Design, Construction and Maintenance of Green Roofs

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Urbanisation affects the water cycle and heat balance in a negative way. Vegetated roofs have the potential to minimise the effects of urbanisation. Converting concrete and tiles roofs into green roofs can increase green urban areas and has the potential to reverse such effects, so the design, construction and maintenance of green roofs are very important.

Keywords: urbanisation ; SDG ; green roof ; retention ; detention

1. Introduction

Currently four billion people live in urban areas in comparison to two billion in 1985 [1]. Such numbers are forecasted to rise to 6.68 billion by 2050, which is 68% of the world's population. This rapid urbanization coupled with climate change effects has led to several primary adverse effects such as waterlogging and flooding, Urban Heat Island (UHI) effects, loss of biodiversity and air pollution. These primary effects result in negative impacts on the physical and mental health of urban residents [2].

The land required for urban development is obtained by destroying forest, agricultural and farming lands. This process adversely affects the catchment hydrology by converting a permeable surface to an impermeable one and reducing evapotranspiration. Razzaghmanesh et al. [3] reported that between 62% and 90% of rainfall becomes runoff from conventional rooftops, with the runoff percentage increasing with tiled and higher degrees of roof slopes. These urbanisation-induced changes in land use/land cover increase the potential for pluvial flash flooding [4]. Such floods have resulted in significant economic losses and casualties worldwide over the past two decades [5]. In China, urban pluvial flash floods have been reported to cause a significant loss of lives and damages to property in megacities such as Shanghai, Wuhan, Shenzhen, Tianjin and Beijing [6].

In terms of water quality, approximately 30 to 50% of the world's surface water has been affected by urban stormwater or other types of pollution since the last century [7]. Non-point source pollution in conjunction with pluvial flooding and combined sewer overflows are reported to be a major threat to human life and property [8]. The heavy metal and polycyclic aromatic hydrocarbons (PAHs) associated with stormwater can cause acute toxicity and may be carcinogenic to humans—salt components such as bromide and chloride can disrupt the nervous system and nitrogen and phosphorus can cause the eutrophication of water bodies [9].

Green infrastructure not only provides stormwater management and air quality improvement, but also provides social benefits which are not easily quantified, such as community cohesion, stress and anxiety reduction and educational benefits [10][11][12][13]. Green infrastructure is also demonstrated as a key to improved public health, as evidenced by recent medical research which suggests that green infrastructure contributes positively to a stronger immune system [14]. A schematic of available green infrastructure types and their effectiveness are shown in **Table 1**.

Table 1. Green infrastructure practices and benefits.

Practice	Stormwater Management		Community Benefits							Footprin
	Improves Quality	Reduces Quantity	Improves Air Quality	Reduces Atmospheric CO_2	Reduce Urban Heat Island Effect	Increase Recreational Opportunity	Improves Community Cohesion	Urban Agriculture	Improves Habitat	Minimal Retrofit
Green Roof	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tree Planting		✓	✓	✓	✓	✓	✓	✓	✓	✗
Bioretention	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗

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Permeable Pavement	✓	✓	✗	✗	✗	✗	✗	✗	✗	✓
Water harvesting	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
Stormwater basins	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗

Increased urban areas are resulting in heat island effects across many cities [15]. For example, AlDousari et al. [16] examined the impacts of changes in land use/land cover on land-surface temperature and urban heat island effects in Kuwait using artificial neural network and support vector machine models; they showed that increased urbanisation would intensify heat island effects. Rahaman et al. [17] adopted a support vector machine and cellular automata algorithms to examine the impacts of land-use change on urban heat island effects in Penang, Malaysia. Kafy et al. [18] noted that in Dhaka city of Bangladesh, the increased urbanisation from 2020 to 2030 will result in higher summer and winter temperatures by 13% and 20%, respectively. Dey et al. [19] noted that a significant increase in urban density and decrease in green cover and water bodies within Rajshahi city in Bangladesh will notably increase the temperature and heatwaves by 2040. Kafy et al. [20] noted that an increase in urban areas is causing reduced vegetation, which is resulting in a higher land-surface temperature.

Nearly 50% of the total impervious area in highly urbanised localities is comprised of building roofs [21]. While the increased trend of urbanisation and subsequent addition to the impervious surface by building roofs are inevitable, there has been a pursuit to explore ways to mitigate their adverse effects. Converting concrete and tiles roofs into green roofs can increase green urban areas [15] and has the potential to reverse such effects. The unique beauty of green roofs is that it can efficiently use the existing building footprint to improve the urban green area [22]. Green infrastructure has also been reported to have significant positive impacts on the reduction in urban heat island effects [23].

2. Design, Construction and Maintenance of Green Roofs

Simmons et al. [24] suggested that "vegetated roofs are increasingly being incorporated as a sustainable practice in building design, often without specific attention to designing the roof to achieve specific functions, or to the conditions of a specific climate".

According to the Technical Guidelines by Inner West Council (2022) of New South Wales, Australia [25], there are four key steps towards green roof construction: complete site analysis, identification of opportunities and constraints, plan and design, and construction and maintenance. These topic areas along with other key design and maintenance issues are discussed below.

i. Complete Site Analysis and Review Site Analysis to Identify Opportunities and Constraints

Site analysis is the most critical factor in designing a green roof. The regional, landscape and site scale need to be considered for the selection of the right type of green roof [26], followed by a thorough review considering plant types based on sunlight and water requirements and cold tolerance [27].

Secondly, properties of new or existing structures on which the green roof is to be built need to be investigated. This should consider the size and slope of green roofs and whether there are any existing plants or equipment, which then leads onto the structural loading. Depending on the budget and loading, there may be an opportunity of integrating solar panels with green roofs. Thirdly, access and constraints for both during construction and long-term maintenance need to be considered. Maintenance is required for plants, irrigation systems, structures and drainage systems. Fourthly, reviewing council planning maps is necessary to identify any heritage requirements of the site. Fifth, water aspects including drainage and irrigation requirements need to be looked at, and lastly, biodiversity, flora and fauna need to be carefully considered. Recently, a law was passed in France mandating new rooftops in commercial buildings to be covered either in greens or solar panels; in 2014, the city of Sydney adopted the green roof and walls policy [28].

ii. Plan and Design

Specialist consultant advice should be sought for the design and documentation of green roofs. Depending on the size of the project, the engagement of a project manager, architect, landscape architect and a civil and structural engineer, and specialist consultants may be required. The benefits of using suitably experienced consultants on green roofs will generally result in a smoother, straight forward design, approval and construction process.

Secondly, local planning requirements and building standards need to be looked at and design objectives including water retention, detention, quality and thermal efficiency need to be considered; in addition, building rating systems need to be considered, irrigation and drainage systems should be thoroughly investigated and maintenance and access need to be planned. Finally, options for co-locating sustainable energy systems need to be considered. Additionally, careful consideration is required for the cost and use of recycled materials.

Design of a green roof system can largely be subdivided into the following categories:

iii. Plant Selection

Plant selection and substrate types and depths should be carried out from locally available guidelines. Plant selection depends on several factors including site conditions and design objectives. Plants adopted on extensive green roofs are typically shallow and fibrous-rooted, and are types of succulents and grasses. Extensive knowledge on plant selection is critical to the design and survival of successful green roofs [29]. Across North America, succulents were found to be the most successful plant species to be able to survive on the harsh roof-top environment.

Sedum showed very successful growth in most states of the US, whereas mixed results were observed in a few areas. Where Sedum roots suffered from low temperature and freezing at some locations, they performed poorly in hot and humid regions [30].

iv. Green Roof Design Elements and Components

The key component—apart from the substrate depth—is the growth media characteristics: materials, distribution of granular particle size, organic and nutrient contents, pH and permeability rates. Further research is required on the type of fabrics.

v. Growth Media Type and Thickness

Succulents were found best on 7 to 10 cm of media but were found to tolerate 5 cm depth as well. In another eco-region, plants sustaining on 2.5 to 5 cm shallow substrates were also reported [31]. Geosynthetics were found to be as critically important for managing moisture [32]. Grass and herbaceous green roof covers generally needed a substrate depth of 15 to 20 cm.

vi. Construction

A safety in design exercise must be completed considering the following Australian Acts:

- Work, Health and Safety Act 2011; and
- Work, Health and Safety Regulation 2017.

Risks and hazards during and after construction must be identified and designed out as far as possible during the concept and detailed design phases. During construction, waterproofing is one of the most important aspects. The growing medium should possess the following characteristics: efficient moisture retention, well aerated and drained, ability to absorb and supply nutrients, provide anchorage for plants, be lightweight and fire-resistant. The construction should be carried out by suitable professionals experienced in constructing green roofs.

vii. Use and Maintenance

As roof tops are not often visited by humans, green roofs are found to be a good habitat for birdlife; in addition, many species of spiders and butterflies are often observed. Two branches of knowledge are extremely critical for the selection of the right plant type: horticulture and ecology. Horticulture could be useful for selecting the right plant type, whereas ecology could be useful for setting up the right symbiotic relationship.

A suitable maintenance plan for the green roof needs to be designed and adhered to for the successful implementation of the green roof. The maintenance regime can be broken down into four phases: establishment maintenance, routine maintenance, cyclic maintenance and reactive/preventative maintenance. To ensure success of the green roof, plants need to receive proper levels of fertiliser depending on the requirements of each species. For larger projects, warranty and guarantee from the manufacturers, suppliers and installers and a suitable defect liability period need to be selected.

viii.End of Life Scenario

Besides the critical factors for establishing a successful green roof, it is also equally important to consider the end-of-life scenario [33]. The green roof soil layers may be reused for agriculture. As per Butler et al. [34], incineration is recommended to be excluded due to the presence of a large amount of inert material. The potential presence of peat in green roof materials makes landfill a suitable disposal location of green roof materials. The end-of-life cost and management involve three steps: identification of products involved, identification of potential waste scenario and determination of cost hypotheses for each case study [35].

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