

Analysis of roof greening technology impact on rain and meltwater retention

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Abstract. Over the past 20 years, a large number of studies have been published on reducing storm runoff by various types of green roofs. This article analyzes the results of experimental studies presented in 39 publications on green roof runoff reduction in a climate similar to the climate of Russia: in Canada, the USA, Finland, Norway, France. An analytical review found that the ability of green roofs to retain rainfall varies from 20 to 99.5% depending on climatic conditions (duration and intensity of rains, duration of dry periods, solar radiation, temperature and humidity, wind conditions), the properties of green roof layers (moisture capacity of the substrate and a drainage layer, the substrate thickness), the type of vegetation, the geometry of a green roof (slope and orientation). Green roofs can be a useful tool for reducing urban storm water runoff. However, in order to ensure high efficiency, it is necessary to use green roof technology with other measures to reduce runoff.

1 Introduction

The process of urbanization leads to an increase in artificial impermeable surfaces in cities: roofs and roadways, thereby disrupting the natural hydrological cycle. There is an increase in rainwater and meltwater runoff intensity, a reduction of infiltration and evapotranspiration, the deterioration of wastewater quality due to increase in pollutants concentration [1, 2].

The building concentration and increase in load on engineering system lead to their wear and tear. Unsatisfactory technical condition of sewer systems in Russia, local damage of pipes of the rain sewer network and wells create problems in the operation of the rain sewer network and can lead to emergency situations: overflow of pipelines and wells and, as a result, flooding of roadways. Wear of sewer systems in most cities of Russia is extremely high, this is due to the discrepancy between the performance of the sewer systems, the vast majority of which were created at the end of the XX century, and the loads during intense rains (e.g., wear of sewer systems in Irkutsk - 48% [3]; Kaliningrad-20-100% [4]).

There is a problem of a sewer system congestion with storm water. It is necessary to carry out measures for effective management of rain and meltwater in areas with overloaded sewer systems. To solve this problem, in addition to the reorganization of worn-out engineering

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sewer systems, it is possible to use environmentally friendly energy-efficient, resource-saving, biopositive building structures and technologies.

Arranging of green roofs can become the tool for managing storm water runoff in urban areas. Since roofs make up approximately 30-50% of urban impermeable surfaces, they contribute to a significant increase in runoff volume.

Transformation of conventional roofs into green roofs in Russia can lead to rainfall retention and runoff reduction in urbanized areas by maintaining rainfall in a green roof layers and delaying peak runoff during a rain, followed by evaporation of moisture from a green roof.

2 Materials and methods

The experience accumulated over the past 20 years shows the insufficiently deep study of the research topic among Russian researchers, in contrast to foreign ones. To date, around the world published more than 1000 works concerning green roofs (Web of Science).

In this paper, an analytical review of foreign articles with experimental studies on the rain and meltwater runoff from green roofs in the period 1975-2020 was performed (Web of Science) for countries with a climate similar to that of Russia: Canada, the USA, Finland, Norway, and France [5, 6]. Scientists from the selected countries published 374 articles, 39 of which provide the results of 32 experimental studies. Statistical data on foreign research are presented in figures 1 and 2.

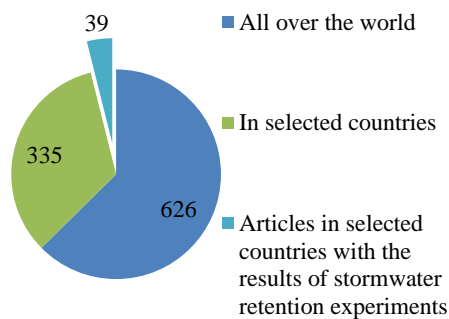


Fig. 1. Published scientific papers in WoS 1975-2020 on the topic of "green roofs".

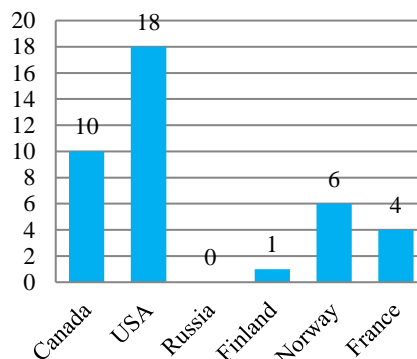


Fig. 2. Published scientific papers in WoS 1975-2020 in selected countries with the results of stormwater retention experiments.

Studies of stormwater retention on roofs with vegetation cover have received a lot of attention in recent years [7-20 et al.], but only a small part of them relate to long-term observations on large experimental areas.

Table 1 provides an overview of the results of laboratory and field experiments to determine the retention coefficient of rainwater and meltwater. Of the 32 experimental studies reviewed, 30 ones were conducted under real conditions, and 2 were made in the laboratory [21-22].

Table 1. Summary with some basic characteristics of reviewed publications on green roofs stormwater retention.

Author. year	Study period	Location	Substrate thickness. mm	Roof slope. %	Water retention. %
Finland					
Krebs. G.. et al.. 2015	7/08/2013-20/10/2013	Lahti	60-70 +30-40	8	25
	9/05/2014-28/08/2014				54
Norway					
Johannessen. B.. et al.. 2019. 2018. 2017. 2016 Hamouz. V.. et al.. 2018	1/05/2016-31/10/2016 1/05/2017-31/10/2017	Bergen	30	16	22
			80		24
			30		21
	Sanders	30	27	33	
		80		31	
	30	27	27		
Trondheim	11/05/2017-30/11/2017	30	16	52	
		80	16	46	
1/01/2010 – 31/10/2010 1/05/2012-31/10/2012	Oslo	200*	2	7	
		30	2	27	
Scherer. L.A.. 2018	2018	lab	50	2	16-71
USA					
Abualfaraj. N.. et al. 2018 Alvizuri.. J.. et al.. 2017	06/2014 – 11/2017	New York	XeroTerr on textile XF157	1-2	75-79
Schultz. I.. et al.. 2018	1/02/2014 - 31/01/2015	Portland	75 125	2	23 33
Todorov. D.. 2018 Carpenter. CMG. et al.. 2016	06/2010 – 11/2013	Syracuse	95	1-15	95.9± 3.6
Hakimdavar. R.. et al.. 2014	08/2011 – 01/2012 08/2011 – 06/2012	New York	32 Xero Flor XF301 + 2FL	2	25-89
Carson. T.B.. et al. . 2013	06/2011 – 06/2012 06/2011 – 06/2013 06/2011 – 04/2014	New York	32 100-200 100	2	36 47 61
Gregoire. B.G.. et al.. 2011	25/02/2009 – 1/02/2010	Storrs	102	2	51.4
Spolek. G.. et al.. 2008	10/2004–04/2007	Portland	100-150 100-150 150	2	12 17 25
Kurtz. T.. et al.. 2008	05/2002–06/2008 03/2007– 06/2008 03/2007– 06/2008	Portland	125 150 75	2	56 74 64
Berkompas. B.. et al.. 2008	02/2007–12/2007 04/2007–06/2007 10/2007–12/2007	Seattle	150 100-125 150	4-21; 4-8 0-25 6	30.5 33 17.1

Moran. A.C.. et al.. 2005	04/2003–09/2004 07/2004 –09/2004	Goldsboro	75 100	7	63 55
Hutchinson. D.. et al.. 2003	01/2002–04/2003	Portland	100-125	2	69
Berghage R. et al.. 2010	08/2007–07/2009	Chicago	76	2	74
Bliss. D. J.. et al.. 2009	08/2006–01/2007	Pittsburgh	140	2	22
Hathaway. A. M.. et al.. 2008	04/2003–06/2004	Goldsboro	75	no data	74
Carter. T. L..& Rasmussen. T. C.. 2007	11/2003- 11/2004	Athens	no data	2	78
Canada					
Connelly. M.. et al.. 2005	01/2005 –12/ 2005	Vancouver	75 150	2	29 26
Liu. K.Y.. et al.. 2005	03/2003 – 11/2004 04/2003 – 11/2004	Toronto	75 100	no data	57
Hill. J.. et al.. 2017	05/2013-10/2013; 05/2014-10/2014	Toronto	100. 150	2	with watering – 70; without – 50
Sims. A. W.. et al.. 2019	28/07/2013- 11/11/2013; 11/04/ 2014 -21/10/2014	London	100	no data	no data
Akther. M.. et al.. 2018	2018	lab	100. 150. 200	1	no data
MacIvor. J. S.. et al.. 2011	05/2007-10/2007; 05/2008-10/2008	Halifax	60	no data	49-73
Vander Linden. K.. & Stone. M.. 2009	2/06/2006– 22/10/2006	Waterloo	35	no data	31.5
Van Seters. T.. et al.. 2009 MacMillan. G.. 2004	05/2003-11/2003; 06/2004-11/2004; 04/2005-08/2005	Toronto	140	10	63
Berghage. R.D.. et al.. 2009	01/2005 – 11/2005	University Park	80-100	8	52.6
France					
Versini. P.-a. et al.. 2015 Gromaire. M. C.. et al.. 2013 Ramier. D.. et al.. 2013	06/2011-08/2012	Trappes	30 30 30 150 150 150	1-2	51 63 69 64 71 74
Yilmaz. D.. et al.. 2016	06/2011-03/2013	Nantes	80 120	3	28 80

* non-vegetated roof

** reference roof

There are many studies that prove the influence of rain characteristics (duration and intensity), duration of the dry periods and climate (solar radiation, temperature and humidity, wind conditions) on the precipitation retention by a green roof. Precipitation retention is inversely proportional to the amount of precipitation [23], and decreases with increasing precipitation intensity [24]. In the article [25] it is reported that the extensive green roof in Toronto during the wet period retained 42% of precipitation, and during the dry period much more (70-93%).

In the experimental studies presented in the table, green roofs with a substrate thickness of 30mm (extensive type of green roof) and 150 mm (semi-intensive / intensive type of green roof) were most often considered. Moreover, the greater thickness of the substrate led to an increase in the retention rate, which is due to the greater moisture capacity. The composition of the substrate and its moisture capacity will also increase this indicator.

In addition to the geometric and physical properties of the roof substrate, precipitation retention is influenced by the roof geometry: its slope and orientation to the cardinal directions. However, foreign studies do not consider the combined influence of slope and orientation. The influence of these factors on the green roof runoff coefficient remains poorly understood. In a small experiment of American scientists [26], there were no differences in the average precipitation retention by the modular green roof system (n=42.1%), located with a South orientation, with slope angles of 1, 20 and 40. According to the authors, such contradictory results may be due to a short study period (9 months), a small area of vegetation and South orientation. A number of studies by other scientists show that the retention of stormwater runoff from green roofs decreases with increasing tilt angle [27].

It is important to study the performance of green roofs in winter conditions, which is especially relevant for the Northern countries, including the Northern parts of Russia. 16 studies [28-38 et al.] out of 32 presented in the table were conducted for winter conditions, but they mainly took into account liquid precipitation. In the study [39], scientists divided rain events into 4 categories based on the amount of precipitation (0-10 mm; 10-20 mm; 20-40 mm; 40 mm and more). for each of the selected categories, precipitation retention was recorded in all seasons. For events with rainfall of 10-20 mm and 20-40 precipitation retention was greatest in summer and least in winter (e.g., for a sample green roof W118 precipitation retention in the summer 70% and 28% in winter), for fall and spring this value was between summer and winter. While for categories 0-10mm and 40mm and more, contrary to expectations, precipitation retention in all 4 seasons was the same (0-10mm-100%; 40 mm and more - 20% on average). Other researchers, having divided rain events by their size into 3 categories (0-20 mm; 20-40 mm; 40 mm or more), came to similar conclusions [40]. In articles [41-43], scientists also divided rain events by their size into 3 categories (0-5 mm; 5-19 mm; 19 mm and more), but the retention rate in these categories did not change significantly by season.

In most studies, the maximum precipitation retention on a green roof occurred in summer, and the minimum in winter. So, in the study [44], the average retention in summer was 92% and 66% in winter. In [45], this indicator was equal to 42% in summer and 12% in winter. A similar pattern in seasonal results was demonstrated by a number of other researchers [46-47].

The complexity of describing and predicting the hydrological behavior of water in green roofs lies in various criteria for evaluating precipitation retention (differences in study periods, differences in the allocation of rain event size categories, variable accounting for solid precipitation, etc.). to predict the hydrology of green roofs, several attempts have been made to model the retention capacity of green roofs using the SWMM stormwater management model [48]. However, the resulting models will only be suitable for describing specific types of "green" roofs under certain climatic conditions.

Thus, there is still a lack of knowledge regarding the simulation of precipitation retention by green roofs, since all indicators in the model reflect a certain type of green roof and its location, experimental research is needed to build new models.

3 Results

It was found that the green roofs stormwater retention rate varies from 20 to 99.5% for the selected countries (figure 3).

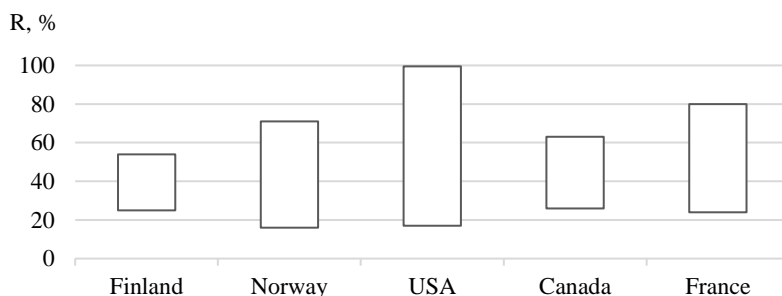


Fig. 3. Range of green roof rainfall retention rates in selected countries.

A number of significant factors that affect the coefficient of green roof stormwater retention have been identified. Green roof precipitation retention depends on the climatic characteristics of the territory (duration and intensity of rainfall, length of dry season, solar radiation, temperature and humidity, wind conditions), the properties of green roof layer (the moisture capacity of the substrate, drainage layer, type of drainage layer, thickness of substrate), type of vegetation, the geometry of a green roof (slope and orientation), as well as the age of the roof (virtually unexplored).

According to the results of the analytical review, the geometric and physical properties of the roof substrate (its moisture capacity, thickness and composition) have the greatest impact on the rain and meltwater retention of green roofs. The thickness of the substrate is a key factor that should be taken into account when design green roofs.

4 Discussion

Such a wide range of results on the ability of a green roof to retain precipitation, as describe in this work, is demonstrated by other review articles of this kind. For example, in the article [49], German scientists Mentens et al. in 2006 summarized data on experimental studies on reducing runoff from green roofs in Germany for the period 1987-2003. The annual decrease in runoff from extensive green roofs was 27-81%, from intensive -65-85%.

A similar range was found in a review article by American scientists [50], where data were collected for the period 2004-2013. The retention of stormwater runoff by a green roof was in the range of 30 to 86%.

5 Conclusions

Thanks to the ability to retain precipitation in the substrate and evapotranspiration processes, green roofs can reduce the volume and intensity of runoff in densely built-up urban areas from 20 to 99.5 %.

Over the past twenty years, significant research efforts have been made to better understand the effectiveness of green roofs in addressing the issue of regulating the volume of rainwater and meltwater. But it is still not known how the slope of a green roof and its orientation will affect the retention rate. Also, of interest for further work is the study of the ability of green roofs to retain water in winter conditions.

In Russia, buildings with green roofs have started to appear relatively recently, in cities such as Moscow, St. Petersburg, Yekaterinburg, Kaliningrad, Tver, Voronezh, and some others. In Russia, such specialists as V. I. Telichenko, M. Y. Slesarev, A. A. Benuzh, E. A. Korol and N. S. Shushunova were engaged in green roofs. However, the arrangement of green roofs cannot become widespread in the country without theoretical and experimental

confirmation of the effectiveness and safety of the technology. There is a need for practical testing and numerical assessment of the impact of green roofs on the environmental safety of urbanized territories, taking into account Russian climatic factors and regulatory and technical requirements for buildings.

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