZ (native soil layer).

In the high-density residential area (RDM I) in the scenario of a bioretention cell without underdrain, the modelling performing RECARGA shows that the existing condition will cause a ponding time of 69.5 hours (Table 2). In general, the ponding duration should be less than 24 hours after a storm event has ended. In the scenario with underdrain in the same area (RDM II) the ponding time will decrease substantially (Table 2). This will improve plant survivability conditions. The drawback is the decrease of stormwater runoff retained in the cell.

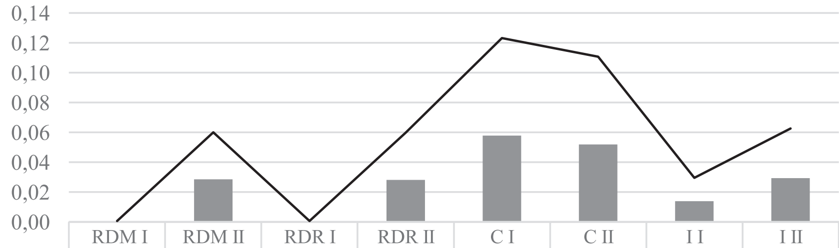
In the case of the low-density residential area the results related to plant survivability conditions for a bioretention cell without underdrain (RDR I) shows that the ponding time exceeds the limit (Table 2). In the scenario with underdrain (RDR II), ponding time decreases from 69 to 47 hours (Table 2). The quantity of runoff retained in the cell decreases as in the case of a high-density residential area (Fig. 2). In the commercial area (C I) the values of the ponding time, of the retained runoff quantity, and of the recharge are very good in the case of a bioetention cell without underdrain (Figs 2-4). Using an underdrain for the bioretention cell from commercial area (C II) decreases ponding time from 22.75 hours to 21.25 hours (Table 2). In this case, the retained runoff (stayon) does not decrease significantly (Table 2).

In the industrial area for a bioretention cell without underdrain (II), the ponding time will reach a total of 58.25 hours (Table 2). Using an underdrain (scenario III), the ponding time decreases from 58.25



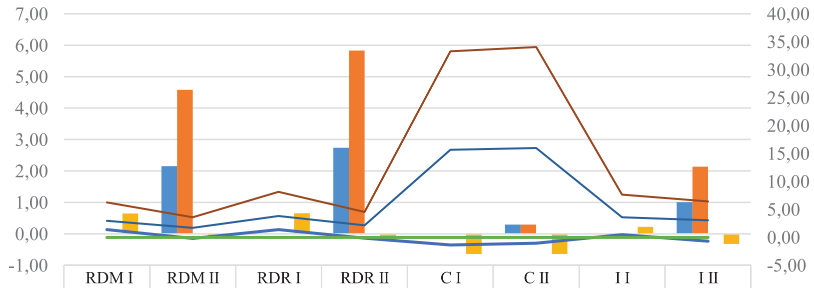
	RDM I	RDM II	RDR I	RDR II	C I	C II	I I	I II
Runon cm	46,54	46,54	45,42	45,42	44,04	44,04	46,36	46,36
Runon %	99,06	99,03	96,64	96,64	93,70	93,70	98,64	98,64
Runon %	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Runoff cm	44,07	43,16	43,18	42,14	31,35	30,71	43,40	42,98
Runoff %	93,76	91,83	91,88	89,65	66,71	65,33	92,34	91,44
Runoff %	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Recharge cm	1,30	1,30	0,59	0,58	13,27	13,46	2,73	2,67
Recharge %	2,77	2,76	1,25	1,24	28,23	29,00	5,80	5,68

Fig. 2. Water balance in bioretention cell: runon, runoff and recharge.



	RDM I	RDM II	RDR I	RDR II	C I	C II	I I	I II
Evaporation cm	0,00	0,03	0,00	0,03	0,06	0,05	0,01	0,03
Evaporation %	0,00	0,06	0,00	0,06	0,12	0,11	0,03	0,06

Fig. 3. Water balance in bioretention cell: evapotranspiration.



	RDM I	RDM II	RDR I	RDR II	C I	C II	I I	I II
Underdrain cm	0,00	2,15	0,00	2,74	0,00	0,29	0,00	1,00
Underdrain %	0,00	4,58	0,00	5,83	0,00	0,29	0,00	2,14
Underdrain %	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Soil moisture cm	0,64	-0,10	0,65	-0,07	-0,65	-0,64	0,22	-0,32
Soil moisture %	1,37	-0,20	1,39	-0,14	-1,37	-1,04	0,47	-0,68
Soil moisture %	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Stay-on cm	2,93	1,68	3,82	2,12	15,65	16,00	3,60	3,02
Stay-on %	6,24	3,58	8,12	4,52	33,29	34,03	7,66	6,43

Fig. 4. Water balance in bioretention cell: underdrain, soil moisture, and stay-on.

to 46.25 hours (see Table 2). The best results in terms of water balance in the bioretention cell have been observed in the case of the commercial area. The most problematic area (58.25 hours ponded) is high-density residential (Figs 2-4), which is due to native soil hydraulic conductivity and texture (Table 1).

The hydrological functions of the bioretention cell are influenced by native soil type, the percentage of

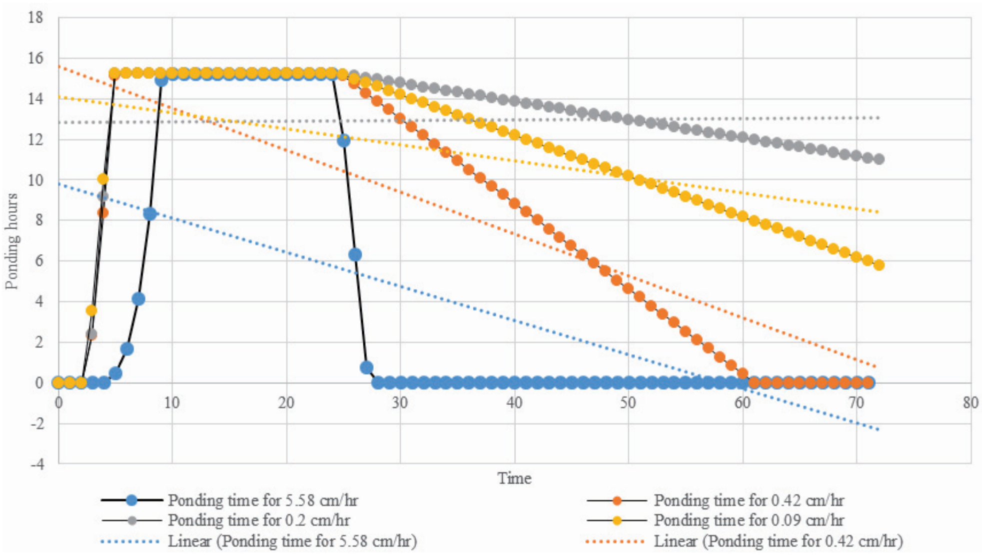


Fig. 5. Influence of hydraulic conductivity on ponding time.

impermeability of the treated area, and the index curve number. The results differ substantially depending on the characteristics of each site. The soil texture was one of the main variables that influenced the results obtained related to the bioretention cell efficient models for Cluj-Napoca. Native soil hydraulic conductivity affects the ponding time following a rainfall event. Ponding time is reduced with the increase of hydraulic conductivity (Fig. 5).

Discussion

Ponding time for sites with reduced hydraulic conductivity of the native soil is high even in the condition of precipitation with lower runoff. Instead, detention of runoff in the cell increases from 8.11% to 54.72%. Le Coustumer et al. (2007) shows that the hydraulic conductivity of the soil layer decreases significantly during their first four weeks of the experiment, and then tends to have a constant value [38]. Bioretention can effectively reduce the impact of development on the hydrological regime in urban areas [39]. The existing research [40-43] indicates that hydrological performance of the bioretention systems is dependent largely on seasonal conditions. Dietz and Clausen [44] reported overflows for only 0.8% of the total runoff captured by the system. Similar results related to the importance of the native soil texture was obtained by Sun et al. [45].

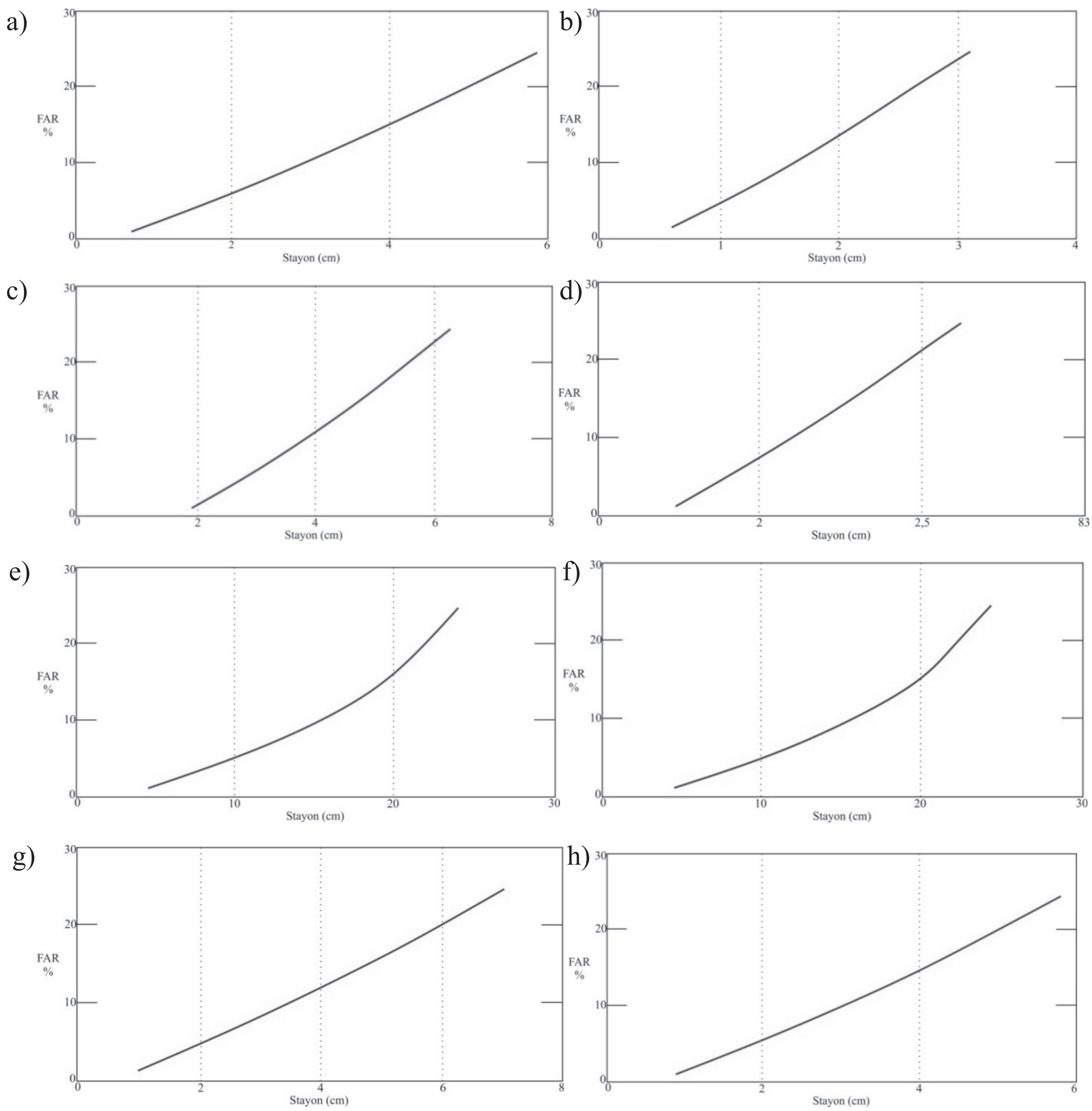


Fig. 6. (a) Facility Area Ratio – FAR; RDM I; (b) Facility Area Ratio – FAR. RDM II; (c) Facility Area Ratio – FAR. RDR I; (d) Facility Area Ratio – FAR. RDR II; (e) Facility Area Ratio – FAR. C I; (f) Facility Area Ratio – FAR. C II; (g) Facility Area Ratio – FAR. I I; (h) Facility Area Ratio – FAR. I II.

The performance of one bioretention cell depends on the balance facility area-tributary area (facility area ratio, or FAR). The results show that the volume of the runoff decreases with the FAR increase (Fig. 6). FAR recorded a 5% increase when the bioretention cell surface increased from 10% to 15% of the tributary area. The same results were obtained in all studied sites.

The depth of the ponding zone provides initial storage for the runoff volume, allowing the water to spread and infiltrate on the entire surface of the bioretention cell. Depths below 15 cm of the area leads to insufficient runoff spread over the entire surface, reducing the efficiency and output in the sedimentation in lower areas [46-47]. In the studied cases, a 15 cm depth is sufficient to meet the objectives of the bioretention cell. Considering the fact that 70% of stormwater runoff comes from 5 cm of precipitation, the models resulting for 47 mm precipitation provides effective function for the existing conditions in the four sites from Cluj-Napoca.

Increasing the thickness of the rooting zone for the bioretention cell modelled for the studied site, we have not observed notable changes in ponding time. The changes that have occurred with the change in value of this component refer to the amount of runoff retained in bioretention. It also noted a decrease of the facility rate. The underdrain reduces the ponding time and increases the amount of filtered water. In the performed modelling, the underdrain allows an additional volume of water to infiltrate through the rooting zone, reducing the maximum ponding time. According to research results and the literature, a minimum thickness of 60 cm of the rooting zone is efficient [48].

The ponding time has decreased and managed to be within the recommended limit to achieve the optimal conditions for plant survivability. Because the water flow through an underdrain is still considered runoff, adding an underdrain reduces ponding time but increases the amount of runoff removed from the cell. Results show that even in cases when the underdrain is not used, the ponding zone can increase the volume captured by the bioretention facility. We recommend the use of underdrains only in areas where the hydraulic conductivity of the native soil leads to a long period for ponding time.

We entirely agree with Davis et al. that using an underdrain is still a technical debate between bioretention system designers. It is wrong to treat the bioretention cells strictly in terms of filtering and to use underdrains for all models [49-50]. This approach would contradict the fact that bioretention systems were originally designed as infiltration systems [51]. The results show that in a high-density residential area with clayey soil, a bioretention cell allows water infiltration even without an underdrain, but over a longer period of time [52]. In general, regardless of the areas included in the study and their characteristics, the results show that resulting bioretention models are effective in reducing the volume, and capturing and detaining stormwater runoff. The results are comparable to those obtained in similar studies [53-60].

Conclusions

Based on the existing conditions related to soil texture, we conclude that bioretention cells can be designed in the commercial area without underground drainage – with ponding time being optimal in both cases (with and without drain). Native soil hydraulic conductivity of the high-density residential, low-density residential, and industrial area with high-density area limits the bioretention cell functions.

Adding an underdrain for the bioretention cell modelled for these areas is possible and the existing conditions do not limit the installation, taking into account the high degree of unevenness of soil. For the industrial area where the amounts of pollutants are higher than in other areas and the native soil hydraulic conductivity is low, we recommend installing bioretention cells based mainly on stormwater runoff filtration.

To obtain relevant results in modelling of the bioretention systems for a given area, it is recommended to use correct data obtained from a detailed assessment of existing conditions that may influence the implementation (native soil texture, hydraulic conductivity, curve number index, the percentage of impervious surfaces, local weather conditions, and the degree of soil compaction).

Locating facilities in areas whose soils favour bioretention functions leads to an improvement in performance. It is important to correctly dimension the bioretention cell based on the macro, meso, and micro-areas. Attention must be directed toward increasing the capacity of infiltration of the pervious surfaces.

Acknowledgements

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