Urban hydrological change and green roofs as source - control measures for stormwater management

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Abstract. Urbanization modifies the natural hydrological cycle by increasing impervious surfaces, reducing infiltration and accelerating stormwater runoff. In dense urban areas, rooftops form a substantial part of impervious cover and contribute directly to the hydraulic load on drainage systems during rainfall events. Green roofs provide a source-control measure that can partially restore retention, detention and evapotranspiration processes at the building scale. This paper discusses the hydrological role of green roofs in the context of urban hydrological change and stormwater management. It focuses on the mechanisms by which green roofs intercept rainfall, store water in vegetation and substrate layers, delay runoff generation and attenuate peak discharge. Particular attention is given to rainfall depth and intensity, antecedent moisture conditions, substrate properties, vegetation cover and detention response. The paper emphasizes that green roofs should not be assessed only through average retention values, because their performance varies with rainfall characteristics and initial substrate conditions. Instead, they should be considered as dynamic decentralized elements of urban stormwater control. This perspective supports their integration into drainage strategies aimed at reducing runoff peaks, relieving drainage infrastructure and improving the resilience of built-up areas under changing rainfall conditions, while supporting more adaptive responses to future hydrological stress in cities.

1 Introduction

Urbanization changes the hydrological functioning of catchments by replacing permeable and vegetated surfaces with roofs, roads, pavements and other impervious areas. This transformation reduces infiltration and evapotranspiration, increases stormwater runoff volume and accelerates the transfer of rainfall into drainage systems [1]. As a result, conventional urban drainage infrastructure may be exposed to higher hydraulic loads, especially during intense rainfall events. In this context, stormwater management is no longer limited to rapid conveyance of runoff away from urban areas, but increasingly includes measures that retain, detain and control water close to the place where rainfall occurs.

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Roofs represent a particularly relevant component of urban impervious cover. In dense urban areas, they may account for a substantial fraction of the total impervious surface, while often remaining underused from a stormwater management perspective [2]. Green roofs can therefore be interpreted not only as building-envelope or landscape elements, but also as source-control measures within urban drainage systems. Their function is based on the temporary storage of water in the vegetation, substrate and drainage layers, followed by delayed runoff release and evapotranspiration during dry periods.

The terminology used for decentralized stormwater management differs between regions, including Sustainable Drainage Systems, Low Impact Development, Best Management Practices, Water Sensitive Urban Design and green infrastructure. Despite these terminological differences, the common principle is to reduce the hydrological impact of urbanization through distributed measures located at or close to the source of runoff. This paper focuses on green roofs as one such measure and discusses their hydrological role in reducing runoff volume, delaying runoff generation and attenuating peak discharge. The aim is to frame green roofs as stormwater-control elements whose performance depends on rainfall characteristics, substrate moisture conditions and system configuration.

2 Urban hydrological change and stormwater runoff

Urbanization alters the natural water balance mainly through the replacement of permeable and vegetated surfaces by impervious materials. This transformation reduces infiltration, groundwater recharge and evapotranspiration, while increasing runoff rate and runoff volume [1]. Under pre-urban conditions, rainfall is partly intercepted by vegetation, stored in soil and gradually returned to the atmosphere. In urban areas, these pathways are limited, and a larger fraction of rainfall is rapidly converted into surface runoff.

The increase in impervious cover also changes the temporal structure of runoff. Impervious urban surfaces increase runoff peaks and volumes and reduce the time delay between peak rainfall and peak runoff [3]. This is critical for drainage systems, because intense rainfall can generate rapid inflows into sewers, roof drainage systems and downstream receiving waters. The hydrological consequence is therefore not only a larger runoff volume, but also a faster and more concentrated runoff response.

Conventional drainage systems have historically focused on collecting and conveying stormwater away from urban surfaces. Although this approach reduces local surface ponding, it can transfer hydraulic load downstream and increase pressure on sewer networks and receiving waters. Contemporary urban drainage strategies therefore increasingly emphasize distributed stormwater management, source control and the restoration of more natural hydrological processes within built-up areas [4]. A common principle of these approaches is to manage runoff closer to the place where rainfall occurs.

Rooftops are particularly relevant in this context because they form a substantial part of urban impervious surfaces. Roof areas may account for approximately 40 – 50 % of impermeable surfaces in urban areas [2]. Unlike many ground-level measures, green roofs can be implemented without requiring additional urban land. They therefore offer a source-control option for modifying the rainfall-runoff response directly at the building scale.

3 Green roofs as stormwater source-control measures

Green roofs modify stormwater runoff directly at the roof surface, before rainfall enters gutters, downpipes or sewer networks. Their hydrological function is based on a layered system composed mainly of vegetation, substrate, filter and drainage components [1]. In this system, rainfall is first intercepted by vegetation and then temporarily stored in the substrate and drainage layer. Water that exceeds the available storage capacity is released as runoff, while retained water may later return to the atmosphere through evapotranspiration.

From this perspective, green roofs can be understood as passive physico-ecological systems. They operate through the inherent properties of vegetation, substrate layers and structural configuration, without requiring external energy input [5]. For stormwater management, this passive character is expressed through rainfall interception, temporary water storage, delayed drainage and evapotranspiration. These processes allow green roofs to act as decentralized source-control elements within urban drainage systems.

The hydrological performance of a green roof is commonly described through retention and detention. Retention refers to the part of rainfall that is held within the roof system and does not leave the roof as runoff, whereas detention refers to the temporal delay between rainfall input and runoff release [6]. Both functions are relevant for stormwater control. Retention reduces the total runoff volume entering drainage infrastructure, while detention modifies the timing of runoff and can contribute to peak discharge attenuation. Together, retention and detention modify both the volume and timing of roof runoff, as schematically shown in figure (Fig. 1.).

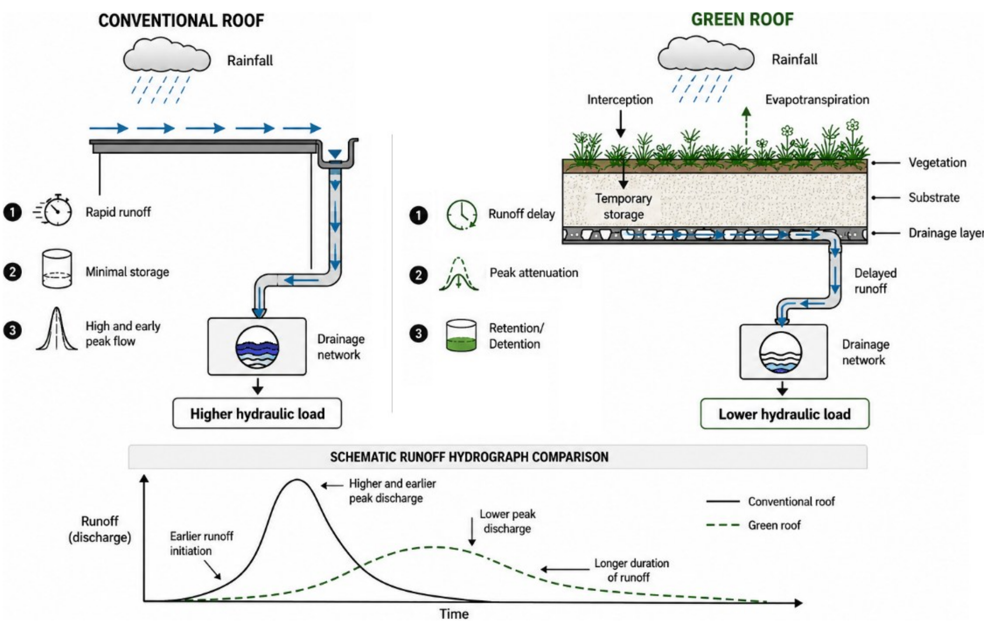

Fig. 1. Conceptual comparison of rainfall-induced runoff response from conventional and green roofs.

The practical value of green roofs therefore lies not only in reducing the amount of stormwater, but also in reshaping the runoff hydrograph. Compared with conventional roofs, green roofs can delay the beginning of runoff, reduce runoff volume and distribute the remaining runoff over a longer period [2]. This is particularly important during intense rainfall events, when rapid runoff from impervious roof surfaces may contribute to short-term hydraulic peaks in urban drainage systems.

4 Hydrological performance and controlling factors

The hydrological performance of green roofs is not constant, but varies according to rainfall characteristics, initial substrate conditions and system configuration. Rainfall depth is one of the most important controlling factors. For small rainfall events, the available storage capacity of the substrate and drainage layer may be sufficient to retain most or all of the incoming water. For larger events, once the storage capacity is approached or exceeded, the retention ratio decreases, and a greater fraction of rainfall is converted into runoff [6].

Rainfall intensity and temporal distribution also affect runoff response. A short, high-intensity event may generate a sharper hydrograph than a longer event with the same total rainfall depth, particularly when the substrate is already moist. Therefore, green roof performance should not be evaluated only through total retained volume, but also through the timing of runoff generation, peak discharge attenuation and hydrograph shape. These indicators are directly relevant for urban drainage systems, where short-term inflow peaks may determine local hydraulic surcharge.

Antecedent moisture condition is another key variable. A dry substrate provides available pore space for water storage, while a wet substrate has limited remaining retention capacity. Studies comparing identical green roof systems in different climates show that antecedent moisture condition can be a strong predictor of retention performance, because it reflects the degree to which evapotranspiration has restored storage capacity between rainfall events [7]. This means that the same rainfall event may produce different runoff responses depending on the preceding dry period and seasonal meteorological conditions.

System configuration further modifies the hydrological response. Substrate depth, substrate composition, porosity, hydraulic conductivity and vegetation cover influence both retention and detention. Deeper substrates generally provide greater potential water storage, but the improvement is not unlimited and depends on rainfall regime, initial moisture and material properties. Recent monitoring and modelling work has shown that substrate type and depth affect retention, peak attenuation and runoff delay, although the differences may be less visible when rainfall is dominated by small events or when antecedent dry periods are short [8].

For urban stormwater control, the most useful assessment should therefore combine several indicators: rainfall depth and intensity, antecedent moisture or dry weather period, runoff volume, retention ratio, time to runoff initiation, peak discharge and runoff delay. Such a combined interpretation avoids overestimating green roof performance from average retention values alone and better reflects the dynamic response of the roof as a hydrological control element.

5 Implications for urban drainage systems

For urban drainage systems, the value of green roofs depends on their ability to reduce both runoff volume and short-term hydraulic peaks. Average annual retention values are useful for describing the general water balance, but they are not sufficient for drainage design. During intense or extreme rainfall events, the available storage capacity of the roof may already be partly depleted, and the resulting runoff response can differ substantially from average conditions. Therefore, performance assessment should distinguish between routine rainfall events and events that are critical for drainage infrastructure.

A key limitation in practical design is the assumption that a rainfall event with a given return period produces a runoff response with the same return period. Long-term observations indicate that this assumption may not be appropriate for green roofs, because the runoff response depends not only on rainfall intensity and duration, but also on antecedent substrate water content [9]. An extreme rainfall event does not necessarily generate an extreme runoff event if the substrate has sufficient available storage. Conversely, a less extreme rainfall event may produce substantial runoff when the roof is already wet.

This has important consequences for the interpretation of design storms. For conventional impervious roofs, the rainfall-runoff transformation is relatively direct. For green roofs, however, the response is mediated by storage, evapotranspiration recovery and drainage processes. As a result, drainage-oriented assessment should consider not only rainfall intensity-duration-frequency data, but also runoff volume, runoff delay, peak discharge and the moisture state of the roof before the event. In this sense, green roofs should be evaluated as dynamic hydrological control elements rather than as surfaces with a fixed runoff coefficient.

The integration of green roofs into urban drainage strategies is therefore most effective when they are considered as part of a wider treatment train. A single roof cannot eliminate the hydrological consequences of urbanization, especially during extreme events. However, when combined with other distributed measures, green roofs can contribute to reducing runoff at the source, delaying inflow to drainage networks and improving the resilience of urban water systems. Their contribution is particularly relevant in dense urban areas, where additional ground-level space for stormwater measures is limited.

6 Conclusions

Urbanization alters the hydrological functioning of built-up catchments by increasing the proportion of impervious surfaces, reducing opportunities for infiltration and accelerating the transfer of rainfall into drainage systems. These changes increase runoff volumes, shorten response times and intensify hydraulic pressure on urban drainage infrastructure. Within this context, green roofs represent a relevant source-control measure because they modify the rainfall-runoff process directly at the roof surface, before stormwater enters gutters, downpipes and sewer networks. Their hydrological function is based on the interaction of rainfall interception, temporary storage in vegetation and substrate layers, delayed drainage and evapotranspiration during subsequent dry periods.

The evaluation of green roof performance should therefore move beyond the use of average retention values alone. Although retention is an important indicator of stormwater volume reduction, it does not fully describe the dynamic behaviour of the roof during individual rainfall events. For stormwater management purposes, green roofs should be assessed using a broader set of event-scale indicators, including rainfall depth and intensity, antecedent moisture conditions, runoff volume, time to runoff initiation, peak discharge attenuation and runoff delay. Such indicators provide a more complete description of how green roofs influence both the magnitude and timing of runoff entering drainage systems.

Green roofs cannot fully compensate for the hydrological impacts of urbanization, particularly during extreme rainfall events when storage capacity may be limited by antecedent wet conditions. Their contribution should therefore be interpreted realistically: they are not standalone flood-protection measures, but functional components of a wider stormwater management strategy. When integrated with other distributed measures, green roofs can reduce runoff at the source, delay inflow into drainage networks and contribute to the overall resilience of urban water systems. Their practical value is strongest in dense urban areas, where ground-level space for conventional stormwater measures is limited and roof surfaces remain an underused part of the urban hydrological system.

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