MAURITIUS RESEARCH COUNCIL

GREEN ROOFS FOR MAURITIUS

Final Report

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Green roofs for Mauritius

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Preface

This guidebook presents information on green roofs, specifically extensive green roofs, as applied in Mauritius, with a focus on the benefits that can be reaped and modifications needed to the current way our buildings are built for the installation of green roofs on our buildings. Research areas are also identified to better understand the characteristics and implications of green roofs when installed in Mauritius.

The place of green roofs as a sustainable component of the built environment is irrefutable, and the main goal of this research work is to make a preliminary assessment of what can be expected from green roofs and pave the way for its integration in Mauritius. Based on results reported in literature, it is hoped green roofs will help to improve stormwater management and energy performance of our buildings, to develop better resilience to flash floods and provide more comfortable indoor environments without the use of active cooling, and from a socio-economic point of view, make better use of our land since roofs are areas generally unutilised in Mauritius, and several households do not have access to a green area at their place due to land scarcity.

We hope this project work will be a useful resource for future research works in this field, and also act as a motivator to implement Mauritian green roofs as it is our belief that they have a lot to offer to our built and natural landscape.

Acknowledgement

Funded under the Unsolicited Research Grant Scheme of the Mauritius Research Council (MRC), this guidebook has been developed by Prodesign Engineering Consultants Ltd.

Prodesign is a multidisciplinary firm of consulting engineers. Since 1997, Prodesign has specialized in sustainability and MEP (Mechanical, Electrical and Plumbing) design and consultancy services for building and infrastructure projects.

This guidebook is the outcome of a yearlong research in green roof systems design and associated technologies. A review of international best practices and related research works was carried out, in view to gathering information on materials that have been used as the various layers of a green roof and benefits reported in terms of stormwater management and energy conservation/thermal comfort. Based on the literature review and survey of local stakeholder (both public and private), a preliminary investigation of the current state of green roofs in Mauritius has been performed, with clear information on the availability of technologies needed to set up green roofs, and gaps in knowledge to be resolved through research projects in identified research areas.

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Illustrator: Isstiac Gooljiar

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Nomenclature

Drainage Layer – Layer that effectively channels rainwater from any area of the green roof to the rain outlets.

Filter Layer – Layer between the substrate and the drainage layer to prevent the substrate from getting carried away into the drainage layer and to the rain outlets.

Green roof – A roof completely or partially covered with vegetation planted in a suitable substrate, and typically consisting of a filter layer, drainage layer, protection mat and root-proof waterproofing membrane.

Peak discharge – Maximum run-off generated over a period or a given point in time.

Protection Mat – Layer between the drainage layer and the waterproofing membrane to protect the latter.

Root-resistant – cannot be pierced by roots of plant, in the context of green roofs, relates to the waterproofing membrane.

Run-off – water generated when rain falls on impermeable surfaces.

Stormwater – Stormwater is differentiated from rainwater although both originates from rain; the former relates to an undesirable rain event due to its high intensity.

Stormwater Quality – The quality of the stormwater relates to particulate matter carried into the run-off consisting of chemicals and debris.

Stormwater Quantity – The quantity of the stormwater is related to the intensity of the rain and describes the volume over a given period and rate of the run-off generated.

Substrate – Growing medium for plants in a green roof, generally not soil-based, and consisting of organic and inorganic components.

Chapter 1: Introduction: Green Roofs

Ancient green roofs were covered with earth and plants for agriculture. The main motivation for having green roof was to provide for cold insulation in winter, heat insulation in summer and shelter against natural elements. Some green roofs were made in this manner due to lack of alternative materials. Traditional green roofs were not waterproof. This became the subject for innovation which led to the green roofs technology we have nowadays, where much emphasis is laid on the water-proofness of the roof and the root-proofness of the waterproofing membrane so that it can safely accommodate plants.

Commercialisation of green roof systems looked at the problem of root ingress into the roof structure and the provision of irrigation networks to sustain the plants. The next evolution in green roof was to provide systems which replicated the functioning of soil as the base medium for plants to grow but doing so with a lighter and cheaper solution which could be applied over a larger roof surface without undue changes in the building structure to take up the additional load. This led to the concept of extensive green roofs, which could be applied to roof surfaces to replicate nature (which was displaced due to the built environment) while protecting the roof surface from natural elements and temperature fluctuations.

Ecological benefits like reduction in energy consumption for HVAC (Heating, Ventilation and Air-Conditioning), stormwater retention, urban heat island effect mitigation and acoustic attenuation are other benefits that were revealed when the scientific community started studying green roofs closer. These added benefits have led to the widespread appeal for green roofs for its ecological and welfare it brings to humans with reported therapeutic benefits while providing air of better quality.

1.1 General benefits of green roofs

Installing a green roof does not benefit only the building owner but also, the community at large.

Table 1-1: Benefits of Green Roof

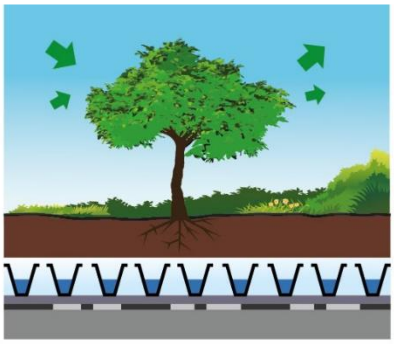
Building User Benefits	Community Benefits
Adds to the aesthetics of the development leading to an increase in property value.	Reduced urban heat island effect
Creation of an outdoor functional space	Stormwater retention and management
Increasing the roof lifespan and reducing renovation costs.	Improved urban air quality through filtration by vegetation
Improved overall energy efficiency of the building (reduction in cooling load, better photovoltaic performance when installed on green roofs)	Carbon sequestration
Acoustic insulation	Possibility for food production

The benefits can also be grouped according to the environmental, social and economic aspects of sustainability as depicted by the following illustrations.

1.1.1 Ecological benefits

Provides Rainwater Management

Depending on the green roof design, the immediate water run-off can be reduced by 50–90 %, greatly reducing drainage flow rates. This enables the rainwater management system to be reduced in capacity, thereby greatly reducing construction costs.



Improves the Microclimate

Green roofs cool and humidify the surrounding air. Thus they create a beneficial microclimate within their immediate area and contribute to improving the microclimate in urban centres. Coordinated urban green roof development can significantly reduce the so-called "Heat Island" effect.

Binds Dust and Toxic Particles

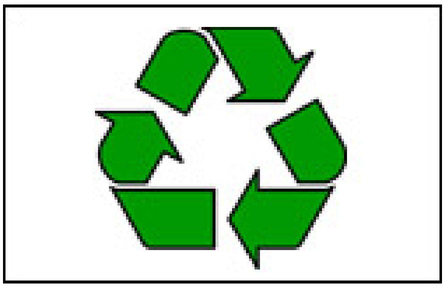
Green roof vegetation helps to filter out dust and smog particles. Nitrates and other harmful materials are absorbed by the plants out of the air and rainfall and bound within the substrate.

Improves Noise Protection

Planted areas are natural sound insulators and absorb more sound than hard surfaces. Green roofs reduce reflective sound by up to 3 dB and improve sound insulation by up to 8 dB. This is very effective for buildings near airports, noisy nightclubs and factories.

Provides Natural Biodiverse Habitats

Landscaped roofs compensate for green spaces, which are lost to building development. They provide natural habitats for wildlife and bring nature back into the cities.



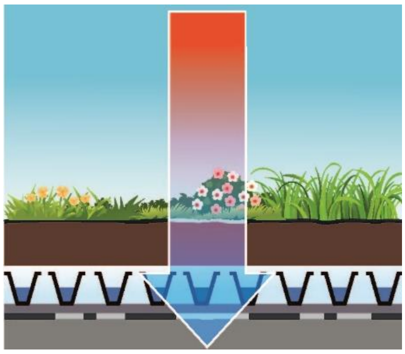
Supports Recycling

Green roofs make extensive use of recycled and recyclable products, saving further valuable resources. Rubber, polyethylene and expanded polystyrene rigid foam are used in the production of drainage elements.

1.1.2 Economic benefits

Reduces Energy Costs

A green roof has the ability to buffer temperature extremes and improve the buildings energy performance.



Increases Water Retention

A green roof can reduce water run-off by 50–90 %; any remaining water flows from the roof with a delay. Outlets, pipes and drains can be reduced in capacity, thereby saving construction costs. Sewer costs can be reduced in some areas.

Reduces Renovation Costs

A green roof protects the waterproofing from climate extremes. UV exposure and mechanical damage. This greatly increases the life expectancy of the waterproofing and results in reduced maintenance and replacements costs.

1.1.3 Social benefits

Provides Additional Space

Converting or designing normally unused areas into green roofs, particularly for recreational or sporting use not only makes use of expensive space, but saves the costs of purchasing additional land. Green roofs often assist in gaining planning consent.

1.2 Project Scope

This project aims to survey the local market to identify the available technologies and the challenges that need to be overcome to realise green roof projects in Mauritius. Various stakeholders from the private and public were interviewed to understand the current context and what needs to be done or addressed to overcome any shortcomings. Based on literature review of the extensive amount of research work performed in the field of green roofs, a preliminary investigation is carried out to quantify the achievable benefits of green roofs in terms of stormwater management and energy savings/thermal comfort. Finally, design considerations for green roofs in Mauritius, together with areas of research which need to be looked at are indicated. Design variants of green roofs are given to suit specific preferences among the various purposes a green roof can be installed for.

1.3 Outline of guidebook

Chapter one of this report has introduced the general subject matter and provided an overview of the main benefits of green roofs. The project scope, leading to aims and objectives, has been set.

Chapter two describes green roofs around the world, with a focus on variants in green roof design. The main findings reported in literature on energy savings and stormwater management of green roofs are given, which are subsequently applied for the Mauritian context to generate preliminary figures on achievable benefits in these two main aspects.

Chapter three presents the considerations for green roof design in Mauritius, based on survey of private and public stakeholders in Mauritius. Recommendations for changes in building regulations for allowing installation of green roofs are provided. Moreover, design variants are given to suit the differing needs or functions of green roofs, namely thermal comfort, stormwater management, green roof for agriculture and drought resistant green roof.

Chapter four describes the stormwater management aspects of green roofs.

Chapter five looks at the thermal comfort aspects of green roofs.

Chapter six concludes the project work.

Appendix A provides information on water test on roof

Chapter 2: Green roofs around the world

2.1 Introduction

Green roofing systems have been around for a very long time. Some literatures cite the pre-historic village of Skara Bay in Scotland [1] and the hanging gardens of Babylon as the earliest forms of green roofs [2]. In more recent times (18^{th}-19^{th} century), green roofs have been predominantly used in cold climates such as the Scandinavian countries, Northern America, Britain, Germany and many others [2]. These early forms of green roofs had turf as the vegetative cover and were mainly used to shelter humans from the caprices of the weather. Excavations in the ruin of Pompeii have provided evidence of roof gardens being used in warmer climates [3].

The twentieth and twenty-first century is seeing a revival of green roofs. Such roofing systems have become a widely-accepted feature of eco-buildings. Moreover, new construction materials that have been developed are more suitable to meet the load bearing and waterproofing capabilities required by green roofs [3]. In Mauritius, green roofing systems are relatively new although roof gardening practices are very popular.

2.2 Definition

During the literature review, it was observed that there seemed to be a confusion between roof gardening and green roofs. Though very similar and having more or less the same benefits, there is a fundamental difference in their construction [4].

Roof gardens are defined as the cultivation of decorative plants or food crops in containers, which can be of varying size [5]. Examples of containers that can be used in Mauritius are: plastic “gallons”, paint pails, wooden crates or veggie bags [6]. Green roofs on the other hand, consist at least of the following layers: waterproofing, drainage, growing media and the vegetative cover [5, 7].

The advantage of having a green roof over a roof garden have been described as follows [5]:

- Even weight distribution over the roof
- Unimpeded drainage
- Various layers provide a protection for the roof.

This research project will focus on the design of green roofs in Mauritius. However, it is to be noted that some of the outcomes of the research will also be applicable to roof gardening.

2.3 Types of green roof

2.3.1 Extensive, intensive and semi-intensive

Green roofs are generally divided into either extensive or intensive. Intensive green roofs have deep substrate layers, and support larger plants, and require frequent maintenance. Extensive green roofs have a thinner substrate layer and smaller plants, typically plants providing groundcover are used. They are targeted to be maintenance free or very little maintenance as compared to intensive green roofs. Semi-intensive green roofs have also been described, which use plants providing groundcover and lawn, but which required frequent maintenance in terms of watering, cutting and fertilisation. Extensive and intensive green roofs can be differentiated by the type of vegetative cover. Table 1 shows the characteristics of the different types of green roofs.

Table 2-1: Characteristics of green roofs [3, 7, 8]

Extensive roof	Intensive roof	Semi-intensive roof
< 150 mm deep	> 150 mm deep	Between 150 and 200 mm deep
Low saturated weight (70 – 170 kg/m2)	High saturated weight (290 – 970 kg/m^2)	Intermediate saturated weight (170 – 290 kg/m^2)
Low plant diversity: Moss, sedum, herbs and grasses	Greatest plant diversity: lawn, perennials, shrubs and trees	Average plant diversity – grass, herbs and shrubs
Inaccessible to building users	Easily accessible	Partially accessible by building users
Low maintenance	High maintenance	Average maintenance
Low	High	varies

As can be deduced from table 2-1, extensive green roofs are the simplest to install. They are usually used more as an ecological protection layer. Intensive green roofs on the other hand, require specialist design attention and act more like rooftop parks. Semi-intensive green roofs are a mix of extensive and intensive green roofs and can be designed to achieve certain specific benefits.

2.3.2 Built-in vs. modular

Another type of classification categorises green roofs as built-ins or modular type green roofs, based on the construction method used [7].

A built-in green roof consists of a series of layers which are installed on site. They typically take a longer time to install and to establish the vegetative cover. They could be more difficult to design and install but are generally less costly [7, 9].

Modular systems on the other hand, are pre-planted trays already covered with vegetation that can be purchased. These trays are made of lightweight high density polyethylene and contain the different layers of the green roof. They come in varying sizes and typically require a higher capital investment. Nevertheless, modular green roofs are popular as [7, 9]:

- Simple design and installation
- An immediate green roof is available
- Can be easily re-adjusted and implemented on retrofits
- Off-site planting possible – this allows a year-round installation of green roofs as plant and root establishment has already occurred
- Different substrate and soil mixture and different soil depths in each module allows for greater plant diversity
- Allows the use of conventional irrigation systems
- Increased capacity of air and water flow

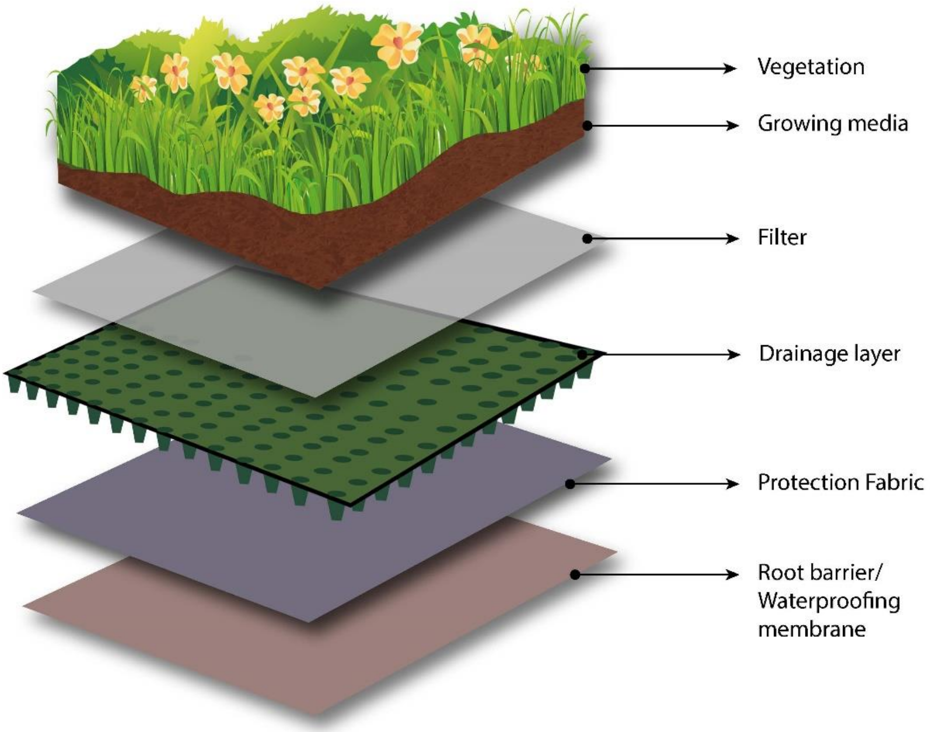


Figure 2-1: Layers of Green Roof

2.4 Components of the green roof

The different components of a green roof aim to mimic the functions of natural soil, i.e., storing and providing water and nutrients to plants while allowing transpiration and drainage [15]. In a green roof system, these are achieved by the drainage layer, reservoir layer and the growing substrate. In addition, a green roof assembly consists of additional layers which are required to protect the building from structural and water damages.

2.4.1 Roof deck

Green roofs can be applied either on concrete, steel or wooden roofs [16]. Since in Mauritius, concrete roof is more common, the focus is on concrete roofs.

For concrete roofs, it is recommended that the substrates used are properly cured and that the surface is dry before application of the waterproofing. To check for the dryness of the concrete deck, an adhesion test should be conducted before application of the waterproofing. This adhesion test consists of applying a small patch of waterproofing membrane, allowing to cure and then peeling it away. Although this is not a standardised test, it does give a very good indication of how adhesion is affected by dust, oil and moisture. In addition to the adhesion test, the contractor should also perform any dryness and adhesion test recommended by the waterproofing membrane manufacturer [16].

In the case of steel and wooden roofs, the NRCA (National Roofing Contractor Association, US) recommends using a moisture resistant gypsum board or cementitious board on top of the roof, before installing the green roof. More details can be found in the NRCA Green Roof Systems Manual [16].

The inclination/deflection of the roof is an important factor in determining its suitability for implementing and retrofitting green roofs. A structural engineer should advise on the recommended deflection of the roof deck so as to minimise the risk of water ponding [16].

2.4.2 Waterproofing

Our literature review reveals that waterproofing is the most critical component of the green roof. In the absence of a good waterproofing, the risk of leakage and hence damage to the building is very high. Hence, it is not recommended to install a green roof system without any waterproofing.

Different types of waterproofing can be used for the installation of a green roof [7, 15, 16, 17, 18]. Although some waterproofing products have been specifically designed for green roofs, more conventional waterproofing membranes can also be used. In the engineered green roof waterproofing membranes, a root barrier (chemical or metal foil) has been inserted between the membrane layers so as to prevent root ingress [7, 16]. More conventional forms of waterproofing membranes that can be used are [16]:

Table 2-2: Waterproofing membranes

Type of membrane	Description	Standards to adhere to
Hot fluid applied Polymer modified asphalt membrane	Consists of refined asphalt, synthetic rubbers and extenders. This membrane comes in the form of a cake which has to be melted before application. After application, the membrane should be fabric-reinforced.	As per manufacturer's specifications
APP and SBS-polymer modified bitumen sheet membrane	Composed of polymer modified asphalt and several layers of reinforcing material. To be used for green roofs, these membranes should be at least two plies.	Reference: Page 36 NRCA green roof guide (table)
EPDM membrane	These are factory fabricated sheets of ethylene propylene diene monomer (EPDM). These membranes cannot be used with bituminous cements and mastics as well as with certain acids and greases. The membrane manufacturer should be consulted to determine the impact of contaminants on the membrane. For green roof application, the membrane installed should be at least 60 mm.	ASTM D6134, Type I – for vulcanised rubber sheets
PVC membrane	Factory fabricated reinforced PCV sheets with a minimum thickness of 80 mm, with stripped laps can be used. When used for green roof, they should adhere to the roof and not be mechanically attached or loose-laid.	None
Elastomeric membranes	These can be one or two fluid applied membranes. They consist of a high solids content polyurethane elastomer in liquid form. When used for green roof, these membranes should be fabric reinforced.	High solids elastomeric membrane: ASTM C836 and ASTM C957 Neoprene and chlorosulphonated polyethylene: ASTM D3468

Before proceeding with the other components of the green roof, the water integrity of the water proofing should be tested. This can be done in two ways:

1. Standing water test
2. Flowing water test

More details on the water integrity test can be found in **Appendix A**.

2.4.3 Root barrier

Root barrier prevent the migration of roots from damaging the waterproofing layer. They can be in the form of root inhibiting substances such as copper sulphates or physical barriers such as high density polyethylene boards. Root barriers are usually combined with the protection course or the drainage course. Some new waterproofing membranes which have been developed for green roofs already contain some form of root barrier [16, 17, 18].

2.4.4 Protection layer

This is an optional layer which gives an added protection to the waterproofing layer [16, 19]. Their use is dependent on the risk of damage of the membrane during green roof installation by contractors and other services being installed on the roof. Materials that can be used as a protection course are:

- Asphaltic boards
- Asphaltic sheets
- Extruded polystyrene boards
- PVC sheets

Water permeable mats made of high density polyester and polypropylene are also used. The protection course is placed directly on top of root resistant waterproofing membranes or above the root barrier layer [18].

2.4.5 Drainage layer

In a green roofing system, the drainage layer is primarily used to evacuate excess rainwater from the roofing surface [16]. When it rains, water is absorbed and retained in the growing medium. Once the growing medium is saturated, excess water will tend to accumulate and be retained in the layers below the growing medium. The additional water load may compromise the structural integrity of the building [16]. Hence a drainage system is required to effectively channel the excess rainwater and prevent ponding.

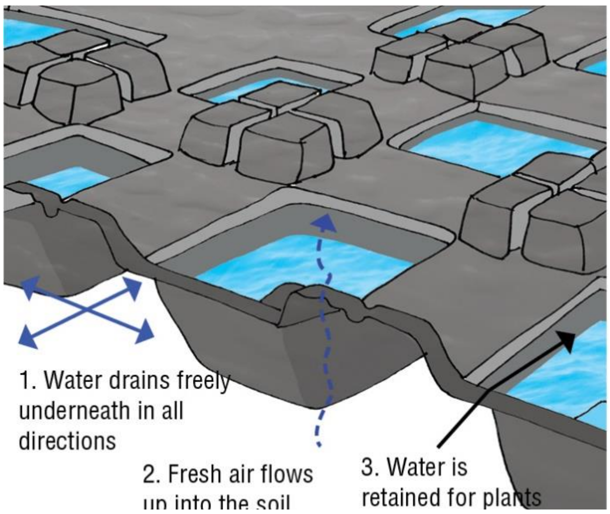


Figure 2-2: Working principles of drainage layer [7]

Traditionally, permeable aggregates such as scoria and gravel were used as the drainage layer. This drainage layer was separated from the growing medium by a filter sheet, to prevent blockages. Newer and more modern drainage layers have been designed to [7]:

- Allow water to drain free in all directions
- Allow air to flow through the soil
- Retain and store water

These drainage layers can be in the form of drainage mats or insulating drainage panels. Three types of drainage materials commonly used are [17]:

- Granular – coarse materials such as gravel, stone chips, broken clay tiles, scoria, pumice can be used. When packed together, large pockets of air are created. This pore space allows water to run through freely. This is the most simple and low tech drainage system for green roofs.
- Porous mats – porous mats essentially act as sponge: they absorb water. Different materials have been used for porous mats including cloth and used car seats.
- Lightweight polystyrene or plastic modules – different proprietary products are available on the market for these drainage systems. These plastic modules can be rigid, open meshed or have an egg-crate design [7]. The popularity of the egg-crate design is increasing as the cups allow the retention of water. The depth of the cup is dependent on the type of green roof and plant species chosen for the green roof. For an extensive green roof with drought resisting plants, the water retention requirement is very low and hence the cups do not need to be very deep. On the other hand, for intensive green roofs, deeper cups are required to meet the plants' water needs.

Insulating drainage panels can also be used and consist of high density moisture resistant insulating boards with grooves so as to channel excess water [16].

The use of rubber crumbs (from used tyres) has been studied (Use of rubber crumbs as drainage layer in green roofs as potential energy improvement material) by Perez et al. [20] and found to yield comparable thermal and hydraulic performance as conventional gravel-based drainage layer. This can be beneficially used to recycle waste tyres, which need to be shredded to rubber crumbs.

During installation, it is preferred to apply the drainage layer as a continuous layer.

2.4.6 Insulation layer

This is an optional layer. As the name suggests, it is used to improve the thermal performance of the green roof assembly. In cold climates, addition of insulation helps reduce heat loss while in hot and warm climates, insulation help reduce heat gains through the roof.

The NRCA recommends using moisture resistant extruded polystyrene (XPS) rather than expanded polystyrene (EPS) for the green roof. Because of its tendency to retain water and increase the weight of the green roof assembly, EPS is used as a fill rather than the primary insulation [16]. However, the popularity of XPS is decreasing due to its environmental impacts during manufacture and eventual disposal [17].

The insulation layer can be installed above or below the waterproofing layer. However NRCA recommended to place the insulation above the waterproofing layer. In this way, the insulation provides thermal protection for the membrane and helps to extend the lifespan of the membrane. Having the insulation layer above the waterproofing layer also helps maintain the growing medium temperature closer to the outdoor temperatures [16] and [18].

Polyisocyannurate insulating boards are recommended to be used below the waterproofing layer. As an additional precautionary measure, moisture resistant gypsum board should be installed on top of the insulating boards [16].

The growing media used can also act as an insulation layer. As a general rule a high moisture content and low density soil indicates greater insulation potential [16].

A building services engineer should be consulted in order to determine the type and thickness of insulation required for a particular building [18].

2.4.7 Aeration layer

This layer is required when insulation is being used in the green roof assembly. The role of the aeration layer is to allow the insulation to retain its R-value (thermal resistivity). This is achieved by:

- Allowing air movement
- Allowing moisture to drain off.

The aeration layer acts in a very similar way to the drainage layer and can be made of the same material. [16]

2.4.8 Moisture retention layer or reservoir layer

This layer can be in the form of an absorptive mat (made from recycled polypropylene fibres) or can be integrated with the drainage layer (egg-crate drainage layer). On intensive green roofs, aggregates are also used in this layer to help retain water. On steep sloped roofs, the reservoir layer helps prevent rapid drainage of water [16].

2.4.9 Filter fabric

Filter fabric separates the growing media from the layers beneath. It prevents the clogging of the drainage layer by fine soil particles. It is an integral part of any green roof system. Also known as geotextiles, the filter sheet is a tightly woven fabric made of polyester or polyethylene. The filter sheet should be installed immediately before placing the growing medium (substrate) [7, 16, 17].

2.4.10 Engineered soil based growth medium

The growing substrate or medium has to provide the right amount of nutrients for the plant species being used on the green roof. The substrate is usually a mix of mineral, organic and synthetics. The blend of mineral, organic and synthetic has to be carefully selected so as to provide the adequate amount of carbon and nitrogen for the plants to flourish. Moreover, the blended substrate also needs to be able to hold enough water so as to sustain the different plant forms on the green roof [16, 17, 18].

Table 2-3: Properties of green roof substrates

Properties of green roof growing substrates		
	Extensive	**Intensive**
Clay and silt content	< 15% by mass	<20% by mass
Proportion of particles > 4mm in diameter	< 50% by mass	< 40% by mass
Organic matter	< 65 g/L (FLL) 10-25% (CUGE)	< 90 g/L (FLL) 5-10% (CUGE)
Settling	No more than 10% of nominal depth	Average < 5cm for substrates at least 50cm deep
Water permeability	0.6 – 7.0 mm/min	0.3 – 30 mm/min
Water storage capacity	> 35% by volume	> 45% by volume (maximum of 65%)
Air-filled porosity	> 10%	> 10%
pH	6.0 – 8.5	6.0 – 8.5
Total soluble salts	1.5 – 3.5 g/L	1.5 – 2.5 g/L

Typical components of the growing medium consist of scoria, ash, pumice, sand, coir, tree barks, porous and chemically inert foam, crushed bricks and roof tiles. In general, the higher the proportion of inorganics the more stable the substrate. The following tables give data related to substrates and their composition [18].

Table 2-4: Materials used in green roof substrates

Comparison of materials used in green roof growing substrates and their saturated bulk density				
Material	**Component**	**Why used**	**Saturated bulk density (kg/m^3)**	**Dry bulk density (kg/m^3)**
Recycled waste products	Ash	Waste product	1160 - 1310	640 - 900
	Organic materials (e.g. coir, pine bark, compost)	Waste product, water retention, CEC	930 - 1100	50 - 360
	Crushed ceramics (brick, roof tile)	Longevity, recycled	1090 - 1300	1640 - 1720
Quarried products	Scoria aggregate rock	Longevity	1290 - 1560	670 - 1000
	Scoria non-descript crushed rock	Longevity	1530 - 1730	1030 – 1270
Inert volcanic products	Perlite	Lightweight	500-800	40
	Pumice	Longevity, porous, lightweight	540-753	260-490
Synthetic additives	Hydrocell	Inert, water retention	660	27
Loamy topsoil			1700-2400	1000-1900
Sand			1800-2200	1440-1650

Local consultations with public stakeholders such as FAREI has revealed that growing substrates for green roofs have not yet been developed. However, substrates for roof gardens and kitchen gardens are available and have been deemed to be a satisfactory substitute. Details of these substrates can be found in **Appendix B**.

2.4.11 Irrigation systems

Extensive green roofs are meant to be self-sustaining. Plant water requirements are met by rain. However during plant establishment, irrigation might be required. For intensive green roofs on the other hand, provisions should be made for an irrigation system. The design and specification of the irrigation system is site and climate dependant. Irrigation for green roofs can be of three types [17, 18]:

- Manual – the manual system is the most basic form of irrigation consisting of a long hose and a water supply.

- Fully automatic irrigation system - programmed to operate at set times with minimum human intervention. The automated irrigation system can take be either through sprinkler heads or a drip irrigation system.
- Semi-automatic irrigation systems – programmable system with manual overrides and activated on an as needs basis.

Layout of irrigation system is dependent on:

- Dispersion height
- Irrigation length
- Specific soil volume
- Dimensions of planters to be irrigated.

The design of the irrigation system for an intensive green should be done by a landscape architect [17, 18].

The following tables present the pros and cons of manual and automatic irrigation systems as applied to green roofs.

Table 2-5: Manual irrigation system

	Advantages	Disadvantages
Manual irrigation system	Reliable and robust Tried and tested Low installation costs Skilled labour not required	High labour costs. Installation of water points may be needed Watering needs to occur during working hours when more evaporation occurs. Water usage is not optimised and efficiency may be difficult to monitor. Water dispersion may be unevenly distributed.
Automatic irrigation system	Reasonable reliable Low recurrent costs Watering can occur at best times to minimise evaporation Water usage is optimised, is easier to control and monitor	High installation costs Space required for pumps and other infrastructure such as controllers. Components are more delicate and planting of vegetation needs more care so as not to damage pipework. Skilled operators are needed to understand programming of control systems.

2.5 Green Roof Permutations

The following illustrations show variants of green roofs to present few of the permutations possible with green roofs, and the associated benefits where relevant.

Figure 2-3: Green roof on flat and pitched roofs

As shown in Figure 2-3, green roofs can be designed for flat roofs as well as pitched roofs, with the latter generally costing 1.5 to 2 times more than the former.

Figure 2-4: Extensive Green Roof

Figure 2-4 shows an extensive green roof, which is generally designed for low maintenance and consists of plants providing ground cover, with shallow roots and having low water requirements.

Figure 2-5: Intensive Green Roofs, showing the possible combination of landscape with hardscape

Figure 2-5 shows the high aesthetic value of green roofs, with multifarious possibilities of merging hardscape with landscape to obtain a broad range of design options, from which clients can choose based on their specific preferences. As the need for tall plants arises, the green roof design becomes an intensive one, which is not covered in the scope of this project.

Figure 2-6: Green roofs used for farming

Figure 2-6 shows the concept of urban farming, where green roofs are used for growing vegetables and fruits. The term 'urban' tends to denote the lack of space in congested urban areas, with little space available to have a garden at ground floor, but in Mauritius this concept can be applied as land scarcity in the residential sector exists both in rural and urban areas.

Figure 2-7: Green for outdoor liveable space

Figure 2-7 shows how a green roof converts a roof into an outdoor liveable space, which shows this unique aspect of a green roof. Typically in Mauritius, roofs are not utilised, except for having a solar hot water system or a water tank; green roofs can redefine how roofs are perceived and used in Mauritius, but with it goes the aspect of safety, which is illustrated in Figure 2-8.

Figure 2-8 shows the safety aspects which should go hand in hand with green roofs. Since the installation of green roofs will mean persons will be spending more time for socialising or maintaining the vegetation, their safety should be ensured either through guardrails or harness systems. This needs to be taken up in our building regulations to address green roof design elements.

Figure 2-8: Safety systems on green roofs

Figure 2-9: Walkways and Driveways

The build-up for green roofs (drainage layer and aggregate) provides the possibility for walkways (pedestrians) and even driveways (cars, trucks and lorries), with the specification of suitable components for the various layers.

Figure 2-10: Green roofs and Solar Energy

Figure 2-10 shows the integration of green roofs with solar PV for generating electricity. In this case, the green roof system provides anchorage for the solar panels, doing away with the need to drill into the roof, and furthermore, the cooling effect provided by green roofs through evapotranspiration has been shown to yield about 5% improvement in the efficiency of the PV system.

2.6 Green roof systems with green materials

The use of bioplastics in the manufacture of green roof system layers is the next contribution to environment protection, and further enhances the sustainability value of green roofs. Bioplastics have been used to make the drainage element, protection mat and filter mat. It will be of interest to note that drainage elements have already been made using sugar cane, which could be of potential interest to Mauritius.

2.7 Stormwater Management

Roofs can account up to 40-50% of impermeable areas in urban set ups, and any measure that improves the run-off capability of these roofs in terms of run-off volume, rate, quality and delay in the peak in run-off will help in stormwater management. With the economic development every nation is aiming for and a growing world population, the increase in impermeable areas is inevitable. The need for a sustainable solution to the increased run-off created by these impermeable surfaces is pressing, and green roofs are increasingly being used as part of Sustainable Urban Drainage Systems (SUDS) [24]. In Switzerland, the sustainable benefits of green roofs have been realised to the extent that it is enforced by legislation for new and renovated premises.

The increase in built-up area leads to increased run-off volume and rate on one hand and reduced infiltration on the other, which can have severe consequences on underground water resources as high run-off rates cannot percolate to underground aquifers, and finds its way to the drain networks carrying along topsoil and useful nutrients, which adversely affect marine ecology down the line. Therefore, the sustainable solution lies in each project site managing its stormwater, and promoting infiltration of same, with little, if not, no reliance on the drain networks. Building drains to cope with the ever increasing built areas is both a technical and economical challenge for governments, and promoting site management of stormwater makes technical, economical and the only viable solution to restore the natural water cycle that prevailed before the construction.

The two main factors that affect stormwater management of green roofs are the actual design of the green roof itself (substrate type and depth, vegetation cover, roof geometry) and the prevailing climatic conditions. It is generally believed in the research community that the effective design of green roofs is very context dependent, and extensive research is needed to customise green roof for a particular region, be it in terms of substrate to be used or plants to be used. Moreover, the benefits reaped from green roofs need further investigation to be able to make definite deductions, and is highly likely to be specific to the particular region of Mauritius it is being designed for.

2.7.1 Stormwater Quantity

The increased likelihood of intense rainfall due to global warming has been proven, and with it urban flooding due to insufficient drain capacity to manage the large amount of run-off generated, and human casualties due to little time available to react to high precipitation rates. Green roofs help in reducing the run-off by retaining and detaining the precipitation to some extent, and subsequently delaying the occurrence of the high run-off volume.

The water retained in the substrate layer of the green roof will be used by the plants themselves for photosynthesis or transpire. These two phenomena lead to a reduction in the run-off volume from green roofs as compared to a bare roof. Therefore, a green roof does not only act to retain and delay the peak in run-off, but reduce the run-off quantity itself through the processes of photosynthesis and evapo-transpiration. The performance of a green roof in terms of stormwater management therefore depends on the soil moisture content before any given rainfall event.

Mentens et al. [25] reported the annual run-off reduction of green roofs in Germany for studies performed over the period 1987 to 2003. The values reported for extensive green roofs were found to range between 27 and 81%. Few similar studies performed by other researchers yielded the following average retention values:

- Bengtsson et al. [27] reported a 46% average retention value
- VanWoert et al. [28] reported a 60.6% average retention value
- De Nardo et al. [29] reported a 45% average retention value
- Carter and Rasmussen [30] reported a 78% retention value

The retention values reported generally fall within the range obtained in Germany, and therefore the range can be used for assessing stormwater management benefits for a preliminary assessment. The retention characteristics of the green roof was found to be inversely proportional to the rainfall event, e.g. Carter and Rasmussen [30] found that for storms less than 25.4 mm, 88% was retained, for storms between 25.4 and 76.2 mm, 54% was retained, and for storms larger than 76.2 mm, 48% was retained. Simmons et al. [33] found that for storm event less than 10 mm, all rainwater was retained. Green roofs were found to delay the peak run-off as compared to bare roofs. The studies by Carter and Rasmussen [30], Simmons et al. [33] and VanWoert et al. concluded on around 10 min run-off delays. However, Getter et al. [31] and Villareal et al. [32] obtained significantly lower run-off delay (1 min for the latter), showing the need to perform in situ-measurement for the specific prevailing conditions. For lower rainfall intensity, DeNardo et al. [29] found that green roofs on average delayed run-off by 5.7 hours and peak to peak run-off by 2 hours.

Razzaghmanesh et al. [21] found that generally the water quality from green roofs were better as compared to those generated from roofs without green roofs.

Uhl et al. [23] concluded that green roofs reduced the stormwater run-off considerably and that the predominant factor in determining the run-off from the roof is the depth of substrate and drainage layer.

Virginia et al. [12] developed a hydrological model for an extensive green roof with the aim to simulate the long-term continuous behaviour of green roofs in terms of run-off and drought resistance. Their study focused on four locations in the UK to show the dependency of the model on climate. Their results show that retention performance is dependent upon local climatic conditions. Volumetric retention ranges from 0.19 in cool and wet climate to 0.59 in warm and dry climate. The need to monitor green roof performance has been stressed by Justyna [26] as important differences have been obtained between early and subsequent years in the performance of green roofs. Getter et al. [31] found that the water holding capacity increased from 17% to 67% in 5 years due to change in organic content of the green roof as well as increase in pore space.

The influence of plant cover on run-off dynamics seem to be diversely commented by the research community with some claiming that the type and depth of substrate is the predominating factor whereas other studies showed that plant selection had an important impact on run-off. Steusloff [34] showed that water retention in green roof with vegetation was twice as compared to a green roof without vegetation in August whereas the performance of the green roof with vegetation and the one without vegetation were comparable in the month of October-December. The differences in performance were found to be related to the availability in water. It was deduced by Wolf and Lundholm [35] that plants do play a role in water retention, but when there is low availability of water; in period of heavy rainfall, the role of the vegetated layer has little influence. Furthermore, the warm months were found to encourage evapotranspiration and regeneration of the retention capacity of the substrate layer.

Villarreal and Bengtsson [32] found that the slope of a roof influences the water retention within the green roof with lower slope leading to increased retention. A slope of 2% (typical for Mauritius) was found to have double retention capacity as compared to a slope of 14%.

2.7.2 Stormwater Quality

Bruce et al. [22] found that a green roof made of shale, compost and Perlite as the substrate retained as much as 51.4% of the precipitation. Vijayaraghavan et al. [11] studied the impact of stormwater run-off quality emanating from green roofs. Specifically, they investigated whether green roofs act as a source or a sink of metal cations, namely (Na^+, K^+, Ca^{2+}, Mg^{2+}, Al^{3+}, Fe^{2+}, Cu^{2+} , Cd^{3+}, Pb^{2+}, Zn^{2+}, Mn^{4+}, Cr^{3+}, Ni^{2+}, Li^+ and Co^{3+}), inorganic anions (NO_3^-, NO_2^- , PO_3^-, SO_4^{2-}, Cl^-, F^- and Br^- respectively as well as cation (NH_4^+). They concluded that the concentration of these ions depends on the nature of substrates used for planting and the rainfall pattern.

2.8 Thermal Comfort

In Mauritius, roofs of buildings are mostly flat and made of concrete, without any insulation layer. Generally, roofs of commercial buildings are protected by a waterproofing layer. Due to its thermal heat capacity, concrete tends to absorb heat during the day. This is particularly true in summer, when for most part of the day, the roof assembly is directly exposed to the sun, and being flat, this exacerbates the solar radiation absorbed. As a result, during daytime, heat is absorbed and stored in the concrete and at night, when the temperature drops, this heat is slowly released inside the building. This is a well-known phenomenon in the Mauritian home. Touching the ceiling of a room which has an exposed roof, at night in summer, feels very hot even though it is cooler outside. Due to the radiation from the warm roof surface, the rooms on the top floor tend to be hotter and more uncomfortable than rooms on the ground floor.

Historically, green roofs have been used as a way to regulate the internal temperature of buildings so as to maintain thermal comfort levels fit for humans. In cold regions, green roofs were used as a means to keep the heat inside while in warmer regions, green roofs served as a heat barrier, keeping the heat outside and away from the roof surface. In both cases, the insulating property of green roofs was used so as to maintain acceptable thermal comfort levels.

With escalating energy prices, the need to find ways to reduce our energy demand is imperative. For buildings in tropical climate, green strategies such as having a green roof can considerably help in reducing a building's cooling load and hence the annual amount of cooling energy required. On the other hand, green roofs allow houses without air-conditioning units to achieve more comfortable conditions for building occupants through passive design measures. However, the physics of green roofs is more complex to understand than laws of physics governing the heating and cooling requirements of buildings.

For buildings, heat gains and heat losses dependent mainly on the conduction gain through the building fabric (i.e. walls, and roof) and glazing. For a green roof, the dynamics of heat transfer is more complicated as it involves not only conduction gains but also shading effect of plants, and the effect of evapo-transpiration.

Alnaqbi [36] identifies three components of heat flux in green roofs in hot climates:

- Shading effect: the type of plants used give different types of ground cover on the exposed soil surface. By intercepting direct solar radiation, the green roof canopy provides a protection to the roof and helps in reducing the roof surface temperature. The extent to which the shading effect contributes to the reduction of heat gains into the building is dependent on the leaf area index (LAI). The leaf area index is a ratio of the projected shadow of the roof canopy to the green roof area. It is a dimensionless factor which determines the amount of shading expected to be offered by the green roof canopy.
- Insulation effect: the different layers of a green roof alter the heat transfer coefficient (U-value) of a green roof assembly. Amongst all the components of a green roof, the growing substrate has the greatest contribution in altering the U-value of the roof assembly. The deeper the growing substrate layer, the more observable the insulation

effect. In addition to the growing substrate layer, some green roofs also consist of an insulation layer, which further increases the insulating effect of the green roof.

- Evaporative cooling effect: biological plant processes such as photosynthesis, transpiration and evaporation occur by absorbing portions of solar radiation and releasing an evaporative cooling effect. This cooling effect is beneficial not only to building occupants but also help in reducing the urban heat island effect.

In the recent decade, a lot of studies have been conducted in order to quantify the extent to which green roofs can lower a building's heating and cooling energy demand. Researchers have used a variety of techniques ranging from experimental laboratory measurements, field measurements, the use of numerical techniques and the use of advanced simulation software. In literature it is quite difficult to obtain an agreement on how much energy savings can be achieved using green roofs.

The reason for this discrepancy is that green roofs are living roofs with an ecosystem which interact and adapt to climatic conditions. Hence, the reduction in energy savings achieved is dependent on several factors such as:

- Local climatic conditions
- Type of plant used
- Leaf area index
- Soil moisture content
- Depth of the growing substrate

Hence it is very difficult to state in absolute terms the percentage energy reduction that can be achieved by green roofs. However, all the studies carried out so far reveal that there is a decrease in the energy demand of the building as a result of installing a green roof. Thus, it can be safely stated that green roofs help in reducing the heating and cooling energy; the reduction in energy demand should be evaluated on a case-to-case basis as there are too many factors which can influence the energy balance of green roofs. This accurate assessment of the energy savings potential in the Mauritian context will be possible when suitable substrates have been developed and the necessary parameters such as evapo-transpiration rate for the plant species have been determined. Achievable improvement in thermal comfort is calculated for a case study using parameters reported in literature to give a preliminary indication [38, 39, 40, 41].

Chapter 3: Design considerations for green roofs in Mauritius

3.1 Design of roof structure and architecture

The additional weight brought about by a green roof system, including all the layers, the substrate when fully saturated with water and the plants at their maximum growth phase should be included in the structural design of the building. In case it is an existing building, it is critical and the foremost criterion to be assessed by a qualified civil/structural engineer whether the load exerted by the green roof on the building structure can be taken up by the existing reinforcement.

Secondly, the roof should preferably not have a 0° slope, i.e. flat, so as to facilitate the drainage of rainwater to the drainage points. The number of drainage points and the size of the down pipes should be sized according to current standards based on an acceptable design storm event. Typically a 1 to 2% slope is used in buildings in Mauritius, which is adequate for green roofs on 'flat' roofs. The slope is an important parameter to be used for specifying the drainage layer type to be used, as described in the stormwater management chapter of this guidebook.

Third important consideration as far as the architecture of the building, specifically the roof, is concerned is the upstand (height of eaves, parapet wall or doorway entrance) that is specified for the building. Incorrect specification of the upstands can lead to water ingress to the interior spaces of the building, which is essential to avoid in the design of a green roof system. Our current building regulations need to be amended to enforce appropriate upstand levels. For example, German norms require to have parapet walls around the roof at least 10 cm above the substrate level and 15 cm on the building side, as illustrated by Figure 3-1 and Figure 3-2.

1.1 Clamping and Protection Profile
1.2 Strip, gravel, d= 16 to 32 mm, width ≥ 300 mm
1.3 Seperation Profile

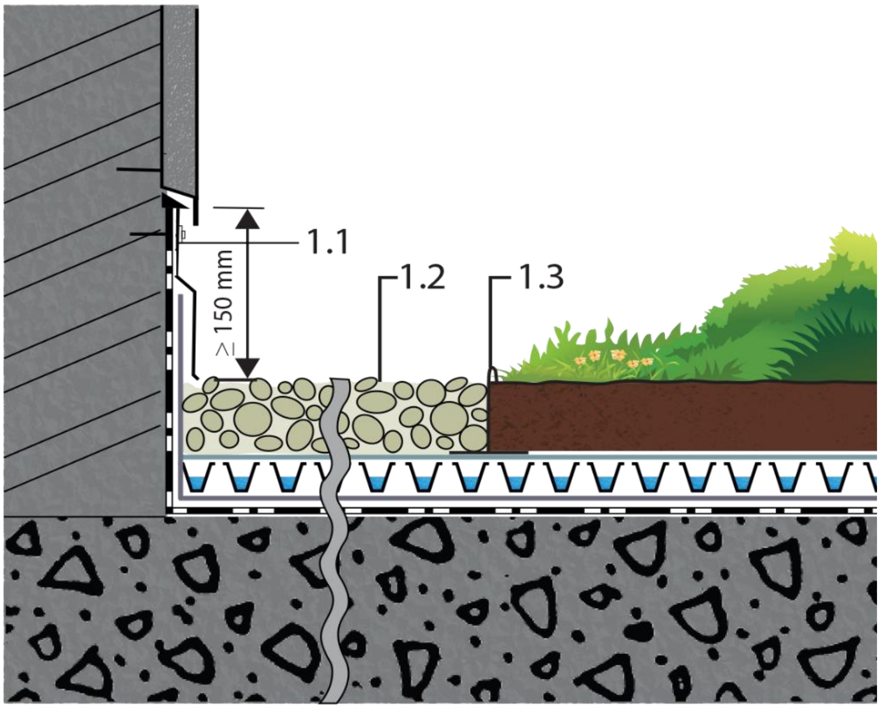


Figure 3-1: Upstand level on building side

1.1 Parapet covering
1.2 Strip, gravel, d = 16 to 32 mm, width ≥ 300 mm
1.3 Seperation Profile

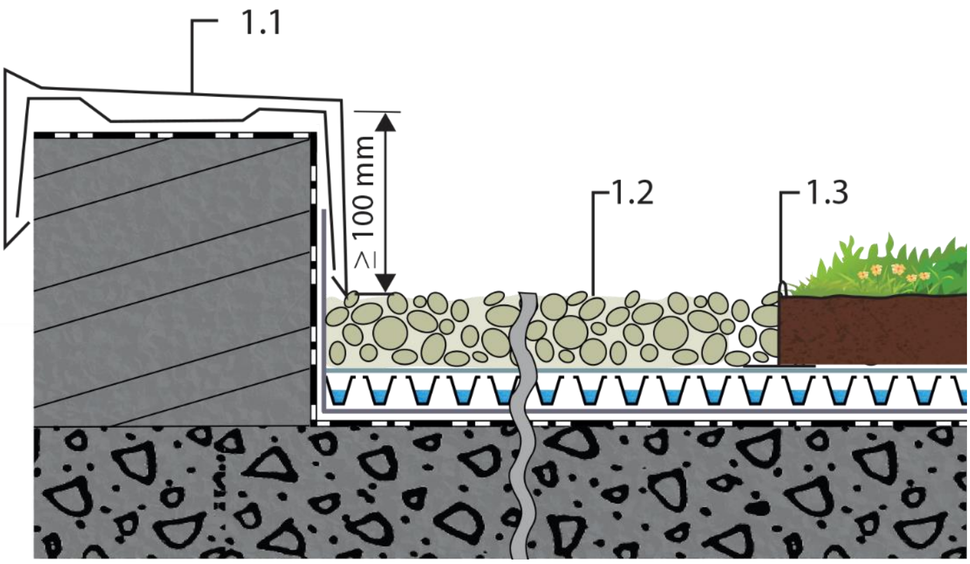


Figure 3-2: Upstand level on parapet wall

Additionally, a doorway grille system or pebble array should be installed in front of doorways so that the green roof system does not end directly at the doorway entrance as the latter scenario can cause undesirable water ingress into the building.

3.2 Waterproofing membrane

A waterproofing membrane is a pre-requisite for a green roof system. It is generally observed in Mauritius that commercial and industrial buildings tend to be waterproofed whereas houses tend not to be waterproofed, principally due to the relatively high capital investment this entails. Due to the fact that rainwater will be in regular, if not constant, contact with the roof surface, having a waterproofing membrane becomes a necessity as any subsequent reparation on the roof to stop any leaks will need the dismantling of the green roof, which is a costly exercise in itself. Therefore, it is highly recommended to have the roof properly waterproofed before installation of the green roof.

The waterproofing specifications to look at are twofold: First is the ability to resist plant root penetration, typically referred to as the root-proofness of the waterproofing membrane. Relevant standards that certify the root-proofness of the waterproofing membrane are FLL or DIN EN 13948 currently used in Germany, or any equivalent standards. Based on surveys carried out from local waterproofing companies, it was claimed that waterproofing with the appropriate root-proofness can be supplied, although not currently installed on our roofs for general waterproofing applications. So it is an important specification for any building owner willing to have a green roof system installed to get the guarantee from the waterproofing company for root-proofness of the membrane. In case the building has an existing waterproofing system installed, it might be more cost effective to install a root barrier membrane over the existing waterproofing membrane as compared to installing a roof-proof waterproofing membrane itself.

The second consideration to be validated with the waterproofing company is whether a protection mat is required or not with the waterproofing membrane. In this case, it is a question of whether the waterproofing membrane is designed to take the stresses exerted by the drainage layer components or not. If yes, no protection mat is needed, if no, a protection mat will be required. Typically the protection mat will be provided by the green roof installer at extra cost.

A survey was conducted amongst waterproofing companies in Mauritius. The objective of the survey was to find out:

- Whether local companies have installed waterproofing for the purpose of green roofs
- Are there any specific standards that they adhere to in terms of water proofing products used for green roofs?
- Whether they will still maintain product warranty if a green roof is retrofitted on an existing waterproofing installation.

The outcome of the survey was as follows:

- Out of the 5 companies contacted, only 3 companies responded.
- Two of these companies have installed waterproofing systems for green roofs.
- The three waterproofing companies provide waterproofing products which are root proof.
- All three companies indicated that they will maintain product warranty on green roof retrofits, provided the green roof is installed according to approved guidelines.

3.3 Protection Layer

As its name implies, the protection layer serves to protect the waterproofing membrane against forces exerted by the drainage layer due to the load of the green roof itself as well as dynamic loads on the green roof due to human and other types of transport on top of the green roof. For the purpose of this guidebook, where the focus is the design of extensive and semi-intensive green roofs, our surveys with local waterproofing companies have shown that the use of the protection mat is not needed in all cases, subject to the specifications of the waterproofing membrane. Therefore, the client/green roof installer is required to ascertain with the waterproofing company whether a protection mat is needed or not (see discussion in waterproofing section above).

However, any green roof design or paved walkways/driveways (not covered in this guidebook) will generally require the use of a protection mat layer.

3.4 Selection of drainage layer

The purpose of the drainage layer is to provide effective drainage of water away from the plant roots so as to prevent the latter from decaying. Additionally, the drainage layer can store a certain volume of water (depending on design of drainage layer element) to provide tolerance against prolonged dry periods. Therefore, the drainage layer needs to be specified based on the design rainfall intensity for the site location as well as the drought tolerance desired. The supplier of the drainage layer components provides technical data relevant to ability of a particular drainage layer design to channel water from a given point on the green roof to a given drainage point on the roof. Therefore, this lays down restrictions on the maximum distance allowable to a drainage point. Conversely, having a drainage design, a suitable drainage layer type can be selected. A detailed calculation of the drainage layer system is given in chapter 4.

3.5 Filter Sheet

The filter sheet allows water from the saturated substrate layer to seep through to the drainage layer but blocks substrate particle to get into the drainage layer. The filter sheet is typically simple geotextile fabric commonly used in landscaping.

3.6 Production of substrate from local materials and pre-consumer/post-consumer recyclables

Since the project aims to encourage the use of local materials as far as possible, importation of substrate (if regulations permit) needs to be considered as the last resort. The substrate for a green roof system consists of two main components: organic and inorganic. It is to be noted that soil is not typically used as substrate for green roof installations or even as a component of the substrate as it does not offer desirable properties within the small depth of substrate used.

The inorganic component provides structural and water retention attributes to the substrate whereas the organic component provides nutrients such as N, P and K in appropriate concentrations. Upon contact with local authorities and nurseries, it has been found that substrates specifically for green roofs have not been developed yet. Therefore, the development of suitable substrates for green roofs needs to be done through research efforts using locally available materials such as clay, coco peat, pine shavings and crushed tiles/stones and compost of suitable nutrient concentrations.

The depth of substrate to be used for a particular green roof depends heavily on the type of plant to be grown. A typical extensive green roof with ground cover type plants having shallow and soft roots (see next section on plant selection) generally requires only 5 to 8 cm of substrate, whereas having grass/lawn necessitates a deeper substrate layer of around 20-25 cm. As we move from the simple extensive type roof to installations with deeper substrate layer, the classification of the green roof changes towards intensive green roofs. Green roof for growing vegetables such as cucumber, potatoes or tomatoes, is termed as urban farming and needs around 30 to 35 cm of substrate, and substrate with higher organic content.

The substrate additionally offers some level of thermal insulation to the concrete structure, meaning the choice of the depth of substrate can be used as a design parameter to reduce heat gains into the building through the roof (which is the source for the greatest solar heat gains in typical, non-fully-glazed building). Therefore, the depth of substrate can be chosen in the first instance to meet the minimum depth needed for the plant species used on the green roof, and also as a measure to limit heat gains into the building. The chapter on assessment of energy benefits of green roofs in Mauritius discusses this subject matter in greater depth.

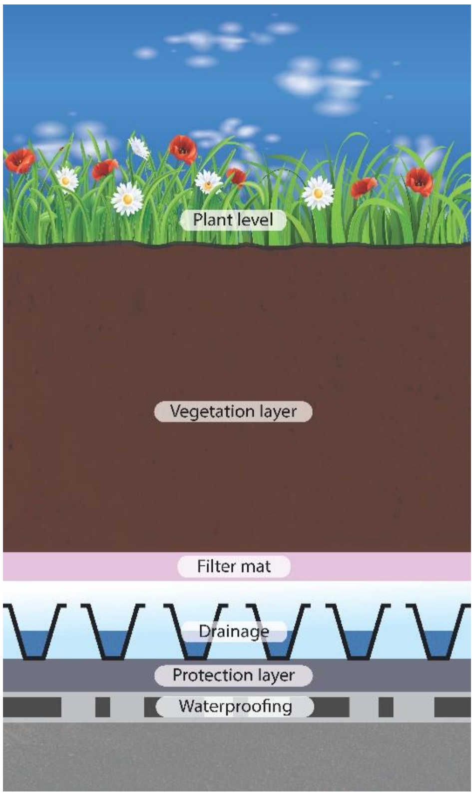
3.7 Choice of plants

As discussed above, the plant species to be used on the green roof is a determining factor for the green roof design since it sets the depth of substrate, the type of green roof, the organic content needed in the substrate, the protection mat specifications to withstand the load from the drainage layer onto the waterproofing and the drainage layer itself. The scope of this guidebook is to provide guidelines on the design of green roofs so that research efforts ensue to start the process of customising the design parameters to the local context with focus on energy saving/conservation and stormwater management, although knock-on benefits are expected such as sound insulation, exterior liveable spaces, air purification etc. Therefore the focus is to provide guidelines for the design of green roofs in the extensive and semi-intensive range, and leave the design of more complex, intensive green roofs to green roof installers as it is done on a case-by-case basis.

The types of plants that can be used for an extensive green roof installation in Mauritius can be obtained from the Ministry of Agro-Industry and Food Industry/FAREI, as those typically providing ground cover and with soft, shallow roots. Consultations can also be done to discuss the suitability of any proposed plant species for the green roof installation. Preference needs to be given to the selection of native or adapted plant species to be used as they tend to be non-invasive and water resistant, while promoting the biodiversity of our flora.

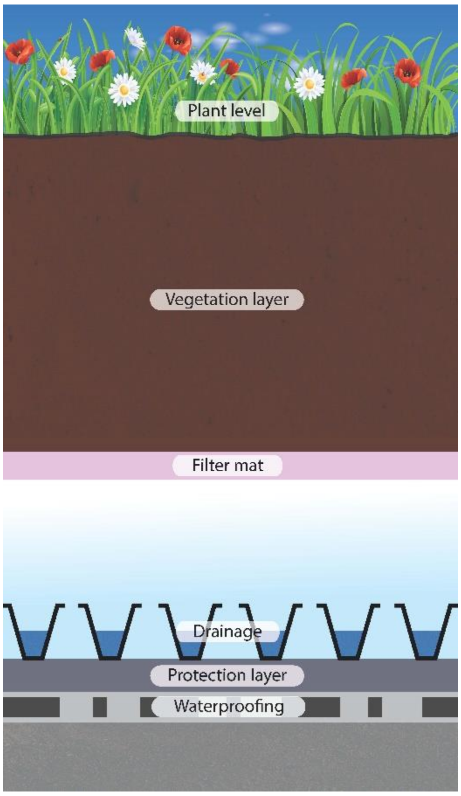
3.8 Design Variants

3.8.1 General extensive green roof



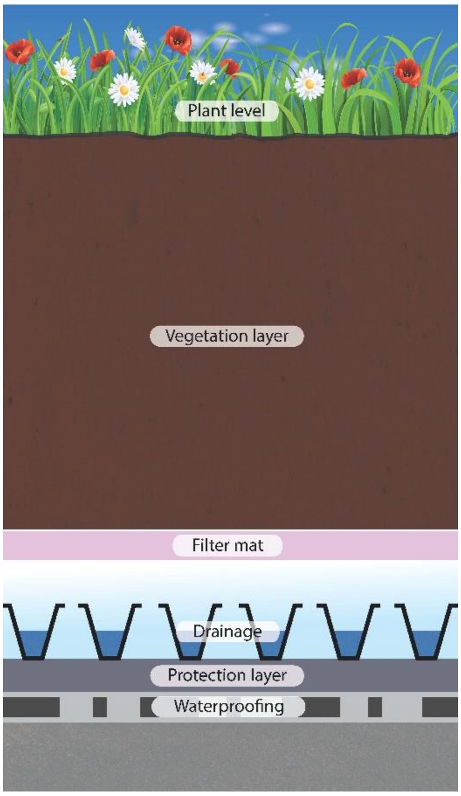
1. Root-proof waterproofing
2. Protection mat (optional), contact waterproofing company
3. Drainage layer, typically 2.5 cm high, needs to consider longest distance to any roof outlet and rainfall intensity
4. Filter sheet
5. Substrate, 5-8 cm
6. Plants: groundcover with soft and shallow roots

3.8.2 Green roof for stormwater management



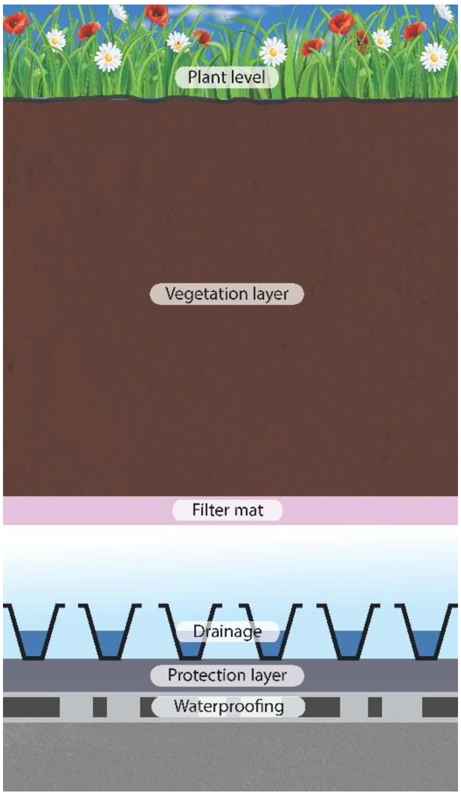
1. Root-proof waterproofing
2. Protection mat (optional), contact waterproofing company
3. Drainage layer, typically 4 to 5 cm high, needs to consider longest distance to any roof outlet and rainfall intensity
4. Filter sheet
5. Substrate, can use deeper than 8 cm to improve water retention and delay of run-off, e.g. 10 to 15 cm
6. Plants: groundcover or plants suitable for depth of substrate used

3.8.3 Green roof for heat gain reduction



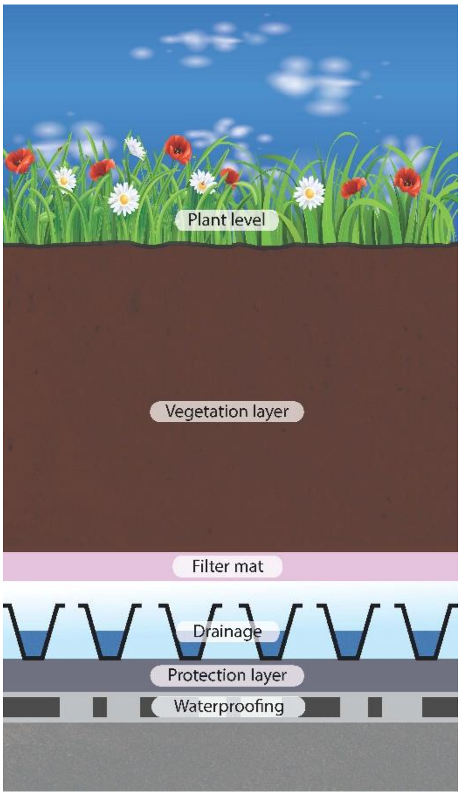
1. Root-proof waterproofing
2. Protection mat (optional), contact waterproofing company
3. Drainage layer, typically 2.5 cm high, needs to be set using longest distance to any roof outlet and rainfall intensity
4. Filter sheet
5. Substrate layer deeper than 5-8 cm for thermal insulation, e.g. 10 – 15 cm
6. Plant species can also be used to limit heat gains through evapotranspiration, further research on local plant species needed to quantify this effect

3.8.4 Green roof for dry regions



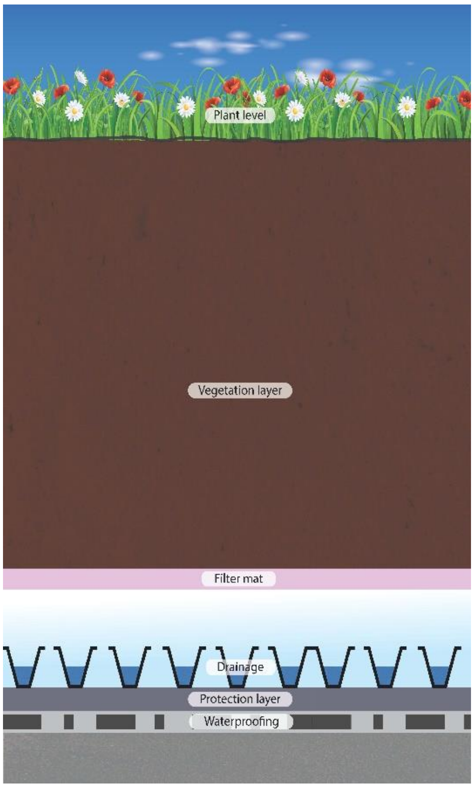
1. Root-proof waterproofing
2. Protection mat (optional), contact waterproofing company
3. Drainage layer, 4-5 cm high, if water storage is provided in drainage layer
4. Filter sheet
5. Substrate, 10-15 cm if storage not provided in drainage layer, combination of high depth of substrate and water storage in drainage layer improves dry climate resistance.
6. Plants chosen to be drought resistant

3.8.5 Green roof for wet regions



1. Same build up as simple extensive green roof can be used as drainage layer does not need to store much water. The same applies for the substrate layer.
2. Note: Drainage layer should meet requirement of design storm event.

3.8.6 Green roof for roof gardening



1. Root-proof waterproofing
2. Protection mat (optional), contact waterproofing company
3. Drainage layer, 4-5 cm high, needs to be set using longest distance to any roof outlet and rainfall intensity
4. Filter sheet
5. Substrate, 30-35 cm
6. Vegetables

Chapter 4: Stormwater Management of Green Roof for Mauritius

With the increased likelihood to have intense rainfall events due to climate pattern shifts through the global warming phenomenon, it has become an utmost challenge to design roadside drainage systems that can cope with rainfall of short duration and high intensity, typically known as flash floods, as well as rainfalls of longer duration and moderate intensity. With an increased conversion of land into built-up areas to support a rising world population and the ever-strong desire for economic growth, the design of drainage systems to cope with rainwater has become a costly investment for governments around the globe, and several mitigation measures have been proposed such as retention and detention systems to reduce the volume and rate of run-off from built-up areas during rainfall events.

These measures form part of incentives for sustainable management of run-off by each building site so that the road drainage network does not have to be oversized to cope with high intensity rainfall events, and also to allow the natural aquifer system to be recharged instead of the run-off being flushed into rivers and down to the sea. The danger in designing drainage networks not properly sized to cater for run-off during heavy rainfall is real, as we have lived in Mauritius in several instances and similar occurrences have been observed around the globe. The sustainable answer to the drainage problems related to stormwater lies in micro-management at site level instead of solely relying on central collection; the latter remains an important back-up but maximum reduction in run-off should occur at the site level.

In comparison to a bare roof system, which creates almost 100% of run-off from rainfall, a green roof has been presented as a system which in addition to the many benefits presented earlier, provides (1) a vegetation layer capable of directing rainwater back to the atmosphere through evapotranspiration, (2) a substrate layer capable of retaining water so that plants can tap into this water reserve during periods of low or no rainfall, and (3) a drainage layer that can store water for use by the plants through diffusion and detain water to slowly discharge the excess water to the discharge outlets. These attributes of the green roof as far as stormwater management in the local context is concerned are as follows:

a. The amount of run-off created by rainfall is reduced; the extent of the reduction depends on the moisture content of the substrate at the start of the rainfall event, which in turn is related to the type of plants used for the green roof installation as this influences the evapotranspiration rate through which moisture can be fed back to the atmosphere. The plants play the critical role of moving water deep from the substrate to the top for evaporation into the atmosphere with a concomitant reduction in the ambient temperature.

   Moreover, the water retention capability of the substrate layer itself influences the volume of run-off from a particular rainfall event. With the current lack of scientific knowledge on the evapotranspiration rates of different plant species native or adapted to Mauritius (that would be preferably used on our green roofs) and a lack of suitable substrates for green roofs for Mauritius, this complex mix of factors that influence the run-off quantity from green roofs present a very rich area of research to better understand how green roofs would perform from a stormwater management point of view.

This would require the development of custom analysis models backed by in-situ measurement of green roof variants under various climate conditions and vegetation layer characteristics. Promising experimental results for similar studies have been obtained with the general finding that green roof perform better at stormwater management during hot, summer conditions as compared to winter conditions. On average, a 50% reduction in run-off quantity could be observed for a whole range of rainfall events, from short periods of heavy rainfall (e.g. 50 mm in one hour) and moderate rainfall over period (e.g. 70 mm in one day). Such a reduction in peak run-off would mean a lot considering the latest flash flood events in Mauritius, reducing the catastrophic consequences and loss of human life, if not possibly totally preventing any such occurrence at all.

As mentioned above, experiments in the local context will need to be carried out to gather relevant data to definitely affirm the benefit of stormwater management, but figures obtained elsewhere show promising results to the extent that building owners who have a green roof installed on their premises have to pay a reduced tax for road drain networks, and the integration of green roofs into a project is rewarded by green building rating systems such as LEED for its stormwater management qualities in addition to other sustainability values.

b. The amount of run-off, as described above is one parameter of importance in designing drainage networks, but of equal importance is the rate of run-off, which for a bare roof is equal to the precipitation rate, but in a green roof is reduced by the retention and detention properties. As it starts raining, the substrate layer starts to absorb most of the rainwater, with little water permeating through the substrate to the drainage layer, meaning the rate of run-off is low initially. As the substrate saturates, the rate of run-off increases until it becomes equal to the precipitation rate when fully saturated. So this delay in run-off is an important property of a green roof, which prevents the road drainage network from receiving run-off from all built-up areas at once. This logically leads to a reduction in the overall run-off rate and time to peak, and thus less likelihood of flooding and as discussed in the next item, carrying away of topsoil and harmful compounds to streams and rivers. Experiments will need to be carried out to obtain definite scientific validation of the reduction in peak run-off and the useful delay in obtaining the peak.

c. A third benefit of green roof, insofar as its stormwater management properties are concerned is the quality of run-off. This is typically measured by the level of Total Suspended Solid (TSS) and any measure used to treat run-off quality is characterised by a Total Suspended Solid Removal Efficiency in %. The run-off quality is concerned at two levels, first the one going into the drains due to the reduced flow rate, which is thus less harmful as it carries less contaminants along, and on a second level the run-off from the green roof itself.

This has been found to be seasonal and plant dependent, with very good run-off quality typically in summer as most water is retained and evaporated and run-off with typically high nutrient content in winter where the retention capability of the green roof is less. Similar tests need to be carried out at different locations in Mauritius over different seasons to understand better the performance of green roofs with respect to run-off quality.

4.1 Design of green roof for effective run-off transport: selection of a suitable drainage layer

The common method to design the rainwater discharge system for a normal roof (one without a green roof) is to choose an acceptable design storm event (e.g. 1 in 5 or 10 years), from which the maximum rainfall intensity is set. From this figure, the number and size of drainage points on the roof and the size of the downpipe to channel the rainwater are calculated. Doing this exercise properly ensures an effective flow of rainwater from any point on the roof to the discharge points, and therefore no overflowing over the eaves as far as the design storm event chosen is not exceeded.

In a similar way, the installation of a green roof should in no way lead to ineffective transmission of run-off to the discharge points, leading to overflowing on top of the eaves or water accumulation on top of the vegetation layer. This is achieved by selecting a drainage layer suitable for the rainfall intensity and for channelling water from any point to its closest drainage point. Any drainage layer is specified in terms of its water carrying capacity, and it then suffices to specify a drainage layer with at least the calculated water carrying capacity. A detailed calculation for the selection of a drainage layer element is presented for a case study in the next section.

4.2 Case Study: Stormwater management using a Green Roof

This section considers a 14m by 14m (around 200 m^2) roof of a house as a case study for showcasing the rainwater system design (see Figure 4-1), and how the drainage layer of a green roof should be properly selected so as not to hamper the effective drainage of rainwater once a green roof is installed. Assuming four roof outlets are to be installed at the four corners of the roof (A, B, C and D), using the guidelines given in BS EN 12065-3 for roof drainage design, for a rain event of 165 mm/h (typically used for building projects), the pipe size obtained for the four rain outlets is 75 mm assuming a pipe filling factor of 33%.

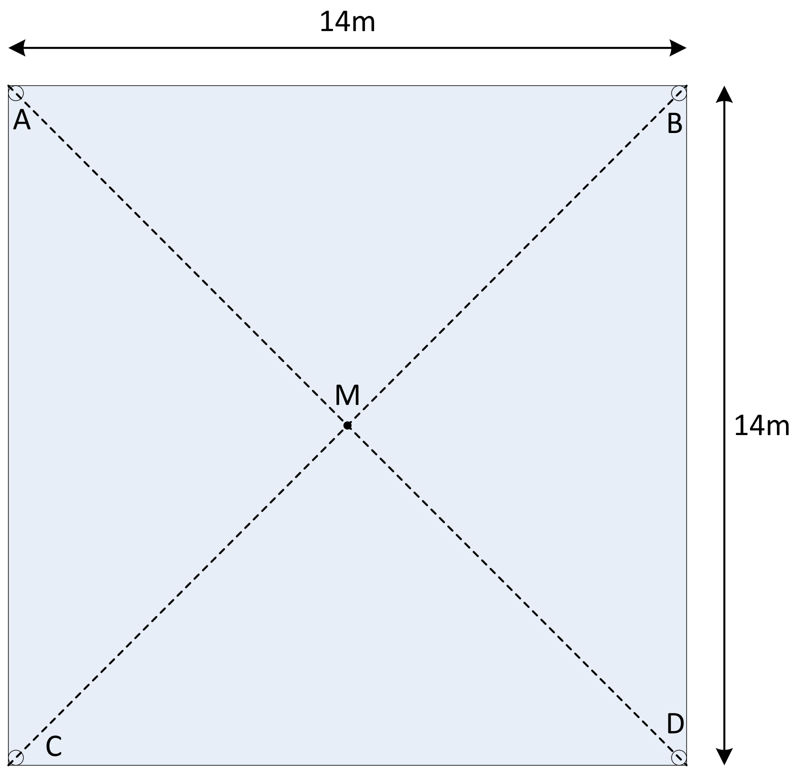


Figure 4-1: Roof example with four 75mm roof outlets at the corners

This drainage system design will ensure that run-off from rain events less severe than 165 mm/h can be effectively channelled away from the roof (provided the rain outlets are not blocked by debris) and prevent any accumulation. If a green roof is to be installed on this roof, run-off should be evacuated as effectively as for the bare roof so as not to lead to undue water accumulation and pooling on the green roof. Wrong selection of the drainage layer or any malfunction of the green roof system as far as rainwater drainage is concerned will lead to water pooling over the top of the green roof; in other words, a properly designed green roof should never have water pools accumulated on top of the vegetated layer.

To validate if a particular drainage layer is suitable for a given green roof, the drainage capacity (amount of water which can be drained away by the drainage element) needs to be obtained from the supplier. It is typically measured in L/sm. The higher the drainage element, the better will be drainage capacity. Another factor which affects the drainage capacity of the drainage element is the slope of the roof, and typically values of drainage capacity are given for 1%, 2%, 3% and 10% slope.

Considering the roof example taken above, the furthest point on the roof is actually at the intersection of the two diagonals (point M), i.e. at a distance of 9.9 m from the roof outlets (e.g. distance between rain outlet A to point M). For a rain event of 165 mm/h, the following set of calculations can be performed:

Rain event: 165 mm/h = 0.0458 mm/s = 0.0458 L/sm^2

For a rain event (RE) with maximum distance (D) from a given point on the roof to the closest rain outlet and a drainage capacity (Q), the following relationship exists:

$$Q = D \times RE$$

Therefore, for a rain event of 0.0458 L/sm2 and a maximum distance of 9.9 m from a given point (M) on the roof to a rain outlet (e.g. A), the drainage capacity for the drainage element can be calculated as follows:

$$Q \geq 0.0458 \times 9.9$$

The minimum drainage capacity for the drainage element to be used is 0.45 L/sm. This drainage capacity must be achieved for the given slope of the roof used.

Figure 4-2 - Green roofs help in reducing run-off from heavy rain by retaining water in the substrate and drainage layer

Chapter 5: Thermal Comfort – Case study

5.1 Background

Green building rating systems such as LEED, BREEAM and Green Star often cite green roofs as a means to reduce the operating energy costs of buildings. As compared to some other energy saving measures, green roofs can easily be installed on new-builds as well as retrofitted to existing buildings. Being an external modification to the building envelope, the disturbance to building users and operation is small.

Green roofs can reduce the energy consumption of buildings in two ways:

- Reducing the heat loss and hence reducing the heating requirements of the building
- Reducing the heat gains and hence the cooling load

In the Mauritian context, the reduction in cooling load is more relevant. Therefore, this research will focus on quantifying the reduction in cooling load in a typical Mauritian building.

There are two aspects of a green roof which help in reducing its cooling load:

1. The different layers which constitute the green roof act as an insulation layer on the roof. This insulation layer thus reduces the amount of heat entering the building and also increases the time lag in heat transfer.
2. Evaporative cooling effect – the plants on the green roof produce a cooling effect due to the phenomenon of evapotranspiration.

The reduction in cooling load due to the insulating effect can be quantified as it brings about a change in the overall heat transfer coefficient of the roof assembly. This can be translated in a reduction in the internal temperature and hence better thermal comfort.

The insulation being applied only to the roof, the reduction in internal temperature is significant only to spaces which have an exposed roof. As such, on a multi-storey building, the reduction in cooling load due to the addition of a green roof is not expected to be significant. However, for residential buildings and low-rise commercial buildings, it is expected that the reduction in cooling load will be more significant.

Hence for the purpose of this study, the reduction in internal temperature will be calculated based on a standard Mauritian house.

However, the reduction in cooling energy as a result of evapotranspiration is more challenging to quantify. This is because the rate of evapotranspiration is dependent on type of plants and climatic conditions. Literature on typical values on the rate of evapotranspiration for different plants is relatively scarce. Moreover, predictive models developed to estimate the cooling effect produced by plants is complex and requires the use of sophisticated tools such as CFD and Matlab modelling. Being beyond the scope of this project, the evapotranspiration effect of plants will not be considered in this project. [38,39,40,41]

5.2 Software used

To demonstrate how a green roof reduces the cooling demand for a building, a simulation technique was adopted in this research. The IESVE 2014 was used to construct a 3D model of a standard Mauritian house. A dynamic simulation was performed for two cases: one for the house without a green roof and one for a house with a green roof.

5.3 Weather file

The weather file used in the simulation was for Vacoas. This was generated using the Meteonorm software.

5.4 Model description

5.4.1 Physical description

The figure 5-1 below shows a floor plan of the house used as the model. The house consists of only a ground floor and has a total floor area of 120 m^2. All the rooms were assumed to be 3.0 m high.

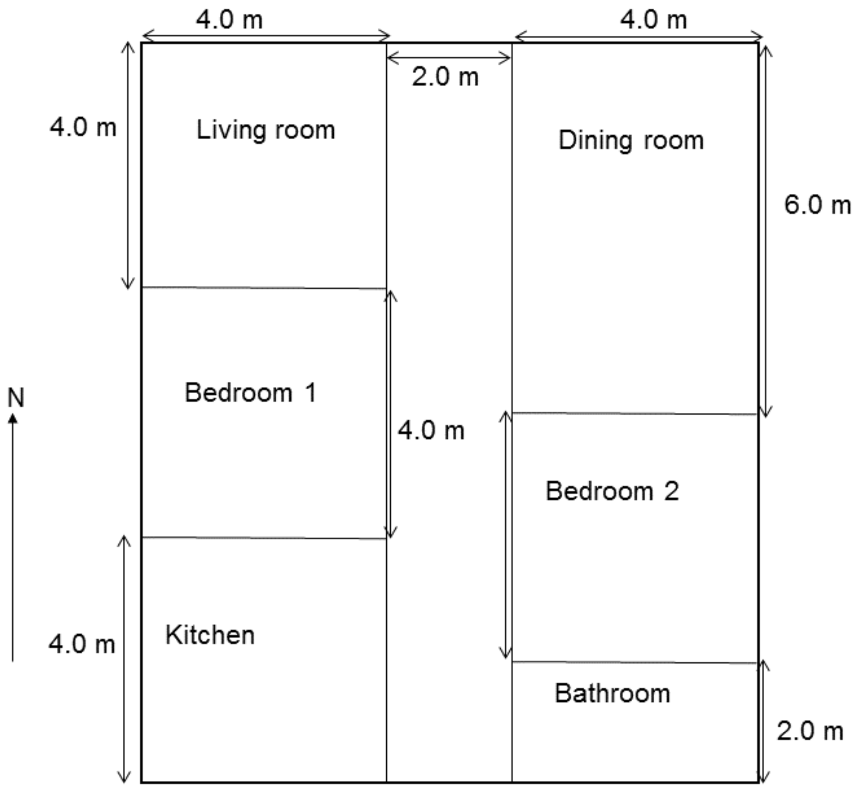


Figure 5-1: Typical Mauritian house layout

The schedule of windows is as follows:

Table 5-1: Windows schedule

Room	Orientation	Quantity and Dimension
Living room	North	1 x 2.0 m x 1.5 m
	West	1 x 2.0 m x 1.5 m
Dining room	North	1 x 2.0 m x 1.5 m
	East	2 x 2.0 m x 1.5 m
Bedroom 1	West	1 x 2.0 m x 1.5 m
Bedroom 2	East	1 x 2.0 m x 1.5 m
Kitchen	West	1 x 2.0 m x 1.5 m
	South	1 x 2.0 m x 1.5 m
Bathroom	East	1 x 0.6 m x 0.6 m

No overhangs were considered.

The model was created in the ModelIT module of IES VE is shown below:

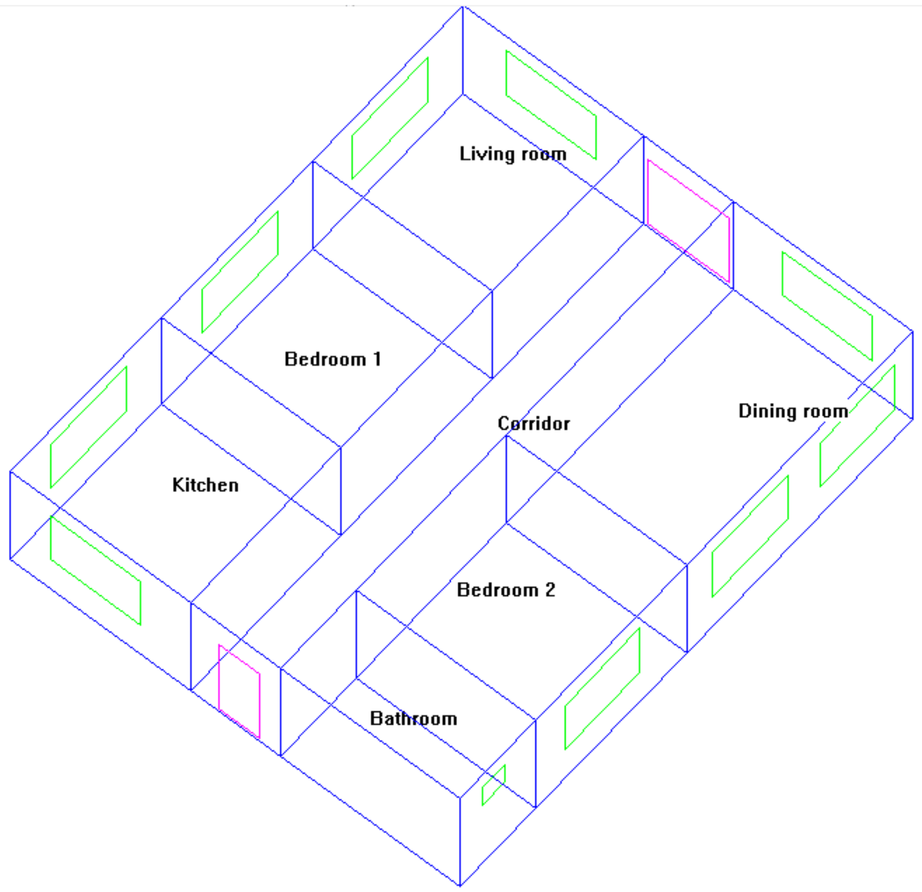


Figure 5-2: 3D house model

5.4.2 Internal conditions and internal gains

The house was assumed to be naturally ventilated. Windows were open from 6 am to 8 am and 5 pm to 9 pm every day. This was done by applying a window opening profile to the windows. During that time the windows were fully open.

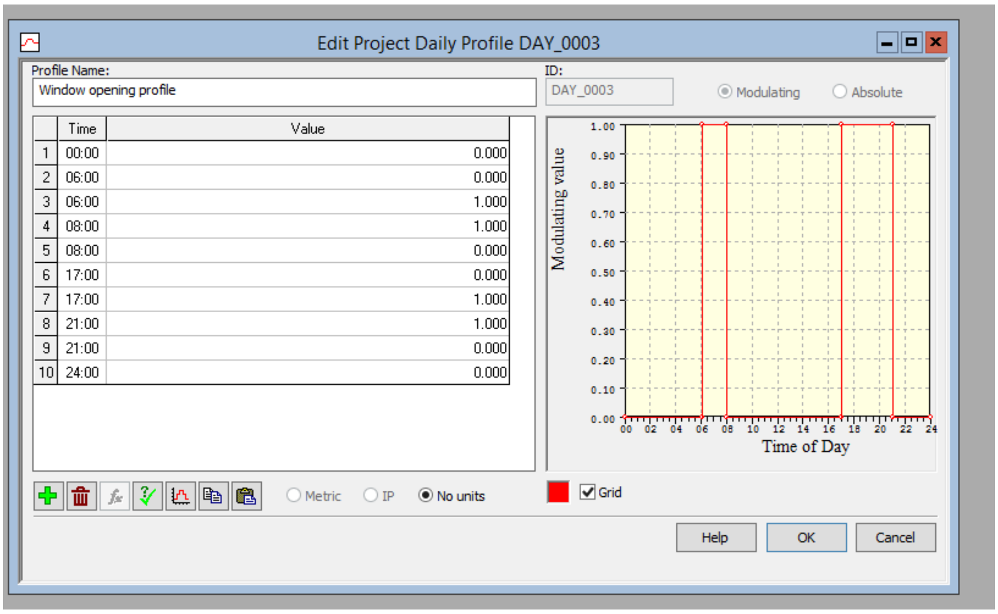


Figure 5-3: Snapshot of window opening profile

As the aim of the simulation was to establish the change in internal temperature as a result of a change in U-value, internal gains (lighting and equipment load), fresh air loads, and occupancy gains were not considered. Infiltration rate was not considered either.

Two cases were simulated: without a green roof and with green roof. In the second case, the green roof was applied to the whole roof area.

5.4.3 Building envelope

Table 5-2: Building envelop description

Building element	Description	U-value (W/m^2K)
External wall	19 mm screed; 200 mm concrete block; 13 mm screed	2.3
Internal partition	13 mm screed; 150 mm concrete block; 13 mm screed	2.2
External glazing	6 mm clear glazing	5.8 SHGC: 0.82
Bare roof	5 mm waterproofing; 75 mm screed; 150 mm cast concrete; 13 mm screed	3.35
Green roof	125 mm growing substrate(with 30% moisture); 25 mm drainage layer; 5 mm geotextile; 5 mm waterproofing; 75 mm screed; 150 mm cast concrete; 13 mm screed	2.54

5.5 Results of simulation

A dynamic simulation was carried out over a year to compare the impact of green roofs on the internal conditions in the house.

For the case of the flat roof, the conduction gain from the external fabric was analysed. It was shown, that the roof was the largest contributor to external conduction heat gain in the house, and that the peak gain occurs in the evening. This demonstrates the thermal mass effect of the roof construction which absorbs heat during the day and releases that heat at night.

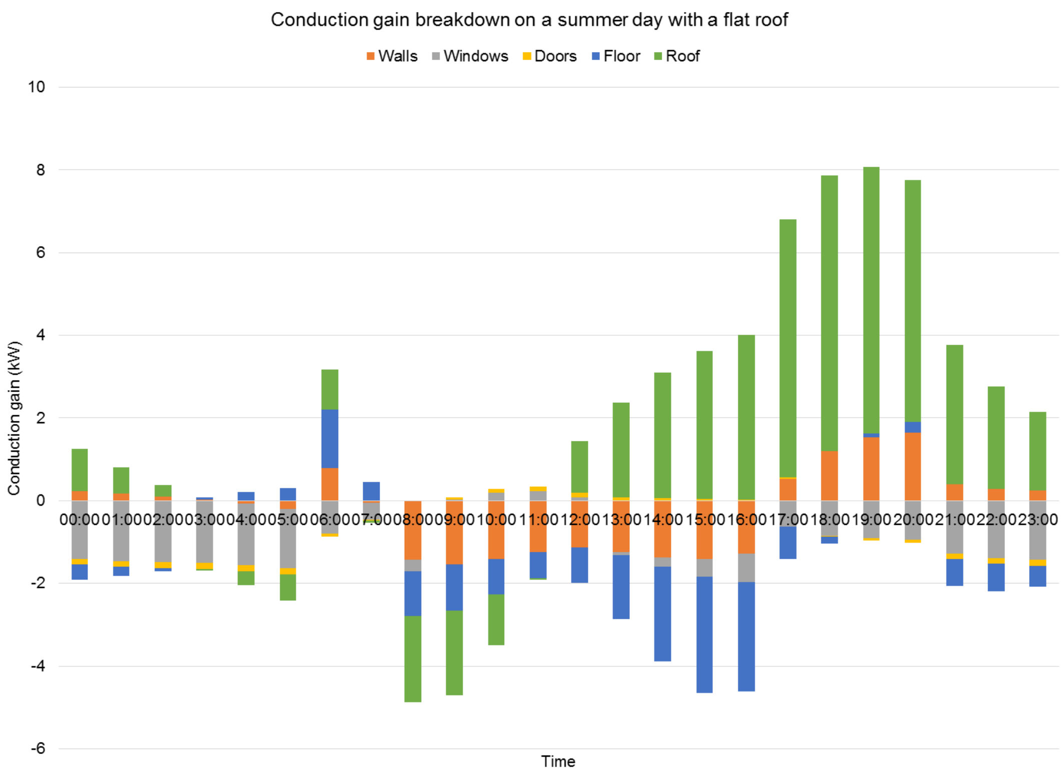


Figure 5-4: Variation of conduction game on a typical summer day for a flat roof

When a green roof is applied, the conduction heat gain through the roof is still the highest contributor but the peak conduction gain is lowered.

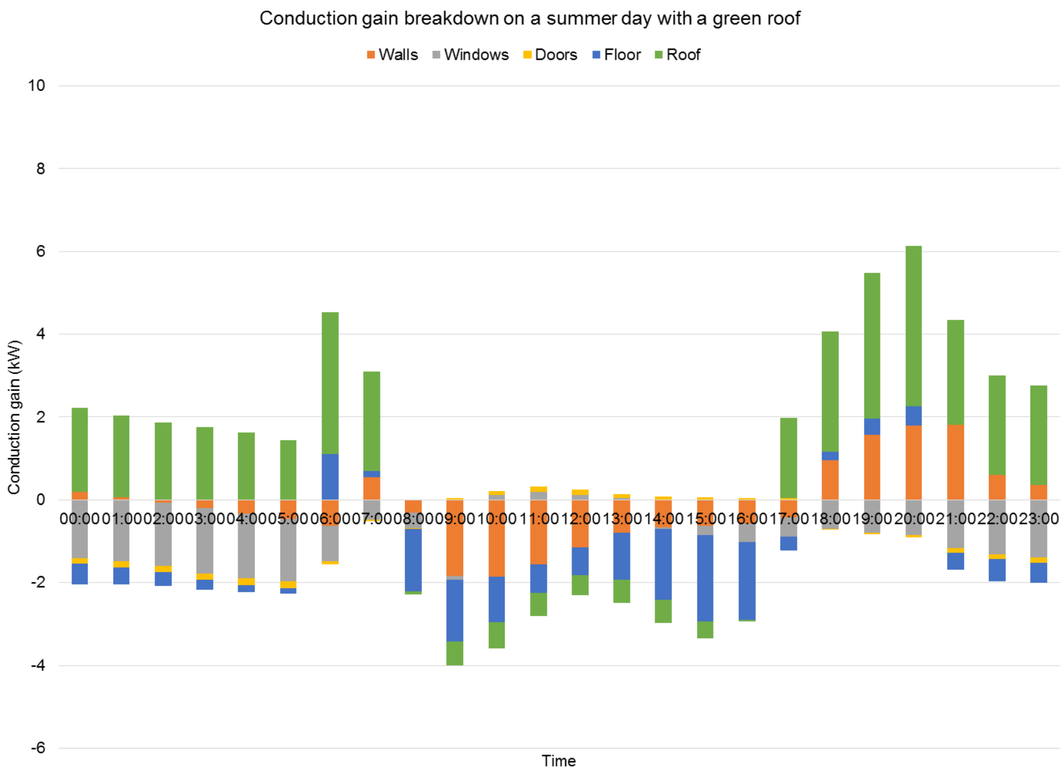


Figure 5-5: Variation of conduction game on a typical summer day for a green roof

Results of the simulation show a 42% reduction in the peak conduction gain through the roof when a green roof is applied.

Table 5-3: Peak conduction through roof

	Flat roof	Green roof	% reduction
Peak roof conduction gain	6.65	3.86	42.0 %

In terms of internal temperatures, on a hot summer day, the insulating effect of a green roof can reduce the internal temperature inside a house by up to 1.7 ^{0}C. From midnight to 11 am, the internal temperature inside the house tends to be slightly higher than if there were no green roofs. However the difference in internal temperatures is less than 1 ^{0}C (between 0 to 0.9 ^{0}C). In the afternoon and evening, when outdoor dry bulb temperatures are also high, the green roof performance is also better.

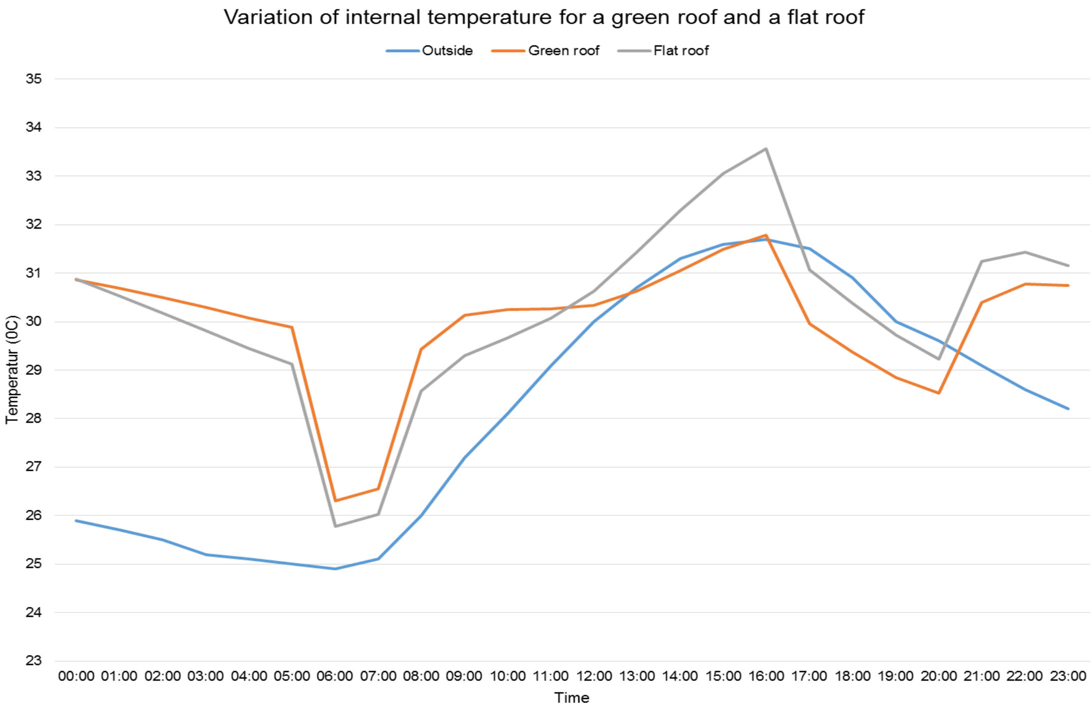


Figure 5-6: Variation of internal temperature for a flat and green roof

5.6 Findings

- In a house, heat gains through the roof is the major component of external conduction gains.
- The peak conduction gains occur at night (after sunset) which explains uncomfortable temperatures experienced in the house on summer nights, even though outside air is cooler.
- The insulating effect of green roofs can reduce internal temperatures by up to 1.7 ^{0}C. However, in real terms, the cooling effect produced could be higher due to the shading effect provided by the plant cover and the evaporative cooling effect.

Chapter 6: Conclusion

The main benefits analysed as part of this research project have been energy savings and stormwater management in using green roofs. In the absence of suitable substrates developed from local or recycled materials and research results on the evapotranspiration rate of suitable plants, definite values for reduction in energy consumption, reduction in stormwater run-off and improvement in run-off quality cannot be obtained pending further research to gather relevant data. However, based on results from studies reported in literature, anticipated energy savings and improvement in stormwater management have been provided.

As part of the project, a survey was also carried out to understand the current status of the green roof market to be able to identify challenges for implementation of green roofs in Mauritius, and areas of research which need to be addressed to better understand green roofs. Design variants have been provided to help persons interested in green roofs to choose the specific design which meet their requirements. Finally changes in building regulations that will need to be considered for safe and effective engineering of green roofs have been identified.

References

[1] Maitland, G (2014), The environmentally friendly roof, IChemE's President Blog, https://ichemepresident.wordpress.com/tag/smog/, last accessed on 1 November 2014

[2] Stewart, C, Thinking above the box: Green roof history and systems, Institute of Agriculture, University of Tennessee

[3] Stater, D (unknown), Green roofs: sustainability from the top down, Faculty of Landscape Architecture, University of California

[4] USEPA (2013), Green roofs,http://www.epa.gov/heatisland/mitigation/greenroofs.htm, last accessed on 1 November 2014

[5] Greenroofs.com (2014), http://www.greenroofs.com/Greenroofs101/faqs.htm, last accessed on 1 November 2014

[6] Rughoo, M (2013), Roof gardening has a direct impact on food security, Interview by Curpen, I. for Le Defi Media Group (http://www.defimedia.info/news-sunday/nos-news/item/39106-mukesh-rughoo-roof-gardening-has-a-direct-impact-on-food-security.html)

[7] Hui, S.C.M., (2013), Guidelines for the design and application of green roof systems, CIBSE

[8] Ecosis (unknown), Green roofs, www.ecosisltd.com

[9] Velazquez, L.S., (2003), Modular green roof technology: an overview of two systems, First Annual Greening Rooftops for Sustainable Communities Conference, Awards

[10] Renterghen, T.V. and Botteldooren, D (2009), Reducing the acoustical façade load from road traffic with green roofs, Building and Environment 44, 1081 – 1087.

[11] Vijayaraghavan, K., Joshi, U.M., Balasubramanian, R., (2012), A field study to evaluate runoff quality from green roofs, Water Research 46, 1337-1345.

[12] Stovin, V., Poë, S., and Berretta, C., (2013), A modelling study of long term green roof retention performance, Journal of Environmental Management 131, 206-215.

[13] Berndtsson, J.C. (2010), Green roof performance towards management of runoff water quantity and quality: A review, Ecological Engineering 36 351–360

[14] Hilten, R.N., Lawrence, T.M., Tollner, E.W., (2008) Modeling stormwater runoff from green roofs with HYDRUS-1D, Journal of Hydrology 358, 288– 293.

[15] Lazarrin, R.M, Castellati, F and Suato, F (2005), Experimental measurements and numerical modelling of a green roof, Energy and Buildings 3, 1260 – 1267.

[16] National Roofing Contractor Association (2007), NRCA green roof systems manual

[17] Townshend, D (2007), Study on green roof application in Hong Kong, Urbis Ltd.

[18] State of Victoria, Department of Environment and Primary Industries (2014), A guide to green roofs, walls and facades in Melbourne and Victotia, Australia

[19]

[20] Gabriel Pérez, Anna Vila, Lídia Rincón, Cristian Solé and Luisa F. Cabeza (2012) Use of rubber crumbs as drainage layer in green roofs as potential energy improvement material, Applied Energy 97 (2012) 347–354

[21] M. Razzaghmanesh, S. Beechama and F. Kazemi (2014) Impact of green roofs on stormwater quality in a South Australian urban environment, Science of the Total Environment 470–471 (2014) 651–659

[22] Bruce G. Gregoire and John C. Clausen (2011) Effect of a modular extensive green roof on stormwater runoff and water quality, Ecological Engineering 37 (2011) 963–969

[23] M. Uhl and L.Schiedt (2008) Green Roof Storm Water Retention – Monitoring Results, 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, 2008

[24] Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., Shaffer, P. (2007) The SuDS Manual (C697), CIRIA (Construction Industry Research and Information Association), London.

[25] Jeroen Mentens, Dirk Raes and Martin Hermy (2006) Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?, Landscape and Urban Planning 77 (2006) 217–226

[26] Justyna Czemiel Berndtsson (2010) Green roof performance towards management of run-off water quantity and quality: A review, Ecological Engineering 36 (2010) 351–360

[27] Lars Bengtsson, Lennart Grahn and Jonas Olsson (2005) Hydrological function of a thin extensive green roof in southern Sweden, Nordic Hydrology 36 (2005) 259-268

[28] VanWoert et al. (2005) Green Roof Stormwater Retention: Effects of Roof Surface, Slope, and Media Depth, J. Environ. Qual. 34:1036–1044 (2005)

[29] J. C. DeNardo et al., Green Roofs: A Stormwater BMP

[30] Carter, T.L. and Rasmussen T.C. (2006) Hydrologic behaviour of vegetated roofs, JAWRA, 42(5),1261-1274.

[31] Kristin L. Getter and D. Bradley Rowe (2006), The Role of Extensive Green Roofs in Sustainable Development, HORTSCIENCE 41(5):1276–1285. 2006

[32] Villarreal, E.L., and L. Bengtsson. (2005) Response of a Sedum green-roof to individual rain events. Ecol. Eng. 25:1–7.

[33] Mark T. Simmons, Brian Gardiner, Steve Windhager and Jeannine Tinsley (2008) Urban Ecosystems December 2008, Volume 11, Issue 4, pp 339-348

[34] Sabine Steusloff (1998) Input and Output of Airborne Aggressive Substances on Green Roofs in Karlsruhe, Urban Ecology pp 144-148

[35] Derek Wolf and Jeremy T. Lundholm (2008) Water uptake in green roof microcosms: Effects of plant species and water availability, Ecological Engineering, Volume 33, Issue 2, 3 June 2008, Pages 179–186

[36] Alnaqbi, A.K (2013), Investigating energy savings due to implementing green roof on existing residential buildings in UAC, MSc Dissertation, The British University, Dubai

[37] CIBSE (2006) CIBSE Guide A, Environmental Design

[38] Capozzoli A., Gorrino, A., Corrado, V., (2013) Thermal characterisation of green roofs through dynamic simulation, Proceedings of BS2013: 13th Conference of Internal Building Performance Simulation Association

[39] Evstaviev B., Gabrovska, K., (2013) Mathematical modelling of the microclimate in buildings with green roofs, Engineering Studies and Research, Vol 19-4

[40] Klein, P.M., Coffman, R., (2015) Establishment and performance of an experimental green roof under extreme climate conditions, Science of Total Environment, 512 -513 , 82 -93

[41] Lazzarin, R.M., Castellotti, F., Busato, F., (2005), Experimental measurements and numerical modelling of a green roof, Energy and Buildings, 37, 1260 – 1267

Appendix A: Water test procedure

Before installing a green roof, waterproofing membranes should be tested to check for their integrity. The water test is carried out to ensure that the membrane is leak free under a standing column or under flowing water conditions. For flat roofs, the standing water test or flowing water test can be used while for roofs with steep slopes, the flowing water test should be used. These two methods are described below:

Standing water test

Procedures

1. Plug or close all drains from the roof
2. Erect temporary dams around the area where the green roof is to be installed
3. Flood the contained area to a maximum depth of 5 cm.
4. Allow the water to stand for at least 24 hours

Precautions

1. Inform all parties concerned before conducting the test
2. Ensure that installation and removal of temporary dams do not damage the membrane.

Flowing water test

Procedures

1. Apply a continuous flow of water to the waterproofing membrane for at least 24 hours

Precautions

1. Inform all parties concerned before conducting the test

Test record sheet

<table>
<tr><th colspan="3">Test record sheet</th></tr>
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<tr><td colspan="3">Project address:</td></tr>
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<tr><td colspan="3">Dates:
Start (date and time)
End (date and time)
Duration:</td></tr>
<tr><td colspan="3">Test conditions:</td></tr>
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Minimum height of water (cm):
Maximum height of water (cm):
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Remarks:</td></tr>
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Appendix B: Local growing substrates and plants

Substrate composition

Substrate mixture	Ratio	Comments
Soil and compost	2:1	
Clayey soil and rocksand	3:1	Rocksand improves the porosity of the soil
Sandy soil and compost	1:1	Sandy soil has a good porosity and can drain water

Soil density

Soil Texture	Ideal bulk densities for plant growth (g/cm3)
Sandy	< 1.60
Silty	< 1.40
Clayey	<1.10

Plants that can be grown on roofs:

- Herbs – thym, coriander, parsley, rosemary, shallot, leek , basilic,..
- Salad crops- carrot , lettuce, beetroot, spinach
- Vegetables– tomato, radish, squash, zucchini, cabbage, broccoli, cauliflower
- Fruit – strawberry
- Decorative plants: Gerbera, geranium, marigold or any plant that can be grown in a pot or flower box