An investigation into untreated greywater as supplementary household water source to augment potable municipal supply with consideration of associated risks.

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Dissertation presented for the degree of Doctor of Philosophy in Civil Engineering in the Faculty of Engineering at Stellenbosch University.

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April 2022

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Abstract

Despite the available body of research regarding supplementary household water sources and in particular, greywater use, there is a critical gap when it comes to understanding the uptake of untreated greywater in suburban areas and the trade-off between the risks and potential water savings. This dissertation focuses on untreated greywater use in residential, fully serviced houses equipped with regular water use appliances and with conventional waterborne sewers. The main objective is to gain an improved understanding of the uptake of untreated greywater and the potential for use and application in suburban areas by exploring the trade-off between expected water savings (associated with quantity) and potential risks (associated with quality) as related to untreated greywater use.

This study starts with addressing on-site supplementary household water sources with a focus on groundwater abstraction, rainwater harvesting, and greywater use as available non-potable supplementary water sources to residential consumers. The legal position in South Africa and an end-use model to assess the theoretical impact of these sources on water demand in formal residential areas, is presented. The model provides valuable strategic direction and indicates a significant theoretical reduction in potable municipal water demand of between 55% and 69% for relatively large properties with irrigated gardens when supplementary household sources are maximally utilised (when compared to exclusive municipal use as a baseline). This load reduction on piped reticulation systems could be an advantage through augmenting municipal supply. However, water service planning and demand management are complicated by the introduction, and possible future decommissioning, of any household water source. The trade off between the advantages and disadvantages of this load reduction defines whether there is a nett positive benefit linked to the use of the household water sources. Groundwater is the household water source considered to have the most notable penetration and intensity to impact potable water demand in residential areas and is coupled to a relatively low risk in terms of water quality relative to other uses such as greywater use. Groundwater, however, has the biggest barrier to entry and requires the highest capital investment of the three supplementary household water sources. The distinct trade off between the advantages and disadvantages of untreated greywater, particularly in comparison to the other supplementary household water sources, provides justification towards it being the focus of this study.

Untreated greywater use at household level is an accessible water source to supplement non-potable water requirements in times of emergency water curtailments, but poses various risks to the consumer, the wider community, infrastructure and the environment. Little is known about unregulated, untreated greywater use practices in suburban communities where consumers have become accustomed to reliable potable water supplied via a pressurised, piped distribution system. There is a lack of knowledge regarding the sources of greywater used, collection methods, -storage and -distribution, the application points, the level of treatment (if any) and the perceived risks related to the greywater use. The City of Cape Town was selected as a case study site for research into greywater use under the threat of “Day Zero” and stringent water restrictions, implemented during the 2017/2018 summer season. A consumer survey and analysis of relevant online forums was conducted in order to obtain the necessary

information. Greywater use practices from a sample group of 351 consumers were identified and classified. Untreated greywater use was found to be common, mainly for garden irrigation and toilet flushing. The results point to high-risk activities in the study group.

By using these reported ad hoc greywater use practices identified through the Cape Town case study, the volume of untreated greywater used by households in formal residential settings was evaluated by means of a stochastic end use model. Untreated greywater use practices (e.g. bucketing) were found to reduce water consumption in a single person suburban household by less than 10%, which is lower than values reported in literature. This relatively low volume weighed up against the high risk of using untreated greywater may result in a negative nett benefit, providing decision making insights for both water service providers and consumers. This quantification of the volumes associated with untreated ad hoc greywater use is the first step in understanding the trade-off between expected water savings (quantity) and potential risks (quality) of untreated greywater use.

The second component of the water saving-risk trade off involved an investigation of untreated greywater quality and related risks, through a statistical analysis of greywater quality results, as sourced from South African studies. Greywater sources included were the bathroom, kitchen, laundry, mixed and general residential sources. Variability in terms of each of the reported physical, chemical and microbiological constituents by source and between result sets was noted. Statistically significant differences were evident between the pH, conductivity and phosphorous values of certain sources. A risk assessment undertaken for each of the constituents revealed further variability. The constituent with the highest number of high-risk samples was total dissolved solids, although further research into specific constituent elements that are of real danger to humans is warranted here.

The finding that water savings due to untreated greywater through manual collection methods is <10% is markedly less than the water savings through the use of multiple household water sources (up to 69% for large properties). This coupled with the relatively high risk and high consequences in greywater practices in terms of public health, the environment, and infrastructure, given its variability, provide insight into the quality-quantity space. There is a need for a more nuanced view of the potential potable savings associated with greywater use and a need for improved risk management.

Risk management and drivers of consumer decision making in the water use space were therefore explored further. As a result, a decision-making matrix was designed as an interim conceptual tool to assist consumers when faced with water use decisions during emergency drought conditions.

This research is unique in that while the use of greywater with purpose-built infrastructure and treatment systems has been studied for a number of locations and configurations, the practices used by individuals in the absence of such infrastructure was not well understood. This study has shed light on the reported volume of untreated greywater used by households in formal residential settings, based on reported ad hoc greywater use practices and on the extent of these potentially risky practices. A novel holistic picture of the risks and trade-offs associated with untreated greywater use was developed, allowing for advancement of knowledge in the field.

Acknowledgements

I would like to acknowledge and express my sincere gratitude to my supervisor Prof. H.E. Jacobs. His belief, guidance, late night emails, and input were greatly appreciated.

I would also like to give special thanks to my family. To Mum- for planting the seed and being a role model, to Dad- for asking questions, to Mark- for patience, continuously supporting my ideas and endless cups of coffee, to my Children – for your resilience, bringing me back to reality and your love.

Finally, I would like to thank God for leading me through.

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ABBREVIATIONS AND ACRONYMS

AADD	Average Annual Daily Demand
ALARP	As Low As Reasonably Practicable
AMDD	Average Monthly Daily Demand
BN	Binomial
CFU	Colony Forming Units
COD	Chemical Oxygen Demand
D	Duration
DALY	Disability Adjusted Life Year
DC	Discrete
DIY	Do It Yourself
DWAF	Department of Water Affairs
ET	Evapotranspiration
F	Frequency
FV	Fixed Value (constant)
GAP	Groundwater Abstraction Point
GI	Garden Irrigation
HH	Household
HWS	Household Water Sources
I	Flow rate
ISS	International Space Station
IWS	Intermittent Water Supply
LN	Lognormal
LSD	Least Significant Difference
NM	Normal
Po	Poisson
R	Rainfall
REUM	Residential End Use Model
RO	Reverse Osmosis
SAR	Sodium Adsorption Ratio
SDA	Soap and Detergent Association

TR	Triangular
TSS	Total Suspended Solids
UN	Uniform
UV	Ultraviolet
V	Volume
WDS	Water Distribution System
WERF	Water Environment Research Foundation
WHO	World Health Organisation
WISA	Water Institute of South Africa
WRC	Water Research Commission
WU	Water Use

CHAPTER 1. INTRODUCTION

BACKGROUND AND RATIONALE

The world's potable water sources are under increased strain due to urbanisation, industrialisation and decreasing supply due to the potential of climate change, high pipe system losses, low adaptability of existing water infrastructure and continued freshwater pollution (Oteng Peprah *et al.*, 2018; Friedler and Gross, 2019). In South Africa, severe drought conditions have been experienced in recent years in many parts of the country with the implementation of stringent water restrictions in many local municipalities in the Western and Eastern Cape in particular. The uptake of supplementary household water sources (HWS) including rainwater, groundwater (Wright and Jacobs, 2016) and greywater - even in regions serviced by potable water distribution systems (WDS) - is inevitable (Nel and Jacobs 2019; Friedler and Gross, 2019). Greywater is a relatively accessible supplementary HWS with a high potential for on-site use and application and has advantages in terms of water savings, despite the risks related to poor quality (Carden *et al.*, 2018).

In poorly serviced areas, the informal use of greywater is common due to the relatively large distances that consumers have to convey water from a nearby standpipe (Carden *et al.*, 2007a, 2007b; Mzini and Winter, 2015). Many greywater studies to date have therefore focused on dense informal settlements (e.g. Carden *et al.*, 2007a, 2007b). Other national and international greywater related research includes greywater use for toilet flushing (e.g. Ilemobade *et al.*, 2013), greywater treatment systems (e.g. Thakur and Chauhan, 2013), greywater characterisation studies (e.g. Eriksson *et al.*, 2002), greywater generation rates based on empirical studies (e.g. Al-Hamaiedeh and Bino, 2010) and greywater public health and environmental risks (e.g. Busgang *et al.*, 2015; Ottoson and Stenstrőm, 2003).

Despite the available body of research regarding greywater use, there is a critical gap when it comes to understanding the uptake of *untreated* greywater in suburban areas and the trade-off between the risks and potential water savings. This dissertation therefore focuses on greywater use in residential fully serviced houses equipped with regular water use appliances, with a reliable supply of potable water and conventional waterborne sanitation practices.

An improved understanding of both the positive and negative impacts of untreated greywater use in a suburban area is needed. Although various end-use models are available to assess the quantity and quality of household water use at the level of individual end-uses, greywater use is not catered for in current models. A novel end-use model, allowing for stochastic modelling of greywater use in terms of quantity and a further exploration of the associated risks at end-use level, allows for advancement of knowledge in the field.

RESEARCH PROCESS OVERVIEW

This research study followed an iterative, cyclical research process as outlined in Figure 1-1. Relevant steps of the process are discussed further below.

Figure 1-1 Research process overview

Problem Statement

The following problem statement was identified:

What is the uptake of untreated greywater in serviced suburban areas and the trade-off between the risks and potential water savings?

Research Aim, Objectives and Hypothesis

The aim of this doctoral study is to gain an improved understanding of the uptake of untreated greywater and the potential for use and application in suburban areas by exploring the trade-off between expected water savings (associated with quantity) and potential risks (associated with quality) related to untreated greywater use.

The following are the specific study objectives:

- Define greywater & supplementary HWS & assess the theoretical impact on water demand (end use model).
- Assess the extent of greywater use in a specific case study area, typical greywater sources & non potable end-uses, general risks & methods of collection, storage & distribution.
- Theoretically estimate the volume of greywater produced & water savings (end-use model).
- Compare the characteristics of reported South African greywater samples through a statistical analysis & undertake a risk assessment.

- Explore the quantity-quality nexus associated with greywater use.

The hypothesis of this research is:

Untreated greywater is employed by consumers particularly in times of crisis, often in ways that contradict what is suggested by research, despite relatively low water savings at household level and the risks to public health, the environment and water services infrastructure.

Study design, data collection and data analysis

The study design of this research centres around four pillars, namely: 1) supplementary HWS and their impact on potable water demand, 2) an investigation into untreated greywater use, 3) untreated greywater volumes/water savings and 4) untreated greywater quality. Literature reviews, end use models, a consumer survey, statistical analysis and risk assessment were utilised in order to meet the study objectives. Further detail on the study design and data collection and data analysis methods as related to these four pillars are outlined in the relevant chapters.

SCOPE AND LIMITATIONS

This research study focused exclusively on supplementary household water sources in urban residential areas - i.e., homes fully serviced by potable water distribution networks and piped sewers equipped with regular water use appliances. The particular focus was on untreated greywater use, as one of the available supplementary sources. For the purpose of this dissertation, the term greywater is defined as all household wastewater except toilet water (Casanova *et al.*, 2001).

Funding constraints and restrictions imposed by the Covid pandemic meant that no field measurements were undertaken. A sufficient amount of greywater quality data could, however, be sourced from literature and theoretical models with inputs based on surveys and previously recorded data, and thus enable relevant conclusions. Some reported greywater parameters employed in the study were average values or values obtained from single samples, which is a limitation in terms of depicting the true extent of the variability of greywater quality. A further consequence of the data limitation was that certain methodological approaches for risk management (e.g. as presented by Theron *at al.* 2010) could not be utilised.

CHAPTER OVERVIEW

Section 2.1.2 of the Stellenbosch University Generic guidelines for thesis and dissertation layout, rules and policies (updated 20 June 2016) state that doctoral dissertations may consist of written chapters, written articles, articles meant for publication in academic journals or a combination of these, provided that the articles included originated after the student registered for the doctoral study. This dissertation was structured as a combination of written chapters and published articles. The published work was reformatted for consistency while content remained unaltered.

This dissertation comprises 8 chapters. Chapter 1 provides an introduction to supplementary household water sources (HWS) and greywater in particular. Chapters 2, 4, 5 and 6 are papers that have been submitted or published in various journals.

Chapter 2 was published in journal *Water SA* and provides a review and describes the legal position of on-site supplementary HWS (groundwater, rainwater and greywater) to augment potable municipal supply in South Africa. An end-use model is presented and used to assess the theoretical impact of HWS on potable water demand in formal residential areas.

Chapter 3 presents a review of all supplementary HWS in terms of both quality and quantity and provides further rationale for the focus of this study which is untreated greywater use.

Chapter 4 presents an investigation into untreated greywater use practices by suburban households under the threat of intermittent water supply and was published in the Journal of Water, Sanitation and Hygiene for Development. Results of a consumer survey and analysis of online forums to obtain information on greywater sources, collection methods, storage and distribution, perceived risks, level of treatment, and application points were showcased.

Chapter 5 reports on an investigation into the quality-quantity nexus associated with untreated household greywater use. The content of Chapter 5 was submitted to the AQUA journal and is currently under review. An exploration of the quantity-quality nexus is presented. The water saving potential of untreated greywater use is evaluated by means of a stochastic end-use model and compared to the findings from literature. This quantification of the volumes associated with untreated ad hoc greywater use is the first step in understanding the trade-off between expected water savings (quantity) and potential risks (quality) associated with untreated greywater use.

Chapter 6 addresses a statistical analysis and risk assessment of untreated household greywater quality. The content of Chapter 6 was submitted to journal *Water SA* and is currently under review. The paper is the second step towards informing the water saving-risk trade off associated with residential untreated greywater use.

Chapter 7 presents a general discussion of greywater risk mitigation decision making while chapter 8 concludes with the findings of each of the chapters, and a concluding section on the study findings and recommendation for future research.

In this study, references as relevant to published research papers were included at the end of the applicable chapter. All other references for unpublished chapters were compiled at the end of the dissertation.

CHAPTER 2. SUPPLEMENTARY HOUSEHOLD WATER SOURCES TO AUGMENT POTABLE MUNICIPAL SUPPLY IN SOUTH AFRICA

The following chapter is a research paper as published in *Water SA.*

CONTEXT OF PAPER WITHIN THIS DISSERTATION

This paper, in addressing on-site supplementary household water sources (HWS) with a focus on groundwater abstraction, rainwater harvesting and greywater use, provides the foundation of this dissertation. Describing the legal position associated with the use of HWS in South Africa and assessing the theoretical impact on water demand in formal residential areas provides an initial insight into these available non-potable HWS. In each case, their application brings advantages and disadvantages, and the extent of these positive and negative impacts are identified in the paper as requiring further research. The trade off of these advantages and disadvantages is explored in the remainder of the dissertation with a focus on greywater use, in particular, as justified in Chapter 3.

The research results presented in this report emanate from a project funded by the Water Research Commission, project K5/1819 entitled: Strategic assessment of household on-site water as supplementary resource to potable municipal supply – current trends and future needs.

PUBLICATION STATUS

Published. This paper was accepted in revised form on 24 August 2017 by the open access journal, *Water SA.*

Reference: Nel N., Jacobs H.E., Loubser C. and du Plessis K.J.A. 2017 Supplementary household water sources to augment potable municipal supply in South Africa. *Water SA* 43 (4).

CONTRIBUTIONS

The extent of contributions by the various authors of this paper was as follows:

- *N. Nel (55%)* which included conceptualisation, literature review and partial write up, journal selection and relevant formatting, submission and review.
- C. Loubser (5%)
- K.J.A du Plessis (15%)
- H.E. Jacobs (25%)

The Declaration of contributions by co-authors can be found in Appendix A.

SUPPLEMENTARY HOUSEHOLD WATER SOURCES TO AUGMENT POTABLE MUNICIPAL SUPPLY IN SOUTH AFRICA

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ABSTRACT

This paper addresses on-site supplementary household water sources with a focus on groundwater abstraction, rainwater harvesting, and greywater reuse as available non-potable water sources to residential consumers. An end-use model is presented and used to assess the theoretical impact of household water sources on potable water demand in formal residential areas. Reliable potable municipal supply to urban consumers via the water distribution system is typically linked to relatively low uptake of household water sources. However, stringent water restrictions in some large South African cities that prohibit outdoor use and reports of intermittent water supply, have led to increased uptake of household sources in South Africa. This paper describes the legal position regarding such sources in South Africa, and describes an end-use model to assess the theoretical impact on water demand in formal residential areas. The model provides valuable strategic direction and indicates a significant theoretical reduction in potable municipal water demand of between 55% and 69% for relatively large properties when household sources are maximally utilised (when compared to exclusive municipal use as a baseline). This load reduction on piped reticulation systems could be an advantage in order to augment municipal supply, but water service planning and demand management are complicated by the introduction, and possible future decommissioning, of any household water source. The extent of both positive and negative impacts of household water sources requires further research.

Keywords: household water use, alternative resources, water demand

SUPPLEMENTARY WATER SOURCES

Rationale

Recent stringent water restrictions in various municipalities in South Africa as well as reports of intermittent water supply has led to increased uptake of supplementary household water sources (HWS) in relatively affluent suburbs. Outdoor use of potable water is often targeted by demand management campaigns and even banned during serious water restrictions. The current water restrictions in Cape Town entail a ban on all use of municipal drinking-quality water for outside and non-essential purposes (City of Cape Town, 2017). However, outdoor residential environments have been found to be extremely important to homeowners (Blaine *et al.*, 2012), also affecting residents' sense of social status or acceptance in the neighbourhood. Clayton (2007) found that gardening has important positive effects on individuals, as well as on the urban ecosystem. Also, a poorly maintained garden has been found to lower property value of not only that property, but also neighbouring ones (Clayton, 2007). Home owners with property in the market during water restrictions could fail to see outdoor water use as non-essential; the cost of water is rightly considered relatively low compared to even a small change in property value.

Consumers with suburban gardens are thus turning to supplementary water sources to meet garden irrigation demands, including rainwater (Beal *et al.*, 2012; Mukheibir *et al.*, 2014), groundwater (Wright and Jacobs, 2016; Botha and Jacobs, 2017) and greywater (Carden *et al.*, 2017). Introduction of a HWS would increase the quantity of household supply, with the perception of improved reliability of household water supply. The impact of supplementary water sources on the potable water supply and demand in formal residential areas is poorly understood.

OVERVIEW OF SUPPLEMENTARY HOUSEHOLD WATER SOURCES

A supplementary HWS is any water source that is available to a household (hh) to supplement potable supply from the water distribution system. The most common types of HWS, that form the focus of this paper, include groundwater abstraction, rainwater harvesting and greywater use. Milne (1979) reported almost 4 decades ago on these sources of “free water” and described ways to collect, store, treat, and distribute the water, with examples of how it has been successfully used for toilet flushing, garden irrigation, washing, bathing and even drinking.

Other alternative household sources include, for example: the use of water supplied via irrigation channels along streets, common in many towns in the Boland region of the Western Cape Province; the use of air conditioner condensate or geyser overflows; dehumidifiers; water abstracted directly from neighbouring mountain streams; stormwater use; importing bottled water from retail outlets for drinking purposes and importing non-potable water in relatively large containers for garden irrigation. Table 2-1 provides a summary of supplementary household water sources in the urban environment.

The available water from a HWS is commonly applied to meet garden irrigation (GI) demand, where water quality issues are often not of a high concern and the quality from the source is generally considered acceptable in view of the intended application (Botha and Jacobs, 2017). Application of greywater use as HWS for toilet flushing has been researched in the past (Grobicki and Cohen, 1999; Ilemobade *et al.*, 2012). For many of the intended end-uses water can be used directly without treatment (Milne, 1979), but issues regarding environmental pollution and community health (Govender *et al.*, 2011) are becoming increasingly important, especially for greywater use (Carden *et al.*, 2017).

Table 2-1: Overview of supplementary household water sources

Type of HWS	**Previous research**	**Comment based on earlier research**			
		Typical yield (Y) or Flow rate (Q) per household	Source water quality	Possible application	Advantages and disadvantages
Groundwater	Wright and Jacobs (2016)	Relatively high yield. 0.1L/s<Q<1.0L/s1	Normally non-potable, but depends on aquifer	Outdoor use and toilet flushing; no storage needed.	High yield possible, but not guaranteed; very high capital and high energy cost; possible environmental impact (e.g., lowering groundwater table)
Rainwater: not internally plumbed	Dobrowksy *et al.* (2014); Mukheibir *et al.* (2014); Fisher-Jeffes *et al.* (2017)	Varies notably2 Low summer yield in winter rainfall regions with Y ≈ 0 in peak summer time	Non-potable	Outdoor use, hand washing of clothes, house cleaning (e.g. floors).	Yield is a function of rainfall, storage and roof size; potential mismatch between seasonal rainfall and highest demand; high capital cost; possible environmental impact (e.g., reduced urban streamflow impacts natural ecosystems)
Rainwater: Internally plumbed tanks	Beal *et al.* (2012)	Varies notably2 Queensland Australia: Y reported to vary from 54 - 260L/hh/d, with ave. 137L/hh/d.	Non-potable	As above plus toilet flushing and clothes washing	
Greywater	Christova-Boal *et al.* (1996); Eriksson *et al.* (2003); WHO (2006)	Reported Y varies from 218 - 346 L/hh/d; or about ±100 L/c/d. Jacobs and van Staden, 2008);	Non-potable, relatively poor quality (Maimon *et al.*, 2010)	Outdoor irrigation (Carden *et al.*, 2017); toilet flush (Ilemobade *et al.* (2012).	Relatively constant yield; yield reduces in line with indoor water savings; relatively high community health risk and environmental risks; high capital and energy cost if treated
Roadside irrigation channels	N/A	Depends on the property “water rights”	Non-potable, poor quality	Flood irrigation methods (incl. backyard vegetable gardens and urban agriculture)	Not common in urban areas; limited to rural towns; use is normally limited to flood irrigation

Abstraction from nearby rivers or streams	N/A	Depends on the property “water rights”	Non-potable (assuming urban streams)	Outdoor use.	
Imported water (potable bottled water)	Doria (2006)	Typically limited to potable consumption < ± 2.0 L/c/d	Potable.	Human consumption	High carbon footprint; exceptionally low yield; has to be physically imported
Containerised imported water (non-potable)	N/A	Delivered by vendors via road in containers (typical during serious water restrictions)	Non-potable	Outdoor use.	May be illegal to sell water in this way to other consumers; expensive; has to be physically imported
Air conditioner condensate	N/A	Relatively low Y for households	N/A	Outdoor - at point of overflow	Limited to air conditioned spaces; exceptionally low yield
Atmospheric water generators (dehumidifiers)	N/A	32L/day to 1kL/day	Potable	Indoor; potable	High capital and high energy cost
Geyser (hot water) overflow	N/A	Relatively low Y for households	N/A	Outdoor - at point of overflow	Emergency overflow only; very low yield
Stormwater (excludes rainwater harvesting)	Fisher-Jeffes *et al.* (2017)	Possible future application: urban stormwater is not typically abstracted from the stormwater system beyond the property boundary for household use, but could be feasible in exceptional cases.			
Seawater	N/A	Possible future application: coastal properties have access to the sea and could potentially obtain rights to abstract and treat seawater.			

Notes: 1) Depends on the abstraction method, infrastructure (e.g. pump capacity) and geohydrology of the consumer’s plot.

2) Critical assumptions relate to tank size, roof collection size, and system components or configuration; parameters that vary notably from one region to another and one house to the next.

3) Internally plumbed rainwater tanks (IPT) substitute mains water in the laundry and toilets and are ideally installed during house construction.

4) Maimon *et al.* (2010) note that the use of untreated greywater is not recommended due to associated risks, even for single households.

IMPACTS OF A HWS ON WATER SERVICES

The application of a HWS has an impact on all municipal water infrastructure:

- an apparent load reduction is experienced on the potable water distribution system with reduced annual average use, reduced monthly use in peak periods, and reduced peak flows for any HWS used;
- for greywater use particularly, an apparent volumetric load reduction is experienced in the sewer system, with reduced sewage flow rates and increased pollutant concentrations due to the lower flow rate;
- rainwater harvesting and storage reduces the total rainwater running off to the stormwater system, and on-site storage tanks may attenuate the hydrograph peak in the stormwater system during small storm events thus inducing an apparent - albeit relatively insignificant - load reduction in the stormwater system (Fisher-Jeffes *et al.*, 2017).

The impacts noted above bring advantages and disadvantages in each case. If managed properly a HWS could hold numerous advantages from the viewpoint of the homeowner and service provider. In contrast, however, various concerns have been noted with introduction of a HWS. One of the most notable impacts of a HWS is reduced consumption, and reduced consumer billing, coupled with reduced income to the service provider. Consumers who can afford a HWS are often those who use water in the relatively expensive tariff blocks for outdoor irrigation (assuming a block tariff structure), thus contributing notably to the service provider’s coffers when using potable water for garden irrigation. Introducing a HWS reduces the generated income from higher tariff blocks. Consumers with a HWS are typically in a position to pay water bills (non-payment is a notable problem in developing countries, especially in lower income areas). Decreased income from water sales due to uptake of a HWS is often not appreciated by decision makers, nor is the topic well researched.

The following aspects also require further investigation:

- Guidelines for estimating water use are often based on analyses of data from consumer water meters, which would no longer accurately reflect the actual total water needs of residential consumers after introduction of a HWS. What would happen to the potable water demand if the HWS were decommissioned in the future, with supply drawn from the piped system again?
- Reduced sewer flows could lead to clogging of sewers and higher pollutant loads at the treatment plant; and reduced stormwater runoff could lead to drainage systems clogging due to insufficient flow rates during peak events, with minimum flow velocity needed to flush the system.

GROUNDWATER

Groundwater is abstracted via one of various "structures" delivering it from under the ground surface to above the surface, including for example a borehole, well point, shallow well or even a fountain or spring. The term groundwater abstraction point (GAP) was adopted in this paper from work by Wright and Jacobs (2016) to describe abstraction of water from underground for terrestrial application, typically garden irrigation. Although research into the yield of GAPs is limited it is widely accepted that the flow rates and yields from different GAPS vary spatially and temporally; for example, some GAPS (especially shallow well-points) may “dry up” as the groundwater table drops below the abstraction point during a dry period.

GREYWATER USE

Greywater is a term often used to describe sullage. "Sullage" is defined in the Oxford dictionary as, "waste from household sinks, showers and baths, but not toilets". Some authors, however, note that greywater excludes wastewater from kitchen sinks. According to Zeisel and Nolde (1995) black water includes wastewater from the toilet, dish washing and food preparation. Kreysig (1996) defined greywater as effluent from washbasins, showers and baths, and could include clothes and washing machine water. A more detailed classification is provided by Carden *et al.* (2017), considering 'light' (Class I and Class II) and 'dark' (Class III) greywater - noting also that the end-use source of greywater should not be used as the sole determinant in classifying greywater into the different classes.

Greywater represents a notable water source that would otherwise be wasted. Greywater use has the potential to alleviate the demand on potable water resources as well as reduce the inflow to wastewater treatment works. Furthermore greywater is also a potential source of nutrients for plant growth, particularly for users who cannot afford fertiliser and the soapy nature of greywater means that under some conditions it may act as a pest-repellent (Rodda *et al.*, 2011). Greywater is, however, inherently variable in quality and is most likely to be applied on a scale where quality monitoring is not feasible (Rodda *et al.*, 2011). A range of contaminants may cause disease and have a negative impact on the environment.

RAINWATER

The term rainwater harvesting implies the intentional diversion of rainwater from roofs to a storage tank. The definition does not include indirect application of rainwater, even if intentional, if it is not stored prior to application. In other words, the (possibly intentional) diversion of gutters into a garden bed would not constitute rainwater harvesting as per this definition. A rainwater harvesting system consists of a number of integrated system components, including a catchment area, a storage vessel and a distribution system. External factors such as climatic conditions, rainfall patterns and the end uses of rainwater, could drastically influence the viability of domestic rainwater harvesting systems (Fisher-Jeffes *et al.*, 2017). Dobrowksy *et al.* (2014) noted that acceptance of rainwater as a source and training of consumers to maintain and use the tank system optimally was essential to ensure that social development projects involving rainwater use would be sustainable. Mukheibir *et al.* (2014) revealed a data gap in knowledge about rainwater tank functionality and the performance of existing rainwater tank systems, noting also that ongoing maintenance of the rainwater system is essential to ensure continued substitution of potable water supplied via the distribution system.

METHODOLOGY

National and international literature was reviewed to gain an overview on HWS, including the application, the impact and the various types of sources. The legal framework relating to the most notable HWS use was then determined through a survey of relevant legislation. The residential end-use model (REUM) presented initially by Jacobs and Haarhoff (2004a) was used in this study to assess the theoretical impact of supplementary HWS on potable water demand. The initial Microsoft Excel based model was extended to include HWS options, with a focus on garden irrigation as an end-use. Various parameters for the modelling exercise were investigated and assumptions were made to describe the hypothetical household investigated.

LEGAL ASPECTS

The right to use water

The theoretical impact of HWS on potable water demand from the municipal supply is investigated in this paper, but of first importance is to learn whether the use of water from a HWS is permitted by law. The legal status regarding the use of HWS by individual home owners is not well delineated. At household level in serviced areas consumers obtain water from a Water Service Provider (WSP), which is normally the local municipality. The legal position is contained in the National Water Act (NWA) (Act No.36 of 1998) and to a limited extent also in the Water Services Act (WSA) (Act No.108 of 1997).

South African legislation - National Water Act

The main objective of the South African National Water Act (Act No.36 of 1998) is to make provision for the management of water resources in South Africa through relevant management structures (RSA, 1998). A HWS could be deemed a water resource. Of specific interest to the household user is the identification of what is considered as permissible use and the procedure associated with this use. It is considered essential to at least obtain some basic knowledge as to the legal implications concerned where a home owner uses groundwater, rainwater or greywater on the particular property where the water is captured. Carden *et al.* (2017) point out that, “some local authorities have introduced policies and by-laws which provide guidance relevant to the management and use of greywater for irrigation, but the status remains in doubt as long as the status of greywater use in terms of the national legislation is not clarified.”

Section 21 of the National Water Act (Act No.36 of 1998) states that, among others, the “taking of water from a resource”, constitutes a water use (RSA, 1998). In general terms a licence is required for any water use and the procedures are dealt with in the Act. Section 26 of the Act also empowers the Minister to make regulations to enforce the registration of all water uses (RSA, 1998). These regulations (Regulation 1352 published in Government Gazette No 20606, 12 November 1999) effectively require the registration of all water use activities within a specific time frame.

This could imply that home owners need to register HWS use with the DWS; however, water uses exempt from the registration process are provided in Section 10 of the Regulation and include:

- Schedule 1 use
- those not required in terms of a general authorisation issued
- water obtained from a bulk water supplier or other management structure.

A number of situations present where water can be used without a licence as stipulated in Section 22 of the Act (RSA, 1998):

"A person may only use water –

(a) without a license -

(i) if that water use is permissible under Schedule 1;

(ii) if that water use is permissible as a continuation of an existing lawful use; or

(iii) if that water use is permissible in terms of a general authorisation issued under section 39."

With reference to section 22 above, Schedule 1 water is defined in the Act as a user who is to (RSA, 1998):

(a) take water for reasonable domestic use in that person's household, directly from any water resource to which that person has lawful access;

(b) take water for use on land owned or occupied by that person, for -

(i) reasonable domestic use;

(ii) small gardening not for commercial purposes; and

(iii) the watering of animals (excluding feedlots) which graze on that land within the grazing capacity of that land, from any water resource which is situated on or forms a boundary of that land, if the use is not excessive in relation to the capacity of the water resource and the needs of other users;

(c) store and use run-off water from a roof.

Most household water uses could be considered Schedule 1 use. Rainwater from roofs, and boreholes for domestic purposes as stated above, could therefore be used without a licence by the consumer on the property where the HWS is located. Water from a HWS may not be sold to other consumers without a licence, because sale of water would constitute commercial activity (and would not be deemed Schedule 1 use). It is, however, still a requirement to ascertain whether a particular municipality could enforce registration of HWS sources in its area of jurisdiction via local by-laws.

An existing use, as is the case of a possible water right registered on an owner's title deed, does not need to go through an application for a licence process but can be continued until a verification or renewal of the licence is requested by the authority (for example property water rights to an irrigation channel running through town). In most cases the water use from these types of systems has been dealt with through the registration process by the responsible municipality or other relevant associated water management body. The registration of an existing use is compulsory in terms of section 151(1)(g) of the Act, stating that (RSA,1998):

> *(1) No person may -*
>
> > *(g) fail to register an existing lawful water use when required by a responsible authority to do so;*

The issuing of a licence will raise critical questions pertaining to the water use, such as whether the existing use is in fact a beneficiary use. The issuing of a licence will depend on these evaluation criteria and might influence the final volume of water for which a licence will be issued. Where no licence is required according to Section 22, a general authorisation would be issued, regulating the water use in specific areas. These authorisations stipulate the quantities of water that can be used in each area without a licence, but the use must still be registered and the final issuing of a licence will once again be subject to a number of critical evaluation criteria.

Water Services Act

The main objectives of the WSA are described in Section 2 of the Act and includes (RSA, 1997): *"The right of access to basic water supply and the right to basic sanitation necessary to secure sufficient water and an environment not harmful to human health or well-being..."*

This right is further emphasised in Section 3 of the Act and "basic water supply" is also defined in the Act as (RSA, 1997): *"...the prescribed minimum standard of water supply services necessary for the reliable supply of a sufficient quantity and quality of water to households, including informal households, to support life and personal hygiene..."*

In subsequent policy documents the Department of Water and Sanitation (RSA, 2001) has defined the minimum basic supply as 25 L/p/d. It is expected from each South African municipality to define these values in the Water Services Development Plan, which forms part of the municipal Integrated Development Plan. These minimum standards can be used in the evaluation of what constitutes a domestic use allowed for in the South African National Water Act.

The "legal rights" of a home owner to a HWS

In view of the above, the requirement for the registration of boreholes or the use of any "personal" household water source by an individual within the municipal area is not dealt with directly in the NWA or the WSA. However, the use of a HWS could be regulated through the issuing of appropriate by-laws by a specific municipality, thus enabling the authority to apply good water governing principles. In summary:

- The use of any HWS for domestic purposes on the consumer's own property in a serviced area could be deemed "legal" in the general case and no registration of the particular use is required, unless

- a municipality has followed the necessary procedures by which by-laws have been put in place thus regulating the registration of such use – in such a case a home owner may be required to register, with potential consequences should the home owner fail to comply.

CONCEPTUAL MODEL DESCRIPTION

Once the legal position of the consumer had been outlined, the theoretical impact of HWS on water demand from the municipal supply was rationally assessed by means of an end-use model. The point of departure was to consider the case of serious water restrictions where outdoor use is banned: any consumer with access to a HWS would thus attempt to maximise use from the HWS, thus minimising the draw from the potable distribution system. The impact of the HWS on volumetric supply was investigated by means of an end-use model. The model is presented schematically in Figure 2-1: Schematic presentation of end-use model and end-uses., showing the consumer water meter (M), and typical indoor and outdoor end-uses. The schematic depicts an end-use model similar to REUM.

Each of these end-uses can be considered independently, keeping in mind that each end-use could be supplied from a different water source, including one or more supplementary HWS. The possible supply sources and waste sinks for a particular end-use should be considered integrally, as presented in Figure 2-2 Schematic presentation of water sources and sinks or end use n. This study focused on households where potable water as primary water source is supplied from the water distribution system, and indoor use is wasted to the sewer system (bold outlines in Figure 2-2 Schematic presentation of water sources and sinks or end use n). Greywater would typically be applied at a different end-use to the one where the greywater was generated. If applied indoors, the wasted greywater should drain away to the sewer system. Water used outdoors drains to the stormwater system, evaporates, or percolates into the soil. From the perspective of HWS application, the most notable end-use n would be garden irrigation (grass and garden beds), where non-potable application and greywater use is deemed feasible in terms of quality, although not necessarily financially viable (Fisher-Jeffes *et al.*, 2017).

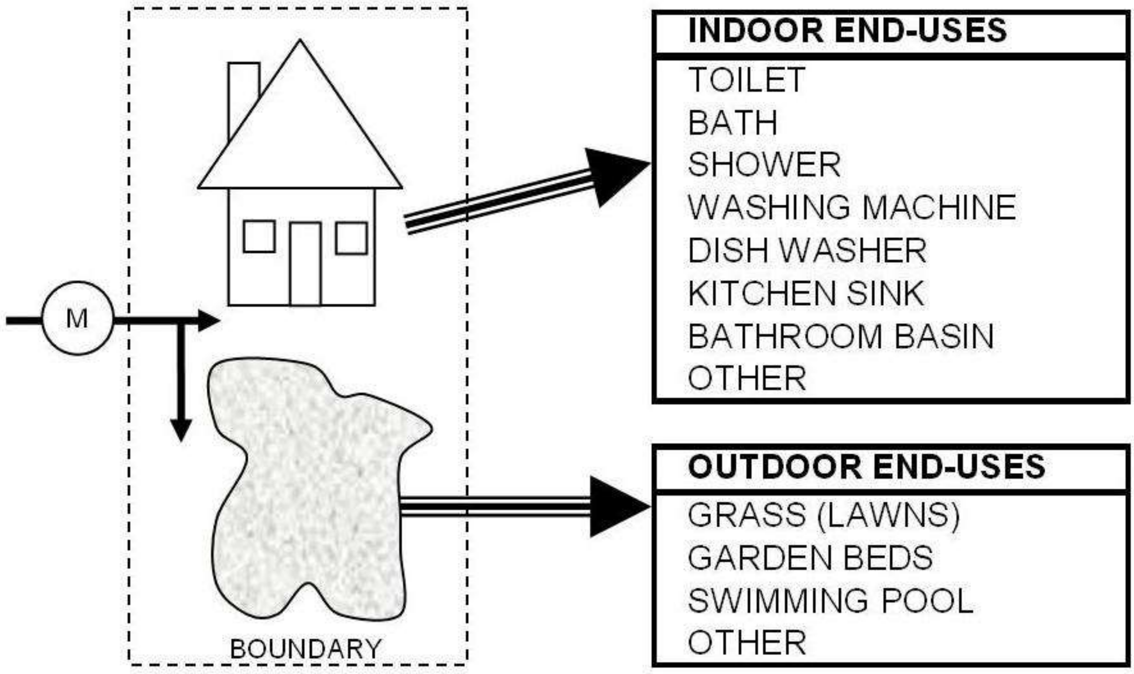

Figure 2-1: Schematic presentation of end-use model and end-uses.

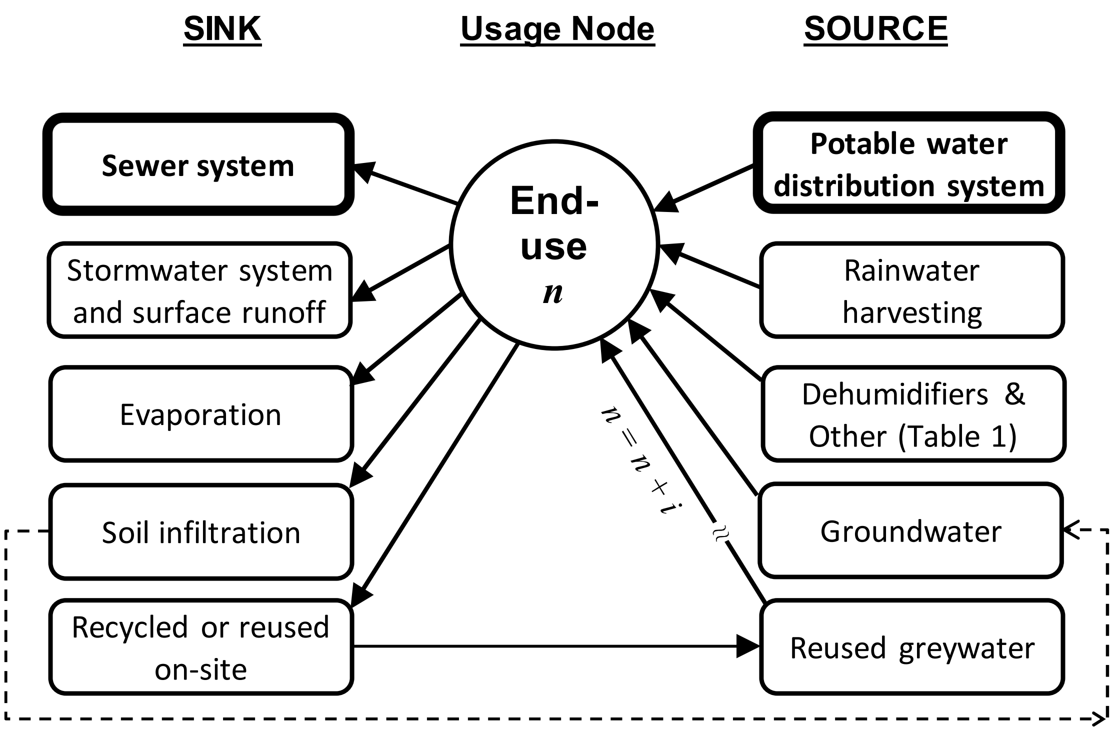

Figure 2-2 Schematic presentation of water sources and sinks or end use n

END-USE MODELLING

REUM

An add-on was developed to incorporate HWS to an end-use model reported on by Jacobs and Haarhoff (2004a). The residential end-use model named REUM, was selected for this investigation due to its availability and open source code in an MS Excel environment. REUM was used as a basis for the research in this study by extending the initial e-model to include HWS options.

Only garden irrigation was considered in this study, meaning that some of the HWS listed in Table 2-1 are not directly relevant to further analysis (for example, bottled water or dehumidifiers). The focus in terms of end-uses was on garden irrigation, because garden irrigation was considered to be the primary application point for water from a HWS. Only in exceptional cases or as part of research projects could information be obtained where home owners applied HWSs at other end-uses, including rainwater for clothes washing (Dobrowksy *et al.*, 2014) and greywater for toilet flushing (Ilemobade *et al.*, 2012). Future research could extend the analyses to include indoor use, such as toilet flushing or clothes washing with non-potable water.

Lawn water demand as end-use

Lawn water demand is described mathematically in the end-use model by a number of different parameters, including weather variables (rainfall, etc.). The theoretical change in specific property's water use and wastewater flow could be evaluated by modifying only selected parameters in REUM, such as the weather variables, to model a similar property in different areas of the country. Garden irrigation is the main end-use resulting in geographic significance, because the water requirement is dependent on weather variables.

In this study, where the focus is on alternative water sources, the end-use model is used to predict the impact on the total household water demand if a HWS were used on the property. Modelling a HWS in REUM is possible by adjusting the parameter f, which describes how much of the theoretical garden water demand is supplied from the municipal supply system. In order to model garden irrigation, four end-uses were identified that are impacted by evaporation. These include three vegetation types and the pool. Of these, the lawn is the most significant in terms of the total volume used (Jacobs and Haarhoff, 2004b) and also the most likely to be irrigated by water from a HWS.

Description of the model and modelling process

In REUM outdoor demand is modelled as different end-uses, including garden irrigation (for three different vegetation types) and pool evaporation (Jacobs and Haarhoff, 2004a). Garden irrigation requirements depend on factors influencing vegetation growth, including rainfall, run-off, infiltration, root zone storage and evaporation. Garden water irrigation is closely related to moisture deficit, or potential evapo-transpiration minus effective rainfall (Makwiza *et al.*, 2017). Johnson (1987) also confirmed this in South Africa. A common method for calculation of evapo-transpiration (ET), also presented by Green (1985), assumes that over a given period ET is directly proportional to pan evaporation, p. In other words, ET=(kp), where k is the empirical constant of proportionality known as the crop factor. Evaporation from a pool surface is also calculated by means of the same equation form, but k would represent the evaporation factor for the pool surface in this case.

Effective rainfall represents that portion of the rainfall that penetrates the soil and thus has an effect in reducing the water demand of plants. Various methods exist to estimate effective rainfall. In all cases the measured monthly rainfall, R (in mm/month), is the independent variable. The equation used in REUM to model the effective rainfall, r, originates from work by Linsley and Franzini (1979) and is reported on by Johnson (1987), who used this method to analyse the garden water demand in Port Elizabeth.

The equation states that rainfall less than 25mm is 100% effective and then decreases linearly until a point where rainfall in excess of 152mm has an effectiveness of only 89mm:

$$r = \begin{bmatrix} R & (R < 25mm) \\ (0{,}504)\cdot R + 12{,}4 & (25 \le R < 152) \\ 89{,}0 & (R \ge 152) \end{bmatrix}$$

In view of the above, the average monthly daily demand (AMDD) for an outdoor end-use e, and month m, is modelled by the following equation (Jacobs and Haarhoff, 2004a):

$$AMDD_{o,m,e} = (f_{m,e} \cdot s_{m,e}) \cdot \frac{(k_{m,e} \cdot p_{m,e}) - r_{m,e}}{days_m}$$

where subscript o denotes outdoor, m denotes month, and e denotes the end-use for the outdoor equation and days m refers to the number of days in a month. A value of 30.44 (the average number of days in a month) can be used to obtain average values, as was done in this study.

The equation for estimating outdoor use shows a relatively simple linear relationship between the explanatory variables and the water demand. In other words, a linear result would be expected when adjusting the factor f for analysis as per this study.

The AMDD for all outdoor end-uses (AMDDo,m in litres/hh/day), the average annual daily demand (AADD) for any specific outdoor end-use e (AADDo,e in litres/hh/day), and the AADD for all outdoor end-uses combined (AADDo in litres/hh/day) are obtained by summing over the 12 months, as reported by Jacobs and Haarhoff (2004a):

$$AMDD_{o,m} = \sum_{e=1}^{4} AMDD_{o,m,e}$$

$$AADD_{o,e} = \sum_{m=1}^{12} AMDD_{o,m,e} \Big/ 12$$

$$AADD_o = \sum_{m=1}^{12} \sum_{e=1}^{4} AMDD_{o,m,e} \Big/ 12$$

This end-use model, combined with the additional water supply from the HWS was used to analyse the effect of a HWS at relatively low-density properties in Cape Town, but not taking into account the actual availability of HWS in that particular region. In other words, the result is a maximum potential (theoretical) reduction due to the use of a HWS. It does not matter from a modelling perspective which type of HWS source is used, because application is for outdoor irrigation, which would be valid for all three types of HWS under consideration.

Garden irrigation factor

The garden irrigation factor f is a theoretical parameter in the end-use model to describe and analyse garden water irrigation. Parameter f can be adjusted to represent changes in the efficiency of the irrigation system, the habits of consumers regarding over- or under-irrigation of vegetation, or as is the case here, also to model water use from alternative water sources. Parameter f would not allow for modelling water use from a HWS indoors, however.

The value of f could be considered to vary between 0 and some higher value. If the factor were set equal to zero (f = 0) the implication is that the garden is not irrigated at all, or the garden is irrigated entirely with water from the HWS (no irrigation water is used from the water distribution system). On the other hand, if the factor is set to unity (f=1) at the property, it tells the analyst that the garden irrigation volume is equal to the theoretical estimate, in other words the theoretical ideal water requirement would be supplied from the potable water distribution system. The upper value of f is determined by over-irrigation of vegetation or wastage due to inefficient irrigation systems. No upper value for f has yet been reported; clearly a field for further research.

RESULTS

Theoretical saving for various scenarios

For the purpose of this modelling exercise, which is essentially a comparison between different HWS scenarios, it is not critical to select a "correct" value for parameter f. The parameter is in fact adjusted between realistic boundaries (say 0 to 1) in order to theoretically assess the impact of HWS use on the potable Municipal supply system. In the modelling exercise parameter f is used to describe:

the fraction of all properties in a particular area that make use of HWS and

the fraction of the total garden irrigation demand met by the HWS.

For this modelling exercise the following parameters were investigated and assumptions were made to describe the hypothetical household subsequently investigated:

- the household size is 3 people per household, but the precise value is not important in this work because the parameter for household size does not affect garden irrigation; the only implication would be when considering the percentage of water used for garden irrigation in relation to the total (or indoor use), for example; the selection of 3 people per household is considered to be realistic for the property size range under investigation at the relatively coarse resolution of this study;

- the total property area is 1000m²;
- in all cases 25% of the area is considered to be covered by irrigated lawn and 10% by garden beds; combined, these vegetation types make up the garden irrigation;
- other model input parameters are set to the values reported for Cape Town in previous research (Jacobs and Haarhoff, 2004b).

The results of the analysis are summarised in Table 2-2 and Figure 2-3.

Table 2-2: Theoretical saving potential for different scenarios

Theoretical potable AADD-reduction for different HWS application scenarios						
% Of properties in area with access to HWS	% Of garden irrigation (GI) demand met by HWS					
	0	20	40	60	80	100
0	0	0	0	0	0	0
20	0	2	4	7	9	11
40	0	4	9	13	18	22
60	0	7	13	20	27	33
80	0	9	18	27	35	44
100	0	11	22	33	44	55

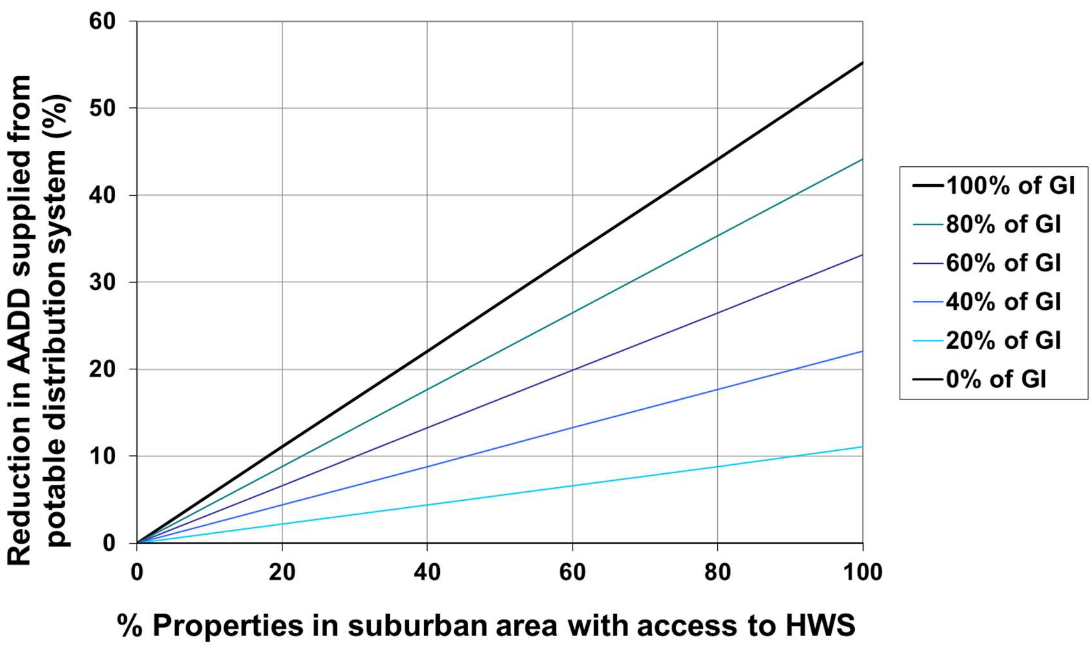

Figure 2-3: Theoretical saving potential for different application scenarios

With reference to these results for a property of 1000m², if 100% of the consumers were to use a HWS source, or combination thereof, to meet 100% of the garden irrigation, a theoretical reduction of 55% in municipal water use could be achieved compared to the baseline value, which was the normal demand with exclusive municipal supply via the potable system. The 100% uptake is considered unlikely and is presented as the upper limit. On the other extreme, if none of the consumers were to have access to a HWS then clearly 0% of the outdoor irrigation would be met from the HWS, then 0% reduction would be achieved, so all water would be supplied from the potable distribution system.

Theoretical garden irrigation demand

Referring to the previous section, it is necessary to determine what percentage of the garden irrigation could typically be supplied by the HWS source. When considering the yield, a sufficient volume from the HWS is needed to meet not only the average annual garden irrigation demand, but the peak irrigation demand (peak summer day), which is a greater concern. The peak day demand could be estimated by the end-use model. The model and limited tests at the Stellenbosch University campus during summer show that the theoretical lawn water requirement is ± 5 L/m² on a typical hot summer's day, with maximum temperatures at ±35˚C and no cloud cover. Garden beds were assumed to have the same demand for modelling purposes. For the 1000m² hypothetical property described above this would equate to a peak garden irrigation demand of ± 1750 L/d, presuming 25% coverage by lawn and 10% garden beds. Although lawns could be stressed (yet survive) with less water, the "ideal" requirement was used in the analysis.

Using the stochastic end-use model for groundwater use developed by Botha and Jacobs (2017), which involved case study data from 10 homes in Cape Town with garden boreholes, it was found that the average garden irrigation peak of 996 L/d could be met ±96% of the time by the GAPs; also, groundwater supply would meet the 90th percentile of garden irrigation peak demand (1954 L/day) with a certainty of almost 70%. Groundwater yield is thus considered sufficient to meet garden irrigation at a typical suburban property.

Rainwater supply is often insufficient in view of garden irrigation in the Western Cape due to relatively low summer rainfall, high irrigation demand, and limited size of rainwater tanks at residential homes. Fisher-Jeffes *et al.* (2017) confirmed that rainwater use, in the Western Cape study area investigated by the team, was not financially viable and underlined the need for future research to better understand the viability of rainwater harvesting in different climatic regions of South Africa.

Also, the available yield from greywater is limited to how much water is used for the bath, shower and washing machine indoors. Further research is needed to link greywater generation to water conservation. Conservation of water at the bath, shower and washing machine is likely to reduce greywater yield from the same home, because the end-use event volume directly generates greywater for re-supply.

For users with access to groundwater the "100% of garden irrigation" curve from Figure 2-3 could be used, neglecting all the other curves that would apply if the yield were insufficient to meet the garden irrigation demand (e.g. those curves would apply for rainwater harvesting and greywater use in the absence of a groundwater source). The analyses from this point focused on the case where 100% of the garden irrigation could be supplied from the HWS, because (i) a consumer clearly has a "right" to use a HWS and also, (ii) the yield from HWSs combined could be expected to meet the total garden irrigation demand and (iii) in order to evaluate the maximum impact on the potable distribution system the maximum draw from the HWS should be considered as first priority.

Results: meeting 100% of garden irrigation demand

The model was used to re-analyse the case where the HWS source would consistently meet 100% of the demand. Two additional property sizes were added to provide estimates of potential savings for a 1500m² and 2000m² sized property. Since the result is linear it was considered appropriate to provide two additional curves. The results are shown in Figure 2-4, with the y-axis presenting the AADD supplied from the potable distribution system.

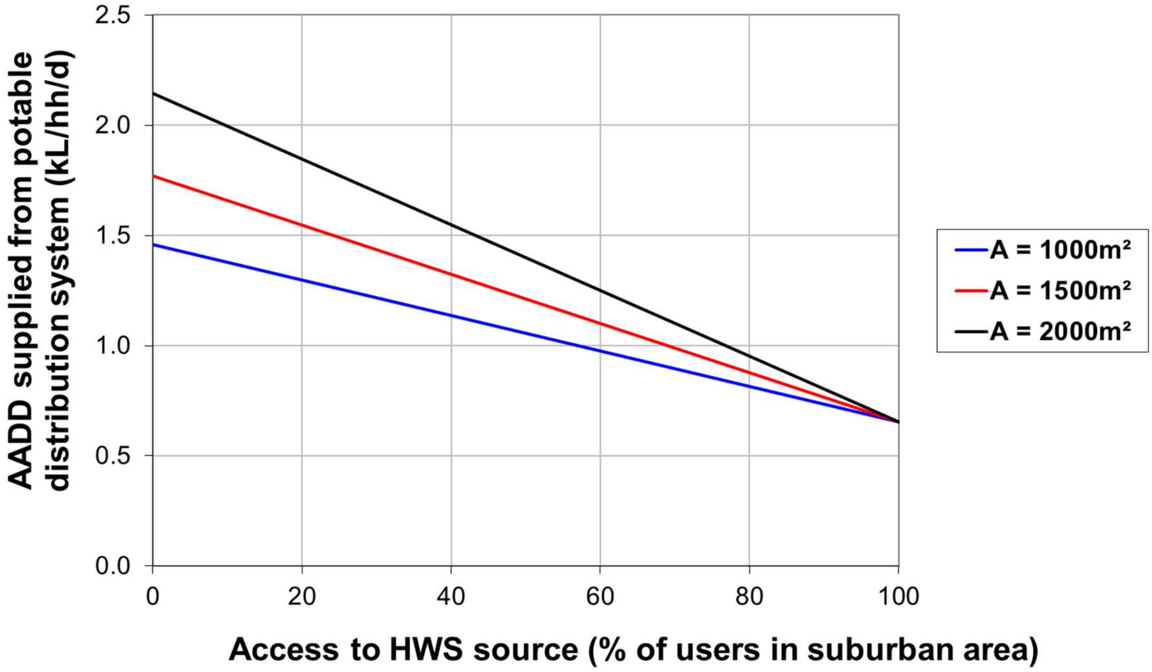

Figure 2-4: Modelled AADD for three property sizes with 100% of GI met by HWS

From Figure 2-4 it is clear that all three lines converge to a point at about 650 L/d (about 20 kL per month, or 217 L/c/day), that is representative of the modelled typical indoor use only for the hypothetical 3-person household analysed. The maximum reduction is for a 2000m² property where the AADD would reduce from 2.1 kL/d (2100 L/day) to 0.65 kL/d (650 L/day), resulting in a reduction of almost 69% in potable supply when a HWS is used. The reduction was earlier noted to be 55% for a 1000m² property. The question remains as to what fraction of users would be likely to commission and sustain supply from a HWS and also to what extent garden irrigation could be met.

The impact on water services planning

Implementation of a HWS significantly complicates water demand management regarding the particular consumer, because water use from any HWS is typically unmetered and the supply - in terms of quantity and quality - cannot be controlled by the service provider. Also, a future shift away from HWS back to municipal supply (say after lifting restrictions) is likely in view of the unit cost of water, because supply from most HWS is considered relatively expensive compared to municipal supply. Water service planning is thus complicated by the introduction, and possible future decommissioning, of any HWS.

The significant reduction in water from piped reticulation systems with wide-scale introduction of HWS could be seen as an advantage in terms of a reduction in demand on the finite and costly potable stream. In contrast, wide-scale decommissioning of HWS would induce a substantial and unexpected load on the water distribution system.

Greywater use would reduce the load (quantity) on the sewer system and on wastewater treatment works. In contrast, however, wide-scale use of HWS could be a concern in instances where analyses of data from consumer water meters is used for planning purposes, which may not accurately reflect the actual total water needs of residential consumers. Reduced flows in sewers could lead to increased incidents of blockages and would lead to higher pollutant loads, because the relatively clean wastewater components would be specifically targeted for greywater use.

CONCLUSION

Supplementary household water sources are available, and are in use locally. This research included a comprehensive review of all supplementary household water sources currently available to consumers. The focus of subsequent analyses was on groundwater, rainwater and greywater. Consumers are faced with the challenge that South African legislation is unclear about the use of HWS, especially greywater which may constitute health and environmental risks if used without treatment and disinfection. Earlier research has underlined that the use of any HWS, including greywater, is not specifically excluded by existing legislation. In terms of the legal implications, despite HWS not being dealt with directly in the NWA or the WSA, it could be concluded from this study that HWS for domestic purposes in a serviced area could be deemed "legal" in the general case. No registration of the particular use is required, unless a municipality has followed procedures by which by-laws have been put in place, thus regulating the registration of such use – in such a case a home owner may be required to register use of a HWS, with consequences if not registered. Another concern with HWS application is the non-potable water quality, associated risks and personal liability to manage the decentralised “private” system, especially when it comes to greywater use (Carden *et al.*, 2017). Maimon *et al.* (2010) note that "...the use of untreated greywater is not recommended due to associated risks, even for single households". Despite a HWS being considered “legal”, consumers with HWS are not excluded from personal liability, which may arise for individual home-owners who make non-potable supplementary water available on the property.

The HWS end-use model described in this paper, and the subsequent results, are valuable in providing strategic direction in terms of water demand. Groundwater is the HWS considered to have the most notable penetration and intensity to impact potable water demand in residential areas, and is coupled to a relatively low risk in terms of water quality relative to (say) greywater use. On-site HWS commonly applied to meet garden irrigation demand could lead to a theoretical reduction of 55% (1000m² property) to 69% (2000m² property) in potable water use from the distribution system, when compared to the case with exclusive potable supply and a specific hypothetical baseline property.

Additional research is required to determine what fraction of users would be likely to apply HWS, or are doing so already. Consumers often implement a HWS during periods of stringent water restrictions or under intermittent supply conditions. The number of people affected by intermittent water supply will most likely increase, because climate change, population growth, rising standards of living and rapid urbanisation causes increased pressure on potable water resources (Kumpel and Nelson, 2015). The links between a HWS, intermittent supply, relatively low system pressure and associated health risks need to be modelled and better understood. Potable water use at home typically reduces during stringent water restrictions (Jacobs *et al.*, 2007) and also potentially under intermittent supply conditions, but community health risks increase due to reduced source water quality and reduced frequency of washing as well as water sharing among family members (Fan *et al.*, 2014).

On-site storage of water, often provided with a HWS, improves water supply system resilience from the viewpoint of the consumer, but the matter is complicated by the fact that the on-site storage is non-potable. The complex interaction between non-potable consumer supply and potable municipal supply, in terms of system resilience and reliability, is poorly understood - especially under conditions of intermittent supply or during system pressure violations.

While it appears that introduction of HWS may improve the quantity of supply to an urban area by reducing the load on the potable water distribution system, the water quality of the entire system may be compromised in the process. Further research needs to address the matter of untreated supplementary water sources potentially becoming cross-connected to potable supply systems, which may lead to cross-contamination of potable supplies.

ACKNOWLEDGEMENTS

The research results presented in this report emanate from a project funded by the Water Research Commission, project K5/1819 entitled: Strategic assessment of household on-site water as supplementary resource to potable municipal supply – current trends and future needs. The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee is gratefully acknowledged.

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CHAPTER 3. SUPPLEMENTARY HOUSEHOLD WATER SOURCES-A FOCUS ON UNTREATED GREYWATER

The following primary on-site supplementary HWS were addressed in Chapter 2:

- groundwater abstraction,
- rainwater harvesting and
- greywater use.

The application of these HWS bring advantages and disadvantages in each case; and the extent of these positive and negative impacts have been identified in Chapter 2 as requiring further research. Exploring the trade off of these advantages and disadvantages provides insight into whether a nett positive benefit prevails with the application of each HWS. One of the most notable positive impacts of a HWS is reduced consumption from the water distribution system (WDS), and reduced consumer billing. These positive aspects from a consumer perspective are, however, coupled with reduced income to the service providers. There may also be trade offs in terms of the environment, public health and water services infrastructure.

SUPPLEMENTARY HOUSEHOLD WATER SOURCES-A FOCUS ON UNTREATED GREYWATER

A comparison between the three primary supplementary HWS as evaluated against yield, costs, environmental impact, human impact and infrastructure impact is presented in Table 3-1. The table provides a basis towards justification of the focus of this study, namely untreated greywater.

Table 3-1 Groundwater, rainwater and greywater comparative table

	Groundwater	**Rainwater (internally plumbed)**	**Rainwater (not internally plumbed)**	**Greywater (full treatment)**	**Greywater (untreated)**
Yield	High yield possible, but not guaranteed (varies spatially & temporally).	Varies notably, (season & roof size dependent).		Relatively constant yield, which reduces in line with indoor water savings.	Yield dependent on collection method (e.g., bucketing) & reduces in line with indoor water savings.
Capital and Maintenance Costs	Very high capital & high energy cost.	High capital cost & energy cost.	High capital cost.	High capital & energy costs.	Low cost.
Environmental Impact	Possible lowering of water table. High energy usage.	Possible reduced urban stormwater runoff may impact natural ecosystems.		High energy usage.	Changes to soil chemistry. Groundwater & stormwater pollution. Impact on crop yield.
Human Impact	Normally not potable – possible health risk.	Not potable - possible health risk.	Not potable - possible health risk.	Minimal if maintained & managed properly.	Not potable – possible health risk.
Infrastructure Impact	-	-	-	Cumulative effect of altered wastewater from many HH could impact sewer network & wastewater treatment works.	
WDS Impact	Reduced load.	Reduced load.	Reduced load.	Reduced load.	Reduced load.
References	Wright and Jacobs (2016)	Beal *et al.* (2012)	Dobrowksy *et al.* (2014); Mukheibir *et al.* (2014); Fisher-Jeffes *et al.* (2017); Kloss (2008)	Ludwig (2000)	Penn *et al.* (2012); Carden *et al.* (2018); Hardie *et al.*, (2021); Jackson *et al.*, (2006); Nel *et al.*, 2013

Despite high yield and relatively low risk, groundwater has a large barrier to entry as it requires the highest capital investment of the three primary supplementary HWS. A further trade off to groundwater use, is that the yield is not guaranteed and is climate and area dependent (Wright and Jacobs, 2019). Groundwater quality varies notably, depending largely on the geology (Saby *et al.*, 2015) and may limit direct application at household level; desalination may be required to improve the quality of saline groundwater (Essink, 2001).

Rainwater, on the other hand, provides a relatively inexpensive supply of water, reduces stormwater runoff and pollution, reduces erosion in urban environments, helps reduce peak seasonal demands if stored and improves demand management for drinking water systems (Kloss, 2008). The trade offs, however, include poor water quality especially in polluted urban areas (i.e., it is non potable), a dependency on climate, rainfall patterns and roof configuration, as well as regional codes and regulations that may not enable its application and act as a barrier to application (Fisher Jeffes, 2017; Kloss, 2008; Kahinda and Taigbenu, 2011).

Despite mitigating water quality risks, treated greywater is expensive and highly complex systems may nullify any economic and environmental benefits due to high energy requirements (Ludwig, 2000). Untreated greywater is the most accessible, the least expensive and is relatively reliable, compared to other primary HWS (Oteng Peprah *et al.*, 2018; Nel and Jacobs, 2019). Greywater has a high potential for on-site use and its application can significantly reduce domestic water demand, despite the risks related to poor quality (Carden *et al.*, 2018). This distinct trade-off between accessibility and water savings, versus the risks to public health (Carden *et al.*, 2018), the environment (Friedler and Gross, 2019) and water services infrastructure (Penn *et al.*, 2012), particularly in comparison to the other supplementary HWS and its inherent variability in quality (Rodda *et al.*, 2011), provides justification towards the focus of this study. Little is known about unregulated, untreated greywater use practices and the inherent risks. These are explored in subsequent chapters.

CHAPTER 4. INVESTIGATION INTO UNTREATED GREYWATER REUSE PRACTICES BY SUBURBAN HOUSEHOLDS UNDER THE THREAT OF INTERMITTENT WATER SUPPLY

The following chapter is a research paper published by the *Journal of Water, Sanitation, and Hygiene for Development*.

CONTEXT OF PAPER WITHIN THIS DISSERTATION

Of the primary HWS addressed in Chapter 2, untreated greywater use is the focus of this dissertation given its accessibility, particularly in times of emergency curtailments, which is juxtaposed with various risks to the consumer, the wider community, infrastructure and the environment (see Chapter 3). Little is known, however, about the uptake of unregulated, untreated greywater use practices under emergency conditions in suburban communities. This paper is therefore an investigation into untreated greywater use practices by suburban households under the threat of intermittent water supply. Results of a consumer survey and analysis of online forums provide insight into greywater sources, collection methods, storage and distribution, perceived risks, level of treatment, and application points associated with greywater use.

Chapter 9, Appendix B provides the consumer survey that was utilised for data collection purposes.

PUBLICATION STATUS

Published. This paper was accepted in revised form on 3 October 2019 by the *Journal of Water, Sanitation and Hygiene for Development.* Available online 23 October 2019.

Reference: Nel N. and Jacobs H.E. 2019 Investigation into untreated greywater reuse practices by suburban households under the threat of intermittent water supply. *Journal of Water, Sanitation and Hygiene for Development*, **9**(4), 627–634. https://doi.org/10.2166/washdev.2019.055.

CONTRIBUTIONS

The extent of contributions by the various authors of this paper was as follows:

- N. Nel (95%) which included the ethical clearance application, conceptualisation, data collection (survey), data analysis, write up, journal selection and formatting, and relevant review.
- H.E. Jacobs (5%)

The Declaration of contributions by co-authors can be found in Appendix A.

INVESTIGATION INTO UNTREATED GREYWATER REUSE PRACTICES BY SUBURBAN HOUSEHOLDS UNDER THE THREAT OF INTERMITTENT WATER SUPPLY

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ABSTRACT

Untreated greywater reuse at household level is an accessible water source to supplement non-potable water requirements in times of emergency water curtailments, but poses various risks to the consumer, the wider community, infrastructure and the environment. Little is known about unregulated, untreated greywater reuse practices under emergency conditions in suburban communities where consumers have become accustomed to reliable potable water supplied via a pressurised, piped distribution system. There is a lack of knowledge regarding the sources of greywater used, collection methods, -storage and -distribution, the application points, the level of treatment (if any) and the perceived risks associated with the greywater reuse. The City of Cape Town was selected as a case study site for research into greywater reuse under the threat of "Day Zero" and stringent water restrictions, implemented during the 2017/2018 summer season. A consumer survey and analysis of relevant online forums was conducted in order to obtain the necessary information. Greywater reuse practices from a sample group of 351 consumers were identified and classified. Untreated greywater reuse was found to be common, mainly for garden irrigation and toilet flushing. The results point to high-risk activities in the study group.

Keywords: Greywater, risk, water restrictions

INTRODUCTION

Background

Various on-site supplementary household water sources are available to residential consumers (Nel *et al.* 2017). In serviced areas with a reliable supply of potable water via the water distribution system such sources may never be required – and thus may never need to be installed. A more proactive, sustainable outlook or desire to preserve water as a precious resource may, however, trigger the use of supplementary water sources. Further prompts to use supplementary sources may be out of necessity due to ongoing intermittent water supply or in an in an emergency situation such as a drought. Recent stringent water restrictions and news of possible water supply system failure in various municipalities in South Africa, have led to increased uptake of supplementary household water sources, even in relatively affluent and well-serviced suburbs. Alternative water sources, such as rainwater (Mukheibir *et al.*, 2014), groundwater (Wright and Jacobs, 2016) and greywater (Carden *et al.*, 2018) are commonly used in some South African cities and towns, although the penetration ratio has not yet been researched. Greywater is the least expensive and most accessible supplementary water source but poses various risks especially when used without treatment. Untreated greywater use at household level is the focus of this study.

Rationale

Nel *et al.* (2017) noted that the interaction between non-potable consumer supply, such as greywater use, and potable municipal supply is poorly understood. There is a critical gap when it comes to understanding the practices regarding the relatively high risk use of untreated greywater in serviced urban areas by residential consumers. This is an investigation into untreated greywater use in serviced suburban areas of the Cape Town Metropolitan area under the threat of "Day Zero". It sheds light on the opportunities and challenges presented by household greywater as a consumer-driven solution to potential water supply system failure.

Case Study Site

The metropolitan area of Cape Town is located in the South Western region of South Africa with a population of 3.7 million people (StatsSA, 2011). The city is characterised by a warm Mediterranean climate with winter rainfall and hot, dry summers. Household water consumption typically peaks in the summer months creating a demand-supply imbalance which is compounded by a heavy reliance on surface water – making up 98% of all available water sources. With dropping dam levels and relatively low rainfall, water demand was poised to outstrip supply early in 2018 but "Day Zero" was ultimately avoided and water restrictions were eased in October 2018.

CONTEXT

The focus of this study is on suburban households, where consumers are accustomed to continuous pressurised drinking water supply, with water quality in line with acceptable potable standards. Prior to the 2017/2018 drought in the study area, suburban residential consumers would generally have had no pressing need to use greywater, but had to consider alternative options, including untreated greywater use, when faced with the urgent and sudden dilemma of having water supply to the entire city potentially fail.

Carden *et al.* (2018) conducted a thorough legal review of greywater use in South Africa and greywater use guidelines for households were published City of Cape Town (2017b) during the drought. These greywater guidelines, however, encourage greywater use in the interest of water saving with less emphasis on the associated risks. They are sometimes in contradiction with information in peer reviewed journals and legislation such as the National Building Regulations and Building Standards Act (Act No. 103 of 1977) which requires that wastewater be disposed of in the sewer.

Cape Town Water Restrictions 2016-2018

In a desperate effort to avert a major crisis with Cape Town's deepening drought, various supply augmentation and demand reduction strategies were employed; and as the drought intensified, additional behaviour changing strategies were introduced which included stringent water restrictions and increased tariffs.

Figure 4-1a and b present an overview of the water restriction levels in Cape Town and the related timelines respectively. In June 2017 all outdoor water use in the City of Cape Town metropolitan area was banned (City of Cape Town, 2017a) and the tariffs became relatively expensive with additional fines imposed on consumers for exceeding certain levels of monthly water consumption. Level 6b water restrictions were implemented in February 2018, with exorbitant tariffs and severe fines imposed on households exceeding 10kL/month.

Water Restriction Level	Pools and Water Features				Tariffs and Fines							General Outdoor Use					
	Pool cover mandatory	No portable pools	No water features	No topping up pool	Increased tariff[B]	Notable tariff increase[C]	Fines for exceeding consumption limit	Fines for outdoor use	Increased fines	WDM Device (high water usage homes)	Per capita use limited	Limited garden watering[D]	No hosing hard surfaces	No hoses or sprayers	Washing vehicles only with buckets	No washing of vehicles	No watering or irrigation
1-2[A]	●				●							●	●				
3-3b	●				●							●	●	●	●		
4-6b	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●

Notes
A) Conservation measures are considered integral to modern urban life under an unrestricted scenario.
B) Consumption-based block tariffs increase relative to the previous step, but within "normal margins".
C) Notably increased water bill (at least by double, thus >200% increase), unless consumption is reduced.
D) Garden watering limited by day of week or time of day, but not completely banned.

<table>
<tr><th rowspan="3">DETAILS</th><th colspan="12">CITY OF CAPE TOWN WATER RESTRICTIONS</th></tr>
<tr><th colspan="12">2016</th></tr>
<tr><th>JAN</th><th>FEB</th><th>MAR</th><th>APR</th><th>MAY</th><th>JUN</th><th>JUL</th><th>AUG</th><th>SEP</th><th>OCT</th><th>NOV</th><th>DEC</th></tr>
<tr><td>Level</td><td colspan="10">2</td><td colspan="2">3</td></tr>
<tr><td>Date</td><td colspan="10">1-Jan</td><td colspan="2">1-Nov</td></tr>
<tr><th colspan="13">2017</th></tr>
<tr><th></th><th>JAN</th><th>FEB</th><th>MAR</th><th>APR</th><th>MAY</th><th>JUN</th><th>JUL</th><th>AUG</th><th>SEP</th><th>OCT</th><th>NOV</th><th>DEC</th></tr>
<tr><td>Level</td><td colspan="5">3</td><td>4</td><td colspan="2">4B</td><td>5</td><td colspan="3">5B</td></tr>
<tr><td>Date</td><td colspan="5">1-Nov</td><td>1-Jun</td><td colspan="2">1-Jul</td><td>3-Sep</td><td colspan="3">1-Oct</td></tr>
<tr><th colspan="13">2018</th></tr>
<tr><th></th><th>JAN</th><th>FEB</th><th>MAR</th><th>APR</th><th>MAY</th><th>JUN</th><th>JUL</th><th>AUG</th><th>SEP</th><th>OCT</th><th>NOV</th><th>DEC</th></tr>
<tr><td>Level</td><td>6</td><td colspan="8">6B</td><td colspan="2">5</td><td>3</td></tr>
<tr><td>Date</td><td>1-Jan</td><td colspan="8">1-Feb</td><td colspan="2">1-Oct</td><td>1-Dec</td></tr>
</table>

Figure 4-1a and b: City of Cape Town water restrictions levels and timelines (2016 – 2018)

Despite these emergency water restrictions, Cape Town was at risk of running out of water. In January 2018 the projected date for "Day Zero" was announced daily in the media and it was defined as a day when all surface water resources combined would reach a level of 13.5% of full supply level. It was envisaged that, on "Day Zero", the water supply to consumers would be closed off, with only 200 distribution points available for the physical collection of 25L per person per day. A result of this shock tactic – and other emergency demand management measures – was that total consumption by the City of Cape Town dropped notably from 1,200 ML/day in February 2015 to 515 ML/day in March 2018 (Gosling, 2018). The implementation of alternative water sources by consumers in the study area would have contributed to the notable demand reduction.

While the reduction on the potable demand is indeed a beneficial result of the "Day Zero" threat, little is understood of the extent and repercussions of the uptake of these alternative water sources (including greywater).

Greywater Use

For the purpose of this study, the term greywater is defined as all household wastewater, except toilet waste (adapted from Ludwig, 1997). Greywater is inherently variable in quality and the negative impacts on health (Christova Boal *et al.*, 1996), the environment (Al- Hamaiedeh and Bino, 2010) and water services (Penn *et al.*, 2012) are well documented. This further highlights the need to better understand untreated greywater use practices during water shortages.

RESEARCH FOCUS AND OBJECTIVES

Past greywater studies in South Africa have focused on dense informal settlements (e.g. Carden *et al.*, 2007) where greywater use is common due to the relatively large distances that consumers have to physically convey water from a standpipe. The informal use of greywater in unserviced areas was considered beyond the scope of this study. The focus is instead on greywater use by middle to high-income households in fully serviced homes, during temporary yet severe water shortages.

The following were the project objectives:

- Identify a study group of greywater users.
- Design a suitable consumer questionnaire for distribution to individual consumers in the study group.
- Assess the greywater use practices and identify sources and end-uses.
- Classify methods of collection, storage and distribution of greywater.
- Identify perceptions in terms of general risks associated with untreated greywater use at individual homes.

DATA COLLECTION

Overview

Data collection for the consumer survey occurred between 1 October 2017 and 30 August 2018; while additional analysis of online forums and social media platforms was undertaken between November 2016 and April 2017 to further determine greywater practices under the threat of "Day Zero". The *Water Shedding Western Cape* Facebook Group provided a particularly rich source of water savings initiatives and greywater use data. The group was started in January 2016 with the onset of stringent water restrictions in the Western Cape in order to share water saving ideas online. At the time of this study, the group had 47 578 members from the greater Cape Town region.

Consumer survey

An online survey was used due to the relatively low cost per survey and the speed with which to retrieve results; and Survey Monkey was utilised as user friendly survey software. A link to the survey was posted with permission on institutional Facebook Pages and further channels were utilised for distribution of the survey. The questions were devised in line with the research objectives and the development tools as listed by Glasow (2005) so as to avoid many of the biases and disadvantages inherent in written surveys and to ensure ease of analysis. The survey included 20 questions, mostly in multiple choice format.

As the purpose of the study was to gain a general sense of greywater use, a small sample size was deemed sufficient to gain a reasonable degree of precision (Glasow, 2005). The distribution of the survey was, however, sufficient to allow for non-responses and incomplete responses (Glasow, 2005).

Ethical considerations

Ethics considerations relating to confidentiality, protection of information and the informed consent process were addressed during the course of this study and an application for ethics approval and institutional permission was accepted by Stellenbosch University in September 2017 before distribution of the survey.

Online greywater forum review

A further review of the online forum Water Shedding Western Cape was conducted to gain greater insight into the extent of greywater use. A search was conducted using keywords such as: “greywater”, “grey water”, “graywater”, “reuse”, “recycling” and “wastewater” in order to hone in on relevant posts. The text strings were extracted, analysed and logically organised.

SURVEY RESULTS

Summary of Study Groups and Responses

The results of the survey are presented below. Respondents in the online consumer survey are referred to as Group A with forum members from Water Shedding Western Cape referred to as Group B.

The investigative online survey for Group A was completed by 175 respondents. Data was organised using Microsoft Excel and all responses were valid and were included in the subsequent analysis. In addition, the Group B sample included another 176 forum members’ posts with a total of 206 greywater related forum posts. Ultimately, 7 different greywater generation points were identified, 12 different end-uses and 3 different methods for collecting and distributing the greywater.

All respondents in Group A were located in the greater Cape Town area and were over the age of 25. Of the group, 78% resided in a suburban house serviced with potable water through a water distribution system (WDS). While it was not possible to determine the type of residence in which Group B members resided, it was inferred by the content of the posts including details of their appliances and plumbing systems, that the majority lived in serviced homes.

Extent of Greywater Use and Barriers to Entry

The extent of greywater use in the survey sample should not be extrapolated to the larger population, because the online nature of the survey targeted respondents that have access to the internet and could create a bias towards greywater users with an interest in the field.

Approximately 161 of the 175 of respondents in Group A used greywater in addition to potable water (and sometimes in addition to other alternative sources such as rainwater and groundwater) at the time of the survey.

Sources and End Uses

Word clouds compiled based on words extracted from the Group A survey responses are portrayed in Figure 4-2 and specifically relate to sources and end uses of greywater. The main subject of these survey responses (excluding pronouns, conjunctions, adjectives etc.) was used for the generation of the word clouds. Repeated answers were excluded and no weighting was given. The investigation indicates that the shower was the most common source of greywater with 87% of group A respondents utilising it at the time of the survey. The bath was utilised by 51% while 49% utilised the washing machine, and 45% utilised the kitchen sink. Bathroom hand basins, laundry troughs and the dishwasher were utilised by a minority. The most common greywater sources in Group B included the shower (27%), washing machine (29%) and bath (20%). Less commonly used greywater sources included water from freezer defrosting, water from food preparation, geyser overflow, duck pond water replacement and hot tub and pool backwash water.

In Group A these greywater sources were mostly used to flush toilets (74%) and irrigate the garden (57%). Other end uses included washing of driveways and paved surfaces and washing of vehicles (11.5%) and bicycles (<6%).

Figure 4-2: Cape Town case study: greywater sources and end uses word clouds

Of Group A respondents who used greywater for garden irrigation, the majority irrigated container plants or small sections of garden (59%); with some watering their lawns (34%), root vegetables (4%), leafy vegetables (7%) and fruit and nut trees (11%). The results from Group B mostly included greywater use for garden irrigation including vegetable garden (67%) and toilet flushing (16%); and a smaller number indicated its use for pool filling (6%).

Methods of Collection, Storage and Distribution

In Group A, 81% of the respondents distributed the greywater by carrying it in buckets to various end-uses, with a further 18% indicating that piping was used for greywater distribution. The remainder utilised a dual plumbing system or a commercial product. Of the Group A respondents reusing greywater for toilet flushing, 79% were transferring directly into the cistern or toilet bowl via buckets. Analysis of the Group B forum posts indicated a fairly even distribution between makeshift, non-commercial piped systems (pumped or gravity fed) installed by the homeowner and bucketing; with a relatively minor number of group members utilising commercial greywater systems with varying levels of treatment.

Of Group A respondents, 76% reported that greywater was used without storage or was stored for less than 24 hours. Storage vessels noted in the various responses included buckets, plastic bottles, wheelie bins etc. Of the respondents who used greywater, 75% did not treat the greywater at all. Only 26 of the 175 respondents from Group A reported any form of treatment or disinfection, generally in the form of basic filtration and by adding bleach or other products. No respondents indicated that they used biological, chemical or other commercial systems. The use of "environmentally friendly" or natural hygiene products at source was also prevalent in both Group A and B.

Risks

A concern was identified during this study with regards to the risk of greywater use and related consumer perception of the risk. Of Group A, 71% of respondents did not perceive there to be any risk to personal health and 57% indicated that there is no environmental risk when reusing untreated greywater.

DISCUSSION

This study probed the greywater use practices of consumers during serious water restrictions. The results paint a picture of actual practices standing in contrast with knowledge from published research, especially in terms of health risks inherent in untreated greywater use. The following table provides a comparison between significant Group A and B survey results and published literature:

Table 4-1 Survey results versus literature

Survey Response	Literature
Sources and End Uses	
The shower was the most common greywater source followed by the bath, washing machine, and the kitchen (Group A). “I place a bucket in the bath for the water which I reuse for my plants. I do the same in the kitchen sink...” Anonymous, January 2017 (Group B)	While greywater composition from a specific source in one household may vary through time depending on a range of variables, certain sources are generally classed in the literature as riskier than others. Kitchen water, for instance, is highly contaminated with disease causing pathogens from food particles, high organic loads, grease and detergents which may further impact on the environment and on public health. Maimon *et al.* (2010) and Carden *et al.*, (2018) suggest that it should not be used at all.
The majority of greywater users did not treat greywater (Group A).	Maimon *et al.* (2010) and Memon and Ward (2019) explicitly advocate for the treatment of greywater to mitigate the risks.
Respondents reusing raw greywater for toilet flushing were transferring directly into the cistern via buckets (Group A).	Undesirable materials potentially present in raw greywater may cause clogging of toilet operating components (Christova – Boal *et al.*, 1996) thus resulting in leaks and negating the intended water savings.
4% were watering root vegetables, 7% were watering leafy vegetables and 11% were watering fruit and nut trees with untreated greywater (Group A). “My 'grey water' tomatoes! Proud. Homegrown. Sweet.” Anonymous, March 2017 (Group B)	Research suggests that microbial contamination of crops can occur from greywater irrigation, providing sufficient scientific grounds to render the practice unsafe. Carden *et al.* (2018) in fact suggest that fruit and vegetables should only be irrigated with greywater in a time of dire food shortage when the risk of disease becomes less than the risk associated with diminished food supplies. Irrigation by means of greywater is especially risky for crops that are eaten raw or lightly cooked.
Harvesting	
The most popular form of greywater harvesting in the survey sample was bucketing (82% of Group A).	When bucketing raw greywater there is a higher chance of direct exposure to harmful pathogens which can be transmitted to the mouth via contaminated hands (Carden *et al.*, 2018), or aerosols.
Encouragingly, most consumers did not store their greywater or used it within 24 hours, but there were exceptions (Group A). “Why can grey water NOT be stored for more than 24 hours? Been using mine after 2 days	Prolonged storage of greywater, including in toilet cisterns, can result in anaerobic conditions and therefore offensive odours, a breeding ground for mosquitoes and the proliferation of microorganisms (Carden *et al.*, 2018).

sometimes." Anonymous, February 2017 (Group B)	
The use of "environmentally/eco friendly"/"biodegradable" or "natural" hygiene products at source was prevalent (Group A and B).	There is no indication that so called 'eco-friendly' products are more suitable for greywater irrigation than conventional products (Carden *et al.*, 2018).
Risk	
71% did not perceive there to be any risk to personal health and 57% indicated that there is no environmental risk when reusing untreated greywater (Group A).	Greywater use and the risks to public health, the environment and water services are well documented in the literature (e.g. Christova-Boal *et al.*, 1996; Al- Hamaiedeh and Bino, 2010; Maimon *et al.*, 2010 and Penn *et al.*, 2012).

The survey results indicate a lack of awareness of the risks of raw greywater use with some practices, in contradiction with the literature. Under emergency conditions, consumers are faced with a trade off between the risks associated with reusing greywater and those associated with not using greywater (e.g. dying garden, no potable supply). Greywater use guideline documents highlighting the risks associated with untreated greywater use, published in the wake of "Day Zero" (e.g. City of Cape Town (2017b)) were ineffective in communicating the potential risks to consumers in the study sample.

CONCLUSIONS

Under the threat of "Day Zero" and severe water restrictions, this small scale survey in Cape Town, South Africa has given valuable insight into direct, raw greywater use practices.

The study highlights a lack of awareness of the significant risk to public health and the environment. It serves as a lesson to the global community facing water challenges of the complexities of conserving the potable supply, the unintended consequences and that risk laden initiatives in the interest of water saving may prevail. The study provides insight into how individuals may respond to emergency water restrictions when given responsibility for global issues. It is a lesson in drought planning and public engagement in an increasingly water stressed world.

This study has also shed light on the need for several areas of further research regarding greywater to better understand the scale of the consequential issues. This would include the effect of country wide, small scale household greywater use greywater use and reduced water consumption on wastewater flows and wastewater quality in serviced areas. The legal implications of greywater mismanagement for both homeowners and water service providers are poorly understood. An examination into waterborne illnesses in the countdown to "Day Zero" will also provide better understanding of the extent of the impact greywater use on public health. A thorough risk assessment through the analysis and evaluation of greywater events in Cape Town or similar case studies is a further knowledge gap. It will provide a window into the vulnerability of consumers, the environment and infrastructure during drought conditions and the trade-off between risk and water saving.

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CHAPTER 5. INVESTIGATING THE QUANTITY-QUALITY NEXUS ASSOCIATED WITH UNTREATED HOUSEHOLD GREYWATER REUSE

The following chapter is a research paper submitted to the *Journal of Water Supply: Research and Technology-AQUA.*

CONTEXT OF PAPER WITHIN THIS DISSERTATION

The results from the case study presented in Chapter 4 showed that untreated greywater use was common in the study group. This provides insight into the relatively high-risk use of untreated greywater in serviced urban areas by residential consumers, as a consumer-driven solution to potential water supply system failure. As highlighted in Chapter 4, and given the backdrop of an increasingly water stressed world and the need to save water, it is also important to understand the vulnerability of consumers, the environment and infrastructure during drought conditions associated with greywater reuse. This paper is an assessment of the quantity of water savings based on reported untreated greywater reuse which is the first component required towards understanding the risk-water saving trade-off (i.e., the quantity-quality nexus). Evaluation of the related risks and further exploration of the trade-off itself is presented in Chapter 6.

Chapter 9, Appendix C provides supplementary background information on the stochastic model inputs employed in this chapter.

PUBLICATION STATUS

Submitted. This paper was received by the *Journal of Water Supply: Research and Technology-AQUA* on 2 August 2021 (Manuscript number: AQUAWIES-D-21-00117) and was improved and resubmitted on 3 February 2022.

CONTRIBUTIONS

The extent of contributions by the various authors of this paper was as follows:

- N. Nel (70%) which included conceptualisation, data analysis, write up and literature review, journal selection, submission, formatting, and review.
- V. Speight (5%)
- M. Crouse (20%)
- H.E. Jacobs (5%)

The Declaration of contributions by co-authors can be found in Appendix A.

INVESTIGATING THE QUANTITY-QUALITY NEXUS ASSOCIATED WITH UNTREATED HOUSEHOLD GREYWATER REUSE

Short title: Quantity-Quality investigation of untreated household greywater reuse

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ABSTRACT

Untreated greywater reuse is available as a supplementary household water source and is used to support non-potable water use requirements, particularly during emergency drought conditions. There is, however, a knowledge gap about the volume of untreated greywater reused in serviced homes where potable water is supplied via a water distribution system, based on reported ad hoc water use practices. Given this gap, the purpose of this work was to explore the related quantity-quality nexus, using a stochastic model to assess the greywater reuse quantity theoretically. Untreated greywater reuse practices (e.g. bucketing) were found to reduce water consumption in a single person suburban household by less than 10%, which is lower than values reported in literature. This relatively low volume weighed up against the high risk of using untreated greywater may result in a negative nett benefit, providing decision making insights for both water service providers and consumers.

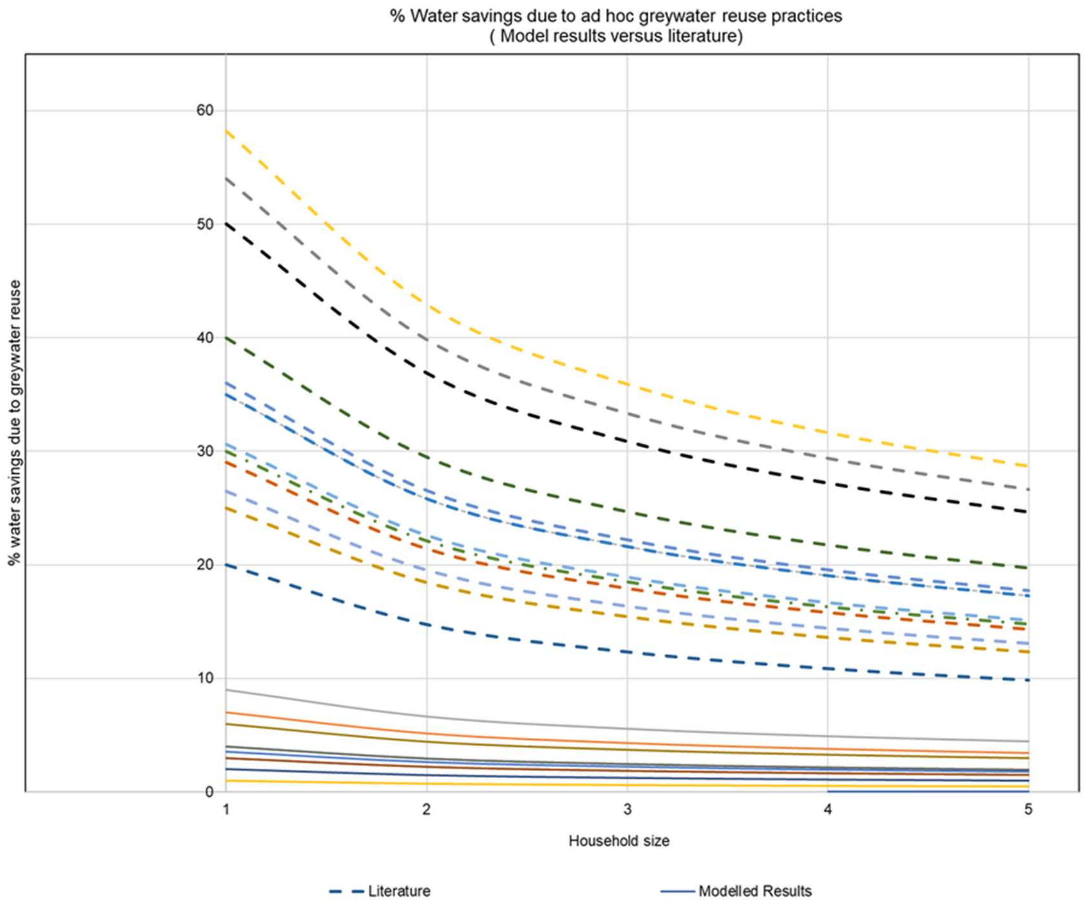
Keywords: greywater, reuse, water use, practices, volume

HIGHLIGHTS

The contribution of untreated greywater to total water savings by the reported ad hoc greywater practices modelled in this study is <10%.

The volume of untreated greywater considered viable for use is markedly less than the reported maximum volume of greywater that could be achieved, with treatment.

GRAPHICAL ABSTRACT



INTRODUCTION

Background

Increasing demand for water through urbanisation and industrialisation and decreasing supply due to the potential of climate change, high pipe system losses, low adaptability of existing water infrastructure and continued freshwater pollution (Oteng Peprah *et al.*, 2018; Friedler & Gross, 2019) are culminating in an increasingly water stressed world (Tsanov *et al.*, 2020). Supplementary water source practices at household level are emerging in well-serviced urban areas, especially in drought-stricken regions. Uptake of supplementary on-site sources – such as greywater, rainwater and groundwater – in regions serviced by potable water distribution systems (WDS), is inevitable (Nel & Jacobs 2019; Friedler & Gross, 2019).

Reported greywater generation rates

Table 5-1 is a summary of greywater generated from serviced households around the world as well as a summary of reported reduction in household water use due to greywater use reported by others. Based on these studies, greywater represents around 50% to 85% of the domestic wastewater stream while the portion of greywater used and therefore the net potable savings is generally less than 50%.

Table 5-1 Summary of reported residential greywater generation rates in different countries and reductions in household water use due to greywater use

Reported Residential Greywater Generation			
Percentage of Water Consumption	Generation Rate (l/c/d)	Location	Reference
80-83%	151	Oman	Jamrah *et al.* (2008)
50%	45-80	South Arica	Ilemobade et al. (2012)
-	20	Gauteng, South Africa	As reported in Oteng Peprah *et al.*, (2018)
60-70%	-	Industrialised Countries	Friedler & Gross (2019)
-	80-110	Vietnam	Oteng Peprah *et al.*, (2018)
-	98	Israel	Ilemobade *et al.* (2012)
-	110	Switzerland	Ilemobade *et al.* (2012)
-	113	Australia	Ilemobade *et al.* (2012)
-	225	Malaysia	Ilemobade *et al.* (2012)
-	84	United Kingdom	Ilemobade *et al.* (2012)
-	72	Nepal	Oteng Peprah *et al.*, (2018
-	30-50	Jordan	Ilemobade *et al.* (2012)
-	14-161	Africa and Middle East	Oteng Peprah *et al.*, (2018)
-	65	Stockholm, Sweden	Oteng Peprah *et al.*, (2018)

-		123	Arizona, USA	Oteng Peprah *et al.*, (2018)	
-		72-225	Asia	Oteng Peprah *et al.*, (2018)	
-		30	Mali	Oteng Peprah *et al.*, (2018)	
50-66%		70-90	India	Manna (2018)	
Reported Reductions in household water use due to greywater use					
Water Source & End Use	Harvesting Technique	Data Collection method	Percentage House Water Saving	Location	Reference
- Not reported **-Toilet Flushing**	Not reported	Not reported	10 - 20% (40 to 60l/c/d)	Not reported	Friedler & Gross (2019)
- Not reported **-Garden Irrigation**	Not reported	Not reported	>40%	Not reported	Friedler & Gross (2019)
- Bath, shower, and wash basin **-Toilet flushing**	Greywater Recycling System	Short term monitoring of 4 houses.	9 - 36%	United Kingdom	Birks *et al.* (2003)
- Not reported **- Lawns and ornamental gardens**	Not reported	Not reported	30 - 50%	Australia	Jeppeson (1996)
- Not reported **-Toilet flushing**	Greywater Recycling System	Not reported.	35%	Syria	Mourad *et al.* (2011)
- Not applicable **- Not applicable**	Greywater Recycling System	Simulation Model based on real, disaggregated water consumption data	55.6-58.2% (hot water) 5.8-30.6% (cold water)	Not applicable	Knuttsson and Knutsson (2021)
Not reported	Not reported	Not reported	30%	Kuwait	As reported in Samayamanthula *et al.* (2019)
Not reported	Not reported	Not reported	29%	Australia	As reported in Samayamanthula *et al.* (2019)
Not reported	Not reported	Not reported	33-54%	Kenya	As reported in Samayamanthula *et al.* (2019)
Not reported	Not reported	Not reported	25%	Turkey	As reported in Samayamanthula *et al.* (2019)
Not reported	Not reported	Not reported	29-35%	Brazil	As reported in Samayamanthula *et al.* (2019)

Not reported	Not reported	Not reported	30%	Malaysia	As reported in Samayamanthula *et al.* (2019)
Not reported	Not reported	Not reported	26.5%	South Korea	As reported in Samayamanthula *et al.* (2019)

Scope and Limitations

For the purpose of this study, the term greywater is defined as all household wastewater except toilet water (Casanova *et al*., 2001). In poorly serviced areas, the informal use of greywater is common (and free), used in relatively large quantities and is known to carry undesirable risks (Carden *et al*., 2007). This study focused exclusively on untreated household greywater use in serviced areas where potable water is supplied via a WDS and waterborne sanitation is in place.

A limitation to the study was a lack of field measurements which were not undertaken due to the Covid 19 pandemic. A second limitation was the extrapolation of model results for a single person household to increased house occupancies based on modelled water savings by Crouch *et al.* (2021).

Motivation

The majority of published papers investigated household greywater generation, with fewer investigating the actual volume of greywater utilised (i.e., the water savings), as summarised in **Error! Reference source not found.**. In addition, earlier research into greywater use in formal residential settings, typically addressed greywater treatment systems and/or greywater quality and the related volume of (treated) greywater. Quantification of the relatively smaller fraction of untreated greywater remains a critical gap. This study addressed the quality-quantity nexus associated with untreated greywater use.

Research questions

Greywater use is most often associated with either technologically advanced greywater treatment systems in formal residential settings, or uncontrolled use of untreated greywater in informal communities. However, in some situations such as emergency drought conditions, individuals in formal homes with in-house access to potable water supply also employ simpler, low cost greywater harvesting techniques, such as collecting untreated greywater from the shower with a bucket for use in toilet flushing (e.g., Nel & Jacobs, 2019). Research questions arise around how much untreated greywater is used in such cases, what the impact on potable household water consumption is and how this can be weighed up against the quality of the greywater?

Aims and Objectives

The aim of this research was to explore the quantity-quality nexus, focussing on untreated household greywater use when employing actual use practices, as reported on in a parallel study. The specific objectives were to: (a) estimate the volume of greywater produced in formal residential areas theoretically, based on reported untreated greywater use practices; (b) derive the reduction in potable water consumption from the piped WDS and (c) investigate the impact of household size on the results.

This research paper is structured by initially providing a methodological section, followed by an analysis and results, and a discussion. The final conclusions then highlight the scientific value, strengths and limitations of the study.

METHODS

Research methodology

This study involved applied research, as it addressed the problem of untreated greywater use volume, employing a former stochastic model for per capita water use by Crouch *et al.* (2021). Figure 5-1 shows the methodology pertaining to this study, with Phase I having been addressed in the introduction of this article and Phase II and III discussed below.

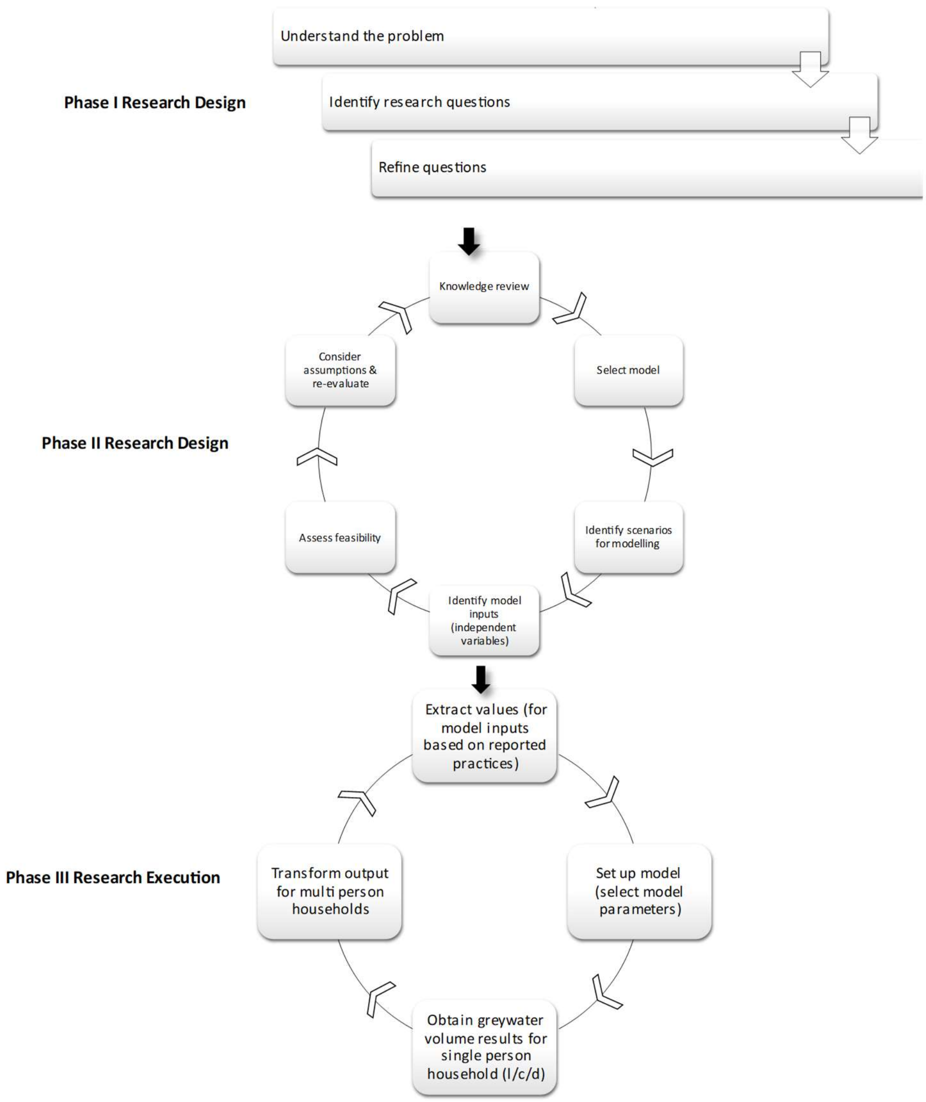


Figure 5-1 Methodology flow chart

Data collection

The following data was collected by means of a desktop review:

- Residential greywater generation rates in different countries and reductions in household water use due to greywater use.
- A relevant stochastic model for the theoretical quantification of residential per capita untreated greywater use for various lifestyle levels.
- Ad hoc greywater use practices to inform the stochastic model.

Analysis procedure

Data analysis was undertaken utilising a stochastic model using @Risk software. The raw data on reported greywater use practices (see Table 5-2) was used to inform the stochastic model. It included small-scale, relatively inexpensive, often temporary, untreated greywater use practices as identified by Nel & Jacobs (2019) as common activities in the study group during the "Day Zero" water scare in Cape Town, South Africa. Greywater sources and end uses that were utilised by around 50% or more of the survey respondents and verified in the online forum were considered for the modelling. These reported ad hoc practices therefore included the bath, shower and washing machine as greywater sources; toilet flushing and garden irrigation as end uses and bucketing as a means of collection.

The stochastic water use model as developed by Crouch *et al.* (2021) was identified as an appropriate model for adaption towards the quantification of untreated greywater use. The model calculates the expected value of water use based upon stochastic simulation of different water use activities within the restrictions associated with various lifestyle levels. Due to the variability in individual greywater use practices (e.g. duration of shower, collection method, etc.), a stochastic approach was required rather than a deterministic approach. So too, the parameters that determine a greywater practice (e.g. bucket size for collection of shower water, volume of water harvested, number of buckets etc.) are interdependent. For example, if buckets of shower water were filled for toilet flushing, then the toilet would obviously have to be flushed and thus the bucket emptied, before the next shower event could lead to subsequent collection of shower greywater.

Data interpretation

The outputs of the stochastic model were utilised to inform an exploration of the quantity-quality nexus associated with greywater use and to generate a graphical representation of per capita water savings in comparison to literature. The raw data collected with regards to household water savings due to greywater use was utilised for graphical comparative purposes. The model and literature findings were extrapolated for increased household size according to per capita water use trends by Crouch *et al.* (2021).

ANALYSIS AND RESULTS

Untreated greywater use practices

Roesner *et al.* (2006) stated that initial applications of greywater in the United States began with residents hand bailing shower and washing machine water to irrigate their gardens during a drought. Roesner *et al.* (2006) further report that greywater is used in relatively developed countries including the United Kingdom, Australia, Germany and Sweden. It is also common practice in Japan to use water from hand washing for toilet flushing through a specially designed dual-purpose bathroom fixture (Carden *et al.*, 2018). Nel & Jacobs (2019) found untreated greywater use to be common in Cape Town, South Africa, during the "Day Zero crisis (De Bruyn & Loubser, 2019) and reported on actual untreated greywater use practices, as summarised in Table 5-2. In terms of untreated greywater collection methods, buckets or homemade piping systems were typically used in the homes.

Table 5-2 Reported ad hoc greywater practices from a consumer survey and online forum as undertaken by Nel & Jacobs, (2019)

Reported Greywater Sources	% of Respondents (Consumer Survey)	% of Posts (Online Forum)
Bath	51%	20%
Shower	87%	27%
Hand Basin	39%	-
Washing Machine	49%	29%
Laundry trough (or similar)	9%	-
Dishwasher	6%	-
Kitchen basin	45%	-
Other (water from freezer defrosting, water from food preparation, geyser overflow, duck pond water replacement and hot tub and pool backwash water)	-	<2%
Reported Greywater End Uses	% of respondents (consumer survey)	% of posts (Online Forum)
Toilet flushing	74%	16%
Irrigation/gardening	57%	67%
Washing of vehicles/driveways/outdoor paved areas	11%	-
Cleaning floors/shower, rinsing dishes, washing bicycles, filling the pool	<6%	-
Pool filling	-	6%

Modelled scenarios

A single person household was used as a conservative quantification of residential per capita greywater use given that per capita water use decreases as the number of household occupants increases

(Crouch *et al.*, 2021). For example, garden irrigation volumes would remain relatively constant irrespective of the number of household occupants. The study findings were then extrapolated for increased household size according to per capita water use trends by Crouch *et al.* (2021).

The greywater analysis was performed for two different lifestyle levels, each of which involve different total water consumption practices. Crouch *et al.* (2021) defined various lifestyle levels with increasing water consumption for increased standards of living as:

- Baseline A. Absolute Basic Consumption (expected value of 92l/c/d): Minimum expected daily water requirement for an individual person considered essential for hygiene and physical wellbeing excluding any outdoor or luxury uses (typically for a temporary time period e.g. during a crisis).
- Baseline B. Ultimate Consumption (expected value of 314l/c/d): Daily water requirements, relating to a high level of needs allowing for luxuries such as irrigated gardens, a swimming pool and/or water feature while considering efficient use and no wastage.

These baseline water consumption rates per person are for a 24-hour period disregarding the spatial location to capture water use across multiple locations (Crouch *et al.*, 2021).

The simulations for this study further adapted the water use model to include greywater recycling. Relevant parameter distributions are indicated in Table 5-3, with 100 000 iterations performed for each case. Three overarching use scenarios were modelled: R1) bath/shower water collection by bucket to use for toilet flushing, R2) bath/shower water collection by bucket to use for toilet flushing and garden, and R3) washing machine water collection by homemade piping to garden. A constant volume of 4L greywater collected per bucket (assuming 5L buckets) was chosen as a practical bucket collection volume for harvesting shower/bath water meant for toilet flushing. A maximum of three buckets was considered as reasonable in view of bucket storage space in the bathroom.

Table 5-3 Stochastic model run descriptions and parameter distributions

Model Run	Use Scenario	Description of Greywater Use Scenario	Volume per event	Baseline Water Use Case applicable to this Greywater Use Scenario	Parameter	Unit	Distribution	Mean Value
1	R1	Bath/Shower to Toilet by bucketing (Nel & Jacobs, 2019)	1 Bucket	Baseline A	Shower bucket volume	L/bucket	Fixed	4
					Number of buckets (shower)	Buckets/shower event	Fixed	1
					Bath bucket volume	L/bucket	Fixed	4
					Number of buckets (bath)	Buckets/bath event	Fixed	1
2			2 Buckets		Shower bucket volume	L/bucket	Fixed	4
					Number of buckets (shower)	Buckets/shower event	Fixed	2
					Bath bucket volume	L/bucket	Fixed	4
					Number of buckets (bath)	Buckets/bath event	Fixed	2
3			3 Buckets		Shower bucket volume	L/bucket	Fixed	4
					Number of buckets (shower)	Buckets/shower event	Fixed	3
					Bath bucket volume	L/bucket	Fixed	4
					Number of buckets (bath)	Buckets/bath event	Fixed	3
4			1 Bucket	Baseline B	Shower bucket volume	L/bucket	Fixed	4
					Number of buckets (shower)	Buckets/shower event	Fixed	1

					Bath bucket volume	L/bucket	Fixed	4
					Number of buckets (bath)	Buckets/bath event	Fixed	1
5			2 Buckets		Shower bucket volume	L/bucket	Fixed	4
					Number of buckets (shower)	Buckets/shower event	Fixed	2
					Bath bucket volume	L/bucket	Fixed	4
					Number of buckets (bath)	Buckets/bath event	Fixed	2
6			3 Buckets		Shower bucket volume	L/bucket	Fixed	4
					Number of buckets (shower)	Buckets/shower event	Fixed	3
					Bath bucket volume	L/bucket	Fixed	4
					Number of buckets (bath)	Buckets/bath event	Fixed	3
7	R2	Bath/Shower to Toilet and Garden by bucketing (Nel & Jacobs, 2019; Roesner *et al.*, 2006)	1 Bucket	Baseline B	Shower bucket volume	L/bucket	Fixed	4
					Number of buckets (shower)	Buckets/shower event	Fixed	1
					Bath bucket volume	L/bucket	Fixed	4
					Number of buckets (bath)	Buckets/bath event	Fixed	1
8			2 Buckets		Shower bucket volume	L/bucket	Fixed	4
					Number of buckets (shower)	Buckets/shower event	Fixed	2
					Bath bucket volume	L/bucket	Fixed	4
					Number of buckets (bath)	Buckets/bath event	Fixed	2

9			3 Buckets		Shower bucket volume	L/bucket	Fixed	4
					Number of buckets (shower)	Buckets/shower event	Fixed	3
					Bath bucket volume	L/bucket	Fixed	4
					Number of buckets (bath)	Buckets/bath event	Fixed	3
10	R3	Washing Machine to garden by homemade piping (Nel & Jacobs, 2019; Roesner *et al.*, 2006)	Entire volume of washing machine effluent	Baseline B	Frequency of clothes washer	events/c/d	Normal (a)*	0,31
					Penetration rate of top loader		Bernoulli	0,37
					Volume of top loader	L/event	Discrete (b)*	
					Volume of front-end loader	L/event	Discrete (c)*	

(a)* Standard Deviation σ=0.11, min =0.07, max=0.43

(b)* Front end loader distribution volume: 20-29L=4.1%; 30-39L=8.5%; 40-49L=41.3%; 50-59L=33.8%; >60L=12.3%

(c)* Top end loader distribution volume: 50-89L=53.6%; 90-110L=15.1%; 111-125L=18.7%; >125=12.6%

Results

The results of the stochastic model using inputs from Table 5-2 are presented in Table 5-4. The table shows residential water consumption for Baseline A and Baseline B and the volume of water and percentage saved from each baseline for a single person household. The single bucket scenarios exceed 4L per day in some model runs because more than one bath or shower event took place per day.

Table 5-4 Residential Water Consumption and Water Savings for Various Lifestyle levels with Untreated Greywater Use

Residential Water Consumption for Various Lifestyle Levels with Untreated Greywater Use					
Scenario	Number of Buckets /Volume of Washing Machine water	Baseline A Water Consumption (L/c/d)		Baseline B Water Consumption (L/c/d)	
R1: Bath/Shower to Toilet by bucketing	1	88.43		309.5	
	2	85.45		305.0	
	3	83.69		302.6	
R2: Bath/Shower to Toilet and Garden by bucketing	1			309.2	
	2			305.6	
	3			301.8	
R3: Washing Machine to garden by homemade piping	Entire Volume of Washing Machine Effluent			295	
Water Saved due to Untreated Greywater Use					
Scenario	Number of Buckets /Volume of Washing Machine water	Baseline A Water Saved (L/c/d & % saved)		Baseline B Water Saved (L/c/d & % saved)	
R1: Bath/Shower to Toilet by bucketing	1	3,57	4%	4,5	1%
	2	6,55	7%	9	3%
	3	8,31	9%	11,4	4%
R2: Bath/Shower to Toilet and Garden by bucketing	1			4,8	2%
	2			8,4	3%
	3			12,2	4%
R3: Washing Machine to garden by homemade piping	Entire Volume of Washing Machine Effluent			19	6%

Under the three greywater use scenarios modelled in this study, the largest volume of water saved was 19L/c/d for the use of the entire volume of washing machine effluent. The smallest water saving was 3.5L/c/d for the use of 1 bucket of shower or bath water for toilet flushing (R1) for Baseline A. The largest percentage water saving (9%) was realised with the use of 3 buckets from the bath or shower for toilet flushing (R1) for Baseline A. The least significant water saving (1%) was realised with the use of 1 bucket of shower or bath water for toilet flushing (R1) for Baseline B.

While the volume of greywater generated in a home is directly dependent on water consumption, the portion of greywater used for various lifestyles is of significance. Of the reported ad hoc greywater practices modelled in this study, no matter the baseline, the contribution of greywater to the total water savings remains <10%.

The following graphical representation is an extrapolation of these water savings results that relate to a single person household to larger household occupancies (solid line) and plotted in relation to literature findings (dashed lines).

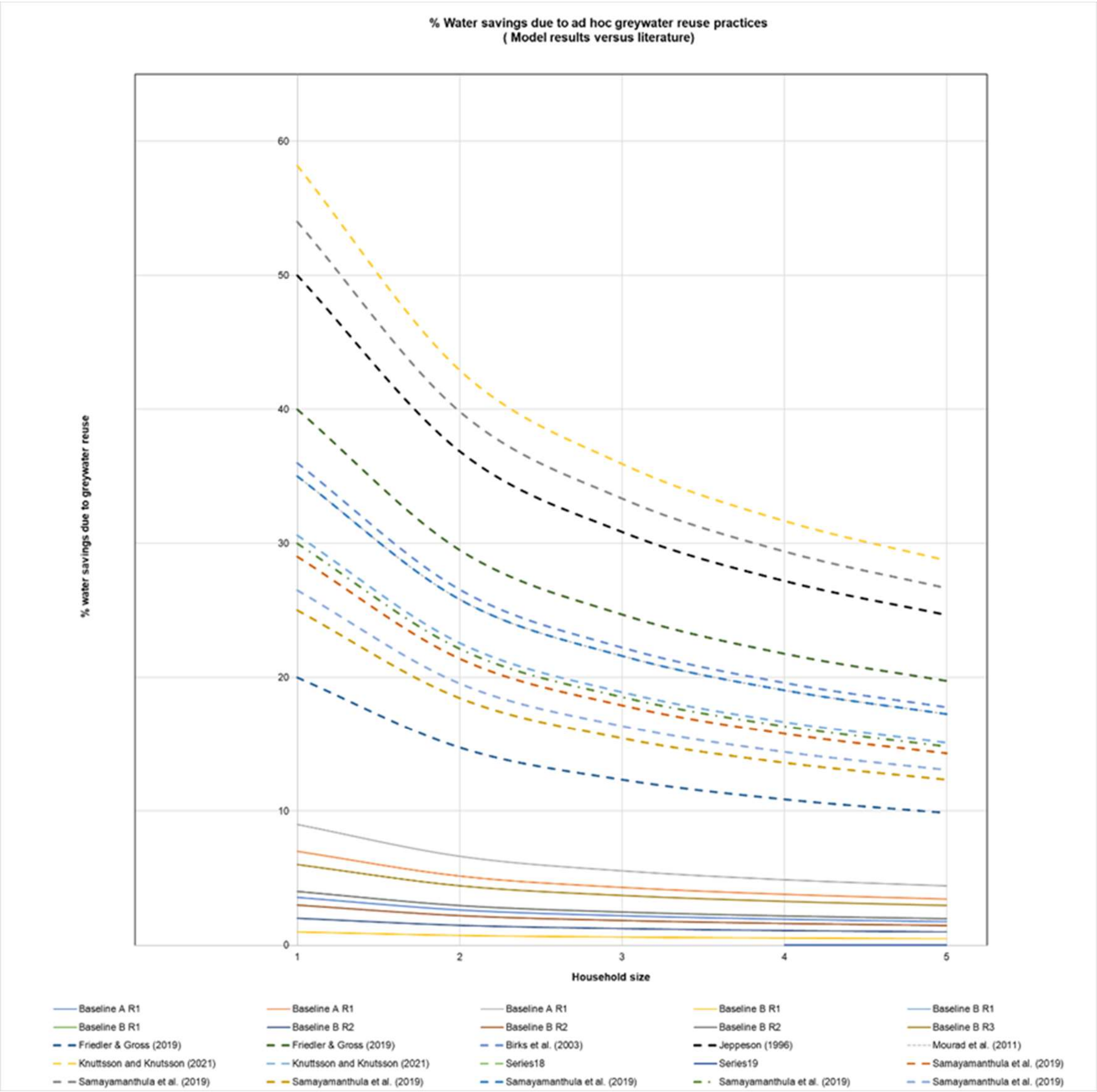


Figure 5-2 Water savings due to ad hoc greywater use practices (model results versus literature)

DISCUSSION

While the use of any supplementary household water sources would reduce the load on the WDS, there are various trade offs surrounding the quality-quantity nexus as related to each. These supplementary household water sources could be framed in the quantity-quality space, as depicted in Figure 5-3 (left). The exclusion of greywater from this part of the figure is due to the relatively complex quantity-quality relationship as discussed below and to the right of the figure.

As the majority of published papers frame greywater volumes as household greywater generation or greywater harvested through the use of greywater treatment systems, it is noteworthy that the contribution of untreated greywater to total water savings as modelled in this study is lower than the literature findings (see

Figure 5-2).

The quantification of this relatively smaller fraction of untreated greywater provides insight into a particular knowledge gap around the greywater quality - quantity nexus. This relatively low volume of water saved, needs to be weighed up against risk (quality) as well as cost and effort required. While highly complex and expensive greywater treatment systems, would ensure a high volume of greywater use as well as mitigate any potential direct risks to the environment (Friedler and Gross, 2019) or human health (Carden *et al.*, 2018), it may result in a negative nett benefit due to high capital and maintenance costs and energy requirements. So too, the low water savings modelled in this study, along with the potential to cause harm to public health, the environment and water services infrastructure (Penn *et al.*, 2012), may also result in a negative nett benefit. This quality – quantity relationship as framed in the following figure needs to be understood when undertaking greywater use practices.

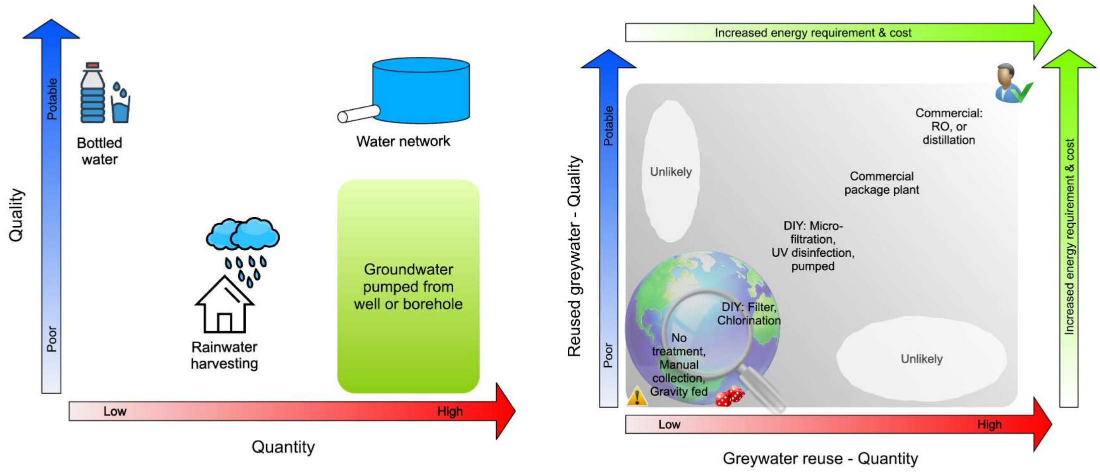


Figure 5-3 The Quantity-Quality relationship for greywater use

CONCLUSION

A novel end-use model allowing for stochastic modelling of greywater use in terms of quantity was utilised in this study. The model results provide an understanding of the volume of untreated greywater used in formal suburban areas, a prediction of water savings by household size in comparison to literature and therefore insight into the quality-quantity nexus. While the use of greywater with purpose-built treatment systems has been studied for a number of locations and configurations, the practices used by individuals in the absence of such infrastructure is not well documented. The use of reported ad hoc greywater practices to inform the stochastic model in this study, therefore provides unique insights in the knowledge field.

It is noteworthy that the contribution of greywater to total water savings modelled in this study, is generally lower than values reported in literature and markedly less than the maximum water consumption reduction that could be achieved with relatively complex greywater treatment systems (

Figure 5-2). This relatively low volume of water saved (<10%), needs to be weighed up against potential risk (quality), particularly as these reported practices may represent the highest potential risk to public health and the environment because of the lack of engineered system controls and treatment. The low volumes reflect the limitations of the manual collection method and along with relatively poor water quality, may be a barrier to the use of collected greywater in and around the home. While any reduction in urban water consumption is important, particularly as water security increasingly becomes a global concern and greywater use in serviced suburban suburbs becomes more widespread, there is value in understanding whether a nett benefit of water savings due to untreated greywater use is in fact realised. The exploration into this quality-quantity relationship provides decision making insights for both water service providers and consumers. Additional investigation into the quality component was undertaken by Nel *et al.* (in review).

Adding to the data in this study with field measurements to inform the results and ultimately a risk analysis would allow for added understanding into the quality-quantity nexus in the greywater use space. Further modelling for increased house occupancy would also provide additional knowledge in the field.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper, or could be requested from the authors.

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CHAPTER 6. STATISTICAL ANALYSIS AND RISK ASSESSMENT OF UNTREATED HOUSEHOLD GREYWATER QUALITY TO INFORM THE WATER SAVING-RISK TRADE OFF

The following chapter is a research paper submitted to *Water SA*.

CONTEXT OF PAPER WITHIN THIS DISSERTATION

Chapter 5 showed that untreated greywater use practices were found to reduce water consumption in a single person suburban household by <10%. This quantification of the volumes associated with untreated ad hoc greywater use was the first step in understanding the trade-off between expected water savings (quantity) and potential risks (quality). This paper aims to inform the second component of the water saving-risk trade off through a statistical analysis of greywater quality results as sourced from other South African studies in order to undertake a risk assessment.

PUBLICATION STATUS

Submitted. This paper was received by *Water SA* on 17 September 2021 and has been accepted for review (reference number: 3946).

CONTRIBUTIONS

The extent of contributions by the various authors of this paper was as follows:

- N. Nel (85%) which included conceptualisation, literature review, data collection, data analysis, write up, journal identification, submission, formatting, and review.
- A. Ilemobade (5%)
- I. Brink (5%)
- H.E. Jacobs (5%)

The Declaration of contributions by co-authors can be found in Appendix A.

STATISTICAL ANALYSIS AND RISK ASSESSMENT OF UNTREATED HOUSEHOLD GREYWATER QUALITY TO INFORM THE WATER SAVING-RISK TRADE OFF

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ABSTRACT

Interest in greywater reuse is increasing, because of the potential to supplement scarce freshwater resources in the face of increasing demand and aridity. This paper aims to inform the water saving-risk trade off, associated with residential untreated greywater use, through a statistical analysis of greywater quality results as sourced from prior South African studies. Greywater sources included in this review were the bathroom, kitchen, laundry, mixed and general residential sources. Variability in terms of each of the reported physical, chemical and microbiological constituents by source and between result sets was noted. Statistically significant differences were evident between the pH, conductivity and phosphorous values of certain sources. A risk assessment undertaken for each of the constituents revealed further variability. The constituent with the highest number of high-risk samples was total dissolved solids. The relatively high risk and high consequences in greywater practices in terms of public health, the environment, and infrastructure, given this variability, provide insight into the trade-off with the potential water savings. There is a need for a more nuanced view of the potential potable savings associated with greywater reuse and a need for improved risk management.

Keywords: greywater, risk, quality

INTRODUCTION

Background and Rationale

Globally, water use is encouraged because of its potential to (i) supplement freshwater resources; (ii) provide reliable water services in remote or environmentally sensitive locations; (iii) mitigate the rising costs of meeting drinking water treatment and wastewater discharge standards; and (iv) reduce sewage discharges to water bodies. In South Africa, interest in greywater use is increasing because of its potential to supplement scarce freshwater resources in the face of increasing demand and aridity (Ilemobade *et al.*, 2013).

Greywater is normally defined as untreated wastewater from all domestic activities other than toilet flushing (Rodda *et al.*, 2010), although some definitions also exclude kitchen wastewater. The informal use of untreated greywater in poorly serviced areas is common (Carden *et al.*, 2007). Untreated greywater is also used at households in fully serviced urban areas (Nel and Jacobs, 2019). Greywater use practices, especially untreated use, negatively impact public health (WHO, 2006; Carden *et al.*, 2018; Oteng Peprah *et al.*, 2018), the environment (Friedler and Gross, 2019), household and agricultural fittings (DWAF,1996) and water services infrastructure (Penn *et al.* 2012). The inevitable increased uptake of supplementary water sources, particularly untreated greywater, in South Africa (Nel and Jacobs 2019; Friedler and Gross, 2019) therefore requires better understanding.

Various technologies exist for the treatment of greywater and the reduction of notable risks associated with handling untreated greywater. However, ignorance, expense, complexity, or lack of risk testing procedures (Toifl *et al.*, 2019) may pose barriers to entry. Where such technologies are used, understanding of safe application may be lacking for the reasons stated above. Additionally, in situations where greywater is used by the consumer to supplement formal supply such as in emergency drought situations, risk always falls on the consumer rather than the local authority. Here, the consumer may decide to ignore risks associated with untreated greywater use when faced with costs of alternative supply options, compared to the perceived benefits of the related water savings.

Research Focus

Based on the findings of a consumer survey and online forum as undertaken by Nel and Jacobs, (2019), the practice of untreated greywater use for non-potable purposes, provides the focus of this study. In light of the trade-off between the risks associated with untreated greywater use and the water savings achieved (i.e., the water saving - risk nexus), particularly under water scarce conditions, a risk-based analysis of residential greywater irrigation is a knowledge gap.

The assessment of greywater use volumes (i.e., water savings) undertaken by Nel *et al.* (submitted) was the initial component identified to inform the water savings-risk trade off. An investigation into potential risks (including to public health, the environment, and infrastructure) associated with untreated greywater use practices in a fully serviced home, is the second component towards exploring the trade off and forms the focus of this study.

Aim and Objectives

This paper informs the water saving-risk trade off associated with residential untreated greywater use. The first objective is to identify reported major hazards, risks, and consequences associated with untreated greywater use at the household level, through a comprehensive knowledge review. The second objective is to identify greywater constituents of interest and accordingly identify relevant South African water quality guidelines. A third objective is to report characteristics (including relevant water quality parameters and source) of greywater samples from prior South African studies. The characteristics of reported greywater samples were compared through a statistical analysis of each parameter, to determine the significance of differences by source and between samples. A risk assessment was presented of each parameter for each reported greywater sample with a view to exploring the trade-off between the identified risks associated with untreated greywater use and the water savings achieved.

Limitation

Some reported greywater parameters employed in this study were based on average values, or values obtained from single samples. This limits the extent of the variability of greywater quality, reported in earlier studies. Insufficiently reported measurements for certain greywater quality parameters were a further limitation and meant that data analysis could not be undertaken for all parameters and all samples.

CONTEXT

Greywater Water Saving Potential

Nel *et al.* (submitted) estimated the water saving potential of untreated greywater use in formal residential areas, using a stochastic end-use water consumption model based on reported ad hoc water use practices. Greywater could represent up to ~50% (Ilemobade *et al.*, 2012), 60-70% (Friedler and Gross), or even ~85% (Jamrah *et al.* 2008) of the domestic wastewater stream. The maximum portion of greywater used after treatment – and therefore the net potable savings – is generally considered to be <50%. When the focus is shifted to untreated household greywater and typical DIY-practices, use was found to reduce water consumption in a single-person suburban household by between 1% and 9% (Nel *et al.*, submitted).

Greywater: hazard, risk, and consequence

Overview

Under emergency conditions, consumers are faced with a trade-off between the risks and consequences of reusing versus not reusing greywater. A correct understanding of the distinction between hazard, risk, and consequence is critical for the determination of the possible impact of untreated greywater use on the health and well-being of the consumer, the environment and water services infrastructure.

Greywater Hazards

A hazard is broadly defined as an agent (such as contaminated greywater) that has the potential to cause harm (Bernstein, 2018). Reported greywater characterisation studies have illustrated the varying physical, chemical, and microbial characteristics of greywater (see Christova-Boal *et al.*, 1996 and Eriksson *et al.*, 2002). Variation in the composition of greywater is heavily dependent on the lifestyle of household occupants, products used in the home, age of the occupants, prevailing health conditions, hygiene practices, the source of the water, the quality of the water supply, and the extent of leaching from piping and processes in the biofilm on the piping walls (Carden *et al.*, 2018; Eriksson *et al.*, 2002; Oteng-Peprah *et al.*, 2018).

Three hazard categories of greywater could be identified:

- Physical hazards: These include constituents such as pH, conductivity, and suspended material amongst others (Toifl *et al.*, 2019).
- Chemical hazards: Residential greywater consists of a complex mix of chemicals originating from various household products used for cooking, cleaning, and personal hygiene. Untreated greywater invariably contains different substances, including fragrances, flavours, preservatives, surfactants and solvents, dyes, sunscreen agents, oil, UV blockers, paints and enzymes (Christova-Boal *et al.*, 1996; Eriksson *et al.*, 2002; Roesner *et al.*, 2006).
- Microbiological hazards: Greywater typically contains microorganisms such as bacteria, protozoa, viruses, and helminths mainly emanating from personal hygiene activities and food handling (Oteng-Peprah *et al.*, 2018). For instance, pathogens associated with faecal matter can be introduced to greywater from showers and baths, as well as washing machines with faecally contaminated laundry.

Greywater Use Risks

Risk is a measure of the likelihood of harm from the hazard – it is a product of probability and consequence (Swartz *et al.*, 2018). Given the potential presence of physical, chemical, and microbial hazards in untreated greywater, the risk of causing harm is further dependent on a complex interplay of various factors. These factors include hazard type and concentration, exposure, vulnerability, and scale of use. Risks to public health, the environment, the household, the agricultural sector and water services infrastructure are linked to untreated greywater use.

Greywater Use Consequences

A consequence is a measure of the severity of the negative impact of an event. The distinction between risk and consequence allows for the evaluation of whether to take a certain risk for improved risk management. Consequences can range from small/moderate to high/severe. Measuring the severity of the impact of a greywater use practice allows for this evaluation and an understanding of various scenarios ranging from low risk/low consequence to high-risk/ high consequence; with the latter being of greater concern.

METHODOLOGY

Data Collection

National and international literature sources were reviewed to gain an overview of the hazards, risks, and consequences of untreated greywater use at household level. Greywater constituents of greatest relevance in the South African context, in terms of human health, plant growth/yield and soil health and infrastructure; and water quality criteria, as presented in Rodda *et al.* (2010) (see Table 6-2), were included. A compilation of reported greywater samples including the measured greywater constituents and the relevant greywater source was compiled through a comprehensive knowledge review of South African studies.

Data Analysis

Statistical Analysis

A statistical analysis of the raw data as derived from literature was undertaken to determine the significance of differences in the quality of greywater for each reported parameter, by source and between samples. Comparisons of different areas were done using one-way ANOVA with Fisher least significant difference (LSD) post hoc testing. Normality was assessed by inspecting normal probability plots and were in all cases found to be acceptable. Levene's test was done to test for homogeneity-of-variance assumption and in cases where this was strongly rejected ($p<0.01$), Games-Howell post hoc testing was reported.

Risk Assessment

A risk assessment was undertaken to inform the exploration of the water saving-risk trade-off. The methodological approach presented by Nel *et al.* (2013) and Swartz *et al.* (2018) was adapted to perform a risk assessment of each reported constituent, per greywater sample, as per the risk matrix shown in

Figure 6-1. The risk matrix is a visualisation of the product of the likelihood (probability) of a hazard and the consequence of the hazard (David and Wilkinson, 2009; Swartz *et al.* 2018). This framework indicates whether the risk is “unacceptable”, “acceptable” or two tiers (Low and High) of “As Low As Reasonably Practicable” (ALARP).

			Probability (Nel and Jacobs, 2019)				
			Rare (Less than once per week)	Unlikely (At least once a week)	Moderate (Between 2 and 4 times a week)	Likely (At least once a day)	Almost Certain (More than once a day)
Consequence			**1**	**2**	**3**	**4**	**5**
Insignificant	Target water quality range (Table 6-2)	**1**	1	2	3	4	5
Minor	Maximum water quality range (Table 6-2)	**2**	2	4	6	8	10
Major	Water quality suitable only for short term use on site -specific basis (Table 6-2)	**3**	3	6	9	12	15
Significant	Water quality not recommended for irrigation use (Table 6-2)	**4**	4	8	12	16	20

Key:

- Acceptable Risk
- ALARP (Low)
- ALARP (High)
- Unacceptable Risk

Figure 6-1 Risk assessment matrix for reported greywater constituents

Table 6-1 shows the consequence and probability levels used in this study to inform the x- and y axes of the risk assessment, as adapted from Swartz *et al.* (2018). The levels of probability were assigned by greywater source based on the findings in Nel and Jacobs (2019) reporting on a small-scale survey in Cape Town, South Africa during 2018 to assess the extent of greywater use under drought conditions. The levels of probability are based on the majority of survey respondents in the study.

The levels of consequences were assigned as per the approach outlined by Swartz *et al.* (2018) of comparing concentrations to a relevant safety reference value. Each reported greywater parameter was evaluated for compliance against irrigation water quality guidelines (i.e., assigned to a water quality range). Once a risk assessment was performed for each recorded parameter, a risk distribution for the physical, chemical, and microbiological constituents, was generated.

Table 6-1 Consequence and probability levels used for risk assessment (adapted from Swartz et al., 2018)

Level	Probability	Consequence
5	Almost Certain (More than once a day)	-
4	Likely (At least once a day)	Significant
3	Moderate (Between 2 and 4 times a week)	Major
2	Unlikely (At Least once a week)	Minor
1	Rare (Less than once per week)	Insignificant

Assignment of levels of probability	
Greywater Source	**Probability (Nel and Jacobs, 2019)**
Bath	Less than once per week
Shower	At least once a day
Hand Basin	More than once a day
Mixed Bathroom Sources	At least once a day
Washing Machine	Between 2 & 4 times weekly
Laundry trough (or similar)	Less than once per week
Dishwashing machine	Less than once per week
Kitchen Basin	At least once a day

Consequence	Water quality range (see Table 6-2)
Significant	Parameter in water quality range not recommended for irrigation use
Major	Parameter in water quality range suitable only for short term use on a site-specific basis
Minor	Parameter in maximum water quality range
Insignificant	Parameter in target water quality range

GREYWATER CONSTITUENTS AND WATER QUALITY GUIDELINES

Rodda *et al.* (2010) provide a consolidated list of greywater constituents that were found to be consistently in excess of water guidelines in various South African studies; and were considered of greatest relevance to use for irrigation in terms of human health, plant growth, crop yield and soil fertility. A graded series of quality ranges were derived by the authors, based on the South African Water Quality Guidelines for irrigation (DWAF, 1996) and other relevant literature where constituents were not available. Table 6-2 provides the quality criteria against which the reported greywater constituents in the subsequent section were compared, in order to determine the associated risks.

Table 6-2 Water-quality guidance for use of greywater for small-scale irrigation in South Africa, as presented in Rodda *et al.* (2010)

Greywater Hazard	Target Water Quality Range (Suitable for unrestricted use with minimal risk to human health, plants, or soil)	Maximum water quality range (Increasing risk to human health, plants, or soil)	Water quality suitable only for short term use on a site-specific basis (Significant risk to human health, plants, or soil; tolerable for short-term use only)	Water quality not recommended for irrigation use (Excessive risk to human health, plants, or soil)
Electrical conductivity ($mS \cdot m^{-1}$)	<40	40-200	200-540	>540
Oil and grease ($mg \cdot L^{-1}$)	<2.5	2.5-10	10-20	>20
+pH	6.5-8.4	6-9	6-9	<6>9
Suspended solids ($mg \cdot L^{-1}$)	<50	50-100	>100	>100
Boron ($mg \cdot L^{-1}$)	<0.5	0.5-4.0	4.0-6.0	>6.0
Chemical oxygen demand (COD, mg·L)	<400	400-5000	>5000	>5000
Sodium adsorption ratio (SAR)	<2.0	2.0-5.0	5.0-15.0	>15.0
Total inorganic nitrogen ($mg \cdot L^{-1}$)	<10	10-20	20-60	>60
Total phosphorus ($mg \cdot L^{-1}$)	<10	10-15	15-50	>50
E. coli (Colony-forming units, CFU·100 mL^{-1})	<1	$1 – 10^3$ (1 – 1 000)	10^3 - 10^5 (1000 – 100 000) Note: Only with appropriate exposure restrictions.	> 10^7 (> 10 000 000)

RESULTS AND DISCUSSION

A total of 49 raw domestic greywater quality samples were captured from the following South African studies: Christen (2019), Jackson *et al.* (2006), Bakare *et al.* (2018), Engelbrecht and Murphy (2006), Madubela (2020), and Water Research Commission (2018). The comprehensive data set is provided in Appendix D. The measurements for each of the constituents listed in Table 6-2 were recorded where possible. Greywater sources included the bathroom, the kitchen, the laundry and mixed (kitchen and bathroom) and general household sources.

In terms of the reported physical constituents, 40 of the samples collected in this manner included conductivity measurements, 40 included pH and 15 included TSS. Of the chemical constituents, 33 samples included values for COD and 30 samples included Phosphorous values. In terms of microbiology, E.coli was recorded in 24 of the 49 raw greywater samples. Four constituents namely Total Nitrogen, oil and grease, Boron and SAR did not have sufficient measurements to perform the data analysis and were thus excluded in the analysis. The statistical analysis of each parameter by source and between samples is presented below.

Variable physical, chemical, and microbiological constituents by source and between greywater samples were evident in the data, which is also an indication of the variation of risk involved with untreated greywater use. The chemistry of a particular sample of untreated residential greywater, for example, could have serious implications for soil quality and the ability of various plants to grow, but may not directly impact on public health. The microbiology, on the other hand, may have a direct, immediate, and often notable impact on public health through various transmission routes due to the presence and survival rate of pathogens in greywater (e.g., Christova Boal *et al.*, 1996), but the plant growth may not be impacted. The physical, chemical, and microbiological constituent findings are discussed separately below.

Physical Constituents

The mean reported conductivity of the greywater samples were 49 mS/m, 230 mS/m, 245mS/m, and 35mS/m for mixed, the kitchen, laundry, and bathroom greywater sources respectively. Application of the Games Howell Post Hoc Test indicated a significant difference (p<0.05) between mixed and laundry greywater sources as well as the bathroom and laundry sources. The mean value for conductivity for the bathroom greywater is the only one of the sources that falls within the target water quality range as per Table 6-2. The highest conductivities were from the kitchen and laundry, which is in alignment with a study by Bakare *et al.* (2018). According to the water quality guidelines (Table 6-2) the water would be suitable only for short-term use on a site-specific basis. While these higher conductivity values could cause a reduction in plant productivity and changes in soil properties (DWAF,1996), the risk assessment for conductivity indicated that the majority of the recorded samples were of acceptable risk and the first tier of ALARP.

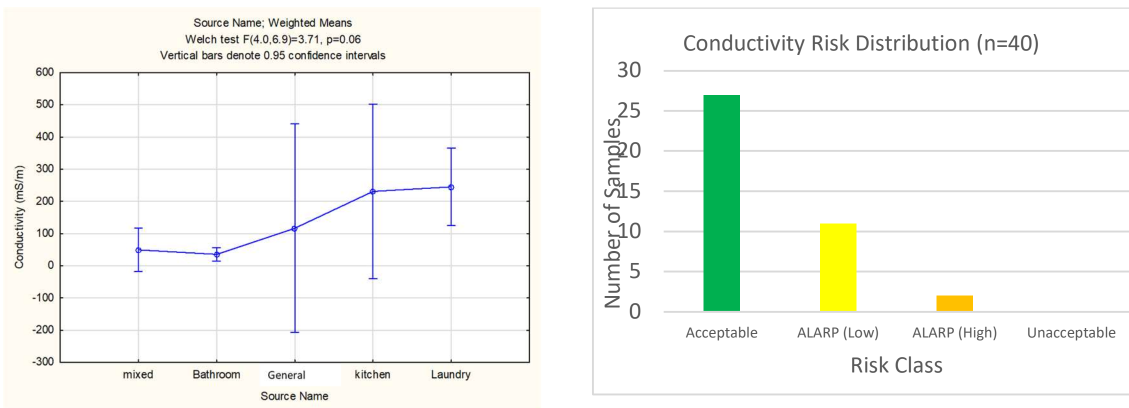


Figure 6-2 Conductivity data analysis results (statistical analysis and risk assessment)

The mean pH value for all the greywater sources was found to be 7.8. The mean pH values per source were found to be 7.4, 7.3, 6.9, and 8.8 for mixed sources, the bathroom, kitchen, and laundry respectively. Greywater from laundry, in particular, had pH values at an unacceptable level (Table 6-2). Application of the Games Howell Post Hoc Test further indicated a significant difference ($p<0.05$) between the pH values of laundry greywater sources compared to the pH values of bathroom and mixed sources. Alkaline greywater as prevalent with powdered detergent use is a contributing factor towards soil degradation (Hardie *et al.*, 2021). Unacceptable pH levels could also cause corrosion of equipment (e.g. pipes), damage to plants, and changes in biochemical processes (Eriksson *et al.*, 2002). The majority of samples were of acceptable risk with an even spread among the two tiers of ALARP and unacceptable risk.

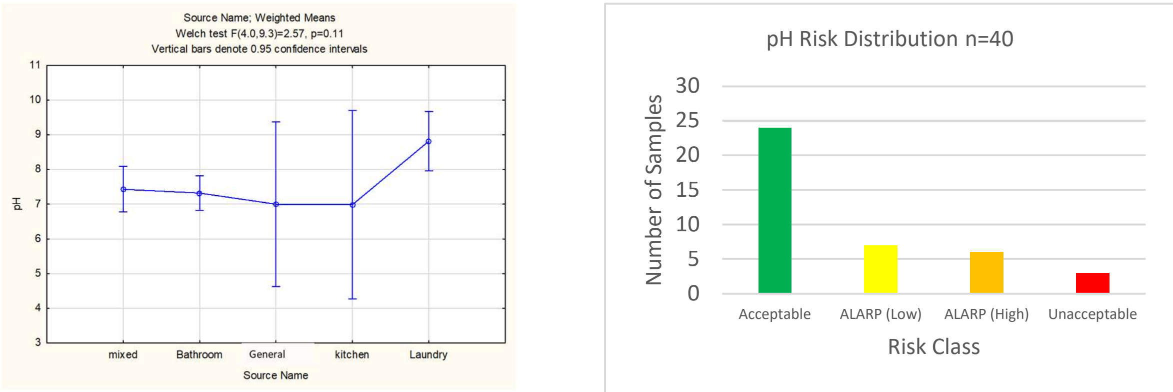


Figure 6-3 pH Data analysis results (statistical analysis and risk assessment)

Values for TSS were only recorded from mixed sources and the bathroom, with mean values at 3338 mg/L and 723 mg/L respectively and therefore both mean values are in the water quality range where the water is not recommended, even for irrigation use (see Table 6-2). High values of suspended solids are also reported by Oteng-Peprah *et al.*, (2018) from kitchen and bathroom washing and rinsing activities who state that high TSS values are common, which, in turn, increases the turbidity. The risk assessment in this study indicated that the majority of samples are high risk or second tier ALARP where high levels of TSS, when using greywater for irrigation, can cause clogging of irrigation emitters and the formation of a soil surface crust which inhibits water infiltration, seedling emergence and soil aeration (DWAF, 1996).

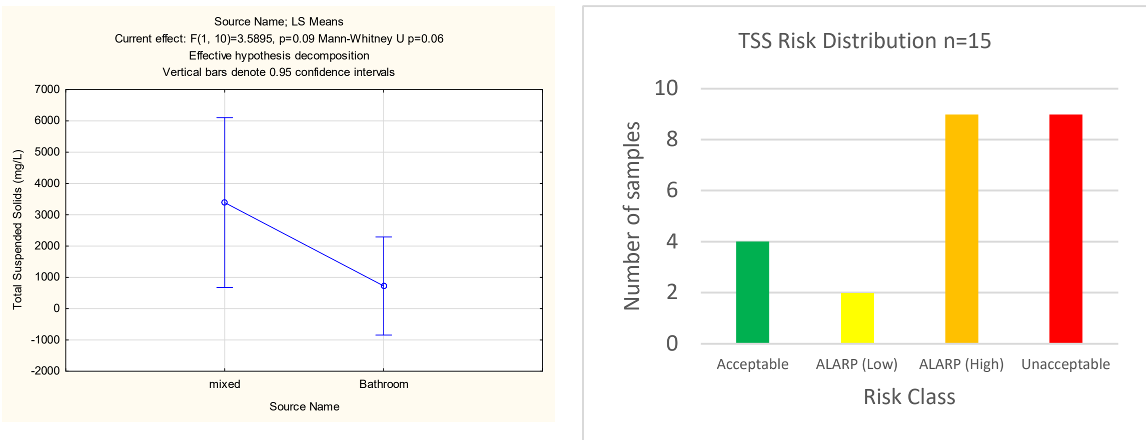
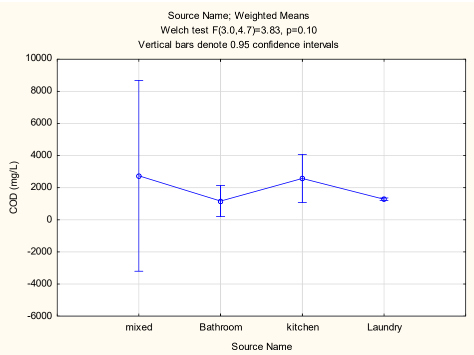


Figure 6-4 TSS Data analysis results (statistical analysis and risk assessment)

Chemical Constituents

The mean values for COD were measured at 2739 mg/L for mixed sources,1165 mg/L for bathroom greywater, 2573mg/L for kitchen greywater, and 1281 mg/L for laundry greywater; and therefore, no mean values fall within the target water quality range for irrigation (see Table 6-2). In alignment with this, Friedler and Gross (2019) state that COD in greywater can range from about 7 mg/L to more than 2500 mg/L. Application of the Games Howell Post Hoc Test indicated no significant differences between the COD values for the four sources. COD measures the amount of oxygen required to oxidise organic material and is an indication of the polluting strength (Bakare *et al.*, 2018). The greywater from mixed sources shows the highest level of organic compounds. Further to this, the risk assessment indicates that the majority of samples have a medium risk to pollute, with some exhibiting an acceptable risk and some, an unacceptable risk.



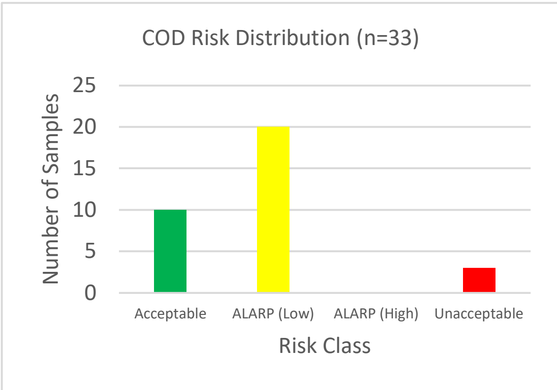


Figure 6-5 COD data analysis results (statistical analysis and risk assessment)

The mean phosphorus values for the domestic raw greywater samples were 6.1 mg/L for mixed sources, 3.5 mg/L for bathroom sources, and 2.8mg/L for laundry sources, and therefore all within the target water quality range (see Table 6-2). While excess phosphorus concentrations can induce clogging of irrigation equipment (DWAF, 1996), the risk assessment indicates that the risk is relatively low. Application of the Least Significant Difference (LSD) Post Hoc Test also indicated a significant difference ($p>0.05$) between the phosphorus values of mixed, bathroom, and laundry greywater sources.

Figure 6-6 Conductivity data analysis results (statistical analysis and risk assessment)

MICROBIOLOGICAL CONSTITUENTS

Mean reported values for E. Coli were 1025mg (counts per 100 mL) for mixed sources and 1429mg (counts per 100 mL) for laundry greywater. Both these mean values fall within the water quality range that is suitable only for short-term use on a site-specific basis (see Table 6-2). Although the risk assessment indicated an acceptable risk for the majority of samples with some samples an ALARP risk (low and high) in terms of causing infection in humans and animals, this does not include an assessment of pathogen types within the microbes. Further research into the specific microbial risk is warranted. This outcome indicates a possible shortcoming in the risk analysis method, indicating that future research into providing more nuanced additions to cater for more detailed risk analysis should be added.

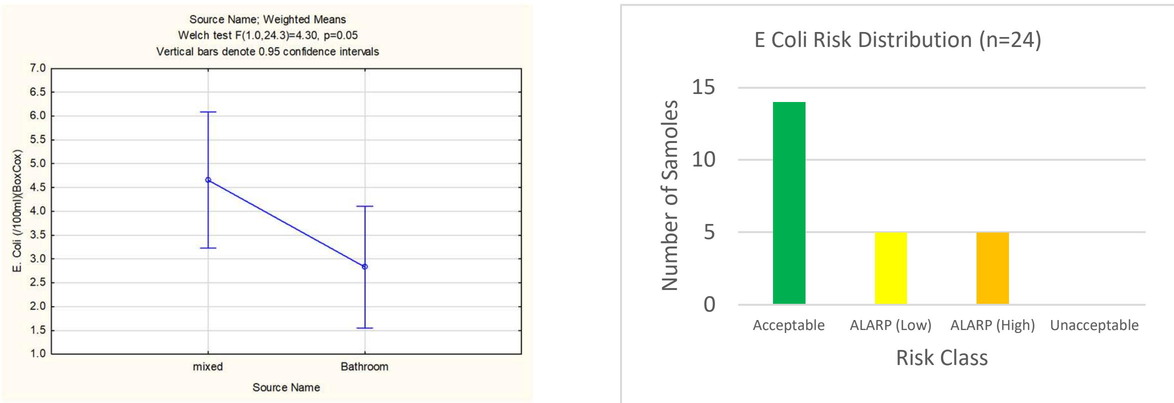


Figure 6-7 E. coli data analysis results (statistical analysis and risk assessment)

The interaction between the type of constituent present and the physical hazards, such as temperature, could influence the hazard concentration because the toxicity and dose level needed for potential infection and the survival rate in the environment are relevant. The storage of greywater further influences the concentration of microbial hazards. Natural processes can create anaerobic conditions within hours, resulting in offensive odours, a breeding ground for mosquitoes, and perfect conditions for the proliferation of microorganisms (WHO, 2006). Another key consideration is the quantity of potable water utilised in the household that will have an impact on the dilution of the greywater produced. For instance, increased water conservation efforts in a home could decrease the quantity used and thus increase the concentration of pollutants in the greywater produced, thereby increasing the risk.

Risk

The risk assessment undertaken in this study has confirmed that the likelihood of a batch of untreated greywater causing harm is complex. Contributing factors to greywater risk include exposure, vulnerability, and scale of use as it relates to humans, the environment, and infrastructure.

Public Health Risk: Exposure and Vulnerability

Pathogens present in greywater have the potential to cause disease, so the exposure of humans to these pathogens, as well as the vulnerability of the individual, influences the health risk. Exposure can occur through the consumption of edible crops that have been irrigated with greywater (Carden *et al.*, 2018); splash-up of contaminated greywater while irrigating; aerosols as a result of irrigation with greywater; filling up a toilet cistern, or aerosols when the toilet is flushed (Christova-Boal *et al.*, 1996); coming into contact with ponded greywater (Roesner *et al.*, 2006); handling greywater-contaminated plants/crops; handling a pet that frequents areas of the garden where greywater is utilised. Accidental cross-connection of greywater and potable water pipes, or drinking water from a garden hose used for greywater irrigation, also generates the risk associated with consumption of greywater.

The public health risk associated with greywater use is further increased according to the age and health of the recipient population, with more vulnerable sectors of society more likely to fall ill when in contact with harmful pathogens (Carden *et al.*, 2018). Ilemobade *et al.* (2013), for instance, employed the Disability Adjusted Life Year (DALY) index to estimate the health risk per annum (using the DALY number and unit cost) due to diarrhoea caused by greywater use for toilet flushing at two universities.

Environmental Risk: Exposure

Certain applications of greywater such as plant bed irrigation (Roesner *et al.*, 2006), can create transmission routes for exposure of the environment to greywater hazards. While the health risks of reusing household greywater due to exposure to potential pathogens are well documented, there is less information on the effects of greywater on soil microorganisms and downstream urban ecosystems; possibly because these impacts may be difficult to predict due to the variability of greywater (Roesner *et al.*, 2006). In terms of greywater chemistry, given its unpredictability, the impacts of greywater irrigation on soil chemistry and aquatic ecosystems are also complex and information is scarce.

Literature on the long-term effects of greywater irrigation on ornamental plants is also scant. Roesner *et al.* (2006) recommend relatively saline tolerant plant species when irrigating with greywater. Dissolved salts can be absorbed up through the plant by the roots and result in scorched leaves. WHO (2006) suggest that plants that can thrive under high alkaline conditions are key to plant health under greywater irrigation conditions.

Nel *et al.* (2013) state that greywater ponding and runoff into the stormwater system (e.g., when irrigating with untreated greywater) poses considerable dangers to the environment (e.g., polluting rivers and wetlands) and public health. Greywater use for garden irrigation can result in pollution of downstream aquatic environments when rain falls on the urban space and stormwater carries the contaminants (originally deposited with the untreated greywater) further downstream. This risk is poorly researched, is hard to quantify and is not appreciated by uninformed home owners who may use untreated greywater with the best intentions.

Infrastructure Risk: Scale of Use

In serviced urban areas, the practice of reusing greywater can alter the quality and quantity of (i) wastewater exiting a particular home and entering the sewage system and (ii) runoff from the plot entering the stormwater system. Sewers and stormwater pipes are designed according to certain criteria, to ensure that the minimum flow velocity met and/or exceeded, as specified, and pipes are regularly scoured to remove settled solids. A notable reduction in flow rate, i.e., as a result of greywater use, would also reduce the flow velocity – ultimately leading to clogging of the pipes. The cumulative effect of altered wastewater from many households could impact the sewer network (leading to sewer blockages), the wastewater treatment works (Penn *et al.*, 2012) and the stormwater system.

Consequences

Public Health Consequences

The varying hazards and the varying risks associated with untreated greywater, also give rise to variable consequences. The public health impact of greywater use could range from a small impact on health or discomfort (e.g., odours and mosquitoes), to death or a permanent reduction in health depending on the risk factors as previously discussed. Contracting a disease could in turn have severe financial consequences due to the required medical care and compromised economic opportunities of an ill individual (Ilemobade *et al.*, 2013).

Environmental Consequences

The environmental consequences of greywater use include changes in soil chemistry (Hardie *et al.*, 2021) and contamination of both groundwater and downstream aquatic ecosystems. Greywater use pollutes the stormwater system and ultimately rivers and wetlands further downstream. This consequence could be severe due to the diverse and important ecological, aesthetic and recreational functions that waterways fulfil in serviced urban areas. In the same vein, contaminated runoff is likely to cross property boundaries and put others at risk, with legal consequences for both homeowners and water service providers. Notwithstanding the notable health risks as previously discussed, studies on the effect of greywater on crop yield have also been undertaken (e.g., Jackson *et al.*, 2006) and indicate varied but mostly non-detrimental impacts (i.e., low consequence).

Environmental degradation (through a decrease in soil health, groundwater contamination, and polluted stormwater) and its direct cost are well documented in the literature (e.g., Ilemobade et. al., 2013). The natural environment fulfils diverse, social, cultural, and economic functions that are all interdependent, and undermining these functions comes at a socio-economic cost.

Infrastructure Consequences

Increased greywater use (coupled with other water conservation efforts in suburban homes) and lower wastewater flows could result in higher incidents of sewer blockages. The consequential infrastructure damage and maintenance requirements could financially impact both water services providers and consumers. Should a pipe burst, or an overflow occur, it may, in turn, cause substantial pollution of the surrounding stormwater system and pose a health risk to those living nearby. The capacity and functioning of stormwater infrastructure may also be compromised with the shift of wastewater flows from the sewer to the stormwater system as a result of outdoor greywater practices, e.g., garden irrigation and hard surface cleaning (Jacobs and Nel, 2019).

At a household level, when using untreated greywater for toilet flushing; hair, various other organic materials, sand, lint, fats and other undesirable materials present in the greywater could cause clogging of the operating components in the toilet cistern, such as the inlet valve (Christova-Boal *et al.*, 1996). Valve clogging results in water leakage into the toilet bowl. Untreated greywater use for toilet flushing could thus negate the intended water savings. Greywater use may lead to clogging of irrigation equipment, particularly drip irrigation and micro-jets (DWAF, 1996). Cross-connections of greywater that is supplied under pressure into any household plumbing system could contaminate the water network via feed into the water distribution pipes, although such connections are normally prohibited by law (or by-laws).

CONCLUSION

Greywater sources included in this study were the bathroom, kitchen, laundry, and mixed sources. Variability in terms of each of the reported physical, chemical, and microbiological- constituents by source and between result sets was noted. These variations concur with studies such as Oteng-Peprah *et al.*, (2018) that identified notable variations in greywater constituents in both place and time. Statistically significant differences were evident between the pH values of laundry greywater sources and the pH values of the bathroom and mixed sources; as well as the conductivity levels of laundry greywater sources compared to mixed and bathroom sources. Statistically significant differences were also found between the Phosphorous levels in the mixed, bathroom and laundry greywater samples. These variations also extend to the risk assessment which was undertaken for each of the constituents. It was found that the constituent with the highest number of high-risk samples was TSS.

The greywater source is often used to classify greywater as a way of determining the potential levels of contamination and thereby the risk, e.g. Carden *et al.* (2018). The variability of greywater by source as shown in this study, however, is an indication that the popular classifications of greywater use by source as a surrogate indicator of its contents and concentration could be inappropriate and misleading. While greywater originating from a particular source in one household could differ from another household, so too greywater composition from a specific source in one household may vary temporarily throughout the day, from day to day and seasonally.

Nel *et al.* (submitted) showed that the use of untreated greywater through manual collection methods contributed <10% to total water savings in a suburban household for various lifestyle levels. While this value is relatively low, the authors recognise that any reduction in water consumption, particularly in water-scarce conditions, is noteworthy and that larger scale use would mean more significant water savings. By contrast, the relatively high risk and high consequences in greywater practices in terms of public health, the environment, and infrastructure given the variability and unpredictability of untreated greywater quality as noted in this study, provide insight into the trade-off of these potential water savings.

The various facets of risk as discussed prior are also escalated as the use of greywater becomes more widespread. Household greywater risk management could be improved through pre-emptive action, either through removing the hazard (e.g., Hardie *et al.* recommending against the use of powdered laundry detergent greywater), removing exposure, or minimising the consequence. Alternatively, the greywater could be treated and disinfected to the desired water quality before application.

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CHAPTER 7. DISCUSSION

This research has addressed the following key questions as related to the research objectives with the following corresponding findings thus far:

Table 7-1 Key questions and corresponding findings in this study

Key Questions addressed in this research	Findings
Which supplementary HWS are typically available to consumers and how do these alternatives compare?	The most notable HWS options are greywater use, groundwater use and rainwater use (listed alphabetically).
Is untreated greywater, identified as one of the most accessible yet poorly researched sources, employed by consumers and in which manner?	Untreated greywater is employed by consumers often in times of crisis, often in ways that contradict what is suggested by research. Untreated greywater use is easily accessible, readily available and often requires no (or limited) on-site plumbing and additional infrastructure (provided that potable water is supplied via a pressurised WDS to the consumer).
What are the typical volumes of untreated greywater produced and the associated water savings from the WDS?	Commonly employed untreated greywater use practices result in relatively low water savings at household level (<10% of household consumption).
What is the implication of untreated greywater quality with regards to the associated risk?	Highly variable and relatively poor greywater quality poses risks to public health, the environment and water services infrastructure.

These findings form the basis of the following assumptions that were used to inform this discussion section.

Table 7-2 Key assumptions informing research discussion

Assumption	Cross Reference
The most notable HWS options are greywater use, groundwater use and rainwater use.	Chapter 2
Untreated greywater use is easily accessible, readily available and often requires no (or limited) on-site plumbing and additional infrastructure.	Chapter 2 and 3
Untreated greywater is employed by consumers in times of crisis, often in ways that contradict what is suggested by research.	Chapter 4
Untreated greywater use is taking place with little awareness of the risks and risk management approaches are not being followed.	Chapter 4
Commonly employed untreated greywater use practices result in relatively low water savings at household level (<10% of household consumption).	Chapter 5
Highly variable and relatively poor greywater quality poses risks to public health, the environment and water services infrastructure	Chapter 6

Given the relatively low reduction in water use from the WDS, coupled with the relatively poor quality of untreated greywater, there is a need to explore risk management and drivers of consumer decision making in the water use space. While logical solutions to the low quantity/low quality nexus associated with untreated greywater use would be to not use it or to treat it (i.e., mitigate the risks), the complexities of emergency situations and human behaviour need to be considered.

Chapter 6 has revealed the variability of the quality of untreated greywater and the potential need for risk management. The various hazards, risks and consequences associated with greywater use as identified in Chapter 6, are summarised in Figure 7-1, which provides insight into the principles of greywater risk management.

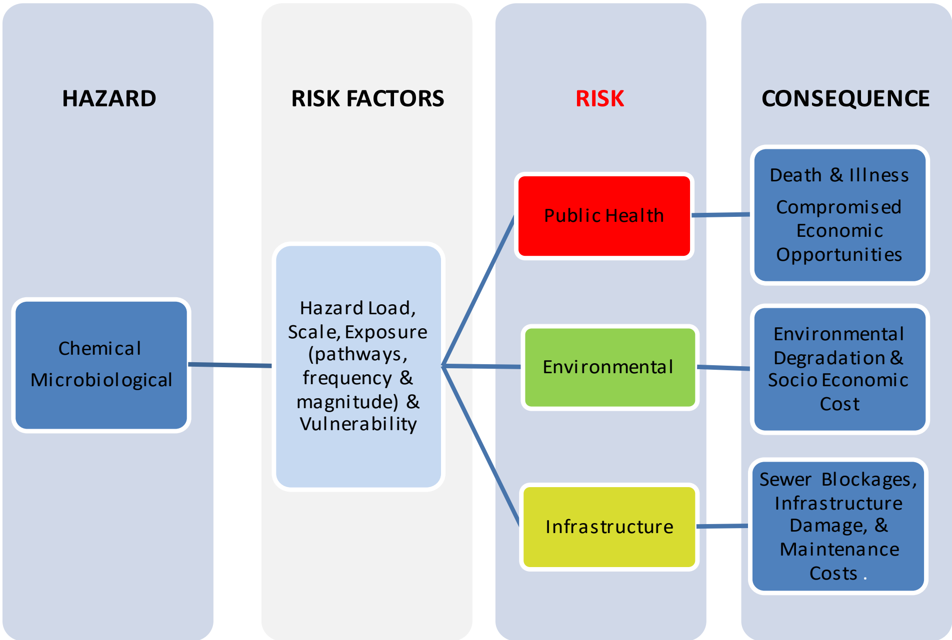

Figure 7-1: Greywater use: hazards, risks and consequences

The three types of risk associated with greywater use are public health, environmental and infrastructure risk. Risk exists only where there is a hazard coupled with exposure to that hazard. Public health and environmental risk can be lessened by improving the quality of the greywater through the removal or reduction of hazards or preventing exposure to the hazards (Rodda *et al.*, 2010) or by minimising the consequences. To this end, the focus in greywater literature is on the need for a multi-disciplinary risk management approach (Carden *et al.*, 2018) through minimising human exposure to given hazards such as by washing hands (e.g. Rodda *et el.*, 2010) or pre-treatment such as chlorination and filtration (e.g. Ilemobade *et al.*, 2013). Infrastructure risk, on the other hand, can be lessened through appropriate infrastructure design taking into account greywater use on a large scale, or altering water infrastructure operation and maintenance to lessen blockages by increased cleaning or flushing frequency for example (i.e. minimising consequences).

There is relatively high risk and high consequences in greywater practices in terms of public health, the environment, and infrastructure, given its variability. As a result, the emphasis on greywater use, particularly in the developed world, is on the treatment and disinfection of raw greywater to lower these risks with strict guidelines in place (e.g. Benami *et al.*, 2010). In low-income communities in the developing world, however, these treatments are not feasible nor affordable (Armitage *et al.*, 2008) and guidelines and by-laws to limit untreated greywater use are often lacking. It is evident from the Cape Town case study (Chapter 4), that greywater use may be gaining in popularity in more affluent serviced areas, particularly during serious water restrictions. The case study indicated that greywater use is taking place with little awareness of the risks and that risk management approaches are not being followed. The need to explore an interim/"crisis" solution towards greywater risk management in emergency situations is therefore needed as an accessible and cost-effective solution to lower possible risks and improve water resilience.

The complexities of consumer decision making in the water use space are explored below with the introduction of a decision-making matrix.

DECISION ANALYSIS

In the field of decision analysis, a formal procedure to balance the factors that influence a decision is undertaken while taking cognisance of personal risk aversion and time preference (Howard, 1966). As the uptake of supplementary HWS – such as greywater, rainwater and groundwater – is inevitable, there is a complex web of decisions that would lead to their initial uptake and the choice of one HWS over the other, or in conjunction with another (e.g. Dixon, 2000).

Various studies on the influencing factors of water use behaviour have been conducted. Gilbert *et al.* (2011) indicate that people in water scarce locations are significantly more likely to be supportive and to participate in water conservation behaviours than people living in areas of water surplus. Majuru *et al.* (2016) performed a study on how households respond to unreliable water supplies, stating that coping strategies include drilling wells, storing water on site, and collecting water from supplementary sources. The choice of coping strategies is influenced by income, level of education, land tenure and the extent of unreliability, which in turn influences the quantity and quality of the supplementary water source used. Graymore and Wallis (2010) identified the source of water supply, previous experience with water shortages and trust in the water authority and government as factors that appear to impact on water-use behaviour. Graymore and Wallis (2010) also cite altruistic reasons, and the need to keep businesses viable as drivers for water saving.

In the Cape Town case study (Chapter 4), in order to avoid a major water crisis, behaviour changing strategies were introduced by authorities which included stringent water restrictions, increased tariffs and the announcement of "Day Zero" (Nel and Jacobs, 2019) and resulted in a significant decrease in water consumption (Booysen *et al.*, 2019). The use of supplementary water sources by consumers in the study area contributed to the notable demand reduction and uptake of untreated greywater use was found to be common. Chapter 3 provides further discussion on factors that could influence a decision around the choice of which HWS to use. The use of greywater in the Cape Town case study was out of necessity in an emergency situation where the alternative was to run out of drinking water, have high water bills, face Intermittent Water Supply (IWS), or pay fines for contravening water restrictions. Further decisions with regards to the combination of greywater source, the harvesting technique and the end use application (i.e., greywater use scenario) may have depended on factors such as convenience, cost, end-use requirements, legalities and awareness of risk. Typical greywater generation points, methods of collection and end uses with ultimate disposal are depicted in Figure 7-2.

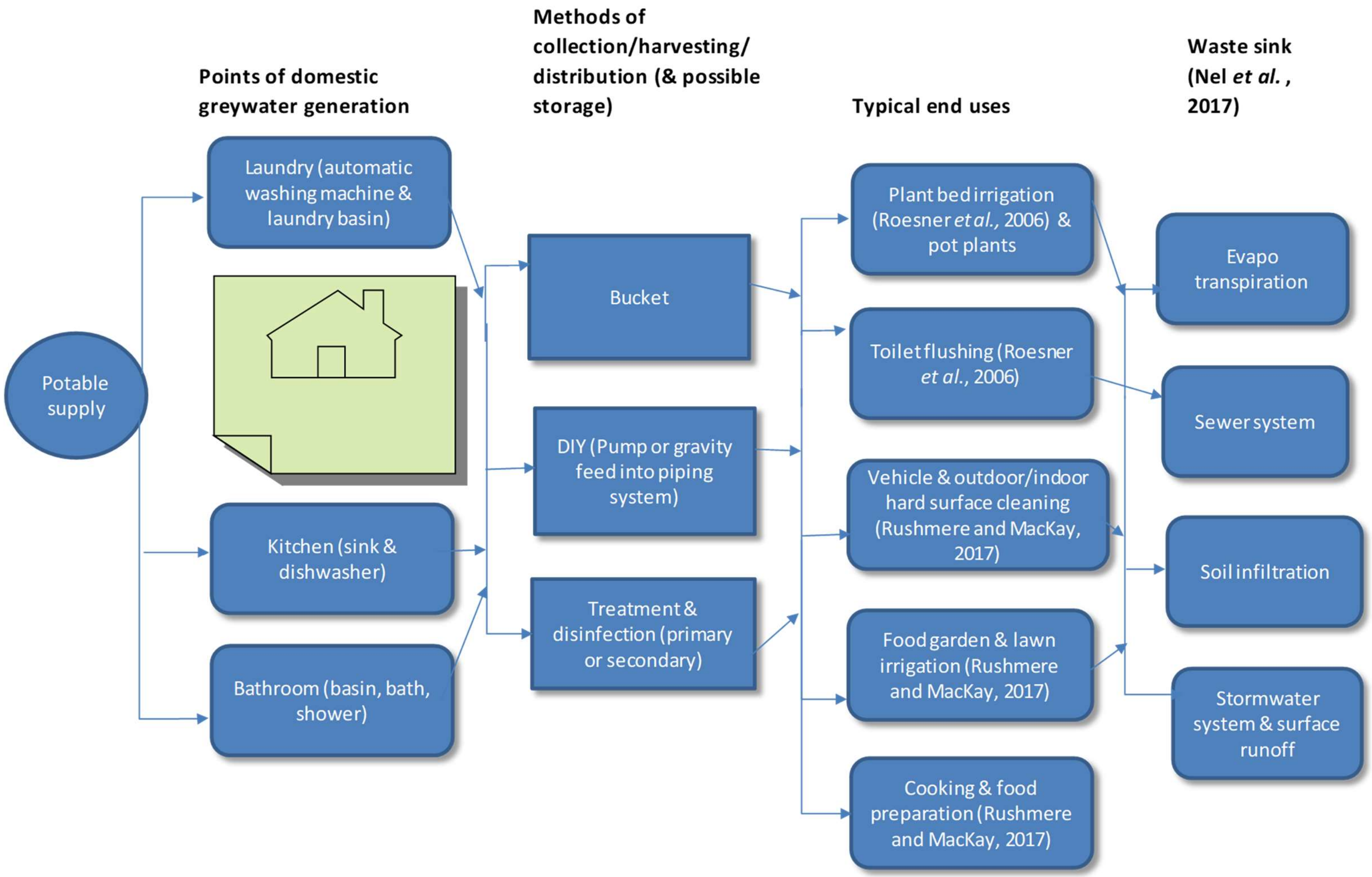

Figure 7-2 Greywater use schematic

This study has provided insight into the quality-quantity nexus associated with greywater use. The reduction in domestic water demand through the use of untreated greywater through manual collection methods is relatively low (see Chapter 5). So too, there are high risk and high consequences in greywater practices (see Chapter 6). Figure 7-2 is a schematic of possible scenarios in terms of greywater use practices and therefore the various decisions at play. For each scenario, there are trade offs (including cost, risk and effort). As such, an exploration of whether a positive nett benefit indeed prevails given the low water savings and risks is undertaken. The complex network of decision-making factors and the trade off in greywater use are discussed below.

Potential trade offs around cost, effort, water savings and risk are ranked subjectively in Figure 7-3. The reported ad hoc practices modelled in Chapter 5 with the addition of the following practices for comparative purposes are illustrated in the figure:

- All greywater sources (treatment with complex technology).
- All greywater sources (untreated).
- Shower "warm up/lag water" (i.e., cold water collected from the shower head while waiting for the water to warm up, which would generally amount to 1 bucket of good quality/low risk greywater straight from the geyser).

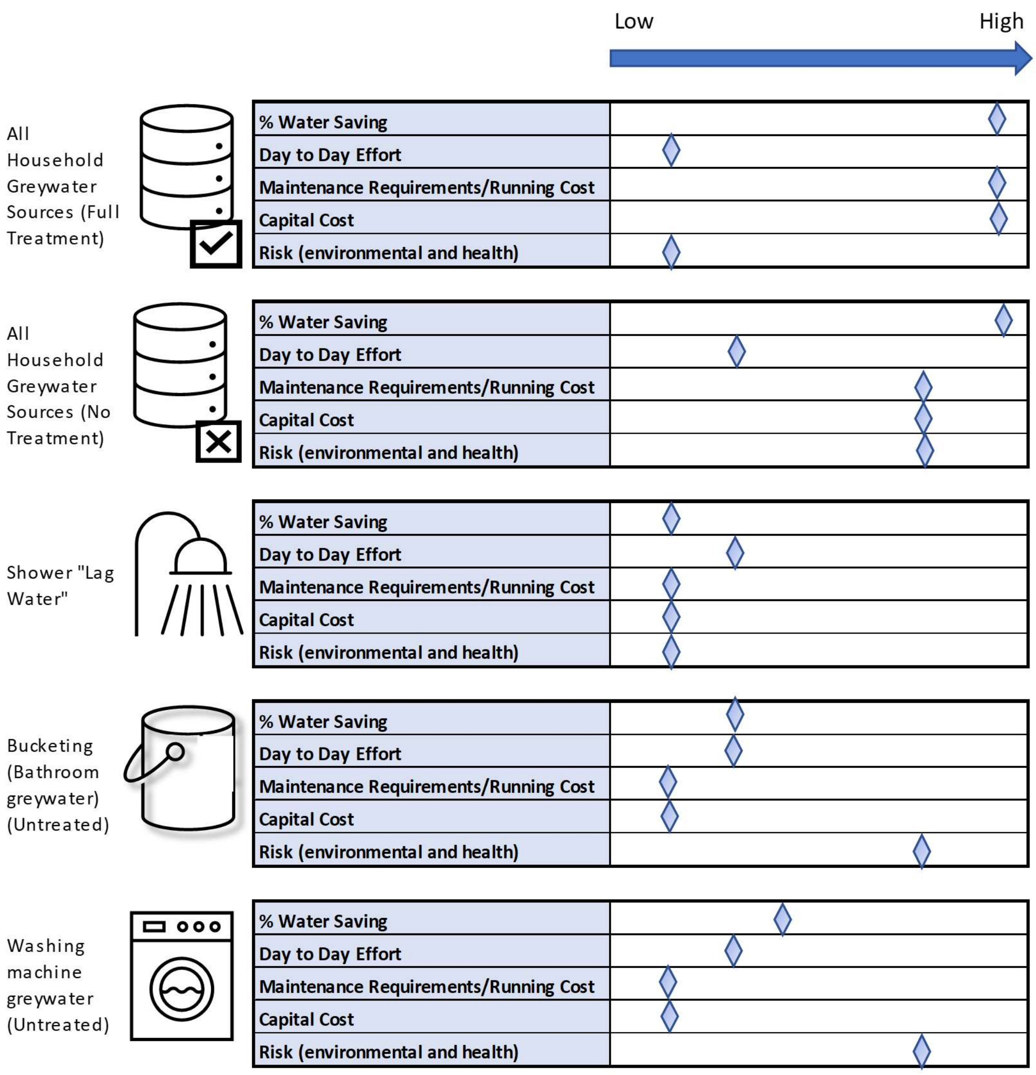

Figure 7-3 A schematic of greywater use trade offs

The trade off exploration in the schematic reveals for instance, that highly complex and expensive greywater treatment systems, while mitigating any potential risks to the environment or human health, may result in a negative nett benefit due to high capital and maintenance costs with inadvertent impacts on the environment with high energy usage. So too, the low water savings as found with the reported ad hoc greywater practices modelled in this study, along with the potential to cause harm to the environment and human health may also result in a negative nett benefit.

In recognition of the need to optimise both the benefits and the risks, detailed formal guideline documents and normative frameworks for greywater use exist; most notably work done by Roesner *et al.* (2006) and WHO (2006); as well as Carden *et al.* (2018) and Rodda *et al.* (2011) for the South African context. A wealth of guidance on greywater use is available to residential consumers from a range of other sources including the internet, greywater system manufacturers and non-governmental organisations. In addition to research publications, greywater use information pamphlets for household use were published by City of Cape Town (2017b) and Rand Water (2015) with the content linked partially to research findings.

The focus of these widely distributed documents is on encouraging greywater use with less emphasis on the associated risks. Information in some of these guideline documents even contradicts information presented in peer reviewed journals. So too, while standards/regulations for greywater use do exist in various parts of the world, the variation in policies between countries (or different regions of a particular country) is noteworthy in many cases (Friedler and Gross, 2019). In an age of online social media, where large amounts of unverified and inaccurate information are easily spread across large networks (Qazvinian *et al.*, 2011), the need to harness scientific information is key.

In times of severe water restrictions in the Cape Town region of South Africa where more consumers were turning to supplementary water sources, such as greywater; increased knowledge to promote its careful management becomes all the more critical. This is particularly pertinent in the case of Cape Town where consumers were mostly unaware of the related risks, yet well aware of the risk of supply failure, leading to ad hoc household greywater use practices not based on scientific principles. With many other parts of the world being classified as water stressed, the situation is likely to get worse (Friedler and Gross, 2019). As increased greywater use occurs in serviced suburban suburbs, there is a need for a more nuanced view of the potential potable savings and a need for risk management and guidance for water use decision making.

A decision-making matrix was therefore designed to assist consumers when faced with water use decisions during emergency drought conditions. The matrix tool provides a practical framework for evaluating and prioritising a list of water use options as an accessible solution to lower possible risks and improve water resilience. The tool includes both objective and subjective assessment criteria and can be developed further by water service providers on an online platform and ultimately inform future risk calculations.

The basis of the decision-making matrix is depicted in Table 7-3where various options that a consumer may consider in an emergency situation (e.g. untreated greywater use or letting the garden die etc.) are assessed according to 11 criteria through scores of between 1 and 3.

Table 7-3 Decision making matrix A (unweighted)

	Assessment Criteria												
Options during emergency water restrictions	Capital Cost (or loss of an asset/income as applicable)	Maintenance Costs (including indirect)	Affordability	Availability/ ease of access	Day to Day Effort	Potable Water Saving	Impact on Consumer Health & Well Being	Environmental Impact	Energy Costs	Infrastructure Impact	Social Acceptability		
Scoring	1 (High) 2 (Medium) 3 (Low/ Not applicable)	1 (High) 2 (Medium) 3 (Low/ Not applicable)	1 (Not affordable) 2 (Quite Affordable) 3 (Affordable)	1.Not accessible 2. Quite accessible 3. Very accessible	1 (High) 2 (Medium) 3 (Low/ Not applicable)	3 (High) 2 (Medium) 1 (Low/ Not applicable)	1 (High) 2 (Medium) 3 (Low/ Not applicable)	1 (High) 2 (Medium) 3 (Low/ Not applicable)	1 (High) 2 (Medium) 3 (Low/ Not applicable)	1 (High) 2 (Medium) 3 (Low/ Not applicable)	1 (High) 2 (Medium) 3 (Low/ Not applicable)	Total Score	
Use untreated greywater	3	3	3	3	2	1	1	1	3	2	2	24	
Use treated greywater	1	1	2	2	3	2	2	2	1	1	2	19	
Use rainwater	2	2	2	2	2	2	2	3	3	2	3	25	
Use groundwater	3	2	1	2	2	3	3	2	2	2	3	25	
Pay a fine for water usage above mandated usage	1	3	1	3	3	3	3	3	3	3	1	27	
Let garden die	1	3	3	3	3	3	2	3	3	3	1	28	Highest Score
Face intermittent water supply	3	1	3	2	3	3	1	2	3	1	1	23	
Replant garden to be water wise	1	2	1	2	2	3	2	3	3	3	3	25	

The option that resulted with the highest score for the unweighted decision-making matrix was to "Let the garden die". It is evident, however, that this unweighted version of the tool is in effect nonsensical in that a high quantity of similar assessment criteria would automatically give these scores more emphasis. The addition of weightings to the scores are therefore warranted and is depicted in Table 7-4 as a further iteration of the matrix. This version of the matrix (B) has weightings that are heavily shifted towards the cost and inconvenience faced by the consumer.

Table 7-4 Decision making matrix B (weighted towards cost and inconvenience to consumer)

	Assessment Criteria												
Options during emergency water restrictions	Capital Cost (or loss of an asset/income as applicable)	Maintenance Cost	Affordability	Availability/ ease of access	Day to Day Effort	Potable Water Saving	Impact on Consumer Health & Well Being	Environmental Impact	Energy Costs	Infrastructure Impact	Social Acceptability		
Weight for each criteria:	16	15	12	12	10	5	5	5	10	5	5	100	
Results adjusted for weight (Option A)												Total score	
Use untreated greywater	0,48	0,45	0,36	0,36	0,20	0,05	0,05	0,05	0,30	0,10	0,10	2,50	Highest Score
Use treated greywater	0,16	0,15	0,24	0,24	0,30	0,10	0,10	0,10	0,10	0,05	0,10	1,64	
Use rainwater	0,32	0,30	0,24	0,24	0,20	0,10	0,10	0,15	0,30	0,10	0,15	2,20	
Use groundwater	0,48	0,30	0,12	0,24	0,20	0,15	0,15	0,10	0,20	0,10	0,15	2,19	
Pay a fine for water usage above mandated usage	0,16	0,45	0,12	0,36	0,30	0,15	0,15	0,15	0,30	0,15	0,05	2,34	
Let garden die	0,16	0,45	0,36	0,36	0,30	0,15	0,10	0,15	0,30	0,15	0,05	2,53	
Face intermittent water supply	0,48	0,15	0,36	0,24	0,30	0,15	0,05	0,10	0,30	0,05	0,05	2,23	
Replant garden to be water wise	0,16	0,30	0,12	0,24	0,20	0,15	0,10	0,15	0,30	0,15	0,15	2,02	

"Untreated Greywater" emerges with the highest scoring for this weighted version of the matrix. This is in alignment with the weightings given the convenience, accessibility and low cost of untreated greywater use. An additional version of the matrix (C) is presented below with weightings heavily shifted towards the impact on consumer wellbeing, the environment and infrastructure.

Table 7-5 Decision making matrix B (weighted towards impact on consumer wellbeing, the environment and infrastructure)

	Assessment Criteria												
Options during emergency water restrictions	Capital Cost (or loss of an asset/income as applicable)	Maintenance Cost	Affordability	Availability/ ease of access	Day to Day Effort	Potable Water Saving	Impact on Consumer Health & Well Being	Environmental Impact	Energy Costs	Infrastructure Impact	Social Acceptability		
Weight for each criteria:	2	2	2	2	0	25	25	25	2	15	0	100	
Use untreated greywater	0,01	0,01	0,01	0,01	0,00	0,01	0,01	0,01	0,01	0,02	0,00	0,09	
Use treated greywater	0,00	0,00	0,00	0,00	0,00	0,03	0,03	0,03	0,00	0,01	0,00	0,10	
Use rainwater	0,01	0,01	0,00	0,00	0,00	0,03	0,03	0,04	0,01	0,02	0,00	0,13	
Use groundwater	0,01	0,01	0,00	0,00	0,00	0,04	0,04	0,03	0,00	0,02	0,00	0,14	
Pay a fine for water usage above mandated usage	0,00	0,01	0,00	0,01	0,00	0,04	0,04	0,04	0,01	0,02	0,00	**0,16**	Highest Scores
Let garden die	0,00	0,01	0,01	0,01	0,00	0,04	0,03	0,04	0,01	0,02	0,00	**0,16**	
Face intermittent water supply	0,01	0,00	0,01	0,00	0,00	0,04	0,01	0,03	0,01	0,01	0,00	0,11	
Replant garden to be water wise	0,00	0,01	0,00	0,00	0,00	0,04	0,03	0,04	0,01	0,02	0,00	0,14	

The highest score for this version of the matrix was to “Pay a fine for water usage above mandated usage” or to “Let the garden die”. “Untreated greywater use” emerges with the lowest score. While this result makes sense in the fact that continued water supply via a normal system is preferable, the result is contradictory given the consumer pays a fine or loses an asset in the form of a garden and therefore faces a cost anyway.

It is evident that the weightings of the matrix significantly influence the results. The decision-making tool, however, provides a foundation for risk management, that could be useful under emergency water restrictions. The tool could also be used in future as a basis to inform policies and decision making at a higher level.

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It is imperative that consumers are made aware and abide by the various guidelines to mitigate the risks associated with untreated greywater use. So too, other HWS options would need to have relevant scientifically based guidelines.

Table 7-6 Greywater risk management guidelines

Do	Do Not	Reference
Avoid direct contact with greywater.	Store greywater for more than 24 hours,	Carden *et al.* (2018) City of Cape Town (2017b) Murphy (2006) Rodda *et al.* (2010)
Preferably use 'low risk' greywater – (e.g. “lag”/warm-up water from hot taps).	Dispose greywater directly to surface or stormwater.	
Keep children and pets away from areas where greywater irrigation is taking place.	Use kitchen wash water or water that has been used to wash nappies.	
Wash hands after greywater contact.	Allow greywater to leave the property.	
	Use greywater if any household member is sick.	
	Apply to uncooked edible crops.	
	Use spraying or misting methods to irrigate with greywater.	
	Allow surface ponding.	

CHAPTER 8. CONCLUSION

SUMMARY OF FINDINGS

This research has met the five research objectives (Chapter 1) as per the findings discussed.

South African legislation is unclear about the use of HWS (especially greywater). These water sources are available and used locally. Focussing on groundwater abstraction, rainwater harvesting and greywater use; an assessment of the theoretical impact on municipal water demand in formal residential areas was undertaken in this study. A significant reduction in HH water use from the WDS of 55%-69% could be achieved for relatively large properties when HH sources are maximally utilised. There are both advantages and disadvantages to this load reduction – where their trade off determines whether there is a nett positive benefit to the use of the HWS. For instance, this significant load reduction on the piped WDS could be an advantage in augmenting municipal supply, but water service planning and demand management are complicated and possible future decommissioning of any household water source may be required. Groundwater is the HWS considered to have the most notable penetration and intensity to impact potable water demand in residential areas and is coupled to a relatively low risk in terms of water quality relative to (say) greywater use. Groundwater, however, has the biggest barrier to entry and requires the highest capital investment of the three primary supplementary HWS. The distinct trade off between the advantages and disadvantages of untreated greywater, particularly in comparison to the other supplementary HWS, provides justification towards the focus of this study.

Untreated greywater use at household level is an accessible water source to supplement non-potable water requirements, particularly in times of emergency water curtailments, but poses various risks to the consumer, the wider community, infrastructure and the environment. Using the City of Cape Town which was under stringent water restrictions during the 2017/2018 summer season as a case study site, a consumer survey and analysis of relevant online forums was undertaken. Untreated greywater use was found to be common, mainly for garden irrigation and toilet flushing. The results pointed to high-risk activities in the study group.

The Cape Town case study provides insight into consumer behaviour when faced with potential water supply system failure. As water security increasingly becomes a global concern and greywater use in serviced suburban suburbs becomes more widespread, it is important to understand the nett benefit of water savings (i.e., the risk - water saving trade off) due to untreated greywater use and the placement of greywater in the quantity-quality space.

By using model inputs from reported greywater use practices in Cape Town, South Africa, during the “Day Zero” drought crisis, viz. collecting water from the shower in buckets for toilet flushing and using washing machine water for garden irrigation, the water saving potential of untreated greywater use was evaluated in this study by means of a stochastic end-use model. These untreated greywater use practices were found to reduce water consumption in a single person suburban household by between 1% and 9%, which is markedly less than the maximum possible greywater use volume that could be achieved when improving greywater quality with relatively complex treatment systems and less than values reported in literature (See Figure 5-2). The relative low values reflect the limitations of the manual collection method and relatively poor water quality, which limit the uses of the collected greywater in and around the home. This quantification of the volumes associated with untreated ad hoc greywater use was the first step in understanding the trade-off between expected water savings (quantity) and potential risks (quality).

The second step was to undertake a statistical analysis of greywater quality results as sourced from previous studies and to undertake a risk assessment. The analysis of greywater quality results revealed variability in terms of each of the reported physical, chemical and microbiological- constituents by source and between result sets. Statistically significant differences were evident between the pH, conductivity and phosphorous values of certain sources. These variations also extended to the risk assessment which was undertaken for each of the constituents. It was found that the constituent with the highest number of high-risk samples was TSS. The variability of greywater by source as shown in this study, however, is an indication that the popular classifications of greywater use by source as a surrogate indicator of its contents and concentration could be inappropriate and misleading. While greywater originating from a particular source in one household could differ from another household, so too greywater composition from a specific source in one household may vary temporarily throughout the day, from day to day and seasonally.

While it is acknowledged that any reduction in urban water consumption is noteworthy, particularly in water scarce situations and that larger scale use would mean more significant water savings, this study has revealed that the use of untreated greywater through manual collection methods contributed relatively low (<10%) total water savings in a suburban household for various lifestyle levels. By contrast, the relatively high risk and high consequences in greywater practices in terms of public health, the environment, and infrastructure given the variability and unpredictability of untreated greywater quality as showcased in this study, provide insight into the quality-quantity nexus and the possible trade-off of these potential water savings. There is a need for a more nuanced view of the potential potable savings associated with greywater use and a need for risk management.

Risk management and drivers of consumer decision making in the water use space were therefore explored further. As a result, a decision-making matrix was designed to assist consumers when faced with water use decisions during emergency drought conditions with the ultimate aim of lowering possible risks and improve water resilience.

NOVEL CONTRIBUTIONS

This research study is unique in that while the use of greywater with purpose-built infrastructure and treatment systems has been studied for a number of locations and configurations, the practices used by individuals in the absence of such infrastructure is not well documented. This study has shed light on the reported volume of untreated greywater used by households in formal residential settings in Cape Town, South Africa, based on reported ad hoc water use practices and on the extent of these potentially risky practices. This has allowed for a novel holistic picture of the overall risks and trade-offs associated with greywater use to be developed.

Although various end-use models are available to assess the quantity and quality of household water use at the level of individual end-uses, greywater use is not catered for in current models. The novel end-use model in this study, allowing for stochastic modelling of greywater use in terms of quantity and a further exploration of the associated risks at end-use level, allows for advancement of knowledge in the field.

The focus on a South African case study, South African legislation, and South African data is a further novel contribution providing insight into the unique issues of suburban settlements in a developing country.

The decision-making matrix presented in this study provides a unique tool to assist consumers in making informed decisions when faced with water use decisions during emergency drought conditions. The tool provides a foundation for further development by water service providers to disseminate scientifically based information and inform future risk calculations.

FUTURE RESEARCH

This study has shed light on the need for several areas of further research regarding HWS and greywater. Only garden irrigation was considered as an end use in parts of this study (i.e., for the end use model in Chapter 2) because garden irrigation was considered to be one of the primary application points for water from a HWS. Future research could extend the analyses to include indoor use, such as toilet flushing or clothes washing with non-potable water, as was partly done in Chapter 5 where toilet flushing with buckets was modelled. Additional scenarios could also be modelled to include other bucket sizes and an increased number of buckets.

Additional research on the extent of the positive and negative impacts, key drivers, collection methods, storage and distribution, perceived risks, and application points of all HWS is required particularly in respect of broader water resilience imperatives. Further research is required to understand the scale of the consequential issues associated with untreated greywater use in suburban homes.

Adding to the data in this study with field measurements to inform both the quality and quantity results and ultimately a risk analysis would allow for further insight into the quality-quantity nexus in the greywater use space.

A further extension of this work could be to determine an appropriate weighting and develop the decision making tool as part of a smart phone or other application. The provision of this and other relevant information and tools (e.g. dam levels, water tariffs, smart meter data etc.) in an accessible format, can assist consumers in managing their water consumption and provide a communication and water demand management platform for water service providers (Warren,2020).

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CHAPTER 9. APPENDICES

APPENDIX A: DECLARATIONS OF CANDIDATE AND CO AUTHORS

Declaration by the candidate (Chapter 2)

The nature and scope of my contribution to Chapter 2 of this thesis, the published paper "*Supplementary household water sources to augment potable municipal supply in South Africa*", was as follows:

Nature of contribution	Extent of contribution
- Paper conceptualisation - Literature review & - Partial write up, - Journal selection - Relevant formatting, submission & review	55%

The following co-authors contributed to Chapter 2 of this thesis, "*Supplementary household water sources to augment potable municipal supply in South Africa*":

Name	e-mail address	Nature of contribution	Extent of contribution
C. Loubser	carloloubser@sun.ac.za	Assisted with editing and compilation of the paper	5%
J.A. du Plessis	jadup@sun.ac.za	Contributed to literature review (legal section) and writing of the paper	15%
H. E. Jacobs	hejacobs@sun.ac.za	Contributed to end use model, editing & compilation.	25%

Signature of candidate: ....

Date: ....10 October 2021...

Declaration by co-authors:

The undersigned hereby confirm that:

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 2 of this thesis "*Supplementary household water sources to augment potable municipal supply in South Africa*",
2. No other author contributed to Chapter 2, "*Supplementary household water sources to augment potable municipal supply in South Africa*", besides those specified above
3. Potential conflicts of interest have been revealed to all interested parties and the necessary arrangements have been made to use the material in Chapter 2, "*Supplementary household water sources to augment potable municipal supply in South Africa*".

Signature	Institutional affiliation	Date
	Stellenbosch University	23 Sep 2021
	Stellenbosch University	23 Spt 2021
	Stellenbosch University	27 Sep 2021

Declaration by the candidate (Chapter 4)

The nature and scope of my contribution to Chapter 4 of this thesis, the published paper "Investigation into untreated greywater reuse practices by suburban households under the threat of intermittent water supply ", were as follows:

Nature of contribution	Extent of contribution
- Ethical clearance application, - Conceptualisation, - Data collection (survey), - Data analysis and literature review - Write up, - journal selection, formatting and relevant review.	95%

The following co-authors contributed to Chapter 3 of this thesis, "Investigation into untreated greywater reuse practices by suburban households under the threat of intermittent water supply ":

Name	e-mail address	Nature of contribution	Extent of contribution
H. E. Jacobs	hejacobs@sun.ac.za	Contributed to conceptualisation and editing of the paper	5%

Signature of candidate: ……… ……………………………….

Date: ……10 October 2021…………………………………………………………

Declaration by co-authors:

The undersigned hereby confirm that

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 4 of this thesis "Investigation into untreated greywater reuse practices by suburban households under the threat of intermittent water supply ",
2. No other author contributed to Chapter 4 of this thesis, "Investigation into untreated greywater reuse practices by suburban households under the threat of intermittent water supply'' besides those specified above, and
3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 4 of this thesis, "Investigation into untreated greywater reuse practices by suburban households under the threat of intermittent water supply''.

Signature	Institutional affiliation	Date
	Stellenbosch University	23 Sep 2021

Declaration by the candidate (Chapter 5)

The nature and scope of my contribution to Chapter 5 of this thesis, the submitted paper "Investigating untreated household greywater reuse in the quantity – quality space", were as follows:

Nature of contribution	Extent of contribution
- Conceptualisation, - Data analysis, - Write up and literature review, - Journal selection, submission, formatting, and review.	70%

The following co-authors contributed to Chapter 5 of this thesis, "Investigating untreated household greywater reuse in the quantity – quality space":

Name	e-mail address	Nature of contribution	Extent of contribution
V Speight	v.speight@sheffield.ac.uk	Contributed to editing and compilation of the paper	5%
M. Crouch	Melissa19crouch@gmail.com	Data management and end use model	20%
H. E. Jacobs	hejacobs@sun.ac.za	Contributed to editing and compilation of the paper	5%

Signature of candidate:
Date: 23 September 2021

Declaration by co-authors:

The undersigned hereby confirm that

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 5 of this thesis "Investigating untreated household greywater reuse in the quantity – quality space",
2. No other author contributed to Chapter 5, "Investigating untreated household greywater reuse in the quantity – quality space" besides those specified above, and
3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 5 of this thesis, "Investigating untreated household greywater reuse in the quantity – quality space".

Signature	Institutional affiliation	Date
	Stellenbosch University	22 Sep 2021
M.L. Crouch	Stellenbosch University	23 Sep 2021
	University of Sheffield	23 Sep 2021

Declaration by the candidate (Chapter 6)

The nature and scope of my contribution to Chapter 6 of this thesis, the submitted paper "A review of untreated household greywater quality to inform the water saving-risk trade off", were as follows:

Nature of contribution	Extent of contribution
- Conceptualisation, - Literature review, - Data collection and data analysis, - Write up, - Journal identification, submission, formatting, and review.	85%

The following co-authors contributed to Chapter 6 of this thesis, "A review of untreated household greywater quality to inform the water saving-risk trade off":

Name	e-mail address	Nature of contribution	Extent of contribution
I Brink	icbrink@sun.ac.za	Conceptualisation & edits	5%
HE Jacobs	hejacobs@sun.ac.za	Conceptualisation & edits	5%
A Ilemobade	Adesola.ilemobade@wits.ac.za	Conceptualisation & edits	5%

Signature of candidate: ……… ………………………………….

Date: …………10 October 2021……………………………………………………

Declaration by co-authors:

The undersigned hereby confirm that

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 6 of this thesis "A review of untreated household greywater quality to inform the water saving-risk trade off",
2. No other author contributed to Chapter 6 of this thesis, "A review of untreated household greywater quality to inform the water saving-risk trade off'' besides those specified above, and
3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 6 of this thesis, "A review of untreated household greywater quality to inform the water saving-risk trade off''.

Signature	Institutional affiliation	Date
	Stellenbosch University	21 Sep 2021
	Stellenbosch University	27 Sep 2021
	University of the Witwatersrand	25 Sep 2021

APPENDIX B: CONSUMER SURVEY CHAPTER 4

The following survey questions were utilised for data collection as outline in Chapter 4.

Question	Response
In what type of dwelling do you reside?	Response
In which municipal area do you live?	Open-Ended Response
Are there water restrictions in place in your Municipality?	Response If yes, what level restrictions are in place?
Do you reuse your greywater?	Response Other, please elaborate
If you answered "no" to the previous question, please elaborate as to why you do not use greywater? (Can select more than one)	Response Please elaborate on your alternative water sources (e.g. rainwater) and/or why you no longer use greywater if applicable
Do you use greywater as an emergency solution? (i.e., during water restrictions etc.)	Response
From which sources in your home do you collect greywater? (Can select more than one)	Bath Shower Hand basins (Bathroom) Washing machine (Clothes) Laundry trough (or similar) Dish washing machine Kitchen basin N/A Other (please specify)
If using greywater for irrigation, please elaborate on your plant growth.	Flowers and shrubs Grass/Lawn Leafy Vegetables (e.g. spinach, lettuce) Root Vegetables (e.g. carrots, onions) Fruit and Nut trees Please feel free to add additional comments on plant growth
If using greywater for irrigation, please specify what is being irrigated. (Can select more than one)	N/A Flowers and shrubs (in pot plants and beds) Grass/Lawn Leafy vegetables (e.g. lettuce, spinach) Root vegetables (e.g. carrots onions) Fruit and nut trees Other (please specify)
What are your end-uses for your greywater? (Can select more than one)	N/A Irrigation/gardening Washing of Vehicles/ Driveways/ Outdoor Paved Areas Toilet Flushing Other (please specify)

What extent of your garden is irrigated with greywater?	Response
How regularly do you make use of your greywater? (Can select more than one)	Bath Shower Hand Basin (Bathroom) Washing Machine Laundry Trough Dish Washing Machine Kitchen Basin
How do you distribute your greywater?	N/A
	External Piping or Hose pipe (DIY- Solution) Dual plumbing system (retrofit or pre-existing) other Carrying in containers or buckets Other commercial product If Other or DIY solution is selected, please describe
If using your greywater for toilet flushing, please specify how this is done.	Response Other (please specify)
Do you treat your greywater and if so, what treatment system do use? (Can select more than one)	N/A I don't treat my greywater. I reuse raw greywater Primary Treatment System (Basic Course Filters or sedimentation: gravity or pump) Physical Treatment System (Sand or membrane filter) Biological Treatment (e.g. activated sludge, biological aerated filters, biorotors etc.) Extensive Treatment (Constructed Wetland) Chemical (e.g. coagulation) Disinfection (e.g. Chlorine, UV) Unsure Other, (please elaborate on system or other greywater device being used)
How would you rate your personal health risk using untreated greywater?	I would rate my health risk as:
How would you rate the environmental risk of your untreated greywater use?	Environmental risk:
Are you aware of a device called a Reduced Pressure Zone (RPZ) back-flow preventer? (These are mandatory in the City of Cape Town if connecting alternative water to the municipal supply in order to prevent contamination of the drinking water system. Non-return valves and standard stopcock valves are not sufficient).	Response Feel free to leave further comments
Do you store your greywater for any length of time (please note this may include storage in the toilet cistern or bowl)?	Response If applicable, please specify storage tank size/ capacity

How effective is greywater in meeting your end-use requirements for the portion of garden for which it is used?	Requirements met
Thank you for participating in this survey. Please feel free to include additional notes:	Open-Ended Response

APPENDIX C: SUPPLEMENTARY MATERIAL FOR CHAPTER 5

This appendix provides supplementary background information on the stochastic model inputs employed in Chapter 5. A stochastic model originally developed by Crouch (2020) for modelling household water use activities, was utilised in this study to quantify the untreated greywater use. An MS Excel spreadsheet using standard @risk simulation was utilised. Water-use activities and their associated water-use requirements were linked to lifestyle levels and various input parameters, with probability distributions used to describe the occurrence of each water-use activity. Scheepers (2012: Chapter 3) presents a comprehensive review of the related probability theory, stochastic processes and goodness-of-fit tests that formed the basis of stochastic modelling for Chapter 5 in this study. The same basis was used in this study to represent identified end-use data elements statistically and informed the stochastic model developed by Crouch *et al.* (2021). Only parameters that related to greywater use were selected from the comprehensive data set presented by Crouch (2020).

Various model input parameters were utilised for the development of the stochastic water use model in Chapter 5. Each greywater use scenario was described by various model inputs, or independent variables, with an initial summary of the equations for each scenario described in Table 9-1.

Table 9-1 Equations used to calculate the untreated greywater use volumes

Model Run	Use Scenario	Description of Greywater Use Scenario	Volume per event	Baseline Water Use Case applicable to this Greywater Use Scenario	Equation
1 - 6	R1	Bath/Shower to Toilet by bucketing (Nel and Jacobs, 2019)	1 – 3 Buckets	Baseline A & B	A binomial distribution determines whether a shower is taken (1 for shower & 0 for bath) & therefore whether the shower/bath equation is utilised. Shower: WU = Occur $_{s}$ F D [Occur $_{s\text{-low}}$ I_{low}+ (1 − Occur $_{s\text{-low}}$) I_{normal}] * Bath: $WU = [Occur\ F\ V]_{\text{cleaning}} + [Occur\ F\ V]_{\text{relax}}$ **
7-9	R2	Bath/Shower to Toilet and Garden by bucketing (Nel and Jacobs, 2019; Roesner *et al.*, 2006)	1 -3 Buckets	Baseline B	
10	R3	Washing Machine to garden by homemade piping (Nel and Jacobs, 2019; Roesner *et al.*, 2006)	Entire volume of washing machine effluent	Baseline B	WU = Occur (F V) ***

Key

WU = water use (L/c/d)
F = frequency (events/c/d)
D = duration (s)
I_{normal} = flowrate of a normal shower head (L/s)
I_{low} = flowrate of a low flow shower head (L/s)
V = volume (L)

* Occurs is a binomial variable (0,1) prescribing the use of shower (1)
Occurs-low is a binomial variable (0,1) prescribing the presence (1) or absence (0) of a low flow shower head
**$Occur_{cleaning}$ is a binomial variable (0, 1) prescribing the occurrence of bathing for cleaning
$Occur_{relax}$ is a binomial variable (0, 1) prescribing the occurrence of bathing for relaxation purposes
In the case of the bath, $Occur_{cleaning}$ and $Occur_{relax}$ are mutually exclusive, meaning if one occurs, the other cannot occur. The use of the bath in this study is dictated by the use of a shower for cleaning purposes.
***Occur is a binomial variable (0,1) prescribing the occurrence (1) of the activity. In the case of the clothes washer, Occur is a binomial variable (0, 1) prescribing the use of a top-end loader (1) or front-end loader (0)

The distributions and parameter values utilised in the equations are summarised in the following table:

Table 9-2 The distributions and parameter values utilised in the equations

Model Run	Use Scenario	Baseline Water Use Case applicable to this Greywater Use Scenario	Parameter	Unit	Distribution[1]	μ	σ	Min	Max
1-3	R1	Baseline A			**Shower**				
			Penetration rate of low flow shower heads	%	BN	1.00			
			Normal shower head flow rate	Not allowed					
			Low flow shower rate	L/s	UN			0.1	0.15
			Shower duration	s	LN	180.00	45.00	120.00	300.00
			Shower frequency	Showers/c/d	DC^M				
					Bath				
			Percentage occurrence for relaxation	Not allowed					
			Frequency of bath for relaxation	Not allowed					
			Volume of bath	L/bath	UN			20	40
			Bath Frequency	Events/c/d	DC^M				
4-6 **7-9**	R1 R2	Baseline B			**Shower**				
			Percentage occurrence	%	BN	0.86			
			Penetration rate of low flow shower heads	%	BN	0.55			
			Normal shower head flow rate	L/s	UN			0.1	0.33
			Low flow shower rate	L/s	UN			0.1	0.15
			Shower duration	s	LN	426.00	228.0		
			Shower frequency	Showers/c/d	LN	0.85	0.49		
					Bath				
			Percentage occurrence of cleaning	%	BN	0.14			
			Frequency of bath for cleaning	Baths/c/d	LN	0.85	0.49		
			Percentage occurrence for relaxation	%	BN	0.37			

			Frequency of bath for relaxation	Baths/c/d	PO	0.04			
			Volume of Bath	L/bath	UN				
10	R3	Baseline B	**Washing Machine**						
			Frequency of clothes washing	Washes/c/d	NM	0.31	0.11	0.07	0.43
			Penetration rate of top loader	%	BN	0.37			
			Volume of top loader	L/wash	DCB				
			Volume of front loader	L/wash	DCC				

Key

[1.] LN = Lognormal; UN = Uniform; TR = Triangular; DC = Discrete; FV = Fixed Value (constant); PO = Poisson; BN = Binomial; NM = Normal

APPENDIX D: SUPPLEMENTARY MATERIAL FOR CHAPTER 6 (GREYWATER QUALITY RESULTS)

Table 9-3 Greywater Quality Results as related to Chapter 6

Guideline	Reference	Christen (2019)	Christen (2019)	Christen (2019)	Christen (2019)	Christen (2019)	Christen (2019)	Christen (2019)	Christen (2019)	Christen (2019)	Jackson et al (2006)	Bakare et al. (2017)*	Bakare et al. (2017)*	Bakare et al. (2017)*	Engelbrecht & Murphy (2006)	Engelbrecht & Murphy (2006)
	Source	BR	BR	B	S	S	S	S	B	B	NR	K	L	B	D	B
	Source Name	BR	BR	Br	BR	BR	BR	BR	BR	BR	NR	K	L	BR	K	BR
	End use	NR	NR	NR	NR	NR	NR	NR	NR	NR	FC	NR	NR	NR	NR	NR
	Physical															
Rodda et al (2010)	Conductivity (mS/m)										267	3	680	156	58	33
Rodda et al (2010)	pH										8,1	6,25	9,58	9,24	7	8
Rodda et al (2010)	Total Suspended Solids (mg/L)														377	270
	Chemical															
Rodda et al (2010)	Boron										3,4				1	0,1
Rodda et al (2010)	COD (mg/L)											2075	1628	1426	3244	1491
Rodda et al (2010)	Phosphorous (mg/L)														14	2
Rodda et al (2010)	SAR														8	5
Rodda et al (2010)	Total nitrogen										206					
	Microbiological															
Rodda et al (2010)	E. Coli (/100ml)	0	0	0	0	0	0	0	0	0	35				100000000	20000

Guideline	Reference	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)	Madubela (2020)
	Source	S & B	D	K	WM -LLD	WM -PLD	FW	S	LLD	LLD	LLD	LLD	LLD	LLD	LLD	PLD	PLD	PLD	PLD	PLD	PLD	D
	Source Name	BR	L	K	L	L	NR	BR	L	L	L	L	L	L	L	L	L	L	L	L	L	L
	End use	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
	Physical																					
Rodda et al (2010)	Conductivity (mS/m)	20	325	121,2	22	350	140	16	15	15	18	21	21	24	37	318	377	409	436	538	560	424,5
Rodda et al (2010)	pH	6,8	9,5	5,36	6,2	9,8	8,6	6,97	7,4	7,4	7,3	7,3	7	7,4	7,4	10,7	10,7	10,5	10,7	10,6	10,4	9,34
Rodda et al (2010)	Total Suspended Solids (mg/L)																					
	Chemical																					
Rodda et al (2010)	Boron							0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,3	0,3	0,3	0,3	0,3	0,3	0,11
Rodda et al (2010)	COD (mg/L)							560	1170	1170	1170	1170	1170	1170	1170	1353	1353	1353	1353	1353	1353	2400
Rodda et al (2010)	Phosphorous (mg/L)							0,11	0,6	0,6	0,6	0,6	0,6	0,6	0,6	5,45	5,45	5,45	5,45	5,45	5,45	111,93
Rodda et al (2010)	SAR							1,8	4	3	4	5	4	5	10	41	27	41	40	50	20	50,5
Rodda et al (2010)	Total nitrogen																					
	Microbiological																					
Rodda et al (2010)	E. Coli (/100ml)																					

Guideline	Reference	Wader (2018)	Wader (2018)	Wader (2018)	Wader (2018)	Wader (2018)	Wader (2018)	Wader (2018)	Wader (2018)	Wader (2018)	Wader (2018)	Wader (2018)	Wader (2018)	Wader (2018)
	Source	B,S,Ba	B,S,Ba	B,S,Ba	B,S,Ba, WM	B,S,Ba, WM	B,S,Ba, WM	B,S,Ba	B,S,Ba	B,S,Ba	B,S,Ba	B,S,Ba	B,S,Ba	B,S,B
	Source Name	BR	BR	BR	M	M	M	BR	BR	BR	BR	BR	BR	BR
	End use	TF	TF	TF	TF	TF	TF	TF	TF	TF	TF	TF	TF	TF
	Physical													
Rodda et al (2010)	Conductivity (mS/m)	32	22	27	18	66	64	22	21	49	29	27	19	2
Rodda et al (2010)	pH	6,7	6,3	6,9	8,9	7,4	8,5	9,2	7	6,8	7,7	6,4	7,6	7
Rodda et al (2010)	Total Suspended Solids (mg/L)	4492	125	63	1920	7613	632	1136	189	143	56	38		
	Chemical													
Rodda et al (2010)	Boron													
Rodda et al (2010)	COD (mg/L)	6038	564	278	2173	5364	680	2412	784	516	237	297	284	25
Rodda et al (2010)	Phosphorous (mg/L)	6	6,8	2,3	1,9	35,8	12,3	12,3	4,3	2,1	4,3	2,2	1,1	1
Rodda et al (2010)	SAR													
Rodda et al (2010)	Total nitrogen													
	Microbiological													
Rodda et al (2010)	E. Coli (/100ml)	2419	860	930	980	2630	1120	2419	250	179	146	740	2005	6

* Average Values

Abbreviations Key

BR=Bathroom
B=Bath
Ba=Basin
S=Shower
K= Kitchen
L=Laundry
D=Dishwasher
NR=Not Reported
M=Mixed
W=Washing machine
LLD=Liquid Laundry Detergent
PLD=Powdered Laundry Detergent
TF=Toilet Flushing
FW=Floor Wash
FC=Food Crops

Colour Coding Key (Rodda *et al.* ,2010- Table 2)

- (Blue) Target Water Quality Range (Suitable for unrestricted use with minimal risk to human health, plants, or soil)
- (Green) Maximum water quality range (Increasing risk to human health, plants, or soil)
- (Orange) Water quality suitable only for short term use on a site-specific basis (Significant risk to human health, plants, or soil; tolerable for short-term use only)
- (Red) Water quality not recommended for irrigation use (Excessive risk to human health, plants, or soil)