Development of a sustainability index for South African dwellings incorporating green roofs, rainwater harvesting and greywater re-use

by
Johannes Tinus van der Walt

Thesis presented in partial fulfilment of the requirements for the degree
Master of Engineering Science at the University of Stellenbosch

Supervisor: Prof Heinz E. Jacobs
Faculty of Engineering
Department of Civil Engineering

March 2012

Declaration

By submitting this thesis/dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

March 2012

Abstract

South African water service providers experience major problems with providing adequate water services to consumers. Water service providers in South African urban areas rely on traditional centralised infrastructure, such as bulk supply networks, to provide water services. Alternative supply and stormwater drainage methods should be encouraged to help mitigate these problems. The researcher thus aims to quantify the potential impact that three alternative methods may have on a given dwelling in terms of its dependence on traditional bulk water services. The three alternatives considered in this thesis are the construction of green roofs, rainwater harvesting and greywater re-use.

An efficiency of dwelling water use index (EDWI) was developed during this research project. It was designed in such a way as to show what portion of municipal water services could be replaced within the given dwelling by using the proposed techniques. The final EDWI-rating is obtained by using the EDWI-software tool developed as a part of this research. The derived EDWI-rating ranges from 0 to 100, with a rating of 100 indicating a dwelling requiring only the removal of a portion of sewage by a municipality, but no external water supply. Such a dwelling would also not require any water from a municipal network to meet domestic demand and all stormwater from its roof would be utilised within the plot boundaries. Results presented in this thesis illustrate how different geographical regions require different system specifications to obtain optimal EDWI-ratings, thereby lowering their dependence on the respective municipal water services.

Validation of the EDWI-system proved difficult as no similar index could be found during the literature review. It was therefore decided to benchmark the EDWI-system using three model dwellings with nine configurations producing a total of 27 analyses. The EDWI-system provides a conceptual foundation for sustainable water services to South African households in serviced urban areas. Future work could further improve the EDWI-system by testing its practical application so that it may be extended to act as a national barometer, used to compare decentralised water services in terms of sustainability.

Opsomming

Suid-Afrikaanse waterdiensverskaffers ondervind groot probleme met die voorsiening van voldoende waterdienste aan verbruikers. Waterdiensverskaffers in Suid-Afrikaanse stedelike gebiede maak staat op tradisionele gesentraliseerde infrastruktuur, soos grootmaatvoorsienings netwerke, om waterdienste te verskaf. Alternatiewe voorsienings- en stormwater dreineringsmetodes moet aangemoedig word om hierdie probleme aan te spreek. Die studie poog dus om die potensiële impak wat drie alternatiewe moontlikhede kan hê op 'n gegewe woning in terme van sy afhanklikheid van die tradisionele waterdienste te kwantifiseer. Die drie alternatiewe moontlikhede wat in hierdie studie ingesluit word is die konstruksie van groendakke, reënwater oes en grys water hergebruik.

'n Huishoudelike water gebruik doeltreffendheids indeks (EDWI) is ontwikkel gedurende hierdie navorsingsprojek. Die indeks is ontwerp om aan te dui watter gedeelte van munisipale waterdienste deur die voorgestelde tegnieke vervang kan word. Die finale EDWI-gradering is verkry deur gebruik te maak van die EDWI-programmatuur wat ontwikkel is gedurende die navorsing. Die afgeleide EDWI- gradering wissel tussen 0 en 100, met 'n telling van 100 wat ’n woning voorstel wat slegs die verwydering van 'n gedeelte van die riool deur die munisipaliteit vereis, maar wat geen eksterne watervoorsiening benodig nie. So 'n woning vereis dus geen water van ‘n munisipale netwerk nie, en alle stormwater van die dak word binne die erf gebruik. Resultate wat in hierdie studie voorgelê word illustreer hoe verskillende geografiese streke ander stelsel spesifikasies vereis om optimale EDWI-gradering te verkry.

Die navorser kon geen indeks kry wat soortgelyk is aan die EDWI-stelsel om dit mee te vergelyk nie. Dit was gevolglik besluit om die indeks te standardiseer deur gebruik te maak van drie model huise met nege samestellings van alternatiewe, waardeur 27 ontledings ontwikkel was. Die EDWI-stelsel bied 'n konseptuele grondslag vir volhoubare waterdienste vir Suid-Afrikaanse huishoudings in gedienste stedelike gebiede. Toekomstige navorsing kan die EDWI-stelsel verder verbeter deur die praktiese toepassing te toets. Die stelsel kan uitgebrei word om ‘n nationale barometer vorm wat gebruik kan word om desentralisasie van waterdienste te meet in konteks van volhoubaarheid.

Acknowledgements

I would like to thank the following people:

- My mother Elize without whose help and support, both financially and emotionally, this project would not be possible.
- To my friends and family who supported me through many a late night.
- To aunty Santie who helped with some finer technical details.
- And to my supervisor Professor Heinz Jacobs for providing much needed technical insight.

List of acronyms

AADD : Average Annual Daily Demand
AFHCO : Affordable Housing Company
AMDD : Average Monthly Daily Demand
AWC : Average winter consumption
BAC : Building and Construction Authority of Singapore
BOD : Biological Oxygen Demand
BOD$_5$: Biological Oxygen Demand over a five day period
COD : Chemical Oxygen Demand
CWSI : Canadian water sustainability index
CWU : Combined system water utilised
DRWH : Domestic rain water harvesting
EC : Electro conductivity
ET : Evapotranspiration
ETTV : Envelope thermal transfer value
EDWI : Efficiency of dwelling’s water use index
FC : Fecal coliform
FLL : Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau
GPS : Global Positioning System
GRRR : Green roof reduction in run-off
GWU : Greywater utilised
IUWM : Integrated Urban Water Management
JDA : Johannesburg Development Agency
LAI : Leaf area index
MAE : Mean Annual Evaporation
MAP : Mean Annual Precipitation
OTTV : Overall Thermal Transfer Value
PRI : Canadian Policy Research Institute
RTTV : Roof Thermal Transfer Value
RVFB : Recycled Vertical Flow Bioreactor
RWU : Rainwater utilised

SABS	: South African Bureau of Standards
SANS	: South African National Standards
SAR	: Sodium Absorption Ratio
SIUWM	: Sustainability Index for Urban Water Services
SKR	: Skylight ratio of roof
SUD	: Sustainable Urban Drainage
TC	: Total coliform
TRW	: Total rainwater utilised
TGW	: Total greywater utilised
UNESCO	: United Nations Educational, Scientific and Cultural Organization
US EPA	: United States Environmental Protection Agency
VBA	: Visual Basic for Applications
WCED	: World Commotion on Environment and Development
WHO	: World Health Organisation
WSI	: Watershed Sustainability Index
WSUD	: Water Sensitive Urban Design
WWR	: Window to wall ratio
YAS	: Yield after spillage
YBS	: Yield before spillage

List of symbols

b_n : Thickness of a material

C : Thermal conductance

Ca : Storage capacity

CF : Solar correction factor for roof

D_n : Portion of total domestic demand met by a system

D_t : Demand during time interval

E_d : EDWI-coefficient expressing reduction on municipal water demand

E_g : EDWI-coefficient expressing green space improvement

E_r : EDWI-coefficient expressing return flow reduction

E_t : Water savings efficiency

k_m : Crop factor

K : Thermal conductivity

L : Litres

L_t : Additional losses during time interval

n : Number of failures

N : Number of time units under observation

p_m : Monthly Evaporation

Q_t : Inflow during time interval

r : Thermal resistivity

R : Thermal resistance

R_e : The fraction of time demand cannot be met

R_i : Air film resistance of internal surface

r_m : Monthly Rainfall

R_o : Air film resistance of external surface

R_t : Total thermal resistance

R_v : Volumetric reliability of a system

SC : Shading coefficient of skylight portion of roof

S_l, S_b : Area of lawn and beds

S_t : Volume in storage

t : Time interval

U : Thermal transmittance

U_f : Thermal transmittance of fenestration

U_r : Thermal transmittance of opaque roof

U_s : Thermal energy transmitted by skylight

U_w : Thermal transmittance of opaque wall

Y_t : Yield during time interval

ΔE : Evaporation losses during time interval

θ : Parameter used to change between YAS and YBS algorithms

Ψ_a : Annual coefficient of discharge of a green roof

℃ : Degrees Celsius

Glossary

Blackwater:

Blackwater is the portion of return flow from a dwelling that has been contaminated to such an extent that intensive treatment would be required for safe disposal or re-use, such as water from a toilet.

Critical period:

The time required by a reservoir at full capacity to empty with no spillage in the given time period, thus from full to the first failure (McMahon & Mein, 1978).

Combined system:

A combined system refers to an alternative water system utilising grey- and rainwater in a single storage combined system.

Dwelling:

Dwellings are defined as a place where people live. In this document the word dwelling refers to houses, town houses, apartments, traditional houses or shacks (Meyer, 2000).

EDWI retaled terms:

The EDWI-system produces an EDWI-rating by using the EDWI-software tool. The EDWI-rating composes of three EDWI-coefficients that in turn depend on the performance and implementation of the three EDWI-components, which are rainwater harvesting, greywater re-use and green roofs.

FLL guidelines:

The “Richtlinie für die Planung, Ausführung und Pflege von Dachbegrünungen” or ‚”Dachbegrünungsrichtlinie” is issued by the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau. These guidelines, commonly referred to as the FLL guidelines, are the most widely accepted green roof guidelines available today.

Green roof:

A green roof is in the most basic of definitions is defined as a roof with plants on it. These multi layered structures can also be referred to as planted, eco, vegetated or brown roofs.

Greywater:

Greywater is defined as the return flow from processes such as bathing, showering, bathroom basins, kitchen sinks, washing machines and dishwashers. The greywater portion of sewage is also seen as less contaminated than blackwater and can therefore be re-used for selected applications.

Rainwater Harvesting:

The collection, storage and use of rainwater for any purpose

User form:

A user form is a popup window used in Excels via Visual Basic for Applications (VBA). In the software developed for this thesis user forms are used to simplify data input and for error checking.

Visual Basic for Applications:

VBA is a programming language used to control any Microsoft office program such as Excel or Word. VBA is based on the more well-known Visual Basic programming language.

Watershed:

A watershed is an area where all the water that drains from it or falls on it goes to the same point of discharge, thus forming a bounded hydrological system.

Xeriscaping:

The practice of planting a landscape to minimise water requirement. This often includes the use of plants native to the specific region.

Table of contents

List of Figures

List of tables

1. Introduction

1.1 Background

In the last few centuries the world has experienced an extreme rise in urbanisation, with the last two centuries seeing the portion of the world's population in large towns or cities grow from 5 % to 50 %. Demographers estimate that this proportion will increase to two-thirds of the population by 2030, with Africa currently being the least urbanised and showing the largest rate of urbanisation of all major regions (McMichael, 2000).

Rapid urbanisation has led to the creation of major cities and towns replacing previously green space with what can best be described as "concrete jungles". This causes, amongst other things, heat to rise through a process called the urban heat island effect (UHI). The UHI can cause the mean annual temperature to rise with between 1 to 3 ℃ and as much as 12℃ at night compared to adjacent areas (US EPA, 2008). When this happens a chain reaction is set in motion. Electricity demand rises as air-conditioners become over utilised causing more carbon emissions in an attempt to meet demand.

The creation of these "concrete jungles" also affects the overall permeability of the area. As green spaces are replaced by impervious spaces such as roads, parking lots and roofs greater portions of rain now converts to run-off. This has been documented as being as much as five times as great as would be observed in surrounding woodland (Downs, 2002). With increased stormwater volumes the risk of flooding also rises. Stormwater, being in larger quantities, now tends to transport more contaminants collected while in transit to its point of discharge (often the closest waterway). This causes the waterway to be eroded at the point of discharge, as well as polluting it.

The loss of green space has more physiological effects than might be imagined. Numerous publications focus on the link between the presence of plants and human well-being (McMichael, 2000; Lewis, 1995; Maller et al., 2005). The presence of plants has been linked to reduction in discomfort and reduced recovery time for surgery patients (Lohr & Pearson-Mims, 2000).

Increasing greenery in urban centres shows great potential to improve the day to day lives of the inhabitants. The introduction of greenery has been seen to improve the communities' image amongst its inhabitancy and especially of the creators (Lewis, 1995).

1.2 Aim with the research

The aim with this research is to develop an index which indicates how effectively a given dwelling can incorporate alternative water resources and green roofs towards a level of decentralisation from municipal water services. The efficiency of dwellings' water use index (EDWI) incorporates the use of greywater, rainwater and green roofs. By estimating normal water usage patterns, associated return flows can be found. When a dwellings' water usage is known, alternative sources of water can be assigned to specific applications. The amount of water harvested from the alternative sources is then seen as an automatic reduction in municipal demand. Further the benefits associated with the incorporation of green roofs are assessed. This is done by estimating the effects seen on water services because of the effects green roofs have on stormwater volumes, peaks and urban greenery. The beneficial effects of the three components are incorporated into the final rating, symbolising what portion of total domestic demand can be met without relying on municipal water services.

1.3 Thesis layout

Investigation

This thesis starts with an investigation of published literature covering sustainability, green roofs, rainwater and greywater. Relevant literature is analysed to show how they have been used, what their advantages are and the potential pitfalls that exist. The literature review is then followed by more practical chapters in which the intention is to show how and why these techniques should be implemented.

Index concept and scope

The concept of the EDWI-system is then explored. This starts by defining the dwelling's the EDWI-system applies to, how to estimate usage patterns and demand is discussed, followed by general water quality classifications. The methods and assumptions used in the EDWI-system, and used to incorporate the components, are then discussed. The process whereby all practical contributions of components are quantified to show the maximum effect their incorporation can provide, is then described.

Software development, index calculation and analysis

The following chapter describes the development of software tool used to produce the final EDWI-rating. Excel was used in combination with Visual Basic for Applications (VBA) by the author to develop the previously mentioned software solution. The developed software is intended as a user-friendly platform to facilitate the analysis and optimisation of any dwelling in South Africa that falls within the predefined boundaries. This chapter further provides all equations used in the calculation procedure of the final rating. In the subsequent chapter four example analyses for a dwelling with the same general characteristics in different cities and geographical regions are provided, followed by the benchmarking procedure.

Discussion

In the final chapter the results are discussed and recommendations are made regarding future work that could improve on the understanding of index or similar concepts.

1.4 Motivation for research

Numerous indexes have been developed to help decision makers understand and analyse the state of water services. These indicators such as the sustainability index for urban water services (SIUWM) are able to form a holistic profile of a city's water situation. There is however no index to quantify how, on a detailed spatial level, the dependence on water services can be reduced by implementing alternative water sources and water management strategies. The spatial scale of this study considers individual residential plots (households). While every dwelling requires access to fresh drinking water, sewage systems and the removal of excess stormwater, there is no reason why all these services should be provided by centralised infrastructure. This is where the EDWI-system comes in. The EDWI-system allows a user to assess how much of its required water services could be provided by using the alternative techniques proposed in this study, thus lowering the dwelling's dependence on centralised infrastructure. The following aspects were assessed in detail and are seen as being of critical importance to the EDWI-system:

- Understand the effects of green roofs and the potentially beneficial impacts they could have in terms of stormwater management and the reduction of impervious roof spaces.
- Assess how much of domestic water demand could be supplied by using alternative water sources instead of municipally supplied water.
- Quantify the potential applications of alternative water resources not adhering to potable standards.
- Assess what portion of return flows as greywater from dwellings could be re-used, taking account of health and safety implications.
- Test the effect of operational algorithms for greywater re-use systems' efficiencies.
- Develop a tool to simplify the process of obtaining an EDWI-rating by means of an uncomplicated software system (called the EDWI-software tool).
- Due to the wide range of climatic conditions that occur in South Africa it was deemed important to assess their impacts on any alternative water system. This would help with the design of specification for these systems in different regions in order for maximum benefits to be obtained from their installation.
- Benchmarking the EDWI-system using three model dwellings with nine configurations.

1.5 Scope and limitations of the study

The EDWI-system developed in this thesis includes rainwater harvesting, greywater re-use and the construction of green roofs. Groundwater is excluded from the scope of this study.

Dwellings that are analysed with the developed index have to have access to a roof and a garden, thus excluding apartment buildings.

In this study water quality is classified in terms of three quality classes in order to focus the work on assessing the sustainability and development of a novel conceptual index. The minimum water treatment required for each application is thus not included.

The rainwater system included in this study refers to permanently installed tank system. The disconnecting of gutters for irrigation is not included in the scope of this study.

2. Literature review

The scope of is chapter covers a review of relevant literature concerning the sustainability in urban water systems, rainwater harvesting, greywater re-use and green roofs.

2.1 Water sensitive urban design and other urban water design philosophies

The terms used to describe urban water design philosophies can be quite vague. Three of these are selected and defined in an attempt to clarify the confusion. They are:

- Water sensitive urban design (WSUD)
- Sustainable urban drainage (SUD)
- Integrated urban water management (IUWM).

IUWM is an emerging approach to managing the entire urban water cycle in an integrated way, which is the key to achieving sustainability of urban water resources and services (Mays, 2009). IUWM incorporates factors that would influence various dimensions of the water sector. These include sources of water, water quality and quantity as well as wider dimensions examining the influence of other sectors on water such as social and economic development. The IUWM philosophy thus aims to view water management as an interdependent entity functioning in a much bigger environment.

WSUD and SUD are similar to IUWM in the sense that they are design philosophies concerned with urban water management, but unlike IUWM the considerations for these two do not include factors outside the water sector. SUD or source control is a design philosophy concerned with controlling surface run-off in ways that do not cause the same or similar problems as those caused by more traditional solutions. WSUD is very similar to SUD and is explained in great detail in the rest of this section.

WSUD is a set of principles or design philosophies that aim to improve the way urban environments are designed. When an area is transformed from a natural environment to an urban one the characteristics of the water cycle change with it. These changes can be seen in the characteristics of floods, run-off volumes as well as their pollutant loads. Excessive stormwater volumes with high pollutant loads are then discharged in the nearest receiving water body, like a lake, dam or river. These sensitive environments can then be completely "washed out" or in the best case scenario, only damaged. Excessive stormwater volumes also increase the risk of flooding and damage to infrastructure. The change in percentage rainfall that translates to run-off caused by the addition of impervious areas is shown in Figure 1.

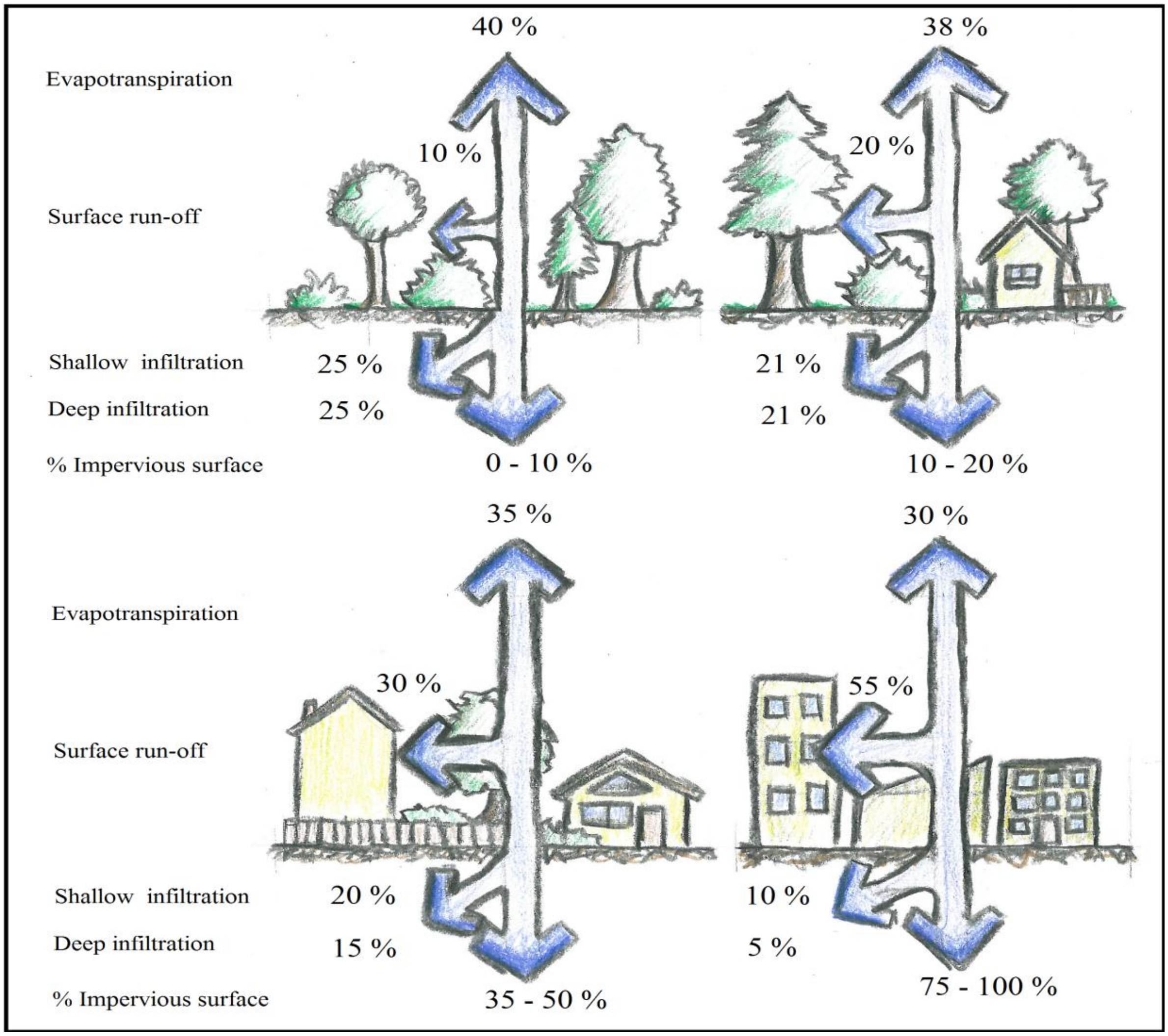


Figure 1: Change in run-off characteristics with urbanisation

(Adapted from Dunnett & Clayden (2007))

WSUD aims to lower these impacts from urbanisation by decreasing impervious spaces, apply natural treatment and protect natural water ways. These measures can include, but are not limited to, the use of detention basins, infiltration basins, constructed wetlands, grass swales, porous pavements and infiltration trenches (Downs, 2002).

The WSUD design philosophy encourages the use of alternative water resources such as rainwater harvesting, groundwater and greywater re-use. The impacts of these techniques might seem small as they normally only lower domestic dependence on a municipal water supply, but when these techniques are implemented on a large scale their effects become much larger.

The overall goals of WSUD are (Downs, 2002):

- To preserve existing topographic and natural features
- To protect surface and groundwater resources
- To integrate public open space with stormwater drainage corridors, maximising public access, passive recreation activities and visual amenities.

These goals are achieved by using a variety of techniques that are softer than traditional drainage systems such as pipes and concrete channels. These WSUD principles could also be a cheaper alternative, in some cases, to the more traditional stormwater management solutions (Dunnett & Clayden, 2007).

WSUD attempts to (Downs, 2002):

- Minimise impervious surfaces
- Minimise the use of formal drainage infrastructure (pipes)
- Encourage infiltration
- Protecting existing vegetation
- Encourage the re-use of stormwater.

In a system designed according to WSUD principles water is seen as a precious resource. Stormwater is now seen as a potential resource and not only as a problem that needs to be removed as quickly as possible. Natural waterways are protected and incorporated in urban design, not just replaced by formal infrastructure. These principles allow for a softer, natural urban environment as opposed to the hard impersonal "concrete jungle" that many of the world's large cities have inadvertently become.

2.2 Sustainability and sustainability indexes

The concept of sustainability is ambiguous and not well understood by many. Sustainability is not about the promise or striving for factors like integration of ecological, social and economic issues or improving quality of life (Sutton, 2000). If a system or society moves towards a more sustainable style or operation it's not to improve the given system or society, but to assure that it can be sustained, thus enabling the current level of for example production to remain where it is, and not to increase or decrease.

Often the definitions of sustainability and also sustainable development only refer to an element of the true all encompassing definition, the whole concept (Mebratu, 1998). Sustainability can be applied to (Sutton, 2000):

- the environment (ecological sustainability)
- society (social sustainability)
- the economy (economic sustainability)
- an organisation (organisational sustainability)
- people within an organisation (human sustainability - in a corporate context).

The Brundtland Commission (1987) gave the most widely used definition of sustainable development (WCED, 1987):

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own"

This definition highlights strong links between poverty alleviation, environmental improvement, and social equitability through sustainable economic growth (Mebratu, 1998).

Sustainability and sustainable development are context bound. Before sustainability can be understood it is important to know what it applies to. According to Robèrt et al. (2002) a sustainable society does not systematically increase the production of substances, or subject nature to increasing concentrations of substances taken from the earth's crust.

2.2.1 Sustainability indexes and indicators

Sustainability indexes are used to measure sustainability by incorporating a range of parameters and indicators that highlight aspects of sustainability. In the following sections a brief explanation of some well known sustainability indicators is provided.

2.2.1.1 Canadian water sustainability index

The Canadian Water Sustainability Index (CWSI) was developed by the Canadian Policy Research Initiative (PRI). The CWSI uses a range of water related data and translates them into a series of indicators. These indicators are divided into five components. With these components a holistic profile is created which represents a given community's water issues (PRI, 2007). CWSI then allows for an intra- and inter-community comparison and analysis.

As mentioned the CWSI comprises of five components, they are (PRI, 2007):

- Resource
- Ecosystem health
- Infrastructure
- Human health and well-being
- Capacity.

These five components each have three indicators. The indicators are each allocated a score between 0 and 100. The average of the three is then used to score the specific component. CWSI is then derived by calculating the average of the five components as shown in Figure 2.

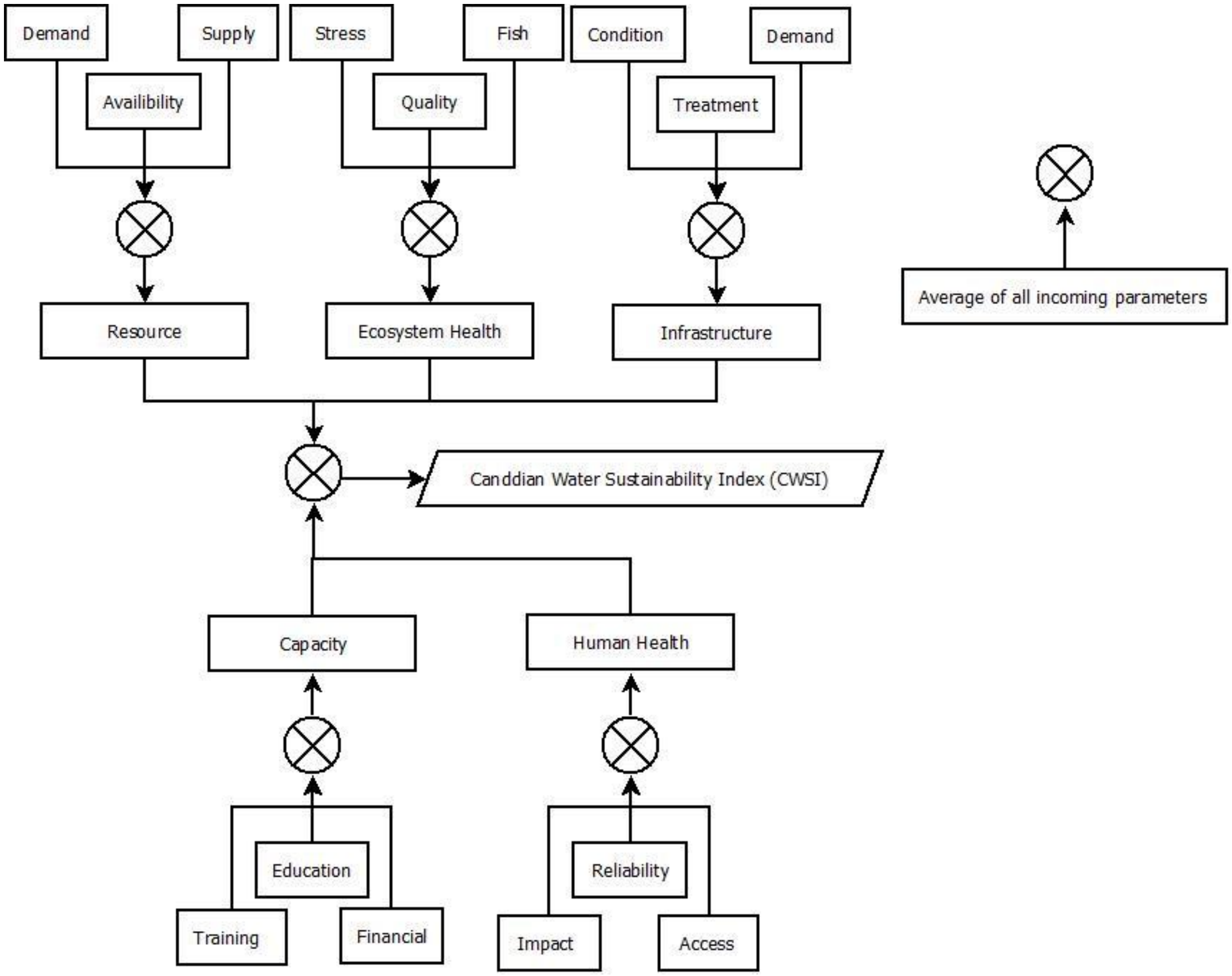


Figure 2: CWSI Components and Indicators

Communities with higher CWSI are in a better position reap the socio-economic, ecological and health benefits associated with a fresh water source (PRI, 2007).

The use of 15 indicators in the CWSI allows an authority to assess a watershed’s overall holistic profile. However the final CWSI rating, because of the numerous factors taken into account, might not highlight any area requiring immediate attention. This is not necessarily a problem because one needs only to also take one step back and first assess the five component’s contributions to the final rating to gain a deeper understanding of a given watershed’s health and where attention is needed.

2.2.1.2 Energy barometer

The Energy Barometer developed by Energy Cybernetics aims to benchmark energy usage in buildings (Grobler, 2010). This is done by comparing these buildings with buildings used for similar purposes, thereby comparing apples with apples. The evaluation process takes into account factors such as climatic conditions, occupancy and floor area. Industry average energy usage is calculated and normlised to a score of 100 and has been used to form a comprehensive data base to evaluate any other building (Grobler, 2010). The owner of any building being audited is able to compare the energy consumption of his or her building with industry standards for this particular type of building.

This energy barometer serves as a very useful tool to asses if energy is being used efficiently. Although not taking water or green roofs into account directly the concept is of great use to aid in the development of similar scales for water usage and re-use.

2.2.1.3 Water footprint

A water footprint is the amount of water required annually by the inhabitants of a given country to meet their direct needs, as well as the water required to produce the goods and services used. The water footprint has two basic components, the first relating to domestic water withdrawals and the second, the external water coefficient, is the water used in other countries to produce the goods and services imported by the inhabitants of the country in question (Hoekstra & Chapagain, 2006).

The ecological footprint is another indicator similar to the water footprint but which differs in that it takes a larger scope into consideration. This ecological footprint, developed by Rees (1992), is the total area required by a discrete urban environment to meet its needs. It is argued by Rees (1992) that modern societies rely heavily on goods and services not produced or rendered in their own areas but imported either locally or internationally. For this reason the total area required to sustain a given city will normally be larger than the physical area occupied by the given city.

2.2.1.4 Watershed sustainability index

The water shed sustainability index (WSI) is a single index that incorporates the HELP index developed by UNESCO. WSI thus integrates the hydrology (H), environment (E), life (L) and policy (P) of a given watershed (Catano et al., 2009). Each of these indicators is first assessed with the three parameters: Pressure, State and Response. The use of this Pressure-State-Response parameter then allows the incorporation of cause-effect relationships providing a broader scope than can be obtained by taking only one into consideration.

Pressure	: Assessment of the extent of human activities on the watershed
State	: Assessment of the quality of watershed in the beginning the study
Response	: Assessment of the willingness of the society to solve ecological problems in the watershed.

The WSI incorporates basic parameters that are normally easily acquired for any basin, parameters such as the Human Development Index, Biological Oxygen Demand over a five day period (BOD_5) and the Environmental Pressure Index. WSI can be derived with equation 2.1 (Catano et al., 2009):

$$WSI = \frac{H + E + L + P}{4} \qquad \text{Equation 2-1}$$

The indicators work with an operational scale between 0 (worst) and 1 (excellent). Quantitative and qualitative parameters are divided into five groups (0, 0.25, 0.5, 0.75 and 1). Each indicator is then assigned a Pressure-State-Response parameter (Catano et al., 2009). The average of the Pressure-State-Response parameter and its corresponding indicator is then calculated to obtain the score of each indicator. The WSI is then acquired by means of the general equation above, thus the average of all indicators

2.2.1.5 Sustainability index for integrated urban water management

The SIUWM is an index that attempts to quantify a town or city's potential to be sustainable. This index developed by De Carvalho et al. (2009) is based on five main components:

- Social and cultural – social fairness and equitable resource distribution
- Economic – economically sound principles, economic growth and cost returns
- Environmental – environmental protection and preservation of ecological systems
- Political – support and international stewardship
- Institutional and technological – capacity and progress

These five components are disaggregated into 20 indicators and ultimately into 64 variables (Carvalho et al., 2009).

The SIUWM provides a very comprehensive picture of the condition and sustainability of urban water. By including components that are not directly linked to the water sector, such as political and social and cultural components, a broader scope is attained. SIUWM has been tested in two cities in South Africa where it was seen that this index is able to highlight areas of concern.

2.3 Green Roofs

2.3.1 Introduction to green roofs

The concept of a green roof entails, in the most basic sense, that a given roof has plants on it. These types of roofs are very popular in Europe, especially in Germany where it is estimated that 14% of flat roofs are now equipped with a green roof system (Köhler & Keeley, 2005). This is no surprise as Germany is known as the modern birthplace of green roofs and currently has the best developed green roof guidelines, FLL (2002), available. Green roofs are not a new idea, perhaps the best known example of an ancient green roof and one of the seven wonders of the ancient world are the gardens of Babylon (Osmundson, 1999). The rebirth of green roofs in modern times took place in Germany in the 1880s with the arrival of the increased industrialisation and urbanisation. At this time flammable tar was often used as a form of inexpensive roofing material. A roofer named H. Koch developed a method of adding sand or gravel to these tar roofs to lower fire risk. Over time seeds naturally colonised these roofs forming meadows over time. In 1980 fifty of these roofs were still intact and completely water proof (Köhler & Keeley, 2005)

Green roof can also be referred to as planted, brown, living and eco or vegetated roofs. Green roofs have two main classifications which are intensive and extensive. An intensive green roof is defined by a thicker substrate depth (> 150 mm) while the depth of extensive green roofs normally range from 40 to 150mm. While both these types of green roofs have many advantages regarding their installation it is commonly accepted that extensive green roofs are more economically viable because of their lower imposed loads requiring less structural reinforcement. Intensive green roofs can support a much greater variety of plants compared to extensive green roofs because of the greater substrate depth. These green roofs, sometimes referred to as roof top gardens, require intensive maintenance and irrigation to keep them aesthetically pleasing and functioning correctly. This is in contrast with extensive green roofs which are normally designed to have lower substrate depths, less load, and to operate with minimal maintenance and, if possible, without irrigation. The retro fitting of extensive green roofs is also often possible without additional structural reinforcement, minimal maintenance considerations and do not require such a high level of accessibility when compared to intensive green roof system, making them the economically preferable choice (Dunnett & Kingsbury, 2004).

Green roofs have numerous benefits associated with the upkeep and running costs of the building as well as the area in which it has been built.

Green roofs have many advantages; these are (Snodgrass & McIntyre, 2010):

- Storm water retention
- Lower energy costs
- Improved aesthetics and marketability
- Mitigation of the urban heat island effect
- Improvement of air quality
- Novel quality improvement of rainwater
- Increased lifespan of roofing membrane
- Habitat for urban wildlife.

The numerous advantages associated with green roofs make them an attractive alternative to conventional roofing systems. These advantages can be seen as directly influencing the owner of the building or being beneficial to the area. The problem with some of the greatest advantages of a green roof system is that they are really observed only when a specific area implements green roofs on a large scale. These are advantages like stormwater retention and the mitigation of the UHI, while the lowering of energy consumption and extension of roof life has a far greater effect on the choice of the building owner.

Stormwater retention is seen as the main advantage associated with green roofs. This however is not very important to building owners who are not responsible for the treatment and management of stormwater generated by their buildings. In the United States many communities have implemented a “stormwater treatment tax” to accommodate the additional load added to the sewer network. These fees are currently too low to reflect the actual cost caused by the extra infrastructure required for the treatment and management of the additional stormwater. But in time this tax may very well improve the feasibility of green roof projects (Luckett, 2009). Appl & Ansel (2004) also reported the important role that green roofs play in Germany as part of a storm water management system.

2.3.2 Types of green roofs

Green roofs can be broadly classified as either extensive or intensive green roofs. While this basic classification is valid there are some more detailed descriptions and classifications of green roofs made according to commonly accepted guidelines. In the FLL guidelines (2002) green roofs can be either:

- Intensive
- Simple intensive
- Extensive.

Whereas the Austrian green roof guidelines mention four types of green roofs (Waldbaum, n.d.):

- Intensive
- Reduced intensive
- Extensive
- Reduced extensive.

The Swiss green roof guidelines only refer to extensive green roofs and refer back to the FLL (2002) guidelines for intensive green roofs (Waldbaum, n.d.).

The FFL (2002) guidelines are by far the most comprehensive green roof guidelines. In terms of classification of green roof types the FLL uses the types of plants used, their irrigation and the maintenance requirements in order to distinguish between them. As an example the main differences between an intensive and a simple intensive green roof is the range of plants used, and the watering, feeding and maintenance requirements (FLL, 2002).

2.3.3 Stormwater retention

Extended urbanisation has led to increased run-off from these areas. This is caused by the large impervious surfaces that replace previously pervious surfaces resulting in much greater surface run-off. It follows logically that more green space is required to retain larger portions of rainwater. Vacant plots can be utilised to retain rainwater but because of economical reasons this is often not feasible. An alternative way to manage this problem is the utilisation of bare and unused roof space as green roofs. Green roofs have been documented to have a significant impact on run-off volumes. In Brussels simulated results showed the effect that would be seen if 10 % of roofs were installed with extensive green roofs. This simulation showed that this additional urban greenery would result in a run-off reduction of 2.7 % (Mentens et al., 2006). A field study conducted in North California quantified the reduction in storm water peaks over a period of eight months. In this study it was found that approximately the first 15 mm of rainfall was retained. For the two test sites used it was also reported that 62 and 63 % respectively of rainfall was retained which resulted in an average peak flow reduction of 78% and 87 % (Moran et al., 2004).

Green roofs lower stormwater peaks in three ways (Mentens et al., 2006):

- Delaying start of run-off due to absorption in the green roof system
- Retaining a part of the rainfall event
- Releasing the retained water over a period of time.

When estimating stormwater peak retentions obtained by given green roof systems there are a few factors that should be considered. Stormwater retention depends on the substrate depth, the moisture content of the substrate just before the rainfall event and the angle of the roof. The type of plants can potentially influence retention but this has been noted to be to a lesser extent (VanWoert et al., 2005). It was found that the main factor influencing retention has been noted in literature as being substrate depth. This finding is supported by results from a study conducted by VanWoert et al. (2005) where the influence of roof slope and substrate depth was tested. This study concluded that a smaller slope combined with a deeper substrate depth increases the amount of rainfall retained and thus reduces the run-off (VanWoert et al., 2005). A statistical analysis performed by Mentens et al. (2005) produced some arbitrary equations to estimate water retention, these equations are however limited to a particular rainfall range and are season specific.

The FLL (2002) guidelines describe the water retention of green roofs. In these guidelines it is stated that the water retention of a green roof is influenced by a few reference values (FLL, 2002:35):

- Maximum water capacity
- Water permeability
- Coefficient of discharge
- Slowing down of water run-off
- Annual coefficient of discharge.

The FLL (2002) guidelines also contain a table of reference values for green roofs stormwater retention based on a mean annual precipitation (MAP) of between 650-800 mm shown in Table 1. This table shows that the portion of stormwater retained by a green roof depends on substrate depth and vegetation type. It is also important to note that regions with an MAP lower than 650 mm have higher stormwater retention portions than those presented in Table 1, and regions with an MAP higher than 800 mm have water retention lower than those specified in the FLL guidelines (FLL, 2002:37).

Type of greening	Course depth in cm	Form of vegetation	Water retention - annual average in %	Annual coefficient of discharge Ψ_a/ sealing coefficient
Extensive greening	2 - 4	Moss-sedum greening	40	0.60
	> 4 - 6	Sedum-moss greening	45	0.55
	> 6 - 10	Sedum-moss-herbaceous plants	50	0.50
	> 10 - 15	Sedum-herbaceous-grass plants	55	0.45
	> 15 - 20	Grass-herbaceous plants	60	0.40
Intensive greening	15 - 25	Lawn, shrubs, coppices	60	0.40
	> 25 - 50	Lawn, shrubs, coppices	70	0.30
	> 50	Lawn, shrubs, coppices, trees	> 90	0.10

Table 1: Green roof reference stormwater retention values (FFL, 2002: 35)

2.3.4 Thermal benefits of green roofs

In order to understand the effects that green roofs have on the thermal properties of a roof better it is necessary to start with how heat enters a building. This characteristic of buildings is well known and documented but quantified changes in heat transfer caused by the installation of green roofs are not. It is evident that green roofs do insulate building roofs, but the extent of this and quantified changes in roof characteristics are not that well understood.

2.3.4.1 How heat entering a building is quantified

In recent years greater emphasis has been placed on the economical design of buildings. Amongst the regulations concerned with economical design are the new guidelines on energy efficient design for air-conditioned buildings. In a seminar organised by the Building and Construction Authority (BAC) and held in Singapore (2001) new regulations were laid out and first published and implemented in 2004. These regulations are mainly concerned with the transfer rate of heat in a building. The envelope thermal transfer value or ETTV for short is the parameter quantifying the building. More seasoned professionals will remember its predecessor the OTTV or overall thermal transfer value. This OTTV parameter has however been replaced by the previously mentioned ETTV, which is basically a modification of the OTTV, because it estimates the three elements of heat gain better.

In South-Africa new regulations dealing with the energy efficiency of buildings, SANS 204, have been developed (SANS, 2010). These regulations are currently non-compulsory but this is poised to change at a time when these regulations are seen as practical. The SANS 204 identifies six climate zones throughout South-Africa and identifies applicable thermal resistance (R or R-Value) for them, both in and out of the building. The meaning of the R- Value is explained later in this section. Heat entering or leaving a building has three components. They are (BAC, 2004):

- heat conduction through opaque walls
- heat conduction through glass windows
- solar radiation through glass windows.

This ETTV can estimate the heat gains of a building through the external walls and windows. The formula for ETTV is presented in equation 2.2 (BAC, 2004).

$$ETTV = 12(1 - WWR)U_w + 3.4(WWR)U_f + 211(WWR)(CF)(SC) \qquad \text{Equation 2-2}$$

where:

ETTV is the envelope thermal transfer value (W/m^2)
WWR is the window to wall ratio (fenestration area / gross area of exterior wall)
U_w is the thermal transmittance of opaque wall
U_f is thermal transmittance of fenestration
CF is correction factor for solar heat gain and
SC is the shading coefficients of fenestration

The formula for ETTV is further modified to account for the use of different materials being used on the same building as well as to take the orientation of the wall into account. This is fully discussed in the Guidelines for Envelope Thermal Transfer Value for buildings (2004).

The same equation can be applied to a roof with a skylight. To avoid confusion the parameter is then called the Roof Thermal Transfer Value or RTTV for short. Similar to the ETTV the RTTV also estimates all three element of heat gain, namely (BAC, 2004):

- heat conduction through opaque roof
- heat conduction through skylight
- solar radiation through skylight.

RTTV is calculated with equation 2.3 (BAC, 2004).

$$RTTV = 12.5(1 - SKR)U_r + 4.8(SKR)U_s + 485(SKR)(CF)(SC) \qquad \text{Equation 2-3}$$

where:

SKR	for Skylight ratio of roof (skylight area / gross area of roof)
U_r	for thermal transmittance by opaque roof
U_s	for thermal energy transmittance by skylight area
CF	for solar correction factor for roof and
SC	for shading coefficients of skylight portion of the roof.

2.3.4.2 Thermal transmittance

To determine the thermal transmittance a few other parameters will first be required.

Thermal conductivity (K) is the given material's ability to transmit heat. This value is measured as the amount of heat that passes through a unit area of unit thickness, in unit time under steady-state conditions when unit temperature difference exists between opposite surfaces. This value is measured in W/m ^{o} K. The reciprocal of the thermal conductivity is the thermal resistivity (r). Thermal resistivity is measured in m ^{o} K/W and calculated with equation 2.4.

$$r = \frac{1}{K}$$ Equation 2-4

Thermal conductance (C) refers to the specific thickness of a material or construction. It is defined as the thermal transmission through a unit area of material per unit temperature difference between hot and cold faces and is calculated using equation 2.5 and is expressed in W/m$^{2\ o}$ K. The reciprocal of the thermal conductance is the thermal resistance (R) derived using equation 2.6. This value is measured in m$^{2\ o}$ K/W.

$$C = \frac{K}{b}$$ Equation 2-5

Where b is the thickness of the material (m).

$$R = \frac{1}{C} = \frac{b}{K}$$ Equation 2-6

Thermal transmittance (U) is the quantity of heat that passes through a unit area of building under steady state conditions. This happens in unit time per unit temperature difference of the air on either side of the section. This value is measured in W/m^2 ^{o}K and obtained using equation 2.7.

$$U = \frac{1}{R_T}$$ Equation 2-7

R_T is the total thermal resistance calculated with equation 2.8.

$$R_T = R_0 + \frac{b_1}{K_1} + \frac{b_2}{K_2} + \ldots + \frac{b_n}{K_n} + R_i$$ Equation 2-8

where:

R_0	is air film resistance of external surface (m^2 ^{o}K/W)
R_i	is air film resistance of internal surface (m^2 ^{o}K/W)
b_1, b_2, b_n	is thickness of basic material (m)
K_1, K_2, K_n	is thermal conductivity of basic material (W/m ^{o}K).

2.3.4.3 Thermal properties and performance of a green roof system

There is a substantial body of literature reporting the possible thermal benefits of green roofs (Del Barrio, 1997; Köhler et al., 2002; Castleton et al., 2010). Because of local climate conditions it is very difficult to generalise the effects of similar green roofs in different parts of the world. The plants used in the tropics further differ from those used in Europe, for example, and since the leaf area index (LAI) of each plant is different so will the effect of the plants on cooling. It is important to note the cooling effect of evaporation. This effect is greater in warmer conditions as more evaporation would occur, provided that water is available. That being said literature from different geographical areas can still be extremely useful as they serve as a benchmark and can highlight potential pitfalls.

When the thermal properties of green roofs are examined it is important to verify the contribution of both the substrate and the plant cover (Liu & Minor, 2005; Wong et al., 2003a; Köhler et al., 2002). This was observed in a study performed in Toronto which quantified the thermal effect of two green roofs with different substrate depths. The two roofs did not have adequate green cover and thus the study's results can, to an extent, be seen as only the effect of the substrate. This study found that these two green roofs both insulated the building in question. The insulating effect can clearly be seen when the results of green roofs are compared with the reference roof. The following results were found on a typical summer's day. In the case of the reference roof the membrane temperature rose to 66 ^{o}C at around 14:00, while the green roofs both lowered and delayed the peak. The first green roof, substrate depth of 75 mm, had a peak of 38 ^{o}C at 18:30 while the second green roof, substrate depth of 100 mm, had a peak of 36 C at 19:30. In the conventional roof heat started to enter the building quite early, around 06:00, while the green roofs were able to delay this process until the afternoon. The maximum heat transfer observed in the conventional roof was 15 W/m^2 while the green roofs lowered this to 2.5 W/m^2. This study showed the great potential of green roofs to reduce and delay heat transfer through a roof (Liu & Minor, 2005).

2.3.4.4 The effect of green roofs on roofing membrane

Green roofs actively lower temperature peaks when compared to traditional roofs (Snodgrass & McIntyre, 2010; Liu & Minor, 2005). Temperature peaks in combination with quicker heat loss creates large changes between the lowest and highest temperatures on a roof each day. With a green roof system these peaks are lowered, and there is less difference between the warmest and coldest time of day on the green roof. This effect lowers the thermal stress on the roof membrane, thereby extending roof life as it is well known that the most important factor influencing degradation is temperature (Björk, 2004).

2.3.4.5 The role of evaporation in the cooling process

The ability of green roofs to retain rainwater is one of the system’s biggest benefits. Although this helps prevent excessive flooding and rainwater infiltration into sewer systems it also plays a big part in the cooling process of a green roof. As water is retained in the substrate and taken up by the plants, it eventually evaporates. This can take place as evaporation from the roof surface or as transpiration through the plants (evapotranspiration). This process of evapotranspiration (ET) is an endothermic process, called evaporation cooling, which requires 2450 J of energy per gram of water that evaporates (Köhler et al., 2002). This required energy for evaporation is then obtained from the surrounding area, thus cooling the given roof. As large volumes of water are evaporated in this way, this effect becomes very beneficial and leads to a lowered energy requirement for air-conditioned buildings. This effect has been seen to be very effective in German summers and will be even more so in the tropics where the benefits can be enjoyed all year.

Literature clearly indicates that ET rates affect the cooling effect of green roof. It is further known that different species of plants have different ET rates making this value difficult to generalise. The process is further complicated as can be seen by the results obtained in a field study conducted in Auckland, New Zealand by Voyde et al. (2010). In this field study which quantified ET rates it was seen that plant species react differently to drought periods. When plants experience a period of drought they become stressed. This stressed state leads to the plant “holding on” to the moisture that it has available. Plants in such a state are thus less effective in terms of potential cooling ability, as ET rates lower. The extent of this is clear when the results are observed. In this trial two species of plants were tested. In unstressed conditions the ET for both was 0.29 mm/h while in stressed it was 0.05 and 0.02 mm/h respectively (Voyde et al., 2010).

In traditional concrete buildings the effectiveness of evaporation is clearly visible when steam is observed rising from a traditional roof after a storm. With a green roof system this effect is not as visually dramatic, but lasts a lot longer as water is retained by the plants and substrate. This allows the evaporation cooling effect to be beneficial for a lot longer.

2.3.4.6 Energy savings

Many studies concerned with the potential energy savings that green roofs can offer by lowering heat transfer through the roofs of buildings, have been conducted. These results often lack definitive data on the roofs' thermal properties and U-values. Because of this they are only applicable to the situation in question (Castleton et al., 2010).

In Singapore a study that quantifies the energy savings and thermal properties of green roofs was conducted by Wong et al. (2003b). This study showed that a five storey commercial building in Singapore would have an energy reduction of up to 15% when installed with a green roof. The study also detailed the change in U and R - Values the roof would have after installation of a green roof. R- Values rose with the addition of substrate, the deeper the higher, and the addition of plants. For the different plant types tested, trees and shrubs, it was concluded that shrubs had the greater effect on the R- Value. The rise in the R-Value of the roof leads to an increase in thermal resistance, and thus to energy savings on cooling in summer an on heating in winter (Wong et al., 2003b). These types of energy savings may not be enough to justify the use of green roofs on their own in newer generation buildings. This is due to new construction regulations like the 2006 UK building regulations which require new buildings to be better insulated. In these buildings green roofs would save very little, if any, energy. Older buildings however are not usually built with adequate insulation, and these types of buildings would benefit greatly in terms of energy consumption by the retro-fitting of a green roof (Castleton et al., 2010).

2.3.5 Green roofs as urban ecosystems

Green roofs offer the potential for re-establishment of formerly lost green space in urban environments. These green spaces are now being investigated to see to what extent they can help improve not only the bio diversity of flora, but also of fauna. Green roofs designed for the purpose of establishing bio diversity are commonly referred to as brown roofs. These roofs are designed to serve as urban habitats for varies species of invertebrates and other animals. A brown roof generally has a varying substrate depth and drainage regimes that allow for the creation of a mosaic of micro habitats. The roof then has the potential to host a far greater range of fauna and flora allowing a far greater bio-diverse ecology to develop.

In London it has also been seen that even extensive sedum covered green roofs can function as sustainable urban environments to those animals that are able to adapt to this harsh environment (Brenneisen, 2006). Another study conducted in London focused on invertebrates colonising sedum and brown roofs. It was observed that a surprisingly large number of invertebrates were found on these roofs, especially the sedum roofs. It was further discovered that at least 10 % of all collected species were considered rare and scarce (Kadas, 2006). This shows the potential these green and brown roofs have in the preservation of these rare species.

In Switzerland ground nesting birds have been seen to move onto flat green roofs. These species, little ringed plover and northern lapwing, are under extreme pressure as their natural habitats give way to urbanisation. It was found in a preliminary study conducted on this “migration” of these birds that many birds nested on green roofs and that eggs hatched, but that no chicks have been documented surviving to adulthood. This could be, according to Baumann (2006), because of the lack of food and extreme environment. These chicks are very dependent on their environment as they are not fed by their parents and require food such as insects, spiders, and other small animals (Baumann, 2006). On brown roofs where a more diverse ecosystem is established food might not be such a great concern.

2.3.6 Disadvantages associated with green roofs

Green roofs are extremely expensive, have a labour intensive as well as complex installation process and require additional structural considerations when compared to traditional roofs. In a country such as South Africa where green roofs have recently entered the market concerns such as these would be more prevalent. South Africa, having only recently been introduced to green roofs, will not have access to a vast range of specialist designers, experienced installation companies or access to engineered substrates at reasonable prices, if at all. Maintenance concerns also arise caused by what is seen by some as the biggest benefit associated with green roofs, which is the retention of stormwater. Green roofs are always installed with a waterproofing layer. Plant roots, amongst other possibilities, may damage this layer allowing water from a saturated substrate layer access to the roofing deck. Damage to the waterproofing layer of a green roof will be a costly problem to solve as the entire roofing system would likely need to be removed for repairs. Run-off from green roofs can further cause the substrate to erode. A Green roof is especially susceptible to this phenomenon when installed at larger angles and in its establishment phase. Although green roofs are generally designed to require little to no irrigation they may not survive arid regions without it (Luckett, 2009). This point is especially valid with intensive green roofs or rooftop gardens due to their larger verity plants associated with higher and more frequent irrigation demands. In water stressed countries like South Africa this irrigation demand will most likely occur at times of droughts stressing the already limited water supply.

2.4 Rainwater harvesting

2.4.1 Introduction

Rainwater harvesting is the collection, storage and use of rainwater. The most widespread form of rainwater harvesting is by the use of roofs. In addition to roofs, rock and treated earth are also used to harvest rainwater (Gould & Nissen-Peterson, 1999). Harvested rainwater can then be used as a water supply for a variety of applications. Perhaps the most beneficial aspect of rainwater harvesting systems is that they can be built exactly where the water is needed. This advantage is reflected in the popularity of these systems in rural areas where there is no access to municipal networks. This is reflected in the frequent occurrence of rainwater systems intended to meet full domestic consumption in coastal and other small towns in South Africa where no reticulation network exists (Jacobs et al., 2010). Even in areas where access to municipal networks exist rainwater harvesting is still extremely beneficial as it can substantially lower municipal demand while simultaneously lowering effluent generated by pre-existing impervious surfaces.

2.4.2 Domestic rainwater harvesting

Domestic rainwater harvesting (DRWH) systems can take many forms. They all have a few things in common: they have a catchment area, some form of storage and some way of getting the water from collection to storage. Typically a roof is used as collection surface and either an above or below ground water tank as storage. Typical DRWH systems contain:

- Gutters and downpipes
- A first flush diverter
- A tank
- A catchment area.

In places where access to a municipal network exists collected rainwater is often used as a secondary or supplementary source of water. Often rainwater is collected to supply water for purposes that do not require water at a potable level. Variables that could potentially influence the operational efficiency of a rainwater system include (Jacobs et al., 2010):

- The MAP of the area
- Rainfall pattern (Monthly distribution)
- Collection surface (roof in the case of DRWH)
- Storage capacity
- The demand imposed on the system
- Alternative water sources (Cheaper alternatives sometimes exist, such as groundwater)
- Cost (The Installation and maintenance costs versus financial benefits).

2.4.3 Quality of rainwater

In general rainwater is of a fair quality. It is well known that rainwater is very "soft", meaning that it has very little to no calcium, magnesium or dissolved salts and it's also sodium free. However as rainwater falls it acquires a slight acidity as it dissolves carbon dioxide and nitrogen on its way to earth (Hari & Krishna, 2005). Accordingly the quality of rainwater can be highly dependent on the area in which it falls, as levels of pollution vary, and therefore the level of dissolved contaminants. Another big factor influencing the quality of collected rainwater is the catchment surface, normally a roof in the case of DRWH. Debris that are deposited on roofs such as dust, deposits from small mammals and birds, leaves and sticks greatly influence the quality of the collected rainwater (Mendez et al., 2011). For this reason first flush diverters are often installed as they divert the first rain that falls during a rain event giving time for contaminants to be "rinsed off" before water is harvested. This is a widely used technique but there is some controversy about the amount that should be spilled. According to Hari & Krishna (2005) a minimum of 38 l for every 93 m^2 of collection area should be diverted. Although this may serve as an adequate "rule of thumb" it has also been seen that the rainfall intensity as well as the number of dry days between rainfall events affects the amount of water required to clean the roof (Yanizi et al., 1989).

The type of material that a roof is made of also affects the quality of harvested rainwater. This is reflected in the results from a study conducted by Mendez et al. (2011). In this study asphalt, fibreglass shingle, galvalume metal, concrete tile, cool and green roofs were examined. After the first flush diversion, as prescribed by Hari & Krishna (2005), it was found that water collected by the asphalt fibreglass shingle, metal, concrete tile, and cool roofs would need treatment for total coliform (TC), fecal coliform (FC), turbidity, aluminium, and iron to meet potable use standards (Mendez et al., 2011). Whereas rainwater harvested from the green roof required treatment for TC, FC, turbidity and aluminium to meet the same drinking water standards.

During a study conducted in the city of New Castle, Australia by Evans et al. (2006) the possible effects that wind speed and rain intensity could have on the microbial composition of roof run-off and roof-harvested rainwater was investigated. This study concluded that weather patterns and relative position to a source can greatly influence the bacterial load of run-off. Wind speed was also shown to have a large effect at the tested sites (Evans et al., 2006). Interesting results have been seen in another study done across eastern Australia, on the bacterial diversity in rainwater tanks. This study was conducted by Evans et al. (2009). The results of this study present evidence that shows the presence of a wide range of bacterial diversity. Because of the cultivated populations and scope of diversity found, functional ecosystems of complex communities of environmental bacteria can be supported in rainwater tanks. These communities could have beneficial impacts on the quality of the harvested rainwater (Evans et al., 2009).

2.4.4 Rainwater harvesting from green roofs

When considering a green roof as catchment surface for rainwater harvesting there are a few aspects that needs to be considered. The aspect of most concern is the effluent originating from green roofs. It is difficult to generalise green roof effluent in terms of nutrient load, pH, hardness and other contaminants. This is partially due to the wide range of green roof designs, substrate types, depths and plants in use. It has however been seen that green roofs tend to increase phosphate and total nitrogen loads (Moran et al., 2004). While Berghage et al. (2009) commented on the increase seen in pH, hardness and phosphate loads seen in the first of two data sets observed. The second, smaller data set showed similar or greater nutrient (phosphate and potassium) and hardness (magnesium and calcium) loads in the run-off from the control asphalt roof. They further hypothesised that green roofs appeared to lower atmospheric nitrates

(Berghage et al., 2009). Green roof effluent has also been noticed to have a slightly yellow colour (Berghage et al., 2009).

Another aspect that needs to be considered is the run-off volumes from green roofs. Green roofs are known to lower run-offs from roofs, so logically the optimal size of a tank would be smaller than for the same size roof of a traditional roofing material. The problem now becomes the estimation, to an adequate degree of certainty, of how much water will run off the green roof. While run-off coefficients have been developed for green roofs (Fewkes & Warm, 2000; FLL, 2002) these are assumed to be constant. This assumption is quite simply not adequate as it is well known that a given green roof's run-off volume depends on such things as the number of dry days before a given rain event, the pitch of the roof as well as substrate depth and composition and even the given season (VanWoert et al., 2005). It might be argued that this approach would result in an over complication of the process, but if these aspects are not adequately addressed, systems of this kind could become very inefficient.

2.5 Greywater

2.5.1 Introduction

All dwellings generate return flow, commonly referred to as wastewater. The wastewater can be divided into two distinct groups; black- and greywater. Greywater is defined as the portion of wastewater generated by showers, baths, kitchen sinks, dishwashers, bathroom basins and washing machines. These processes contribute as much as 50 % to the total wastewater generated by most dwellings (Jacobs & Van Staden, 2008). Unlike blackwater, greywater can be seen as relatively unpolluted, although it contains chemicals and micro organisms that can be harmful to humans and the surrounding environment (Jeppesen, 1996). The strategic use of this underutilised resource shows great potential to reduce domestic water demands for functions such as watering gardens and toilet flushing. The use of greywater is not a new idea. Greywater has been used in dry periods by urban gardeners and to water food crops in low income areas (Rodda et al., 2010). Large scale implementation of this technique can be seen in Berlin where advanced systems have been installed, one serving 70 people, boasting with the creation of a risk free service by means of biological treatment (Nolde, 1999).

2.5.2 Greywater characteristics

The characteristics of contaminants found in greywater are highly variable. They depend on an array of factors such as the use of detergents, soaps and other specific habits the occupants of the dwelling might have.

Physical pollutants are usually found in greywater in varying concentrations and sizes. This can be attributed to the many different methods that are used to control suspended solids. These methods range from coarse filters that can be found at inlets such as sinks or showers, or filters that prevent hair from entering the greywater stream. Jefferson et al. (2004) reported on the wide range of concentrations of suspended solids found in their study. They reported suspended solids concentrations of between 24 to 202, 12 to 104 and 73 to 379 $mg.L^{-1}$ for the shower, bath and hand basins respectively.

The chemical compounds and characteristics of importance normally found in greywater are (Morel & Diener, 2006):

- pH
- Alkalinity as $CaCO_3$
- Electrical conductivity (EC)
- Sodium absorption ratio (SAR)
- Biological oxygen demand (BOD) and chemical oxygen demand (COD)
- Nutrient content (nitrogen, phosphorous)
- Heavy metals
- Organic pollutants in detergents.

Normally the pH of greywater ranges between 6.5 and 8.4 (US EPA, 2004). But the use of sodium hydroxide-based soaps and bleach could raise pH to between 9.3 and 10 as observed by Christova-Boal et al. (1996). EC is an indication of salt content of greywater. The EC of greywater could originate from sodium chloride (table salt) or from other sources such as salts found in sodium based soaps or nitrates and phosphates present in detergents and washing powders (Morel & Diener, 2006). Greywater usually has an EC of 300 to 1,500 µS/cm (Morel & Diener, 2006). The SAR of greywater is an indication of sodium hazard that quantifies the portion of sodium to calcium to calcium (Morel & Diener, 2006). Gross et al. (2005) found the SAR of greywater range to be between 2.8 and 6.0.

COD and BOD are indicators that show the level of organic pollutants in water. COD indicates the amount of oxygen required to oxidise all organic matter and BOD reflects oxygen demand of bacteria thought through biological oxidation in a given time frame (Morel & Diener, 2006). Gross et al. (2005) found that household greywater would have COD and BOD concentrations of an average of 686 and 270 $mg.L^{-1}$ with standard deviations of 60 and 21 respectively.

The biodegradability of greywater can be indicated by using the COD/BOD ratio. Greywater is considered as easily biodegradable when it has a COD/BOD ratio of between 2 and 2.5. As mentioned earlier greywater characteristics are very dependent on the types of contaminants that are added during the processes that generate greywater. This is also the case with the biodegradability of greywater as it is primarily dependent on synthetic surfactants found in detergents and on the quantity of oil and fat present (Morel & Diener, 2006).

The presence of FC in greywater sends a clear sign of a risk of pathogens being present. Gross at al. (2005) found the average FC in their study to be 106 FCU g^{-1}.

2.5.3 Risks associated with the use of greywater

Greywater contains many contaminants, potentially dangerous micro organisms and viruses. The quality of greywater is also extremely varied depending on the source and for instance the amount and type of soap and washing detergent used. This can be expected resulting from cultural, lifestyle and habitual differences between different people and communities. Greywater can be classified as medium strength sewage in terms of its highly variable organic contents (Jefferson et al., 2004). The composition of greywater is of such a nature that it is highly recommended that humans should minimise or, if at all possible, avoid contact with it (Jeppesen, 1996). These fears are further expressed in terms of the method of application of greywater. Greywater that has not been treated should not be stored for more than 24 hours and if at all possible, not for more than a few hours (Carden et al., 2007b).

The risks associated with irrigation by means of greywater are also of great concern. The literature clearly indicates the potential for the contamination of food crops (WHO, 2006). This risk is greater for crops that are normally eaten raw. In the rural areas where these techniques could bring the greatest benefits in terms of food security and poverty alleviation, the potential risk is greatest. People who live in these areas often do not wash these corps sufficiently, mainly because of a lack of fresh water, so the condition they are harvested in often needs to be acceptable for human consumption (Jackson et al., 2006). Possible concerns arise as some pathogens are known to survive in the soil and on crop surfaces for extended periods of time, such as Helminth eggs which, in extreme cases, can survive in soils for several years (WHO, 2006). Concerns have also been raised over the long term effects on the soil because of the levels of phosphate, sodium and chloride found in greywater (Christov-Boal et al., 1996).

Treatment of greywater could overcome health concerns associated with human contact with greywater (Christov-Boal et al., 1996). With the application of an adequate treatment system greywater can now be stored and used in applications such as toilet flushing with minimal fears of health risks (Jeppesen, 1996).

2.5.4 Greywater for irrigation

The idea of using greywater for irrigation has been studied by a number of authors (Christov-Boal et al., 1996; Rodda et al., 2010; Faruqui, 2002; Jacobs & Van Staden, 2008; Pinto et al., 2010). Christov-Boal et al. (1996) and Jacobs & Van Staden (2008) investigated the effects of greywater irrigation on garden beds and lawns, while Rodda et al. (2010) and Pinto et al. (2010) investigated the effects on greywater irrigation on food crops. From the literature presented it can clearly be seen that no consensus has been reached. While some authors approve of the regulated use of greywater (Jacobs & Van Staden, 2008) for irrigation, others discourage this (WHO, 2006). Greywater contains “contaminants” which have a negative effect on the environment if discharged into a water way, but in the right concentration they are beneficial to plants.

As reported by Rodda et al. (2010) greywater contains nutrients such as nitrogen and phosphorus which can help plants to grow optimally and the soapy nature of greywater can act as an insect repellent. It was also reported by Jacobs & Standers (2008) that extremely satisfactory plant growth was observed with no real implications to the soil when greywater was used to water a lawn. A rise in sodium levels was however observed. Faruqui (2002) conducted experiments on the impacts of growing food crops with greywater in rural Jordan to help create food security and generate additional income. His research showed this method to hold great potential. It was reported that the women who participated in this experiment said that they felt empowered by these new skills they had acquired and the ability to better provide for their families. The study did not report any significant adverse effects on the soil, this was partly attributed to the low volumes applied and to the physical properties of the soil (Faruqui, 2002). In glasshouse experiments conducted by Pinto et al. (2010) the effect irrigating silverbeet plants with greywater only, potable water only and a mixture of grey- and potable water, with a ratio of 1:1, was tested to see the effects on soil properties and plant growth. It was found that although greywater irrigation had no significant effect on the soil’s total nitrates or total phosphates levels, changes were observed with respect to the soil's pH and EC (Pinto et al., 2010). Despite these promising results the author does not recommend the unrestricted use of greywater in this way. Other authors have also commented positively about the results obtained from greywater irrigation of food crops (Jackson et al., 2006; Salukazana et al., 2005). Possible negative effects are however highlighted by other researchers and guidelines such as decreased crop yields and possible contamination of crop, implying health risks to its consumers (Rodda et al., 2010; WHO, 2006).

2.5.5 Greywater in high density non-sewered areas

The University of Cape Town has conducted a study on greywater management in non-sewered areas in South-Africa. This study used data obtained from 36 settlements in six provinces. In this study it was found that the greywater is generally disposed of by discarding it onto the ground (Carden et al., 2007b). This method seems to have minimal effects as long as the settlement is not too densely populated. These types of disposal techniques are acceptable as long as the following are prevented (Carden et al., 2007b):

- Pooling of greywater
- Greywater entering surface water systems
- Build up in soil to the extent that damage to soil occurs or pollution of ground water.

In rural communities nuisance factors such as odour and insects breeding, especially mosquitoes, have led to some communities finding their own solutions. It has been seen that in some more densely populated settlements or in areas with poorly draining soil people discard greywater in selected areas, such as the closest stormwater drains or channels (Carden et al., 2007b).

Research revealed that the re-use of greywater is generally not advised in non-sewered areas unless it is done under controlled conditions (Carden et al., 2007b). Additional findings have also shown that for settlement densities above 50 dwellings per hectare (du/ha) greywater re-use poses unacceptable risks to the occupants and alternative means of disposal need to be found. Carden et al. (2007a) also noted that the characteristics of greywater in non-sewered areas differs significantly to that found in higher income sewered areas in that it has much higher concentrations of pollutants and could even be classified as hazards.

The following chapter provides practical information about green roof design and structure. Further information is provided about the possible role green roofs can play in sustainable cities and green roof projects in South Africa.

3. Green roofs and their place in South Africa

This chapter provides a more practical approach to green roofs in terms of construction principles, recognised guidelines and their incorporation to South African building regulations.

3.1 Green roof construction basics

A green roof consists of a few basic parts or components. The extent of their use and manner in which they are used are normally determined by the type and function of the green roof. Most types of green roof have the following components in common, refer to Figure 3:

- Plants
- Growing medium
- Filter layer
- Drainage layer
- Root protection layer
- Water proofing layer.

Green roofs can be installed modularly or "build in place". The choice between these two is made by the intended function or feature that the roof is designed to serve. For example a green roof designed to function as a rooftop garden would require different considerations when compared to a system designed to optimize stormwater retention or energy savings.

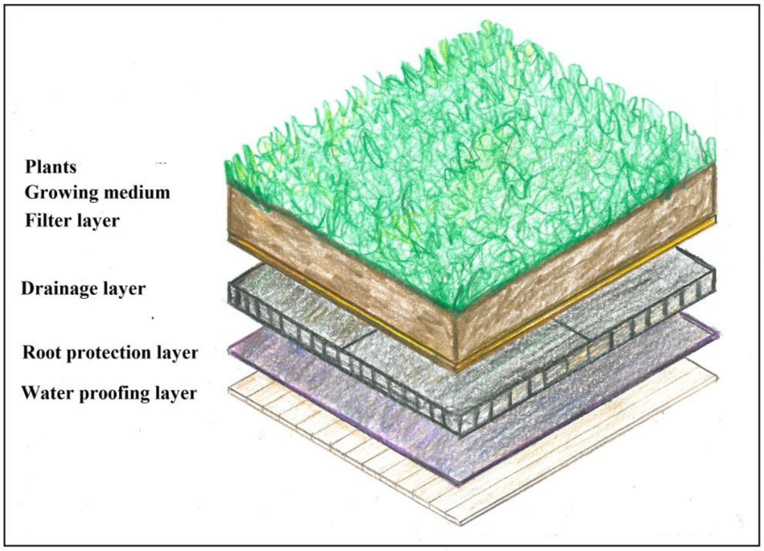


Figure 3: Green roof layers

3.1.1 Modular design

Modular type of green roof construction consists of planters, essentially trays, that the growing medium and plants are placed in (Luckett, 2009). The planters are simply placed on the roof to create a green roof. Damage to the roof can easily be repaired in this type of project as the modules can simply be moved. The planters can be constructed from rigid materials or they can be fabric modules. The rigid planters have the advantage that they can be grown off site and when installed form an instant green roof, while fabric modules have to be grown in place (Snodgrass & McIntyre, 2010). The rigid modules can however be difficult to place in irregular areas. Different modules, in terms of plants and substrate depth can be used in combination with walkways and seating areas to create simple rooftop gardens. If accessibility is not a concern gardens of this type could make a welcome addition to any building by offering a previously lost green space where the occupants of the building can relax.

Modular design, while an attractive option, is not always advisable. These units are for example less than ideal when an intensive green roof is considered. By definition intensive green roofs have deeper growing medium (> 150 mm) to accommodate the larger variety of plant species with which they are associated. This extra load, because of the deeper layer, then makes these modules hard to move or even immobile, defeating their main purpose (Luckett, 2009).

This modular design construction is best suited for an extensive green roof project which makes the planters lighter and more mobile. When a smaller project is considered in an area of a roof which is not easily accessible modules are often also a good choice as their self-contained nature makes accessibility less of a problem. Planters are often a good design consideration when a small part of a building is to be retro-fitted (Snodgrass & McIntyre, 2010). These modules are also a preferred choice by researchers conducting green roof research as they can be set up almost anywhere (Luckett, 2009).

3.1.2 "Build in place" green roofs

A "build in place" green roof is the more traditional approach to green roof construction. This method consists of layering the different elements of a green roof directly on the support structure, the roof. By using a "build in place" design the designer has the advantage of obtaining uninterrupted planting space. When an intensive green roof project is proposed "build in place" is the best design option. This method allows the designer to customise his design better as the uninterrupted plant space makes variations in substrate dept possible, and hence a greater pallet of plant species, easer.

Large scale projects which use extensive systems are normally "build in place". This method often produces the most economically viable option as a modular design would require numerous planters to be placed which would only add to the costs. The built in place option will be the most cost effective option in projects where stormwater management is the main consideration (Snodgrass & McIntyre, 2010).

By incorporation additional components such as treated wood bracing of plastic products modelled in a honeycomb shape allows green roofs to be installed at significantly larger angels. The additional components helps keep the substrate from eroding or being blown out of place while plants are still in the establishment phase.

3.2 Green roof construction, a more technical approach

The most comprehensive green roof guidelines known as the German “Richtlinie für die Planung, Ausführung und Pflege von Dachbegrünungen” or ,”Dachbegrünungsricplace’phtlinie” are issued by the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FFL). The 2002 version of these guidelines was translated to English in 2004 and is now simply referred to as the FLL guidelines. The FLL guidelines have since been adopted by numerous other countries and form a general basis for other guidelines such as the Swiss and Austrian green roof guidelines (Waldbaum, n.d.).

To date there are no official green roof guidelines in the United Kingdom. The Green roof Organisation has however produced a document intituled “Guidelines to green roofing”, but this refers to the FLL guidelines on most technical points (GRO, 2011).

In North America the FLL (2002) guidelines are also normally used. Although the city of Toronto has launched green roofing standards, these standards also refer to the FLL guidelines (Borooah, 2006).

3.2.1 The German guidelines

The FLL guidelines were first published in 1982 under the title of “Principles for Green Roofs” and were renamed “Directive” in 1990 (Waldaum, n.d.). After the first version of the FLL guidelines was published, many revisions have been made incorporating the experience gained during numerous green roof projects. Being of German origin, the FLL has always been published in German, making it difficult for non-German speaking nations to benefit from their wealth of experience. In 2004 the 2002 version of the FLL was translated into English and since then has been incorporated by, to the best of the author’s knowledge, all non-German guidelines either partially or entirely.

The FLL was developed to set out basic principles and requirements relating to the planning, execution and maintenance of green roof projects utilising all available knowledge and the latest technology. These guidelines deal with additional basic principles relating to planning and construction with a special emphasis on technical requirements in respect to construction and vegetation (FLL, 2002). The FLL (2002) as technical guidelines, are intended to be used by professionals and craftsmen functioning in the roof-greening sectors and trade.

3.2.2 South-African building regulations

The South-African Bureau of Standards (SABS) 0400: “National building regulations” is used as basis for the design of roofs in South Africa. The SABS 0400 does however not refer to green roofs and therefore also not on their construction. Although not directly specifying green roof construction there are a few general requirements that needs to be adhered to. According to the general requirements set out by SABS 0400 a roof should (SABS, 1990):

- Resist the forces that the roof will be subjected to
- Be durable and waterproof
- Not allow the pooling of rainwater
- Assure that the roof ceiling setup leaves enough space for the floor directly under it.

Because green roofs retain rainwater their loads vary depending on whether the roof is dry or saturated. The least load exerted by the green roof will be in its dry state and the maximum will be when it is completely saturated, this excluding all other applicable live loads.

The loads imposed by a given green roof are categorised in two groups, live and dead loads. Live loads refer to loads that are not necessarily applied, or in a certain combination, and dead loads are always imposed on the structure. These two loads are then used in combination to obtain the maximum design load that should be resisted by the building. In the case of green roofs additional considerations should be taken into account such as (FFL, 2002):

- The thermal insulation and damp proof lining of the green roof must have an adequate compressive strength where spot loads are being considered
- In a layered superstructure care should be taken to assure that any substance used as an intermediate layer does not push the load above the design limit

- Special consideration is required when vegetation is to serve as protection against negative pressures created by wind.

Green roofs are far more complex structures than traditional roofing methods. In the SABS 0400 there is no mention of these structures, so in the absence of adequate local standards or guidelines it is proposed that the most comprehensive international guidelines be used, called the FLL (2002) guidelines.

3.3 The role of green roofs in sustainable cities

To truly appreciate the role green roofs could play in developing sustainable cities one needs to look far beyond the well known and quantifiable advantages they could provide. Instead of viewing green roofs as a way to receive a “check” in a box on a form to acquire some sort of green rating they should rather be viewed as the environmentally friendly alternative to regular roofs. This is not to say that their well known and quantifiable advantages are to be ignored, but rather that all the small contributions that seem minute will add up, over time and as more are built, to make a valued contribution towards creating sustainable cities.

With the increase of world populations and rapid expansion of urban centres localised greenery has taken a backseat to the demands imposed on these areas. Rapid urbanisation has caused large impervious areas to be created in the form of roads, paving, parking lots and roofs, replacing previously green spaces. These impervious spaces cause problems not only to the city’s infrastructure and operation, but also to the mental welfare of its inhabitants.

Buildings and other infrastructure have an adverse effect on the climate, and in turn the climate on them. This effect is commonly referred to as the UHI. In an urban environment radiation from the sun is absorbed by impervious surfaces such as roads and roofs. In woodlands this absorbed radiation is used for the evaporation and transpiration of moisture. But in urban areas, the radiation is stored and is released during the night causing urban temperatures to rise (Golden, 2004). The UHI is greater in areas with higher urbanisation and less vegetation. Green roofs, by bringing back these lost green spaces, can help manage this effect of urbanisation.

Perhaps the best known effect of urbanisation and increase of impervious spaces is the effect seen on the stormwater volumes and flood characteristics of these areas. There are a few techniques that can be implemented in order to improve stormwater management in these urban centres. Technologies such as pervious pavements, infiltration basins and rainwater harvesting can all bring similar, equivalent or even greater benefits when compared to green roofs. They can also be more cost effective than green roofs. However this in no way means that these alternatives should always be implemented instead of green roofs, but rather that they all should be incorporated as small parts in a much bigger system. Furthermore the choice whether or not to implement a green roof should not be made for one single reason, but should be considered as an attractive alternative that has the potential not only to serve its design purposes, but also to give back previously lost green space and the beauty associated with it.

While modern living has doubled our life expectancy, it has created disparities between our ancient origins and modern ways of living that may have caused the emergence of new serious diseases (Maller et al., 2005). Maller et al. (2005) further show that urban green space, such as parks or possibly green roofs, not only play a vital part in protecting the essential systems of life and biodiversity, but also provide a setting for health promotion and the creation of well-being. The requirement for “contact with nature” is as ingrained in us as any of our other primal desires and is universal across all cultures and nations. This point is best illustrated in the words of C.A. Lewis (1995) who said:

> “The response of humans to plants is not a function of country of culture, but rather is a function of our humanness... Plants could survive without people, but people would perish without plants.”

Literature clearly indicates a strong link between the presence of plants and human well-being. However this does not necessarily imply that these same people would prefer having these plants on their roofs opposed to having them in their general environment. White & Gatersleben (2011) found that people in the United Kingdom seem to prefer certain types of vegetation either as living walls or green roofs to regular roofs and walls. It concluded that people tend to prefer vegetation that depicts a natural environment, natural meadow roof, when compared to neat vegetation showing human maintenance such as a turf roof.

3.4 South African green roofs

Green roofs have only recently been introduced to the South African market. To the best of the author's knowledge there are currently two green roof initiatives active in South Africa, the first being the eThekwini Municipality's green roof pilot project in Durban as part of the city's Climate Protection Programme. The second is a rooftop vegetable garden in the inner city limits of the city of Johannesburg intended to improve inner city food security (Mabotja, 2011).

The eThekwini Municipality's pilot green roof was built on top of one of the city's engineering complex buildings. The 550 m^2 test site now tests different construction methods, substrate mixtures, variety of indigenous plant species and different watering rates (Greenstone, 2009). In 2004, as a response to higher temperatures and increased frequency of severe floods and droughts, the Climate Protection Programme was initiated, and focused on the effects of climate change that the city would experience. The future of green roofs looks good as a team has been selected to continue the research as well as to implement green roofs on all municipal buildings where they are deemed sustainable (Greenstone, 2009).

The Johannesburg rooftop vegetable garden is a joint initiative of the Johannesburg Development Agency (JDA) and the Affordable Housing Company (AFHCO). This garden is the first of its kind in Johannesburg and is intended to increase urban food security and sustainability in a city where it is estimated that 42 % of households are food insecure (Rudolph et al., 2009). The tenants of this building now have access to a cheap source of fresh vegetables, and plans are underway to grant access to this source to all who live in the inner city of Johannesburg (Mabotja, 2011).

The next chapter provided information about rainwater harvesting system design and analysis. Possible methods of incorporating rainwater harvesting into the EDWI-system is discussed.

.

4. Rainwater harvesting

This chapter details practical considerations, assumptions and specifications for rainwater harvesting systems. Some of the theory presented in this chapter will be incorporated in the EDWI-index.

4.1 Domestic rainwater harvesting

As population growth puts increasing pressure on South African fresh water resources failures in conventional water distribution systems are becoming more frequent. Water originating from a dam is first put through a purification process after which it is pumped through a municipal distribution network to where it is required. Along this path many losses occur. These can include leaks as well as water theft. With DRWH water is not transported but rather used at the point of source; it is used where it is harvested. Even in provinces or regions where rainfall patterns are not exactly suited to DRWH it should be noted that every drop that is harvested in this manner does not have to be taken from a municipal network. DRWH systems are defined in this thesis as having gutters and downpipes transporting rainwater from the connected roof area to a permanently installed tank.

4.2 Different incorporations of domestic rain water harvesting

DRWH systems come in many forms; from a simple rain barrel under a downpipe for irrigation to complex systems with underground tanks for primary supply. These complex systems intended as the primary supply of potable water are normally only really cost effective where no access to a municipal network exists. Large portions of the population in urban environments are connected to a municipal network. For these people it might not be worth while to introduce a large and complex system to meet total domestic demand, but there are cheaper and easier ways to reap the benefits of this technique. Water buds (also called cisterns or rain barrels) can be very effective collection systems. For example, if you were to use a system of four rain barrels of 250

L each connected to a traditional pitched tile roof with a projected size of 100 m^2 you would be able to fill all of them in one rain event of about 15mm.

4.3 Rain water harvesting calculations

In the following section recognised procedures used for the design of rainwater harvesting systems are described.

4.3.1 Estimating demand

The design of any rainwater system depends on the demand imposed upon it. South African is classified as a semi-arid region with a below average MAP. Thus it is unlikely that a rainwater system will be able to meet total domestic demand. However when only some uses are considered for harvested rainwater a system could prove to be an effective way of lowering demand imposed on a municipal network. A detailed description on demand estimation is included in this thesis in section 6.4.

4.3.2 Catchment area

In general roofs are used as catchment areas for DRWH systems. When selecting a catchment surface it is important to remember that some roofing materials produce undesirable effects. Metal roofs for example can cause dissolution of metal ions (Memon & Butler, 2006). It is worth noting that the roof area used in these calculations does not refer to the true area, but rather the projected area. This implies the area that would be seen if the roof was viewed from above, not accounting for roof angle in any way. Refer to Figure 4 for details.

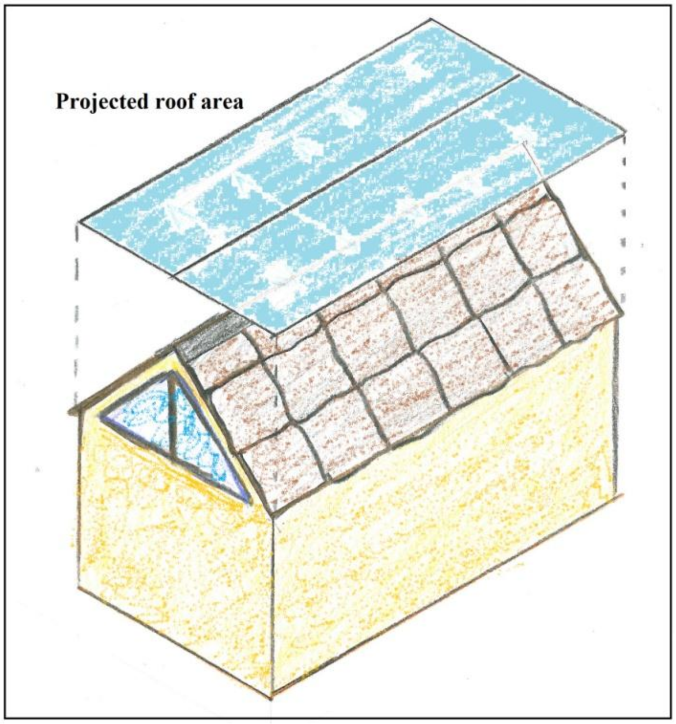


Figure 4: Projected roof area

4.3.3 Roof run-off coefficients and system efficiency

Run-off coefficients are used to estimate how much of the rainfall will be translated into run-off (Hari & Krishna, 2005). The losses that occur because of the type of roof used as collection surface to capture rainwater can be quite large. This is especially noticeable on flat roofs where pooling takes place as water is now able to evaporate prior to reaching the reservoir (Gould & Nissen-Petersen, 1999). Approximate values of run-off coefficients are listed in Table 2 below (Fewkes & Warm, 2000).

Roof run-off coefficients for different roofs (Fewkes & Warm, 2000)	
Roof/system type	Run-off coefficient
Pitched roof covered with tiles or slates (Total flow type)	0.90 - 1.00
Pitched roof covered with tiles or slates (Diverter flow type)	0.75 - 0.95
Flat roof covered with impervious membrane	0.00 - 0.50
Flat green roof	0.00 - 0.50

Table 2: Roof run-off coefficients

Almost all rainwater harvesting systems experience secondary losses. These can be attributed to either spillage as water is transported to the tank, high intensity rainfall events causing flow rates greater than that which can be accommodated by the gutters, or many others. For this reason a "system efficiency constant" is used to estimate efficiency of a rainwater harvesting system. The efficiency of a rainwater harvesting system has been found to be between 75 and 90% (Hari & Krishna, 2005).

The efficiency of a rainwater harvesting system is influenced by its design. Gould & Nissen-Petersen (1999) highlights some of the more commonly seen design mistakes that can occur in a rainwater harvesting system:

- Gutters that are horizontal or sloping away from tanks
- Overflow pipes below top of tank
- Outlet tap above bottom of tank
- Not utilising the entire available roof area.

These mistakes lower system efficiency and ultimately lead to a lower system yield and the system being less cost effective that it could be. The hydraulic capacity of gutters used should also be considered as a large catchment area can cause accumulated flow to exceed capacity.

4.3.4 Yield before or after spillage

The process used to calculate the potential of rainwater harvesting systems boils down to quite a simple mass balance equation. But the assumptions used to determine in and outflows during this balance could impact heavily on its accuracy. Fewkes & Butler (2000) detail two possible algorithms, yield before spillage (YBS) and yield after spillage (YAS). In the YBS algorithm yield is subtracted before the water has spilled and, as the name implies, in YAS the water first spills and then the yield is taken from the volume in storage. The two main operating algorithms that could be adopted to calculate yield and storage volume for YBS and YAS are shown in equations 4.1 to 4.4 (Fewkes & Butler, 2000):

YBS:

$Y_t = Min(D_{t,} S_{t-1} + Q_t)$ Equation 4-1

$S_t = Min(C_{a,} S_{t-1} + Q_t - Y_t)$ Equation 4-2

YAS:

$Y_t = Min(D_{t,} S_{t-1})$ Equation 4-3

$S_t = Min(S_{t-1} + Q_t - Y_t, C_a)$ Equation 4-4

where:

D_t:	Demand at time t
Y_t:	Yield at time t
C_a:	Storage capacity of tank/s
S_t:	Storage at beginning of time t
Q_t:	Inflow during tth time interval

The choice between using an YBS or YAS operation algorithm depends on a mixture of factors and can be significantly influenced by the ratio of supply to demand (Liaw & Tsai, 2004). Fewkes & Butler (2000) found that YAS produces a conservative estimate of the overall rainwater collecting system while being independent of the selected time interval.

Latham (1983) defined these operating algorithms in a general form by the addition of a θ parameter. The general form can be either YBS (θ = 0) or YAS (θ = 1). This general form is given in equation 4.5 and 4.6.

$Y_t = Min(D_{t,} S_{t-1} + \theta\, Q_t)$ Equation 4-5

$S_t = Min(C_a - (1 - \theta)Y_t\,, (S_{t-1} + Q_t - \theta\, Y_t) - (1 - \theta)\, Y_t)$ Equation 4-6

The general form of these operating algorithms as described by Latham (1983) was implemented into the software developed in this thesis. It should be mentioned that both grey- and rainwater systems are simulated using a behavioural model implementing the before mentioned operating algorithm (equation 4.5 and 4.6). This implies that yield in the first time interval is assumed to be zero as yield depends on the capacity in storage in the previous time interval and in the case of the first day this value does not exist.

4.3.5 Reliability of supply

The performance of a rainwater harvesting system is normally associated with the reliability of supply. Two basic methods are available to derive reliability of supply. Reliability can either be expressed volumetrically (R_v) or as a fraction the time that demand could not be met (R_e).

These are presented by Liaw & Tsai (2004) and are shown in equations 4.7 and 4.8:

R_v = actual supply/ demand Equation 4-7:

$R_e = 1 – n/N$ Equation 4-8:

where:

N = Number of time units under observation
n = Number of failures in observed time

In a study specific to Taiwan it was observed by Liaw & Tsai (2004) that small storage capacities accompanied by large water demands produces inadequate results. It is also mentioned by the authors that this will not be the case with a high water demand and storage. Thus the use of R_v is preferable as it is applicable in all situations (Liaw & Tsai, 2004).

4.3.6 Water saving efficiency

The water saving efficiency (E_T) is a measure of a rainwater collection system's performance. E_T represents the portion of demand that is met by a rainwater system in a given period of time (Dixon et al., 1999). E_T is calculated by equation 4.9, shown below: .

$$E_T = \frac{\sum_{t=1}^{T} Y_T}{\sum_{t=1}^{T} D_T} x\ 100\%$$ Equation 4-9:

where:

Y_T: Demand met by rainwater system over time T

D_T: Actual demand imposed by on the system over time T.

Although water saving efficiency is a parameter primarily intended to be used to describe the water saving efficiency of a rainwater system it was decided also to use E_t to describe the water saving efficiency of greywater and combined systems as well.

4.4 Reservoir sizing

The optimal size of a reservoir depends on the average and distribution of rainfall in the region, as well as the catchment size and the demand imposed on the system. Further the system's characteristics such as run-off coefficients and the system's efficiency dictate how much of the potential rainwater will be harvested. There are many methods that can be used to estimate the optimal reservoir size. These vary in complexity, accuracy and data requirements. Some of these methods are described in this section.

4.4.1 Demand side method

The demand side approach gives an estimated storage capacity required for a rainwater harvesting system. This method does not take into account parameters such as average, median or monthly distribution of rainfall. The system is sized to meet a quaternary demand without any significant rainfall. It has been reported that this method, popular with installers, could cause unnecessarily high storage requirements which will be reflected in the system cost (Hari & Krishna, 2005). Methods that only take one side, demand or supply, into account are inherently "weaker" at estimating a system's total performance and reliability of supply and should only be used in areas where no rainfall data exists.

A dry season analysis can also be used. The principle is the same, but with a dry season analysis the size of the tank is determined by the length of the dry season and not by quaternary demand. This method is however only applicable in regions where there is a distinct dry season and has the added advantage that no explicit rainfall data are required (Gould & Nissen-Petersen, 1999).

4.4.2 Graphical method

This method optimises storage capacity by representing roof run-off and water demand graphically. Reasonable estimates can be obtained by using this simple method, but it is important to use small time intervals such as daily or weekly records to obtain more accurate estimates (Gould & Nissen-Petersen, 1999).

The first step is to draw a bar graph of the cumulative mean monthly run-offs, that is to say the amount of water collected from the catchment. Next a line representing the cumulative monthly demand is drawn (Gould & Nissen-Petersen, 1999). The maximum difference between the bar graph, supply, and the line, demand, then represents the approximate required storage capacity. Figure 5 shows a graphical representation of this method.

This graphical method presented by Gould & Nissen-Petersen (1999) is very similar to the mass curve method first proposed by Rippl (1883), described later in section 4.4.3.1, in the sense that they both use a graphical representation of demand and supply to obtain a adequate storage volume. However the graphical method has some not worthy differences from the mass curve method. Where the graphical method requires mean monthly roof run-offs, thus 12 months, the mass curve method would normally be either use a period of years of either historical or stochastic data. Also the graphical method described here is specifically intended to be applied to rainwater harvesting systems and not large scale supply reservoirs as is the case with the mass curve method.

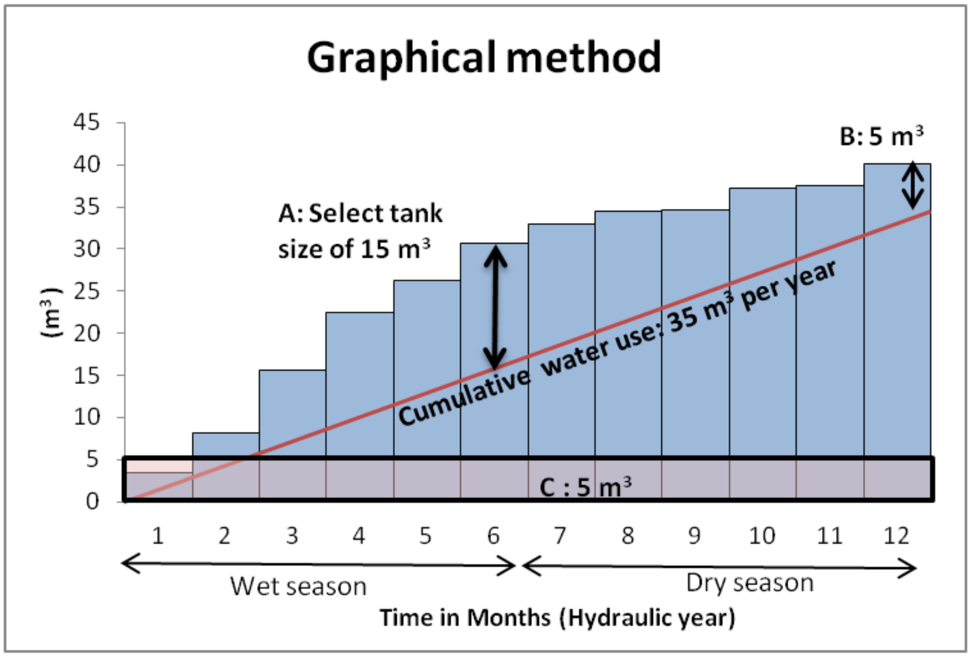


Figure 5: Graphical method

The graphical method provides more information about the average year of operation than just tank size. The difference between supply and demand, if positive, at the end of the dry season indicates the residual rainwater that will be in storage at the beginning of the next dry season (Gould & Nissen-Petersen, 1999). Figure 5 presents an example, where B represents the residual storage at the end of the dry season and C the “carry over” from the end of the dry season to the next wet season and A, rounded up to the first available tank size commonly in use, the required storage capacity.

Due to the use of average monthly roof run-offs the graphical method does not take droughts or floods into account. This implies that for any given year with significantly different rainfall than the average used to draw the bar graph, as shown in Figure 5, could result the system being either be too large or small for that year.

4.4.3 Critical period methods

A critical period is generally defined as the time required by a reservoir at full capacity to empty with no spillage in the given time period (McMahon & Mein, 1978). This definition of a critical period implies that only one failure can occur in any given critical period. As mentioned by McManon & Main (1978) critical period methods can be classified in two groups:

- The use of historical rainfall data and estimated demand to simulate volumetric behave of the reservoir
- The use of only periods with low flows (droughts).

Depending on the specific method some critical period methods will determine the reservoir size that will not fail for the given series of historical data, while the rest enables the user to select a reservoir size with a certain probability of failure (McMahon & Mein, 1978). Using a broad definition for critical period methods such as that low flows dictate required storage all these types of methods can be seen as critical period methods.

4.4.3.1 Mass curve method

This technique, first proposed by Rippl (1883), is credited as being the first rational method for estimating required storage capacity to meet demand. The mass curve method uses a cumulative historical inflow line with a cumulative demand line over a series of years to determine the required storage capacity. This is done by first plotting the cumulative inflow line and then superimposing cumulative demand lines at a tangent to each hump on the inflow line. Monthly flows are usually used in this method (McMahon & Mein, 1978). The required storage capacity of the reservoir will then be the greatest difference between the cumulative flow graph and a draft line.

The use of historical data in the mass curve method implies that it is assumed that no drought greater than one found in the given time series will occur. This further implies that if the analysis period is extended to cover these more severe droughts the storage capacity obtained will be larger than previously obtained to accommodate the previously mentioned more severe droughts.

The product of this procedure could then produce storage capacities that might not be economically feasible and too large for normal operation when applied to rainwater systems. However the mass curve does take seasonality, serial correlation and other flow parameters which are included in the historical series used from the analysis (McMahon & Mein, 1978) into consideration. The mass curve method is explained in greater detail by McMahon & Mein (1978).

4.4.3.2 Variations on the mass curve method

There are quite a few variations on the standard mass curve method as first described by Rippl (1883). These include the semi-infinite reservoir and residual mass curve method. Although based on the principles of the mass curve method these variations have procedural difference worth noting.

Instead of using cumulative flows the residual mass curve method uses residual flows. Accordingly flow is now expressed as the flow with the mean flow subtracted. This method is more complicated than the straight forward mass curve method, but does give a better graphical representation because of scale in certain circumstances (McMahon & Mein, 1978).

4.4.3.3 Behavioral models

Behavioural models use simulated mass flows through an operational algorithm to simulate a reservoir (Fewkes & Butler, 2000). These models simulate operations with respect to time; either minutes, hours, days or monthly time intervals can be used, over a period of years. In behavioural models withdrawals, losses and inflows, within the selected time step, are subtracted and added to the storage volume at the beginning of the time step. The result of this forms the new storage volume at the end of this time step, which then becomes the storage volume at the beginning of the next time step. This procedure is repeated until the desired analysis period is achieved.

This method has two key points (Hari & Krishna, 2005):

- Catchment area and rainfall determine supply
- Demand dictates required storage capacity.

The general form for this procedure is shown in equation 4.10 (McMahon & Mein, 1978). But for the purpose of a rainwater system a simplified version could be used as shown in equation 4.11, as no leakage or evaporation would be assumed.

$$S_{t+1} = S_t + Q_t - D_t - \Delta E_t - L_t \qquad \text{Equation 4-10}$$

$$S_{t+1} = S_t + Q_t - D_t \qquad \text{Equation 4-11}$$

where:

t : Selected time interval
S_{t+1} : Storage at the end of the t^{th} time interval or at the beginning of the $(t + 1)^{th}$ time interval
S_t : Storage at the beginning of the t^{th} time interval
Q_t : Inflow during the t^{th} time interval
D_t : Draft during the t^{th} time interval
L_t : Other losses during the t^{th} time interval
ΔE_t : Evaporation losses during the t^{th} time interval

This chapter dealt with rainwater system design and simulation. After the review of relevant literature included in this chapter it was decided to simulate rainwater systems using a YAS algorithm implemented in a behavioural model. The following chapter provides information about greywater system simulation, concerns and treatment. The system that will be used to analyse greywater systems is also described.

5. Greywater and re-use

For the purpose of this thesis the end-uses considered as producing greywater are baths, showers, washing machines and bathroom basins. The water from a pool's backwash cycle can also be re-used if the right processes are followed, but this topic is not covered in this thesis. Water from dishwashers and the kitchen sink are excluded from the greywater sources as defined in this thesis as they are known to have high quantities of oil and grease (Fewkes & Ferris, 1982). Oil and grease contaminated greywater is undesirable as extra processes, such as grease traps, would be required to re-use it safely.

5.1 Controlling grey water quality and safe implementation

The cost and vulnerability of any greywater treatment system is directly linked to the nature and concentrations of contaminants added by end-uses (Morel & Diener, 2006). For this reason source control of quantities and characteristics of cleaning products, soaps, and detergents etc is of extreme importance. Morel & Diener (2006) list four source control measures that should be adopted by all who live in a dwelling where greywater is used. :

- Minimise water use
- Optimise use of common cleaning products
- Avoid disposal of problematic substances such as oil, fats, bleach and solvents
- Substitute hazardous products with environmentally friendly ones.

Products that contain high levels of phosphates such as many types of washing powders, or contain any sodium hypochlorite, such as bleach, should not be used when greywater is re-used (Morel & Diener, 2006). The use of phosphate rich washing powders will, over time, lead to poisoning of soil and for this reason phosphate free products should be used (Water Rhapsody, n.d.). It is important to remember that the choice of cleaning products and quantities have a strong influence on the impact greywater has on the environment (Morel & Diener, 2006).

Pumped greywater systems should always be operated at low heads, not higher than 6 m head at sprinkler (Water Rhapsody, n.d.). Low pressures will help prevent atomising of greywater particles. To minimise the risk of clogs, amongst other reasons, it is also advised that suspended solids that might be found in greywater are removed as close as possible to its source. Screens, water traps and filters can be used for this purpose.

Without treatment greywater should newer by stored. Some authors disagree with this statement rather imposing a time limit of 24 hours but also state that a few hours is preferable (Carden et al., 2007b). Water Rhapsody (n.d.), South African greywater system installer, states that greywater should never be stored (no direct reference to treatment is made) and lists this point as one of their golden rules for greywater re-use. This extreme statement could however be attributed to the fact that greywater systems can produce unwanted odours which are more noticeable in systems that incorporate storage. These odours may impact negatively on the firm's image and that could cause potential clients to reconsider implementing a greywater system. The point is however valid as public perception is important in technologies of this type. Accordingly it is further advised that if greywater is considered for re-use it should only be done with low storage capacities similar to , or not much larger than the average amount of greywater produced by end-uses considered for greywater re-use. This measure will insure that re-used greywater does not stay in storage for more than a few hours, and at most 24, as proposed by Carden et al. (2007b).

Greywater has a relatively high temperature and contains nutrients beneficial to bacterial growth (WHO, 2006). A system that does not incorporate adequate treatment or where no treatment is applied along with storage can create the perfect environment for aerobic bacteria to flourish. As a by-product the bacteria produces methane and hydrogen sulphate resulting in offensive odours (Water Rhapsody, n.d.).

5.2 Greywater treatment

Filtration systems can increase greywater quality to an adequate level for re-use purposes (Christova-Boal et al., 1996). As is well known greywater contains suspended solids which could cause blockages when pumped through an irrigation system. Christova-Boal et al. (1996)

proposed a simple three stage filter system that can remove enough suspended solids to make the water safe for such a system. The first stage calls for the installation of strainers at shower- and bath outlets and the laundry trough. This removes all large matter. Secondly, a mess filter is installed in the collection tank that catches all incoming soap particles, hair and lint. Finally a fine filter is installed at the supply line to the intended use. It was further reported by Christova-Boal et al. (1996) that geotextile sock filters worked well for this purpose. Figure 6 shows a very simple configuration only comprising a filter to remove suspended solids, and a pump used to pump the greywater to where it is required. The system presented in Figure 6 does not incorporate storage explicitly but some storage does take place as the greywater is pumped to an irrigation system only if the pump chamber is filled (Water Rhapsody, n.d.).

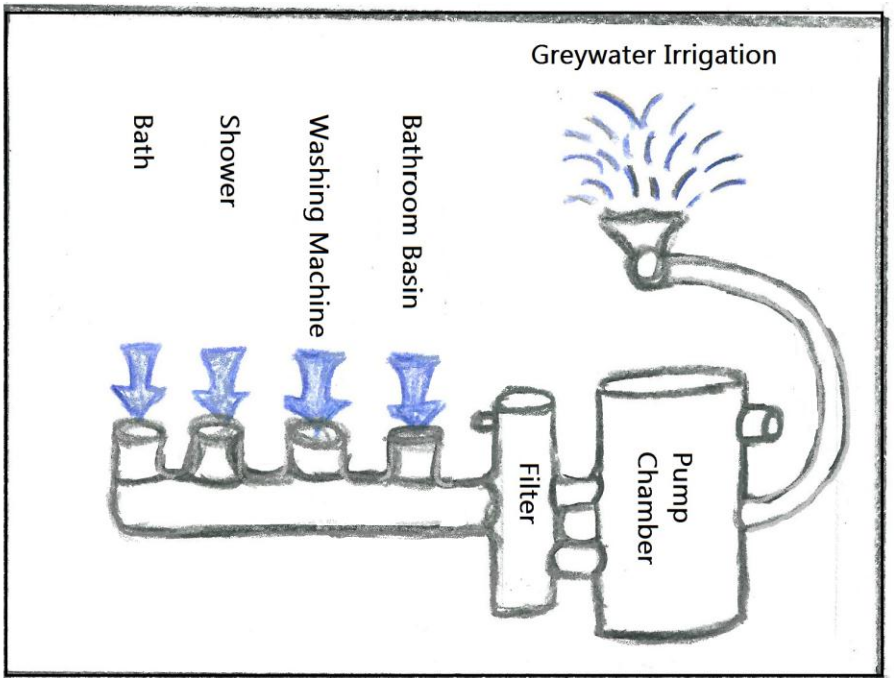


Figure 6: Simple greywater irrigation system without storage

Gross et al. (2007) developed and tested a recycled vertical flow bioreactor (RVFB) for the purpose of greywater recycling. This process was able to lower concentrations of NO_3-N, total ammonia nitrogen, NO_2-N, total suspended solids, anionic surfactants and boron below maximum allowable levels for recreation and irrigation (Gross et al., 2007). However an increase in heterotrophic bacteria and surfactant-degrading bacteria was observed in the RVFB. The RVFB comprises four modules (Gross et al., 2007):

- Organic soil module
- Trickling module
- Lime pebble module
- Reservoir and recirculation module.

As greywater is produced it enters the organic soil module where a large negatively charged surface enables the adsorption of contaminants. After this the greywater flows to the trickling module, similar to a trickling filter, which allows for aeration and re-aeration. The trickling module may also prevent odour generation associated with anaerobic processes (Gross et al., 2007). Greywater then enters the lime pebble module where additional filtration takes place as well as the buffering of potential losses in alkalinity due to nitrification processes producing acidity. Finally the greywater enters the reservoir and recirculation module which functions as a flow equaliser. This function is important as greywater is constantly re-circulated from the back to the front of the system. In a single household this is an important function as processes such as laundry washing cause rapid short term changes in greywater generation rates (Gross et al., 2007).

The use of wetlands has also shown great potential to treat greywater. Wetlands are effective at reducing BOD, phosphates, nitrogen, suspended solids and reducing concentrations of organic chemicals, pathogens and metals (Gross et al., 2007). The creation of wetlands can also serve as a habitat for a variety of species and be aesthetically pleasing.

The treatment of greywater can improve the quality to such an extent that it can be used for flushing toilets. Nolde (1999) states that there is enough proof that all the water needed for toilet flushing can be substituted with treated greywater without hygienic risks or loss of comfort. It should be mentioned that the treatment applied to the greywater in the case Nolde (1999) was referring to was quite extensive. These systems are not likely to be cost effective on a private scale as suggested by Jeppesen (1996) but have proved to be effective on large scale projects in Germany such as hotels (Nolde, 1999). Domestic re- use of greywater has however been shown to be economically feasible if the system does not incorporate treatment (Jacobs et al., 2010).

In Japan population densities and low space has forced the implementation of greywater re-use schemes to meet demands (Dixon et al., 1999). Recovered greywater is used in Japan for toilet flushing, environmental water, in-stream flow augmentation and industrial re- use (Ogoshi et al., 2000). Many major Japanese cities have mandated dual distribution systems for all new buildings constructed (Ogoshi et al., 2000).

5.3 Simulating greywater flows and operating algorithms

The inherent randomness associated with water end-use patterns is directly linked to their associated wastewater flows. This implies that a greywater stream in a dwelling would be governed by the same factors governing demand. Given the random nature of water use in a dwelling Fewkes & Ferris (1982) used a Monte Carlo analysis to develop a usage pattern to simulate greywater volumes with respect to time. While this method undoubtedly produces representative results this is not in the scope of this thesis.

For the purpose of this thesis it was decided to estimate greywater streams by means of a simple deterministic method. Greywater streams are developed in this thesis by using data describing the demand for end-uses considered for re-use and consequently their associated greywater return flows are then obtained. The data used for this purpose is described in detail in section 6.4.

As described in section 4.3.4 a rainwater system can be simulated by either YBS or YAS operational algorithms. It was further found in literature that for a rainwater system YAS is the preferable operating algorithm as this produces conservative answers (Fewkes & Butler, 2000). However, as mentioned, rainwater systems, because of the random nature of rainfall events, require large storage capacities to obtain optimal efficiencies (Fewkes, 1996). Greywater systems on the other hand have a much more regular supply pattern, and thus require lower storage capacities to achieve optimal system operation. It was therefore decided to test and compare a greywater system with YBS and with YAS algorithms to see the effect on the system's efficiency. Further, because the YAS algorithm can, at most, produce a yield equivalent to the storage capacity, it was decided to test this effect on the system's efficiency. It logically follows that if a system has a larger supply and demand than its storage capacity, even when supply is much larger than demand, the YAS algorithm will only produce a maximum yield equal to the system capacity. The starting capacity of the following time interval will then be the volume in storage from the previous time interval plus the greywater harvested during the time interval in question, to a maximum equivalent to tank size, minus the yield in the time interval in question.

The proposed analysis is based on a greywater system which supplies the toilet flushing requirement supplied by water from a bath, shower and washing machine in a dwelling occupied by 4 people. This setup produced an AADD of 212 L/day with an average of 286 L/day of greywater available for re-use. The results are presented in Figure 7.

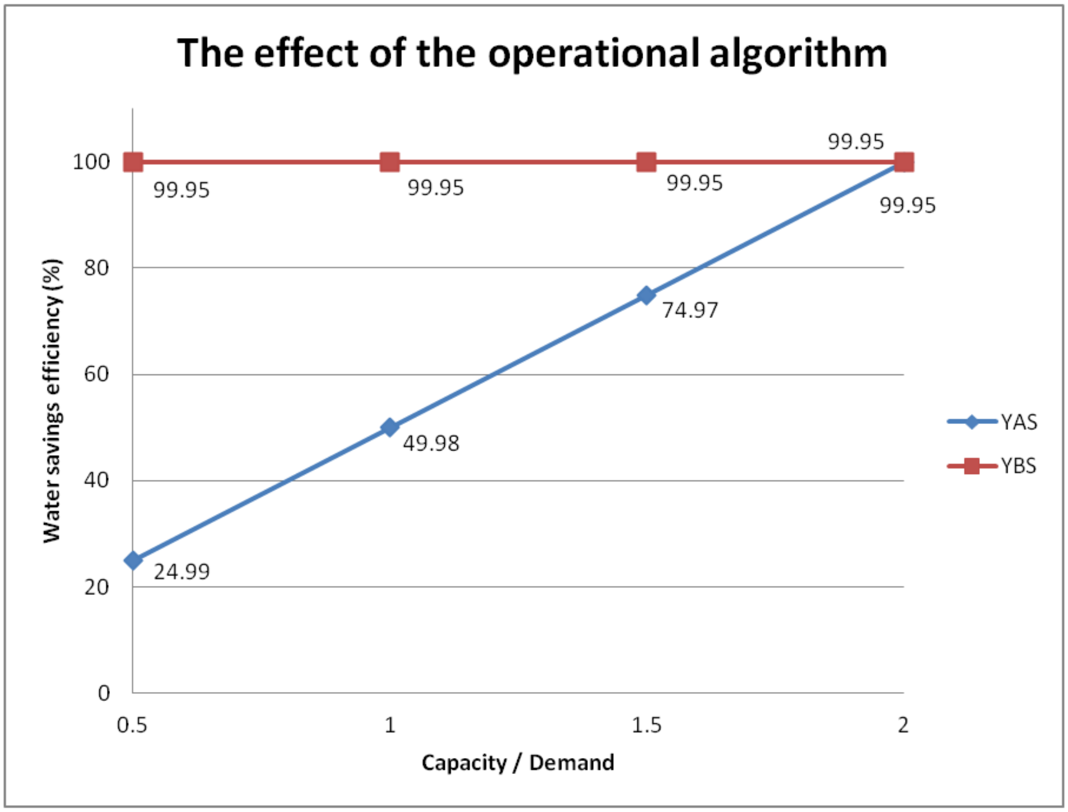


Figure 7: The effect of the operational algorithm on system performance

The system specifications used for this analysis are very similar to those used by Dixon et al. (1999), the main differences being the time interval, Dixon et al. (1999) used hours, and, as proposed by Fewkes & Ferris (1982), the use of a Mote Carlo simulation to produce a greywater flow sequence. Ghisi & de Oliveira (2007) used a deterministic method similar to the one used in this thesis to produce average greywater supply and demand with a daily time interval using an YBS operational algorithm. In both cases mentioned above, as with the analysis presented in this section, supply exceeded demand.

Fewkes & Ferris (1982) analysed factors influencing storage requirements. They found that the storage capacity is relatively insensitive to time series (daily, hourly or minutes) and usage patterns within a day. However, it was found that weekly usage patterns and occupancy has a large effect on the E_t. The greywater stream proposed in this thesis does not take weekly usage patterns into account. It was therefore expected that the results from the method proposed in this thesis would produce lower E_t than were found by Dixon et al. (1999). This was confirmed as Dixon et al. (1999) found that a system similar to the one analysed in Figure 7 could produce an E_t of over 90 % with a storage volume of between 100 to 200 L, whereas according to this method, a capacity of 350 L using a YAS algorithm, and with a YBS no storage capacity would be required. It was decided to simulate the greywater system with a YAS algorithm, such as used by Fewkes & Ferris (1982).

5.4 Problems with greywater reuse

Greywater contains many contaminants depending on the origin. Greywater that originates from a washing machine for example could contain a lot of lint and other fibres as well large quantities of sodium and other substances associated with washing powder. These fibres found in greywater could cause problems such as clogging when greywater is being pumped through an irrigation system.

Odours can originate from a greywater re-use scheme. Systems that incorporate storage are especially susceptible to this problem as greywater characteristics are greatly affected by residence time in a re-use system (Al-Jayyousi, 2003). Greywater contains microbiological organisms (Jeppesen, 1996). To minimize growth of these organisms greywater should be used as it is captured or with minimal retention time. Regular maintenance of a greywater system will reduce odours from the system. Local greywater installer, Water Rhapsody (n.d.), notes that with their maintenance plan only a faint odour is generated while the system is spraying greywater. Other sources discourage the use of greywater through spray systems in favour of subsurface irrigation that can be up to 60 % more effective because of minimal to no evaporation losses and lower health risks (Jeppesen, 1996), however plants are known to sprout roots towards the closest source of water. For this reason subsurface irrigation piping would need to be moved from time to time to assure that roots don't block the outlets along the pipe.

5.5 Combining grey and rainwater

The benefits associated with grey and rainwater in a single storage system have been investigated by a few authors (Dixon et al., 1999; Ghisi & de Oliveira, 2007). Dixon et al. (1999) showed that up to 80 % of toilet demand can be met by using grey and rainwater with a 50 litre storage tank. However it is also pointed out that in this application the addition of rainwater offers no real improvement to the E_t (Dixon et al., 1999). This could be caused by the fact that most, if not all, dwellings would produce significantly more greywater than the potential rainwater that could be harvested. Ghisi & de Oliveira (2007) tested two houses with greywater only, rainwater only and grey and rainwater in separate systems. They found that in both cases these separate grey and rainwater systems would produce potable water savings between 6 and 9 % higher when compared to the potable water savings with a greywater only system. The two systems working separately would however result in a dwelling now having to install and maintain two systems that could lead to high initial costs. In rainfall regions with characteristically low MAP's this point will most likely be more prominent. However, rainwater being of much better quality than greywater could balance service water quality as well as quantity (Dixon et al., 1999).

In the next chapter the concept of the EDWI-index is explored and developed. Fundamental assumptions required by the EDWI-system are reported and explained as well as incorporating the three EDWI-components is described.

6. Concept of South African sustainability index

The EDWI-system is a scale that attempts to quantify firstly the dependence of a given dwelling on a municipal water network and secondly the effect the dwelling can have on the local hydrological cycle by implementing green roofs, rainwater harvesting and greywater re-use.

When developing an index to rate water usage at such a low level as proposed in this thesis, it is important to identify the factors that will influence this. At domestic level water is normally obtained through a bulk water network provided proper access is possible. Alternatives may not be able to completely decentralise a dwelling from a large system but by incorporating alternatives in the most feasible way a level of decentralisation can be achieved. In this thesis three alternatives are examined and incorporated to rate the efficiency of water use. These were selected because they are, for the most part, accessible to all. As an example the use of groundwater, while a vast and underutilised resource, is not available to users without access to a well. Figure 8 depicts the in- and return flows from a traditional dwelling.

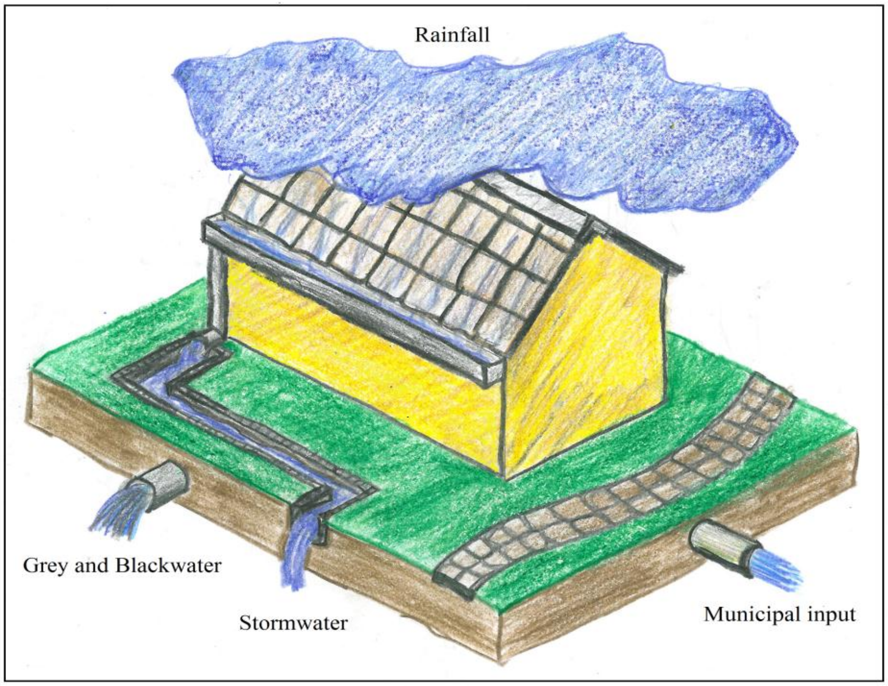


Figure 8: Most common in and return flows of a dwelling

One of the EDWI-system's goals is to estimate to what extent return flows can be minimised and utilising these return flows to lower municipal water demand. The feasibility of these alternative techniques depends on factors unique to every type of dwelling such as roof area, usage patterns within the dwelling, outdoor water use and demand.

Figure 8 illustrates the most basic in- and return flows associated with a typical dwelling. The EDWI-system aims not only to show the effects of efficient use in terms of demand reduction but also to incorporate the reduction in nuisance factors such as stormwater volumes and sewage effluents. The use of rainwater in effect causes firstly the reduction in water demand for selected uses such as toilet flushing, pool filling and irrigation. Secondly, the quantity of stormwater originating from the given dwelling is lowered, further improving the water efficiency of the dwelling by lowering the stormwater volumes that needs to be transported elsewhere. With the implementation of a greywater re-use system, return flows will also be lowered causing lower flows to treatment plants and reduced demands for the selected uses of greywater re-use as municipal input will no longer be required for these uses.

The EDWI-rating, in the simplest terms, represents the change in efficiency of water use from a dwelling with a traditional design as shown in Figure 8, to the same dwelling now incorporating the alternative water sources and control measures. It follows that when a given dwelling achieves a rating of 50 % with the use of systems selected for the analysis, the dwelling's water efficiency will be improved by 50%, thus the dwelling will require less input from traditional water services.

To produce a final rating a few assumptions about dwellings needed to be made. All assumptions are listed below.

It is assumed that any dwelling analysed with the EDWI-software tool utilise the following indoor end-uses:

- Washing machine (with either a low, typical or high water requirement)
- Bath
- Shower

- Dish washer (with either a low, typical or high water requirement)
- Kitchen sink
- Toilet (either dual flush or traditional)
- Bathroom basin.

Irrigation demand is assumed as the amount of water for optimal plant growth, described in greater detail in section 7.2.1. Further outdoor demand as defined in this thesis only represents irrigation demand.

The reduction in stormwater volumes represents only the reduction of stormwater volume from the roof and does not include other impervious surfaces.

6.1 Water quality classification

For the purpose of this thesis water quality will be classified in such a way as to simplify allowable applications. Water quality is defined as follows:

- Class 1: Potable use
- Class 2: Bathing standards
- Class 3: Contaminated but can be used for selected applications.

Grey and rainwater would require some form of treatment such as filtration to avoid blockages that could be caused by suspended solids and debris. With this minimum treatment greywater is classified as a class 3 resource and rainwater as a class 2. The exception to this rule would be rainwater harvested from a green roof, which is classified as class 3. Green roof effluent tends to have higher nutrient loads, pH, hardness and other contaminants than harvested rainwater from traditional roofing materials. The characteristics of green roof effluent was described in greater detail in section 2.4.4. It is further suggested that water of class 2 should adhere to the UK’s bathing water standards as proposed by Jackson & Ord (2000). If treated greywater adheres to the UK’s bathing water standards there would be minimal fears of adverse health effects. As part of future work the minimum water treatment required for each application should be included, since it would impact the developed EDWI-index by integrating it to the model.

These classifications allows demand to be separated into different streams according to the water quality required for a specific end-uses. Thus total demand will not have to be met in full by water adhering to potable standards, but could be met as a combination of water of class 1, class 2 and class 3.

6.2 Defining dwellings

Meyer (2000) defines dwellings as houses, town houses, apartments, traditional houses or shacks. They are quite simply a place where people live. In terms of the EDWI-system dwellings can only be assessed when they have access to a roof, serve a single family unit and have a garden area.

For the purpose of this thesis informal settlements, shacks and low cost housing are excluded from the general definition of dwellings. This exclusion is justified due to the fact that these settlements are not know to use all of the water end-uses assumed by the EDWI-system, refer to section 6.3 for details.

The term dwelling it terms of this thesis thus includes houses, town houses and traditional houses and incorporate all indoor end-uses as listed at the beginning of this chapter.

6.3 Water usage at a domestic level

Figure 9 shows the most common uses of water at a domestic level, possible sources of water as well as expected return flows. The water end-uses listed in Figure 9 are assumed to be used by dwellings analyses with the EDWI-system.

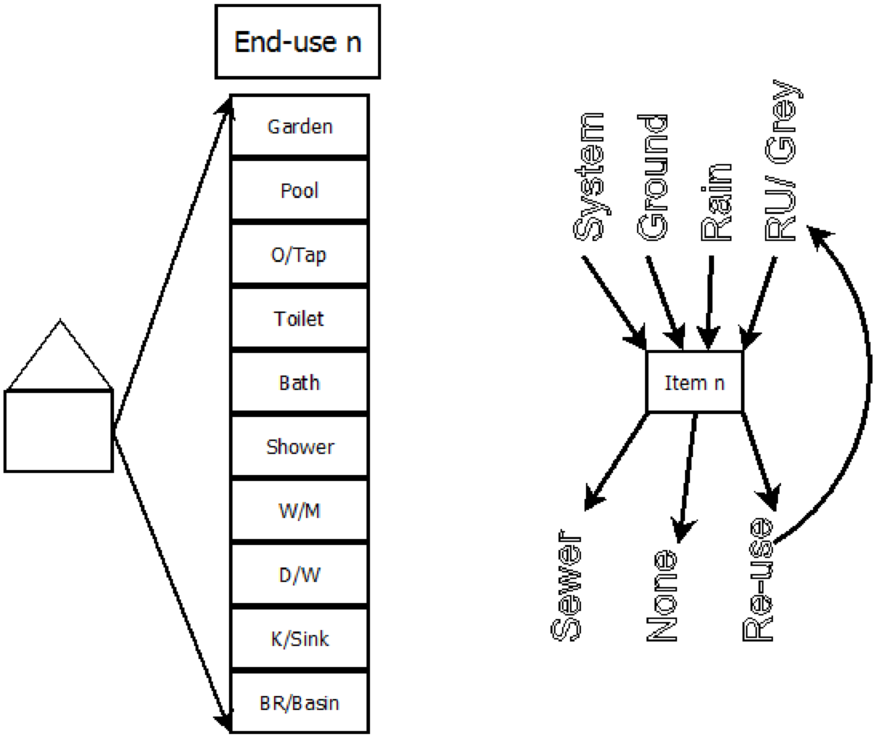


Figure 9: Water sources, uses and return flows (Jacobs, 2011)

These uses can be divided into groups according to the water quality they require. While uses such as the kitchen sink and shower require water at potable standards, the garden or pool do not. Minimum quality requirements are given in Table 3 as well as the quality of their return flows.

	In	Out
Garden	Class 3	None
Pool	Class 2	Black
Outside Tap	Class 1	None
Toilet	Class 2	Black
Bath	Class 1	Grey
Shower	Class 1	Grey
Washing machine	Class 1	Grey
Dishwasher	Class 1	Black
Kitchen Sink	Class 1	Black
Bathroom Basin	Class 1	Grey

Table 3: In and out flow classes for water uses

When examining Table 3 it is clear that very few water applications can function without water at potable standards. However the water used for toilet flushing can be up to 30 % of total indoor water demand (Fewkes & Ferris, 1982). The use of greywater in toilets is however problematic as it is not possible to guarantee that the water will not come into contact with human skin. Applying treatment to greywater can solve this problem, but rainwater could be a simpler alternative.

Outdoor water demand is very difficult to estimate as this is too dependent on factors which can vary considerably even between plots in the same street. If no treatment is applied to greywater it is still possible to use it for irrigation purposes (Jacobs & Van Staden, 2008), preferably by means of sub surface irrigation (Jeppesen, 1996). For outdoor applications such as pool filling, greywater should not be considered unless adequate treatment has been applied. Greywater could contain impurities that are detrimental to the filtering system of a pool. Pool filling could be done with rain water with minimal fear of adverse effects.

6.4 Estimating demand and end use distribution

A few papers referring to demand estimation (Jacobs et al., 2004; Mayer et al., 1999) have been written. Specifics on what is being done with the water are however harder to find. Jacobs et al. (2006) estimated the water demand by means of surveys and Mayer et al. (1999) used pattern recognition to log uses electronically and compared them with survey data. To improve the accuracy of the EDWI-system it is of utmost importance to know firstly how much water is being used and secondly for what purpose.

In South Africa the method used for demand estimation is normally linking usage with stand size (CSIR, 1983). This traditional area based method has however been shown to overestimate demand, resulting in possible overdesign of services (Jacobs et al., 2004; Van Zyl et al., 2008). While a simple area based equation would simplify demand estimation it is traditionally not applied to a specific dwelling, but rather to an entire area composed of many plots for the purpose of designing bulk water supply networks. Nevertheless the method as described by Van Zyl et al. (2008) can be a good indication of expected demand. This method of estimating annual average daily demand (AADD) with stand size and its equation is shown in Figure 10.

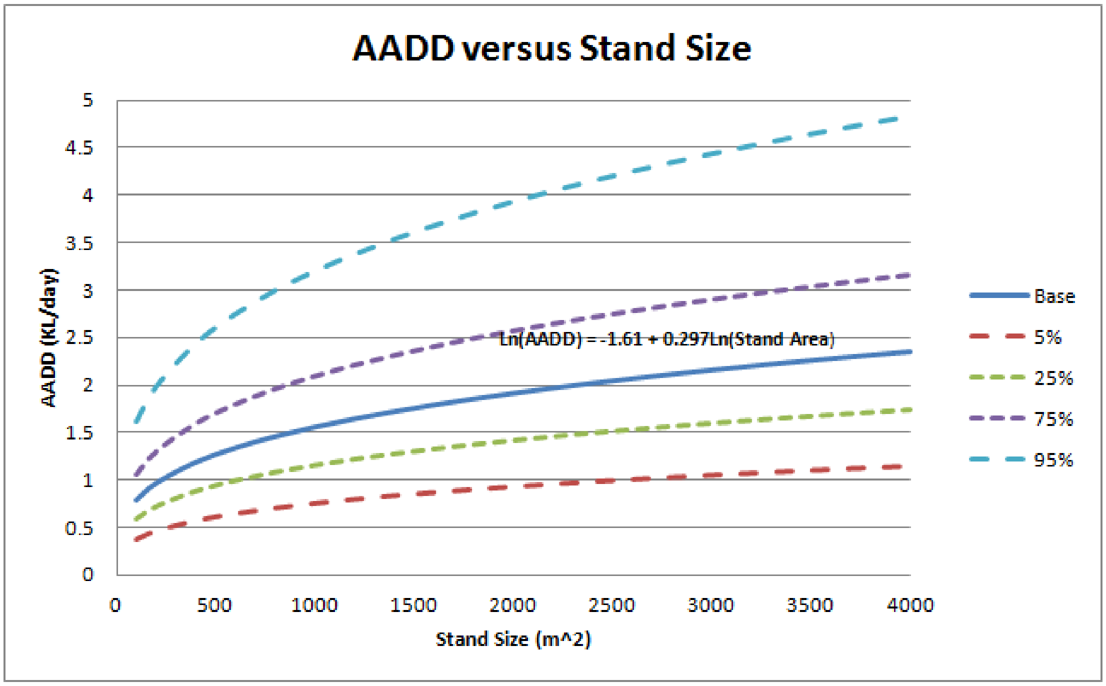


Figure 10: AADD versus. Stand size (Van Zyl et al., 2008)

Mayer et al. (1999) conducted an extensive study on residential end uses of water. The patterns that were found in this study serve as a good approximation of what can be expected in an average middle to upper class South African dwelling. The residential indoor uses by category as found by Mayer et al. (1999) are shown in Figure 11. Taps are then further divided into outdoor and indoor tap use which is 58 and 42 % respectively (Mayer et al., 1999).

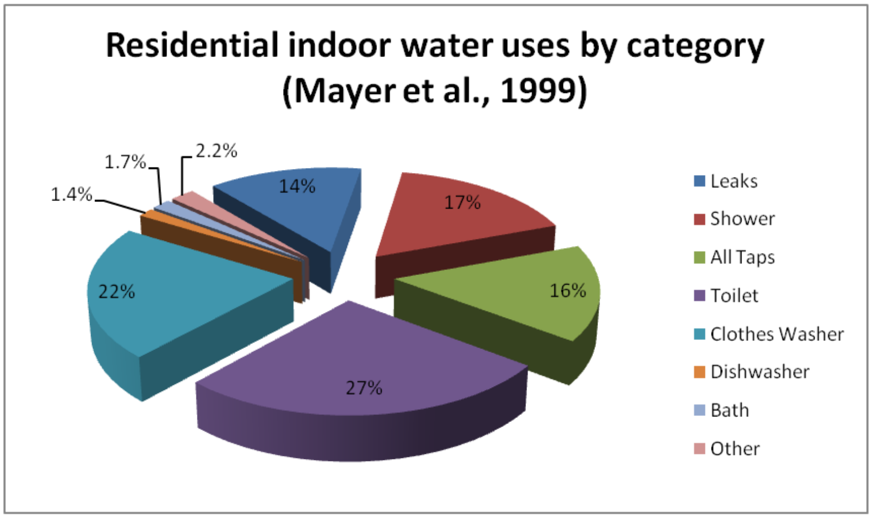


Figure 11: Residential indoor water uses by category (Mayer et al., 1999)

The end-use distribution derived by Mayer et al. (1999) is an adequate approximation of an average user's water usage. But this approximation can be more accurate if the user specifies a few key inputs. This would include factors like occupancy, specifying components in use and the amount of water used for a given event, such as toilet flushing. Frequency of use of different end-uses as found by Mayer et al. (1999) is shown in Table 4 and compared to what was found by Jacobs & Haarhoff (2004a).

Frequency of use per capita (events/person/day)		
From	Jacobs & Haarhoff (2004a)	Mayer et al. (1999)
Bath	0.24	-
Shower	0.31	*0.64
Shower and Bath	-	0.75
Bathroom basin	3.60	-
Kitchen sink	1.00	-
All Faucets (min/person/day)	-	8.10
Dishwasher	0.25	0.10
Toilet	3.70	5.05
Washing machine	0.30	0.96
Notes: * indicates a calculated value		

Table 4: Frequency of use per capita

Events also have different water requirements. Table 5 lists the amount of water required for each event as set out by Jacobs & Haarhoff (2004a) and Mayer et al. (1999).

Event	Water usage per event (L)				
	Jacobs & Haarhoff (2004a)			Mayer et al. (1999)	
	Low	Typical	High	Mean	Std. Dev.
Bath	39.00	80.00	189.00	-	-
Shower	7.60	59.10	303.00	65.12	40.12
Bathroom basin	0.30	3.80	60.00	-	-
Kitchen sink	0.60	6.70	73.00	-	-
Dishwasher	15.10	25.00	43.00	-	-
Toilet - standard	8.00	14.30	26.50	13.17	4.50
Toilet - dual flush (low)	2.00	3.00	4.00	-	-
Toilet - dual flush (high)	4.00	6.00	6.10	-	-
Washing machine	60.00	113.60	200.00	154.80	46.20

Table 5: Water usage per event

The data in Table 5 obtained from the study conducted by Mayer et al. (1999), shows the average water per event as calculated from flow gage readings, collected from more than 1000 dwellings over an extended period of time.

Data in Table 4 and Table 5 can be used to estimate indoor demand if the user is willing to specify a few characteristics of his dwelling and end-uses. This method can result in a more specific approximation than would be achieved by using only plot area, as proposed by Van Zyl et al. (2008).

To estimate outdoor water demand presents considerably more challenges. This is due to the fact that outdoor water demand is highly dependent on factors that are not so easily quantified. These include behaviour of occupants, time of year, type of plants in the garden and size of the irrigation area. The simplest way to estimate outdoor water demand is to subtract the average winter consumption (AWC) from metered readings in summer. With this method it is assumed that no water is used outdoors in winter as outdoor water demand is normally associated with summer. While this method could serve as a fair estimate of outdoor demand in certain regions, it will not account for water used in dry winter months (Mayer et al., 1999).

It was decided to estimate outdoor demand by assuming that a garden under irrigation comprises of two distinctly different plant types each having its own irrigation requirement varying monthly. In the EDWI-system a garden is seen as having a lawn and beds portion. The lawn portion is assumed as being kikuyu grass and the beds as being representative of the local region’s natural veld type as described by Midgley et al. (1994). This assumption is valid in gardens where Xeriscaping principles are in use.

Monthly variation in outdoor water demand is caused by the plants own monthly requirement, by the region’s contribution to demand as monthly rainfall and water lost due to evaporation and ET. The governing equation for irrigation requirement is presented in 7.2.1 along with a table of natural veld and kikuyu grass type crop factors along with evaporation rates for four South African cities.

Monthly rainfall is assumed to be the same as the average monthly rainfall obtained by analysing the five-year stochastic sequence used to simulate the rainwater system. Rainwater harvesting systems are generally analysed over a period of years, as noted by Fewkes & Butler (2000). The time of simulation of five years was selected accordingly based on the subjective discretion of the author to illustrate seasonal variation. In months where rainfall exceeds irrigation demand, no irrigation demand will exist. Refer to section 7.2.1 for a detailed discussion.

The crop factors that are used in this thesis are the natural veld type crop factors as proposed by Midgley et al. (1994), and the crop factor for kikuyu grass as presented by Short & Colmer (1999).

6.5 Incorporating greywater

Greywater originates from processes that don’t contaminate the water to such an extent that it cannot be re-used. These processes traditionally include water from baths, showers, tap use, washing machines and dish washers. Precisely which processes should be included in a greywater re-use system depends upon the discretion of designer and could include all processes mentioned above. For the purpose of this thesis greywater sources considered for re-use are as follows:

- Bath
- Shower
- Washing machine
- Bathroom basin.

All water from kitchen use is excluded because of oils and grease that are often present in the effluent (Al-Jayyousi, 2003). These contaminants can clog certain filtration systems.

Untreated greywater is classified as being of class 3 quality. This implies that it can only be used for garden irrigation. This limitation can be lifted by applying additional treatment as described in section 5.2. If a user chooses to elevate the greywater quality to class 2, the potential applications increase. It is possible to improve the quality of greywater to class 1 by applying additional treatment, but this requires complex treatment systems that are costly. The three water uses that could be considered for greywater re-use and their minimum required water quality are presented in Table 6.

	Greywater applications	
	Class 2	Class 3
Toilet	X	
Washing machine	X	
Irrigation		X

Table 6: Greywater applications

Even when greywater is only applied as a class 3 resource, some filtration is still advisable. This is because of possible clogging problems that could arise in the system from lint, hair and other fibres that could be found in greywater (Christov-Boal et al., 1996).

Greywater systems can incorporate storage, or the water can be used as it is generated. When storage is incorporated the system operates in the same manner as a rainwater harvesting system, the main differences being the source of water utilised, treatment considerations, inflow patterns and optimal storage capacity.

When it is decided to incorporate greywater re-use in a given dwelling the EDWI-rating is affected in two ways. Firstly there will be a direct reduction in municipal demand associated with the selected applications for greywater re-use and secondly there will be a reduction in return flow as the greywater portion will now be partially or completely removed and re-used.

6.6 Incorporating green roofs

Green roofs offer numerous benefits to the occupants of a dwelling. Some of these beneficial effects are however not easy to quantify. In terms of evaluating the contribution that a green roof will bring to the EDWI-system there are however a few benefits that can be assumed. They are stormwater retention, reduction and the decrease of impervious surfaces.

6.6.1 Stormwater retention

The amount of stormwater that a given green roof will reduce is very difficult to predict, as discussed in section 2.3.3. By means of an extensive data comparison of the work of many green roof researchers Mentens et al. (2005) was able to obtain equations that predict water retention. These equations are however only applicable to a 100 mm substrate and under a range of MAP's that are not comparable with South African conditions. The FFL (2002) guidelines contain a table that generalises stormwater retention portions but, as with the equations from Mentens et al. (2005), they are not representative of South African conditions.

To estimate the stormwater retention caused by a green roof it is however important to assume a portion retained and the accompanying run-off coefficient. For lack of better data the table presented by the FLL (2002:37) guidelines is used for this purpose. The table presented in FFL (2002:37) is assumed instead of the equations developed by Mentens et al. (2005) because it is based on a larger body of kwnology and caters for a larger range of green roof substrate depths, not just green roofs with a substrate depth of 100 mm. Due to the lower rainfall and higher temperatures in South Africa these values can be seen as conservative, refer to Table 1.

6.6.2 Increasing green space

As mentioned in section 3.3 loss of green space in urban environments has very negative side effects. Thus increasing green space can be seen as a benefit for any water body or river receiving run-off from these areas.

The decrease in impervious surfaces is calculating by firstly obtaining the total impervious surface before the green roof, or without, and then the area of the green roof and by dividing the green roof area with the total roof area and multiplying by 100. The product will then indicate the percentage reduction obtained by the installation of the green roof. It should be mentioned that impervious surface as defined in this thesis only includes the total projected roof area of a dwelling.

6.7 Incorporating rainwater harvesting

When a dwelling incorporates rainwater harvesting, the harvested rainwater can be seen as a direct reduction in municipal demand. The effectiveness of such a system depends on factors such as roof area, roof type, and roof pitch, efficiency of the system, volume of tank and rainfall amount and distribution. Depending on the level of application of harvested rainwater, portable or not, additional considerations could arise.

After all required parameters have been obtained, it is then possible to simulate the system performance for a five year period using stochastic daily rainfall data. The rainfall data can be obtained through a website which allows its user to click on the approximate area in South Africa where he or she lives. With the specific GPS coordinates known the user can then navigate to the nearest rainfall station. The historic rainfall data from this station is then used to generate the five-year stochastic data series by means of the simulator incorporated in the South African rainfall atlas developed by the Water Research Commission of South Africa (WRC, n.d.). The site also contains data for the neighbouring countries, Lesotho and Swaziland.

It is then possible to estimate the average water savings and efficiency of the system. The system can then be calibrated to collect as much rainwater as possible, maximise yield, by increasing storage capacity or to assure that the selected demands are met with higher E_t’s.

6.8 Potential constraints

Of the three EDWI-components greywater is perhaps the most controversial. The EDWI-software tool has been developed in such a way as to allow the user to analyse greywater systems with any storage capacity. It has however been mentioned earlier in this document that low storage capacities are preferred for greywater systems. While this is a sound assumption in terms of supply and demand, it however does imply that the system has been developed with adequate treatment to assure that greywater can be safely re- used and not produce unwanted odours and that the system will not require excessive maintenance.

Greywater production in any dwelling is inherently stochastic. This inherent stochastic nature of greywater production is not reflected in the daily time step used by the EDWI-system. The effect of time interval selection has however been shown not to have a major effect on results (Fewkes & Ferris, 1982). Also, as mentioned earlier, the simulated greywater stream is modelled as a discrete stream developed by using frequency of use and volume per use of end-uses obtained from Jacobs & Haarhoff (2004a), implying that each day's simulated greywater volume will be the same as the next and previous day's volume. This implies that there would be no fluctuations in daily greywater production in a given week. Weekly fluctuations are however known to exist, and as reported by Fewkes & Ferris (1982), these fluctuations within a week have a significant impact on results. These fluctuations can be attributed people doing mutable loads of washing in a relatively short period of time, not 0.3 events/person/day as assumed by the EDWI-system.

The following chapter further develops the EDWI-system to the point where the conceptual equations are obtained. The reader is introduced to the EDWI-software tool developed by the author as a part of the research that allows for the calculation of the final rating. The meaning of the final rating is also clarified.

7. Development of a novel sustainability index

7.1 Introduction

The EDWI-software tool that was developed by the author is explained in this chapter. This user-friendly platform consists of an “input sheet”, “output sheet”, “behavioural model sheet”, “demand estimation sheet” and a sheet for each of the techniques included in the EDWI-system. The sheets for the three different EDWI-components display all assumed data for their incorporation such as sources of greywater, uses of grey and rainwater and general assumptions used to determine the effect of a green roof. The “demand estimation sheet” contains the user-defined characteristics of the dwelling’s water use and the assumed distribution, according to user input of end-uses in the specific dwelling.

The three sheets, one for each of the EDWI-components, show the user-specified level of implementation. These specifications are then be used to simulate a five-year period of operation to obtain the average reduction or change in municipal water demand and the effect on the local environment in respect to aspects such as stormwater volumes and return flows. Data from these simulations is then used to calculate several factors quantifying system operations, refer to section 7.5. These factors allow for the calculation of the three EDWI-coefficients, which are used to obtain the final EDWI-rating as described in section 7.6.

Figure 12 shows a flow diagram of the process to obtain all data and calculate the EDWI-rating. All data required by EDWI-software tool is obtained via excel user forms, this is done for data validation purposes.

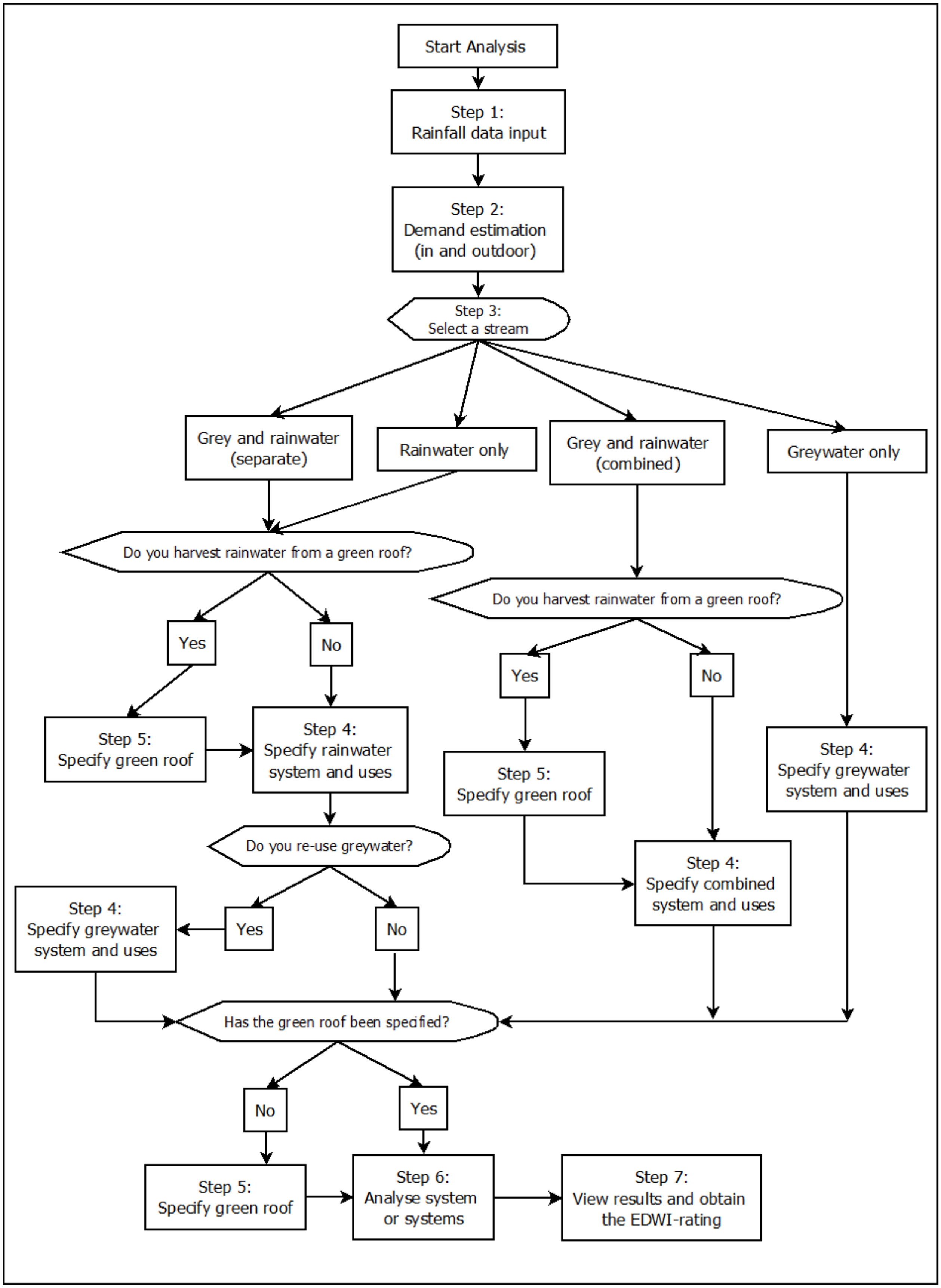


Figure 12: EDWI-software tool process

There are seven steps that need to be completed in the EDWI-software tool to obtain the EDWI-rating of a dwelling. The sequence which needs to be completed depends on the type of stream selected as can be seen in Figure 12. For more detail on the EDWI-software tool refer to the user manual in Appendix A.

7.2 A brief overview of the final rating and its meaning

When a user has completed all the steps in the EDWI-software tool they receive the final EDWI-rating for the dwelling. This EDWI-rating ranges from 0 to 100. An EDWI-rating of 100 is the maximum rating any dwelling can receive. If a dwelling receives an EDWI-rating of 100, the dwelling will then:

- Require no input from a municipal water network (All water used will originate from alternative sources).
- All greywater produced by end-uses included in the EDWI-system, is utilised.
- The dwelling will require removal of blackwater only (Reduced return flow from dwelling).
- All stormwater originating from the dwelling's roof will be utilised (no stormwater removal will be required).
- All roofs are green roofs (no impervious roof spaces are created by the dwelling).

On the other end of the spectrum are dwellings that receive an EDWI-rating of zero. These dwellings will then:

- Require all water services to be provided from an external source (e.g. local municipality)
- No green roof (All roofs will be traditional impervious roofs)
- No rainwater harvesting
- No greywater re-use
- All return flows from dwelling will be discharged into a sewage network.

Higher EDWI-ratings indicate dwellings that are less dependent on water services supplied from outside sources like a local municipality. Thus a dwelling with an EDWI-rating of 20 will require double the external input as water services, when compared to a dwelling that obtained an EDWI-rating of 40. In the simplest of terms, the higher the EDWI-rating of a dwelling, the less input it will require from external sources such as a municipality.

The final EDWI-rating composes of three EDWI-coefficients. These are:

- The return flow reduction (E_r)
- The green space improvement (E_g)
- The reduction on municipal water demand (E_d).

These EDWI-coefficients are further elaborated upon in section 7.6. Figure 13 shows how the EDWI-components affect the different EDWI-coefficients that form the final EDWI-rating of a dwelling.

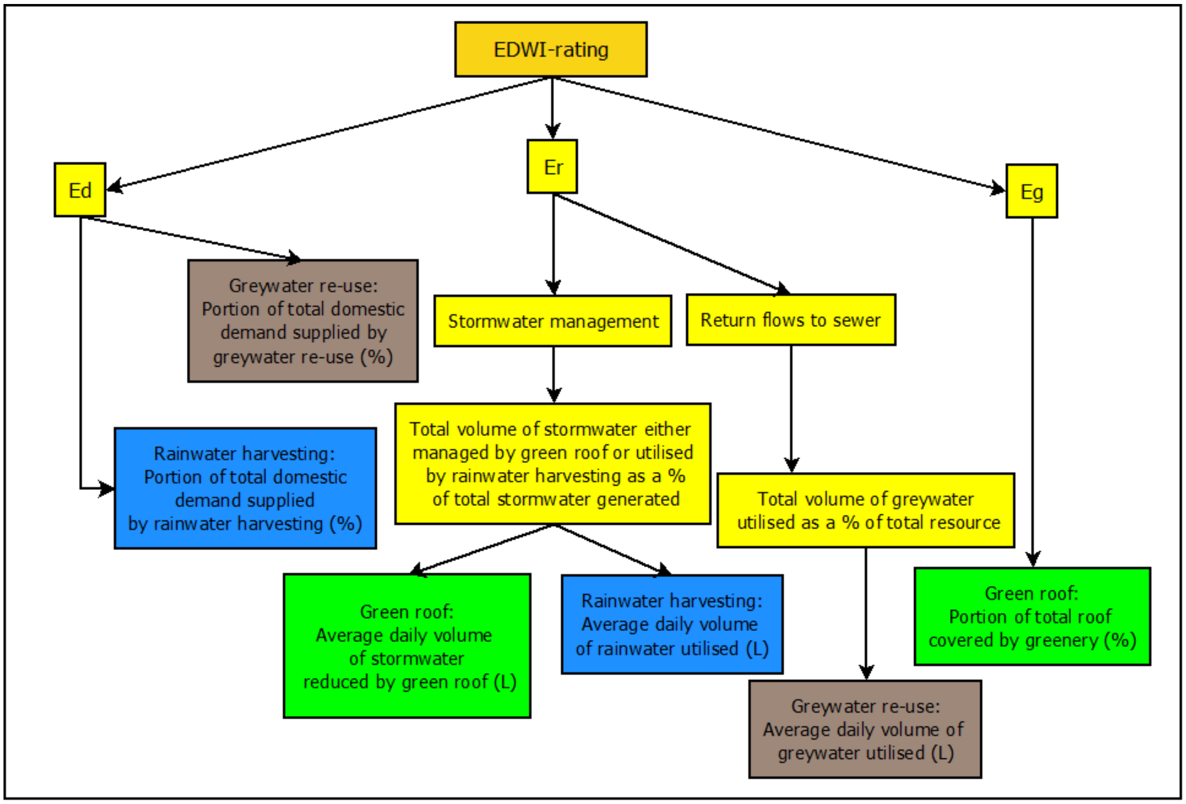


Figure 13: EDWI-rating composition

Formulas for all EDWI-coefficients and how they form the final EDWI-rating are included in section 7.6. Each of the EDWI-components affects at least two of the three EDWI-coefficients, as can be seen when Figure 13 is examined, thus ensuring that they are incorporated as evenly as possible.

7.3 Rain and greywater streams

When a user selects a grey- and rainwater system he or she might want to combine the two systems into one. This idea is described in section 5.5, but it is important to realise that if a class 2 and 3 resource were to be combined the quality of the combination would be that of the lower of the two streams, thus class 3. This limitation would severely limit the possible applications, but with additional treatment the greywater, and thus the combination of the two, could be improved to a class 2 resource. For this reason if grey and rainwater are to be combined in a single stream it is assumed as being the same as a greywater system, minimal treatment will thus produce a class 3 resource. The EDWI-software tool automatically shows a behavioural model of grey-, rain- or the combined streams, but the combination is only used for the model if indicated by the user.

7.3.1 Simulated greywater stream

Greywater streams are by definition extremely random and thus difficult to simulate. As described in section 5.3 a greywater stream can be developed by using a Monte Carlo analysis as demonstrated by Fewkes & Ferris (1982). For the purpose of this thesis it was however decided to use a deterministic method.

As with water demand estimation, greywater streams depend on the applicable end-uses, their specific water requirements, frequencies of use per capita as well as their associated return flows. Accordingly the EDWI-software tool estimates greywater volumes by using the same data used for demand estimation. Table 4 shows these assumed frequencies of use and associated volumes per event. Table 5 provides different volumes per end-use data.

7.3.2 Tank sizing

The final tank size for a system is user-defined after the initial trial run with an initial tank size also selected by the user. After this initial analysis the model produces the system efficiency and associated water savings. Using trial and error the user is then able to see what effect changing the tank size will have on the system's performance. This procedure will need to be repeated for every system. It is also worth mentioning that when running the behavioural model for a given stream the associated tank size should be selected, and if satisfactory the data will then be added to the "results sheet" automatically after completing that section.

7.4 Model assumptions

7.4.1 Demand estimation

Indoor water demand is estimated as described in section 6.4. The end-uses used to estimate indoor water demand each have three possible water requirements as low, typical or high. Deciding which requirement to apply at what frequency of use for each end-use is a complex problem due to the extreme variation of human habits and lifestyles. This topic falls well outside the scope of this thesis. With this in mind it was decided to assume that all end-uses excluding washing machines and dishwashers, which are user-defined, have a typical demand, refer to Table 5.

Toilet flushing was assumed as having a typical water requirement, but a distinction between normal and dual flush toilets are made in the EDWI-software tool by the user.

Outdoor demand is estimated by using a method presented by Jacobs & Haarhoff (2004b). After obtaining the size of each of the two assumed parts of the garden, lawn and beds, their individual water requirements can be obtained and combined to produce an annual monthly daily demand (AMDD) by using equation 7.1.

$$AMDD = S_l.\frac{k_{l,m}.p_{l,m} - r_m}{D_m} + S_b.\frac{k_{b,m}.p_{b,m} - r_m}{D_m}$$ Equation 7-1

where:

S_l, S_b	is area of lawn and beds
$k_{l,m}$,$k_{b,m}$	is corp factor from lawn and bed for month m respectively
p_m	is the A-pan evaporation for month m
D_m	is the total number of days in month m
r_m	is rainfall in month m.

Crop factors for the eleven generalised veld types found in South Africa and kikuyu grass are listed in Table 7 along with the mean annual evaporation (MAE) and monthly distributions for four South African cities.

Vegetation Type	Average Value	Monthly crop factor											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kikuyu (grass / lawn)	0.46	0.68	0.68	0.60	0.47	0.31	0.22	0.22	0.22	0.30	0.47	0.61	0.68
Coastal tropical forest	0.64	0.75	0.75	0.74	0.69	0.61	0.56	0.40	0.51	0.60	0.67	0.69	0.75
Inland tropical forest	0.67	0.78	0.78	0.75	0.70	0.65	0.50	0.40	0.55	0.65	0.73	0.78	0.78
Tropical bushveld	0.48	0.59	0.59	0.58	0.50	0.44	0.32	0.27	0.35	0.45	0.51	0.56	0.59
Karoo and karroid	0.39	0.50	0.50	0.48	0.46	0.37	0.25	0.20	0.22	0.33	0.41	0.46	0.50
Pure grassveld	0.42	0.62	0.62	0.55	0.43	0.28	0.20	0.20	0.20	0.27	0.43	0.56	0.62
Fynbos	0.50	0.60	0.55	0.55	0.55	0.45	0.40	0.20	0.35	0.50	0.60	0.60	0.60
False fynbos	0.46	0.55	0.55	0.50	0.50	0.40	0.35	0.20	0.35	0.50	0.55	0.55	0.55
False Bushveld	0.45	0.62	0.62	0.58	0.53	0.38	0.25	0.20	0.23	0.35	0.48	0.58	0.60
Forest and scrub	0.51	0.61	0.60	0.60	0.57	0.46	0.36	0.29	0.36	0.48	0.58	0.61	0.61
False Karoo	0.36	0.50	0.50	0.46	0.36	0.26	0.21	0.20	0.20	0.27	0.36	0.45	0.50
False grassveld	0.52	0.73	0.73	0.67	0.61	0.43	0.24	0.20	0.27	0.41	0.53	0.65	0.73
Location / Town	**MAE (mm/yr)**	**Monthly A-Pan Evaporation (mm/month)**											
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Bloemfontein	2428.0	328.0	246.4	213.9	144.2	106.1	76.7	90.8	134.0	200.6	259.3	292.6	335.3
Cape Town	2004.0	295.2	249.1	217.6	135.5	78.2	60.1	66.5	78.2	114.8	175.6	245.1	288.2
Durban	1674.5	201.2	172.5	167.2	120.6	97.4	80.0	86.3	103.2	124.9	149.5	177.5	194.2
Johannesburg	2228.0	249.5	205.0	189.4	142.1	113.0	88.9	102.9	151.1	208.1	256.7	257.1	264.2

Table 7: Crop factors and evaporation data (Midgley et al., 1994; Short & Colmer, 1999)

The upper terms in equation 7.1, ($k_{l,m} \cdot p_{l,m} - r_m$) and ($k_{b,m} \cdot p_{b,m} - r_m$), can become negative when rainfall is greater than plant requirement. This happens in months with a higher rainfall than irrigation requirement. Irrigation is not needed during these months due to ET being smaller than irrigation requirement, and accordingly outdoor demand is set to zero. Thus in winter rainfall regions such as the Western Cape irrigation may not be required during all the winter months. However it was decided not to assume a zero winter demand but to verify monthly demand by verifying that the calculated demand, obtained with equation 7.1, is larger than zero. This proposed method produces demands that will decrease as rainfall increases and not just be assumed to be nonexistent for the entire rainfall season.

7.4.2 System simulation

All systems in the EDWI-software tool are simulated using a behavioural model. To create easy-to-understand software and to simplify the code it was further decided only to simulate one water stream at a time. The results from this analysis are added to the “results sheet” as the user accepts them and a different stream can then be analysed if required. There are four possible streams that could be used. These streams are:

- Rainwater only
- Greywater only
- Rain and greywater systems (separate)
- Combined rain and greywater system.

It is advised that greywater is seen as a single stream or in combination with rainwater. Greywater should not be divided into different streams as this will produce complex systems that are unlikely to be cost effective, and this concept is not incorporated in the EDWI-software tool.

The behavioural model’s rainfall component is based on a five-year stochastic daily rainfall series. The model calculates the “average” efficiency and associated water savings of the dwelling over the previously mentioned five-year simulation period. To produce an accurate representation of the system it was decided to use daily rainfall records and associated daily demands. The system efficiency of greywater re-use is calculated in the same manner as with rainwater and expressed as the system's E_t.

7.5 Factors for the final rating

The three EDWI-coefficients comprises of factors that are obtained while completing the seven steps of the EDWI-software tool, refer to Figure 12.

The first two factors benchmark the "state" of the dwelling without any EDWI-components. They are the total roof run-off without green roof and rainwater harvesting (TRW) and the total greywater produced by end-uses considered for re-use (TGW). These two factors are measured in average L/day.

TRW is calculated with equation 7.2.

$$TRW = A_{Troof} \frac{MAP}{365}$$ Equation 7-2

TGW is calculated with equation 7.3.

$$TGW = \sum_{n=1}^{4} AADD_n$$ Equation 7-3

The rainwater utilised (RWU), greywater utilised (GWU) and green roof reduction in run-off (GRRR) are factors used to incorporate the change experienced by the dwelling due to the EDWI-components incorporated in terms of return flow. These factors are measured in average L/day.

RWU is calculated with equation 7.4.

$$RWU = E_{tRW} D_{tRW}$$ Equation 7-4

GWU is calculated with equation 7.5.

$$GWU = E_{tGW} D_{tRW}$$ Equation 7-5

In the case of a combined system the combined system water utilised (CWU) will be used and it's calculated with Equation 7.6.

$$CWU = E_{tC} D_{tC}$$ Equation 7-6

Green roof reduction in run-off (GRRR) is calculated with equation 7.7.

$$GRRR = \frac{(1 - \Psi_{\mathrm{a}}) A_{green} MAP}{365}$$ Equation 7-7

The last two factors express the portion of total domestic water demand met by the alternative water sources. The final two factors are expressed as the percentage of total domestic demand they are expected to supply.

Equation 7.8 and 7.9 are used to calculate the portion of total domestic demand met by a rain- and greywater system respectively.

$$D_{nRW} = 100 \frac{Y_{tRW}}{AADD}$$ Equation 7-8

$$D_{nGW} = 100 \frac{Y_{tGW}}{AADD}$$ Equation 7-9

where:

A_{Troof}, A_{green}	is the total roof area and green roof area
D_{tRW}, D_{tGW}, D_{tC}	is the average daily draft from a rain-, greywater and combined system during time t (daily)
E_{tRW}, E_{tGW}	is the systems water savings efficiency for rain and greywater system
Y_{tRW}, Y_{tGW}	is the average daily yield from the rain- and greywater system
Ψ_a	is the annual coefficient of discharge from a green roof.

7.6 The final rating

After completion of the steps required by the developed EDWI-software tool a final rating is assigned to the dwelling. This EDWI-rating and how it is calculated is explained in this section.

The EDWI-rating is calculated with equation 7.10 show below.

$$EDWI - rating = \frac{E_r + E_g + E_d}{3} \quad \text{Equation 7-10}$$

The three EDWI-coefficients (E_r, E_g and E_d), as with the EDWI-rating, range from 0 to 100%. These coefficients are calculated using factors described in section 7.5.

E_g is the coefficient that expresses the increase of green space obtained by the addition of a green roof. E_g is calculated using equation 7.11.

$$E_g = 100\frac{Green\,roof\ area}{Total\,roof\ area} \quad \text{Equation 7-11}$$

E_d expresses what percentage of the dwelling's demand can be met by the alternative water resources from the systems selected by the user. The specific equation used to calculate can change depending on user specifications. Equation 7.12 shows the general form.

$$E_d = D_{nGW} + D_{nRW} \quad \text{Equation 7-12}$$

In the case where a combined system was selected E_d would be equal to only the portion of domestic demand met by the combined system (D_{nC}).

The last coefficient, E_r, expresses the fraction of reduction on the dwelling's return flow because of the techniques incorporated. E_r depends on the reduction in roof run-off (due to a green roof and rainwater harvesting) and the reduction in return flows (caused by the re-use of greywater). Because of the four types of system combinations available in the EDWI-system there are four formulas for E_r, each for a different system setup.

The most general system selection is a grey- and rainwater systems not combined and it is calculated with equation 7.13.

$$E_r = 50\left({}^{GWU}\!/_{TGW}\right) + 50\left(\frac{(RWU + GRRR)}{TRW}\right) \qquad \text{Equation 7-13}$$

A grey- and rainwater system combined uses equation 7.14.

$$E_r = 100\left(\frac{CWU + GRRR}{TGW + TRW}\right) \qquad \text{Equation 7-14}$$

Two possible single systems can be utilised, grey- or rainwater only. Their equations are given in equation 7.15 and 7.16 respectively.

$$E_r = 50\left({}^{GWU}\!/_{TGW}\right) + 50\left({}^{GRRR}\!/_{TRW}\right) \qquad \text{Equation 7-15}$$

$$E_r = 100\left(\frac{GRRR + RWU}{TRW + TGW}\right) \qquad \text{Equation 7-16}$$

7.7 How to simulate a dwelling using the developed software

In section 7.7.1 to 7.7.2 a step by step process will be presented that details the data requirements, it is worth mentioning that the model can only be as accurate as the data provided by the user. Screenshots of the EDWI-software tool are included in this section. For easy reference detailed an explanation of the EDWI-software tool is available as a user guide in Appendix A.

7.7.1 Data requirements

All data inputs are managed by the “input sheet” via user forms (Excel name for windows) activated by buttons. The ““input sheet” contains seven steps which guides the user through the data input process.

These steps are:

- Load rainfall data
- Demand estimation
- System and tank specifications
- System or systems uses and sources
- Green roof (defined before rainwater system if green roof run-off is harvested)
- System balance and optimisation
- View results and obtain EDWI-rating.

All steps are controlled using user forms initiated by clicking on a button. The buttons are set as invisible when the procedure is first initiated and as the user completes a section, the next section's button is enabled and the completed section's button's colour changes from grey to blue. This procedure assures that sections are completed in a logical order which simplifies the data validation process.

7.7.1.1 Rainfall data

The rainfall data required for the EDWI-software tool is a five-year stochastic series of daily rainfall in millimetres. The data can be obtained by any means but leap years should not be included. Section 6.7 describes where the data can be obtained easily.

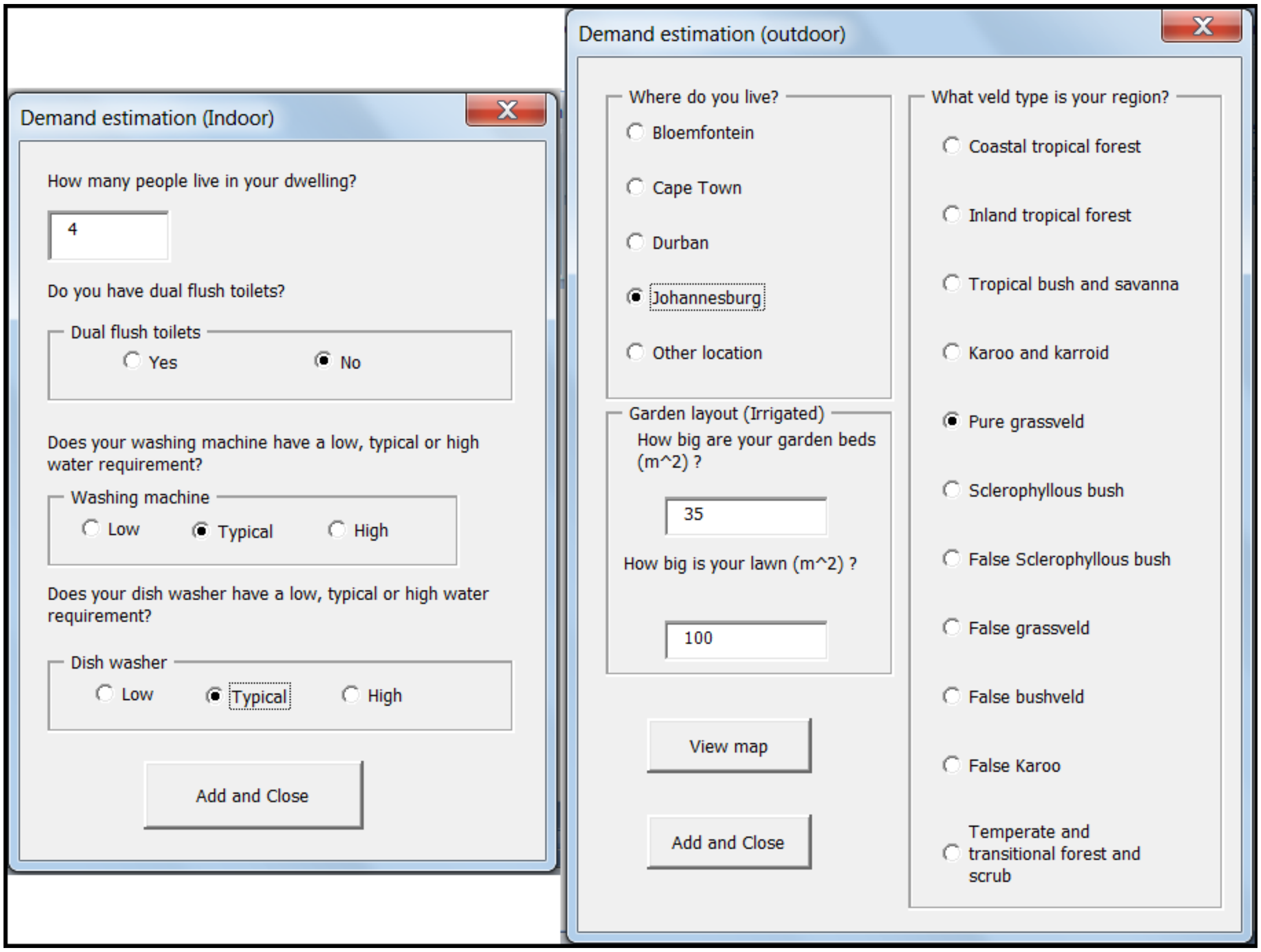
The rainfall data is imported through a ".csv" file (a simplified format similar to a single excel sheet without any formulas). It is important that the csv file's name should be typed including the extension, thus if the file is named "rainfall" the user needs to type "rainfall.csv". The location of this file is also required, and needs to be specified in the applicable text box.

All rainfall data imported into the EDWI-software tool needs to comply to a specific format. When entering rainfall data, start with the first day in January's rainfall, in cell A1, followed by the second day's in the adjacent column, ext. This is then repeated for the entire first year. The second year's data is inserted in the same manner, only starting at cell A2. All five years' data have to be included in this form to avoid mistakes. It is also important to ignore leap years and to remember that the rainfall should be in millimetres. Refer to the user manual in Appendix A for details on how to load rainfall data into the EDWI-software tool.

7.7.1.2 Demand estimation

Demand estimation is done by using two user forms. In the first form indoor water demand is calculated and in the second form, outdoor, assumed as only including irrigation.

The "indoor demand estimation" user form is shown with the outdoor demand user form in Figure 14. The indoor demand user form contains four fields that need to be specified. These inputs then allow indoor demand to be estimated and accordingly the distribution of end-uses and associated water requirements and return flows.



Demand estimation (Indoor)

How many people live in your dwelling?

4

Do you have dual flush toilets?

Dual flush toilets
○ Yes ● No

Does your washing machine have a low, typical or high water requirement?

Washing machine
○ Low ● Typical ○ High

Does your dish washer have a low, typical or high water requirement?

Dish washer
○ Low ● Typical ○ High

Demand estimation (outdoor)

Where do you live?
○ Bloemfontein
○ Cape Town
○ Durban
● Johannesburg
○ Other location

Garden layout (Irrigated)

How big are your garden beds (m^2) ?

35

How big is your lawn (m^2) ?

100

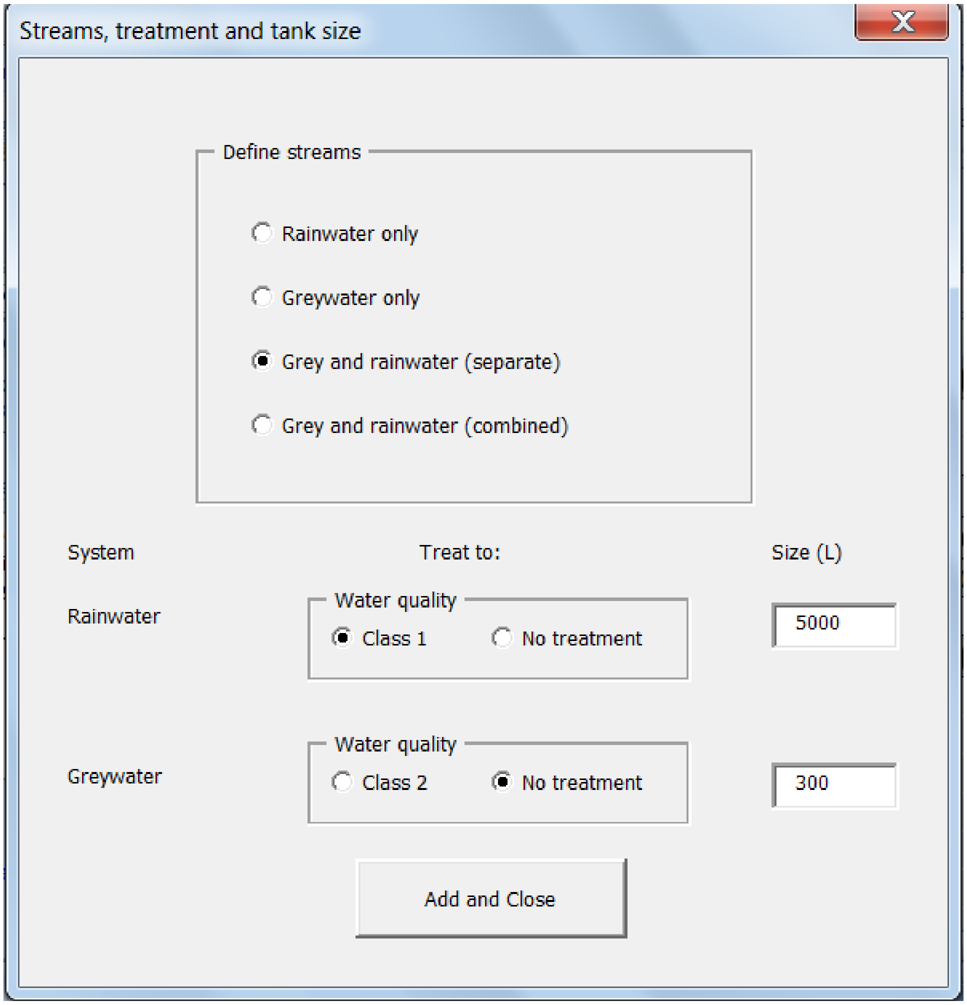
What veld type is your region?
○ Coastal tropical forest
○ Inland tropical forest
○ Tropical bush and savanna
○ Karoo and karroid
● Pure grassveld
○ Sclerophyllous bush
○ False Sclerophyllous bush
○ False grassveld
○ False bushveld
○ False Karoo
○ Temperate and transitional forest and scrub

Figure 14: Demand estimation user form

The "outdoor demand" user form requires the user to specify the dwelling's location, the corresponding veld type and the areas of lawn and beds under irrigation. These values then allow the EDWI-software tool to calculate an AMDD. For the cities shown in Figure 14 the corresponding veld types are automatically selected as they are. If the "other" location is selected the user will need to specify the respective veld type manually.

7.7.1.3 System and tank specifications

The system and tank specification user form allows the user to specify what type or types of system or systems he or she would like to incorporate. The choices are a rain- or greywater system only, a combined system or rain- and greywater systems separately. After specifying the type of system the user form prompts the user to specify the quality classification the water will be treated to. This quality classification will dictate possible end-uses for the stream. Initial tank sizes are also specified but can be changed when the system is analysed. Figure 15 shows the system and tank specification user form.



Streams, treatment and tank size

Define streams

○ Rainwater only
○ Greywater only
● Grey and rainwater (separate)
○ Grey and rainwater (combined)

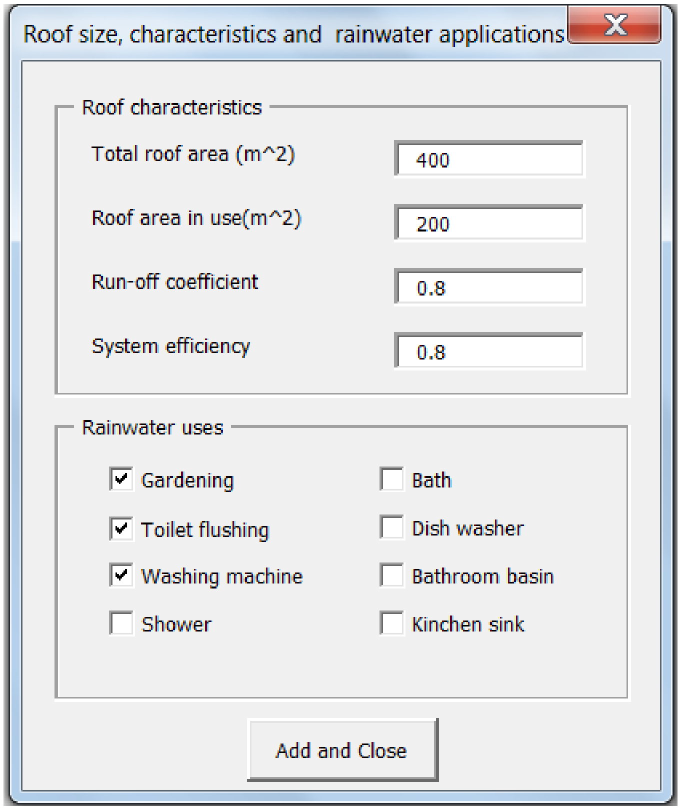
System	Treat to:	Size (L)
Rainwater	Water quality ● Class 1 ○ No treatment	5000
Greywater	Water quality ○ Class 2 ● No treatment	300

Figure 15: Streams, treatment and tank user form

When the stream or streams are defined the buttons controlling these specific stream or streams are enabled on the “input sheet”. For the example shown in Figure 15 the buttons controlling rain and greywater specifications and uses will then be enabled.

7.7.1.4 Specify applications

There are three user forms linked to three different buttons controlling this step. These user forms collect parameters such as run-off coefficients, system efficiency, roof area and uses for rainwater and sources and uses for greywater, but only when a given dwelling incorporates them. As an example the user form for rainwater is shown in Figure 16.



Roof size, characteristics and rainwater applications

Roof characteristics

Total roof area (m^2): 400

Roof area in use(m^2): 200

Run-off coefficient: 0.8

System efficiency: 0.8

Rainwater uses

☑ Gardening

☑ Toilet flushing

☑ Washing machine

☐ Shower

☐ Bath

☐ Dish washer

☐ Bathroom basin

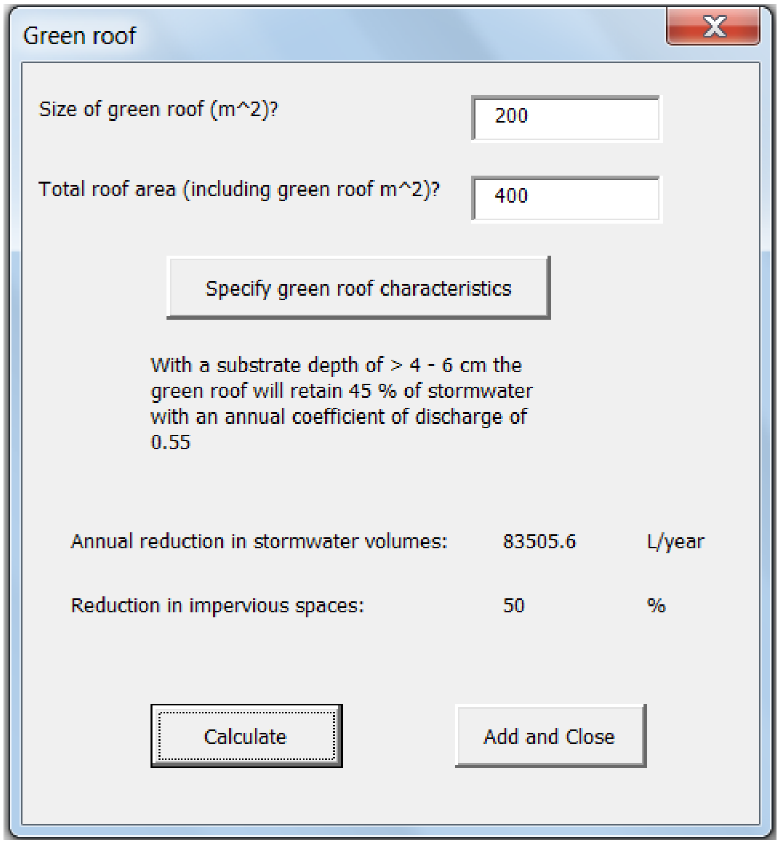
☐ Kinchen sink

Figure 16: Rainwater uses and characteristics user form

In the example shown in Figure 16 it can be seen that all potential uses are enabled. This implies that the harvested rainwater has been selected as being of class 1. This would not have been the case if class 1 treatment was not selected as the software only shows possible uses according to water quality classifications.

7.7.1.5 Green roof

The green roof user form is shown in Figure 17. This user form is used to obtain parameters relating to the physical characteristics of the green roof and parameters that allow the EDWI-software tool to calculate the theoretical effect that the green roof might have on its direct environment.



Green roof

Size of green roof (m^2)? 200

Total roof area (including green roof m^2)? 400

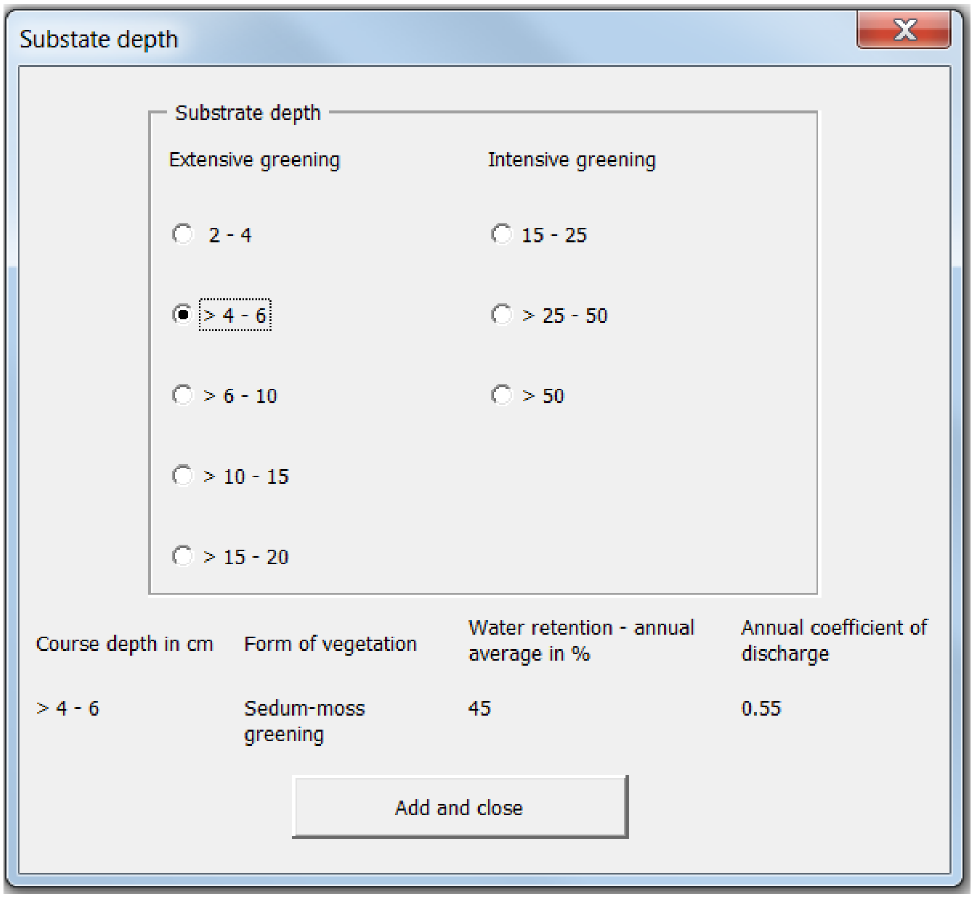
With a substrate depth of > 4 - 6 cm the green roof will retain 45 % of stormwater with an annual coefficient of discharge of 0.55

Annual reduction in stormwater volumes: 83505.6 L/year

Reduction in impervious spaces: 50 %

Figure 17: Green roof user form

The “Specify green roof characteristics” button prompts the “Substrate depth” user form. This user form allows the user to specify a substrate depth and according to the user selection the associated stormwater retention and run-off coefficient is then set. The theoretical values of these retentions and run-off coefficients are obtained by using a table presented in the FFL guidelines (2002:37). The “Substrate depth” user form is shown in Figure 18.

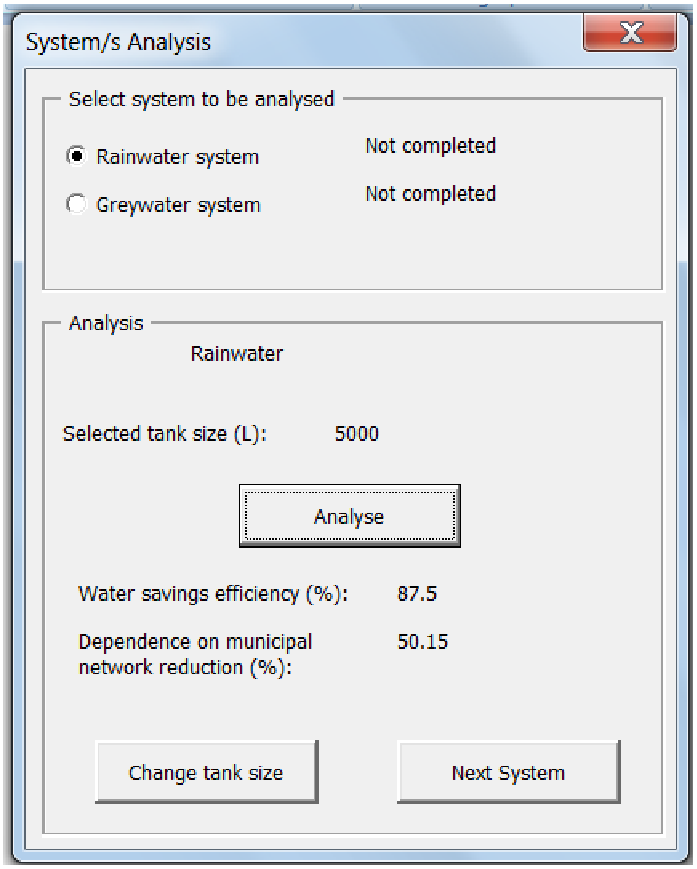


Course depth in cm	Form of vegetation	Water retention - annual average in %	Annual coefficient of discharge
> 4 - 6	Sedum-moss greening	45	0.55

Figure 18: Substrate depth user form

7.7.1.6 System balance

Figure 19 shows the version of the system analysis user form that will be displayed if the user chooses a grey and rainwater system separately. The user now selects the first system analysed. The system's E_t and the D_n is then calculated by the "behavioural model sheet" and reflected on this user form. The system tank size can then be changed by clicking on the "change tank size" button. This button then prompts a user form that allows the user to specify different tank sizes and observe the effect that this change will have on the system's performance.



● Rainwater system Not completed
○ Greywater system Not completed

Rainwater

Selected tank size (L): 5000

Water savings efficiency (%): 87.5

Dependence on municipal network reduction (%): 50.15

Figure 19: System analysis user form

The other system can then be analysed in the same manner. If only one system remains, the "Next System" button will become an "Add and Close" button, allowing the final system to be analysed and specified.

7.7.1.7 View results

All results are displayed in the "results sheet". This sheet can either be accessed by selecting the tab itself or by clicking on the results button on the "input sheet". The results button automatically activates and displays the "results sheet".

The "results sheet" contains all results of the analysis including a final EDWI-rating, the three EDWI-coefficients which results into the final EDWI-rating and other general parameters and characteristics.

7.7.2 Data validation and optimisation

When a dwelling incorporates rain and greywater systems separately it is important that the same use is not assigned to both. This potential problem is solved by disabling the selection of uses selected by the one system in the options list in the other.

Most of the user forms developed in the EDWI-software tool contains at least one text box. These are used to allow users to type in data such as roof area. Validation of data inserted by the user now becomes important to prevent text being entered in an area requiring numbers. This required validation was not done, but if the analysis is completed it will become clear if all data was not correctly inserted due to faulty results on the “results sheet”.

In next chapter the EDWI-rating is explored. This chapter provides the benchmarking procedure which reveals the inner workings of the index and shows how components affect the final EDWI-rating.

8. Results and interpretation

In order to validate the accuracy of the EDWI-system it is important to compare results from the EDWI-software tool with other published results found in literature. Ideally the index is best validated by comparing the EDWI-rating, and changes caused by certain factors, with a similar index. This however proved difficult because a similar index, taking the same factors into account, could not be found. For this reason parts of the model will be tested and compared to published results thereby validating the mathematical validity of the EDWI-software tool. Further, the EDWI-system was benchmarked using three model dwellings with nine configurations producing a total of 27 analyses.

8.1 Greywater only versus combined systems

This section shows the improvement, if any, that can be expected when a greywater only system adds rainwater, thus forming a combined system. Combined systems of this kind are subject to the same limitations as greywater only systems in respect to the low storage capacities that should be used. However, it was decided to test the effect of increasing storage capacity although this would cause greywater to be stored for longer periods of time, which could produce unwanted consequences. This is described in greater detail in section 5.4 and 5.5.

Table 8 lists the dwelling and system characteristics as well as greywater sources and uses for grey- and rainwater systems.

Location: Johannesburg			
Roof and rainwater harvesting	Value	Imposed demand by greywater system	Value
Total roof area (m^2)	400	Garden irrigation	
Green roof area (m^2)	50	Sources of greywater	
Roof Area (connected to tank in m^2):	200	Bath	
Green roof substrate depth (cm):	4-6	Shower	
Run-off Coefficient:	0.8	Bathroom basin	
System Efficiency:	0.8	Washing machine	
		Imposed demand by rainwater system	
Demand estimation		Toilet flushing	
Occupancy:	4	Washing machine	
Dual flush toilets:	No	Garden characteristics	
Washing machine requirement:	Typical	Lawn (m^2)	100
Dishwasher requirement:	High	Beds (m^2)	35

Table 8: Johannesburg grey and combined system analysis

It was decided to simulate the dwelling with a greywater tank size of 350 L, followed by a combined system with a tank of the same size to see if the addition of rainwater leads to any improvement. This procedure was repeated with storage capacities of 500, 750 and 1000 L.

Capacity (L)	Combined (%)	Greywater (%)	Change (%)
350.00	48.93	48.93	0.00
500.00	68.64	68.64	0.00
750.00	86.55	85.05	1.73
1000.00	90.95	85.28	6.24

Table 9: Results of grey and combined system analysis

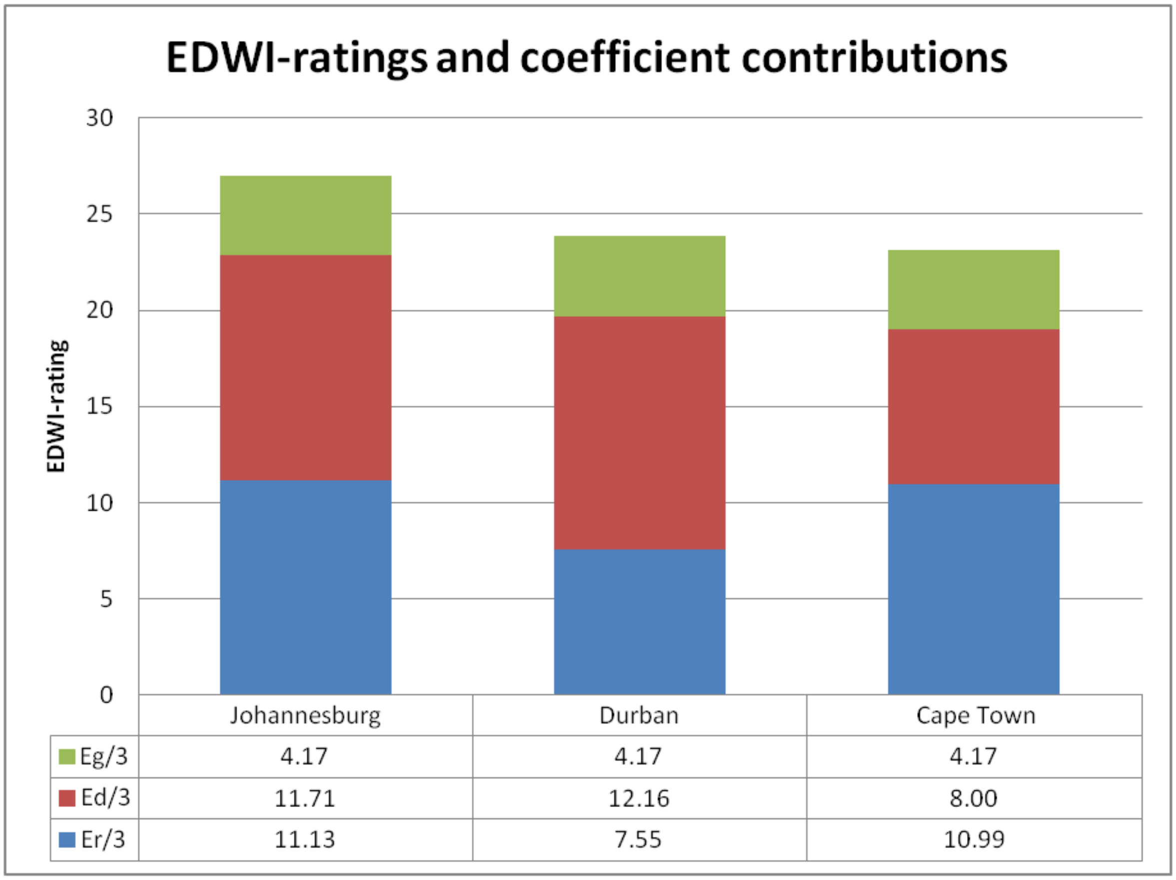
According to the results presented in Table 9 there is no improvement to system performance when low volume storage in used. These results are confirmed by similar findings by Dixon et al. (1999). However as the storage capacity rises an improvement is seen. These large storage capacities are however undesirable as greywater will now be retained for extended periods of time. It is possible to implement a combined system successfully with such large capacities but this will result in complex treatment systems.

8.2 Comparison between Johannesburg, Cape Town and Durban

In this section a “sample” dwelling is analysed in three different South African cities. It is worth mentioning that the “sample” dwelling’s systems analysed in this section is in no way an optimised solution for any of the cities. This analysis is intended to show how factors such as MAP, MAE, natural veld type and their distributions affect the EDWI-rating and accordingly the selection of an optimised solution.

It was decided to use the same dwelling characteristics such as roof area, and the same system types for all locations. The dwelling and system characteristics are identical to those used in section 8.1, refer to Table 8. It was further decided to simulate grey and rainwater systems separately with tank sizes of 300 and 5000 L respectively. The greywater tank size of 300 L was selected so that the greywater system’s retention time would be less than 24 hours as proposed by Carden et al. (2007b). Retention time will be less than 24 hours because supply and demand both exceeds 300 L/day. The rainwater tank size of 5000 L was selected as tanks larger than 5000 L are considered inappropriate for a residential stands (Jacobs et al., 2010), as they are seen as being visually unappealing. It was also decided to apply only minimal treatment to the systems, producing greywater of class 3 and rainwater of class 2.

It was decided to compare dwellings in Durban, Johannesburg and Cape Town. These locations differ in MAP, MAE and natural veld type, as well as Cape Town being a winter rainfall area, Johannesburg a summer rainfall are, and Durban having all year rainfall. The results of these analyses are presented in Appendix B and the EDWI-ratings and component contributions are presented in Figure 20. Note that the values of all EDWI-coefficients in Figure 20 are listed as their contribution towards the final EDWI-rating.



	Johannesburg	Durban	Cape Town
🟩 Eg/3	4.17	4.17	4.17
🟥 Ed/3	11.71	12.16	8.00
🟦 Er/3	11.13	7.55	10.99

Figure 20: EDWI-rating location comparison

The Johannesburg dwelling achieved the highest EDWI-rating and the Cape Town dwelling the lowest. E_g is, as expected, constant across all locations as this coefficient is not affected by location.

Of the three selected locations Durban enjoys the highest and best distributed rainfall. This is reflected in the E_t of the rainwater system 10 % higher than Johannesburg and 20 % higher than Cape Town. Refer to Table 11 for details. Accordingly this allows the Durban rainwater system to provide 31 % of total water demand whereas Johannesburg and Cape Town systems achieve 23 and 15 % respectively. The Cape Town dwelling has the least efficient rainwater system. This is caused by the relatively low rainfall the region receives. However, if the inner parameters are examined it can be seen that 40 % of total roof run-off is utilised in Cape Town, which is more than in Durban and Johannesburg, where 34 and 37 % are achieved respectively. Refer to Figure B 1 to 3.

Irrigation demand was assigned to the greywater systems. Of the three selected locations the Johannesburg system was able to utilise the highest portion of available greywater, followed by Cape Town and then Durban. The Durban greywater system utilised the lowest portion of greywater because of the low irrigation requirement expected in this region which is the result of a combination the region's veld type and rainfall. See Table 10 for monthly irrigation demands for all locations.

Irrigation demand (AAMD) in L			
	Cape Town	Johannesburg	Durban
Jan	668.57	160.53	49.52
Feb	581.63	226.78	78.97
Mar	420.88	102.10	0.00
Apr	123.86	40.79	0.00
May	0.00	54.42	0.00
Jun	0.00	0.00	62.96
Jul	0.00	93.38	0.00
Aug	0.00	21.76	0.00
Sep	58.20	181.05	0.00
Oct	416.31	214.25	0.00
Nov	635.51	264.08	109.81
Dec	738.20	395.48	162.24

Table 10: Irrigation demand

The Cape Town greywater system achieved the lowest water savings efficiency because of the large irrigation demand in summer. These larger irrigation demands, especially in January and December, are larger than the storage capacity of the system and the supply of greywater, making them impossible to meet. The Durban greywater system reaches the highest E_t, but this only makes up 5.2 % of total annual demand. This is because of the characteristic high rainfall experienced by the region. See Table 11 for details. From these results it can clearly be seen that during the selection of systems and system characteristics, as well as what they will be used for, local climate conditions should be taken into account.

Table 11 presents the rain and greywater system efficiencies and the portion of domestic demand they are able to meet, D_n, for all locations.

Location	Rainwater		Greywater	
	E_t (%)	D_n(%)	E_t (%)	D_n(%)
Johannesburg	53.53	22.80	69.09	12.33
Durban	63.64	31.22	97.30	5.25
Cape Town	43.85	15.38	26.78	8.63

Table 11: Grey and rainwater systems performance

Of the three EDWI-coefficients two are geographically dependent. These two are the E_r and E_d coefficients. As expected, the Durban dwelling has the lowest E_r. This is the result of the high volumes of roof run-off and the low irrigation requirement which causes irrigation to account for a very low portion of total demand compared to that in the other locations analysed, refer to Table 11.

To improve the efficiency of the Cape Town dwelling, and the final EDWI-rating, it is recommended that the irrigation demand be met by another source of water or in combination with another, or to quite simply reduce the area under irrigation. Even if it was decided to utilise the Cape Town rainwater system to meet irrigation demand, system efficiency is unlikely to improve by much. This is because of the characteristic winter rainfall experienced in the Western Cape region causing large volumes of water to be available when there is no irrigation required. In contrast the Durban dwelling might consider utilising the greywater system towards a demand with a higher year round requirement, such as toilet flushing, and utilising rainwater for the small irrigation demand and other end-uses for which class 2 quality water is suitable.

The highest EDWI-rating was obtained by the Johannesburg dwelling. Because of the characteristics of the area, the Johannesburg dwelling has the most evenly distributed irrigation demand, making greywater re-use ideal for this region. Further, as seen in this example, there is only one month in an average year that will impose a daily irrigation demand higher that the storage capacity and greywater supply. The rainwater system can however be improved by increasing storage capacity. This will result in an increase in the E_r and E_d EDWI-coefficients and accordingly the EDWI-rating.

8.3 Benchmarking the sustainability index

In the literature review preceding the development of the EDWI-system no similar index could be found to compare its results to. It was therefore decided to benchmark the EDWI-system using three model dwellings. The model dwellings are intended to represent a low (type 1), medium (type 2) and high (type 3) cost dwelling. These three model dwellings where analysed using nine configurations of the three EDWI-components. The benchmarking process produced a total of 27 analyses.

Table 12 shows the characteristics of the three model dwellings used in the benchmarking procedure.

House types and specifications

	Roof size (m^2)	Tank size in L (DRWH)	Tank size in L (Greywater)	Roof run-off coefficient *	System efficiency (%)	Green roof substrate depth (cm)
Type 1	50	2000	350	0.8	0.8	> 2- 4
Type 2	200	5000	350	0.8	0.8	> 2- 4
Type 3	400	10000	350	0.8	0.8	> 2- 4
	Beds (m^2)	Lawn (m^2)	Dishwasher requirement	Washing machine requirement	Dual flush toilets?	Occupancy
Type 1	5	5	Typical	Typical	No	4
Type 2	10	20	Typical	Typical	No	4
Type 3	30	100	Typical	Typical	No	4

* In the cases where the green roof and rainwater harvesting systems both utilise the entire roof the roof run-off coefficient changes to that of the green roof

Table 12: House types and specifications

The nine configurations used in the benchmarking procedure are presented in Table 13.

Configurations					
	% of roof as green roof	% of roof used for rainwater harvesting	End-uses used for greywater re-use	End uses for DRWH	End-uses for greywater re-use
I	No green roof	No DRWH	No re-use	-	-
II	50	50	Bathroom basin and bath	Toilet flushing and washing machine	Irrigation
III	100	100	All sources	All class 1 end-uses	All class 2 and 3 end-uses
IV	No green roof	100	No re-use	Total domestic demand	-
V	100	No DRWH	No re-use	-	-
VI	No green roof	No DRWH	All sources	-	All class 2 and 3 end-uses
VII	100	100	No re-use	Total domestic demand	-
VIII	No green roof	100	All sources	All class 1 end-uses	All class 2 and 3 end-uses
IX	100	No DRWH	All sources	-	All class 2 and 3 end-uses

Table 13: Configurations

Configurations were selected with different combinations of components and levels of implementation. The configurations were selected in this manner as to reveal the affect of individual components on the final rating. Some of the results from the benchmarking process are presented in Figure 21. All benchmarking results are included in this thesis in Appendix C.

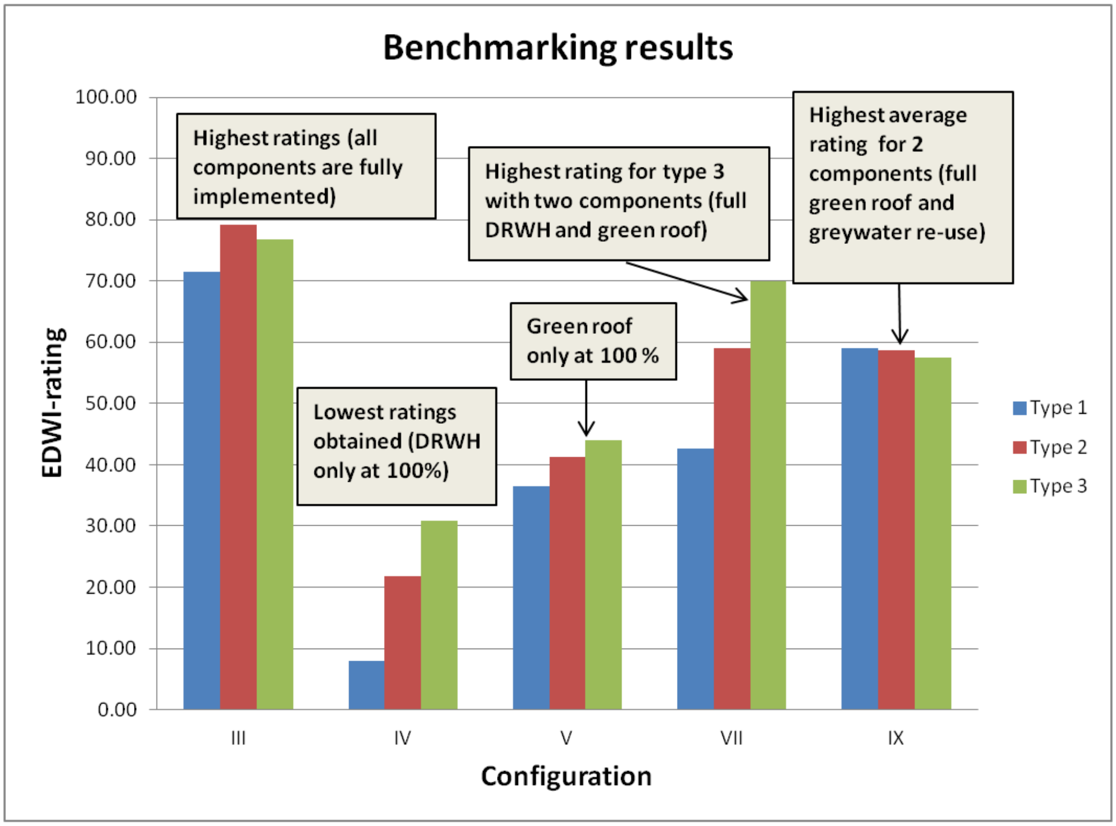


Figure 21: Benchmarking results

Configuration III produces the highest EDWI-rating for all dwelling types, as expected due to this configuration implementing all components to their fullest extent. The lowest single component configuration was found to be configuration IV that only implements rainwater harvesting. Configuration V produces the highest EDWI-ratings of all single component configurations. Green roofs are fully implemented in configuration V. Further, configuration IX (full green roof and greywater re-use) produces the highest average ratings of all configurations implementing two components fully. The highest rating for dwelling type 3 implementing two components fully is obtained with configuration VII which implements rainwater harvesting and a green roof fully.

The final chapter provides a discussion on the results presented in this chapter. Conclusions are drawn and recommendations for future work are provided.

9. Discussions and conclusion

9.1 Discussion

9.1.1 The sustainability index examined

It is the subjective opinion of the author that the EDWI-system forms a tangible base for dwelling owners to decide to what extent to incorporate the EDWI-components and further provides a better understanding of the possible effects of doing so. Dwelling owners are now able to test different levels of implementation and observe the change to the EDWI-rating quickly and easily. Municipalities can use the EDWI-system to assess the effects of the proposed techniques and advise residents to the most effective solution for their given area in order to lower domestic demand. If successful this will relieve some of the stress experienced by their water services.

From the comparative analysis presented in section 8.2 it can be concluded that the region that the dwelling is located in has a large effect on the final optimised solution. The analysis indicates the strong link between supply and the demand that needs to be considered when selecting systems and their uses. This point is emphasised by the results obtained in the Durban dwelling's greywater system's characteristics. The Durban dwelling's greywater system obtained an water savings efficiency of 97.30 %, but the system only supplies 5.25 % of total domestic demand. This indicates that the demand imposed on the greywater system is too low to justify the large resource (greywater) used to satisfy it. In the case of the Durban dwelling it can therefore be concluded that the greywater system should be used to meet more than just irrigation demand so that the resource is better utilised. The Cape Town dwelling shows the other end of the scale. In the case of the Cape Town dwelling's demand which is too varied and high to be met with the greywater system alone as its greywater system achieves an water savings efficiency of 26.78 % while providing 8.63 % of total domestic demand.

The benchmarking procedure reported in section 8.3 produced model EDWI-ratings for three broadly defined dwelling types. The selection of configurations used further allows for the evaluation of the effect of each of the EDWI-components. The benchmarked results reported in this thesis can be used to evaluate and be compared to any similar index that may be developed in future.

9.1.2 Shortcomings of the developed index

The EDWI-system, being a sustainability index, attempts to reflect all areas of sustainability. Perhaps one of the most important components of sustainability not included in the EDWI-system is the cost of these components. This shortcoming is reflected in results obtained with the benchmarking process presented in section 8.3. When the results for configuration V are examined, refer to Table 14, it is clear that green roofs have the largest effect on the final rating of all components. This point is reflected when examining the configurations implementing one component fully (configuration IV, V and VI), the green roofs option produce the highest EDWI-ratings for all dwelling types. These results are likely to change if the large construction costs associated with green roofs were to be included in the calculation of an EDWI-rating.

The minimum water treatment requirements for specific end-uses are not included in the scope of this study. Currently the EDWI-index classifies water quality requirements in general groups. This method may produce a rating that does not reflect all complexities at the required depth.

Leaks are not included in the EDWI-system. In dwellings where leaks occur this assumption is likely to produce demand estimates that will be lower than measured data at the dwelling. The more leaks a given dwelling has, the more severe the consequences to the demand estimated by the system and accordingly to the EDWI-rating.

9.2 Future work

9.2.1 Incorporating cost into the rating system

The EDWI-system, as is, makes no mention of the potential cost, savings or a payback period that will be incurred. This limitation implies that the final rating depends on the system’s physical performance and the efficiency of the system. While these results will, as first intended, show how dependence on municipal water services can be reduced, adding the element of cost associated with the installation and maintenance of a system will produce a more realistic rating for practical application. For this reason it is proposed that these costs should be included in the EDWI-system. This can be achieved by firstly estimating the construction costs. The next step is to relate water savings associated with municipal bills to physical rates that are applied by the municipality. Annual operational and maintenance costs will then be required. By means of a cost analysis it will then be possible to add a monetary component to the EDWI-rating. This improved rating will then allow an efficient and cost effective decision making process.

9.2.2 Green roof test site

The table used to obtain retention and run-off coefficients in the EDWI-system are adopted from the FLL (2002) guidelines. While these values, associated with substrate depths, can be considered as conservative, the EDWI-rating would be greatly benefited if this table was replaced with a similar one based on South African green roof data. For this reason it is proposed that green roof test sites should be created to obtain data of this nature for local conditions.

However, because of the noticeable differences between different geographical regions in South Africa one test site, while a step in the right direction, will not be an accurate representation for all regions. It is therefore further proposed that different regions should be used for green roof test sites, perhaps according to the MAE and MAP.

9.2.3 Incorporating minimum quality classifications for end-uses

The EDWI-index, as is, uses a very simplified water quality classification. Assigning individual quality requirements for each of the end-uses will produce a model that could represent reality with more accuracy. As part of future work the minimum water treatment required for each application should be included, since it would impact the developed EDWI-index by integrating it to the model.

9.3 Conclusion

The EDWI-system provides a conceptual foundation for evaluating sustainable water services to South African households in serviced urban areas. This novel index was developed as a part of this research project. Subsequent benchmarking values were presented as a basis for future work. With further development of the index its practical application could be extended to act as a national barometer, used to compare decentralised water services in terms of sustainability.

10. Reference list

Al-Jayyousi, O. 2003. Greywater reuse: towards sustainable water management. *Desalination*, **156**: 181-192.

Appl, R. & Ansel, W. 2004.Future Oriented and Sustainable Green Roofs in Germany. Green roofs for sustainable communities. Greening rooftops for sustainable communities, Portland, 2-4 June 2004.

Baumann, N. 2006 .Ground-Nesting Birds on Green Roofs in Switzerland: Preliminary Observations. *Urban Habitats*, **4**(1): 37-50.

Berghage, R. D. Beattie, A. Jarrett, C. Thurig, F. Razaei, & Oconnor, T. 2009. *Green Roofs for Stormwater Runoff Control*. U.S. Environmental Protection Agency. EPA/600/R-09/026, Washington DC.

Björk, D.F. 2004. *Green roofs effect on durability of roof membranes*. International green roof institute, Publication number 006. Malmö, Sweden.

Blackhurst, M. Hendrickson, & C. Matthews, H.S. 2010. Cost-Effectiveness of Green Roofs. *Journal of Architectural Engineering*, **16**(4): 136-143.

Borooah, A. 2006. Green roof construction standard for Toronto. World Organization of Building Officials Seventh World Congress, Toronto.

Brenneisen, S. 2006. Space for Urban Wildlife: Designing Green Roofs as Habitats in Switzerland. *Urban Habitats*, **4**(1): 27-36.

Building and Construction Authority of Singapore (BCA). 2004. *Guidelines on envelope thermal transfer value for buildings*. Building and Construction Authority, Singapore

Canadian Policy Research Initiative (PRI). 2007. *Canadian Water Sustainability Index (CWSI)*. PRI Project Sustainable development, ISBN 978-0-662-45045-0, Canada.

Carden, K. Armitage, N. Winter, K. Sichone, O. Rivett, U. & Kahonde, J. 2007a. The use and disposal of greywater in the non-sewered areas of South Africa: Part 1 – Quantifying the greywater generated and assessing its quality. *Water SA*, **33**(4): 425-432.

Carden, K. Armitage, N. Winter, K. Sichone, O. Rivett, U. & Kahonde, J. 2007b. The use and disposal of greywater in the non-sewered areas of South Africa: Part 2 – Greywater management options. *Water SA*, **33**(4): 433-442.

Castleton, H.F. Stovin, V. Beck, S.B.M. & Davison, J.B. 2010. Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings*, **42**: 1582–1591.

Catano, N. Marchand, M. Staley, S. & Wang, Y. 2009. *Development and validation of the watershed sustainability index (WSI) for the watershed of the Reventazón river*. Report prepared for the Commission for the Preservation and Management of the Watershed of the Reventazón River, Costa Rica.

Christova-Boal, D. Eden, R.E. & McFarlane, S. 1996. An investigation into greywater reuse for urban residential properties. *Desalination*, **106**: 391-379.

CSIR. 1983. Guidelines for the provision of engineering services in residential townships (Blue Book). Compiled for the Department of Community Development.

De Carvalho, S.C.P. Carden, K.J. & Armitage, N.P. 2009. Application of a sustainability index for integrated urban water management in Southern African cities: case study comparison – Maputo and Hermanus. *WaterSA*, **32**(2).

Del Barrio, E.P. 1997. Analysis of the green roofs cooling potential in buildings. *Energy and Buildings*, **27**: 179-193.

Dixon, A. Butler, D. & Fewkes, A. 1999. Water saving potential of domestic water reuse systems using greywater and rainwater in combination. *Water science and technology*, **38**(4): 25-32.

Downs, J. 2002. Water Sensitive Urban Design Guidelines. Reviewed by Davies, R. PPK Environment & Infrastructure, Melbourne.

Dunnett, N. & Clayden, A. 2007. *Rain gardens: Managing water sustainably in the garden and* *designed landscapes*. Portland: Timer Press.

Dunnett, N. & Kingsbury, N. 2004. *Planting Green Roofs and LivingWalls*. Portland Oregon, Timber Press.

Evans, C.A. Coombes, P.J. & Dunstan, R.H. 2006. Wind, rain and bacteria: The effect of wather on themicrobial composition of roof-harvested rainwater. *Water Research*, **40**(1): 37-44.

Evans, C.A. Coombes, P.J. Dunstan, & R.H. Harrison, T. 2009.Extensive bacterial diversity indicates the potential operation of a dynamic micro-ecology within domestic rainwater storage systems. *Science of the total Environment*, **407**(19):5206-5215.

Faruqui, N. & Al-Jayyousi, O. 2002. Greywater Reuse in Urban Agriculture for Poverty Alleviation A Case Study in Jordan. *International Water Resources Association*, **27**(3): 387-394.

Fewkes, A. & Butler, D. 2000. Simulating the performance of rainwater collection and reuse systems using behavioural models. *Building Serv. Eng. Res. Technol*. **21**(2): 99-106.

Fewkes, A. & Ferris, S.A. 1982. The recycling of domestic waste water. A study of the factors influencing the storage capacity and the usage patterns. *Building and Environment*, **17**(3): 209-216.

Fewkes, A. & Warm, P. 2000. Method of modelling the performance of rainwater collection systems in the United Kingdom. *Building Services Engineering Research and Technology*, **2**(4): 275-265.

Fewkes, A. 1996. Field testing of a rainwater collection and reuse system. *Proc. Of Water Recyclying: Technicla and Social Implications*, IChemE, London.

Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau(FLL). 2002. *Guideline for planning, Execution and Upkeep of Green Roof Sites*. Published by Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau, Bonn.

Ghisi, E. & de Oliveira, S.M. 2007. Potential for potable water savings by combining the use of rainwater and greywater in houses in southern Brazil. *Building and Environment*, **42**: 1731-1742.

Golden, J.S. 2004. The Built Environment Induced Urban Heat Island Effect in Rapidly Urbanizing Arid Regions - A Sustainable Urban Engineering Complexity. *Environmental Sciences*, **1**(4): 321-349.

Gould, J. & Nissen-Peterson, E. 1999. *Rainwater catchment systems for domestic supply: Design, construction and implementation*. Warwickshire: Intermediate Technology Publications.

Green Roof Organisation (GRO). 2011. *The GRO Roof Code: Green Roof Code of Best Practice for the UK 2011*. Published by the Green Roof Organisation, United Kingdom.

Greenstone, C. 2009. Rooftop gardens and the greening of cities - a case study of UKZN. Unpublished masters thesis: University of Kwazulu-Natal.

Grobler, L.J. 2010. An overview of the Energy Cybernetics Energy Barometer. *Presented at the Energy Efficiency Forum*, Cape Town, South Africa, 14 September 2010.

Gross, A. Azulai, N. Oron, G. Ronen, Z. Arnold, M. & Nejidat, A. 2005. Environmental impact and health risks associated with greywater irrigation: a case study. *Water Science & Technology*, **52**(8): 161 - 169.

Gross, A. Kaplan, D. & Baker, K. 2007. Removal of chemical and microbiological contaminants from domestic greywater using a recycled vertical flow bioreactor (RVFB). *Ecological Engineering*, **31**(2): 107-114.

Hari, J & Krishna, P.E. 2005. *The Texas Manual on Rainwater Harvesting, Third Edition.* Texas Water Development Board. Austin, Texas.

Hoekstra, A.Y. & Chapagain, A.K. 2006. Water footprints of nations: Water use by people as a function of their consumption pattern. *Water Resource Management*, **21**(1): 35-48.

Jackson, R. & Ord, E. 2000. Greywater reuse- benefit or liability? The UK perspective. *Water21*, **2**(3): 38-40.

Jackson, S. Rodda, N. & Salukazana, L. 2006. Microbiological assessment of food crops irrigated with domestic greywater. *Water SA*, **32**(5): 700-704.

Jacobs, H.E. & Haarhoff, J. 2004a. Structure and data requirements of an end-use model for residential water demand and return flow. *Water SA*, **30**(3): 293-304.

Jacobs, H.E. & Haarhoff, J. 2004b. Application of a residential end-use model for estimating cold and hot water demand, wastewater flow and salinity. *Water SA*, **30**(3): 305-316.

Jacobs, H.E. & Van Staden, S. 2008. *Direct on-site greywater reuse- an illicit or illustrious option?* Water Institute of South Africa 2008 Biennial Conference & Exhibition, Sun City, South Africa, 18-22 May 2008.

Jacobs, H.E. 2011. *Sustainability in Urban Drainage*. Sewer system course (8-10 June). Institute for Water and Environmental Engineering, Stellenbosch, University of Stellenbosch.

Jacobs, H.E. Geustyn, L.C. Loubser, B.F. Van der Merwe, B. 2004. Estimating residential water demand in southern Africa. *Journal of the South African Institution of Civil Engineering*. **46**(4): 2-13.

Jacobs, H.E. Wright, T. Loubser, C. Du Plessis, J.A. & Kock, J. 2010. *Strategic assessment of household on-site water as supplementary resource to potable municipal supply* – current trends and future needs. Report to the Water Research Commission by the University of Stellenbosch, WRC Report No. 1891/1/10.

Jefferson, B. Palmer, A. Jeffrey, P. Jeffrey, R. & Jeffrey, S. 2004. Grey water characterisation and its impact on the selection and operation of technologies for urban reuse. *Water science and technology*, **50**(2): 157-164.

Jeppesen, B. 1996. Domestic greywater re-use: Australia's challenge for the future. *Desalination*, **106**(1-3): 311-315.

Kadas, G. 2006. Rare Invertebrates Colonizing Green Roofs in London. *Urban Habitats*, **4**(1): 66-86.

Köhler, M. & Keeley, M. 2005. *Green Roofs: Ecological Design And Construction*., Atglen, PA: Schiffer Books.

Köhler, M. Schmidt, M. Grimme, F.W. Laar, M. Paiva, M. De Assunção, V.L. & Sergio, T. 2002. Green roofs in temperate climates and in the hot-humid tropics - far beyond the aesthetics. *Environmental Management and Health*, **13**(4): 382-391.

Latham, B.G. 1983. The design of single-purpose reservoirs. MASc thesis, University of Canada.

Lewis, C.A. 1995. Human health and well-being: The psychological, physiological, and sociological effects of plants on people. *Horticulture in Human Life*, **391**: 31-39.

Liaw, C.H. & Tsai, Y.L. 2004. Optimum storage volume of rooftop rain water harvesting systems for domestic use. *Journal of the American Water Resources Association (JAWRA)*, **40**(4): 901-912.

Liu, K. & Minor, J. 2005. Performance evaluation of an extensive green roof. Greening Rooftops for Sustainable Communities, 1-11.

Lohr, V.I. & Pearson-Mims, C.H. 2000. Physical discomfort may be reduced in the presence of interior plants. *HorTechnology*, **10**(1): 53-58.

Luckett, K. 2009. *Green roof construction and maintenance*. New York : McGraw-Hill.

Mabotja, K. 2011. Going green in the inner city. Availible on the official website of the city of Johannesburg.[Online].http://www.joburg.org.za/index.php?option=com_content&view=article&id=7342&catid=88&Itemid=266 [1 November, 2011].

Maller, C. Townsend, M. & Pryor, A. 2006. Healthy nature healthy people: "contact with nature" as an upstream health promotion intervention for populations. *Health promotion international*, **21**(1): 45-54.

Mayer, P.W. DeOreo, W.B. Opitz, E.M. Kiefer, J.C. Davis, W.Y. Dziegielewski, B. & Nelson, J.O. 1999. Residential End Uses of Water. Published by the AWWA Research Foundation and American Water Works Association, USA.

Mays, L.W. 2009. Integrated urban water management: arid and semi-arid regions. International hydrological programme. *Urban water series*, **3**. UNESCO.

McMahon, T.A. & Mein, R.G. 1978. *Reservoir capacity and yield*. Developments in water science. Amsterdam: Elsevier.

McMichael, A.J. 2000. The urban environment and health in a world of increasing globalisation: issues for developing countries. *Bulletin of the World Health Organization*, *78*(9): 1117-1126.

Mebratu, D. 1998. Sustainability and sustainable development: historical and conceptual review. *Environmental Iimpact Assessment Review*, **18**: 493–520.

Memon, F.A. & Butler, D. 2006. *Water demand management*. IWA Publishing, London.

Mendez, C.B. Klenzendorf, J.B. Afshar, B.R. Simmons, M.T. Barrett, M.E. Kinney, K.A. & Kirisits, M.J. 2011. The effect of roofing material on the quality of harvested rainwater. *Water Research*, **45**:2049-2059.

Mentens, J. Raes, D. & Hermy, M. 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning*, **77**(3): 217-226.

Meyer, J.P. 2000. A review of domestic hot-water consumption in South Africa. *R & D Journal*, **16**(3): 55-61.

Midgley, D.C. Pitmann, W.V. & Middleton, B.J. 1994. Surface Water Resources of South Africa. Report Number 298/5.1/94, compiled for the Water Research Commission by the University of Witwatersrand.

Moran, A.C. Hunt, W.F. & Jennings, G.D. 2004. A North Carolina Field Study to Evaluate Green Roof Quantity, Runoff Quality, and Plant Growth. Portland, Oregon: *In Proceedings of Green Roofs for Healthy Cities Conference*.

Morel, A. & Diener, S. 2006. Greywater management in low and middle-income countries, Review of different treatment systems for households or neighbourhoods. Swiss Federal Institute of Aquatic Science and Technology (EAWAG). Dübendorf, Switzerland.

Nolde, E. 1999. Greywater reuse systems for toilet flushing in multi-storey buildings ± over ten years experience in Berlin. *Urban water*, **1**: 275-284.

Ogoshi, M. Suzuki, Y. & Asano, T. 2000. Non-potable urban water reuse- a case of Japanese water recycling. *Water21*: 27 - 30.

Osmundson, T.H. 1999. *Roof gardens: history, design, and construction*. Ney York, Norton.

Pinto, U. Maheshwari, B.L. & Grewal, H.S. 2010. Effects of greywater irrigation on plant growth, water use and soil properties. Resources, *Conservation and Recycling*, **54**: 429 - 435.

Rees, W.E. 1992. Ecological footprints and appropriated carrying capacity: what urban economics leave out. *Environment and Urbanization*, **4**(2): 121-130.

Rippl, W. 1883. The capacity of storage reservoirs for water supply. *Proc. Inst. Civil Engineers* **17**(1): 270-278.

Robèrt, K. Schmidt-Bleek, B. Aloisi de Lardere, J. Basile, G. Jansen, J.L. Kuehr, R. Price Thomas, P. Suzuki, M. Hawken, P. & Wackernagel, P. 2002. Strategic sustainable development — selection, design and synergies of applied tools. *Journal of Cleaner Production*, **10**(3): 197-214.

Rodda, N. Carden, K. Armitage, N. & du Plessis, H.M. 2010. Guidelines For Sustainable Use Of Greywater In Small-Scale Agriculture And Gardens In South Africa. *Presented at the Water institute of South Africa 2010 Biennial Conference & Exhibition*, Durban, South Africa, 18-22 April 2010.

Rodda, N.Salukazana, L. Jackson, S.A.F. & Smith, M.T. 2011. Use of domestic greywater for small-scale irrigation of food crops: Effects on plants and soil. *Physics and Chemistry of the Earth*, **36**:1051–1062.

Rudolph, M. Ruysenaar, S. Dlamini, T. & Kroll, F. 2009. Food Security, Poverty and Health in Three Study Areas in Johannesburg. Unpublished Report for AFSUN, Cape Town.

Salukazana, L. Jackson, S. Rodda, N. Smith, M. Gounden, T. McLeod, N. & Buckley, C. 2005. Re-use of grey water for agricultural irrigation. *Paper presented at the Third international conference on ecological sanitation*, Durban, South Africa, 23-26 May 2005.

Short, D. & Colmer, T. 1999. Update on Western-Australia Water Use Study: A Comparison of Eleven Turf Grass Genotypes during Summer in Perth. University of Western Australia, November.

Snodgrass, E.C. & McIntyre, L. 2010. *Green Roof Manual*. Portland: Timber Press.

Sutton, P. 2000. Sustainability: What does it mean? [Online]. Available: http://www.green-innovations.asn.au/sustblty.htm [2011, June 25].

Teemusk, A. & lo Mander, U. 2009. Greenroof potential to reduce temperature fluctuations of a roof membrane: A case study from Estonia. *Building and Environment*, **44**: 643–650.

The council of the South-African bureau of standards (SABS). 1990. The Application of the South-African building regulations. Published by SABS Standards Division. Groenkloof, Pretoria

The council of the South-African National Standards (SANS). 2010. 204, Energy efficiency in buildings. Published by SANS Standards Division. Groenkloof, Pretoria.

U.S. Environmental Protection Agency (EPA). 2004. Guidelines for water reuse. EPA/625/R-04/108 , Washington DC.

U.S. Environmental Protection Agency (EPA). 2008. Reducing urban heat islands: Compendium of strategies. Urban heat island basics.

Van Zyl, H.J. Ilemobade, A.A. & Van Zyl, J.E. 2008. An improved area-based guideline for domestic water demand estimation in South Africa. *Water SA*, **34**(3): 381- 392.

VanWoert, N.D. Rowe, D.B. Andresen, J.A. Rugh, C.L. Fernandez, R.T. & Xiao, L. 2005. Green Roof Stormwater Retention: Effects of Roof Surface, Slope, and Media Depth. *Journal of Environmental Quality*, **34**: 1036–1044.

Voyde, E. Fassman, E. Simcock, R. & Wells, J. 2010. Quantifying Evapotranspiration Rates for New Zealand Green Roofs. *Journal of hydrologic engineering*, **15**(6): 395-403.

Waldbaum, H. N.d.. Comparison between the German (FLL), Austrian and Siwiss green roof directives/guidelines. Availible at www.Livingroofs.org.

Water Research Commission (WRC). N.d.. South Africa rain atlas. [online]. Availible: http://134.76.173.220/rainfall/index.html [2011, September 13].

Water Rhapsody. N.d.. Rules of Grey water. Availible at: http://www.waterrhapsody.co.za/grey-water- systems/rules-of-grey-water/ [2011, March 29].

White, E.V. & Gatersleben, B. 2011. Greenery on residential buildings: Does it affect preferences and perceptions of beauty? *Journal of Environmental Psychology*, **31**: 89-98.

Wong, N.H. Chen, Y. Ong, C.L. & Sia, A. 2003a. Investigation of thermal benefits of rooftop garden in the tropical environment. *Building and Environment*, **38**: 261–270.

Wong, N.H. Cheong, D.K.W. Yan, H. Soh, J. Ong, C.L. & Sia, A. 2003b. The effects of rooftop garden on energy consumption of a commercial building in Singapore. *Energy and buildings*, **35**: 353-364.

World Commission on Environment and Development. 1987. *Our Common Future*. Oxford University Press, Oxford.

World Health Organisation (WHO). 2006. WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater, Volume IV, Excreta and Greywater Use in Agriculture. WHO Press. Geneva, Switzerland.

Yaziz,M.I. Gunting, H. Sapari, N. & Ghazali, A.W. 1989. Variations in rainwater quality from roof catchments. *Water Research*, **23**(6): 761-765.

Appendix A: User manual

This user manual contains all the steps required to analyse a dwelling in the EDWI-software tool developed in conjunction with the thesis. Before any dwelling is assessed it is important that some attention be given to a few technical details.

Leaks

Leaks are not included in the EDWI-software tool and in accordance with this the software assumes there are no leaks. For this reason it is recommended that before a dwelling is simulated, some attention should be paid to the areas which are known to produce leaks.

The two main causes of leaks are (Mayer et al., 1999):

- Bib leaks caused by faulty facets
- Leaks originating due to faulty toilet flaps.

To verify that no leaks are present in a dwelling the user can perform a simple test. This is done by closing all taps and verifying that all toilet bowls and water heaters are full, not being filled. If this is done correctly there should be no water demand from the dwelling. The user can then verify that there are no leaks by seeing if any flow is being logged by the plots water meter, normally located close to the street.

Definition of irrigation area

Irrigation areas can either be beds or lawns. The EDWI-software tool assumes that all lawns are planted with Kikuyu grass and all beds are representative of the region's natural veld type as described by Midgley et al (1994). To validate the use of natural veld types it is important to apply Xeriscaping principles to all irrigated beds.

Storage volumes for greywater and combined systems

To assure that a grey- or combined system functions correctly and without unwanted odours it is important to minimise retention time. For this reason it is proposed that greywater systems should be sized relative to the average daily greywater produced by end-uses considered for re-use. When a system receives 300 L a day on average of greywater it is recommended that a tank size not smaller than 300 L or larger than 350 L be selected. Refer to section 5.3 in the thesis for a detailed discussion on this topic.

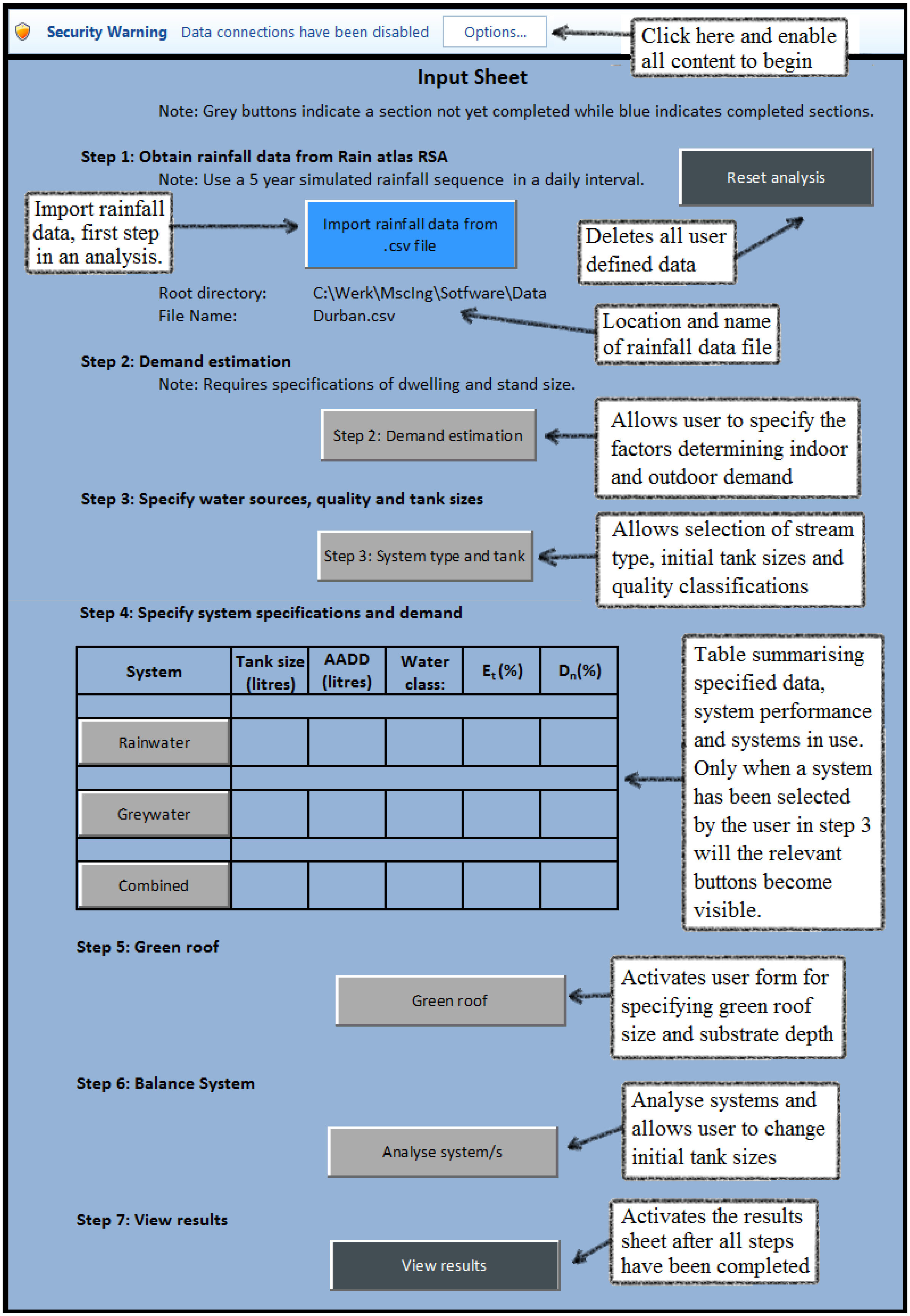
Combined systems can be seen as being very similar to greywater systems. It is therefore proposed that the same approach be used for the selection of tank size. However, if adequate treatment is applied, larger storage volumes can be selected but this might result in complicated and expensive treatment systems. As shown in section 8.1 in the thesis no improvement is seen after adding rainwater to a greywater system at low storage volumes.

Modelling a dwelling with the EDWI-software tool

The EDWI-software tool contains a total of seven sheets. They are the “input sheet”, “results sheet”, “behavioural model sheet”, “demand estimation sheet” and sheets for each of the three EDWI-components. The “input sheet” is the first sheet and controls all the steps required to perform an analysis, refer to Figure A 1.

After an analysis has been completed all results are summarised in the “results sheet”, refer to Figure A 17. The sheets for each of the three EDWI-components contain characteristics such as sources of greywater, roof sizes and user defined data such as run-off coefficients and system efficiency.

There are seven steps that need to be completed in order to analyse a dwelling using the EDWI-software tool. All of these steps have to be completed in the correct order, from one to seven. The exception to this rule is in the case where the user indicated the intention to harvest rainwater from a green roof. This is explained in greater detail in a later section. Figure A 1 shows the “input sheet” with all buttons visible.



Click here and enable all content to begin

Input Sheet

Note: Grey buttons indicate a section not yet completed while blue indicates completed sections.

Step 1: Obtain rainfall data from Rain atlas RSA

Note: Use a 5 year simulated rainfall sequence in a daily interval.

Import rainfall data, first step in an analysis.

Deletes all user defined data

Root directory: C:\Werk\MscIng\Sotfware\Data

File Name: Durban.csv

Location and name of rainfall data file

Step 2: Demand estimation

Note: Requires specifications of dwelling and stand size.

Allows user to specify the factors determining indoor and outdoor demand

Step 3: Specify water sources, quality and tank sizes

Allows selection of stream type, initial tank sizes and quality classifications

Step 4: Specify system specifications and demand

System	Tank size (litres)	AADD (litres)	Water class:	E_t(%)	D_n(%)
Rainwater					
Greywater					
Combined					

Table summarising specified data, system performance and systems in use. Only when a system has been selected by the user in step 3 will the relevant buttons become visible.

Step 5: Green roof

Activates user form for specifying green roof size and substrate depth

Step 6: Balance System

Analyse systems and allows user to change initial tank sizes

Step 7: View results

Activates the results sheet after all steps have been completed

Figure A 1: Input sheet

When the user starts the EDWI-software tool, or resets a previous analysis, only the button for step 1 will be visible. On completion of step 1, step 1's button will change colour from grey to blue and the button for step 2 will become visible. Then when step 2 has been completed, its button will also turn from grey to blue and the next step's button will become visible, and so on for all steps.

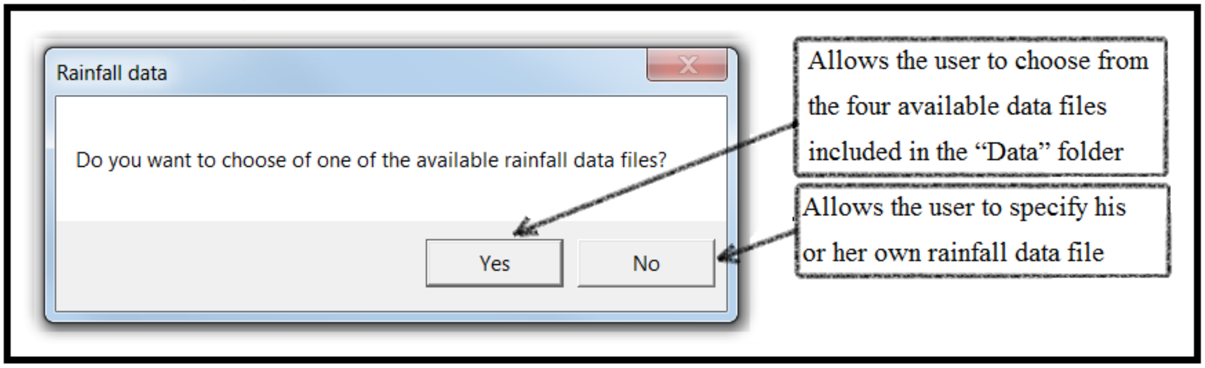
Step 1: Rainfall data

The EDWI-software tool uses a five year stochastic daily rainfall data series to simulate the operation of rainwater collectors. The rainfall data is imported with a ".csv" file. This ".csv" file needs to adhere to the following specifications:

- Data starts at cell A1 in the csv file
- Each row in the csv file contains one year of rainfall data(Thus there will be five rows)
- The data is assumed to start in January (Cell A1 will represent the rainfall on 1 January)
- Daily rainfall must be in millimetres
- Leap years are not included.

When the user opens the EDWI-software tool for the first time, only two buttons will be visible. These are the "Reset" and "Import rainfall data" buttons.

To start the analysis the user first needs to click on the "Import rainfall data" button prompting a user form asking the user if he or she would like to choose from the four rainfall data files included in the "Data" folder included in the CD. These cities are Bloemfontein, Cape Town, Durban and Johannesburg. If the user wishes to use an alternative file he or she needs to click on the "No" option on the form prompted by clicking on the "Import rainfall data" button. This form is presented in Figure A 2. This action will prompt the user form shown in Figure A 4. Alternatively, if the "Yes" option was selected, refer Figure A 3, the user can select one of the four cities previously mentioned. After choosing a city and specifying the root folder location, the rainfall data file can be loaded by clicking on the "Add and Close" button on the user form, Figure A 3.



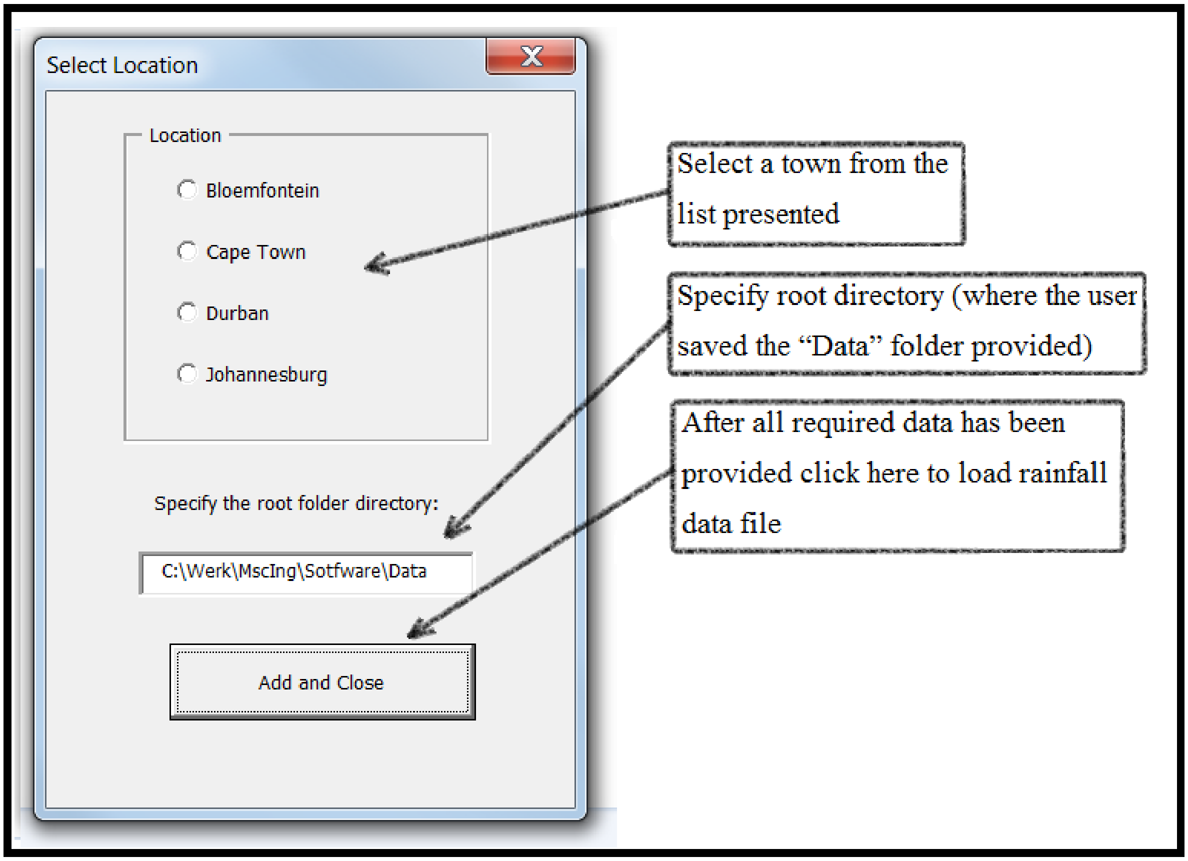
Do you want to choose of one of the available rainfall data files?

Allows the user to choose from the four available data files included in the “Data” folder

Allows the user to specify his or her own rainfall data file

Figure A 2: Rainfall data user form

If the user chooses to use one of the rainfall files included in the Data folder, the form shown in Figure A 3 will pop up. After specifying the location of the data folder and selecting a city the user can click on the “Add and Close” button to load the data file, refer to Figure A 3.



○ Bloemfontein
○ Cape Town
○ Durban
○ Johannesburg

Specify the root folder directory: C:\Werk\MscIng\Sotfware\Data

Select a town from the list presented

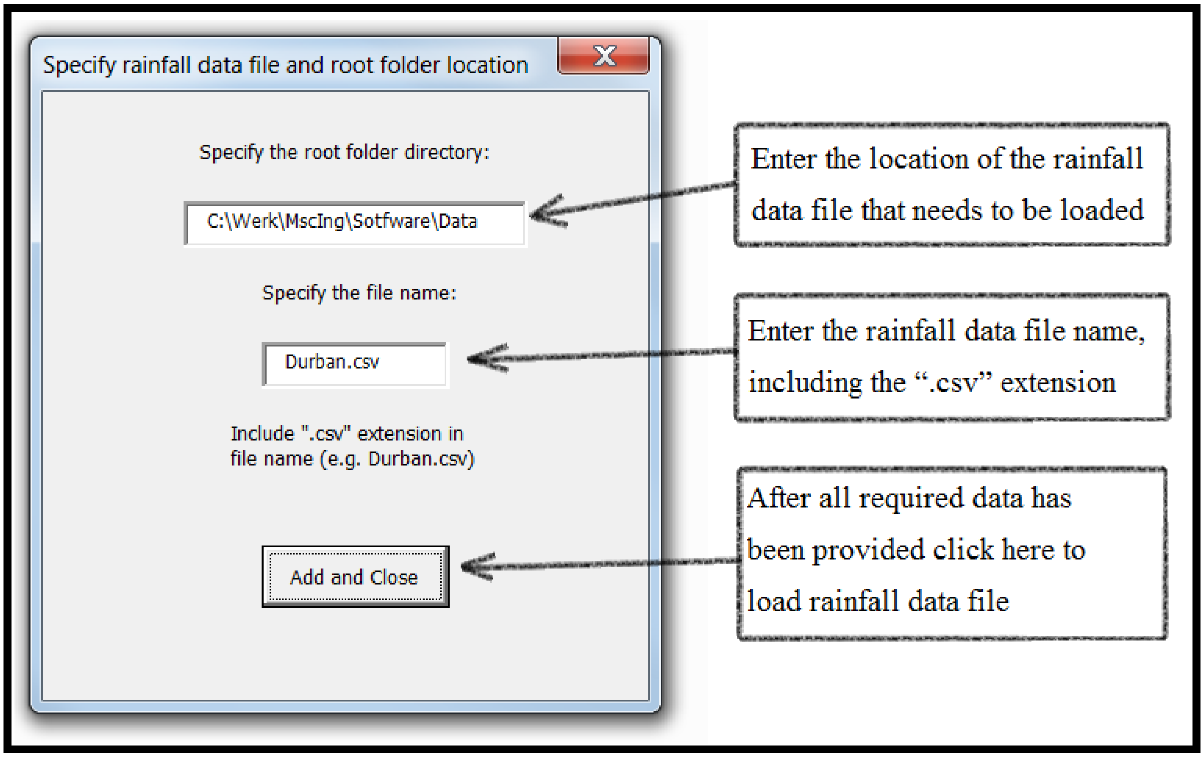
Specify root directory (where the user saved the “Data” folder provided)

After all required data has been provided click here to load rainfall data file

Figure A 3: User form to load included rainfall data

It is important to specify the root directory of the folder where the data files are located, as this may not be the same as the predefined location.

Alternatively the user could choose to use data he or she obtained through some other means. If this option is selected the user form shown in Figure A 4 will pop up.



Specify the root folder directory: C:\Werk\MscIng\Sotfware\Data

Specify the file name: Durban.csv

Include ".csv" extension in file name (e.g. Durban.csv)

Enter the location of the rainfall data file that needs to be loaded

Enter the rainfall data file name, including the ".csv" extension

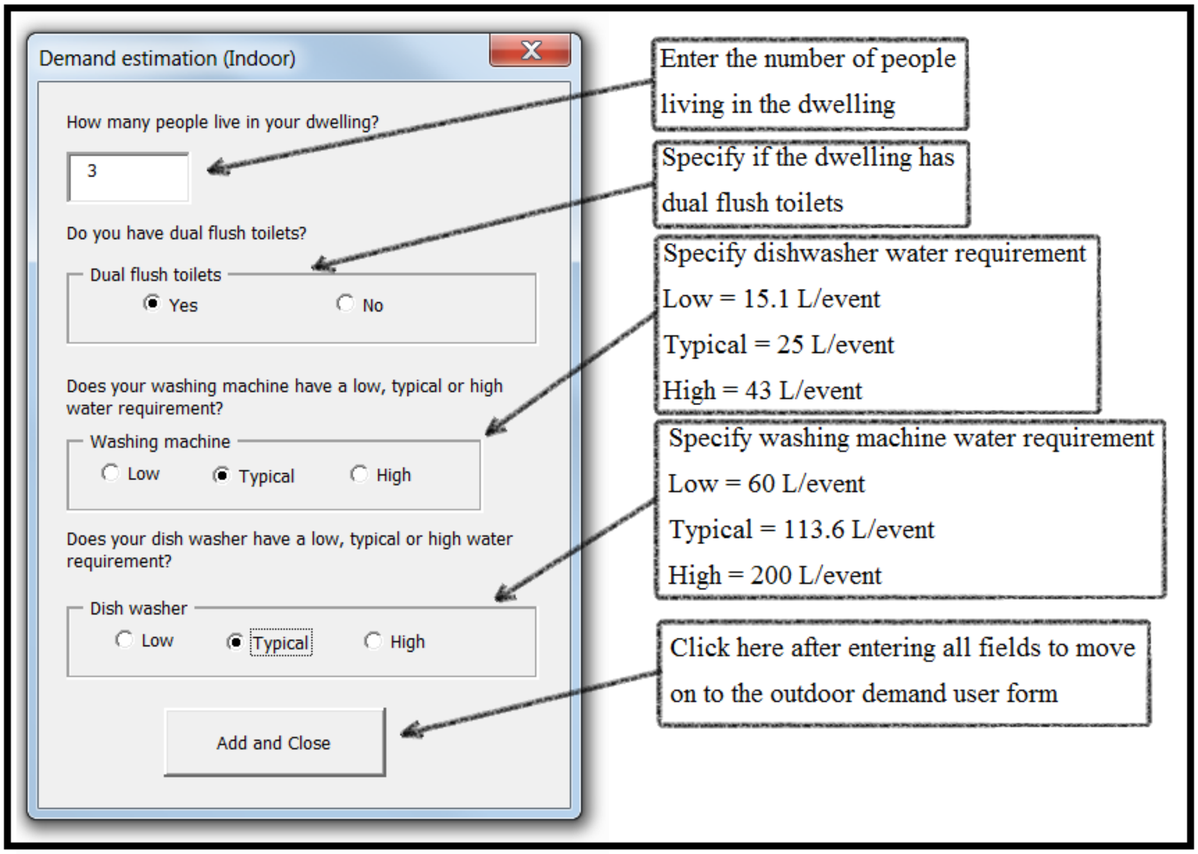
After all required data has been provided click here to load rainfall data file

Figure A 4: User specific data user form

As before it is extremely important to make sure that both the file name and root folder location are entered correctly.

Step 2: Demand estimation

After successfully loading the rainfall data file the next step becomes available. This can be seen as the next button will become visible. The now visible “Demand estimation” button has two parts. First the “Demand estimation (Indoor)” user form will pop up, shown in Figure A 5.



How many people live in your dwelling?
3

Do you have dual flush toilets?
Dual flush toilets: ● Yes ○ No

Does your washing machine have a low, typical or high water requirement?
Washing machine: ○ Low ● Typical ○ High

Does your dish washer have a low, typical or high water requirement?
Dish washer: ○ Low ● Typical ○ High

Enter the number of people living in the dwelling

Specify if the dwelling has dual flush toilets

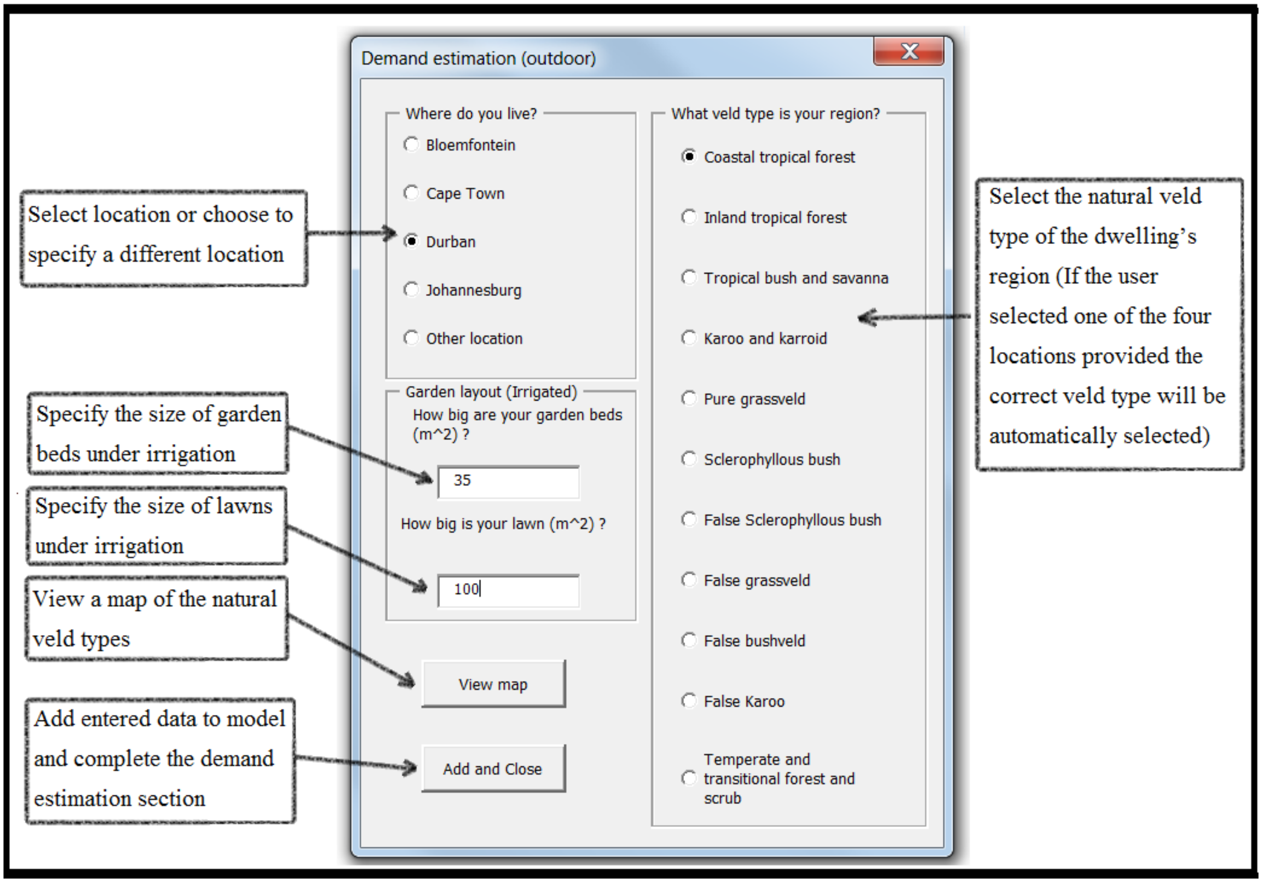
Specify dishwasher water requirement
Low = 15.1 L/event
Typical = 25 L/event
High = 43 L/event

Specify washing machine water requirement
Low = 60 L/event
Typical = 113.6 L/event
High = 200 L/event

Click here after entering all fields to move on to the outdoor demand user form

Figure A 5: Indoor demand user form

After the indoor user form has been completed, the “Demand estimation (Outdoor)” user form will become visible. This is shown in Figure A 6.



Demand estimation (outdoor)

Where do you live?
○ Bloemfontein
○ Cape Town
● Durban
○ Johannesburg
○ Other location

Garden layout (Irrigated)
How big are your garden beds (m^2) ?
35
How big is your lawn (m^2) ?
100

View map

Add and Close

What veld type is your region?
● Coastal tropical forest
○ Inland tropical forest
○ Tropical bush and savanna
○ Karoo and karroid
○ Pure grassveld
○ Sclerophyllous bush
○ False Sclerophyllous bush
○ False grassveld
○ False bushveld
○ False Karoo
○ Temperate and transitional forest and scrub

Select location or choose to specify a different location

Specify the size of garden beds under irrigation

Specify the size of lawns under irrigation

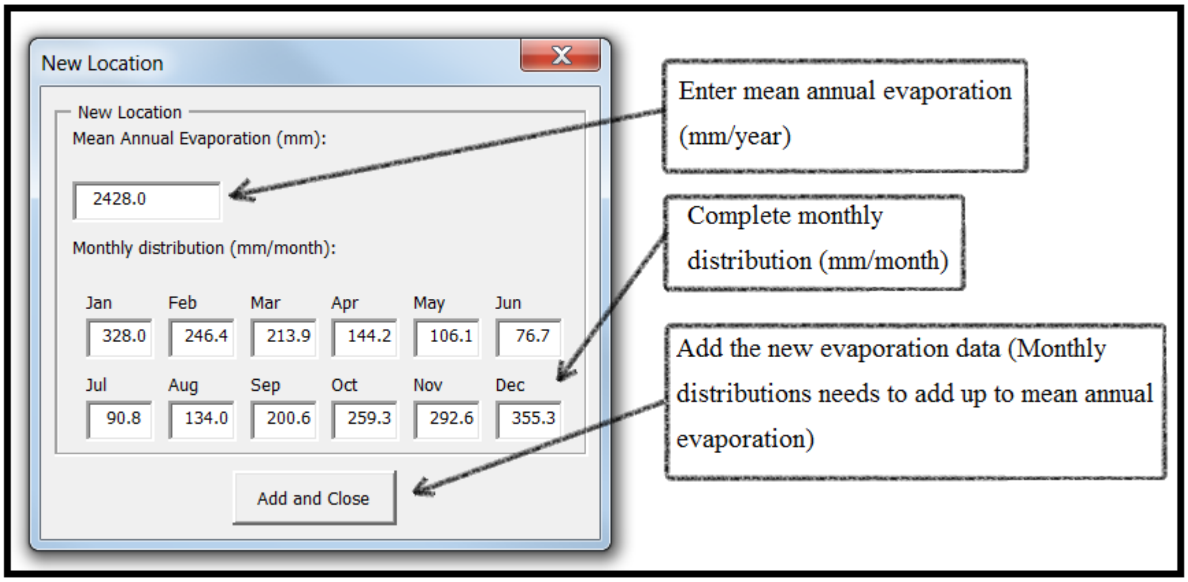
View a map of the natural veld types

Add entered data to model and complete the demand estimation section

Select the natural veld type of the dwelling's region (If the user selected one of the four locations provided the correct veld type will be automatically selected)

Figure A 6: Outdoor demand user form

If the user chooses to specify a different location to those shown in Figure A 6, he or she will also need to specify monthly and MAE for the specific location and select the appropriate natural veld type. In the case of any of the locations included in Figure A 6, evaporation data is automatically provided and the correct veld type selected. Figure A 7 shows the user form that will pop up when the user selects the “Other location” option in Figure A 6.



New Location

Mean Annual Evaporation (mm): 2428.0

Monthly distribution (mm/month):

Jan	Feb	Mar	Apr	May	Jun
328.0	246.4	213.9	144.2	106.1	76.7

Jul	Aug	Sep	Oct	Nov	Dec
90.8	134.0	200.6	259.3	292.6	355.3

Enter mean annual evaporation (mm/year)

Complete monthly distribution (mm/month)

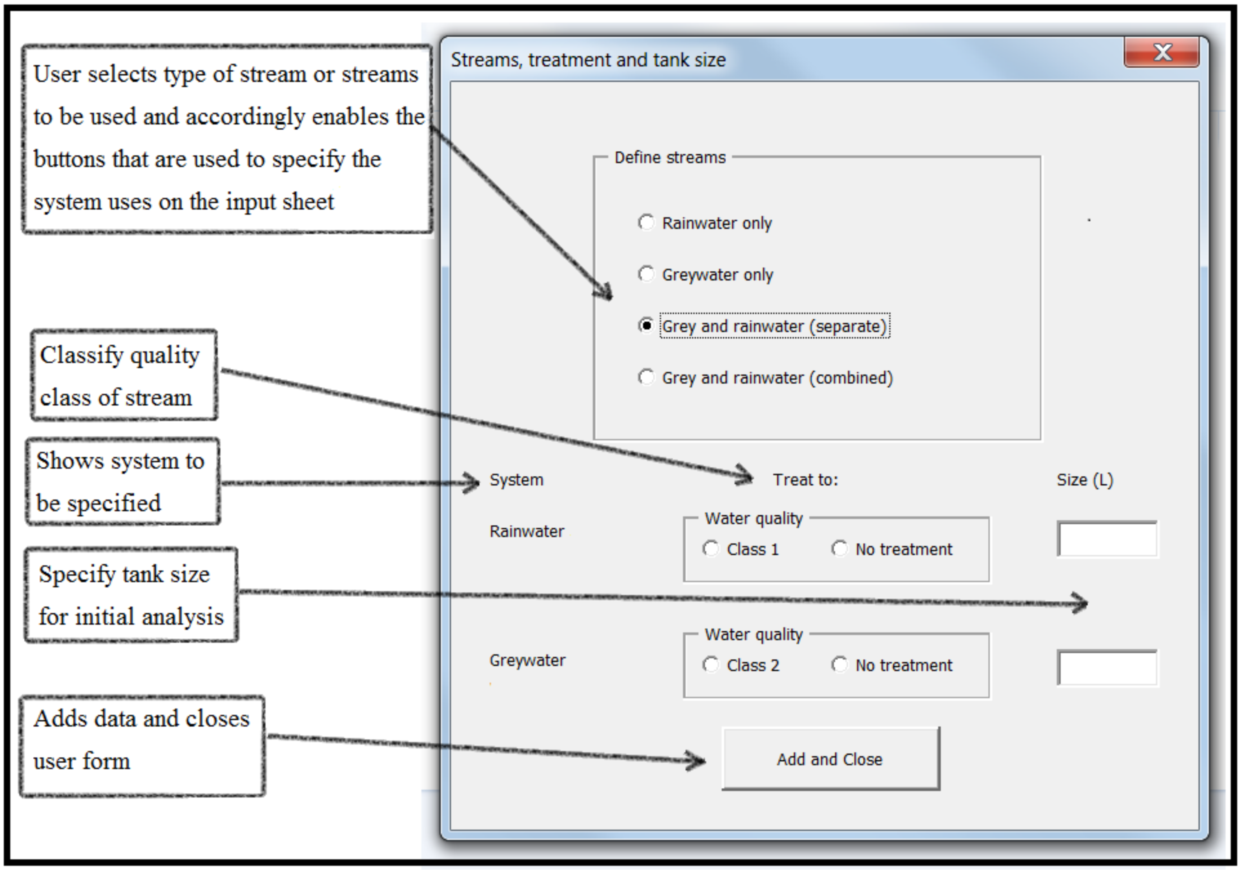
Add the new evaporation data (Monthly distributions needs to add up to mean annual evaporation)

Figure A 7: New evaporation data user form

Step 3: Specifying streams, tank sizes and quality classifications

With the completion of the demand estimation section the next section (specifying streams, tank sizes and quality classes) becomes available.

As seen in Figure A 8 there are four options of streams that could be selected. The quality classifications of the streams are defined in section 6.1 of the thesis and depending on the users selections different applications of these streams will become available.



User selects type of stream or streams to be used and accordingly enables the buttons that are used to specify the system uses on the input sheet

Classify quality class of stream

Shows system to be specified

Specify tank size for initial analysis

Adds data and closes user form

Streams, treatment and tank size

Define streams

○ Rainwater only
○ Greywater only
● Grey and rainwater (separate)
○ Grey and rainwater (combined)

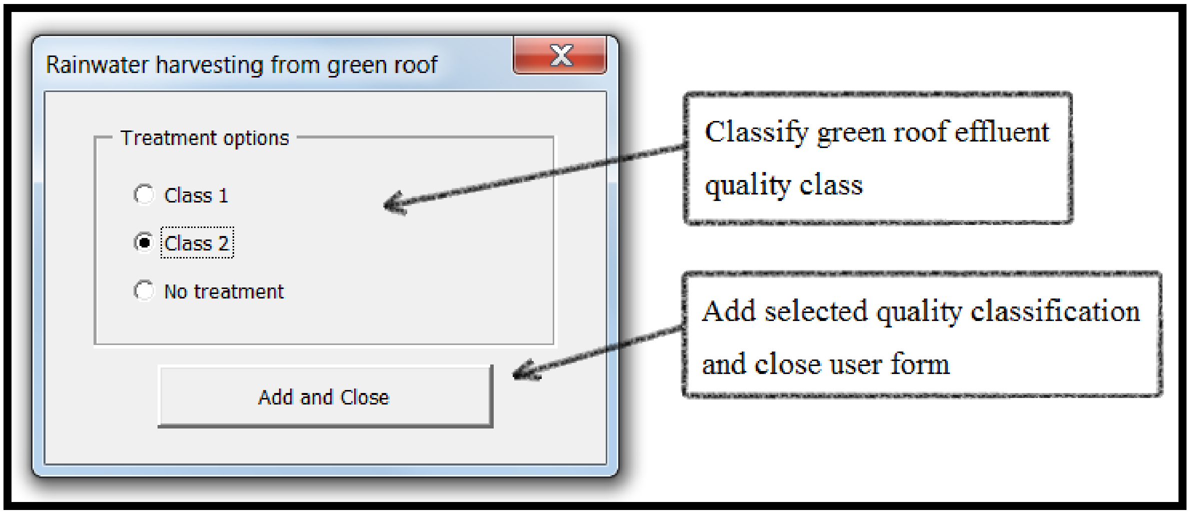
System	Treat to:	Size (L)
Rainwater	Water quality: ○ Class 1 ○ No treatment	
Greywater	Water quality: ○ Class 2 ○ No treatment	

Figure A 8: Streams, treatment and tank size user form

Step 4: Specifying system uses and characteristics

The systems now need to be specified. The systems and types of characteristics that will be required will depend on user’s selection as shown in Figure A 8. As an example of this the user forms for rain and greywater systems are presented in Figure A 10 and A 11 respectively.

For a stream selection such as shown in Figure A 8, the user will need to specify the rainwater system before specifying the greywater system. When the user clicks on the “Rainwater” button on the “input sheet”, a user form similar to Figure A 2 pops up which asks the user if he or she intends to harvest rainwater from a green roof. If the user selects the “Yes” option he or she will have to redefine the water quality class (refer to Figure A 9) as green roof effluent is not automatically classified as being the same as normal roof effluent. This topic is discussed in great detail in section 2.4.4 of the thesis.



Rainwater harvesting from green roof

Treatment options

○ Class 1

● Class 2

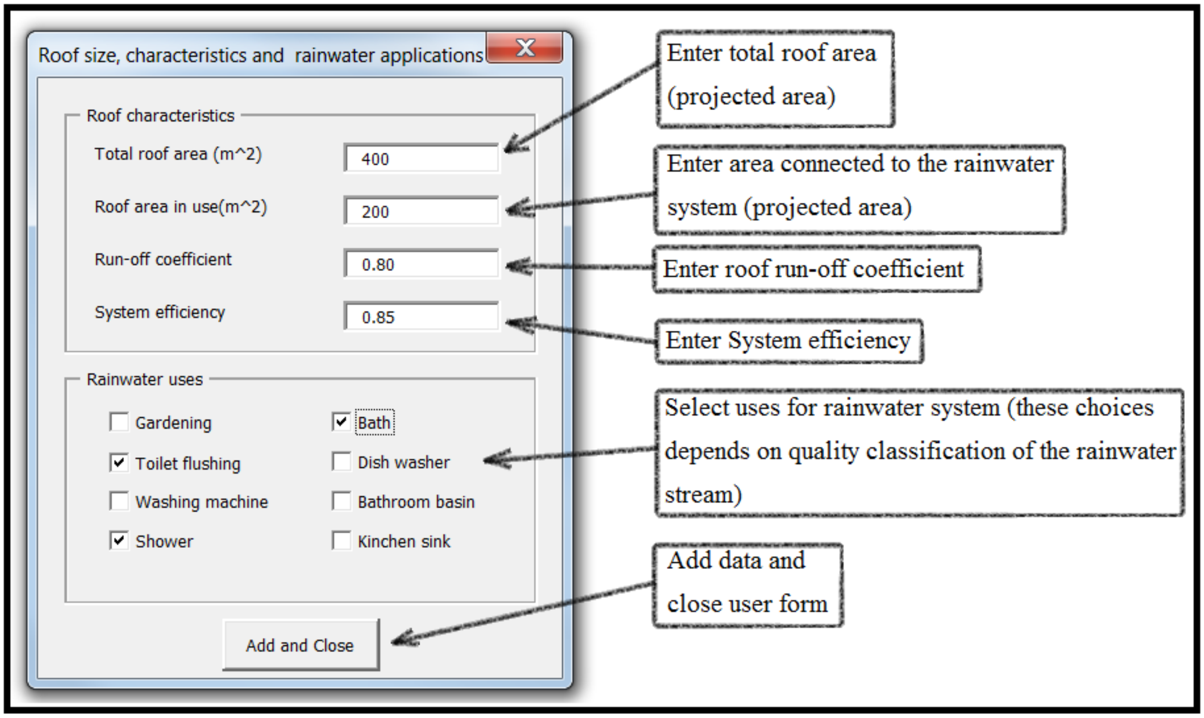
○ No treatment

Classify green roof effluent quality class

Add selected quality classification and close user form

Figure A 9: Rainwater harvesting from green roofs quality user form

After the water quality classification has been verified, the green roof user form pops up. This user form is described later in this document. After completing the green roof user form (see Figure A 13) the rainwater user form (refer to Figure A 10) pops up and will then need to be completed. If the user indicates that he or she does not intend to harvest rainwater from a green roof, the rainwater user form (refer to Figure A 10) will pop up and the green roof will be specified at a later stage.



Roof size, characteristics and rainwater applications

Roof characteristics

Total roof area (m^2) 400

Roof area in use(m^2) 200

Run-off coefficient 0.80

System efficiency 0.85

Rainwater uses

☐ Gardening ☑ Bath

☑ Toilet flushing ☐ Dish washer

☐ Washing machine ☐ Bathroom basin

☑ Shower ☐ Kinchen sink

Enter total roof area (projected area)

Enter area connected to the rainwater system (projected area)

Enter roof run-off coefficient

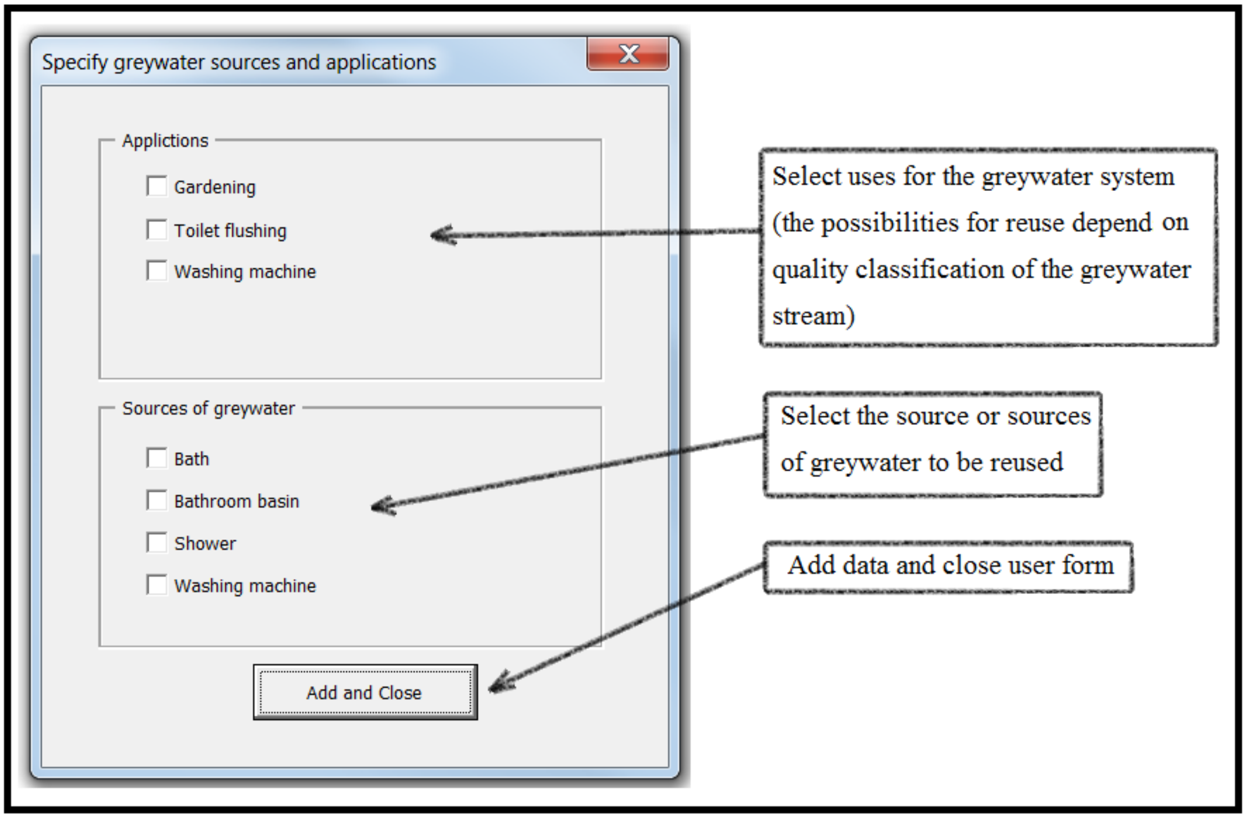
Enter System efficiency

Select uses for rainwater system (these choices depends on quality classification of the rainwater stream)

Add data and close user form

Figure A 10: Rainwater harvesting characteristics user form

After completing the rainwater user form, Figure A 10, the greywater system can be specified (in the case where greywater is selected as a stream). Figure A 11 shows the user form for specifying a greywater system.



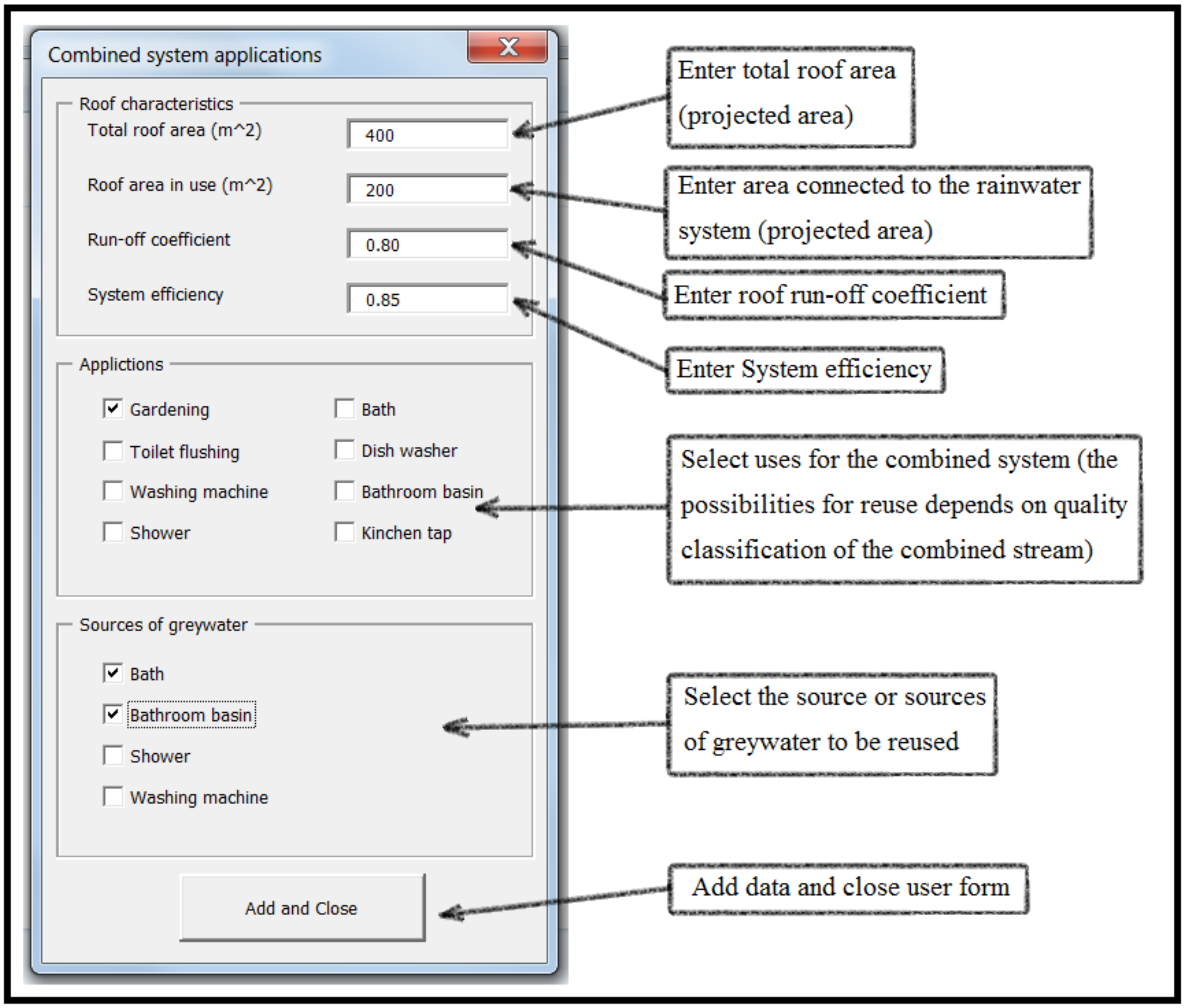
Select uses for the greywater system (the possibilities for reuse depend on quality classification of the greywater stream)

Select the source or sources of greywater to be reused

Add data and close user form

Figure A 11: Greywater sources and applications user form

If the user selects the “Grey and rainwater (combined)” option on Figure A 8, only a combined system will need to be specified. In this case only the “Combined” button will be visible on the “input sheet” and as for any other stream will need to be specified. Figure A 12 shows the combined system user form.



Combined system applications

Roof characteristics

Total roof area (m^2) 400

Roof area in use (m^2) 200

Run-off coefficient 0.80

System efficiency 0.85

Applictions

☑ Gardening ☐ Bath
☐ Toilet flushing ☐ Dish washer
☐ Washing machine ☐ Bathroom basin
☐ Shower ☐ Kinchen tap

Sources of greywater

☑ Bath
☑ Bathroom basin
☐ Shower
☐ Washing machine

Enter total roof area (projected area)

Enter area connected to the rainwater system (projected area)

Enter roof run-off coefficient

Enter System efficiency

Select uses for the combined system (the possibilities for reuse depends on quality classification of the combined stream)

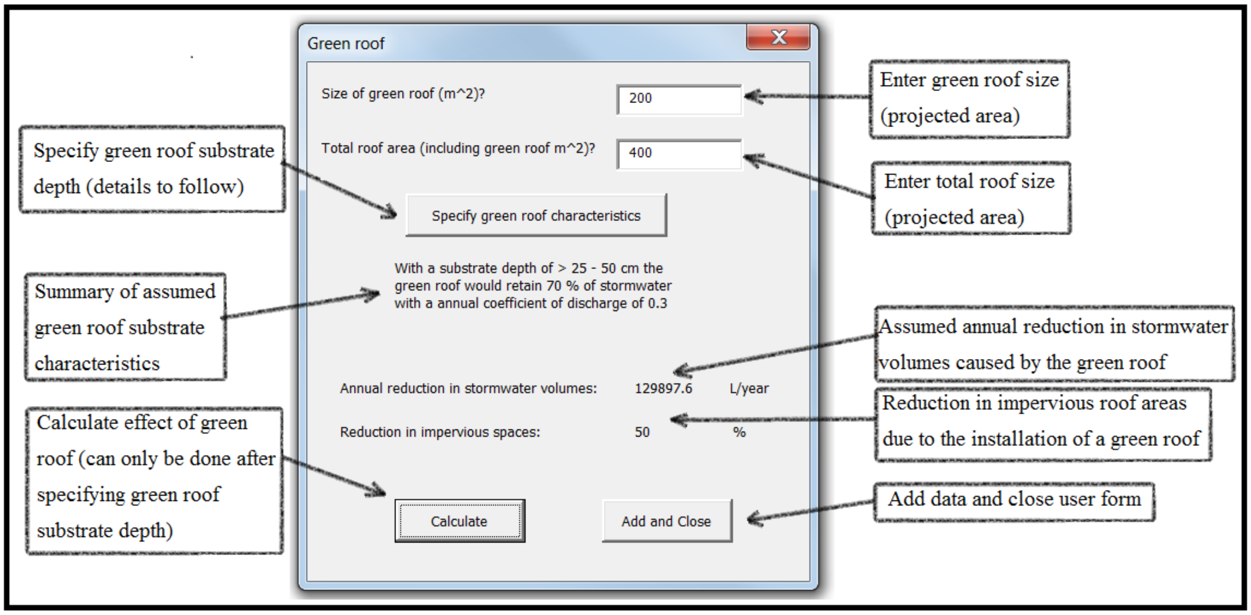
Select the source or sources of greywater to be reused

Add data and close user form

Figure A 12: Combined systems user form

Step 5: Specify green roof

After step 4 has been completed, the button controlling step 5 becomes visible, the exception to this rule being the case where user indicates the intention to harvest rainwater from a green roof. In this case the green roof section (step 5) would have been completed before completing step 4. When the user clicks on the green roof button on the “input sheet”, the green roof user form pops up. This is shown in Figure A 13.



Size of green roof (m^2)? 200

Total roof area (including green roof m^2)? 400

With a substrate depth of > 25 - 50 cm the green roof would retain 70 % of stormwater with a annual coefficient of discharge of 0.3

Annual reduction in stormwater volumes: 129897.6 L/year

Reduction in impervious spaces: 50 %

Enter green roof size (projected area)

Specify green roof substrate depth (details to follow)

Enter total roof size (projected area)

Summary of assumed green roof substrate characteristics

Assumed annual reduction in stormwater volumes caused by the green roof

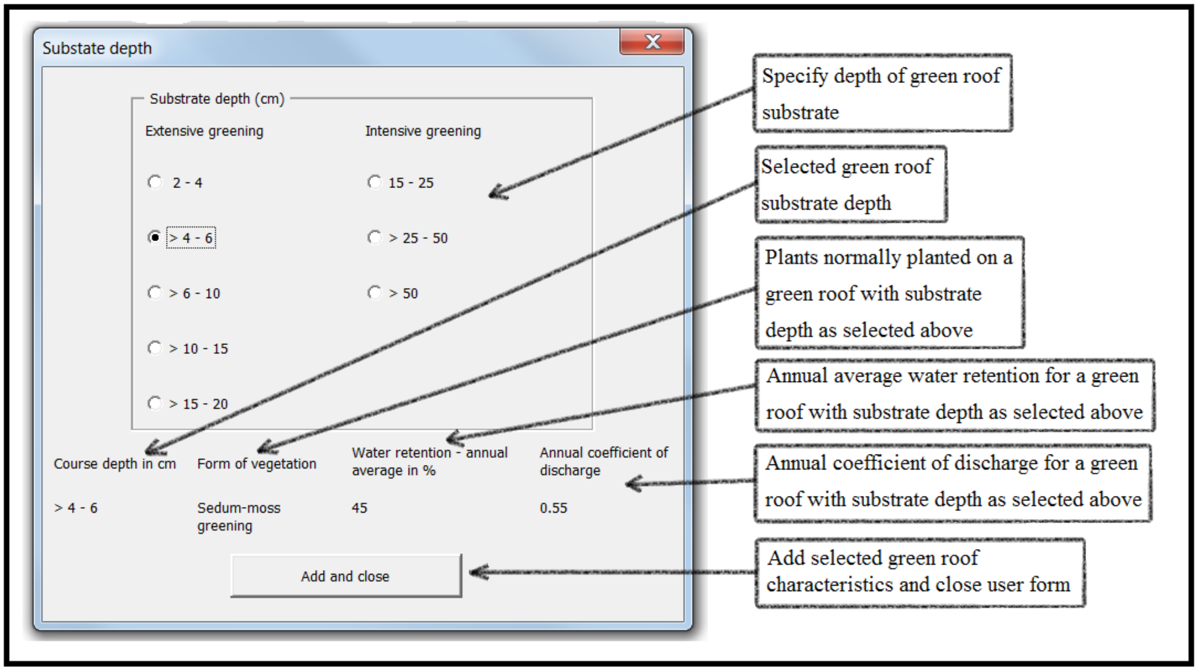
Reduction in impervious roof areas due to the installation of a green roof

Calculate effect of green roof (can only be done after specifying green roof substrate depth)

Add data and close user form

Figure A 13: Green roof user form

Before analysing the effect of the green roof it t is necessary to specify substrate depth. Substrate depth is specified by clicking on the "Specify green roof characteristics" button. See Figure A 13. The "Substrate depth user form" shown in Figure A 14, will then appear.



Substrate depth (cm)

Extensive greening
○ 2 - 4
● > 4 - 6
○ > 6 - 10
○ > 10 - 15
○ > 15 - 20

Intensive greening
○ 15 - 25
○ > 25 - 50
○ > 50

Course depth in cm	Form of vegetation	Water retention - annual average in %	Annual coefficient of discharge
> 4 - 6	Sedum-moss greening	45	0.55

Specify depth of green roof substrate

Selected green roof substrate depth

Plants normally planted on a green roof with substrate depth as selected above

Annual average water retention for a green roof with substrate depth as selected above

Annual coefficient of discharge for a green roof with substrate depth as selected above

Add selected green roof characteristics and close user form

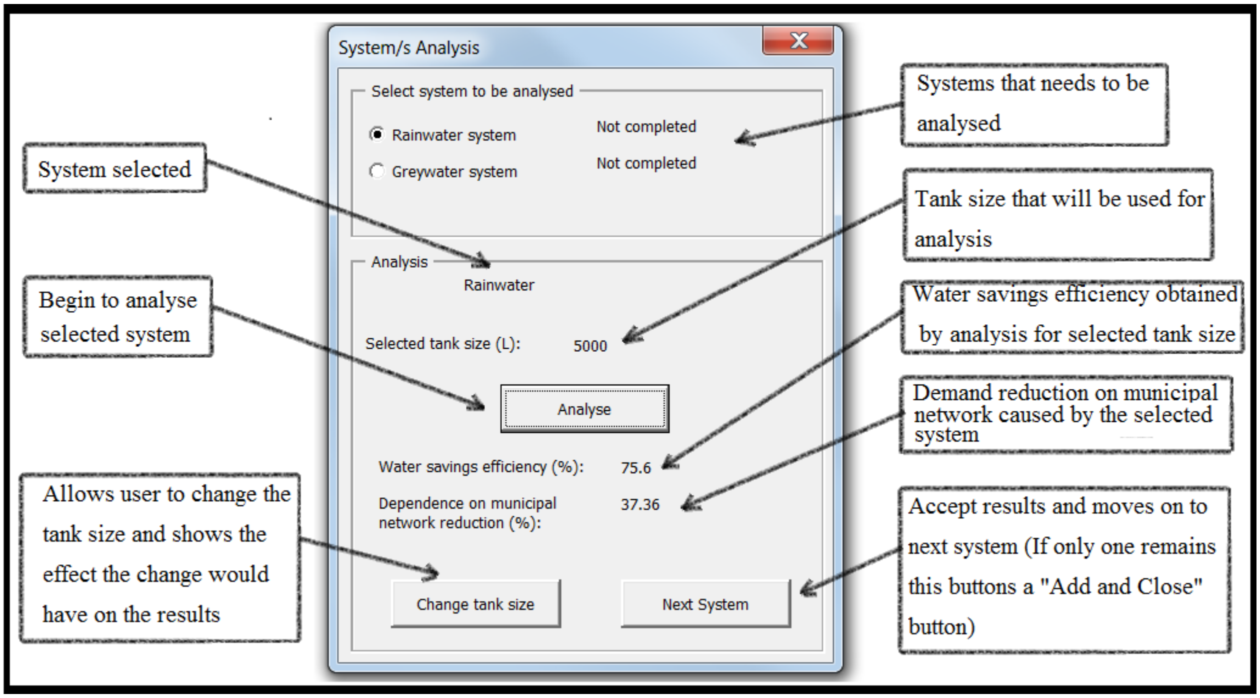
Figure A 14: Substrate depth user form

When the user clicks on a predefined substrate depth rang, the characteristics that will be assumed are shown in the bottom portion. See Figure A 14.

After completing Figure A 14 the user can calculate the effect of the green roof by clicking on the "calculate" button. See Figure A 13. After doing the calculation, the user should use the "Add and Close" button to add the specified data and close the user form.

Step 6: Analyse and finalise system

After the user has specified the green roof, step 5, the systems can be analysed. When the user clicks on the "Analyse system" button, the user form presented in Figure A 15, appears. The user then selects the system with which he or she wants to start, if there is more than one system in use. When the system is selected, the data entered in previous sections are loaded automatically. After this selection the user clicks on the "Analyse" button to run the analysis. When the analysis has been completed, the "Water savings efficiency" and "Dependency on municipal network reduction" characteristics are shown, as can be seen in Figure A 15.



● Rainwater system Not completed
○ Greywater system Not completed

Rainwater

Selected tank size (L): 5000

Water savings efficiency (%): 75.6

Dependence on municipal network reduction (%): 37.36

System selected

Begin to analyse selected system

Allows user to change the tank size and shows the effect the change would have on the results

Systems that needs to be analysed

Tank size that will be used for analysis

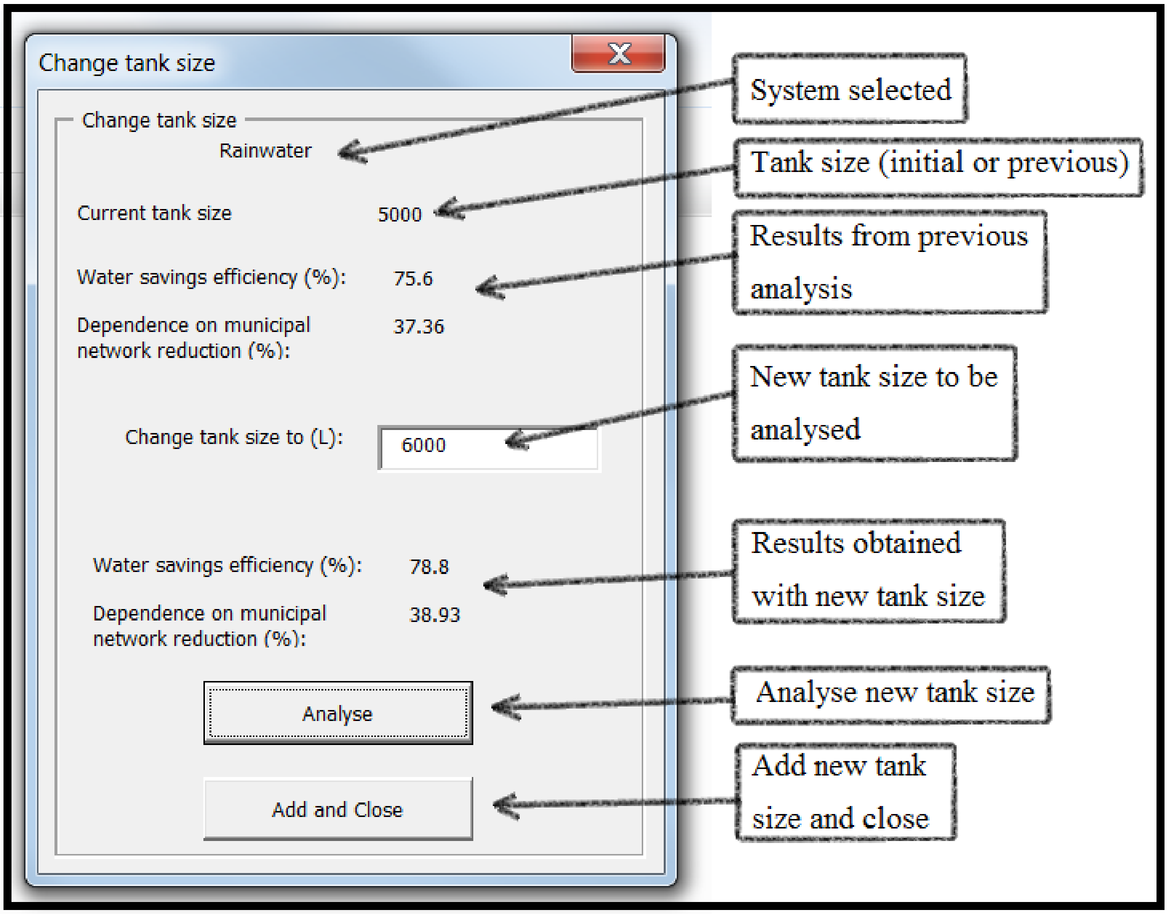
Water savings efficiency obtained by analysis for selected tank size

Demand reduction on municipal network caused by the selected system

Accept results and moves on to next system (If only one remains this buttons a "Add and Close" button)

Figure A 15: Analyses user form

If the user is not satisfied with the results he or she can opt to change the tank size and rerun the analysis. This is done by clicking on the "Change tank size" button. See Figure A 15. This reveals the user form shown in Figure A 16. The user can now enter a new tank size and run the analysis. It should be mentioned that when the user clicks on the "Add and Close" button the data in the new analysis section is used.



Rainwater

Current tank size 5000

Water savings efficiency (%): 75.6

Dependence on municipal network reduction (%): 37.36

Change tank size to (L): 6000

Water savings efficiency (%): 78.8

Dependence on municipal network reduction (%): 38.93

System selected

Tank size (initial or previous)

Results from previous analysis

New tank size to be analysed

Results obtained with new tank size

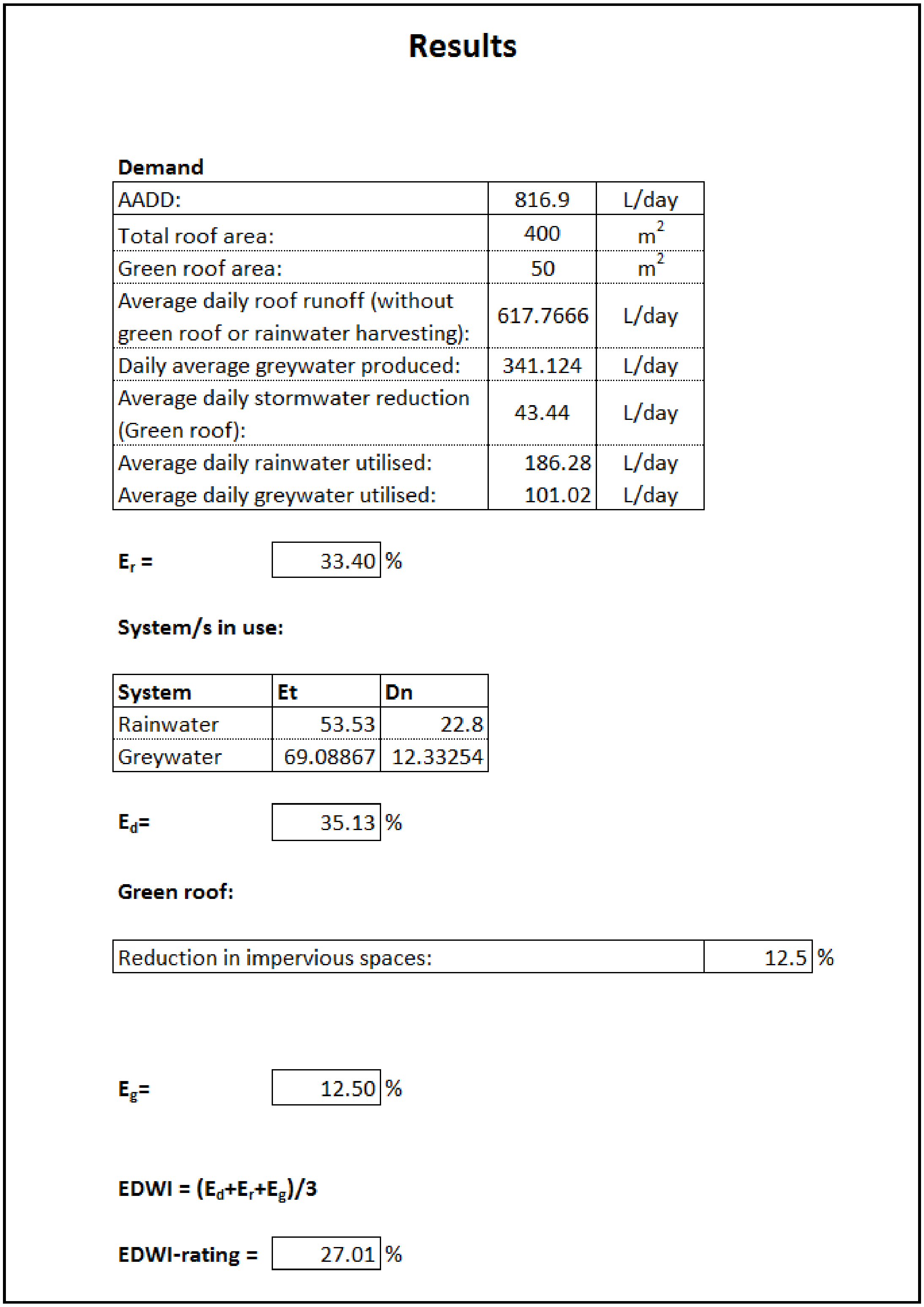
Analyse new tank size

Add new tank size and close

Figure A 16: Change tank size user form

Step 7: View results

Step 7 requires no data inputs. Step 7 activates the "results sheet" which displays all results after completion of the first 6 steps. Figure A 17 shows an example of what the output sheet looks like.



Results

Demand

AADD:	816.9	L/day
Total roof area:	400	m^2
Green roof area:	50	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	617.7666	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	43.44	L/day
Average daily rainwater utilised:	186.28	L/day
Average daily greywater utilised:	101.02	L/day

E_r = 33.40 %

System/s in use:

System	**Et**	**Dn**
Rainwater	53.53	22.8
Greywater	69.08867	12.33254

E_d= 35.13 %

Green roof:

Reduction in impervious spaces:	12.5	%

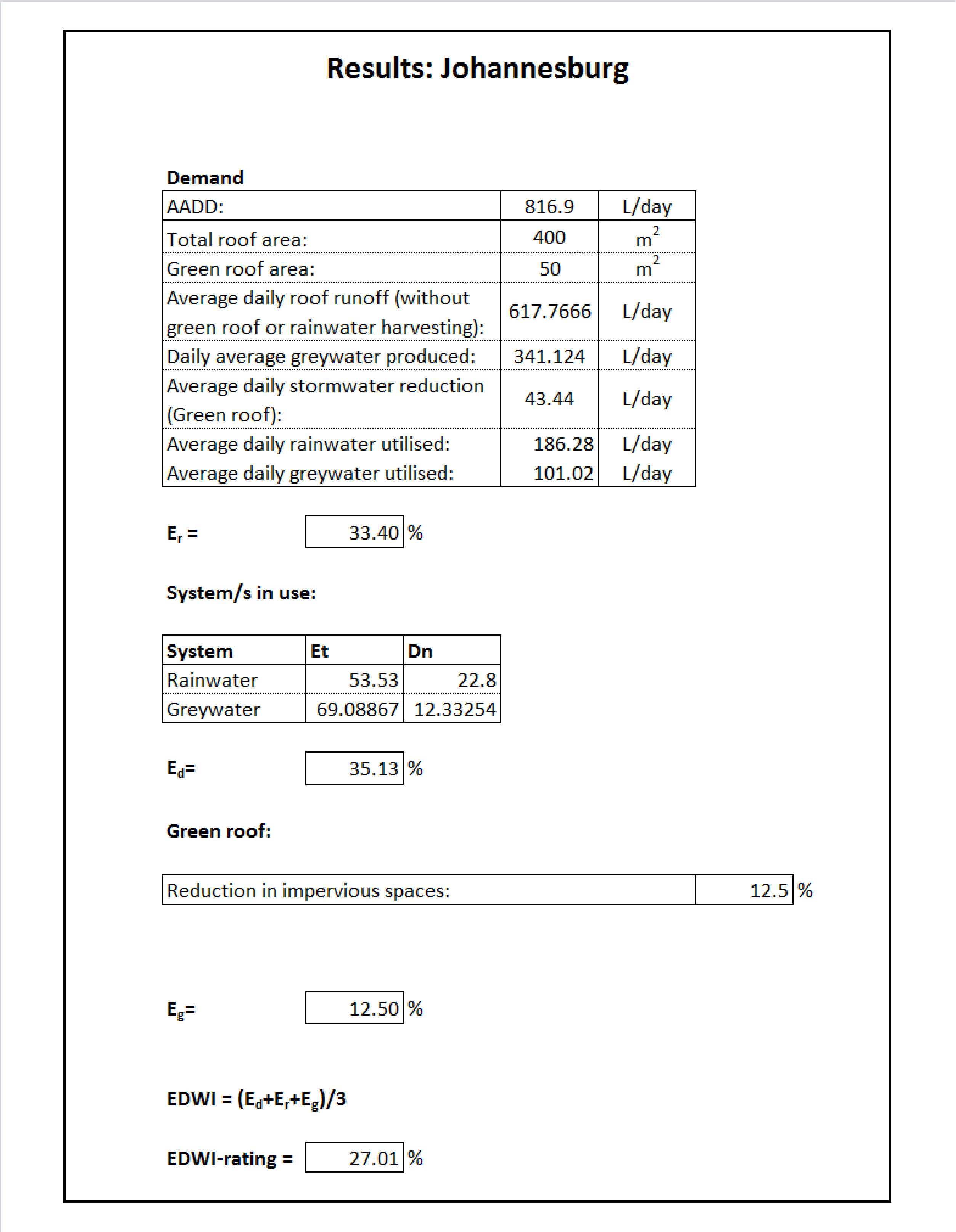
E_g= 12.50 %

EDWI = $(E_d+E_r+E_g)/3$

EDWI-rating = 27.01 %

Figure A 17: Results sheet

Appendix B: Comparative analysis data



Results: Johannesburg

Demand

AADD:	816.9	L/day
Total roof area:	400	m^2
Green roof area:	50	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	617.7666	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	43.44	L/day
Average daily rainwater utilised:	186.28	L/day
Average daily greywater utilised:	101.02	L/day

E_r = 33.40 %

System/s in use:

System	Et	Dn
Rainwater	53.53	22.8
Greywater	69.08867	12.33254

E_d= 35.13 %

Green roof:

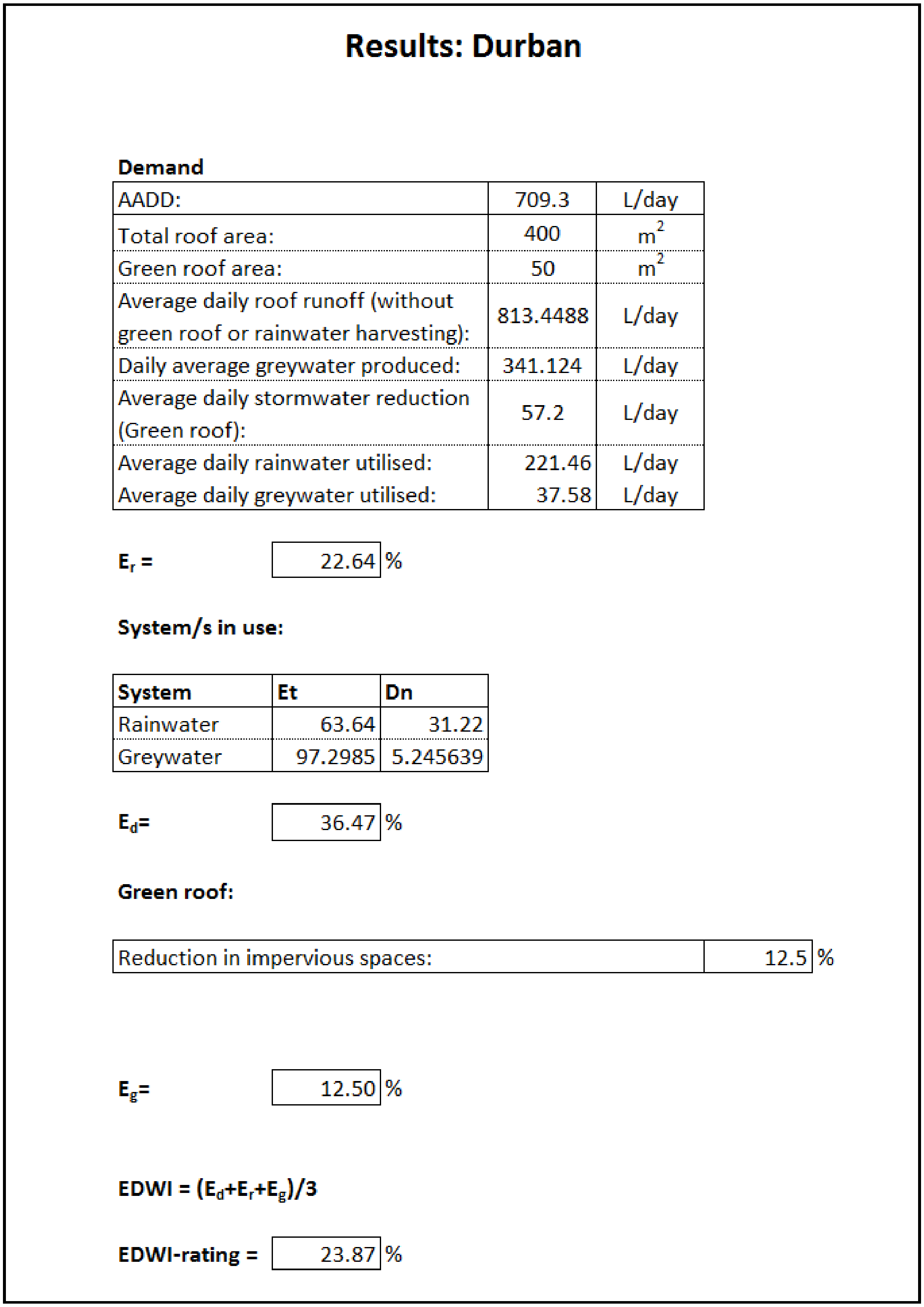
Reduction in impervious spaces:	12.5	%

E_g= 12.50 %

EDWI = $(E_d+E_r+E_g)/3$

EDWI-rating = 27.01 %

Figure B 1: Johannesburg



Results: Durban

Demand

AADD:	709.3	L/day
Total roof area:	400	m^2
Green roof area:	50	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	813.4488	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	57.2	L/day
Average daily rainwater utilised:	221.46	L/day
Average daily greywater utilised:	37.58	L/day

E_r = 22.64 %

System/s in use:

System	**Et**	**Dn**
Rainwater	63.64	31.22
Greywater	97.2985	5.245639

E_d= 36.47 %

Green roof:

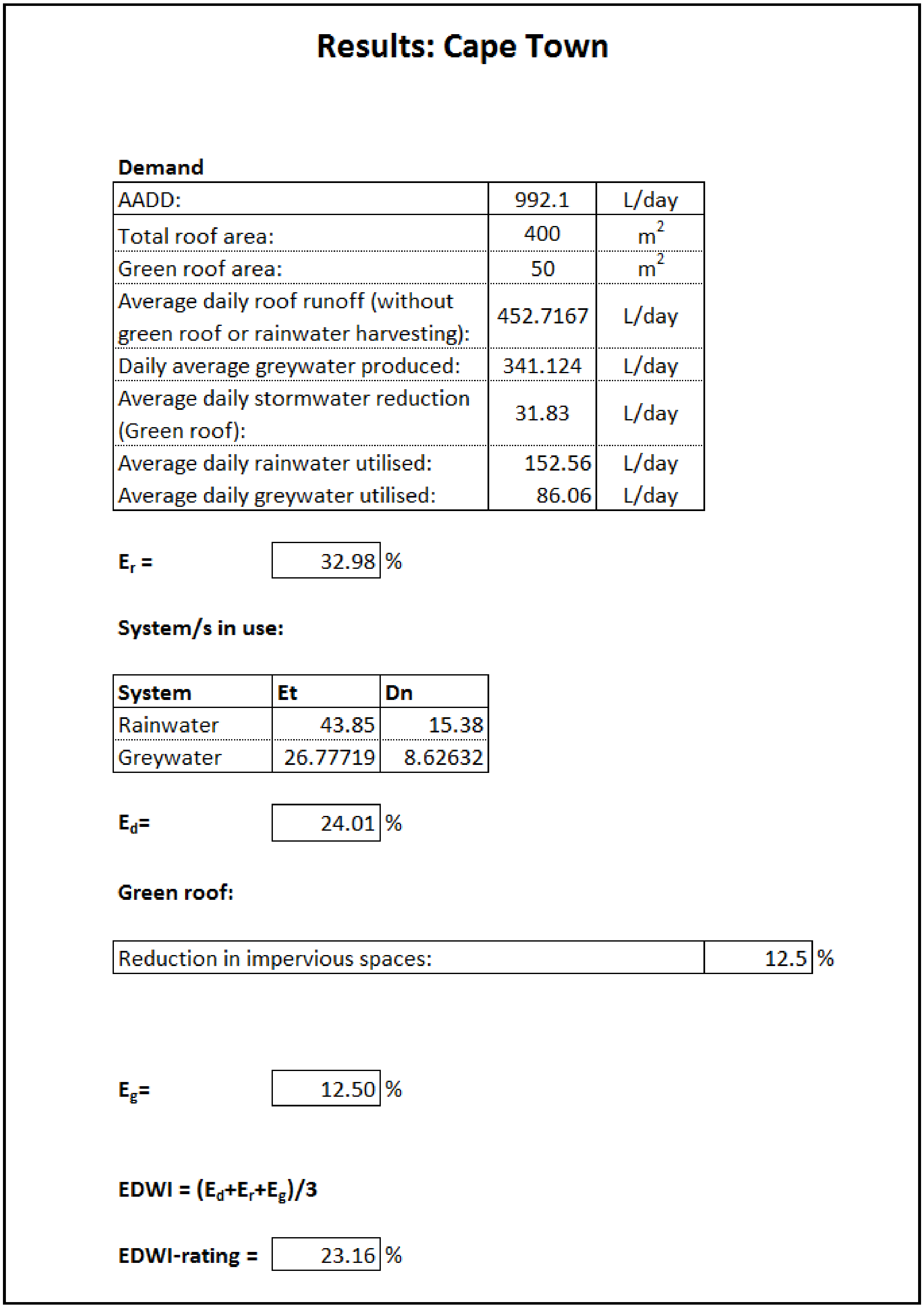
Reduction in impervious spaces:	12.5	%

E_g= 12.50 %

EDWI = $(E_d+E_r+E_g)/3$

EDWI-rating = 23.87 %

Figure B 2: Durban



Results: Cape Town

Demand

AADD:	992.1	L/day
Total roof area:	400	m^2
Green roof area:	50	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	452.7167	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	31.83	L/day
Average daily rainwater utilised:	152.56	L/day
Average daily greywater utilised:	86.06	L/day

E_r = 32.98 %

System/s in use:

System	Et	Dn
Rainwater	43.85	15.38
Greywater	26.77719	8.62632

E_d= 24.01 %

Green roof:

Reduction in impervious spaces:	12.5	%

E_g= 12.50 %

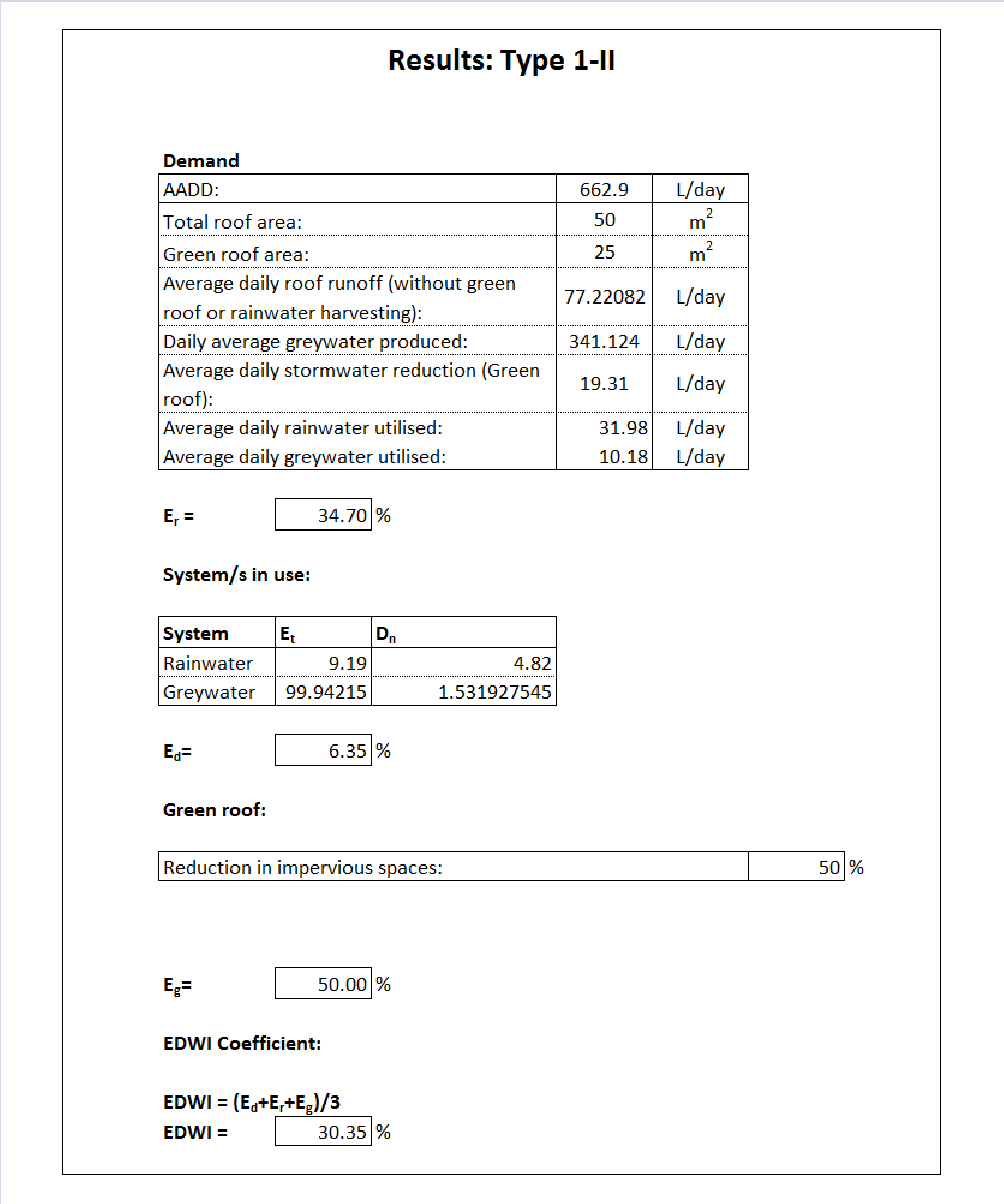
EDWI = $(E_d+E_r+E_g)/3$

EDWI-rating = 23.16 %

Figure B 3: Cape Town

Appendix C: Benchmarking results

The results from configuration I are not included as all dwellings produce an EDWI-rating of zero.



Results: Type 1-II

Demand

AADD:	662.9	L/day
Total roof area:	50	m^2
Green roof area:	25	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	77.22082	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	19.31	L/day
Average daily rainwater utilised:	31.98	L/day
Average daily greywater utilised:	10.18	L/day

E_r = 34.70 %

System/s in use:

System	E_t	D_n
Rainwater	9.19	4.82
Greywater	99.94215	1.531927545

E_d= 6.35 %

Green roof:

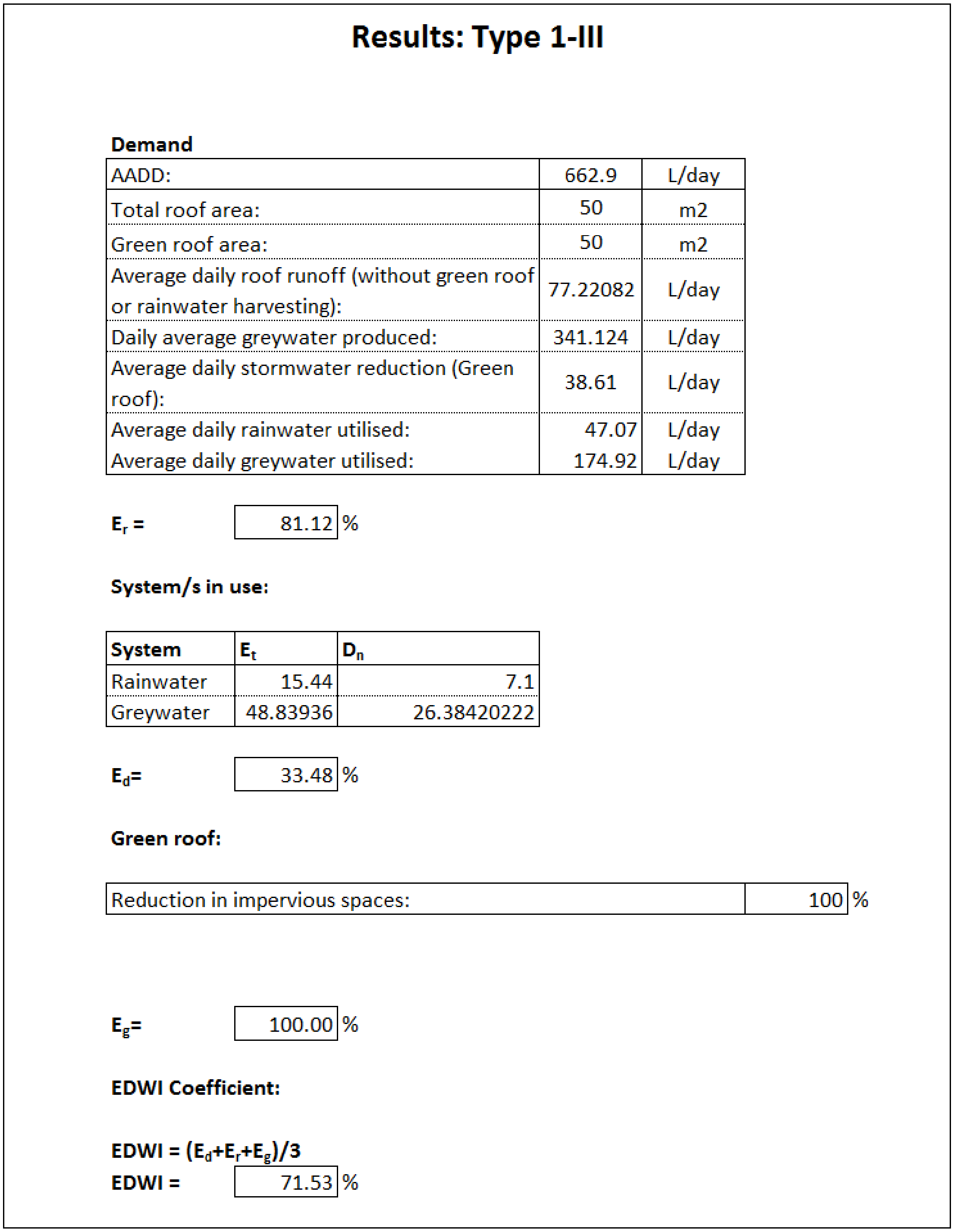
Reduction in impervious spaces:	50	%

E_g= 50.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 30.35 %



Results: Type 1-III

Demand

AADD:	662.9	L/day
Total roof area:	50	m2
Green roof area:	50	m2
Average daily roof runoff (without green roof or rainwater harvesting):	77.22082	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	38.61	L/day
Average daily rainwater utilised:	47.07	L/day
Average daily greywater utilised:	174.92	L/day

E_r = 81.12 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	15.44	7.1
Greywater	48.83936	26.38420222

E_d= 33.48 %

Green roof:

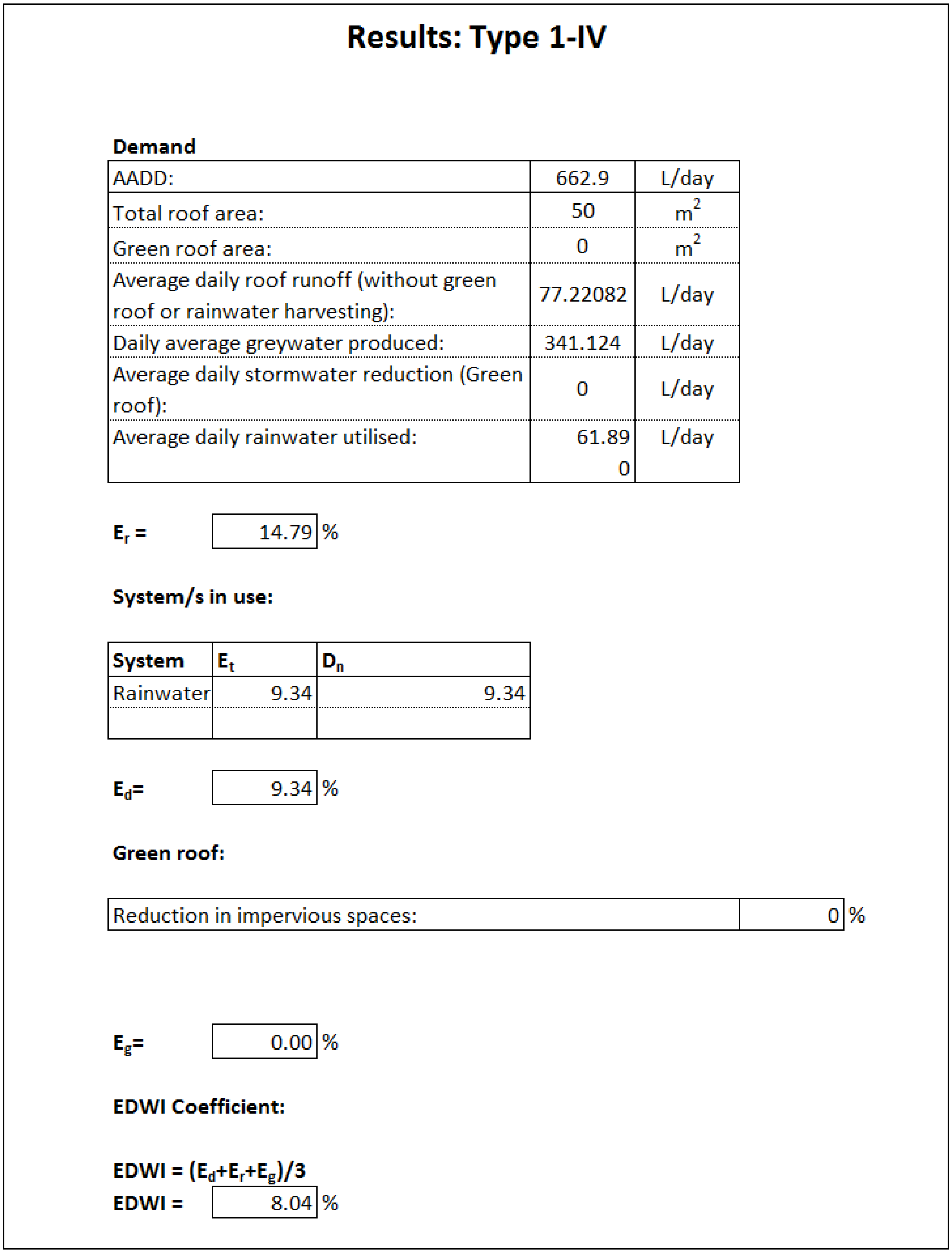
Reduction in impervious spaces:	100 %

E_g= 100.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 71.53 %



Results: Type 1-IV

Demand

AADD:	662.9	L/day
Total roof area:	50	m^2
Green roof area:	0	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	77.22082	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	0	L/day
Average daily rainwater utilised:	61.89 0	L/day

E_r = 14.79 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	9.34	9.34

E_d= 9.34 %

Green roof:

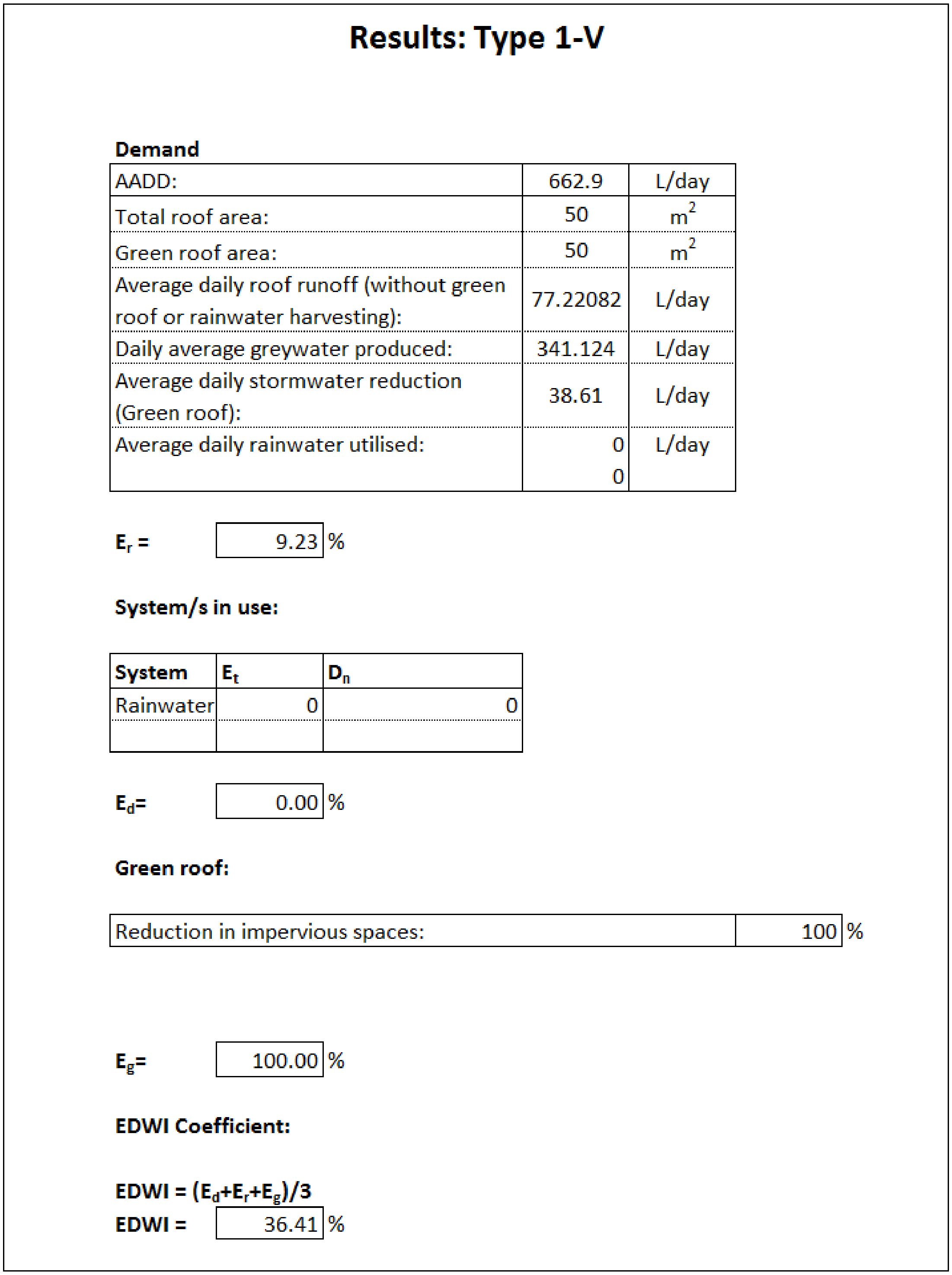
Reduction in impervious spaces:	0 %

E_g= 0.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 8.04 %



Results: Type 1-V

Demand

AADD:	662.9	L/day
Total roof area:	50	m^2
Green roof area:	50	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	77.22082	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	38.61	L/day
Average daily rainwater utilised:	0 0	L/day

E_r = 9.23 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	0	0

E_d= 0.00 %

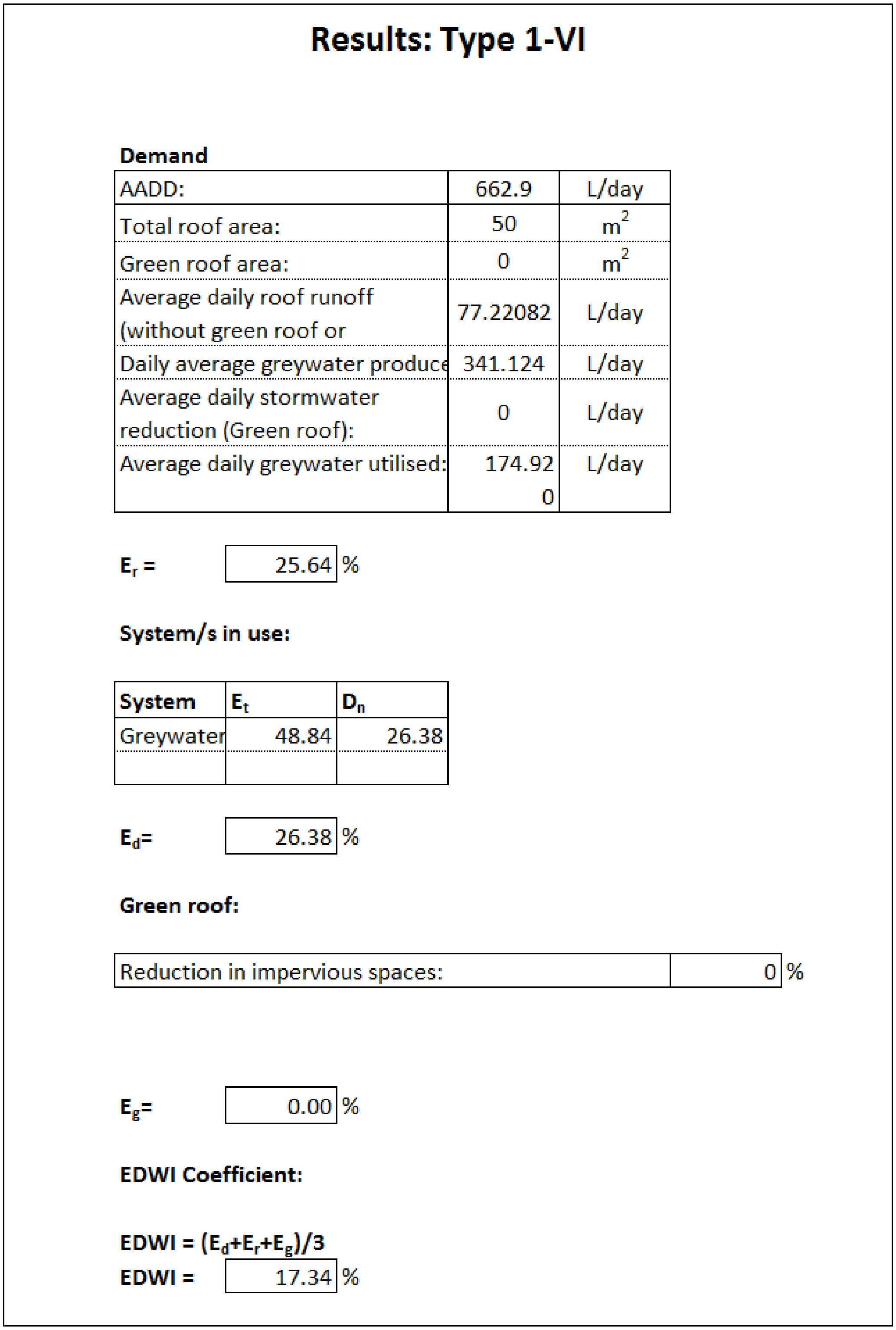
Green roof:

Reduction in impervious spaces:	100	%

E_g= 100.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$
EDWI = 36.41 %



Results: Type 1-VI

Demand

AADD:	662.9	L/day
Total roof area:	50	m^2
Green roof area:	0	m^2
Average daily roof runoff (without green roof or	77.22082	L/day
Daily average greywater produce	341.124	L/day
Average daily stormwater reduction (Green roof):	0	L/day
Average daily greywater utilised:	174.92 0	L/day

E_r = 25.64 %

System/s in use:

System	**E_t**	**D_n**
Greywater	48.84	26.38

E_d= 26.38 %

Green roof:

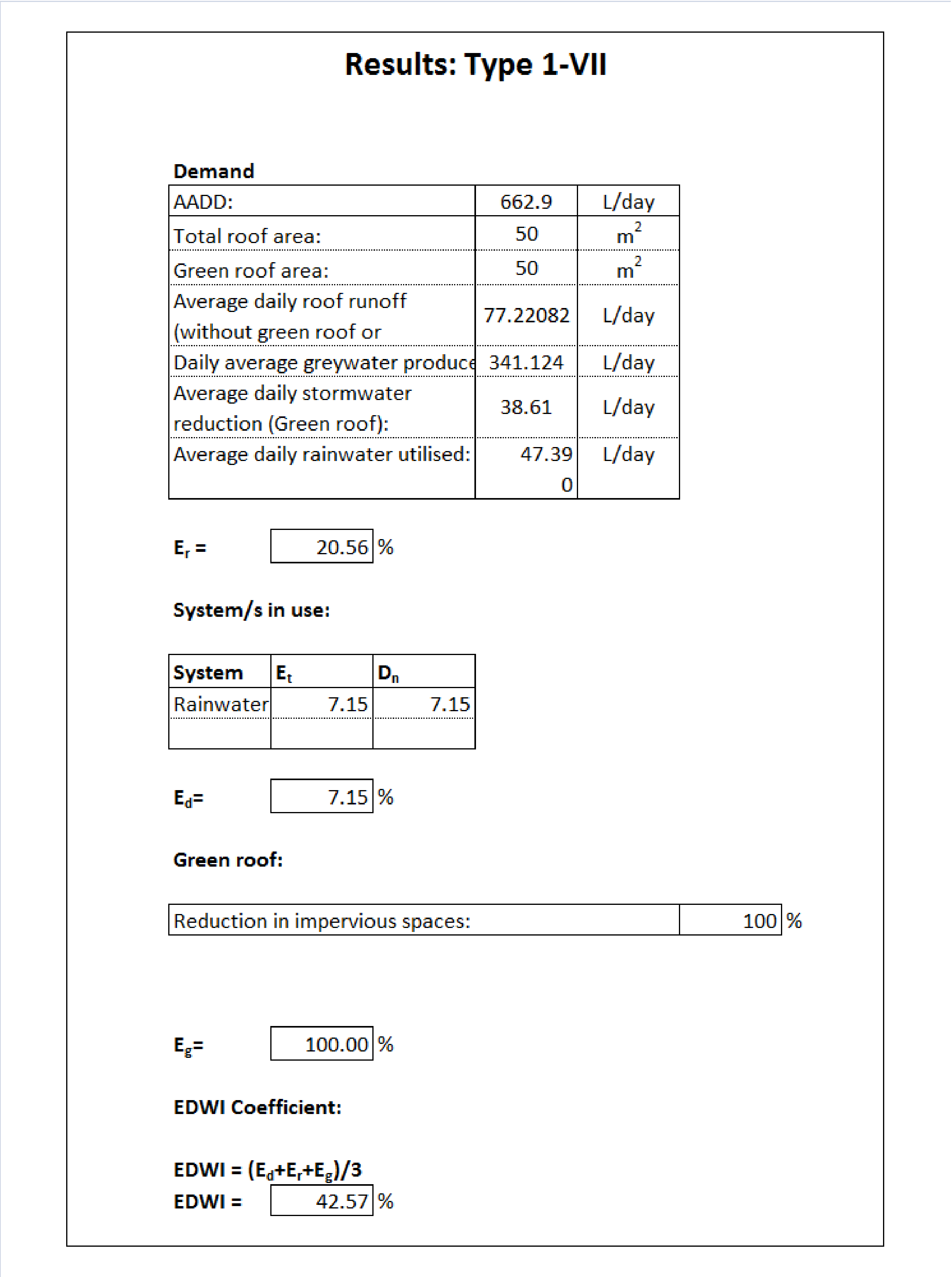
Reduction in impervious spaces:	0	%

E_g= 0.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 17.34 %



Results: Type 1-VII

Demand

AADD:	662.9	L/day
Total roof area:	50	m^2
Green roof area:	50	m^2
Average daily roof runoff (without green roof or	77.22082	L/day
Daily average greywater produce	341.124	L/day
Average daily stormwater reduction (Green roof):	38.61	L/day
Average daily rainwater utilised:	47.39 0	L/day

E_r = 20.56 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	7.15	7.15

E_d= 7.15 %

Green roof:

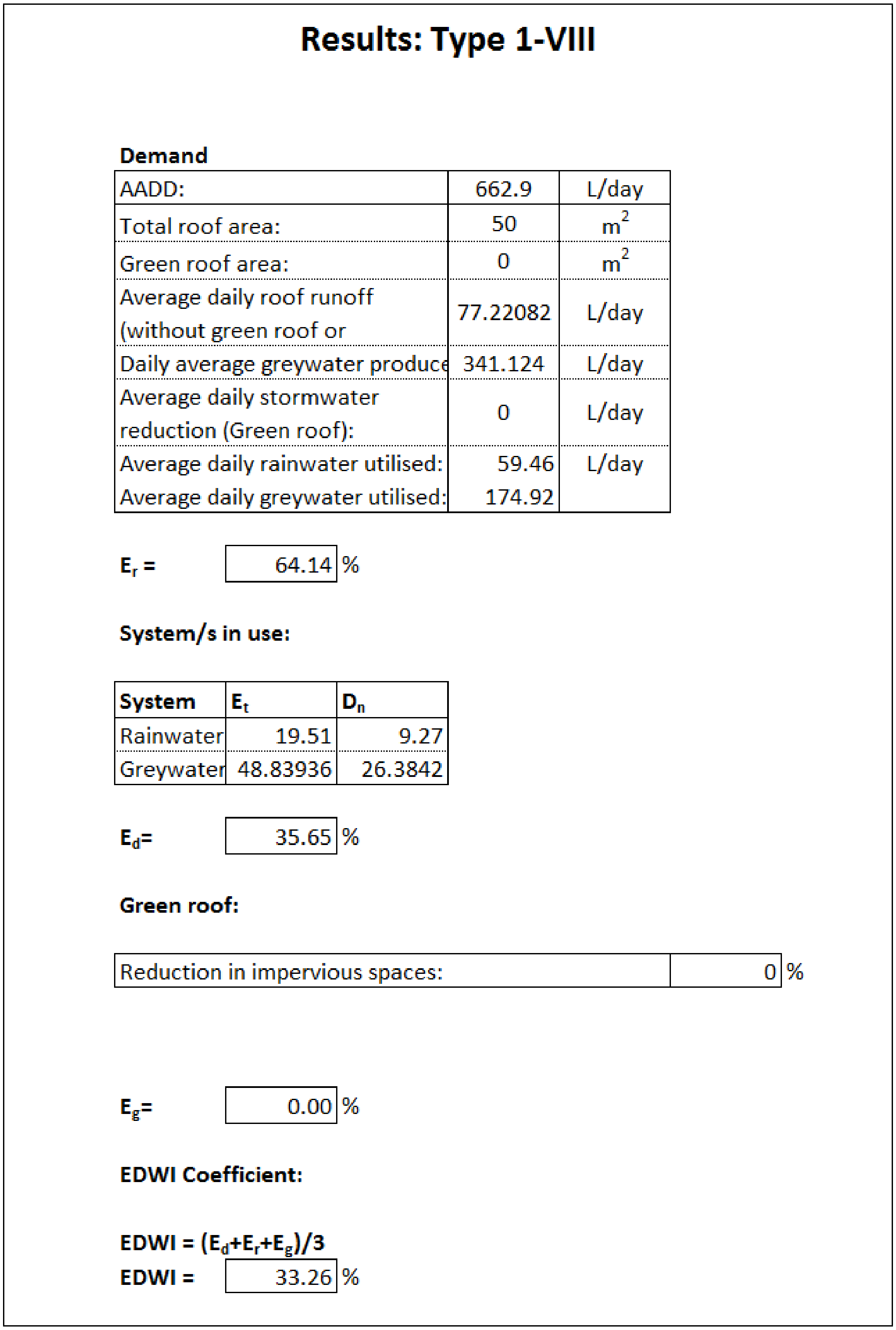
Reduction in impervious spaces:	100	%

E_g= 100.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 42.57 %



Results: Type 1-VIII

Demand

AADD:	662.9	L/day
Total roof area:	50	m^2
Green roof area:	0	m^2
Average daily roof runoff (without green roof or	77.22082	L/day
Daily average greywater produce	341.124	L/day
Average daily stormwater reduction (Green roof):	0	L/day
Average daily rainwater utilised:	59.46	L/day
Average daily greywater utilised:	174.92	

E_r = 64.14 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	19.51	9.27
Greywater	48.83936	26.3842

E_d= 35.65 %

Green roof:

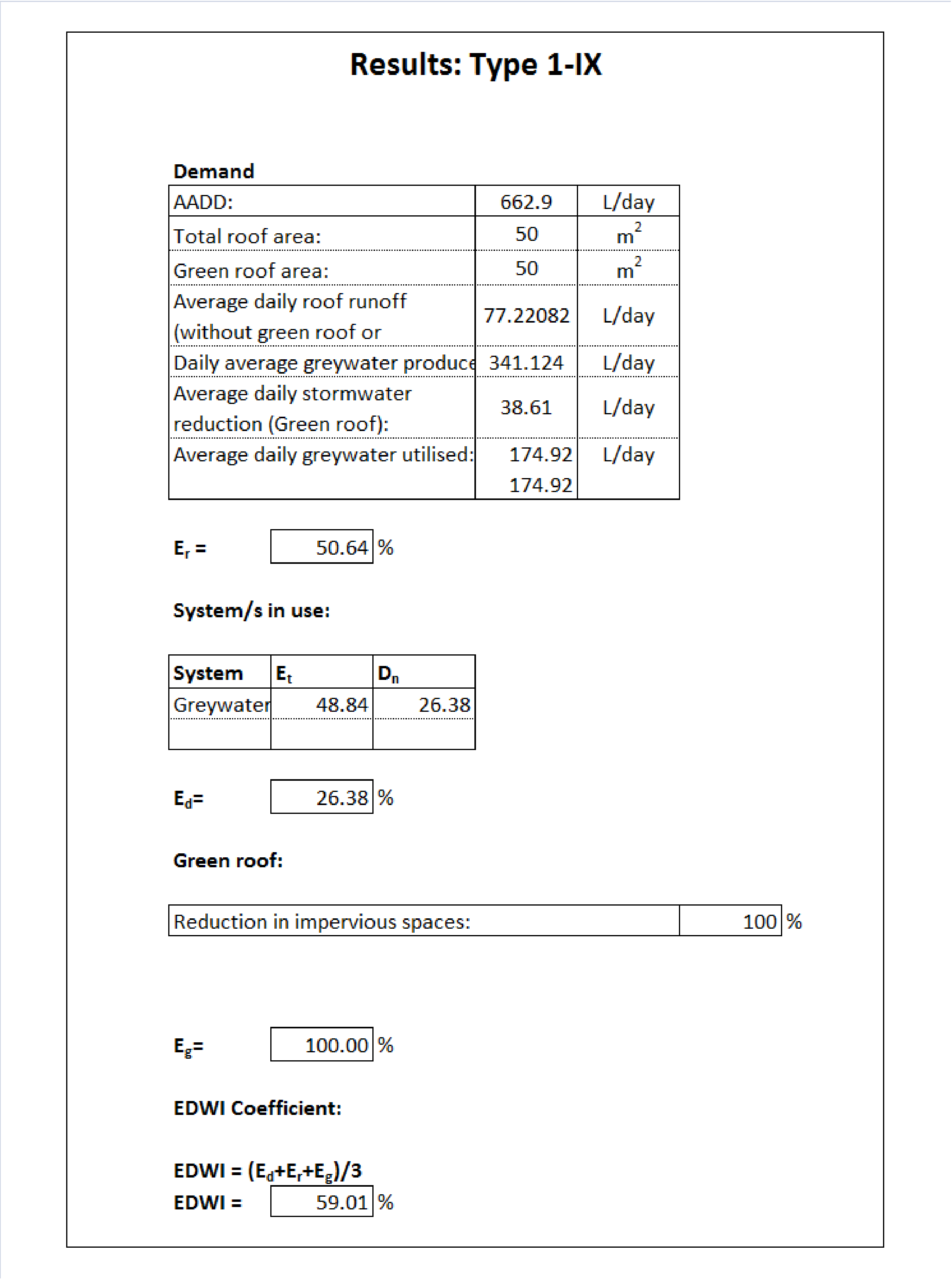
Reduction in impervious spaces:	0 %

E_g= 0.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 33.26 %



Results: Type 1-IX

Demand

AADD:	662.9	L/day
Total roof area:	50	m^2
Green roof area:	50	m^2
Average daily roof runoff (without green roof or	77.22082	L/day
Daily average greywater produce	341.124	L/day
Average daily stormwater reduction (Green roof):	38.61	L/day
Average daily greywater utilised:	174.92 174.92	L/day

E_r = 50.64 %

System/s in use:

System	**E_t**	**D_n**
Greywater	48.84	26.38

E_d= 26.38 %

Green roof:

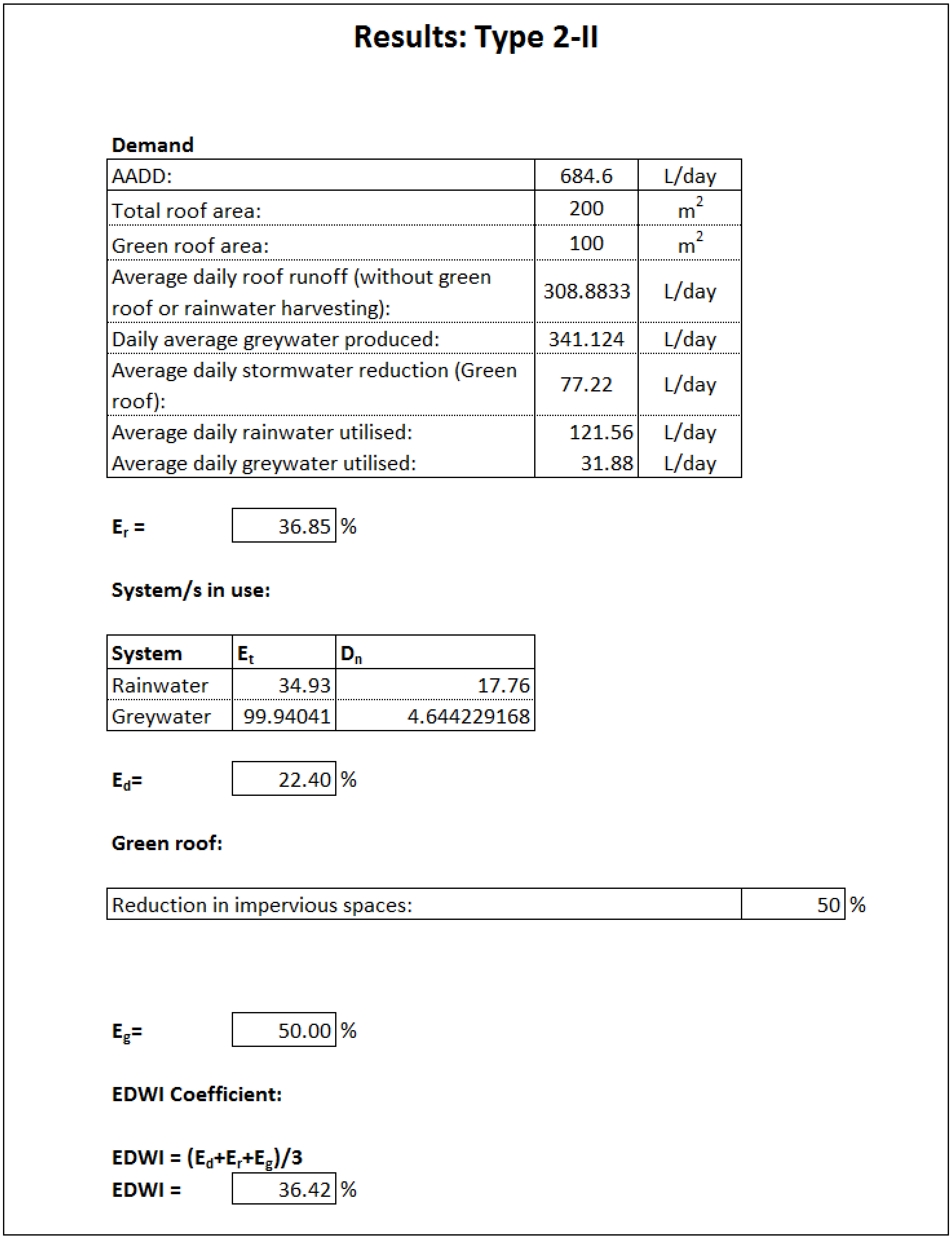
Reduction in impervious spaces:	100	%

E_g= 100.00 %

EDWI Coefficient:

EDWI = (E_d+E_r+E_g)/3

EDWI = 59.01 %



Results: Type 2-II

Demand

AADD:	684.6	L/day
Total roof area:	200	m^2
Green roof area:	100	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	308.8833	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	77.22	L/day
Average daily rainwater utilised:	121.56	L/day
Average daily greywater utilised:	31.88	L/day

E_r = 36.85 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	34.93	17.76
Greywater	99.94041	4.644229168

E_d= 22.40 %

Green roof:

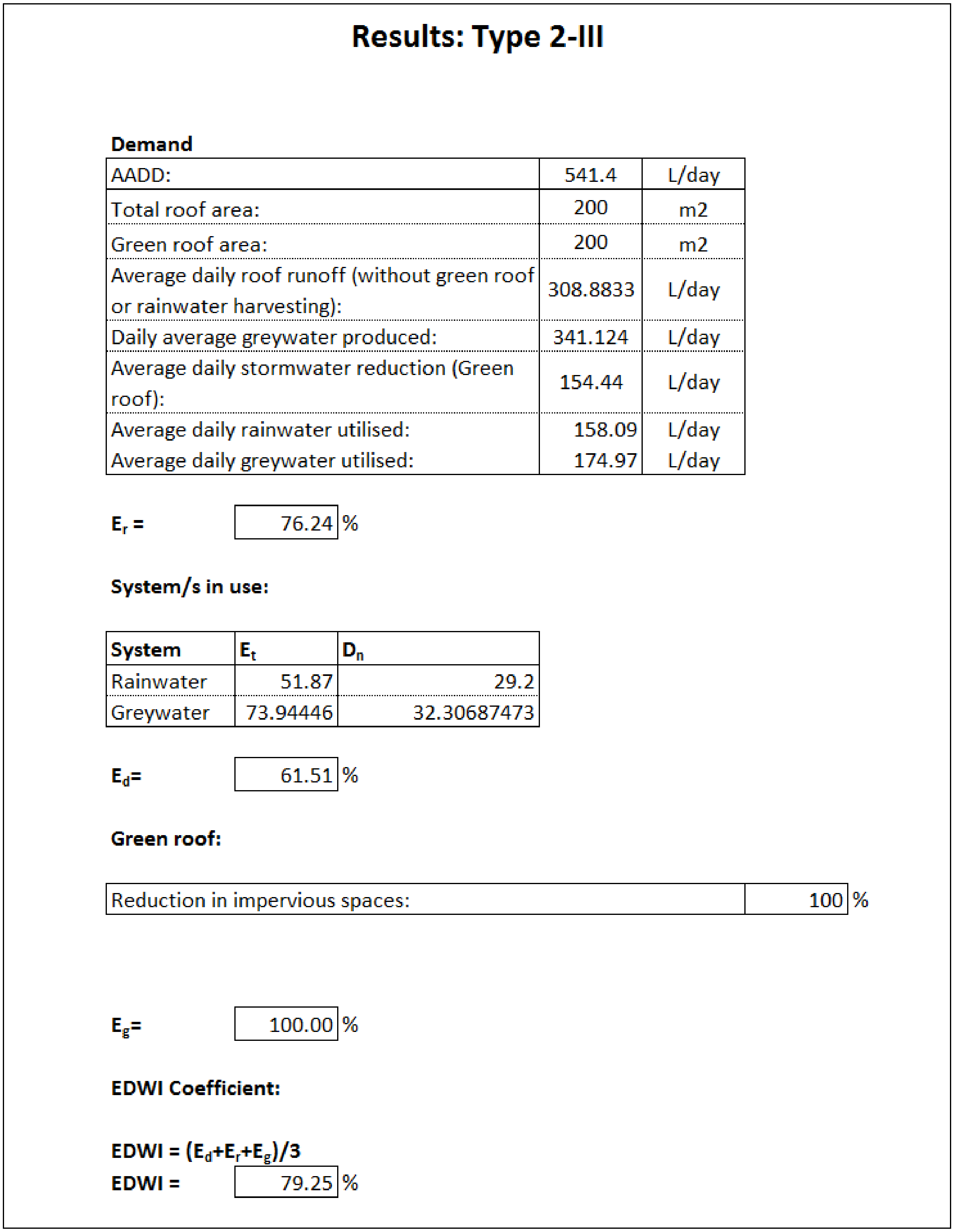
Reduction in impervious spaces:	50	%

E_g= 50.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 36.42 %



Results: Type 2-III

Demand

AADD:	541.4	L/day
Total roof area:	200	m2
Green roof area:	200	m2
Average daily roof runoff (without green roof or rainwater harvesting):	308.8833	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	154.44	L/day
Average daily rainwater utilised:	158.09	L/day
Average daily greywater utilised:	174.97	L/day

E_r = 76.24 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	51.87	29.2
Greywater	73.94446	32.30687473

E_d= 61.51 %

Green roof:

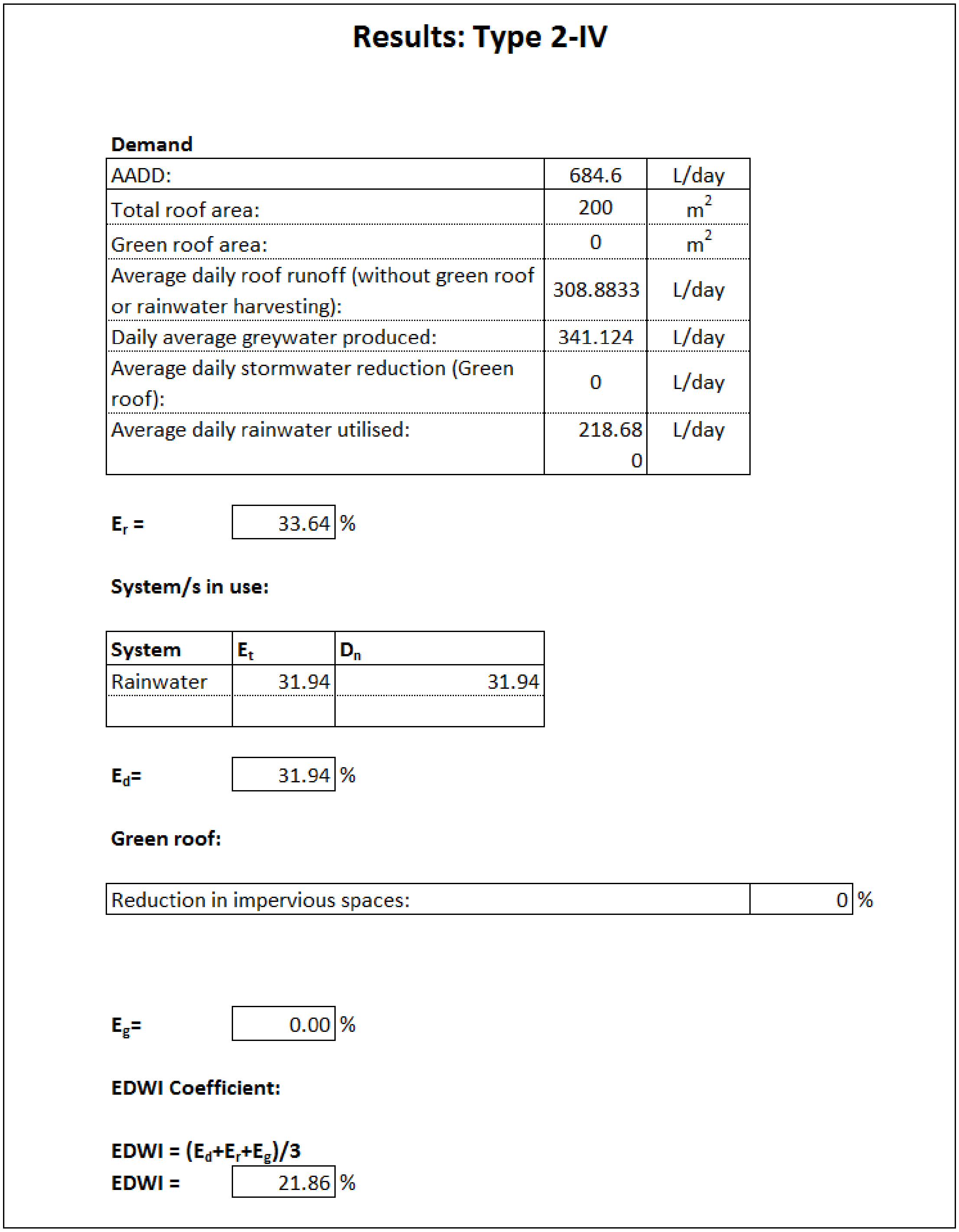
Reduction in impervious spaces:	100	%

E_g= 100.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 79.25 %



Results: Type 2-IV

Demand

AADD:	684.6	L/day
Total roof area:	200	m^2
Green roof area:	0	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	308.8833	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	0	L/day
Average daily rainwater utilised:	218.680	L/day

E_r = 33.64 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	31.94	31.94

E_d= 31.94 %

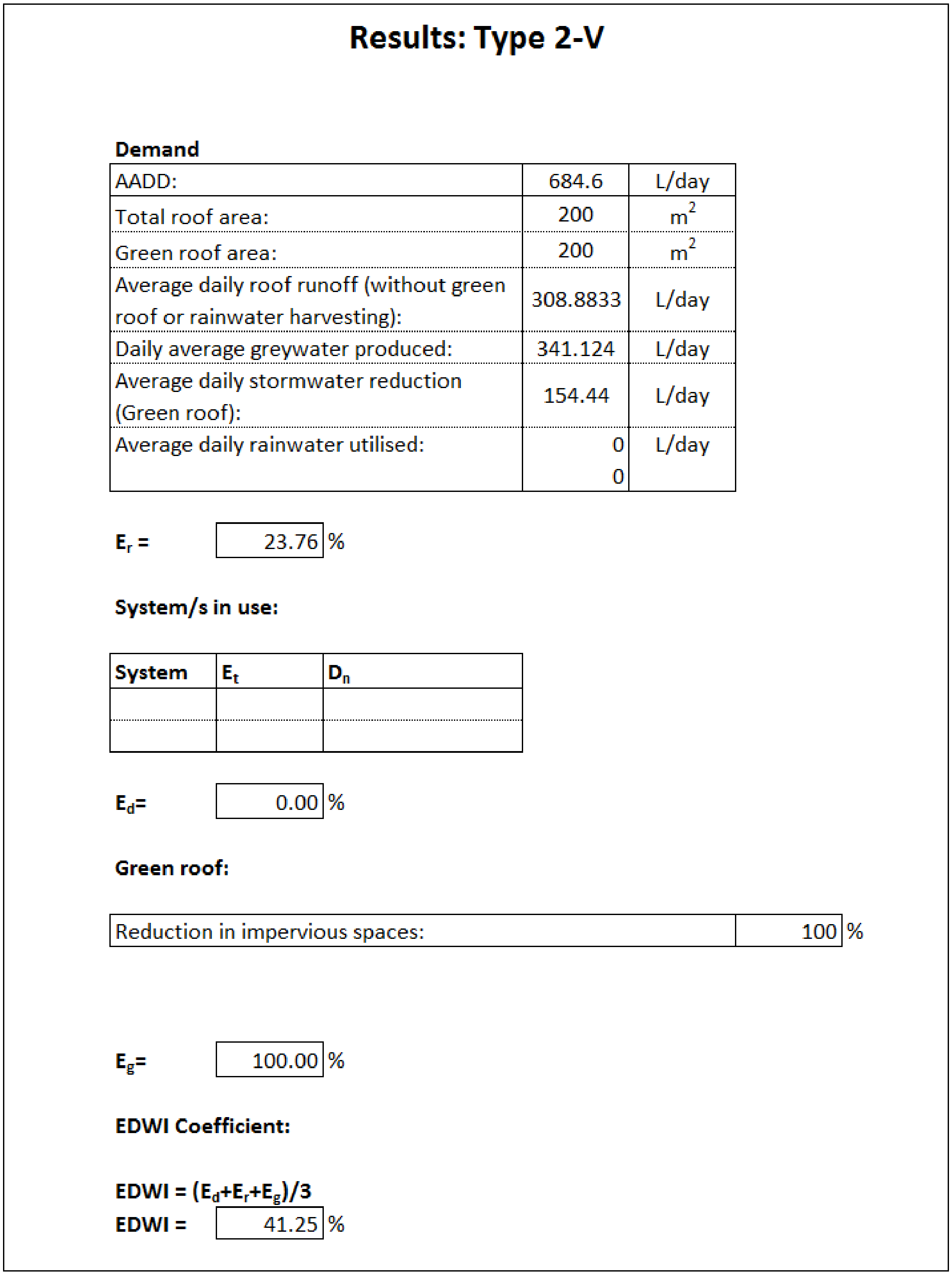
Green roof:

Reduction in impervious spaces:	0	%

E_g= 0.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$
EDWI = 21.86 %



Results: Type 2-V

Demand

AADD:	684.6	L/day
Total roof area:	200	m^2
Green roof area:	200	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	308.8833	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	154.44	L/day
Average daily rainwater utilised:	0 0	L/day

E_r = 23.76 %

System/s in use:

System	E_t	D_n

E_d= 0.00 %

Green roof:

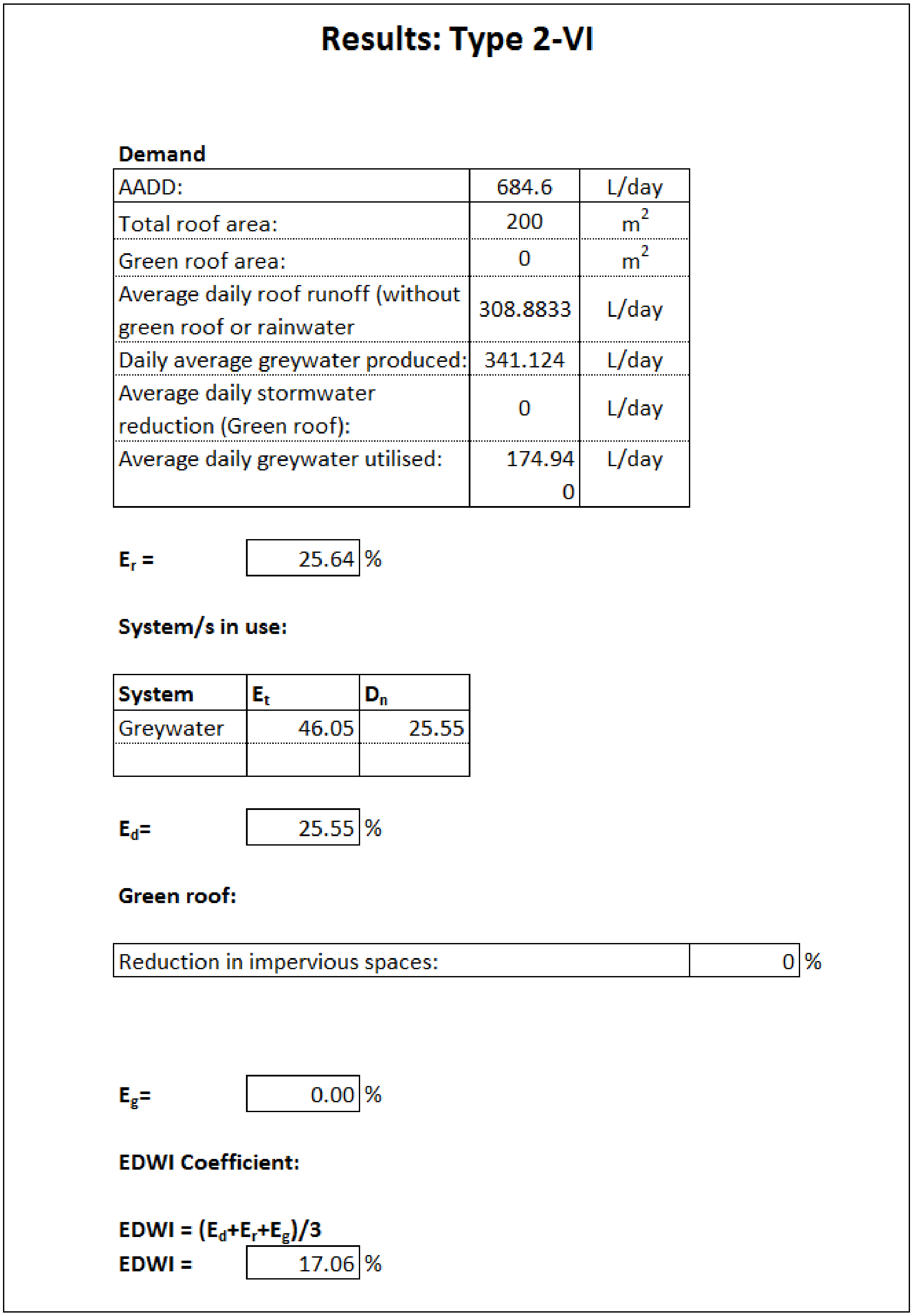
Reduction in impervious spaces:	100	%

E_g= 100.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 41.25 %



Results: Type 2-VI

Demand

AADD:	684.6	L/day
Total roof area:	200	m^2
Green roof area:	0	m^2
Average daily roof runoff (without green roof or rainwater	308.8833	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	0	L/day
Average daily greywater utilised:	174.94 0	L/day

E_r = 25.64 %

System/s in use:

System	**E_t**	**D_n**
Greywater	46.05	25.55

E_d= 25.55 %

Green roof:

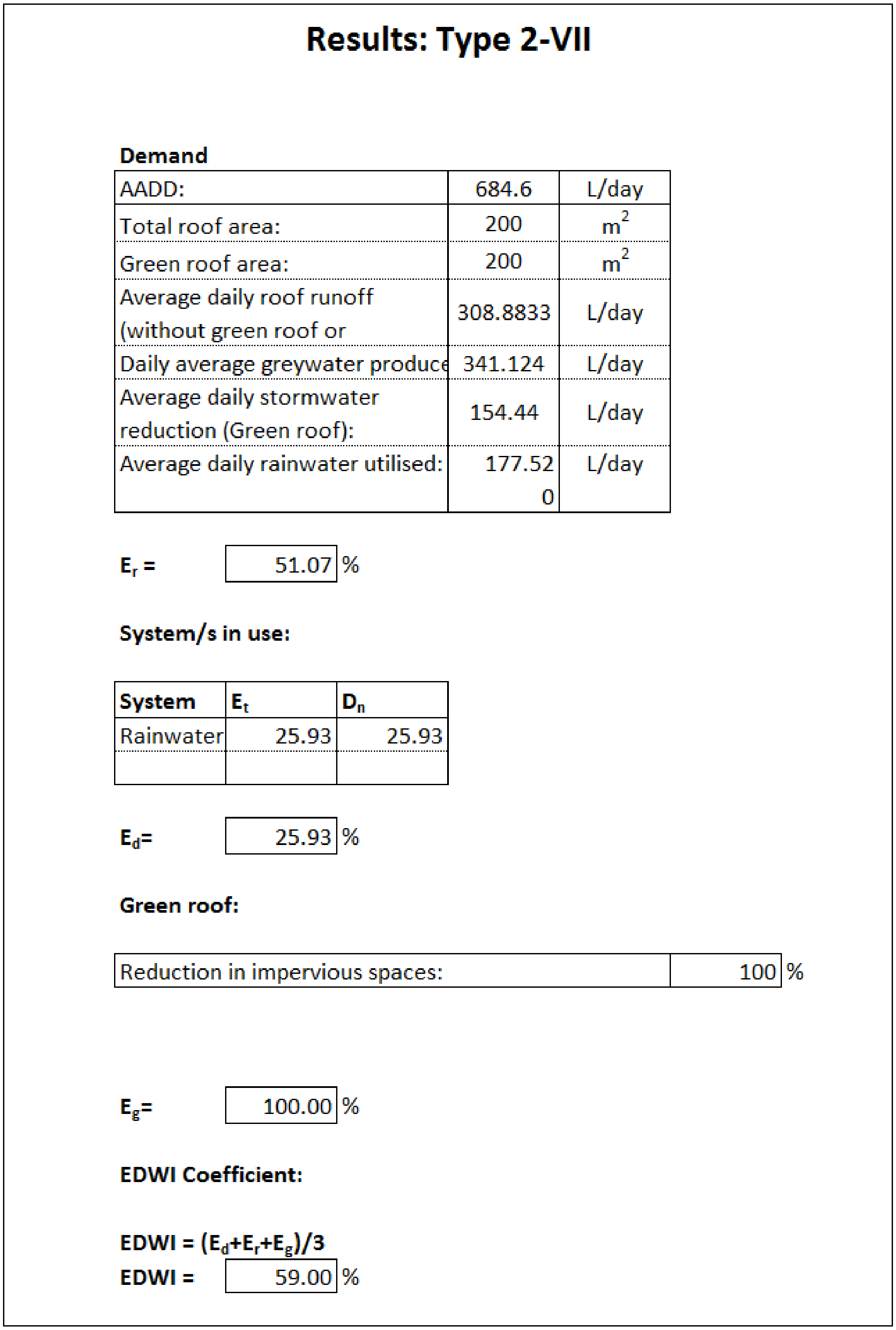
Reduction in impervious spaces:	0	%

E_g= 0.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 17.06 %



Results: Type 2-VII

Demand

AADD:	684.6	L/day
Total roof area:	200	m^2
Green roof area:	200	m^2
Average daily roof runoff (without green roof or	308.8833	L/day
Daily average greywater produce	341.124	L/day
Average daily stormwater reduction (Green roof):	154.44	L/day
Average daily rainwater utilised:	177.520	L/day

E_r = 51.07 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	25.93	25.93

E_d= 25.93 %

Green roof:

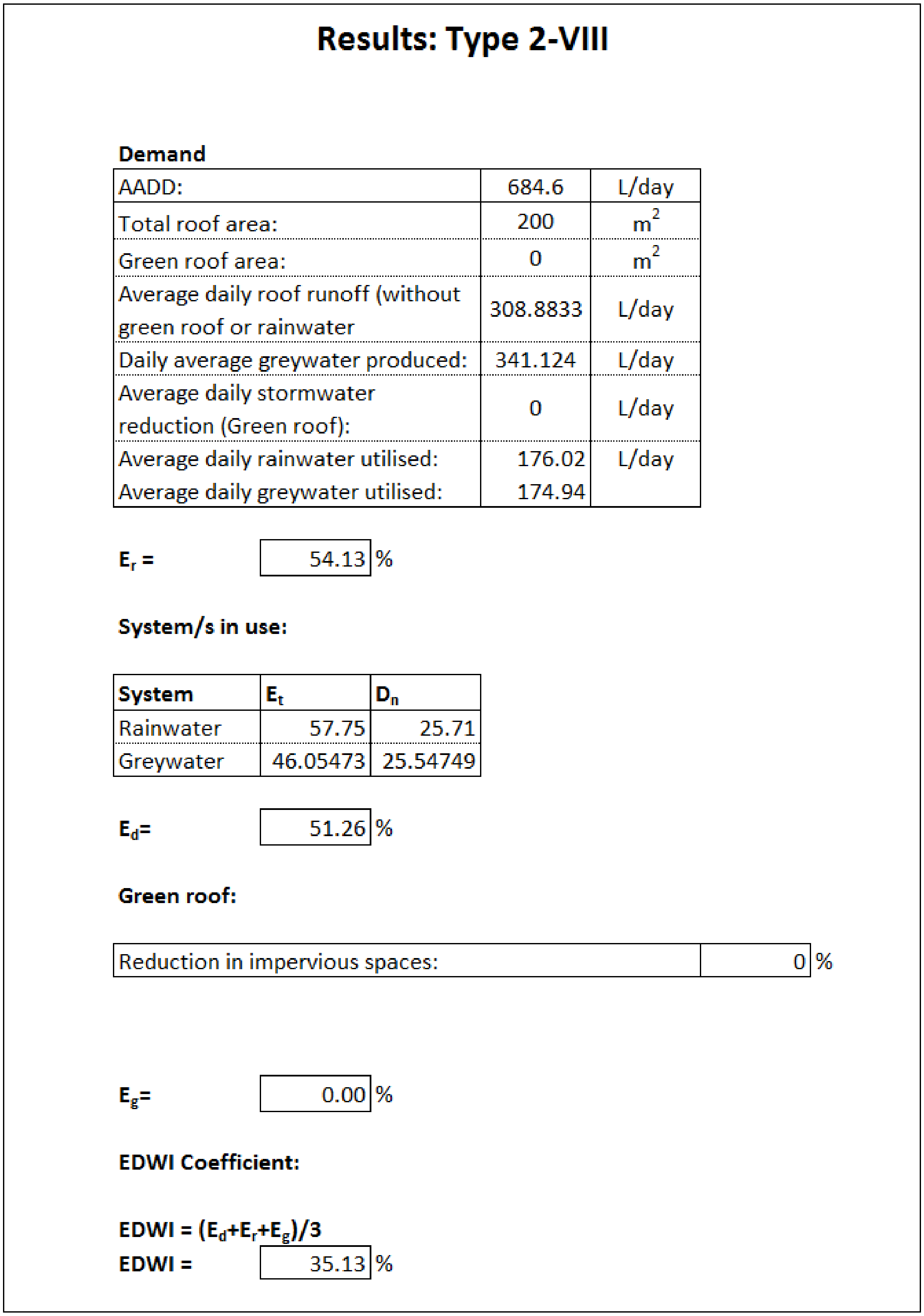
Reduction in impervious spaces:	100 %

E_g= 100.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 59.00 %



Results: Type 2-VIII

Demand

AADD:	684.6	L/day
Total roof area:	200	m^2
Green roof area:	0	m^2
Average daily roof runoff (without green roof or rainwater	308.8833	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	0	L/day
Average daily rainwater utilised:	176.02	L/day
Average daily greywater utilised:	174.94	

E_r = 54.13 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	57.75	25.71
Greywater	46.05473	25.54749

E_d= 51.26 %

Green roof:

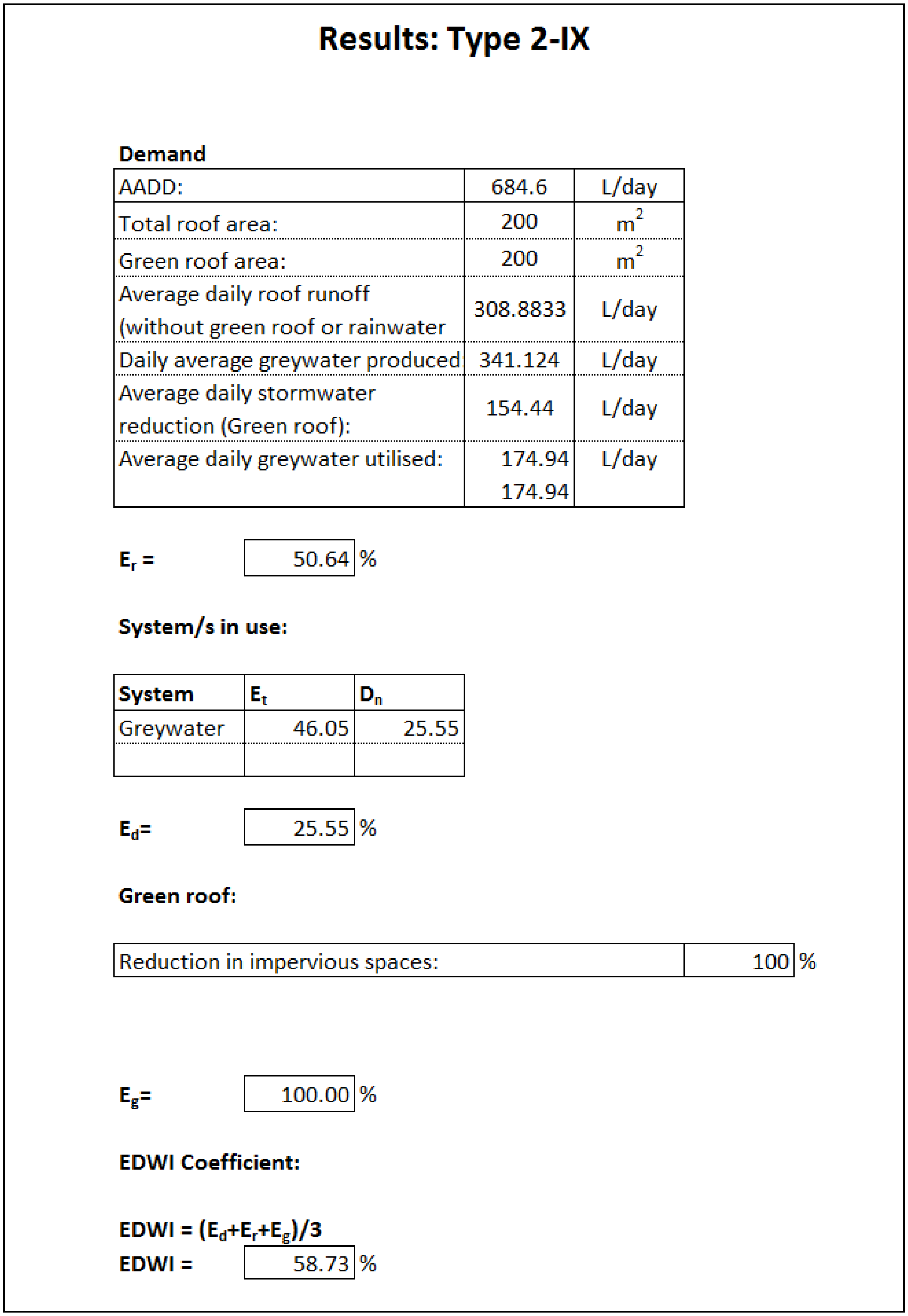
Reduction in impervious spaces:	0	%

E_g= 0.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 35.13 %



Results: Type 2-IX

Demand

AADD:	684.6	L/day
Total roof area:	200	m^2
Green roof area:	200	m^2
Average daily roof runoff (without green roof or rainwater	308.8833	L/day
Daily average greywater produced	341.124	L/day
Average daily stormwater reduction (Green roof):	154.44	L/day
Average daily greywater utilised:	174.94 174.94	L/day

E_r = 50.64 %

System/s in use:

System	E_t	D_n
Greywater	46.05	25.55

E_d= 25.55 %

Green roof:

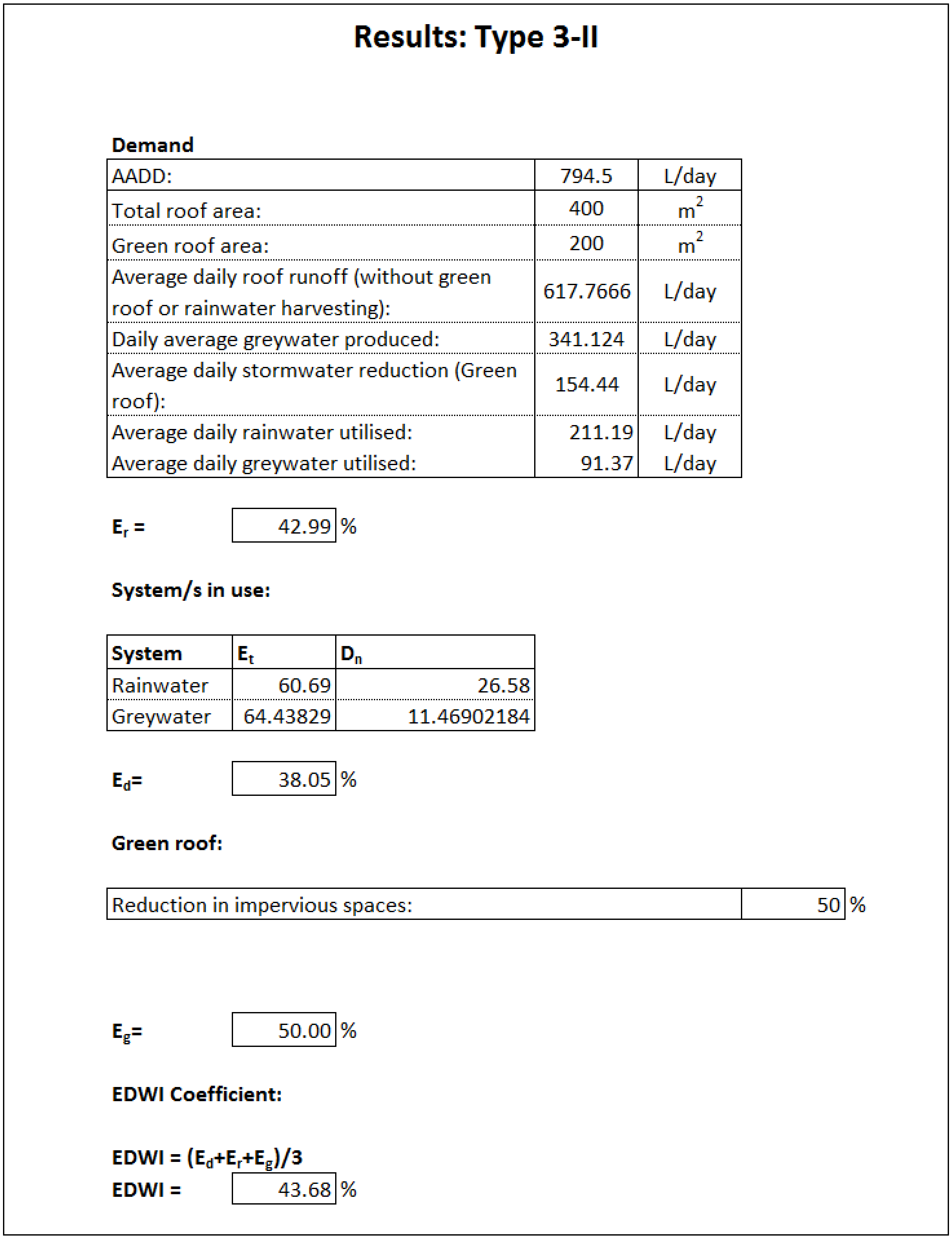
Reduction in impervious spaces:	100	%

E_g= 100.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 58.73 %



Results: Type 3-II

Demand

AADD:	794.5	L/day
Total roof area:	400	m^2
Green roof area:	200	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	617.7666	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	154.44	L/day
Average daily rainwater utilised:	211.19	L/day
Average daily greywater utilised:	91.37	L/day

E_r = 42.99 %

System/s in use:

System	E_t	D_n
Rainwater	60.69	26.58
Greywater	64.43829	11.46902184

E_d= 38.05 %

Green roof:

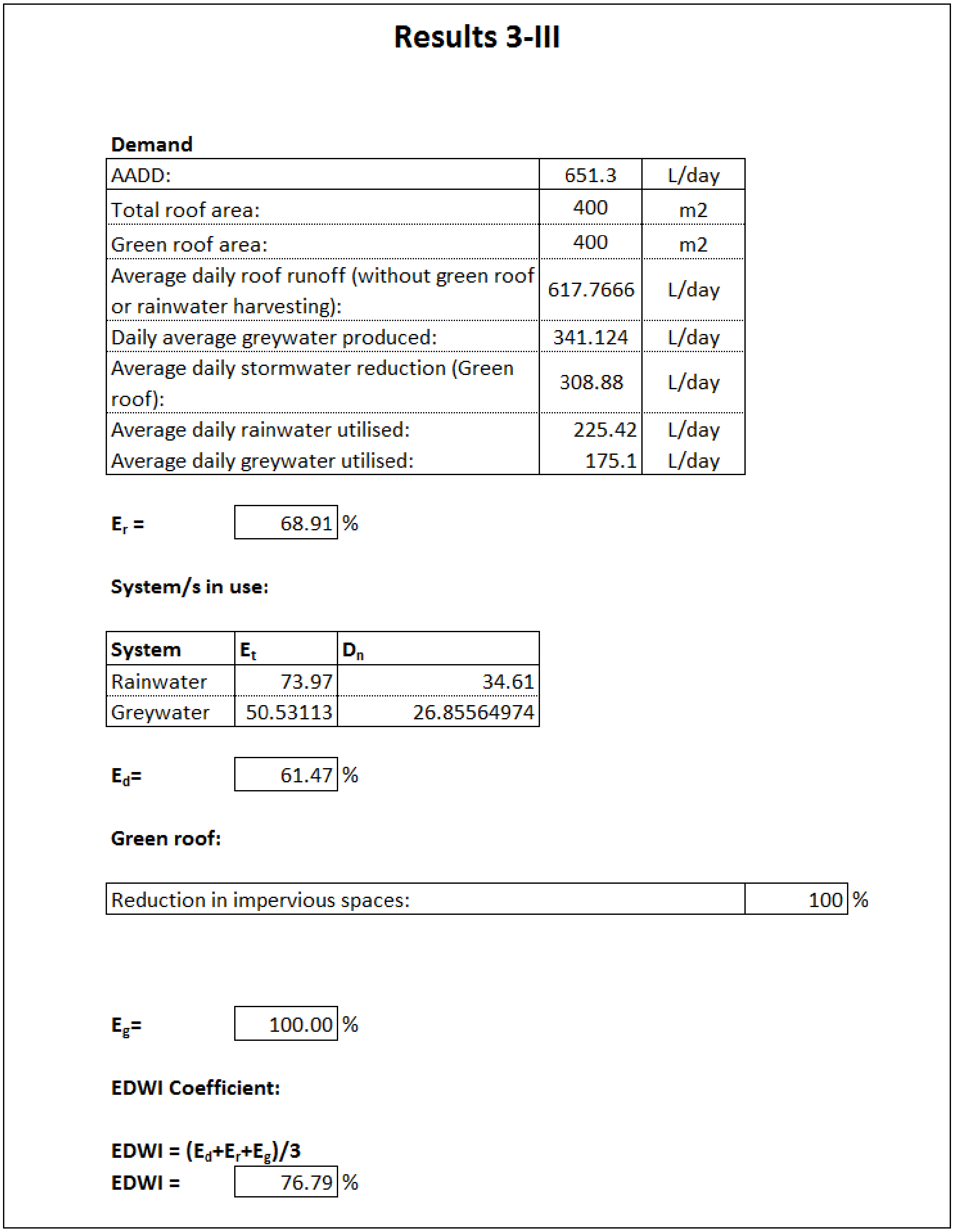
Reduction in impervious spaces:	50	%

E_g= 50.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 43.68 %



Results 3-III

Demand

AADD:	651.3	L/day
Total roof area:	400	m2
Green roof area:	400	m2
Average daily roof runoff (without green roof or rainwater harvesting):	617.7666	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	308.88	L/day
Average daily rainwater utilised:	225.42	L/day
Average daily greywater utilised:	175.1	L/day

E_r = 68.91 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	73.97	34.61
Greywater	50.53113	26.85564974

E_d= 61.47 %

Green roof:

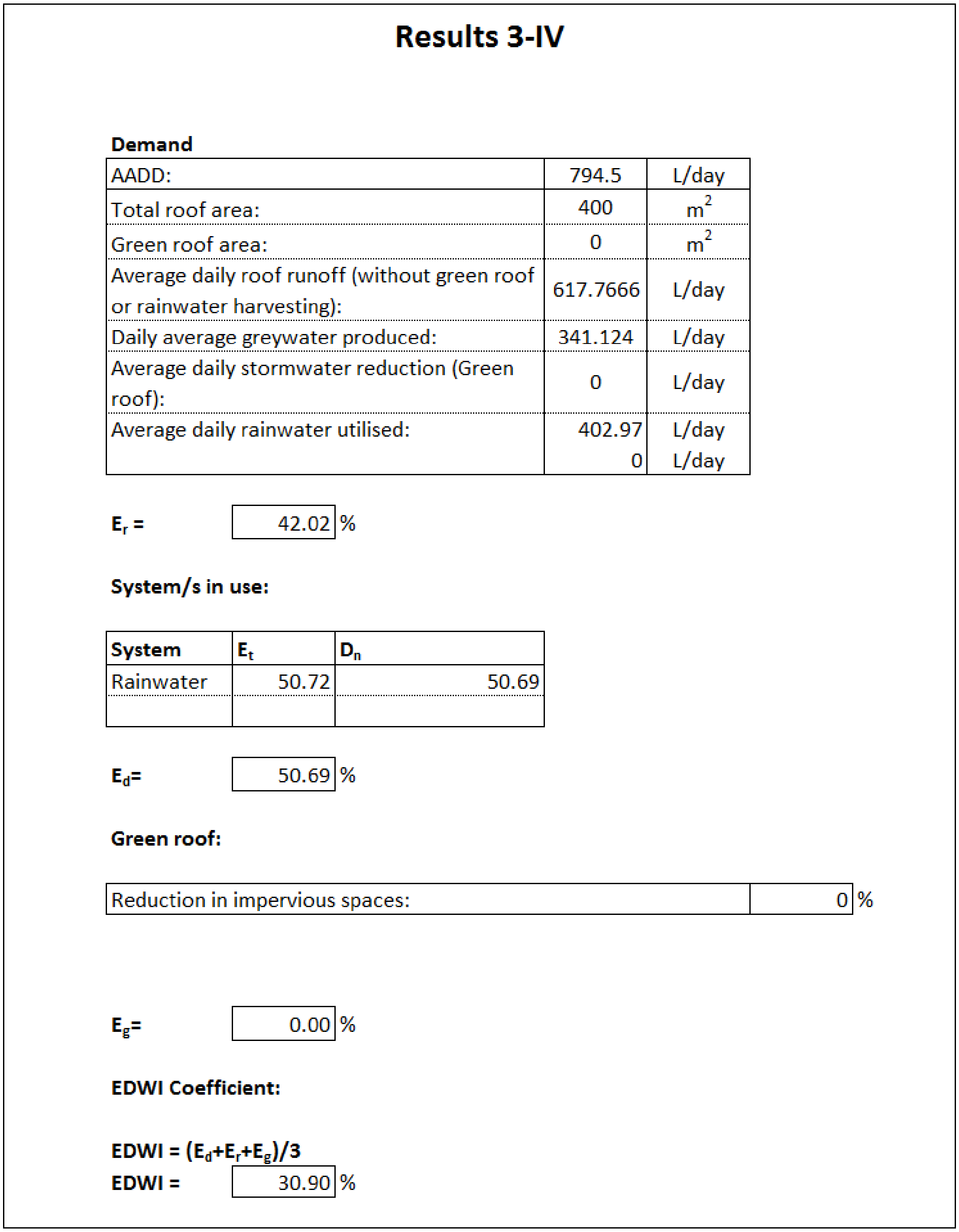
Reduction in impervious spaces:	100	%

E_g= 100.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 76.79 %



Results 3-IV

Demand

AADD:	794.5	L/day
Total roof area:	400	m^2
Green roof area:	0	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	617.7666	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	0	L/day
Average daily rainwater utilised:	402.97	L/day
	0	L/day

E_r = 42.02 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	50.72	50.69

E_d= 50.69 %

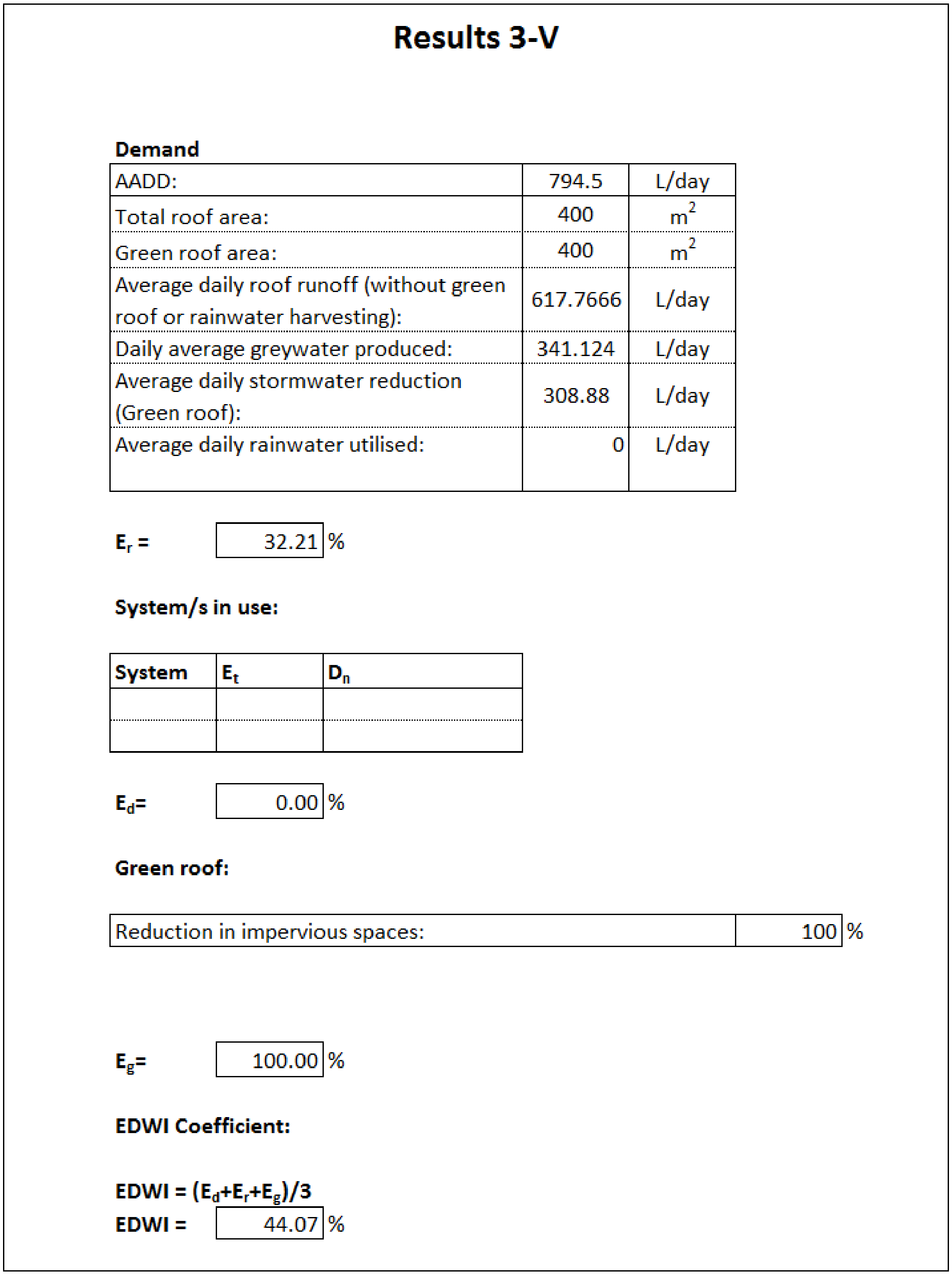
Green roof:

Reduction in impervious spaces:	0	%

E_g= 0.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$
EDWI = 30.90 %



Results 3-V

Demand

AADD:	794.5	L/day
Total roof area:	400	m^2
Green roof area:	400	m^2
Average daily roof runoff (without green roof or rainwater harvesting):	617.7666	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	308.88	L/day
Average daily rainwater utilised:	0	L/day

E_r = 32.21 %

System/s in use:

System	**E_t**	**D_n**

E_d= 0.00 %

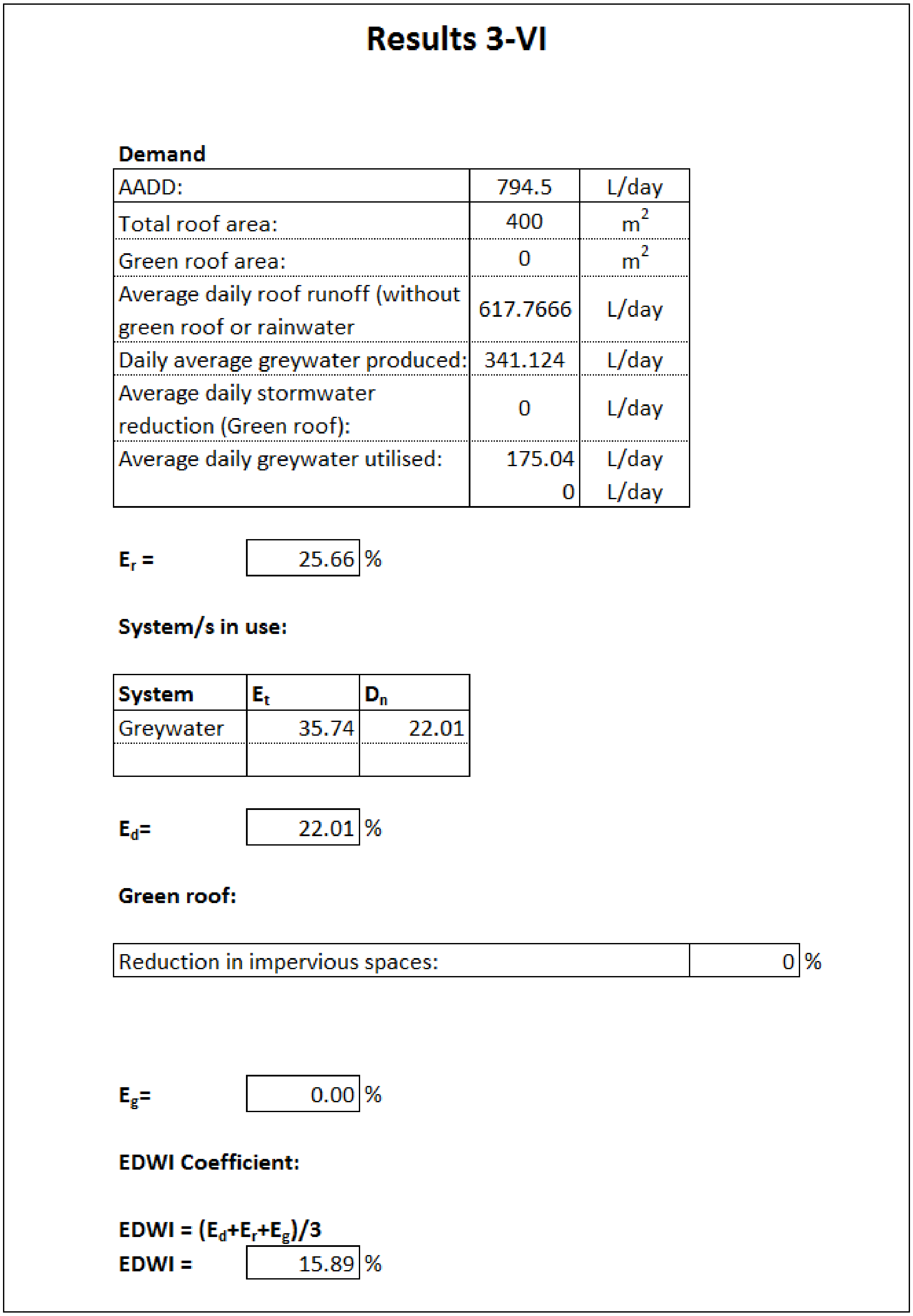
Green roof:

Reduction in impervious spaces:	100	%

E_g= 100.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$
EDWI = 44.07 %



Results 3-VI

Demand

AADD:	794.5	L/day
Total roof area:	400	m^2
Green roof area:	0	m^2
Average daily roof runoff (without green roof or rainwater	617.7666	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	0	L/day
Average daily greywater utilised:	175.04 0	L/day L/day

E_r = 25.66 %

System/s in use:

System	**E_t**	**D_n**
Greywater	35.74	22.01

E_d= 22.01 %

Green roof:

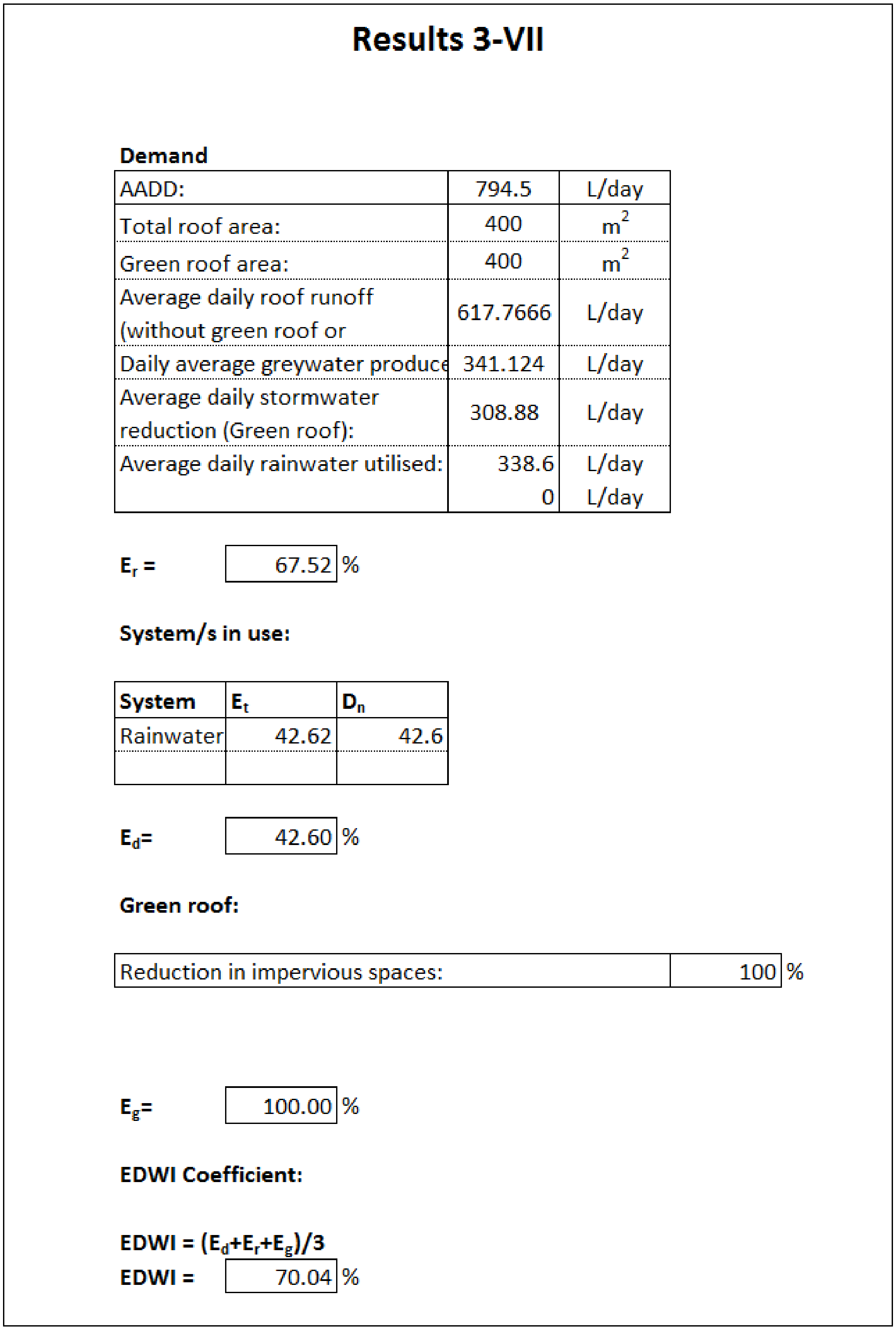
Reduction in impervious spaces:	0 %

E_g= 0.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 15.89 %



Results 3-VII

Demand

AADD:	794.5	L/day
Total roof area:	400	m^2
Green roof area:	400	m^2
Average daily roof runoff (without green roof or	617.7666	L/day
Daily average greywater produce	341.124	L/day
Average daily stormwater reduction (Green roof):	308.88	L/day
Average daily rainwater utilised:	338.6 0	L/day L/day

E_r = 67.52 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	42.62	42.6

E_d= 42.60 %

Green roof:

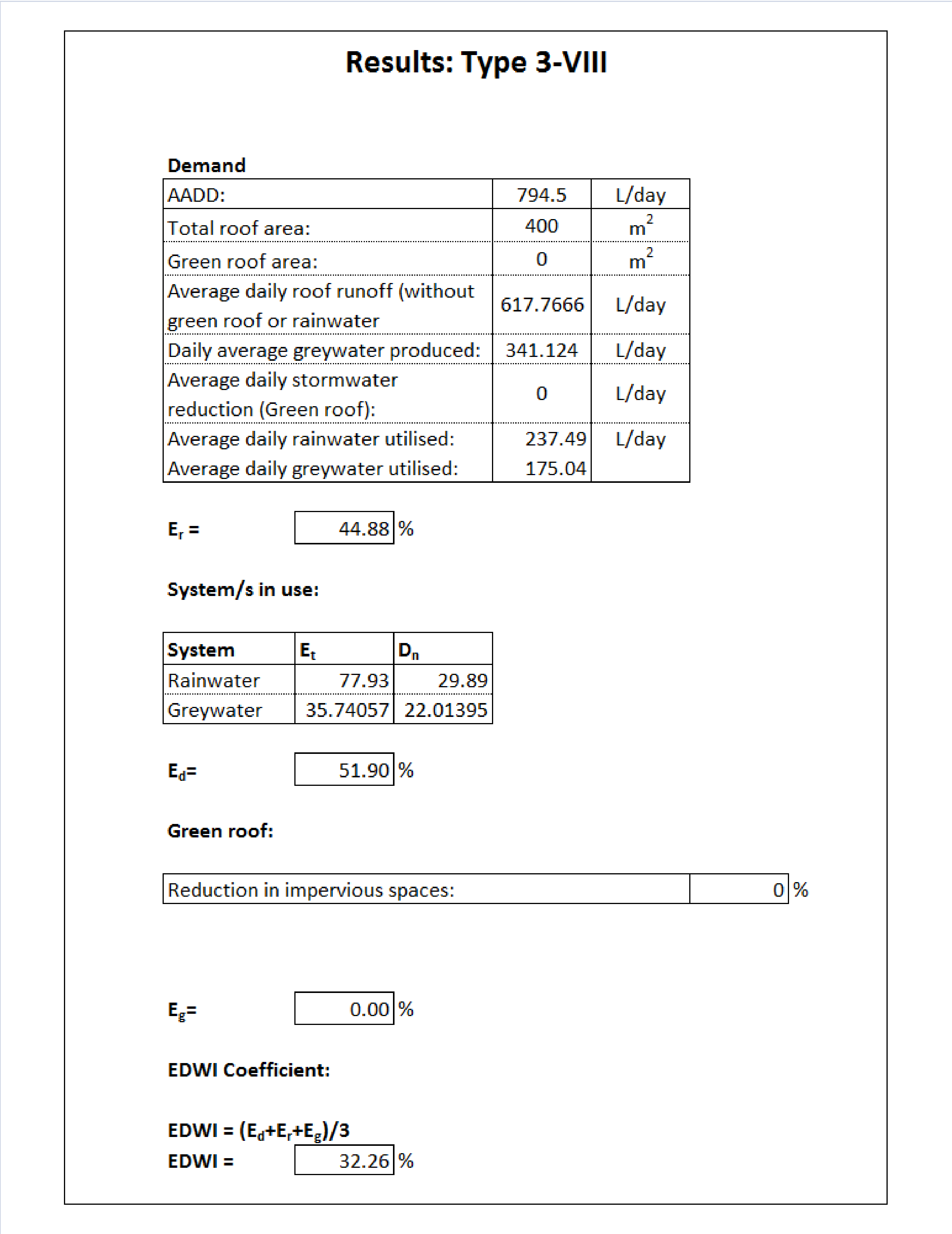
Reduction in impervious spaces:	100	%

E_g= 100.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 70.04 %



Results: Type 3-VIII

Demand

AADD:	794.5	L/day
Total roof area:	400	m^2
Green roof area:	0	m^2
Average daily roof runoff (without green roof or rainwater	617.7666	L/day
Daily average greywater produced:	341.124	L/day
Average daily stormwater reduction (Green roof):	0	L/day
Average daily rainwater utilised:	237.49	L/day
Average daily greywater utilised:	175.04	

E_r = 44.88 %

System/s in use:

System	**E_t**	**D_n**
Rainwater	77.93	29.89
Greywater	35.74057	22.01395

E_d= 51.90 %

Green roof:

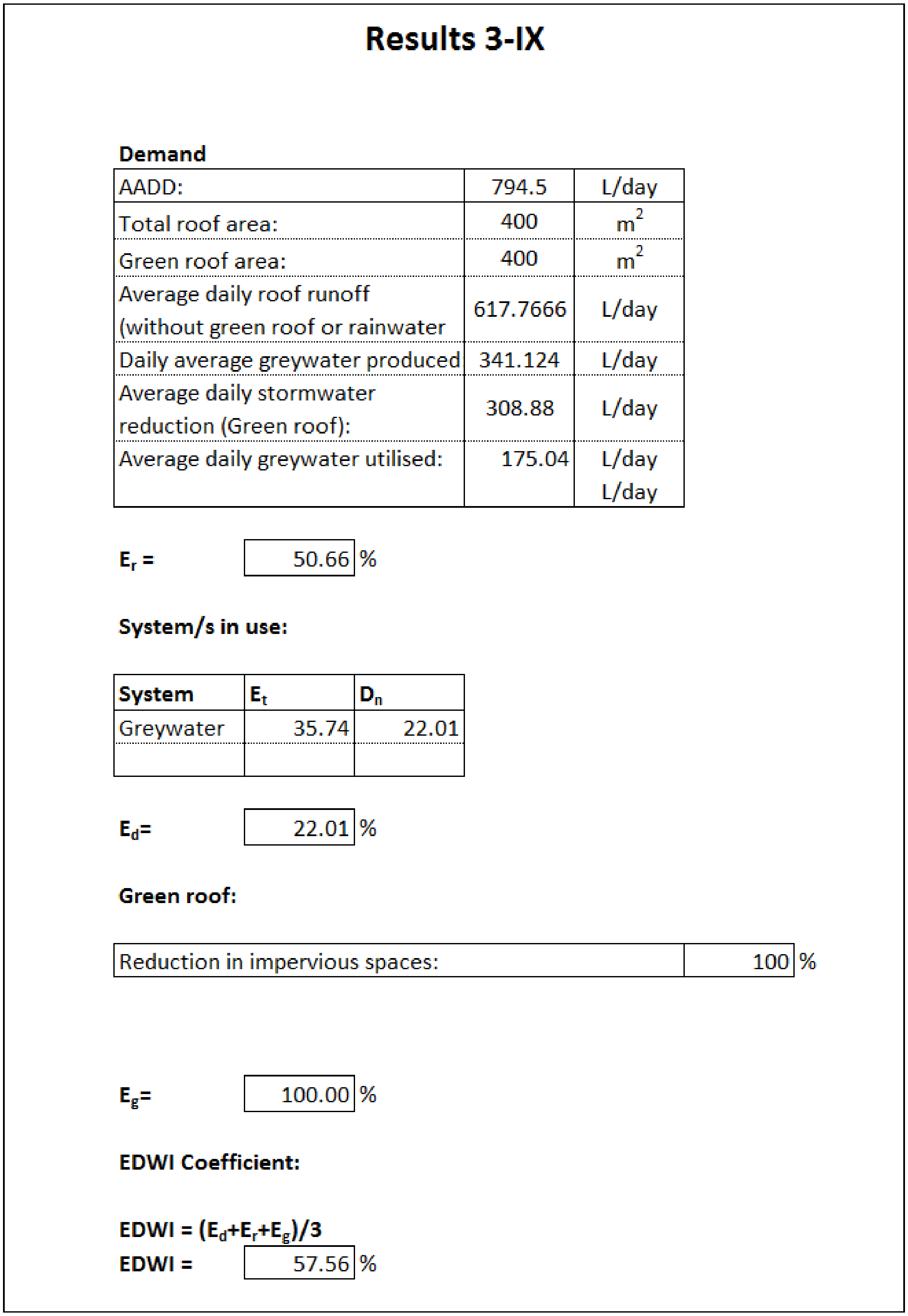
Reduction in impervious spaces:	0	%

E_g= 0.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$

EDWI = 32.26 %



Results 3-IX

Demand

AADD:	794.5	L/day
Total roof area:	400	m^2
Green roof area:	400	m^2
Average daily roof runoff (without green roof or rainwater	617.7666	L/day
Daily average greywater produced	341.124	L/day
Average daily stormwater reduction (Green roof):	308.88	L/day
Average daily greywater utilised:	175.04	L/day
		L/day

E_r = 50.66 %

System/s in use:

System	**E_t**	**D_n**
Greywater	35.74	22.01

E_d= 22.01 %

Green roof:

Reduction in impervious spaces:	100 %

E_g= 100.00 %

EDWI Coefficient:

EDWI = $(E_d+E_r+E_g)/3$
EDWI = 57.56 %