Energy-water management and minimal cost solution in residences

by

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SUMMARY

ENERGY–WATER MANAGEMENT AND MINIMAL COST SOLUTION IN RESIDENCES

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Energy and water insecurities are global challenges with wide impact because of their necessities, wide utilisation and interconnection with other challenges such as food insecurity, climate change and ecosystem collapse. Therefore, there is an urgent need for sustainable and economic solutions to these problems. The need for these solutions has sparked a renewed interest in energy-water nexus, a concept that defines the mutual relationship between energy and water. Energy-water nexus has been studied extensively at provincial, national, international and global levels but only a few studies have explored energy-water nexus at the residential level. Studies on rainwater harvesting (RWH), greywater recycling (GWR), water desalination and other alternatives conclude that the RWH and GWR systems are the most economical, sustainable and suitable solutions to water insecurity in residences. Additional water security, water savings and reliability will be achieved with integrated rainwater harvesting and greywater recycling (RWH-GWR) system. Despite this knowledge, no previous work has investigated optimal tank sizing, optimal operations and the interplay between tank sizing and operation of the integrated RWH-GWR system. Therefore, this study investigates the design and performance of an integrated RWH-GWR system in residence to improve its economic attractiveness. An optimisation model is formulated to minimise the storage volume of the water tanks and operational cost of the proposed RWH-GWR system subject to technical and operational constraints including the time-of-use

(TOU) electricity tariff. This model is applied to a practical case study of a single-family building in Durban, South Africa. The optimisation problem is solved and simulation results are compared to the baseline energy and water consumption.

A mixed binary linear programming problem is developed and solved by the solving constraints integer programming (SCIP) solver interfaced in MATLAB. The simulation results validated the effectiveness of the proposed model. It produces the optimal size of the water tanks and system operation. It also validates that accurate tank sizing, system operation and increased non-potable water utilisation will improve the economic attractiveness of the integrated RWH-GWR system. Sensitivity analyses are carried out to evaluate the robustness of the proposed model to fluctuations in water demand, rainfall intensity, electricity pricing and discount rate. Performance and economic analyses of the integrated RWH-GWR system sized by optimisation and Rippl methods of tank sizing are carried out to determine the most economic tank sizing methods.

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To my family in Nigeria, I really appreciate your prayers, love, encouragement and emotional supports. Finally to myself for dreaming, believing and working on my dreams.

To God be the glory, I have finally finished.

DEDICATION

To:

The Almighty God;

For his goodness and mercies.

and

My dear parents, late Mr Ambrose Azuka Njepu and Mrs Rose Akwuabata Njepu;

For their love, sacrifices, encouragement and teachings.

LIST OF ABBREVIATIONS

BILP	Binary integer linear programming
DRWH	Domestic rainwater harvesting
DSM	Demand side management
EV	Electric vehicle
FV	Future value
GA	Genetic algorithm
GW	Greywater
GWR	Greywater recycling
HPWH	Heat pump water heater
IEA	International Energy Agency
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LEED	Leadership in Energy and Environmental Design
MILP	Mixed integer linear programming
MINLP	Mixed integer non-linear programming
MPC	Model predictive control
NIC	National Intelligence Council
NPV	Net present value
NPW	Non-potable water
PBP	Payback period
POET	Performance, operation, equipment and technology efficiencies
PV	Present value
PW	Potable water
RW	Rainwater
RWH	Rainwater harvesting
RWH–GWR	Rainwater harvesting-greywater recycling
SCIP	Solving constraints integer programming
SDG	Sustainable development goals
SSM	Supply side management

TVM	Time value of money
UN	United Nations
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
WEF	World Economic Forum
YAS	Yield-after-storage

LIST OF SYMBOLS

A_r	Rooftop collection area (m^2)
A_t	Uniform cross-sectional area of the tanks (m^2)
C_c	Capital cost of the proposed system
C_o	Operational cost of the proposed system
D_{npw}	Non-potable water demand (m^3)
D_{ov}	Volume of tank overflow (m^3)
D_{pw}	Potable water demand (m^3)
D_{tot}	Total residential water demand (m^3)
h_i	State variable representing the water level from the bottom of the tanks (m)
H_i	Height of the uniform cross-sectional area water tanks (m)
i, j	Indexes of sampling intervals $i, j = 1, \ldots, N$
I_P	Input parameters for sensitivity analysis
ΔI_p	Changes in input parameters for sensitivity analysis
I_t	Rainfall intensity (mm)
$\bar{J}_i$	Normalisation factor; maximum values of the sub-objectives
L_b, U_b	Lower and upper bounds of the decision variable, X.
m	Service life
m_x	Last year with negative net present value
n	Future year
N	Total number of samples
P	Pumping power (kW)
Q	Pump and valve flowrates (m^3/h)
r	Discounting ratio
R	Rand, the official currency of the Republic of South Africa
R_c	Run-off coefficient
s_1, s_2	Auxiliary variables for potable water and non-potable water pumps
S_{npw}	Non-potable water supply (m^3)
S_{pw}	Potable water supply (m^3)
T_1	Rooftop potable water tank
T_2	Rooftop non-potable water tank

T_3	Underground non-potable water tank
t_s	Sampling time
u	Binary decision variable representing the on/off switching of the pumps
V_{gw}	Volume of greywater collected (m^3)
V_{rw}	Volume of rainwater harvested (m^3)
w	Weighting factor
ΔY	Changes in output parameters for sensitivity analysis
α	The last negative net present value of cashflows
β	The present value of the cashflows
ξ	Sensitivity
ρ_e	Electricity tariff (R/kWh)
ρ_{off}	Cost of electricity at off-peak TOU period
ρ_{pk}	Cost of electricity at peak TOU period
ρ_{std}	Cost of electricity at standard TOU period
ρ_w	Water tariff
τ	Fraction of the residential water consumption collected as greywater

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CHAPTER 1 INTRODUCTION

1.1 CHAPTER OVERVIEW

This is the introductory chapter of this dissertation. Section 1.2 presents the problem statement. The research objectives and questions are presented in Section 1.3. The goals of this research are stated in Section 1.4. The research hypothesis and approach followed are presented in Section 1.5. The research outputs, i.e. conference and journal publications, are presented in Section 1.7. Finally, Sections 1.6 and 1.8 are the research contributions and the overview of this dissertation.

1.2 PROBLEM STATEMENT

The United Nations and other international organisations have identified energy and water scarcities as high impact global challenges because of their impact level, wide utilisations and interconnections with other global challenges[1]. These organisations report that water and energy scarcities will rise by 40% and 50% in 2030, respectively, these will be due to the unsustainable trend of demand and supply of these resources. The demand for energy and water increases with population, industrial and economic growths, and these are expected to keep rising continuously. In addition, climate change and global warming are exacerbating the already bad situation. Therefore, economical and sustainable solutions are needed to address these challenges urgently, else it will result in severe multi-dimensional global crises. Studies have proposed the demand side and supply side management solutions to these problems. The demand-side management (DSM) solutions modify the consumers' demand pattern through various means such as financial incentives, policies and education, while supply-side management (SSM) solutions include actions and policies taken from the supply side to ensure that resource generation,

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[1] http://reports.weforum.org/global-risks-2019/chapter-one/

transmission and distribution are done efficiently. However, comparative analysis reveals that the DSM solutions are preferred because of the benefits of reduced utility bills, economic and environmental sustainability. DSM solutions to water scarcity include water conservation, efficiency and re-use. Water conservation comprises policies, strategies and activities that manage freshwater reserves, protect the hydrosphere and maintain the hydrological cycle to meet the current and future water demand sustainably. Water efficiency involves effective freshwater utilisation, and finally, water re-use collects, treats and transports treated water for use. Rainwater harvesting (RWH) is a typical example of water conservation. Optimal operation and improved water utilisation are examples of water efficiency, and greywater recycling (GWR) is a typical example of water re-use. Combined water conservation, water efficiency and re-use will be an ideal solution to water scarcity. In terms of energy, decentralised renewable energy, energy conservation, energy efficiency and demand-side practices are ideal demand-side management solutions to energy scarcity. Renewable energy sources include solar, wind, biomass, thermal and hydropower. Energy efficiency measures the deviation of the energy output from the energy input, and demand-side solutions are incentivised practices that motivate and reward consumers for minimising energy consumption. Example include load shifting that reduces the cost of energy consumed by redistributing loads from peak to off-peak TOU periods when the cost of electricity is lowest. Similarly, combined energy conservation, energy efficiency and DSM will provide an ideal solution to energy scarcity. Energy-water nexus refers to the mutual relationship between energy and water; therefore, the implementation of DSM to energy-water nexus will contribute to improving water and energy securities. For instance, water treatment plants are one of the largest energy consumers globally. It collects, treats and transports treated water to the consumers. The larger the capacity of the water treatment plant, the more energy is required for water treatment and transportation and vice versa. Therefore, energy and water efficiencies in water treatment plants will contribute to improving energy and water securities globally. Water treatment is an energy and capital intensive process that reduces the economic feasibility of water supply systems. Studies have investigated various methods of improving the energy efficiency of water treatment plants [1,2]. These studies found out that the quality of water produced varies with the energy intensity of the treatment process. The water quality produced by water treatment plants is usually high and highly recommended to be used for non-potable water purposes other than toilet flushing and lawn irrigation that can be met with non-potable alternatives such as rainwater and greywater. Previous studies on GWR and integrated RWH-GWR systems losses water by emptying the non-potable water tank daily to prevent the breeding of harmful bacteria due to partial water treatment before storage [3–5]. Therefore, this study proposes full water treatment before storage to improve the water storage duration, water security, reliability and the economic attractiveness of the water supply systems.

Water tanks are expensive but essential components of water supply systems. Its performance varies with the size of the tank; therefore, accurate tank sizing is critical for improving the performance and economic attractiveness of water supply systems. Other benefits of tank sizing include improved water savings, reliability and flood control. Small tanks are consumers' preferred choice because of their low initial capital investment and installation costs, however, this will increase the switching frequency of the pumps and subsequently increases the operation and maintenance cost of the system. On the contrary, an oversized tank improves the reliability and water savings potential of the water supply system at the expense of a long payback period (PBP). Therefore, optimal tank sizing is proposed to improve the economic attractiveness of the system. There is no study that has investigated tank sizing in relation to system operation and the economic feasibility of the proposed integrated RWH-GWR system, therefore this study seeks to investigate this relationship.

Hydroelectricity generates electrical energy from the conversion of the kinetic energy of moving water to mechanical energy that drives the turbine to produce electricity. It accounts for 16.4% of the world's energy generation mix. Other electrical energy generators require water for manufacturing, cleaning and cooling. Similarly, water treatment plants are large energy consumers that use energy for water treatment and distribution. These examples confirm the existence of a mutually interdependent relationship between energy and water, referred to as an energy-water nexus. Therefore, this study aims to address the challenges of energy-water nexus in residences by using the integrated RWH-GWR system, indirect-gravity distribution and fit-for-purpose water treatment. This study also aims to improve the economic attractiveness of the proposed RWH-GWR system by optimal tank sizing and pump scheduling subject to the technical and operational constraints including the TOU tariff.

1.3 RESEARCH OBJECTIVES AND QUESTIONS

The primary objectives of this dissertation are to improve energy and water securities, and the economic attractiveness of the proposed water supply system in residences. In view of these, the following sub-objectives have to be achieved:

1. To formulate and test the validity of the binary integer linear programming (BILP) model to minimise the operational cost of a typical residential potable water supply system.
2. To formulate and test the validity of the mixed binary linear programming model with the objectives of improving the economic attractiveness of the proposed RWH-GWR system by minimising the size of the tank and the operational cost of the system.
3. To investigate the relationship between tank sizing and system operation.
4. To establish the economic superiority between the optimisation and Rippl methods of tank sizing.
5. To investigate the robustness of the proposed model to uncertainties in water demand, rainfall intensity, electricity pricing and discount rate.

In order to achieve the above research objectives, the following questions will be addressed in this dissertation:

1. What are the impacts of optimal pump scheduling in residential potable water supply system?
2. The challenges of the proposed RWH-GWR system include accurate tank sizing, poor non-potable water utilisation, water savings and its economic attractiveness. Therefore, what are the least tank sizes that satisfy the residential water demand? Increased non-potable utilisation improves potable water savings and the economic attractiveness of the system. How can these objectives be achieved?
3. What are the impacts of optimisation and Rippl methods of tank sizing to the operational cost and the economic attractiveness of the proposed system?
4. What is the sensitivity of the proposed model to uncertainties in water demand, rainfall intensity, electricity pricing and discount rate?

1.4 RESEARCH GOALS

The goals of this dissertation are stated as follows:

1. To formulate, test and validate the performances of the optimisation models in achieving the set objectives.
2. To improve the operational cost of the proposed RWH-GWR system.

3. To improve non-potable water utilisation and the economic attractiveness of the proposed RWH-GWR system.
4. To do a comparative analysis of the operational and economic performance of optimisation and Rippl method of tank sizing.
5. To test and validate the robustness of the proposed model to uncertainties in water demand, rainfall intensity, electricity pricing and discount rate.

1.5 HYPOTHESIS AND APPROACH

It is hypothesised that optimal tank sizing, improved non-potable water utilisation and operational cost savings will enhance the performance and economic attractiveness of the proposed RWH-GWR system. In order to attain the goals aforementioned, the following hypotheses have been formulated:

1. Accurate tank sizing will contribute to improving the reliability, water utilisation, initial capital investments and the operational cost of the proposed system.
2. Optimal pump scheduling will improve the operational cost of the proposed system.
3. Full water treatment before storage will improve its storage duration, non-potable water utilisation and the economic attractiveness of the proposed residential water supply system.

The following steps will be followed to achieve the objectives of this study:

1. Literature review – Literature survey to establish the current body of knowledge on the component systems are carried out to uncover the previous research done and identify research gaps for future research. The component systems include the RWH, GWR, water storage, treatment and distribution systems.
2. Mathematical model formulation – Mathematical models that describe the component systems and the optimisation problems are developed. The optimisation model defines the objectives to be achieved subject to technical and operational constraints. In this research, an optimal pump scheduling model is formulated to minimise the operational cost of the residential potable water supply system in Chapter 3. Also, a second optimisation model is formulated to reduce the storage volume of water tanks and the operational cost of the proposed RWH-GWR system in

Chapter 4. The simulation results obtained in Chapter 3 is used as the baseline for evaluating the performance of the proposed model in Chapter 4.

3. Simulation and results – Solution algorithms were formulated and applied to a practical case study. The mathematical model formulated were simulated and solved in MATLAB by the SCIP solver. The simulation results validate the objectives of the optimisation problem subject to the stated constraints.
4. Discussion – Detailed analysis and consideration of the performance, savings and economic attractiveness of the proposed solution have been carried out.

1.6 RESEARCH CONTRIBUTIONS

In this study, the centralised potable water supply system is the main water supply to the residence. A BILP problem is formulated to minimise the pumping cost of the centralised potable water supply subject to technical and operational constraints in Chapter 3. The BILP problem is solved, and operational analysis shows that the proposed pump scheduling strategy improved the operational cost savings of the system. The life cycle cost analysis (LCCA) carried out shows that the proposed strategy improves the operational cost savings of the system but does not repay its initial capital investment in its lifetime. Therefore, an optimal tank sizing and operations of the integrated RWH-GWR system is proposed in Chapter 4.

RWH and GWR have been known and used for non-residential purposes in decades. However, they are currently gaining renewed attention and residential applications due to growing threats of water scarcity. An integrated RWH-GWR system is introduced in Chapter 4 to improve water savings through increased non-potable water utilisation. Optimal tank sizing is also examined to improve the reliability and the economic attractiveness of the proposed RWH-GWR system. Previous studies empty their non-potable water tanks daily to eliminate the breeding of pathogens caused by partial water treatment before storage. Therefore, this research proposes full water treatment before storage and periodic disinfection during storage to improve water storage duration, non-potable water utilisation, potable water savings potential and the operating cost savings of the system.

To the best knowledge of the author, no study in the current literature has investigated optimal tank sizing, operation of the proposed RWH-GWR system and their interacting effects at the same time.

Therefore, this research presents the first attempt to develop an optimisation model with the objectives of minimising the storage volume of the tanks and the operational cost of the proposed RWH-GWR system. The sensitivity of the proposed system to uncertainties in water demand, rainfall intensity, electricity pricing and discount rate are also examined. Economic analysis was carried out to evaluate the economic performance of the proposed system and the comparative performance of optimisation and Rippl methods of tank sizing.

1.7 RESEARCH OUTPUTS

JOURNAL PAPERS

1. Ambrose Njepu, Lijun Zhang, Xiaohua Xia, "Minimum cost solution to residential energy-water nexus through rainwater harvesting and greywater recycling," *Applied Energy*, submitted, 2019.

CONFERENCE CONTRIBUTIONS

1. Ambrose Njepu, Lijun Zhang, Xiaohua Xia, "Optimal tank sizing and operation of energy-water supply systems in residences," in *Applied Energy Symposium and Forum, REM 2018: Renewable Energy Integration with Mini/Microgrid*, Rhodes, Greece, 28 – 30 Sept. 2018.

2. Ambrose Njepu, Lijun Zhang, Xiaohua Xia, "Optimal pumping operation for domestic water supply system," in *11th International Conference on Applied Energy (ICAE2019)*, Vasteras, Sweden, 12 – 15 Aug. 2019.

3. Ambrose Njepu, Lijun Zhang, Xiaohua Xia, "The effects of tank sizing on the operation of residential rainwater harvesting and greywater recycling system,"in *Applied Energy Symposium and Summit, CUE2019: Low Carbon Cities and Urban Energy Systems*, Xiamen, China, 16 – 18 Oct. 2019.

1.8 OVERVIEW OF STUDY

Chapter 1 presents the introduction of this dissertation. It contains the study background, problem statement, research objectives, questions, goals and contributions. It also includes a brief overview of the chapters.

Chapter 2 reviews relevant literature to establish the bounds of knowledge, previous research done and identify gaps for future research.

Chapter 3 presents an optimal pump scheduling for the residential potable water supply system. An optimisation model is formulated to minimise the operating cost of the potable water supply system subject to technical and operational constraints. The optimisation problem is solved and economic analysis is performed to evaluate the economic feasibility of the proposed strategy. The simulation result obtained, that is the optimal pump schedule, is used as a baseline for evaluating the performance of the integrated RWH-GWR system in Chapter 4.

Chapter 4 presents an optimal tank sizing and operation of an integrated RWH-GWR system in residences. In this chapter, a mixed binary linear optimisation model is formulated to minimise the size of the water tanks and the operational costs of the proposed RWH-GWR system simultaneously. Comparative analyses of the performance and cost-effectiveness of the optimisation and Rippl methods of tank sizing are carried out, and the interplay between tank sizes and system operation is also studied. Finally, sensitivity analyses are carried out to evaluate the robustness of the system to uncertainties in water demand, rainfall intensity, electricity pricing and discount rate.

Chapter 5 presents the conclusion of the research and recommendations for future works.

CHAPTER 2 LITERATURE STUDY

2.1 CHAPTER OVERVIEW

This chapter presents the literature review for this study, its objectives are to establish the current body of knowledge on this project and identify research gaps to be considered. In Sections 2.2 and 2.3, literature reviews on energy demand management and water demand management are carried out, respectively. Energy efficiency and demand side management (DSM) solutions to energy scarcities in industries, transportation and building are performed in Section 2.2. Rainwater harvesting, greywater recycling and the integrated rainwater harvesting–greywater recycling systems are also discussed in Section 2.3. Sections 2.4 and 2.5 are literature reviews for tank sizing and energy-water nexus, respectively. The unexplored or under-explored areas to be investigated in this study (i.e. research gap) can be found in Section 2.6.

2.2 ENERGY DEMAND MANAGEMENT

Energy insecurity is a global challenge that has a wide range of impact ranging from water scarcity, food scarcity, industrial and economic developments. Studies have proposed supply and demand-side management solutions to energy scarcity. Comparative studies have revealed that DSM solutions are more economic and sustainable than SSM solutions. Historically, global energy security has been heavily dependent on oil security, therefore fluctuations in oil production and prices caused energy scarcity. For instance, the 1970s global energy crises (i.e. the 1973 and 1979 global energy crises) were due to oil peaking in industrialised nations, these justify the heavy reliance of heavy economies and energy security on oil security. This has opened discussions and research into sustainable energy alternatives that are independent of oil. Subsequent energy crises include the 2000s energy crisis caused by the falling value of Dollar against oil price and limited oil production, California energy crisis (2000–2001), Argentina energy crisis (2004), China energy crisis (2005, 2008 and 2011), Central Asia energy crisis (2008) and the South African energy crisis in 2008.

An energy crisis is due to unequal growth rates between energy demand and supply, such that demand outpaces supply. Industry, transportation and residence are the three largest energy consumers, and their demand increases with population, industrial and economic growths. Therefore, a small percentage of energy savings from these sectors has the potential of improving energy security and the reliability of the grid. In the industrial sector, the advent of the Fourth Industrial Revolution (4 IR) will further increase energy demand from the telecommunication, education, medicine, engineering, information technology and security industries. Therefore, large scale solutions are proposed, else severe energy scarcity is anticipated if the current trend of increasing energy demand versus depleting supplies is not reversed. In the transportation industry, the rapid penetration of electric and hybrid electric vehicles are placing huge pressure on the grid. Industrial, commercial and economic growths come with increased immigration, urbanisation, real estate expansion and the associated urban lifestyle that is often energy-intensive. This increasing demand for energy also threatens energy security and sustainable solutions are necessary to ensure that the demand does not exceed supply. The non-expansion, shutting down and slow replacement of conventional thermal plants with viable alternatives are also threatening energy security because of the unsustainable energy demand and supply trend. Furthermore, climate change is further threatening energy and water securities with global warming which is depleting freshwater reserves that can be used for hydroelectricity and other forms of energy generation. Therefore, there is an urgent need to slow down climate change and its effects by a reduction in greenhouse gas (GHG) emission through wide uptake of clean energy and reduction in the burning of fossil fuel. Energy demand is projected to increase by 50% in 2030 [6–8], therefore DSM solutions to energy scarcity such as energy conservation, energy efficiency, fuel substitution, load management, load building and self-generation hold the key to sustainable energy security [9].

In response to the 2008 energy crisis in South Africa, the Centre for New Energy Systems (CNES) at the University of Pretoria has developed four classifications of energy efficiency namely performance, operation, equipment and technology (POET) efficiencies [9–11]. The POET classification unifies the classifications of energy efficiency, the performance indicators and applications to energy auditing. Performance efficiency (PE) is a measure of energy efficiency that is determined by external but deterministic indicators such as energy sources, production, cost, environmental impact and technical indicators. In situations with conflicting indicators, a compromise has to be made to reach a decision. Operation efficiency (OE) is a system-wide approach that measures the coordination of the different component subsystems. The following indicators are used to evaluate the operational efficiency of a system: physical coordination (sizing and matching), time coordination (time control) and human coordination. Equipment efficiency (EE) measures the energy output of isolated energy equipment to its design specifications. It aims to measure the extent of deviation of the equipment parameter from the design specifications. Its performance is evaluated by the following indicators: capacities, specifications, standards, constraints and maintenance. Finally, technology efficiency (TE) is a measure of the efficiency of conversion, processing, transmission and the use of energy. It is limited only by natural laws, like the law of energy conservation. TE is assessed by the following indicators: feasibility, life cycle costing, return on investment and the co-efficient of energy conversion, processing and/or transmission. Industry, transportation and building are the three biggest energy consumers by sector; therefore, a small percentage of energy savings in these sectors will improve the reliability of the power grid. Therefore, Energy efficiency and DSM studies have been carried out in various industries for different industrial processes such as coal washing [12, 13], line conveyor belts [14–17], pumping system [18, 19] and mining processes [20–22]. Energy efficiency studies in the transportation sector include modelling, optimisation and control of trains [23–25], cranes [26, 27] and electric vehicles [28, 29]. Heating, cooling and lighting are the biggest energy-consuming units in buildings; therefore, energy efficiency and conservation studies have been carried out to improve the energy efficiency of these loads. For instance, the performance of the residential direct expansion air conditioning system to: improve indoor thermal comfort and air quality was investigated in [30], improve thermal comfort and energy efficiency of the direct expansion air conditioning system was studied in [31], while the performance of different air conditioners at set temperature was investigated in [32]. For heating loads, the performance of residential heat pump water heater (HPWH) using model predictive control (MPC) was studied in [33]. Energy efficiency studies in [34–36] investigated the performance of domestic HPWH system powered by hybrid sources, while [37] examined the optimal operation of the solar water heating system. For lighting loads, an optimal sampling plan for lighting system was developed in [38], an optimal sampling plan and lamp population decay of lighting systems were studied in [39], while the effects of retrofitting and maintenance of the lighting system was studied in [40]. Other energy efficiency studies include building retrofit planning for greenhouse standard [41], building retrofit planning using the Leadership in Energy and Environmental Design (LEED) standard [42] while maintenance planning for the retrofitted building was carried out in [43].

2.3 WATER DEMAND MANAGEMENT

The World Economic Forum (WEF) global risks report has identified water scarcity, in addition to energy scarcity, to the list of the most significant global threats with the largest impact[1]. These problems will get worse with climate change; therefore, sustainable solutions are required to slow down climate change and improve water security. Seventy percent of the earth's surface is covered by water, out of which 97% is saline, and the remaining 3% is freshwater. However, only 0.014% of the earth's water is both fresh and easily accessible [44]. On the demand side, higher plants and animals need fresh water to survive. One-third of the world's population live under severe water scarcity for at least one month of the year, and over half a billion people live under severe water scarcity all year [45, 46]. This water demand to supply trend is unsustainable and will get worse with climate change, population, industrial and economic growths. This unsustainable water dynamics has caused the projection that water scarcity will increase by 40% in 2030 [46]. To address this problem, a corresponding increase in freshwater supply is necessary to maintain a sustainable hydrological cycle. Agriculture, household and industry are the three largest freshwater consumers, and they account for 60%, 30% and 8% of the world's freshwater consumption, respectively.

Studies have proposed demand and supply-side management solutions to water scarcity. Supply-side management water solutions seek to minimise the water deficit from the supply side, while the DSM water solutions seek to narrow the water deficit from the demand side. Like energy, DSM water solutions are preferred because they are relatively economical and sustainable. DSM water solutions are classified into water conservation and water demand management. In terms of water conservation, many studies have investigated water alternatives such as groundwater extraction, GWR, RWH, seawater desalination and water reclamation. RWH and GWR systems are considered the most suitable and economical solution to water insecurity in residences; hence, they will be discussed in the subsequent sections.

2.3.1 Rainwater harvesting system

Rainwater harvesting is an economical and environmentally sustainable alternative that collects and stores rainwater for later use. It is easy to install, operate and maintain; therefore, it has a relatively

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[1] https://www.weforum.org/reports/the-global-risks-report-2019

low installation, operation and maintenance costs [47–49]. The benefits of RWH systems include improved water savings, reliability and economic feasibility. Reliability, in this context, refers to the percentage of the number of days that the RWH system can meet its demand to the total number of days under consideration [50, 51]. Rainfall harvesting reduces the demand on the traditional surface or ground freshwater reserve and centralised water supply, thereby improving the reliability of freshwater supply. RWH also contribute to reduces floods and erosion, hence it is beneficial to the environment. The RWH system can be classified into two categories, namely the rooftop RWH system and the surface run-off RWH system. The rooftop RWH system collects rainwater from the rooftop collection area for treatment, storage and distribution to use-points, while the surface run-off RWH system collects surface run-off water into reservoirs for later use. The rooftop rainwater is relatively clean and has broad applications ranging from indoor to outdoor use-points, while the surface run-off RWH system can only be used for irrigation purposes because of its impurity level. The rooftop RWH system is used in this study; therefore, any mention of RWH systems hereafter refers to the rooftop RWH system. The performance of the RWH system is dependent on rainfall parameter, catchment area and the run-off coefficient [52]. The rainfall parameter includes rainfall intensity, duration and frequency, and the rainfall intensity is the most critical factor for evaluating the performance of the RWH system. Assuming a constant rainfall intensity, the catchment area will be used to evaluate the performance of the RWH system, this is because the volumetric performance of RWH system is the product of rainfall intensity, catchment area and the run-off coefficient, where the run-off coefficient is a constant that defines the effectiveness of the RWH system. The higher the run-off coefficient towards one, the better the performance of the RWH system. The major challenges of RWH systems are the design considerations; such as tank sizing, water treatment and transportation [53]. The quality of rainwater collected depends on the atmospheric pollution level, roof cleanliness, rainfall intensity and rainfall frequency. The atmospheric pollution are due to industrial, chemical, agricultural, biological and transportation waste, while the cleanliness of the roof depends on rainfall intensity and rainfall frequency. The quality of rainwater collected in rural areas or suburbs located in the tropical rainforests is better than the water quality collected in urban areas located in arid or semi-arid regions due to the rainfall characteristics and the pollution level of the location. For instance, the rainwater collected in the tropics require primary water treatment before use because of the high rainfall intensity and frequent rainfall experienced in these locations unlike those collected in semi-arid or arid regions with low rainfall intensity and long rainfall frequency. In many cases, the rainwater collected in rural areas located in the tropics are used directly for non-drinking purposes with little or no treatment, however, this is not a safe practice. In view of this, the United States Environmental Protection Agency

(US EPA) recommends first-flush, filtration and disinfection as the minimum rainwater treatment before use [8]. Also, the US EPA has established water standards for various end uses, this will encourage energy-efficient water treatments such as the fit-for-purpose water treatment. For instance, first-flush and filtration water treatment can be applied to harvested rainwater that will be used for toilet flushing, while first-flush, filtration and tertiary disinfection can be applied to harvested rainwater for laundry [54]. Economic studies have shown that RWH systems have low to medium payback period between 2 – 35 years depending on the size of the system, water utilisation, initial capital investment, operational and maintenance cost [47, 54]. The economic feasibility of RWH systems can be improved with increased water savings, water and energy tariffs and government policies. Like the RWH system, the GWR system is a decentralised alternative that is relatively more stable than the RWH system.

2.3.2 Greywater recycling system

Greywater re-use is a popular alternative in rural areas, and it is gradually gaining popularity in urban cities because of increased threats of water scarcity, government policies and the associated economic benefits. Greywater is wastewater without faecal contamination that is generated from the kitchen, bathroom, shower and laundry. It accounts for 50 – 70% of the total wastewater generated in residences [55], while toilet flush and irrigation account for 20 – 34% of the residential water budgets [56], hence the GWR has significant potential for improving potable water savings in residences. GWR system is a collection of subsystems that collects, treats, stores and distributes treated water to the use-points. Unlike the RWH system, the performance of the GWR system is heavily dependent on the residential water consumption pattern and not on external hydrological factors; therefore it is more reliable and robust to external uncertainties. Other advantages of the GWR system include reduced wastewater released to the treatment plant, improved non-potable water utilisation and water security [2]. Despite these benefits, the installation of the GWR system is limited by its capital and energy intensive nature, and this can be improved with energy-efficient treatment technologies and operations [57]. In comparison with RWH systems, GWR systems have secondary and tertiary water treatments, additional treatment kits, additional installation and maintenance costs.

The direct use of greywater can be dangerous to plants, animals, and human [58]; therefore, water treatment is essential for GWR systems. However, greywater treatment is capital and energy-intensive, hence accurate and energy-efficient treatment is vital to conserve energy. There are three stages of greywater treatment, namely primary, secondary and tertiary treatments [1, 2, 57]. The primary treatment is the pre-treatment stage that removes physical contaminants, while secondary treatment removes biological waste through biological processes and finally, the tertiary treatment uses chemical disinfectants to eliminate pathogens. The secondary water treatment also known as the biological water treatment can be further classified into aerobic and anaerobic treatment depending on the availability of oxygen. The aerobic treatment uses oxygen to decompose organic matter and other pollutants, while the anaerobic treatment uses anaerobic bacteria to perform these functions instead. The tertiary treatment uses chemical disinfectants such as chlorine, chlorine dioxide, hypochlorite, hydrogen peroxide and ozone to disinfect the water. The energy intensity for water treatment depends on the impurity level, water use-points and the required water standard [59–62]. The performance of the combined aerobic biological treatment and hydrogen peroxide, as a chemical disinfectant, is studied in [62]. The recycled vertical flow constructed wetland (RVFCW) [63] and the upflow-downflow greywater treatment [61] are developed to improve the economic feasibility of GWR system by reducing the energy and capital requirements for greywater treatment. Therefore, a fit-for-purpose greywater treatment that delivers the tailored water treatment to produce the required water standard for specific end-uses is widely regarded as the most economical alternative.

The payback period is an important indicator for evaluating the economic feasibility of non-potable water solutions. It refers to the duration it takes a project to repay its initial capital investment, the shorter the PBP the more economical the system is. Some studies report that GWR systems have short PBPs [58, 60, 64], while others report that GWR systems are energy and capital intensive; thus, they have long PBPs [55, 65]. In comparison with RWH systems, GWR systems have medium to long PBPs depending on the level of greywater utilisation, capacity of the system, water treatment, water tariffs and tank sizes. For instance, GWR systems installed in multi-storey buildings, malls and hotels are more economical than those installed in single-family buildings because of the population density and increased non-potable water utilisation [66]. RWH and GWR systems are economical and sustainable decentralised water alternatives for water security. They possess their unique properties, strengths and weaknesses, and they are also complementary alternatives meaning that the strengths of one can be used improve the weaknesses of the other and vice versa, thereby forming a more reliable integrated water supply system. For instance, RWH systems have low initial capital investments and operational cost, low water savings potential, and poor reliability because they are easily affected by external hydrological factors. On the other hand, GWR systems have high initial capital investments and operational cost, high potable water savings potential and improved reliability. Therefore, an integrated RWH-GWR system will combine the properties of the component systems to form a better water supply system in terms of water savings, reliability and economic feasibility.

2.3.3 Integrated rainwater harvesting and greywater recycling system

Previous studies have proposed RWH and GWR systems, separately, as the most economical solution to water scarcity in residence. However, an integrated RWH-GWR system will also provide an economical solution that is more reliable at the additional cost of integrating these systems. In addition to improved water security and reliability, other benefits of the combined RWH-GWR system include ease of maintenance, improved water and energy savings, and improved economic attractiveness of the system. The benefits of the RWH system include the ease of maintenance, water and energy savings, reduction in water and energy bills, backup for peak water demand and stormwater management. However, its weaknesses include poor reliability, high initial capital investment, frequent maintenance and long PBP [48]. The advantages of GWR systems include improved water savings, improved non-potable water utilisation, sewage reduction and the associated cost, improved reliability and environmental sustainability. Its major disadvantages are a health risk, energy and capital intensiveness. Therefore, an integrated RWH-GWR system is proposed to leverage on the strengths of the individual component systems, complement their respective weaknesses and produce a more stable, sustainable, reliable and economically attractive alternative [3, 5, 52, 64, 67]. The performance of the integrated RWH-GWR system depends heavily on the characteristics of the component systems [68–70]. For instance, an integrated RWH-GWR system installed in a tropical climate with regular rainfall will have a dominant RWH system properties relative to GWR properties. Similarly, an integrated RWH-GWR system installed in a semi-arid region will exhibit stronger GWR properties [52, 70]. In terms of economic feasibility, there are conflicting studies on the economic attractiveness of the RWH and GWR systems. Gois *et al*. [71] reported that the RWH system is more economical than the GWR system, while [52, 72] report that the GWR system is more economical because of improved reliability and potable water savings. The conclusions obtained from these studies vary with locations, non-potable water utilisation, weather conditions and tariffs. Therefore, the economic feasibilities of these systems vary with the case studies.

There are two configurations for the integrated RWH-GWR system, the independent RWH-GWR subsystem and the connected RWH-GWR subsystem. In the independent type, the RWH and GWR systems are stand-alone systems that are completely separated from the other [52], while for the connected type the RWH and GWR systems share common treatment, storage facilities and end-use points [4]. The independent RWH-GWR subsytem is capital intensive because of the capital, installation, operation and maintenance costs of the stand-alone subsystems. Economic analysis showed that the independent RWH-GWR subsystem is not economically feasible because it does not pay back its initial investment in its lifetime [52]. Therefore, the connected-type RWH-GWR system, with common treatment, storage and end-use points, is used in this study because of its comparative economic benefits. Accurate tank sizing is proposed to improve the reliability of water supply and economic feasibility of the integrated RWH-GWR system.

2.4 TANK SIZING

A water tank is an essential but expensive component of the water supply system installed to improve the reliability of water supply. Therefore, accurate tank sizing is necessary to satisfy water demand at the right quantity, quality, pressure and cost without making trade-offs. The tank is a storage device that collects and stores water for future use where water supply is unreliable, and its benefits include improved reliability, water savings, water utilisation and flood control, and these benefits increase with the size of the tank. Locations with defined long drought pattern require large storage tanks to improve the reliability of the system at the expense of initial capital cost [50, 73, 74]. Small storage tanks are most suitable for situations when both water demand and supply are either high or low at the same time provided the water demand does not exceed its supply. Although small tanks have low capital cost and they are not effective in dry regions, they can improve the reliability of water supply systems when installed in locations with steady rainfall. The improved reliability of this water supply system coupled with the small size of the tank will contribute to improving its economic attractiveness. The water tank is a capital-intensive component of the water supply system, therefore, accurate sizing is required to meet the water demand at the least cost. Previous studies have investigated various methods of tank sizing ranging from the water balance model [73, 75–77], mass diagram method [78], programming and optimisation methods [73], efficiency and reliability methods [77, 79], Rippl method [74], software and others. The water balance model describes the water dynamics of the tank over a given period [50, 51, 80, 81]. It can be classified into daily, monthly and annual water balance model depending on the availability of rainfall parameters. The daily water balance model uses daily rainfall parameters, water demand and supply, therefore it produces the most accurate and largest tank size among other water balance classifications because it takes into account detailed daily parameters, while the monthly and annual water balance models use cumulative approximations of the daily parameters.

Souza and Ghisi used the daily water balance model to determine the size of water tanks and water savings potential of RWH system [80]. The analysis was done using the Neptuno software, and the results show that RWH systems installed in regions with regular rainfall, not necessarily high rainfall intensity, have the greatest water savings potential, while those installed in arid regions with low rainfall have the smallest water savings potential. Hajani and Rahman formulated a regression equation to evaluate the reliability and economic feasibility of the RWH system [82]. The findings of this study agree with [50, 52, 70], that the reliability and economic attractiveness of RWH systems improve with the size of the tanks, rainfall intensity and in wet years. Hajani *et al.* [82] also reported that regions with defined long drought periods require large tanks to enhance the reliability of the RWH systems installed in these locations. The relationship between water demand, tank size and system reliability using water balance simulation and the yield-after-storage (YAS) algorithm was investigated in [51]. The simulation results show that the relationship between tank sizing and the reliability curve varies with the rainfall characteristics of the region. The reliability of the RWH system increases with the size of the tank, but this relationship is not consistent in regions with frequent rainfall. This study also reports that small tanks are suitable for locations with frequent rainfall because of the effects of improved reliability and economic attractiveness. A combined minimum cost-based approach and regressive models for optimal tank sizing to maximise potable water savings and minimise tank overflow was developed in [50]. A comparative analysis of the performances of the daily water balance method and dry period demand method for sizing water tanks was carried out in [81]. The simulation results show that the dry period demand method produced a smaller tank size relative to the daily water balance method. Study in [81] agrees with [82] that the resulting storage volume determined from using the dry period method depends on the duration of the drought. Therefore, the longer the duration of the drought, the larger the storage volume required to improve the reliability of the water supply system. Erain [83] and Neptuno [80] are software programs developed to determine the optimal size of rainwater tanks. Erain is also an economic analysis tool designed to evaluate the economic feasibility of RWH systems using the daily system performance and LCCA as input parameters. Amos *et al.* [83] agree with many other studies that the reliability of the RWH systems is strongly dependent on the size of the water tanks. In terms of the programming methods for tank sizing, a linear programming problem was formulated to determine optimal tank size and the economic benefits of RWH system [73]. The simulation results show a direct relationship between tank size and population density, therefore large tanks are required to meet the demand in densely populated buildings. An optimisation model to improve the economic feasibility of domestic rainwater harvesting (DRWH) system was developed in [84]. The simulation results show that accurate tank sizing has the potential of improving freshwater savings in RWH systems. Imteaz *et al.* [48] examined the optimal design of large rainwater tanks. They also performed an economic analysis to evaluate the performance of large rainwater tanks in three different climates in Melbourne, Australia. Matos *et al.* [74] investigated various tank sizing methods to evaluate the most economical configuration that simultaneously maximises financial savings and environmental benefits. This study also states that the daily simulation method using 80% efficiency criteria and the Rippl method produced tank sizes with the best economic savings to the installation cost ratio. The Rippl method of tank sizing will generate a tank size that is both economical and reliable to ensure regular water supply during the most extended drought period. The tank size produced by the Rippl method corresponds to the accumulated difference between the non-potable water demand and supply [74, 85]. Its drawbacks are sampling errors in observed data and coarse discretisation time, however, the effects of coarse discretisation can be corrected by using daily time intervals instead of monthly.

Studies have investigated various aspects of water tanks ranging from tank sizing, overflow control, reliability and economic feasibility. Simulation of water balance model is the most widely used method of tank sizing, and the simulation of the daily water balance model is considered one of the most accurate methods for sizing water tanks. To improve the economic attractiveness of the water storage system, Matos *et al.* [74] also investigated various efficiency criteria of the daily water balance model ranging from 100%, 80%, 60% and 50% efficiency criteria. Tank sizing is a complex process that is affected by internal and external factors such as rainfall parameters, collection area, water demand, population density and supply, climatic conditions and rainfall year. The reliability of water supply in dry years can be improved with a larger tank at the expense of the economic feasibility of the system. To the author's knowledge, no study in the current literature has compared the performance of optimisation and Rippl methods of tank sizing, effects on system operation and economic feasibility. This dissertation will conduct a comparative study on the performance of optimisation and Rippl method of tank sizing. The interplay between tank sizing and system operation will also be investigated. Furthermore, economic analysis will be carried out to evaluate the economic attractiveness of the proposed system when sized by optimisation and Rippl methods of tank sizing.

2.5 ENERGY-WATER NEXUS

Hydroelectricity is electricity generated from the use of the potential energy of stored water to drive the turbine of power generators. All forms of energy generation require water for extraction, generation, cooling, manufacturing and cleaning, thereby making energy one of the largest consumers of freshwater. Similarly, energy is required to collect, extract, treat, transport, heat and cool water that can be used or recycled for energy generation. These examples show the occurrence of a mutually interdependent relationship between energy and water called energy-water nexus.

Historically, energy and water have been studied separately until 1994 when Peter Gleick discovered the existence of an intricate relationship between freshwater and energy [86]. This discovery opened up a huge unexplored territory that is currently attracting significant research interests, grants and funds because of the importance of this concept to sustainable societies. An accurate understanding of this concept will assist policymakers, stakeholders and industries develop policies, processes and tools to translate energy-water nexus information into policies and sustainable society and investment decisions [87–91]. The UN,United States Department of Energy (US DOE), US EPA are among the biggest investors towards this research. The spread of this concept is hampered by a lack of understanding of the concept and its implications. This problem can be solved with public sensitisation. The other challenges of this concept are intrinsic to water and energy scarcities. The US DOE has proposed four solutions for addressing these problems, these are (1) optimising water efficiency in energy generation, (2) optimising energy efficiency in water extraction, (3) efficient water treatment and transportation, and (4) the exploitation of sustainable energy, water alternatives and their relationship (energy-water nexus) [7]. Policymakers, industries and other stakeholders that are used to handling energy and water in silos are currently experiencing challenges of making policies that will ensure joint sustainable energy and water securities. These challenges are due to lack of information, proper understanding of the concept, the impact of water policies and regulations on energy security, impact of energy policies and regulations on water security, effects of sustainable climate policies on energy, and the complexities of making policies that will promote joint energy and water securities [44,74]. Studies have explored energy-water nexus at the country level, with a few at industrial and residential levels [4] to gain insight into this concept and its applications. At country level, the impact of energy-water nexus has been investigated in Mexico [88], Spain [89], USA [90], South Africa [4,69], Australia [92] and China [64]. Among other things, these studies agree there is a direct relationship between climate change, energy and water securities, therefore increasing climate change cause further damage energy and water securities. Therefore, there is an urgent need to slow down climate change to achieve the UN goal of a sustainable world by 2030. Other studies on energy-water nexus include: a life cycle assessment (LCA) study to evaluate the impact of water on energy generation [86], LCA to evaluate expenses on water water used in wind power system [93], while the water-to-energy conversion efficiency for different forms of energy was studied in [7, 94].

In this study, the optimal operation of residential RWH-GWR system is proposed to investigate energy-water nexus and energy and water efficiencies in residences. Also, a full water treatment prior to storage and periodic disinfection are proposed to improve the water quality, duration of storage, water savings, operational cost savings and the economic feasibility of the proposed RWH-GWR system. A combined pumped and indirect gravity-fed water distribution system is proposed to improve energy savings and the operational cost of the proposed RWH-GWR system. In this study, the optimal operation of residential RWH-GWR system is proposed to study energy-water nexus in residences. To improve the effectiveness of the water treatment, a full non-potable water treatment before storage and periodic disinfections during storage are proposed to improve the water quality, storage duration, potable water savings potential and economic attractiveness of the proposed system. In addition, the indirect-gravity water distribution, that released pumped water to the end-use points under gravity, is also proposed to improve energy savings through combined pumped and gravity-fed water distribution system.

2.5.1 Water distribution

Historically, many ancient civilisations originated close to water bodies because of the availability of water to support human life and water bodies to support migration for trade and commerce. Population growth, industrialisation and climate change come with a corresponding increase in water demand, this increase in water demand coupled with the depleting freshwater reserves calls for efficient water management and distribution to ensure its sustainable supply. The water supply system is a network of engineered hydrologic and hydraulic components that supply water to meet demand. It is made of the drainage basin, water collection points, purification, storage, distribution, pipes and sewer return network. The drainage basins are tributaries that drain into the collection points (lakes) from where it will be transported to the water treatment plants, the water is treated and stored in reservoirs, tanks or towers (as the case may be), from where it will be transported to the customers using pumps and pipes. After which, greywater is collected and returned to the water treatment plant, through the sewer return network, for treatment and re-use.

Many central water suppliers are currently experiencing the challenges of poor infrastructure, management, water losses and financial unsustainability. On the demand side, customers are bearing the brunt of the gross inefficiency from the central water suppliers through high tariffs and unreliable water supply. Many centralised water utilities are not profitable, and their operations are not sustainable, therefore, decentralised alternatives are proposed. Water distribution system transports water from one point to another using pressure pumps and the earth's gravitational pull. Pumps are electrical loads that transport water (and other fluids) from one point to another by mechanical action. It can transport water along with horizontal or up-vertical distances, while water stored at height is released to the use-points under gravity. Water distribution in RWH and GWR systems can be classified into three categories depending on the placement of the tanks, namely: the direct-pumped, indirect-pumped and indirect-gravity distribution systems. In the direct-pumped water distribution, water is pumped from the water tank directly to the use-points. In the indirect-pumped water distribution, water is pumped from the ground-level tank to the rooftop tank from where it will be pumped to the end-use points. Finally, the indirect-gravity water distribution pumps water from the ground-level tank to the rooftop tank from where it will be released to the use-points under gravity. These water distribution systems have their unique strengths, weaknesses and applications. Comparatively, the indirect-gravity method is considered the most economical alternative because it consumes less energy by using the earth's gravitational pull for water distribution. The direct-pumped water distribution method was used for lawn irrigation in [95], while the indirect-gravity water distribution was used in [4, 33]. The indirect-gravity water distribution method is adopted in this study because of its superior economic benefits.

2.6 RESEARCH GAP

Previous studies have investigated the performances of RWH systems, GWR systems and integrated RWH-GWR systems, in terms of water savings, energy savings, water treatment, reliability and economic feasibility. An open-loop optimal control and closed-loop MPC strategies were developed to minimise the operational cost of an integrated RWH-GWR system without consideration of tank sizing [4]. In addition to minimising the operational cost of the integrated RWH-GWR system, there is a need to determine the optimal size of water tanks and minimise the operational cost and PBP of the proposed system. Therefore, this dissertation presents the first attempt to develop an optimisation model with the objectives of minimising tank sizes and the operational cost of RWH-GWR system subject to technical and operational constraints under the TOU electricity tariff. The end-goal is to improve the economic feasibility of the integrated RWH-GWR system. It also presents a more detailed and realistic financial analysis of the integrated RWH-GWR system.

Furthermore, an additional novelty of this study is tank sizing. Previous studies have investigated various methods of tank sizing [50, 70, 73] and system performance in terms of water savings and reliability [77, 82, 96]. In addition to the optimal sizing of the rooftop tanks and system operation in [97], this study also determines the optimal sizing of the underground tank, and the corresponding operation of the system. Furthermore, this study presents the first attempt to carry out a comparative analysis of the performance of the optimisation and Rippl methods of tank sizing. The impacts of optimisation and Rippl methods of tank sizing on the operation of the system is also studied to provide insight into the dynamics of the interplay between tank sizing and system operation. A comparative economic analysis of the proposed system when only the underground tank is sized by optimisation and Rippl methods is carried out to assist project managers and other stakeholders make informed decisions on the tank sizing methods. Also, full water treatment and periodic disinfectants are proposed to improve the water quality, storage duration, reliability and non-potable water utilisation in the residence.

2.7 CHAPTER SUMMARY

In this chapter, the literature surveys on energy demand management, water demand management, tank sizing and energy-water nexus is seen in Sections 2.2, 2.3, 2.4 and 2.5, respectively, to establish the current body of knowledge and research gaps. Section 2.6 contains unexplored or under-explored areas that will be investigated in this study. Like previous studies, DSM solutions to energy and water scarcities are adopted in this study to improve the economic feasibility and sustainability of the proposed solutions. The literature review on energy demand management in industries, transportation and buildings are performed to capture energy efficiency in these sectors because they are the three largest energy consumers by sector. The survey on water demand management structured into rainwater harvesting, greywater recycling and the integrated rainwater harvesting–greywater recycling systems. Relevant literature on energy-water nexus, water treatment and transportation were reviewed to establish the existing bodies of knowledge and identify research gaps for further investigation. Most studies on energy-water nexus have investigated this concept at global, national and the provincial level, therefore this study also aims to investigate energy-water at residential levels. Therefore, this study investigates optimal tank sizing and operations of the integrated RWH-GWR system in residences. Unlike previous studies, the performance of full water treatment before storage and optimisation method of tank sizing will be explored in this study.

CHAPTER 3 BINARY INTEGER LINEAR PROGRAMMING MODEL FOR OPTIMAL PUMP SCHEDULING IN RESIDENCES

3.1 CHAPTER OVERVIEW

This chapter presents a BILP model to minimise the operational cost of a residential potable water supply system. Section 3.2 contains the introduction, literature review and research motivation. The mathematical models of the subsystems are developed in Section 3.3. The optimisation problem and its solution algorithm are developed in Section 3.4. Section 3.6 contains the simulation results, discussion and economic analysis. LCCA shows that the proposed pump schedule does not repay its initial capital investment in its lifetime, therefore, an optimal tank sizing and operation of an integrated RWH-GWR system is proposed in Chapter 4 to improve the economic attractiveness of residential water supply system. The optimal pump schedule in Section 3.4 will be used as a baseline for evaluating the technical, operational and economic performance of the proposed RWH-GWR system in Chapter 4.

3.2 INTRODUCTION

Water treatment and distribution are the two largest energy consuming units in water supply systems. Energy is required to treat contaminated water to the recommended applicable standards and transport the treated water to the use-points. This study focuses on the energy consumption of pumped-storage water distribution scheme in residences. To address the energy-intensive nature of the pumping system, previous studies have investigated pump scheduling at industrial, commercial levels and for agricultural purposes, and there is a need to investigate optimal pump scheduling in residences to minimise the operational cost of the residential water supply system. Therefore, this chapter presents an attempt to design an optimal pump scheduling strategy for residential potable water supply system with the objective to minimise pumping cost subject to the TOU electricity tariff. A pumped-storage scheme is adopted in this study to improve the operational cost and reliability of residential potable water supply system. Previous studies on energy-water nexus investigated pumping operation in multi-product pipeline [98, 99]. Optimal energy and water management in batch process industries using recycled greywater was carried to improve energy and water efficiencies [100]. Zhang and Xia [18] developed an optimisation model to improve energy efficiency and operational cost savings in coal beneficiation plant. A fuzzy method was used to control the pumping pressure of water distribution in water supply networks [101]. A hybrid-time genetic algorithm (GA) was used to optimise pump scheduling in water supply systems [102]. Zhuan and Xia [23] investigated optimal pump scheduling of multiple pumps in a pumping station to improve operational cost savings and economic feasibility of the water supply system. Wanjiru and Xia [4, 33] carried out a comparative analysis on the performance of the open-loop optimal control and closed-loop model predictive control (MPC) strategies for optimal pump scheduling in the residential water supply system. The simulation results showed that the performance of the open-loop and closed-loop MPC strategies are similar without disturbances. However, the closed-loop MPC strategy performs better under disturbances because of its robustness to uncertainties. A life cycle assessment (LCA) study [99] compared the performance of commercial RWH system to a municipal water supply system. The study results show that the commercial RWH system is more economical than the municipal water supply system because of utility tariffs and high operating cost relative to the initial investment cost. Electricity and water costs are the major contributors to the operational cost of the municipal water supply system, therefore efficient management is proposed to improve the operational cost and economic attractiveness of the system. Human interference in residential potable water supply system also affects the energy efficiency of the water treatment and transportation processes, therefore, automation and control of residential water distribution system are proposed to improve the economic feasibility of the system.

In this chapter, a BILP problem with the objective of minimising the electricity cost of the pumped-storage scheme in residential potable water supply system subject to technical and operational constraints is formulated. Level sensors are also introduced to maintain the water level within the bounds of the upper and lower bounds of the water tank. The optimisation model is solved by SCIP solver,

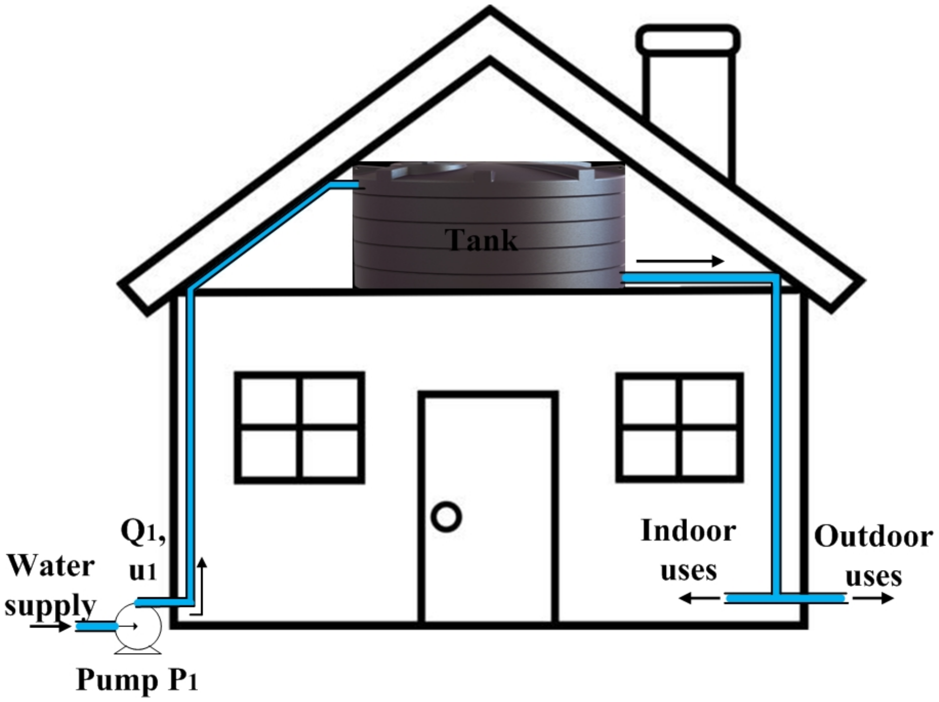

Figure 3.1. Schematic layout of the residential potable water supply system

which is one of the fastest non-commercial solvers available in MATLAB's OPTI toolbox.

3.3 MATHEMATICAL MODEL FORMULATION

3.3.1 Schematic model layout

Figure 3.1 shows the schematic layout of the residential potable water supply system. It is made up of the centralised potable water supply, pump, rooftop storage tank, pipes and end-use points. The centralised water system supplies potable water to the residence through the water distribution network. The pump transports the water to the rooftop tank for storage and later use. The stored water is released to the end-use points under gravity. In this study, the end-use points include the various residential end-use points and lawn irrigation. In Figure 3.1, Q_1 is the flowrate of pump P_1. u_1 is the binary decision variable that controls the switching operation of the pump.

The height of the tank constrains the dynamics of the water level within the lower and upper bounds of the tank. Therefore, changes in the height of a uniform cross-sectional area tank will affect its volume (tank size), model and analysis of the system. An increase in the height of the tank will increase the tank size and reduce the switching frequency and maintenance cost of the pump by augmenting adjacent switching, and vice versa. In this chapter, constant tank size is assumed to investigate the optimal operation of the system subject to the time-of-use tariff. The interaction between tank sizing and operations will be investigated in Chapter 4. The mathematical models that describe the dynamics of the water level in the tank are given in Section 3.3.2:

3.3.2 Rooftop potable water tank

In this study, a uniform cross-sectional area cylindrical tank is placed at the rooftop to collect pumped water for storage and distribution to the end-use points. The volume of water in the tank (V_1) is expressed as:

$$V_1 = A_{t1} \times h_1 = t_s Q_1 u_1 - D_{tot}, \tag{3.1}$$

where A_{t1} and h_1 are the uniform cross-sectional area (m^2) and water level (m) from the bottom of the tank, respectively. Q_1 is pump flowrate (m^3/h) and D_{tot} (m^3) is the total residential water demand which is the sum of the potable and non-potable water demand in the residence. $(t_s Q_1 u_1(i) - D_{tot}(i))$ represents the water deficit or excess water obtained from the difference between water demand and supply. Equation (3.1) is expressed in discrete-time domain in terms of water level as:

$$h_1(j) = h_1(0) + \frac{1}{A_{t1}} \sum_{i=0}^{j-1} \left[t_s Q_1 u_1(i) - D_{tot}(i) \right], \tag{3.2}$$

where $h_1(0)$ and $h_1(j)$ are respectively, the water levels from the bottom of the tank at $i = 0$ and j. In addition, level sensors are introduced to keep the water level, which is the state variable of the optimisation problem, within the lower and upper bounds of the tank. Hence, (3.2) will become:

$$h_1^{min} \leq h_1(0) + \frac{1}{A_{t1}} \sum_{i=0}^{j-1} \left[t_s Q_1 u_1(i) - D_{tot}(i) \right] \leq h_1^{max}, \tag{3.3}$$

where h_1^{min} and h_1^{max} are the lower and upper bounds of the state variable, respectively. j is the sampling instances from 1, ..., N, where N is the total number of intervals.

3.4 OPTIMISATION MODEL

The case study is a manually operated pumping system that when switched on, will operate continuously irrespective of the TOU period to meet the residential demand until the tank is full. Its pumping operation will serve as a reference for evaluating the performance of the proposed pump scheduling strategy. A single objective BILP problem is formulated to minimise the pumping cost of the residential potable water supply system as follows:

$$\min J = \sum_{j=1}^{N} t_s \rho_e P u(j), \tag{3.4}$$

subject to the following constraints:

$$h_1^{min} \leq h_1(0) + \frac{1}{A_{t1}} \sum_{i=0}^{j-1} \left[t_s Q_1 u_1(i) - D_{tot}(i) \right] \leq h_1^{max}, \tag{3.5}$$

$$u(j) \in \{0, 1\}. \tag{3.6}$$

where ρ_e is the cost of electricity. Constraint (3.5) models the dynamics of the water level within the lower and upper bounds of the tank, while Constraint (3.6) denotes the bounds of the binary decision variable. The operation cycle is 24 h, sampling time t_s = 0.25 h = 15 mins. j = 1, …, N is sampling intervals and N is the total number of samples (N = 24 h/ 0.25 h = 96).

3.4.1 Algorithm formulation

The mathematical model formulated is expressed in standard linear form as:

$$\min f^T X, \tag{3.7}$$

subject to:

$$\begin{cases} MX \leq b; & \text{linear inequality constraint,} \\ M_{eq}X = b_{eq}; & \text{linear equality constraint,} \\ L_b \leq X \leq U_b; & \text{boundary constraint,} \end{cases} \tag{3.8}$$

where f and X are the vectors of the objective function and the decision variable of the optimisation problem, respectively. M and M_{eq} are respectively, the matrices of the inequality and equality constraints. b and b_{eq} are respectively, the corresponding vectors of the inequality and equality constraints. L_b and U_b are the vectors of the lower and upper bounds of the decision variable. The vectors of the objective function and decision variable are expressed as:

$$f = \Big[t_s\rho_e P_1 u_1(1),\ t_s\rho_e P_1 u_1(2),\ t_s\rho_e P_1 u_1(3),\ \ldots,\ t_s\rho_e P_1 u_1(N)\Big]_{1\times N}, \tag{3.9}$$

$$X = \Big[u_1(1),\ u_1(2),\ u_1(3),\ \ldots,\ u_1(N)\Big]^T_{N\times 1}, \tag{3.10}$$

The matrices and vectors of the inequality constraint are expressed as:

$$M_1 = -\frac{t_s}{A_{t1}} \begin{bmatrix} Q_1 & 0 & \cdots & 0 \\ Q_1 & Q_1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ Q_1 & Q_1 & \cdots & Q_1 \end{bmatrix}_{N\times N}, \tag{3.11}$$

$$M_2 = -M_1, \tag{3.12}$$

$$b_1 = \begin{bmatrix} h_1(0) - h_1^{min} - \frac{1}{A_{t1}}[D_{tot}(1)] \\ h_1(0) - h_1^{min} - \frac{1}{A_{t1}}[D_{tot}(1) + D_{tot}(2)] \\ \vdots \\ h_1(0) - h_1^{min} - \frac{1}{A_{t1}}[D_{tot}(1) + D_{tot}(2) + \cdots + D_{tot}(N)] \end{bmatrix}_{N\times 1}, \tag{3.13}$$

$$b_2 = \begin{bmatrix} h_1^{max} - h_1(0) + \frac{1}{A_{t1}}[D_{tot}(1)] \\ h_1^{max} - h_1(0) + \frac{1}{A_{t1}}[D_{tot}(1) + D_{tot}(2)] \\ \vdots \\ h_1^{max} - h_1(0) + \frac{1}{A_{t1}}[D_{tot}(1) + D_{tot}(2) + \cdots + D_{tot}(N)] \end{bmatrix}_{N\times 1}. \tag{3.14}$$

There are no equality constraints in the optimisation model, therefore M_{eq} = [ ] and b_{eq} = [ ]. The vectors of the boundary constraint are expressed as:

$$L_b = \begin{bmatrix} 0, & 0, & 0, & \cdots, & 0 \end{bmatrix}^T_{N\times 1}, \tag{3.15}$$

$$U_b = \begin{bmatrix} 1, & 1, & 1, & \cdots, & 1 \end{bmatrix}^T_{N\times 1}. \tag{3.16}$$

3.5 CASE STUDY

The case study for this study is a middle-class family residing in a single-family building in Durban, KwaZulu-Natal province of South Africa. It has both indoor and outdoor water use-points and its hourly water demand profile is shown in Figure 3.2. In this study, the centralised water supply is used to meet all the residential water demand. The pump is operated manually to pump water to the rooftop water tank, its mode of operation is such that once pumping is initiated, the pumping operation will continue until the tank is full irrespective of the TOU period (see Figure 3.3). To give manually pumping operation the benefit of the doubt, an optimisation model is formulated to minimise the pumping electricity cost of the system subject to technical and operational constraints and the optimisation result (i.e. optimal pump schedule) will be used as the baseline for evaluating the performance of the proposed RWH-GWR in Chapter 4. The optimisation problem is solved, the optimal pump schedule and water dynamics are seen in Figure 3.4. To evaluate the performance of the proposed optimal pumping strategy, the simulation result is compared to the manually operated system. The residence is equipped with a rooftop potable water tank; the tank is a uniform cylindrical cross-sectional area tank having a cross-sectional area of 0.5 m^2. Furthermore, the tank is equipped with level sensors to maintain the water level within the lower and upper bounds of 50 L and 500 L, respectively. The pump has a power rating of 700 W and a flow rate of 0.55 m^3/h. The optimal pump schedule obtained from this study will serve as the baseline for evaluating the performance of the proposed RWH-GWR system in Chapter 4.

3.5.1 Electricity tariff

The TOU electricity tariff is a time-differentiated electricity pricing structure with different electricity charges for different TOU periods and seasons. It is a mutually beneficial electricity pricing structure that intelligently influences the consumers demand pattern and encourages load shifting from peak to off-peak TOU periods. Also, it rewards cooperating customers with low tariffs and penalises non-

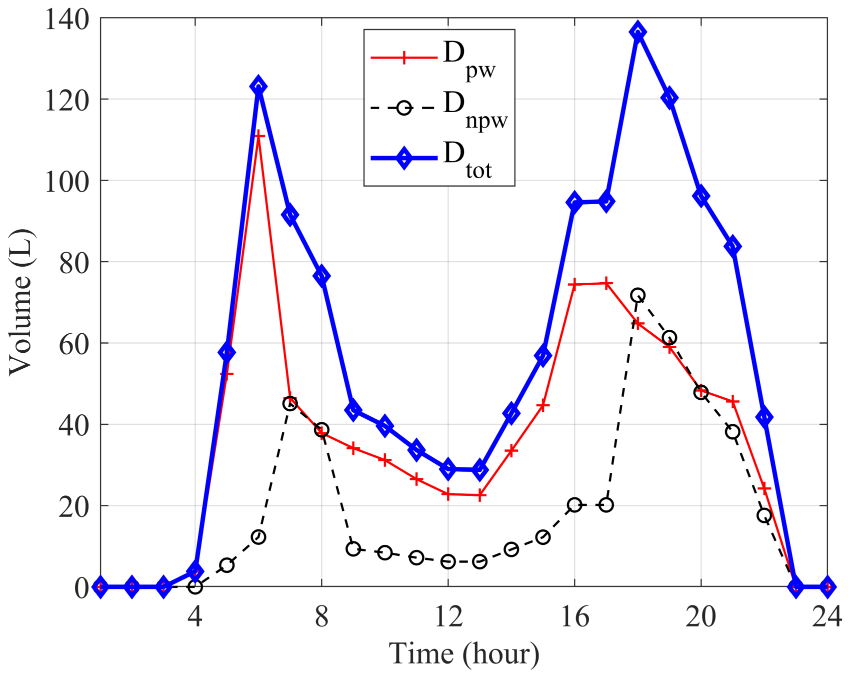

Figure 3.2. Residential water demand

cooperating customers with high tariffs. The TOU periods are time blocks with different electricity charges per kWh that are based on the intensity of electricity demand on the grid during the day. The TOU periods are classified into the peak, standard and off-peak TOU periods. The peak TOU period is the timespan with the most considerable electricity demand and the highest electricity charges per kWh. The off-peak TOU period is the timespan with the lowest energy demand and the least electricity charges per kWh, and the standard TOU period is the remaining time between the peak and off-peak TOU periods.

Eskom, the South African power utility company, introduced the Miniflex TOU tariff structure for its residential customers. The distribution of electricity to customers is shared between Eskom and the local municipality, therefore the local authority Miniflex TOU tariff structure for residential customers in Durban is given as[1]:

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[1] www.eskom.co.za/CustomerCare/TariffsAndCharges/Documents/Eskom%20schedule%20of%20standard%20prices %202018_19.pdf

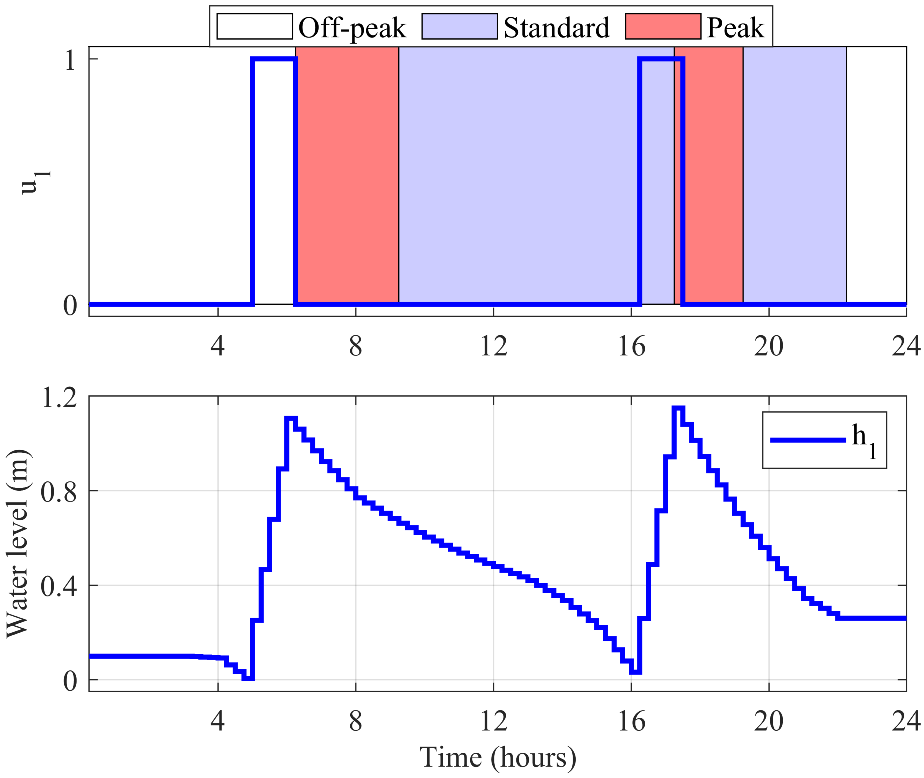

Figure 3.3. Manually operated pump switching and the corresponding change in water level

$$\rho_e(t) = \begin{cases} \rho_{off} = 0.5732 \text{ R/kWh}, & \text{if } t \in [0,6] \cup [22,24], \\ \rho_{std} = 1.0504 \text{ R/kWh}, & \text{if } t \in [9,17] \cup [19,22], \\ \rho_{pk} = 3.452 \text{ R/kWh}, & \text{if } t \in [6,9] \cup [17,19], \end{cases} \tag{3.17}$$

where t is the time of the day in hours. $\rho_e(t)$ is the hourly cost of electricity that is made up of the electricity charges at off-peak (ρ_{off}), standard (ρ_{std}) and peak (ρ_{pk}) periods. The unit of the electricity charge is Rand per kilowatt-hour (R/kWh), where Rand (R) is the official currency of the republic of South Africa.

3.5.2 Water tariff

Water tariff is the pricing structure assigned by the water utility provider for the volume of water consumed. In most cases, water utility companies are publicly owned, and their tariffs are set to maintain sustainable operation and not for profit. Water tariffs comprise of water and wastewater tariffs; these cover the operational cost of water treatment, storage, transportation and collection. The increasing block tariff (IBT) is a form of volumetric tariff with water charges changing with the blocks of water consumed is adopted in South Africa to encourage efficient water consumption. Like the TOU tariff, the IBT encourages efficient water consumption and the adoption of demand-side water solutions. In this pricing structure, the cost for the first block of water consumption is set at a very low rate to protect residences with low consumption rate, and subsequent water rates increase with the blocks of water consumed. On the other hand, the wastewater tariff follows the structure of the water tariff. In the case of IBT, the wastewater tariff is set based on the volume of wastewater supplied to the treatment plant. Therefore, the IBT for residential customers in Durban, KwaZulu province of South Africa is given as[2]:

Table 3.1. Water tariff

Volume used/ discharged (m^3)	0-6	7-25	26-30	31-45	≥ 45
PW rates (R/m^3)	0	17.23	23.59	51.99	57.18
Sewage rates (R/m^3)	0	6.01	8.25	18.14	19.99

3.6 RESULTS AND DISCUSSION

The optimal pump scheduling for the proposed model in Section 3.4 is carried out. A BILP, single objective optimisation problem is formulated. The corresponding algorithm is formulated and simulated in MATLAB for an operating cycle of 24 h and sampling time t_s of 15 mins. To validate the performance of the proposed model, the optimal pumping scheduling obtained is compared to the reference system operation without optimisation.

3.6.1 Optimal operation of the proposed system

This section discusses the optimal pump schedule for the residential potable water supply system. Figure 3.3 shows the pumping operation of the case study when the pump is operated manually, and Figure 3.4 shows the optimal pump schedule and the corresponding variations in state variable (water level) of the proposed model. From Figure 3.3, it is observed that its pumping operation is continued until the tank is full irrespective of the TOU period, while the proposed model operates the pump at

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[2] http://www.durban.gov.za/Resource_Centre/Services_Tariffs/Water%20Tariffs/Forms/AllItems.aspx

off-peak and standard TOU periods to satisfy the objective of minimising the operational cost of the system. u_1 is the binary decision variable that controls the operation of the pump P_1. When switched on (i.e. $u_1 = 1$), it operates the pump to supply water to the rooftop tank, and when it is switched off (i.e. $u_1 = 0$) it stops the pumping operation, and the water level starts falling continuously at a rate that correlates with water demand. Over the 24 h operation cycle, the pump is switched on at time 01:45 h for 45 mins to provide sufficient water to meet the early morning water demand. Thereafter, the pump is switched off, and the water level starts falling with demand until 05:45 h when it is turned on for 15 mins to provide sufficient water required to meet the water demand during the peak TOU period. Next, the pump switch is operated at 12:45 h for 45 mins and at 15:15 h, 16:45 h and 20:45 h for 15 mins each to provide sufficient water required to meet the residential water demand.

To evaluate the performance of the proposed pumping strategy, the simulation results (in Figure 3.4)

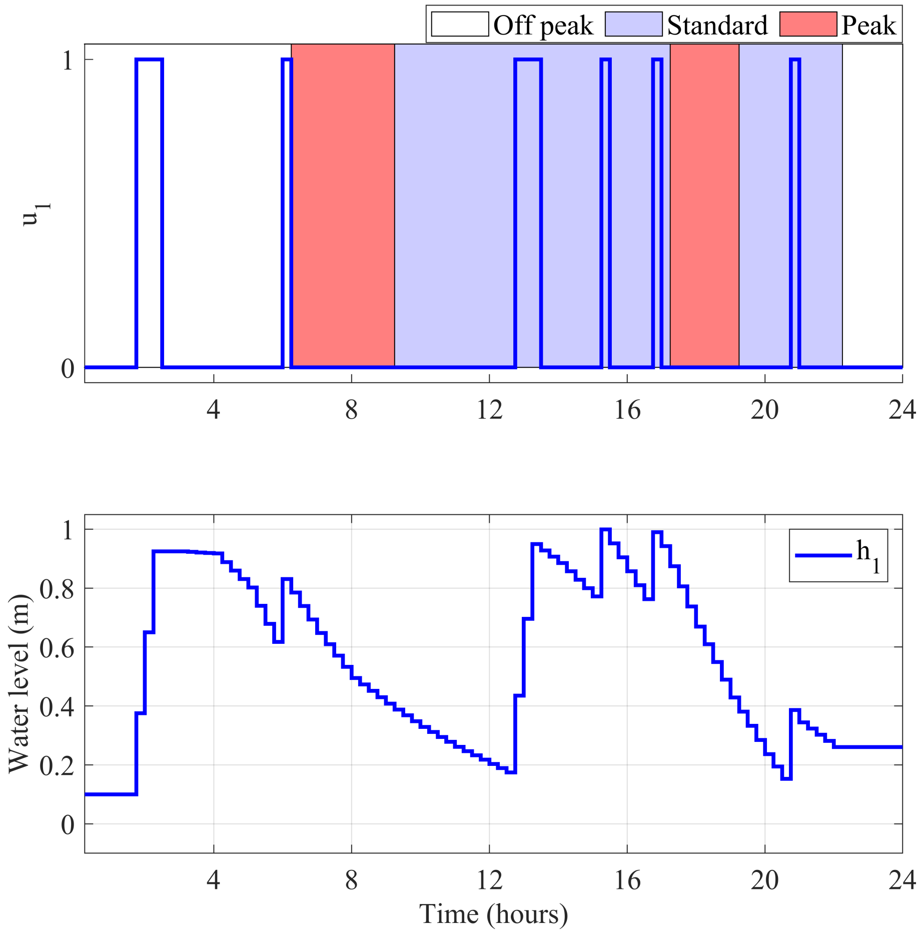

Figure 3.4. Pump scheduling strategy: Optimal pump switching and variations in water level

is compared to the original operation without optimisation in Figure 3.3. Table 3.2 summarises the relative performance of the proposed model to the case study without optimisation. It shows that the proposed model produced an energy cost savings of 18.31% due to the pump scheduling at off-peak and standard TOU periods. This result agrees with [101, 102] that optimal pump scheduling improves the financial benefits of the proposed system. In conclusion, the optimisation problem is solved, and the objective is achieved without violating the technical and operational constraints of the system.

Table 3.2. Comparison of the operational cost of the systems with and without optimisation

	Baseline	Optimisation	Savings (%)
Potable water			
Amount consumed (m^3/month)	41.25	41.25	
Cost (R/month)	1030.21	1030.21	0
Wastewater discharged			
Amount (m^3/month)	22.69	22.69	
Cost (R/month)	100.29	100.29	0
Energy consumption			
Amount (kWh/month)	52.5	52.5	
Cost (R/month)	55.23	45.12	18.31
Monthly total (R/month)	1185.73	1175.62	
Annualized total (R/year)	14228.77	14107.49	0.85

3.6.2 Economic analysis

It is important to evaluate the cost-effectiveness of the proposed optimal pump scheduling strategy in residential potable water supply system based on the cost-benefit relationship. The present worth method is used to discount future value (FV) of cash flows to their present values (PV) with the exemption of capital costs. The cumulative sum of the PVs forms the net present value (NPV). The NPV is an important indicator for determining the economic feasibility of projects. If NPV is positive, the investment is considered to be economically attractive and vice versa. The NPVs of cost-effective projects increases from negative to positive values as the operational benefits increases. The investment reaches a break-even point or PBP when NPV equal zero. The PBP is the time it takes the project to repay its capital investment and become profitable. LCCA is an extension of NPV economic analysis over the lifetime of the project, thereby capturing the capital investments and all the operational cost of the project.

$$LCC = C_c + C_o, \tag{3.18}$$

where C_c and C_o are respectively, the capital and operational costs of the system. The capital cost includes the total capital, installation and labour costs. In this study, the operational cost includes water, energy and maintenance cost of the proposed system. The life cycle costing of the project can be written in terms of discount rate as:

$$LCC = C_c + \frac{C_o(n)}{(1+r)^n}, \tag{3.19}$$

where r is the discount rate required to convert the FV of cash flows from nth year to their present values. m is the service life of the project. The capital, operational and maintenance costs are based on the South African market rate, and all cash flows are in South African Rand (ZAR). To perform this analysis, the following assumptions are made: The service life or lifespan of the project (m) is 20 years. The 2018 average inflation rate of South Africa is used as the discount rate, and it is assumed to be constant throughout the service life of the project. A discount rate of 5.2% is used to convert future cash flows to their present values. The water and energy tariffs are also assumed to be constant for the service life of the project.

The annualised cost and revenue are obtained from daily values. Table 3.3 shows the LCC analysis of the proposed residential water supply system. In this table, cash outflows or expenses incurred are negative values enclosed in brackets, while cash inflows or revenue are indicated with positive values. Although the proposed strategy improved the financial savings on electricity cost by 18.31% as seen in Table 3.2 and the life cycle cost of the system by 0.85% (in Table 3.3), they are not enough to repay the initial investment of the system in its lifetime. Therefore, the proposed system does not reach a payback period in its lifetime. The economic attractiveness of the proposed system can be further improved with government incentives, rebates on capital investments, cost-reflective energy and water tariffs, and economical water and energy alternatives.

Table 3.3. Life cycle cost analysis of the proposed system

Capital investment		Annualised operational cost						
	(R)	Year	Baseline O&M (R)	Proposal O&M (R)	Savings (R)	Discount factor	Discounted cash flows (R)	Cumulative cash flows (R)
Storage tank	1625.00	0				1		(10425.00)
Pump	1250.00	1	(14796.77)	(14675.49)	121.28	0.95	115.28	(10309.71)
Controller	4000.00	2	(14796.77)	(14675.49)	121.28	0.90	109.59	(10200.13)
Accessories	1500.00	3	(14796.77)	(14675.49)	121.28	0.86	104.17	(10095.96)
Installation cost	2050.00	4	(14796.77)	(14675.49)	121.28	0.82	99.02	(9996.94)
Total investment	10425.00	5	(14796.77)	(14675.49)	121.28	0.78	94.13	(9902.81)
		6	(14796.77)	(14675.49)	121.28	0.74	89.47	(9813.34)
		7	(14796.77)	(14675.49)	121.28	0.70	85.05	(9728.29)
		8	(14796.77)	(14675.49)	121.28	0.67	80.85	(9647.44)
		9	(14796.77)	(14675.49)	121.28	0.63	76.85	(9570.59)
		10	(14796.77)	(14675.49)	121.28	0.60	73.05	(9497.54)
		11	(14796.77)	(14675.49)	121.28	0.57	69.44	(9428.1)
		12	(14796.77)	(14675.49)	121.28	0.54	66.00	(9362.09)
		13	(14796.77)	(14675.49)	121.28	0.52	62.75	(9299.34)
		14	(14796.77)	(14675.49)	121.28	0.49	59.64	(9239.70)
		15	(14796.77)	(14675.49)	121.28	0.47	56.69	(9183.00)
		16	(14796.77)	(14675.49)	121.28	0.44	53.89	(9129.11)
		17	(14796.77)	(14675.49)	121.282	0.42	51.22	(9077.88)
		18	(14796.77)	(14675.49)	121.28	0.40	48.70	(9029.18)
		19	(14796.77)	(14675.49)	121.28	0.38	46.29	(8982.89)
		20	(14796.77)	(14675.49)	121.28	0.36	44.00	(8938.89)
Life cycle cost			(295935.4)	(293509.8)				

3.7 CHAPTER SUMMARY

This chapter presented an optimal pump scheduling strategy for a residential potable water supply system. A BILP problem was formulated to minimise the pumping cost of the system subject to the technical and operational constraints that include the TOU electricity tariff. The algorithm was formulated and solved by the SCIP solver embedded in MATLAB. The simulation results based on a practical case study showed the potential of the proposed optimal pump scheduling to save pumping energy cost by 18.31%. Furthermore, an economic analysis was performed to evaluate the economic attractiveness of the proposed pump scheduling strategy using LCC analysis. The results showed that although the optimal pump scheduling improved the energy cost savings by 18.31% and life cycle cost savings by 0.85%, the system does not repay the initial capital investment in its lifetime. Therefore, an optimal tank sizing and operation of an integrated RWH-GWR system is proposed to improve the economic attractiveness of residential water supply system in Chapter 4. The simulation results in Chapter 3 (Figure 3.4) will be used as the baseline for evaluating the performance and potential of the proposed RWH-GWR system in Chapter 4.

CHAPTER 4 OPTIMAL TANK SIZING AND PUMP SCHEDULING FOR RESIDENTIAL RAINWATER HARVESTING AND GREYWATER RECYCLING SYSTEM

4.1 CHAPTER OVERVIEW

A mixed binary integer linear programming model is formulated to minimise the size of the tanks and the operational cost of the residential RWH-GWR system subject to technical and operational constraints under the TOU period. The proposed system is made up of the municipal water and energy supplies, RWH system, GWR system, water treatment, pumps, water tanks and the residential end-use points. The mathematical models of the subsystems are formulated in Section 4.3. The optimisation model and solution algorithm are formulated in Section 4.4. The Case study is presented in Section 4.5. The optimisation problem is solved by the solving constraints integer programming (SCIP) solver embedded in MATLAB. The simulation results are discussed in Section 4.6. Economic and sensitivity analyses of the proposed model are discussed in Sections 4.7 and 4.8, respectively. The economic analysis is carried out to evaluate the economic feasibility of the proposed system, while the Sensitivity analysis is also performed to investigate the robustness of the proposed model to uncertainties in water demand, rainfall, electricity pricing and discount rate. A comparative analysis of the performance and economic feasibility of optimisation and Rippl methods of tank sizing are also discussed in this study.

4.2 INTRODUCTION

Water scarcity is a global challenge that is due to an insufficient water supply to meet demand; therefore, there is an urgent need for economically sustainable solutions to this problem [45]. Seventy percent of the earth's surface is covered by water, of which 97% is saline and the remaining 3% freshwater, and only 0.014% of the earth's water is fresh and easily accessible[1]. One-third of the world's population experiences severe water scarcity at least once in a year, while over half a billion people live under water scarcity. Additionally, Agriculture, household and industry are the three largest freshwater consumers globally, they account for 60%, 30% and 8% of freshwater consumption, respectively [103, 104]. The water demand from these sectors will increase with population, industrial and economic growths, thus placing pressure on the limited resource, this unsustainable trend between water demand and supply has caused the United Nations and other international organisations to investigate and report that water scarcity will increase by 40% in 2030 [103, 105, 106]. The World Bank further analysed that the degree of local water scarcity will vary with regions, existing water infrastructures, climatic conditions and technological advancements, therefore it reports that water scarcity will increase by 43% in North America to 280% in sub-Sahara Africa by 2030 [106]. Similarly, energy scarcity is a global menace caused by insufficient energy supply to meet the growing energy demand due to population, industrial and economic growths [46]. Hydroelectricity accounts for 16.4% of the world's energy generation and 70% of the world's renewable energy capacity. Additionally, every form of energy generation, ranging from nuclear, thermal, biomass, solar and wind turbine, need water for manufacturing, cooling, cleaning and energy generation; therefore, water is essential for energy security. However, the demand for energy is fast outpacing its supplies [7] causing the United Nations and other international organisations to report that energy scarcity will increase by 50% in 2030 [6]. However, there is a mutually interdependent relationship between energy and water termed energy-water nexus [87, 107]. One of the implications of this overlapping relationship is that water scarcity will cause energy scarcity and vice versa. This concept, energy-water nexus, also justifies the effects of climate change on water and energy securities [108]. Previous studies have examined groundwater extraction [109], seawater desalination [109], RWH [53] and GWR [2], however, [72] concludes that RWH and GWR systems are the two most economically sustainable solutions to water scarcity in residences. Therefore, this study proposes an integrated RWH-GWR system as an environmental and economically sustainable demand-side solution to the challenges of energy-water

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[1] https://www.worldenergy.org/data/resources/resource/hydropower/

nexus in homes.

RWH involves the collection, treatment, storage and use of rainwater for domestic, industrial and agricultural purposes. It is gaining renewed interest and attention due to the widespread water scarcity. In addition, it provides an economical and sustainable alternative solution to water scarcity. There are two classifications of RWH system, namely: the rooftop and run-off RWH systems. The rooftop RWH system collects water from the rooftop catchment area, while the run-off RWH system traps and collects surface run-off or stormwater for use [48, 110]. The rooftop RWH system is an economical alternative for residences; therefore, it is used in this study, and any mention of RWH system subsequently refers to the rooftop RWH system. The quality of the rainwater harvested depends on atmospheric and rooftop impurity level, water treatment, and storage and distribution pipes [111]. However, the use of rainwater for non-potable purposes require at most primary treatment, while first-flush and filtration are the least recommended treatments for potable end-uses [112]. The performance of RWH systems, in terms of potable water savings and reliability, varies with rainfall parameters and catchment area [70, 72, 113, 114]. It performs best in wet regions (wet years in dry regions) under large catchment area and high non-potable water utilisation rate. The RWH system is most economical in locations with regular rainfall and high non-potable water utilisation [115]. In terms of PBP, RWH systems repay their initial investments between 2 – 35 years depending on water demand, non-potable water utilisation and collection area [54, 116, 117].

Greywater is wastewater without faecal contamination that is collected from the kitchen sinks, showers or baths and laundry machines. The GWR system is an assembly that collects, treats and stores greywater for re-use [59]. Greywater supply is reliable, and it accounts for 43–70% of the total wastewater generated in residences [60–62]. Prathapar *et al.* [118] report that GWR has the potential of producing 30 – 50% potable water savings from irrigation and toilet flushing. Therefore, it is potential to improve water security increases with greywater utilisation and potable water substitution. Water treatment is essential to maximise the performance of GWR systems. Greywater treatment is classified into three stages namely: physical, biological and chemical treatments [119]. The physical treatment removes solids, organics and surfactants. The biological treatment eliminates pathogen, while chemical treatment disinfects the water for safe use [120, 121]. Some common biological water treatment methods include rotary biological contactors [2], biological aerated filters [57] and membrane bio-reactors [122, 123]. Common chemical disinfectants include hypochlorite, chlorine, ozone and ultraviolet radiations. Generally, GWR is an energy and capital intensive process that is mainly due to the energy and capital intensive nature of the water treatment process [124]. Therefore, Siang *et al.* [62] proposed a fit-for-purpose water treatment that delivers tailored treatment according to the standard water quality required at the end-use points. Elsewhere, a recycled vertical flow constructed wetland (RVFCW) [63] and upflow-downflow greywater treatment plants [61] were developed to reduce the energy and capital intensity of GWR systems. Studies on the integrated RWH-GWR systems found out that the performance of the RWH and GWR subsystems affect the performance of the overall system [5]. All three systems (RWH, GWR and RWH-GWR systems) have high water savings potential and long PBP, however, their relative performance varies with rainfall, occupancy rate and non-potable water utilisation [72]. Zhang *et al.* [64] investigated the performance of the combined RWH-GWR system in Beijing, China. This study agrees with [125] that GWR systems are more effective in densely populated locations, multi-storey and multi-family buildings, RWH subsystems are more effective in places with regular rainfall, and the integrated RWH-GWR system is the most effective, reliable and robust alternative irrespective of population density and rainfall properties. South Africa is a developing country with heavy water consumption. In addition, it is a semi-arid country possessing an average annual rainfall of 500 mm and Durban is a coastal city in eastern South Africa that has an annual rainfall of 1009 mm. Therefore, an integrated RWH-GWR system is proposed to leverage on its water recycling and harvesting potential to improve water security in this region. Based on literature, there are two configurations of RWH-GWR system which are: the independent RWH-GWR subsystems and connected RWH-GWR subsystems. In the independent RWH-GWR subsystems, the RWH and GWR subsystems are completely isolated from each other, while the RWH and GWR subsystems in the connected RWH-GWR subsystems share water treatment and storage facilities. However, both systems are limited by water losses caused by the daily emptying of the storage tank due to partial water treatment before storage. Therefore, this study adopts the complete water treatment before storage to improve water savings and reliability of the integrated RWH-GWR system.

A water tank is a storage device that collects and holds water for future use. It is mostly used in locations with unreliable and expensive water supply. It has the benefits of improving water savings, reliability and the economic attractiveness of the water supply system. However, the performance of water tanks are affected by its size; therefore, it is essential to investigate tank sizing properly. There is a direct relationship between tank sizing and potable water savings because of the more substantial the tank, the better its potable water savings potential. Potable water savings also depends on the availability and utilisation of non-potable water; therefore, large tanks have better water savings potential because of its ability to hold and supply a large volume of water for use [50, 74, 114]. There is also a direct relationship between tank sizing and the reliability of water supply because the reliability of the water supply system increases with the size of the tank [51, 82]. Regions with defined extended drought periods require large storage volumes to improve the reliability of water supply at the expense of high purchasing and installation costs [82]. However, smaller tanks installed in wet or coastal regions with regular rainfall will produce a similar effect on the reliability of water supply as large tanks installed in dry regions because of the frequent rainfall to meet demand. Therefore, small tanks installed in wet or coastal regions improve the reliability of water supply at a cheaper cost, thereby improving the economic attractiveness of the water supply system [77]. There are direct relationships between tank sizing, water savings potential [70] and the reliability of water supply systems [51], and an inverse relationship between tank sizing and the economic attractiveness of the water supply systems [116] because increased capital investment on large tanks will improve the water savings potential and reliability of water supply systems at the expense of its economic attractiveness. Furthermore, tank sizing is affected by internal and external factors such as demand profile, rainfall, weather and climatic conditions, thereby increasing the complexities of tank sizing. Studies on tank sizing have mainly been associated with RWH system, while GWR systems assume fixed tank size to meet the daily water demand only. With respect to integrated RWH-GWR system, Ghisi *et al.* [52, 72] sized the rooftop tanks without considering system operations and water loss control. Wanjiru *et al.* [4] investigated the optimal operation of the integrated RWH-GWR system based on the open-loop and closed-loop model predictive control strategies without tank sizing and water loss control. Therefore, there is a need to determine the accurate size of water tanks for integrated RWH-GWR system without making trade-off on reliability, potable water savings and economic attractiveness. In view of this, studies on tank sizing include: the water balance model [76], probabilistic method [96], reliability curve method [77, 79], minimum cost-based and regressive model approach [50], linear programming method [73], mass diagram method [78] and Neptune computer programming method [72]. Matos *et al.* [74] state that the Rippl method and the daily simulation method using the 80% efficiency criteria are the most cost-effective tank sizing methods because of their high economic savings to installation cost ratio.

Previous studies on tank sizing focused on RWH systems [73, 74, 79, 81], but none has explored tank sizing in GWR systems. In addition, studies on integrated RWH-GWR system have focused on design [52, 64, 72], with very little attention to system operation. An open-loop optimal control and closed-loop model predictive control strategies for an integrated RWH-GWR system were developed and their relative performances compared without considering tank sizing and water loss control [4]. The water tank is an essential but capital intensive component for reliable water supply; therefore this study introduces the first attempt to develop a model for optimal tank sizing and operation of the integrated RWH-GWR system under the TOU electricity tariff. This study aims at improving the economic attractiveness of integrated RWH-GWR system by minimising capital cost on water tanks and operational cost, simultaneously. The interplay between tank sizing and operation of the integrated RWH-GWR system is also investigated in this study. A comparative analysis of the performance of optimisation and Rippl methods of tank sizing on system operation is carried out to evaluate their relative performances. Previous studies on RWH, GWR and integrated RWH-GWR systems experience water loss to emptying of the water tank daily to eliminate the breeding of pathogens [4,60,124,126,127]. Therefore, this study also proposed and developed a model that accommodates full water treatment before storage to improve the duration of water storage, water savings potential, reliability of water supply and the economic attractiveness of the proposed RWH-GWR system. The main contributions of this chapter include: (1) restructuring and modelling the proposed system to ensure complete water treatment before storage to improve the duration of water storage, water utilisation and reliability, (2) optimal tank sizing and operation to enhance the economic attractiveness of the proposed RWH-GWR system, (3) comparative analysis of the optimisation and Rippl methods of tank sizing to system operation, (4) financial feasibility of the proposed system, and (5) sensitivity analysis to evaluate the robustness of the proposed model to uncertainties in input parameters.

4.3 MATHEMATICAL MODEL FORMULATION

4.3.1 Schematic model layout

Figure 4.1 shows the schematic layout of the proposed RWH-GWR residential water supply system. It is made-up of the RWH system, GWR system, storage tanks, pumps and municipal energy and water supplies. In this study, the connected RWH-GWR subsystem is adopted; in the connected type, the RWH and GWR subsystems share the water treatments, water tanks, non-potable water pump and end-use points. In addition to the rooftop catchment area and the greywater collection points for the RWH and GWR systems, respectively. The storage system comprises of the rooftop potable (T_1) and non-potable water (T_2) tanks, and the underground tank (T_3). The rooftop potable water tank collects water that is pumped from the municipal line to the rooftop potable water tank. Similarly, the rooftop

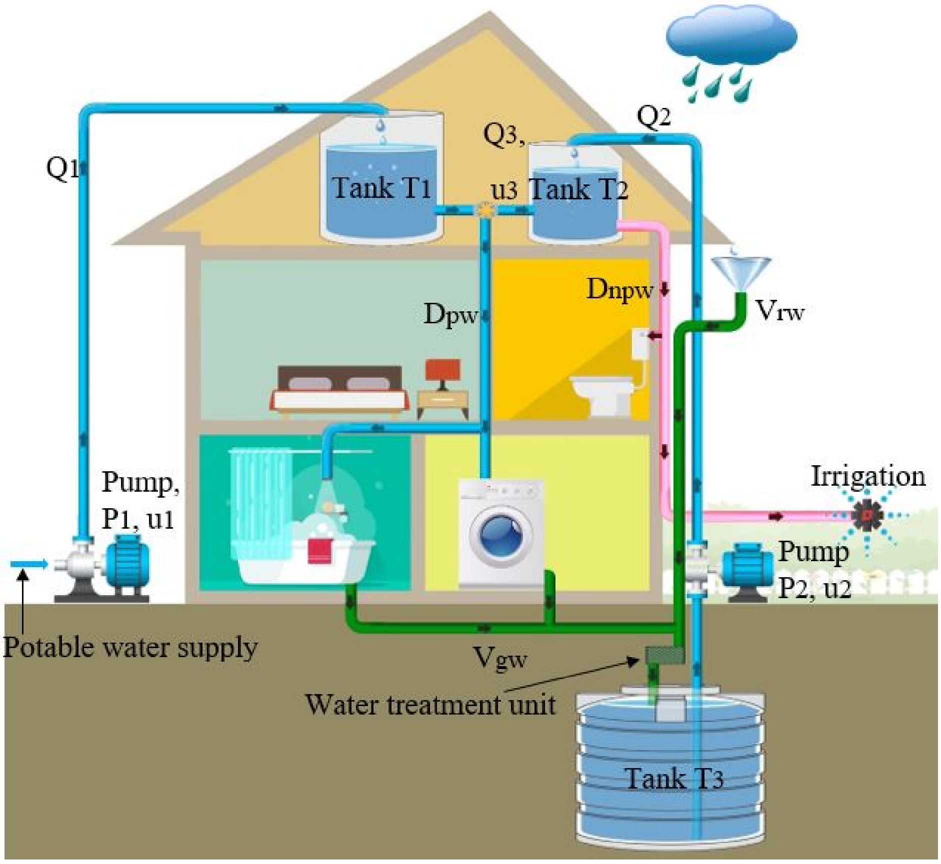

Figure 4.1. Schematic layout the proposed residential rainwater harvesting and greywater recycling system

non-potable water tank receives treated non-potable water (rain and grey water mixture) that is pumped from the underground tank by the non-potable water pump. The municipal potable water supply is used to meet the residential potable water demand, while the non-potable water supply is used to meet the residential non-potable water demand that includes toilet flushing and irrigation. In cases when the non-potable water tanks (T_2 and T_3) are unable to meet their demand, potable water is released from the rooftop potable water tank to meet this demand. In Figure 4.1, P_1 and P_2 are respectively, the potable and non-potable water pumps, while Q_1 and Q_2 are their flowrates. T_1, T_2 and T_3 are the rooftop potable water, rooftop non-potable water and the underground tanks, respectively. D_{pw} and D_{npw} are the potable and non-potable water demands. V_{rw} and V_{gw} are the volumes of rain and grey water collected. In this schematic model, the decision variables include: H_1, H_2 and H_3 that represent the storage volume of the tanks (in terms of height), and u_1, u_2 and u_3 are the pump switches and the valve.

The mathematical model of the subsystems are given in Sections 4.3.2, 4.3.3 and 4.3.4:

4.3.2 Rooftop potable water tank

In this study potable water is pumped into the rooftop tank for storage and distribution to the end-use points under gravity. This is a vertical uniform cross-sectional area cylindrical tank and the volume of water in the tank is expressed as:

$$V_1 = A_{t1} \times h_1 = t_s Q_1 u_1 - t_s s Q_3 u_3 - D_{pw}, \tag{4.1}$$

where V_1 is the volume of water in the tank (m^3), which is the product of the cross-sectional area (m^2) and the water level from the bottom of the tank (m). Q_1 and Q_3 are the flowrates (m^3/h), and D$_{pw}$ is the volume of residential potable water demand (m^3). Equation (4.1) is expressed in terms of water level (h) in discrete-time domain as:

$$h_1(j) = h_1(0) + \frac{1}{A_{t1}} \sum_{i=0}^{j-1} \left[t_s Q_1 u_1(i) - t_s Q_3 u_3(i) - D_{pw}(i) \right]. \tag{4.2}$$

4.3.3 Rooftop non-potable water tank

This is a vertical uniform cross-sectional area cylindrical tank that receives treated rain and grey water mixture that is pumped from the underground tank. The volume of water in this tank (V$_2$) is expressed as:

$$V_2 = A_{t2} \times h_2 = t_s Q_2 u_2 + t_s Q_3 u_3 - D_{npw}, \tag{4.3}$$

where Q$_2$ and D$_{npw}$ are respectively, the flowrate (m^3/h) of the non-potable water pump and the non-potable water demand (m^3). Equation (4.3) is modelled in terms of water level in discrete-time domain as:

$$h_2(j) = h_2(0) + \frac{1}{A_{t2}} \sum_{i=0}^{j-1} \left[t_s Q_2 u_2(i) + t_s Q_3 u_3(i) - D_{npw}(i) \right]. \tag{4.4}$$

4.3.4 Underground tank

This is a horizontal uniform cross-sectional area cylindrical tank that collects non-potable water mixture for storage and distribution to the rooftop non-potable water tank. The volume of water in this tank (V_3) is expressed as:

$$V_3 = A_{t3} \times h_3 = V_{rw} + V_{gw} - t_s Q_2 u_2 - D_{ov}, \tag{4.5}$$

where V_{rw}, V_{gw} and D_{ov} are respectively, the volumes (m^3) of rainwater harvested, greywater collected and water lost in tank overflow. Similarly, Equation (4.5) is modelled in terms of water level in discrete-time domain as:

$$h_3(j) = h_3(0) + \frac{1}{A_{t3}} \sum_{i=0}^{j-1} \Big[V_{gw}(i) + V_{rw}(i) - t_s Q_2 u_2(i) - D_{ov}(i) \Big]. \tag{4.6}$$

All three tanks are uniform cross-sectional area cylindrical tanks with water levels h_i, where the subscript $i = 1,\ 2,\ 3$ represents the rooftop potable water, non-potable water and the underground tanks, respectively. The rooftop and underground tanks are vertical and horizontal water tanks, respectively. Indexes $i = 1, 2, \ldots,$ N and $j = 1, 2, \ldots,$ N denote the i-th and j-th sampling instances within the Nt_s scheduling interval, where t_s is the sampling time and N is the total number of intervals in the 24-hour operating cycle, therefore $N = \frac{24}{t_s}$. The volume of rainwater harvested V_{rw} is expressed in discrete time domain as [52]:

$$V_{rw}(i) = \frac{A_r R_c I_t(i)}{1000}, \tag{4.7}$$

where A_r is the rooftop collection area (m^2), I_t is rainfall intensity (mm) and R_c is the run-off co-efficient (dimensionless). The volume of greywater collected (V_{gw}) is a fraction of the residential PW demand, this can be expressed in discrete time domain as [4]:

$$V_{gw}(i) = \tau D_{pw}(i), \tag{4.8}$$

where τ is the constant denoting the percentage of the total water consumed collected as greywater for treatment and re-use. Tank overflow is calculated by [51]:

$$D_{ov}(i) = \begin{cases} V_3(i) - V_3^{max}, & \text{if } V_3(i) > V_3^{max}, \\ 0, & \text{if } V_3(i) \leq V_3^{max}, \end{cases} \tag{4.9}$$

where the volume of water in tank T_3, $V_3 = A_3h_3$. V_3^{max} is the upper bound of the tank.

4.3.5 Rippl method for tank sizing

The Rippl method is a tank sizing technique that is based on the cumulative water deficit between water demand and supply during the period of insufficient water supply to meet the residential water demand for the most extended period of drought [85]. Unlike other tank sizing methods, the Rippl method focuses on the water deficit during the most prolonged period of successive droughts and the total water deficits in this interval is the storage volume produced by the Rippl method. It can use either daily or monthly water parameters depending on the availability of accurate data. Therefore, the storage volume produced by Rippl method is:

$$V_{rpl} = \sum (D_t - S_t), \text{ if } D_t > S_t, \tag{4.10}$$

where V_{rpl} is storage volume (m^{3}Narrative conclusion should be given based on Figures 4.5-4.10 and Table 4.7 about sensitivity of the proposed model to uncertainties)produced by the Rippl method from the accumulated difference between the total non-potable water demand (D_t) and supply (S_t). In this study, the Rippl method serves as a reference for evaluating the performance of the optimisation method for tank sizing. Therefore, the total non-potable water supply to the underground tank is the sum of the rain and grey water collected for toilet flushing and irrigation.

$$S_t = V_{rw}(i) + V_{gw}(i). \tag{4.11}$$

4.4 OPTIMISATION MODEL

The objectives of this study are to minimise the storage volume of the water tanks and the operational cost of the proposed RWH-GWR system. Therefore, a multi-objective optimisation problem is formulated to minimise the storage volume of the tanks, pumping cost and potable water consumption.

The weighted-sum method, which is the most widely used technique for solving multi-objective optimisation problem, is used in this study. This method converts multi-objective optimisation problems into aggregated single objectives using weighting factors. Therefore, the optimisation problem becomes:

$$J = w_1 J_1 + w_2 J_2 + w_3 J_3 + w_4 J_4, \tag{4.12}$$

where $w_1 - w_4$ are weights for varying the sub-objectives according to the user's preference and $\sum_{i=1}^{4} w_i = 1$. $J_1 - J_4$ are sub-objectives of the optimisation model. The first objective $\left(J_1 = A_{t1}H_1 + A_{t2}H_2 + A_{t3}H_3\right)$ represents the storage volume of the tanks, the second objective $\left(J_2 = t_s \sum_{j=1}^{N} \rho_e(j)[P_1 u_1(j) + P_2 u_2(j)]\right)$ represents pumping cost, the third and fourth objectives $\left(J_3 = Q_3 u_3(j)\right)$ and $\left(J_4 = \sum_{j=1}^{N} [s_1(j) + s_2(j)]\right)$ represent potable water consumption and the switching frequency of the pumps, respectively. In this study, the sub-objectives have different dimensions, therefore, they will be normalised to standardise the objective function. The standardised objective function is:

$$J = w_1 \frac{J_1}{\bar{J_1}} + w_2 \frac{J_2}{\bar{J_2}} + w_3 \frac{J_3}{\bar{J_3}} + w_4 \frac{J_4}{\bar{J_4}}, \tag{4.13}$$

where $\bar{J}_1, \bar{J}_2, \bar{J}_3$ and $\bar{J}_4$ are the normalisation factor of the sub-objectives J_1, J_2, J_3 and J_4, respectively, obtained from the maximum values of the sub-objectives [128, 129]. Another benefit of the weighted-sum method is its provision for decision maker's interference by tuning the weighting factors according to the user's priorities to achieve the desired result. Regular switching increases maintenance cost due to pump wear and tear. Therefore, the Pretorian method developed by Mathaba and Xia is used to minimise the switching frequency of the pumps [130]. This method introduces binary auxiliary variables that switches from 0 to 1 when the pumps transitions from off to on and vice versa. The auxiliary variables will also augment adjacent pump switching to minimise the switching frequency and the maintenance cost of the pumps. In this study, the operation cycle is 24 h with a sampling time, t_s = 0.25 h (15 mins), j = 1, ..., N is sampling interval and N is the total number intervals N = 24 h / 0.25 h = 96 sampling intervals. The objective function is solved subject to the following constraints:

$$u_m \in \{0,1\}, \text{ for } m = 1,2,3. \tag{4.14}$$

$$s_1,\ s_2 \in \{0,1\}, \tag{4.15}$$

$$u_1(j) - s_1(j) \leq 0, \tag{4.16}$$

$$u_1(j) - u_1(j-1) - s_1(j) \leq 0, \tag{4.17}$$

$$u_2(j) - s_2(j) \leq 0, \tag{4.18}$$

$$u_2(j) - u_2(j-1) - s_2(j) \leq 0, \tag{4.19}$$

$$h_1^{min} \leq h_1(j) \leq h_1^{max}, \text{ for } j = 1,2,\cdots,N, \tag{4.20}$$

$$h_2^{min} \leq h_2(j) \leq h_2^{max}, \text{ for } j = 1,2,\cdots,N, \tag{4.21}$$

$$h_3^{min} \leq h_3(j) \leq h_3^{max}, \text{ for } j = 1,2,\cdots,N, \tag{4.22}$$

$$H_1^{min} \leq H_1 \leq H_1^{max}, \tag{4.23}$$

$$H_2^{min} \leq H_2 \leq H_2^{max}, \tag{4.24}$$

$$H_3^{min} \leq H_3 \leq H_3^{max}, \tag{4.25}$$

where ρ_e is electricity cost. H_1, H_2 and H_3 are decision variables representing the size of the rooftop potable water, non-potable water and underground tanks, respectively. u_1, u_2 and u_3 are decision variables for pumps and valve switching, while s_1 and s_2 are the auxiliary variables that minimise the switching frequency of the pumps. Constraints (4.14) – (4.15) are boundary constraints for the binary decision variables. Constraints (4.16) – (4.18) initialises the auxiliary variables as the initial status of the pump switches. Constraints (4.17) – (4.19) minimises the switching frequency of the pumps by augmenting adjacent switchings. Constraints (4.20) – (4.22) are respectively, the boundary constraints for the state variables, that is, the water level (h) in the potable water, non-potable water and underground tanks. Constraints (4.23) – (4.25) are the boundary constraints for the storage volume of the potable water, non-potable water and underground tanks, respectively.

4.4.1 Algorithm formulation

The mathematical model formulated is expressed in standard linear form as:

$$min\ f^T X, \tag{4.26}$$

subject to

$$\begin{cases} MX \leq b; & \text{linear inequality constraint,} \\ M_{eq}X = b_{eq}; & \text{linear equality constraint,} \\ L_b \leq X \leq U_b; & \text{boundary constraint,} \end{cases} \tag{4.27}$$

where f is the vector of the objective function. M_{eq} and M are matrices of the equality and inequality constraints, and b_{eq} and b are vectors of the equality and inequality constraints. L_b and U_b are vectors of the lower and upper bounds of the decision variables X. Therefore, the optimisation model can be expressed as:

$$f^T = \begin{bmatrix} t_sA_1, & t_sA_2, & t_sA_3, & t_sP_1\rho_{e,1\cdots N}, & t_sP_2\rho_{e,1\cdots N}, & Q_{3,1\cdots N}, & 1_{1\cdots N}, & 1_{5,1\cdots N} \end{bmatrix}^T_{1\times(3+5N)}, \tag{4.28}$$

$$X = \begin{bmatrix} H_1, & H_2, & H_3, & u_{1,1\cdots N}, & u_{2,1\cdots N}, & u_{3,1\cdots N}, & s_{1,1\cdots N}, & s_{2,1\cdots N} \end{bmatrix}^T_{1\times(3+5N)}, \tag{4.29}$$

The matrices and vectors of the inequality constraints, (4.20) $-$ (4.25), are expressed as:

$$M_1 = \frac{t_s}{A_{t1}} \begin{bmatrix} -1 & 0 & 0 & Q_1 & 0 & \cdots & 0 & 0 & \cdots & 0 & -Q_3 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ -1 & 0 & 0 & Q_1 & Q_1 & \cdots & 0 & 0 & \cdots & 0 & -Q_3 & -Q_3 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ -1 & 0 & 0 & Q_1 & Q_1 & \cdots & Q_1 & 0 & \cdots & 0 & -Q_3 & -Q_3 & \cdots & -Q_3 & 0 & \cdots & 0 & 0 & \cdots & 0 \end{bmatrix}_{N\times(3+5N)}, \tag{4.30}$$

$$b_1 = \begin{bmatrix} -h_1(0) + \frac{1}{A_{t1}}[D_{pw}(1)] \\ -h_1(0) + \frac{1}{A_{t1}}[D_{pw}(1) + D_{pw}(2)] \\ \vdots \\ -h_1(0) + \frac{1}{A_{t1}}[D_{pw}(1) + \ \cdots \ + D_{pw}(N)] \end{bmatrix}_{N\times 1}, \tag{4.31}$$

$$M_2 = -\frac{t_s}{A_{t1}} \begin{bmatrix} 0 & 0 & 0 & Q_1 & 0 & \cdots & 0 & 0 & \cdots & 0 & -Q_3 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & Q_1 & Q_1 & \cdots & 0 & 0 & \cdots & 0 & -Q_3 & -Q_3 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & Q_1 & Q_1 & \cdots & Q_1 & 0 & \cdots & 0 & -Q_3 & -Q_3 & \cdots & -Q_3 & 0 & \cdots & 0 & 0 & \cdots & 0 \end{bmatrix}_{N\times(3+5N)}, \tag{4.32}$$

$$b_2 = \begin{bmatrix} h_1(0) - h_1^{min} - \frac{1}{A_{t1}}[D_{pw}(1)] \\ h_1(0) - h_1^{min} - \frac{1}{A_{t1}}[D_{pw}(1) + D_{pw}(2)] \\ \vdots \\ h_1(0) - h_1^{min} - \frac{1}{A_{t1}}[D_{pw}(1) + \;\cdots\; + D_{pw}(N)] \end{bmatrix}_{N\times 1}, \tag{4.33}$$

$$M_3 = \frac{t_s}{A_{t2}} \begin{bmatrix} 0 & -1 & 0 & 0 & \cdots & 0 & Q_2 & 0 & \cdots & 0 & Q_3 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & -1 & 0 & 0 & \cdots & 0 & Q_2 & Q_2 & \cdots & 0 & Q_3 & Q_3 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & -1 & 0 & 0 & \cdots & 0 & Q_2 & Q_2 & \cdots & Q_2 & Q_3 & Q_3 & \cdots & Q_3 & 0 & \cdots & 0 & 0 & \cdots & 0 \end{bmatrix}_{N\times(3+5N)}, \tag{4.34}$$

$$b_3 = \begin{bmatrix} -h_2(0) + \frac{1}{A_{t2}}[D_{npw}(1)] \\ -h_2(0) + \frac{1}{A_{t2}}[D_{npw}(1) + D_{npw}(2)] \\ \vdots \\ -h_2(0) + \frac{1}{A_{t2}}[D_{npw}(1) + \;\cdots\; + D_{npw}(N)] \end{bmatrix}_{N\times 1}, \tag{4.35}$$

$$M_4 = -\frac{t_s}{A_{t2}} \begin{bmatrix} 0 & 0 & 0 & 0 & \cdots & 0 & Q_2 & 0 & \cdots & 0 & Q_3 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & Q_2 & Q_2 & \cdots & 0 & Q_3 & Q_3 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 0 & Q_2 & Q_2 & \cdots & Q_2 & Q_3 & Q_3 & \cdots & Q_3 & 0 & \cdots & 0 & 0 & \cdots & 0 \end{bmatrix}_{N\times(3+5N)}, \tag{4.36}$$

$$b_4 = \begin{bmatrix} h_2(0) - h_2^{min} - \frac{1}{A_{t2}}[D_{npw}(1)] \\ h_2(0) - h_2^{min} - \frac{1}{A_{t2}}[D_{npw}(1) + D_{npw}(2)] \\ \vdots \\ h_2(0) - h_2^{min} - \frac{1}{A_{t2}}[D_{npw}(1) + \;\cdots\; + D_{npw}(N)] \end{bmatrix}_{N\times 1}, \tag{4.37}$$

$$M_5 = \frac{t_s}{A_{t3}} \begin{bmatrix} 0 & 0 & -1 & 0 & \cdots & 0 & -Q_2 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & 0 & -1 & 0 & \cdots & 0 & -Q_2 & -Q_2 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & -1 & 0 & \cdots & 0 & -Q_2 & -Q_2 & \cdots & -Q_2 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \end{bmatrix}_{N\times(3+5N)}, \tag{4.38}$$

$$b_5 = \begin{bmatrix} -h_3(0) - \frac{1}{A_{t3}}[V_{gw}(1) + V_{rw}(1) - D_{ov}(1)] \\ -h_3(0) - \frac{1}{A_{t3}}[(V_{gw}(1) + V_{gw}(2)) + (V_{rw}(1) + V_{rw}(2)) - (D_{ov}(1) + D_{ov}(2))] \\ \vdots \\ -h_3(0) - \frac{1}{A_{t3}}[(V_{gw}(1) + \cdots + V_{gw}(N)) + (V_{rw}(1) + \cdots + V_{rw}(N)) - (D_{ov}(1) + \cdots + D_{ov}(N))] \end{bmatrix}_{N\times 1}, \tag{4.39}$$

$$M_6 = \frac{t_s}{A_{t3}} \begin{bmatrix} 0 & 0 & 0 & 0 & \cdots & 0 & Q_2 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & Q_2 & Q_2 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 0 & Q_2 & Q_2 & \cdots & Q_2 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \end{bmatrix}_{N\times(3+5N)}, \tag{4.40}$$

$$b_6 = \begin{bmatrix} h_3(0) - h_3^{min} + \frac{1}{A_{t3}}[V_{gw}(1) + V_{rw}(1) - D_{ov}(1)] \\ h_3(0) - h_3^{min} + \frac{1}{A_{t3}}[(V_{gw}(1) + V_{gw}(2)) + (V_{rw}(1) + V_{rw}(2)) - (D_{ov}(1) + D_{ov}(2))] \\ \vdots \\ h_3(0) - h_3^{min} + \frac{1}{A_{t3}}[(V_{gw}(1) + \cdots + V_{gw}(N)) + (V_{rw}(1) + \cdots + V_{rw}(N)) - (D_{ov}(1) + \cdots + D_{ov}(N))] \end{bmatrix}_{N\times 1}, \tag{4.41}$$

The matrice and vector of the auxiliary variables in (4.16) – (4.19) are combined in:

$$M_7 = t_s \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & \cdots & 0 & 0 & 1 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & -1 & \cdots & 0 & -1 & \cdots & 0 \\ 0 & 0 & 0 & -1 & 1 & \cdots & 0 & 0 & -1 & 1 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \cdots & -1 & 1 & 0 & 0 & \cdots & -1 & 1 & 0 & \cdots & 0 & 0 & \cdots & -1 & 0 & \cdots & -1 \end{bmatrix}_{N\times(3+5N)}, \tag{4.42}$$

$$b_7 = \begin{bmatrix} 0 & \cdots & 0 \end{bmatrix}^T_{N\times 1}, \tag{4.43}$$

where M_1, M_2, M_3, M_4, M_5 and M_6 are matrices of the inequality constraints (4.20), (4.21) and (4.22), while b_1, b_2, b_3, b_4, b_5 and b_6 are their corresponding vectors. M_7 and b_7 are the matrix and vector of the auxiliary variables in constraints (4.16), (4.17), (4.18) and (4.19). These are combined and expressed in the form of $MX \leq b$ with:

$$M = \begin{bmatrix} M_1 \\ M_2 \\ M_3 \\ M_4 \\ M_5 \\ M_6 \\ M_7 \end{bmatrix}_{7N\times(3+5N)}, b = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_6 \\ b_7 \end{bmatrix}_{7N\times 1}, \tag{4.44}$$

There are no equality constraints, hence its matrix and vector are empty. Finally, the vectors of the boundary constraints are:

$$L_b = \begin{bmatrix} H_1^{min} & H_2^{min} & H_3^{min} & 0 & \cdots & 0 \end{bmatrix}^T_{(3+5N)\times 1}, \tag{4.45}$$

$$U_b = \begin{bmatrix} H_1^{max} & H_2^{max} & H_3^{max} & 1 & \cdots & 1 \end{bmatrix}^T_{(3+5N)\times 1}, \tag{4.46}$$

where H^{min} and H^{max} with subscripts 1, 2 and 3 are the lower and upper bounds of rooftop potable water, non-potable water and the underground tanks, respectively.

4.5 CASE STUDY

In addition the case study described in Section 3.5, an integrated RWH-GWR system is proposed in this chapter to improve water savings, reliability and the economic attractiveness of the residential water supply system. The RWH subsystem has a rooftop catchment area of 100 m^2. Its rainfall intensities are obtained from Durban weather station, KwaZulu-Natal. The GWR system collects water from the collection points for treatment, storage and redistribution to end-use points. Two additional non-potable water tanks (i.e. the rooftop non-potable water and underground tanks) are introduced to improve non-potable water consumption and the reliability of water supply system. The potable and non-potable water pumps have similar characteristics in terms of pumping power of 700 W and flowrates of 0.55 m^3/h. Table 4.1 shows the physical parameters of the potable water, non-potable water and underground tanks in the proposed system.

Table 4.1. Physical parameters of the water tanks

Water tanks	Area (m^2)	H^{min} (m)	$h_i(0)$ (m)	H^{max} (m)
T_1	0.5	0.1	0.15	1.0
T_2	0.5	0.1	0.15	1.0
T_3	1.0	0	0	1.5

4.5.1 Water and electricity tariffs

The water and electricity tariffs are given in Sections 3.5.1 and 3.5.2.

4.6 RESULTS AND DISCUSSION

Optimal tank sizing and pump scheduling using the case study in section 4.5 are investigated. Simulations are carried out in MATLAB for an operating cycle of 24 h and sampling time, $t_s = 0.25$ h $= 15$ mins.

4.6.1 Optimal operation of the proposed RWH-GWR system

This section aims at discussing optimal tank sizing and pump scheduling of the proposed RWH-GWR system. Figure 4.2 shows the optimal pump schedule and the corresponding variations in water levels (state variables) when w_1=w_2=w_3=w_4=0.25. The optimal size of the rooftop potable and non-potable water tanks and the underground tank obtained from the simulation results are 220 L, 321 L and 236 L, respectively. In the simulation results, it is seen that the pumps are operated at off-peak and standard TOU periods to maximise financial savings on electricity cost subject to the TOU tariff. It is also observed that the objective of improving the economic feasibility of the proposed system by minimising its capital investments and operational cost is satisfied. High switching frequency of the pumps are not desirable because they increase the operational and maintenance cost of the system due to pump wear and tear, and overcoming the start-up toque of the pumps which are not accounted for in this study. In the optimal pump schedule (see Figure 4.2), u_1 is switched on at 01:45 h and 05:45 h for 15 and 30 mins each to provide sufficient water to meet the morning water demand. The potable water control switch, u_1, is switched off and the water level starts dropping continuously with water demand. Thereafter, u_1 is switched on again at 11:00 h, 15:00 h, 17:00 h and 19:15 h for 15 mins each to supply sufficient potable water required to meet the residential water demand. Similarly, u_2 is operated at 09:45 h, 11:30 h and 19:15 h for 15 mins each to supply sufficient non-potable water required to meet the residential non-potable water demand.

In summary, u_1 and u_2 are control switches (binary decision variables) that control the switching operation of the potable and non-potable water pumps, respectively. These control switches are operated

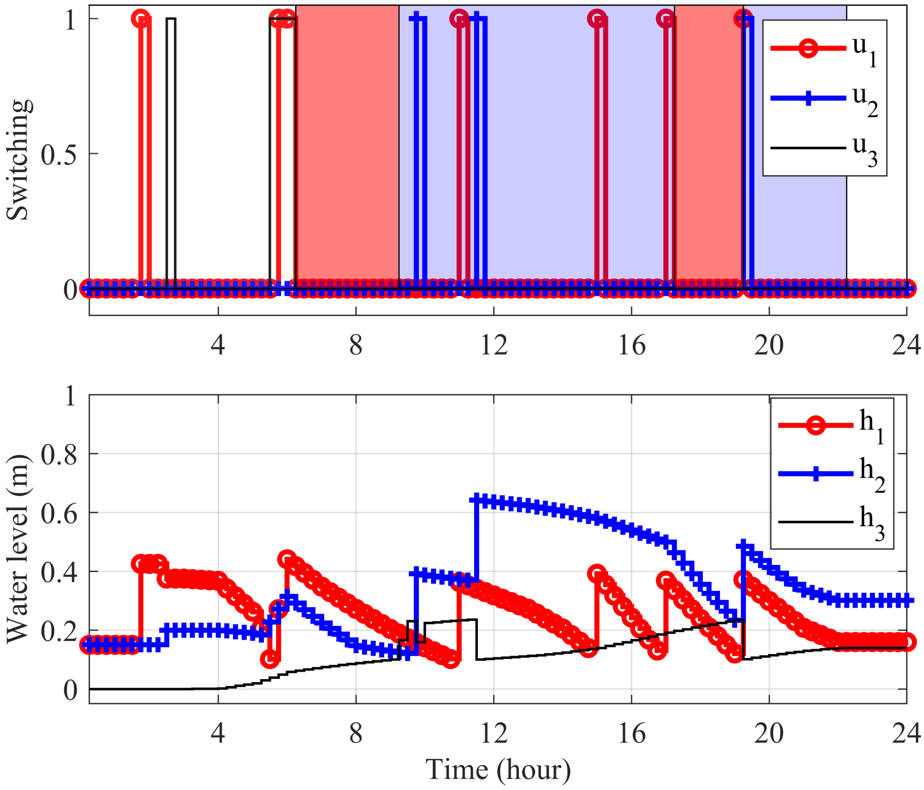

Figure 4.2. Switching operation and water levels of the proposed system

at off-peak and standard TOU periods only to maximise financial savings on pumping operation subject to the TOU tariff. This pumping operation causes a rise in water level that corresponds to the difference between water demand and supply into the tank. The control valve, u_3, is an energy-free binary decision variable that opens to release potable water to the rooftop non-potable water tank when it is empty and unable to meet its demand. It is operated at 02:30 h and 05:30 h for 15 and 45 mins each.

Finally, the optimisation problem is solved without violating the stated constraints. Table 4.2 compares the operational cost of the baseline to the proposed system. It shows that the proposed system has an operational cost savings of 59.35%, 92.70% and -5.55% on the cost of potable water, wastewater released to the treatment plant and electrical energy, leading to a total operational cost savings of 59.70%. This finding agrees with previous studies that increased potable water substitution and non-potable utilisation improve savings and the operational cost of the system [74, 116].

Table 4.2. Operational cost of the baseline vs. the proposed system

	Baseline	Proposed system	Savings (%)
Potable water consumption			
Amount (m^3/month)	41.25	28.875	
Cost (R/month)	1030.208	418.781	59.35
Wastewater discharged			
Amount (m^3/month)	22.688	7.219	
Cost (R/month)	100.292	7.325	92.70
Electrical energy			
Amount (kWh/month)	52.5	52.5	
Cost (R/month)	45.125	47.630	(-5.55)
Operating cost (R/month)	1175.624	473.736	
Operating cost (R/year)	14107.490	5684.832	59.70

4.6.2 Tank sizing and system operation

This subsection compares the performance of optimisation and Rippl methods of tank sizing on the operation of the proposed system.

4.6.2.1 Tank sizing by optimisation

Tank sizing were determined by optimisation using the optimisation model (formulated from (4.12) - (4.25)) and the monthly rainfall parameters collected from the Durban weather station. The optimisation problem was solved by the solving constraints integer programming solver embedded in MATLAB. The simulation results produced optimal storage volumes of 220L and 321L for the potable and non-potable water rooftop tanks, respectively. It is observed that the simulation results produced the same storage volumes for the rooftop tanks for all the monthly simulations because the rooftop tanks are sized to meet the daily residential water demand (seen in Figure 3.2). The simulation results also produced twelve different storage volumes for the underground tank for the varying monthly rainfall intensities. The smallest and largest underground tank sizes were obtained in the months of June and January which are the driest and wettest months of the year, respectively. In this study, the largest tank size is selected to improve the water savings potential, non-potable water utilisation and the reliability of the water supply system. Therefore, the optimal size of the rooftop potable, non-potable water and the underground tanks produced by optimisation are 220 L, 321 L and 374 L, respectively. The simulation results also show that the system operation relative to the TOU period are similar, therefore their operational costs are the same. Figure 4.3 shows the typical switching operation and variations in water levels of the proposed system when the tanks are sized by optimisation.

4.6.2.2 Tank sizing by Rippl method

The Rippl method is a tank sizing technique that is based on the cumulative difference between water demand and supply during the longest period of drought. The resulting tank size will ensure continuous water supply during this period. In this study, the underground tank size using Rippl method is determined using the practices and information obtained from [74, 85]. Table 4.3 shows the Rippl method for sizing the underground tank. The monthly rainfall parameters were obtained from the average monthly rainfall intensities measured at the Durban weather station from the year 2000 – 2010. Monthly rainfall parameters are used in the absence of daily rainfall data. These rainfall data are used to calculate the volume of rainwater collected using (4.7). Similarly, the volume of greywater collected is obtained from the residential potable water demand using (4.8). Therefore, the total non-potable water supply is the sum of the rain and grey water collected. The monthly water demand is determined from the daily water demand profile. The difference between the non-potable

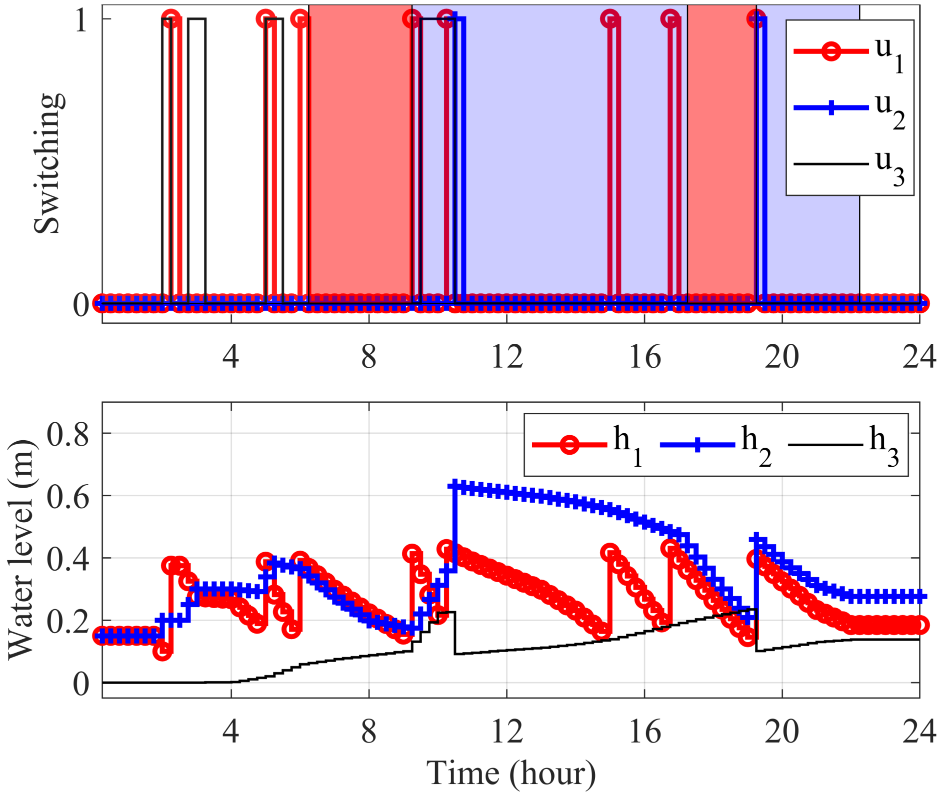

Figure 4.3. Switching and water levels when the underground tank is sized by optimisation

water demand and supplies is water deficit, and the cumulative sum of the water deficits over the period of insufficient non-potable water supply is the size of the underground tank produced by the Rippl method (see (4.10)). In this study, the Rippl method produced an underground tank storage capacity of 1280 L that corresponds to the cumulative water deficits in June and July that are the driest months in Durban, South Africa.

4.6.2.3 Tank sizing and system operation

The tank sizes obtained by optimisation and Rippl methods in Sections 4.6.2.1 and 4.6.2.2 are used to solve for their respective optimal operations. Figures 4.3 and 4.4 show the optimal operation of the proposed system when the underground tank is sized by optimisation and Rippl method, respectively. It was observed that their pumping operations relative to the TOU periods are similar, therefore their operational costs will also be similar. Table 4.4 confirmed that both tank sizing methods have the same operational costs. These lead to the conclusion that the Rippl method is relatively not economical in comparison to the optimisation method because it does not improve the operational cost savings of

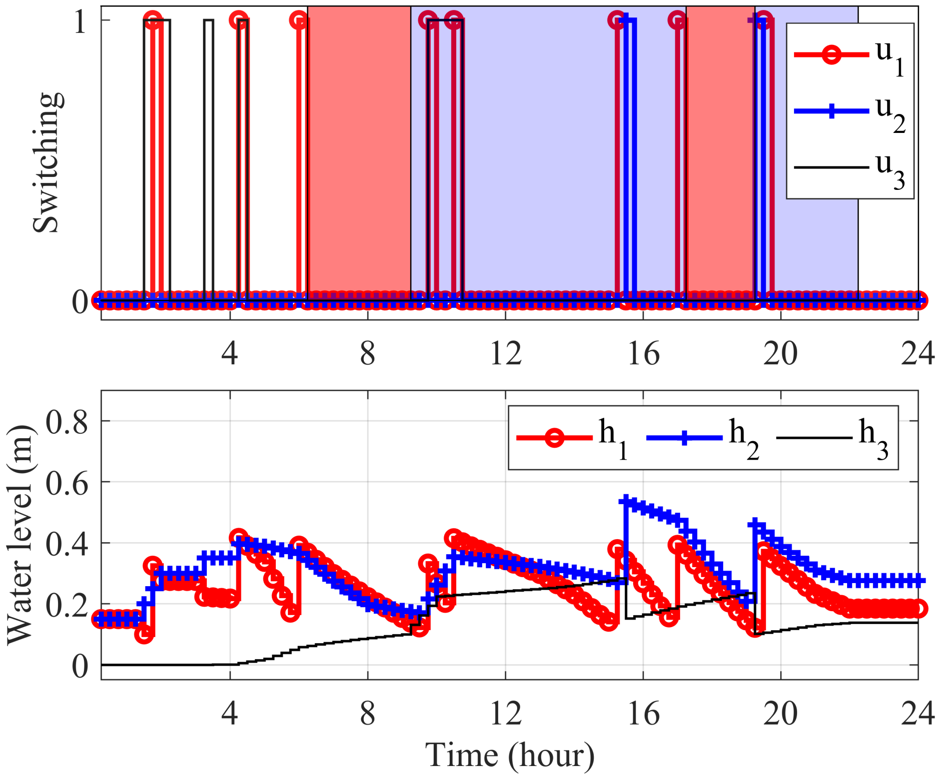

Figure 4.4. Switching and water levels when the underground tank is sized by Rippl method

the system, instead it will further increase the capital cost of purchasing and installing the large tank produced.

4.7 ECONOMIC ANALYSIS

It is important to evaluate the economic feasibility of any project based on the relationship between the cost and revenue components. In this study, the present worth method that discounts future cash flows to their present values is used. It is based on the concept of time value of money, that the present value (PV) of cash flows is worth more than its future value (FV), hence FV of cash flows are discounted to their PVs using discounting factor [131]. Thereafter, the cumulative sum of these PVs forms the net present value (NPV) of cashflows. A project is considered to be economically attractive if its NPV is positive and vice versa. The PV is expressed as [132]:

$$PV = \frac{FV}{(1+r)^n}, \tag{4.47}$$

Table 4.3. Tank sizing using Rippl method

Months	Rainfall (mm)	V$_{rw}$ (m^3)	V$_{gw}$ (m^3)	S$_{npw}$ (m^3)	D$_{npw}$ (m^3)	Water deficit col.5−col.6
Jan.	134	12.06	9.01	21.07	13.11	7.96
Feb.	113	10.17	9.01	19.18	13.11	6.07
Mar.	120	10.80	9.01	19.81	13.11	6.70
Apr.	73	6.57	9.01	15.58	13.11	2.47
May	59	5.31	9.01	14.32	13.11	1.21
Jun.	38	3.42	9.01	12.43	13.11	(0.68)
Jul.	39	3.51	9.01	12.52	13.11	(0.59)
Aug.	62	5.58	9.01	14.59	13.11	1.48
Sept.	73	6.57	9.01	15.58	13.11	2.47
Oct.	98	8.82	9.01	17.83	13.11	4.72
Nov.	108	9.72	9.01	18.73	13.11	5.62
Dec.	102	9.18	9.01	18.19	13.11	5.08
Avg. daily	2.79					
Avg. monthly	84.92					
Total	1019					(1.28)

where r and n are the discount rate and future year, respectively. The NPV is expressed as [133]:

$$NPV = \sum_{n=1}^{m} PV - C_c, \tag{4.48}$$

where C_c and m are the capital cost and the service life of the project, respectively. The payback period is the time it takes the project to repay its capital investment. It is reached when NPV is zero and its expressed as:

$$PBP = m_x + \frac{\alpha}{\beta}, \tag{4.49}$$

where m_x is the last year with negative NPV (α), and β is the PV in the following year ($m_x + 1$). In this study, the capital cost includes the purchasing and installation cost of water tanks, pumps, water

Table 4.4. Operational cost of the proposed system when the tanks are sized by optimisation vs. Rippl method.

	Tank sizing	
	Proposed sys. (Opt.)	Proposed sys. (Rippl)
Potable water consumption		
Amount (m^3/month)	33.00	33.00
Cost (R/month)	601.29	601.29
Wastewater discharged		
Amount (m^3/month)	8.25	8.25
Cost (R/month)	13.52	13.52
Energy consumption		
Amount (kWh/month)	52.5	52.5
Cost (R/month)	47.63	47.63
Operating cost (R/month)	662.44	662.44
Operating cost (R/year)	7949.31	7949.31

treatment and other accessories. Operation and maintenance (O&M) cost are recurrent expenses that ensure the sustainable operation of the project. The operational cost is the annualised cost of potable water consumed, wastewater discharged and electricity consumed seen in Tables 4.2 and 4.4, and the value of the maintenance cost is obtained by subtracting the operational cost from the O&M cost. In this study, it is assumed that the discount rate, water tariff and revenue are constant throughout the service life of the project, while the cost of electricity increases by 15% in the first three years of the project, reduced to 9.6% in the fourth year and assumed to remain constant for the remainder of the project. The service life of the project (m) is 20 years. A discount rate of 5.2%, which is the 2018 inflation rate in South Africa, is used. All cash flows are in South African currency, Rand.

Tables 4.5 and 4.6 show in the initial capital investment and the economic analysis of the integrated RWH-GWR system using the net present value method. In Table 4.6, expenses and revenues are indicated as negative (in bracket) and positive values, respectively. It shows that the proposed system using the average daily rainfall intensity has a PBP of 5.8 years. A comparative economic analysis of the optimisation and Rippl methods of tank sizing was also carried out. The comparative economic analysis shows that the optimisation method used to size the underground tank has a PBP of 8.9 years relative to the Rippl method that has a PBP of 10.5 years. This further confirms that the proposed system is economically feasible, and the optimisation method of tank sizing is economically more attractive than the Rippl method. These findings agree with previous studies [52, 64, 72, 110] that the proposed RWH-GWR system will be more economical with reduced capital cost and increased non-potable water utilisation. Unlike the independent RWH-GWR subsystems that does not repay its initial investment due to the additional capital of separate tanks and treatment kits [4, 52], this study shows that the accurate tank sizing and full water treatment will further improve the economic attractiveness of the connected RWH-GWR subsystem. The economic attractiveness of the proposed RWH-GWR system can be further improved by cost-reflective water and electricity tariffs.

Table 4.5. Initial capital investment

		Tank sizing	
Capital investment	Optimal solution (R)	Optimisation (R)	Rippl (R)
Rooftop tanks (× 2)	3500	3500	3500
Underground tank	1575 (236 L)	2685 (374 L)	7910 (1280 L)
Pumps (× 2)	2480	2480	2480
Water treatment kit	8260	8260	8260
Controller	10050	10050	10050
Accessories	6200	6200	6200
Installation	8200	8200	8500
Total	40265	41375	46900

Table 4.6. Economic analysis using the NPV method

Yr	Baseline (O&M) (R)	Optimal soln (O&M) (R)	Tank sizing (O&M) (R)	Savings (soln) (R)	Savings (sizing) (R)	Disc. Fct.	PV (soln)	PV (sizing)	NPV (Soln)	NPV (Opt)	NPV (Rpl)
0	14675.5	6434.8	8699.3	8222.7	5958.2	1	8222.7	5958.2	(40265)	(41375)	(46900)
1	14738.7	6520.6	8785.1	8218.2	5953.7	0.95	7811.9	5659.4	(32453)	(35716)	(41241)
2	14832.1	6619.2	8883.6	8213.0	5948.5	0.90	7421.1	5375	(25032)	(30341)	(35866)
3	14939.5	6732.5	8997.0	8207.0	5942.5	0.86	7049.2	5104.1	(17983)	(25237)	(30762)
4	15018.6	6816.0	9080.5	8202.6	5938.1	0.82	6697.1	4848.3	(11286)	(20388)	(25913)
5	15105.3	6907.5	9171.9	8197.8	5933.3	0.78	6362.4	4604.9	(4923)	(15783)	(21308)
6	15200.2	7007.7	9272.2	8192.5	5928.1	0.74	6044	4373.4	1120.7	(11410)	(16935)
7	15304.3	7117.6	9382.0	8186.8	5922.3	0.70	5741.2	4153.2	6861.8	(7257)	(12782)
8	15418.4	7238.0	9502.5	8180.4	5915.9	0.67	5453.2	3943.6	12315	(3313)	(8838)
9	15543.4	7370.0	9634.4	8173.5	5909	0.63	5179.2	3744.3	17494	431.1	(5094)
10	15680.5	7514.6	9779.1	8165.9	5901.4	0.60	4918.6	3554.6	22413	3985.8	(1539)
11	15830.6	7673.1	9937.6	8157.5	5893.1	0.57	4670.7	3374.2	27084	7359.9	1834.9

4.8 SENSITIVITY ANALYSIS

Practically, there are uncertainties in input parameters and there is a need to investigate the impact of these uncertainties on the performance of the proposed model. Therefore, sensitivity analysis is an analytical tool that investigates the reliability and robustness of models (systems) to uncertainties in input parameters [19]. It is expressed mathematically as:

$$\xi = \frac{\Delta Y/Y}{\Delta I_p/I_p} \tag{4.50}$$

where ξ is sensitivity, ΔI_p and ΔY are the changes in the input and output parameters. In this study, $\pm 5\%$ uncertainties are applied to the input parameters, this is expressed as:

$$\Delta I_p = I_p \pm 5\% I_p. \tag{4.51}$$

Figures 4.5 and 4.6; 4.7 and 4.8; 4.9 and 4.10 show the optimal operation of the proposed RWH-GWR system to $\pm 5\%$ uncertainties on water demand, rainfall intensity and electricity cost, respectively. Table 4.7 summarises the sensitivities of the proposed model to $\pm 5\%$ uncertainties on water demand, rainfall intensity, electricity pricing and discount rate. It also shows the percentage change in the size of the water tanks due to these uncertainties.

Table 4.7. Summary of sensitivity analysis

Quantity	ξ	ΔT_1	ΔT_2	ΔT_3
Water demand (+5%)	1.53	31.94	-3.54	5.25
Water demand (-5%)	-0.094	3.79	3.47	-5.26
Rainfall (+5%)	0.17	0	0	5.33
Rainfall (-5%)	0.17	0	0	-5.33
Electricity cost(+5%)	0.082	0	0	0
Electricity cost(-5%)	0.25	0	0	0
Discount rate (+5%)	-0.40	–	–	–
Discount rate (-5%)	-0.41	–	–	–

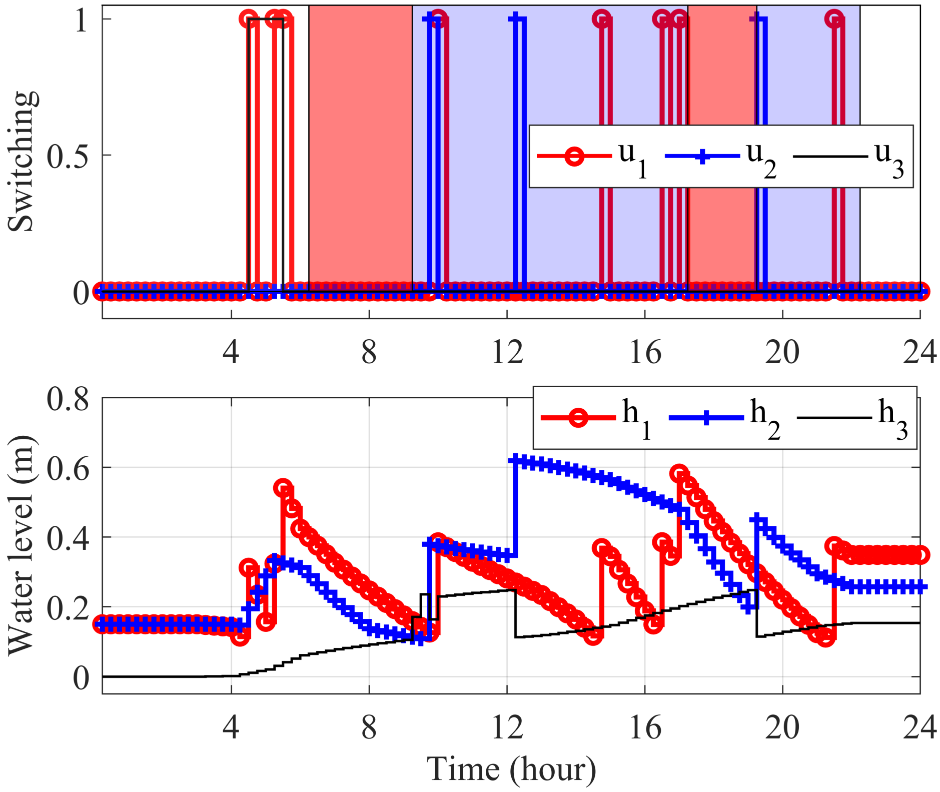

Figure 4.5. Simulation results at +5% uncertainty on water demand

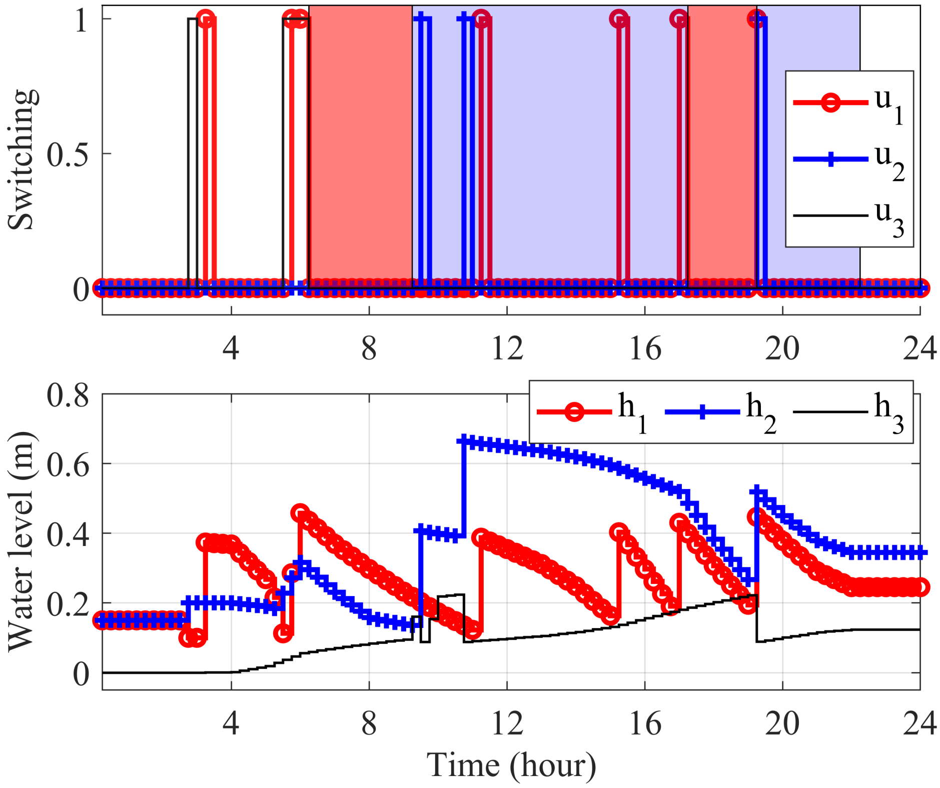

Figure 4.6. Simulation results at −5% uncertainty on water demand

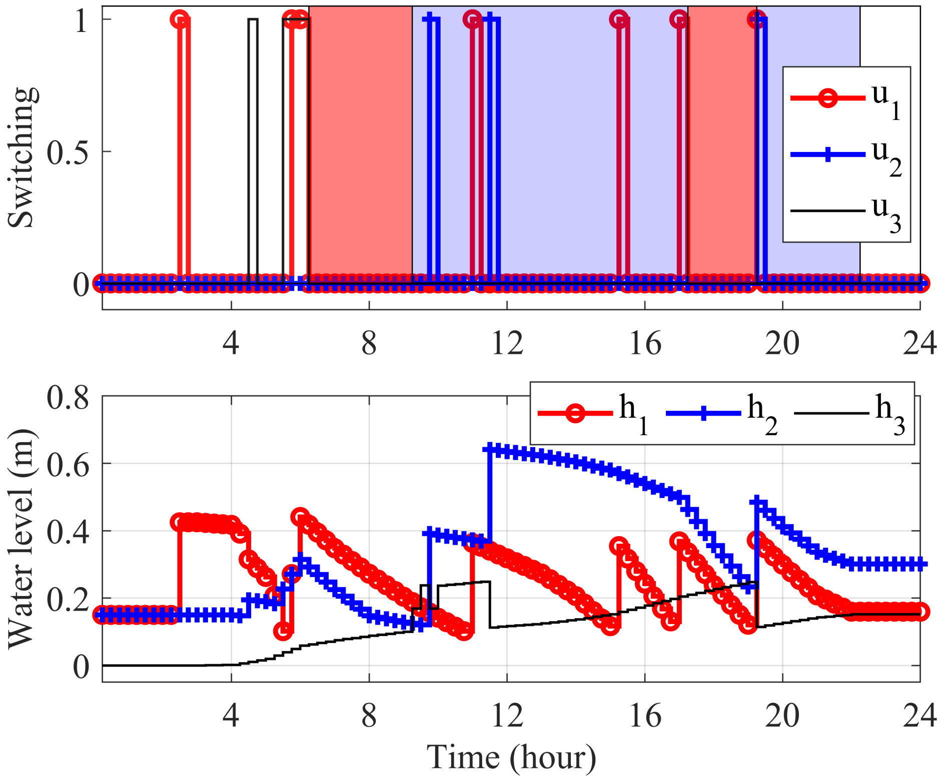

Figure 4.7. Simulation results at +5% uncertainty on rainfall intensity

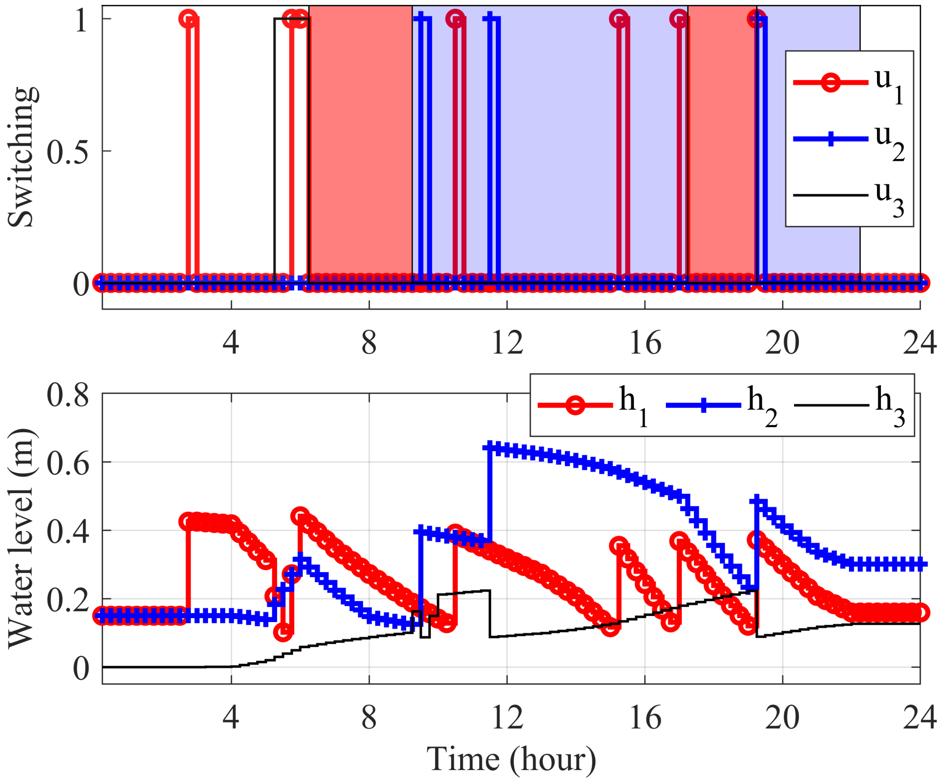

Figure 4.8. Simulation results at −5% uncertainty on rainfall intensity

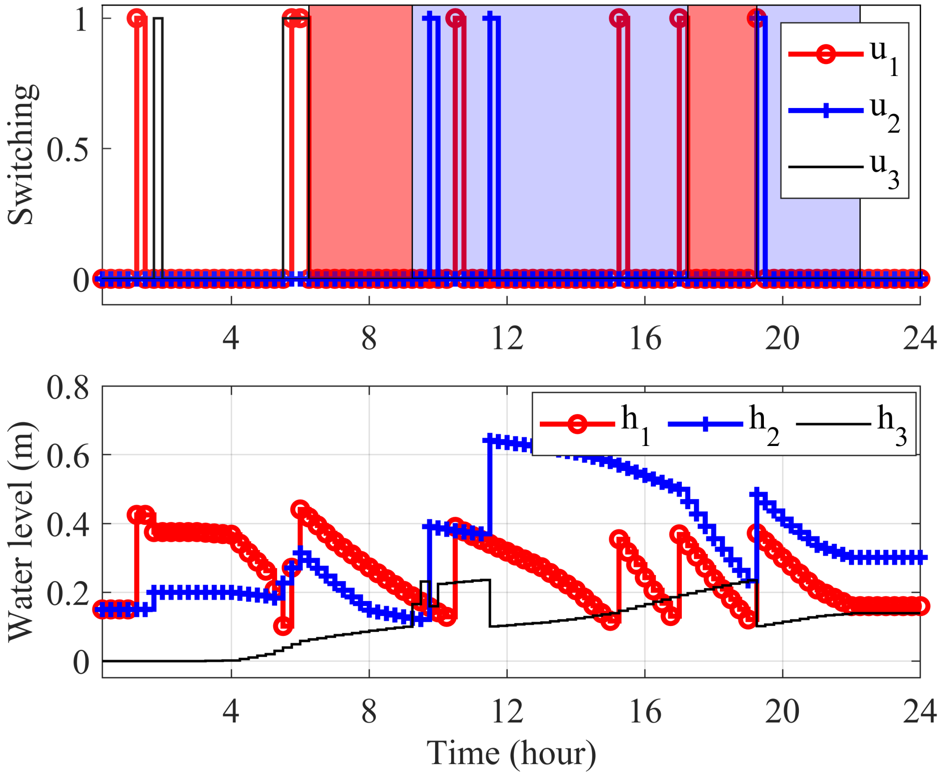

Figure 4.9. Simulation results at +5% uncertainty on electricity pricing

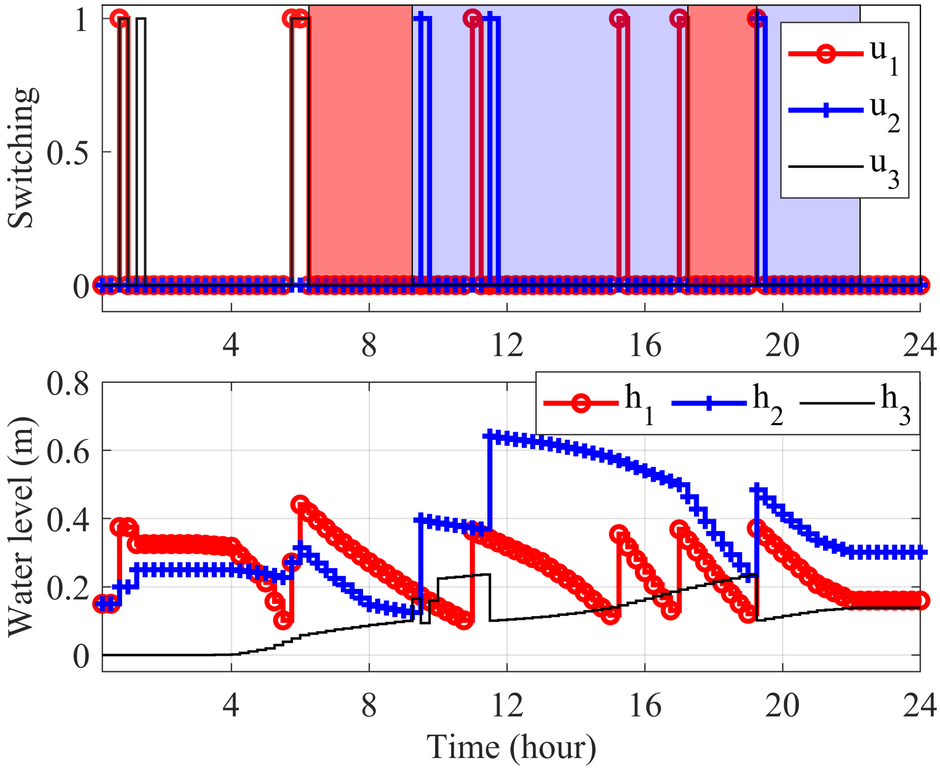

Figure 4.10. Simulation results at −5% uncertainty on electricity pricing

In conclusion, visual comparison of Figure 4.2 to Figures 4.5 - 4.10 shows close similarities between the optimal operation of the proposed system with and without uncertainties. It is observed that the pumps are operated at different times of the day but their switching frequencies with respect to the TOU period are the same. However, a $+5\%$ uncertainty on water demand caused the switching frequency of the potable water pump to increase from seven to eight within 24h operating cycle. Table 4.7 shows the robustness of the system to uncertainties on the input parameters. This table also shows that the proposed system is most robust to $+5\%$ uncertainty on the cost of electricity and least robust to $+5\%$ uncertainty in water demand, therefore changes in the water demand can cause significant uncertainty on the performance of the system, therefore it should be monitored carefully.

4.9 CHAPTER SUMMARY

A multi-objective optimisation problem that is essentially a mixed binary linear programming problem with the objectives of minimising the storage volume of the water tanks and operational cost of the residential RWH-GWR system is formulated subject to technical and operational constraints based on a practical case study of a single-family building in Durban. The simulation produced optimal tank sizes of 220 L, 321 L and 236 L for the rooftop potable water, non-potable water and underground tanks, respectively. The optimal pump schedule produced caused operational cost savings of 59.35% and 92.70% on potable water consumption and wastewater recycled, respectively, leading to a total operational cost savings of 59.70%. Economic analysis showed that the proposed residential RWH-GWR system has a PBP of 5.8 years, therefore it is economically attractive. Comparative performance and economic analyses of the optimisation and Rippl method of tank sizing were carried out. The optimisation method for tank sizing produced an underground tank storage volume of 375 L and the Rippl method produced an underground tank size of 1280 L, however, the storage volume produced by the Rippl method does not affect the operational cost of the system instead it increases the initial capital investment of the system. The comparative economic analysis showed that the proposed residential water supply system when the underground tank is sized by optimisation and Rippl methods, separately, has a PBP of 8.9 years and 10.5 years, respectively. Therefore, the optimisation method for tank sizing is more economical than the Rippl method. Sensitivity analyses are carried out to evaluate the robustness of the proposed model to changes in input parameters such as water demand, rainfall intensity, electricity tariff and discount rate. Therefore, this study concludes that optimal tank sizing, system operation and increase non-potable water utilisation will improve the economic attractiveness of the proposed RWH-GWR system. The economic attractiveness of the proposed system can be further enhanced through cost-reflective energy and water tariffs, government policies, regulations, subsidies and incentives to promote the penetration of alternative water supply in residences.

CHAPTER 5 CONCLUSION

5.1 CHAPTER OVERVIEW

This is the concluding chapter of this dissertation. Chapters 1, 2, 3 and 4 are summarised in Section 5.2. The operational cost savings and economic analysis of the optimal pump scheduling strategy are presented. Similarly, the operational cost savings and economic analysis of the proposed RWH-GWR system are also presented. Finally, future works and recommendations are given in Section 5.3.

5.2 RESEARCH CONCLUSIONS

Chapter 1 presents an introduction to this research. It contains the problem statement, research objectives, questions, goals, hypothesis, approach and contributions. Chapter 2 presents a literature survey that establishes the existing body of knowledge on energy demand management, water demand management, tank sizing and energy-water nexus. Research gaps were also identified. Chapter 3 presents a BILP model to improve the operational cost savings of optimal pump scheduling in a pumped-storage residential water supply system. Chapter 4 presents a mixed binary linear programming model for optimal tank sizing and operation of integrated RWH-GWR system. The contributions of this chapter include: (1) restructuring and modelling the proposed RWH-GWR system to ensure complete water treatment before storage to improve the duration of water storage, water utilization and reliability, (2) optimal tank sizing and operation to improve the economic attractiveness of the proposed RWH-GWR system, (3) comparative analysis of the optimization and Rippl methods of tank sizing, (4) economic feasibility of the proposed system, and (5) sensitivity analysis to evaluate the robustness of the proposed model to uncertainties in input parameters.

The simulation results in Chapter 3 showed an energy cost savings of 18.31%. However, the LCCA revealed that the proposed strategy does not pay back the capital cost of the system in its lifetime. Therefore, an optimal tank sizing and operation of integrated RWH-GWR system is proposed in Chapter 4 to improve the economic attractiveness of residential water supply system. The proposed RWH-GWR system will also improve non-potable water utilisation and water savings. Comparative analysis showed that the proposed RWH-GWR system produced a potable water cost savings of 59.35%, recycled wastewater cost savings of 92.70%, leading to a total operational cost savings of 59.70% relative to the optimal pump scheduling strategy in Chapter 3. Economic analysis showed that the proposed RWH-GWR system has a PBP of 5.8 years, which is an improvement in the economic analysis of the optimal pump scheduling strategy in Chapter 3. Holistically, when compared to the original pump schedule of the residential potable water supply system in Chapter 3, the proposed RWH-GWR system produced an energy cost savings of 18.3%, potable water cost savings of 59.35%, recycled wastewater cost savings of 92.70%, leading to a total operational cost savings of 59.70%.

5.3 FUTURE WORKS

Although the objectives of this research have been met, there are still rooms for improvement. This work can be further improved with:

1. The use of variable speed pumps to optimise the use of renewable energy such as solar photovoltaic and wind turbine that is intermittent.
2. Future research should investigate stand-alone residential RWH-GWR system.
3. Furthermore, the start-up operational and maintenance cost of the pumps should be considered in subsequent studies.

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