OPTIMIZATION MODEL OF LARGE SCALE RAINWATER HARVESTING SYSTEM

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To my dearest husband, parents, children and family:
Whose love have nourished and sustained me always.

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ABSTRACT

Rapid urbanization, population growth, and industrialization are contributing to the large-scale increase of water demand in Malaysia. The present scheme of inter-state water transfer to meet the increasing demand is unsustainable. It is expected that Johor, Malaysia will face water shortages after 2025. Hence, a new source of water needs to be identified to meet the water demand. Many studies have been done to tackle the issue of water shortage using small scale rainwater harvesting. However, there should be a study on large scale rainwater harvesting systems (LSRWHS) that could provide better economic and environmental benefits because of the ability to mitigate both water scarcity and flood issues in urban areas. An optimization model for systematic design and planning to determine the optimal sizing and network design for LSRWHS to meet the regional supply-demand distribution at minimum cost has been proposed in this research for variation of water supply and demand. A case study of Nusajaya, Johor with the rainfall daily data for 20 years collected from 200 houses rooftop was employed in this research. This thesis introduces three main contributions. (1) A methodology to determine an optimal water storage tank and total outsourced water utility supply required using a new numerical technique (graphical technique) named as Rain Water Harvesting Pinch Analysis (RAGPA). (2) A mathematical model approach to determine an optimal water storage tank to satisfy consistent water demand. The results in the first and second objectives were then used to validate the effectiveness of both methodologies. (3) A spatial planning and scheduling mathematical model for LSRWHS to satisfy inconsistent water demand and determine an optimal location for the construction of LSRWHS. It was found that the optimal size of storage tank based on 20 years rainfall data was 617 m^3 using a numerical method and as proposed in the first methodology. This finding shows a very good agreement using the mathematical method with less than 2% error. For third methodology result, it was found that the minimum cost system was RM 475 437 with the optimal size of storage tank 727 m^3.The optimizer tend to selects location with the shortest distance of pipe length and larger area as the optimal location for LSRWHS. Sensitivity analysis was further performing by modifying the water demand, roof area collection and water utility cost. The result generated shows area of rooftop and water demand play an important role in the economic analysis. The application of all new methodologies has demonstrated the applicability of the model to design an optimal rainwater harvesting system to face water scarcity problem in future and provide relatively clean, reliable water to people in need.

ABSTRAK

Pembangunan pembandaran yang pesat, pertumbuhan penduduk, dan perindustrian telah menyumbang kepada peningkatan keperluan air di Malaysia. Program yang sedang diusahakan kini iaitu penyaluran sumber air antara negeri untuk memenuhi keperluan penduduk adalah tidak ekonomi. Johor dijangka akan menghadapi kekurangan bekalan air pada tahun 2025. Maka, satu inisiatif sumber air yang baharu perlu dikenalpasti untuk memenuhi permintaan keperluan air. Terdapat banyak kajian yang telah dijalankan untuk mengatasi masalah kekurangan bekalan air dengan menggunakan sistem pengumpulan air hujan pada skala yang kecil. Walau bagaimanapun sepatutnya ada kajian terhadap sistem pengumpulan air hujan pada skala besar (LSRWHS) yang dapat memberikan kebaikan yang lebih besar dari segi ekonomi dan alam sekitar kerana kebolehannya untuk mengatasi masalah banjir dan kekurangan bekalan air di kawasan bandar. Dalam kajian ini, model yang optimum untuk reka bentuk dan perancangan sistematik dalam menentukan saiz optimum dan reka bentuk rangkaian LSRWHS yang dapat memenuhi pengagihan bekalan permintaan serantau pada kos minima telah dicadangkan bagi bekalan dan permintaan air yang berbeza. Kajian kes Nusajaya, Johor dengan data taburan hujan selama 20 tahun yang dikumpulkan daripada 200 buah rumah telah digunakan dalam penyelidikan ini. Tesis ini memperkenalkan tiga sumbangan utama. (1) Satu kaedah untuk menentukan tangki simpanan air optimum dan jumlah bekalan utiliti air dari sumber luar yang diperlukan melalui teknik berangka baharu (teknik grafik) yang dinamakan Analisis Jepit Pengumpulan Air Hujan (RAGPA). (2) Pendekatan model matematik bagi menentukan saiz optimal sistem pengumpulan air hujan untuk memenuhi keperluan bekalan air yang konsisten. Keputusan daripada objektif pertama dan kedua ini dibandingkan untuk disahkan keberkesanan kedua-dua kaedah ini. (3) Perancangan ruang dan penjadualan model matematik bagi LSRWHS untuk memenuhi permintaan air yang tidak konsisten dan menentukan lokasi yang optimum bagi pembinaan LSRWHS. Melalui teknik berangka seperti cadangan yang pertama, didapati saiz tangki yang optimum bagi sistem pengumpulan air hujan ialah 617 m^3 berdasarkan 20 tahun data taburan hujan. Dapatan ini menunjukkan kebersamaan yang sangat baik dengan kaedah matematik dengan ralat kurang daripada 2%. Melalui keputusan kaedah yang ketiga, didapati kos sistem yang minima ialah RM 475 437 dengan saiz tangki yang optimum 727 m^3. Analisis sensitiviti telah dijalankan lebih lanjut dengan mengubah jumlah keperluan bekalan air, keluasan atap rumah dan harga bekalan utiliti air. Keputusan menunjukkan keluasan atap rumah dan bekalan utiliti air menjadi faktor yang penting didalam analisis ekonomi. Penggunaan semua kaedah baharu ini telah menunjukkan kebolehan model ini untuk mereka bentuk sistem pengumpulan air hujan yang optimum bagi menghadapi masalah bekalan air pada masa akan datang dan menyediakan sumber air yang bersih, dan mencukupi untuk keperluan manusia.

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LIST OF ABBREVIATIONS

AWER	-	Association of Water and Energy Research Malaysia
BMPs	-	Best management practices
DID	-	Department of Irrigation and Drainage
FOMCA	-	Federation of Malaysian Consumers Associations
GAMS	-	General Algebraic Modelling System
GCC	-	Grand Composite Curve
KeTTHA	-	Kementerian Tenaga, Teknologi Hijau dan Air
KTAK	-	Ministry of Energy, Water and Communication
LCCA	-	Life cycle cost analysis
LP	-	Linear Programming
LSRWH	-	Large scale rainwater harvesting
RWHS	-	Rainwater Harvesting System
MCM	-	million cubic meters per annum
MLD	-	Million liters per day
MILP	-	mixed integer linear programming
MOSTI	-	Ministry of Science, Technology and Innovation
NAHRIM	-	National Hydraulic Research Institute Malaysia
NRW	-	Non-revenue water
NRE	-	National Resources Environment
OFM	-	on-farm reservoir
PoPA	-	Power Pinch Analysis
RAWHPANS	-	Rainwater Harvesting Pinch Analysis System
SIRIM	-	Scientific and Industrial Research Institute of Malaysia
SPAN	-	National Water Services Commission
YAS	-	yield after spillage

LIST OF SYMBOLS

Coef	-	Roof Coefficient
CPiPCOST	-	Capital cost for Pipe System
CPumPCOST	-	Capital Cost for Pump System
CSTORE	-	Capital cost for storage Tank
FF	-	First Flush system
LOCDistance	-	total length for piping system (m)
N	-	Life span for the system
OMCOST	-	Operating and maintenances cost
PipeCOST	-	Piping cost system (RM/km)
Qstore	-	Storage Tank Volume
Rain	-	Rainfall depth (mm)
Roof	-	Roof area (m^2)
RW	-	Rainwater volume (m^3)
RWacc_after	-	Rainwater accumulated after it was transferred to the demand side
RWacc_before	-	Rainwater accumulated before it was transferred to the demand side
RWAC	-	Rainwater accumulated
RWC	-	Rainwater cumulative (m^3)
RWCD	-	Cumulative different volume of rainwater (m^3)
RWsupp	-	Rainwater Supply
SLj	-	Binary variable for selection of storage location
Storage	-	Storage Tank Size (m^3)
T	-	Time period
TOTout	-	Total outsources water (m^3)
TOTCOST	-	Total Cost system (RM)

UCOST	-	Water Utility Cost
VWAT	-	Volume for water utility
WATUPrice	-	Water utility Price
WD	-	Water Demand (m^3)
WUTL	-	Water Utility Volume

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CHAPTER 1

INTRODUCTION

1.1 Introduction

World's population is persistently increasing and so is the water demand. Demand on water resources has increase day by day due to the population growth and expansion in urbanization, industrialization and irrigated agriculture. High number of population could be the cause of water shortage problem. By optimizing water usage and the conservation of water as a natural resource, this problem could be solved. Adopting the concept of sustainability and conservation of water resources can help to deal with global water shortage. This chapter introduces the research background that includes the outlook of world's rainwater harvesting system, and Malaysia's implementation in development for sustainability, followed by the problem statement. Next, the objectives and scopes of this study focus on the development of a novel optimization model for a large-scale rainwater harvesting system. Finally, this chapter highlights the significance of this study towards the optimization of large-scale rainwater harvesting system in Malaysian region, and other cities as a whole.

1.2 Research Background

1.2.1 World Overview on Rainwater Harvesting

In most urban areas, population is increasing rapidly and the issue of supplying adequate water to meet societal needs is one of the most urgent and significant challenges faced by decision-makers. Among the various alternatives of technology to augment freshwater resources, rainwater harvesting is environmentally sound, which can avoid many environmental problems. Rainwater harvesting (RWH) is proposed as the concept of accumulation and deposition of rainwater for use instead of allowing it to runoff. It is a good option in areas where good quality fresh surface water or groundwater is lacking. The application of appropriate rainwater harvesting technology is important for the utilization of rainwater as a water resource. RWH systems are able to simultaneously address the water scarcity problem and reduce the dependence on domestic water supply (Gois *et al.*, 2014; Sample and Liu, 2014; Thomas *et al.*, 2014; Unami *et al.*, 2014; Morales-Pinzon *et al.*, 2015).

The United Nations Environment Programme (2015) has reported that there are a number of cities around the world which implements rainwater harvesting system project. For example in Tokyo, to overcome water shortages, control floods, and secure water for emergencies, rainwater harvesting system is utilized in the Ryogoku Kokugikan Sumo-wrestling Arena, in Sumida City. The rainwater is collected from the 8,400 m^2 rooftop of this arena and drained into 1,000 m^3 of underground storage tank which is used for toilet flushing and air conditioning. Rainwater utilization system in Tokyo has been introduced in many new public facilities due to the successful project in Kokugikan. Meanwhile in Korea, a successful rainwater harvesting project is featured in the Star City, Seoul Korea. The construction was completed in April 2007 with a 3000 m^3 rainwater tank decentralized rainwater harvesting system that is used for department stores and four apartment blocks. Rainwater from the rooftop is collected to the basement storey block where three separate storage tanks, each of 1000 m^3 capacity is situated The rainwater is used in water saving, flood mitigation and emergency response. With the success of Star City rainwater harvesting system, it has influenced 47 cities across South Korea, including Seoul, to enact regulations on rainwater management (Han and Mun, 2011).

In Singapore, limited land resources and a rising demand for water has led to the construction of applied rainwater harvesting system as an alternative source. The utilization of rainwater harvesting system that exists in Changi Airport shows the largest practicing system in Singapore. Rainfall from the runways and surrounding is diverted into two impounding storage tank systems. One is designed to collect the rainfall while the other storage tank is used to balance the flow during the coincident high runoffs. The rainwater is used primarily for non-potable uses such as toilet flushing and fire-drills. The rainwater harvesting system gives approximately 33% of water saving (Gustaf, 2015).

In Malaysia, the government has been promoting the use of RWH system since 1999. With the recent increasing of water shortage and rationing events, RWH has started to gain its practical application. For the support of the Government's interest in rainwater harvesting, NAHRIM (National Hydraulic Research Institute Malaysia) through its collaboration with other government agencies, has been pursuing R&D on rainwater harvesting with focus on system design and installation cost, system performance, system operating and maintenance cost, unit cost, effectiveness in reducing the urban flash flood problems, policies by-laws and proposing incentives for system implementation. Consequently, NAHRIM has carried out three main pilot projects for small-scale rainwater harvesting, which include a double-storey terrace house located and a mosque complex (Feng and Shanahan, 2003). Based on the pilot project conducted by NAHRIM, software called TANGKI NAHRIM was created to determine the optimal sizing of rainwater storage tank system and its reliability, total volume of collected and distributed rainwater, and rainwater system efficiency. It is beneficial to researchers and engineers to design an accurate and suitable rainwater system since it has the whole Malaysian rainfall data in its database software. However, TANGKI NAHRIM software have some limitations which are determination of minimum cost system for rainwater installation, daily rainwater trend used, water utility used, water excess and daily amount of rainwater collected and stored in the storage tank. Hence, with the model development from this study, all the limitations have been achieved and improved. However, deducing from the previous studies, rainwater harvesting systems in Malaysia are available only in small-scale, usually installed for a household utilization. Nevertheless, with abundant of rainfall, the Malaysian Government should also consider implementing large-scale rainwater harvesting system as an alternative source for clean water. Therefore, a large-scale rainwater harvesting system (LSRWHS) in Malaysia is beneficial to deal with water scarcity problem in the future.

1.2.2 Problem Statements

Rainwater is a clean source of water and the quality of rainwater is often better than ground water or water from rivers and basins. Rainwater can easily be used for irrigation purposes without damaging plants and roots. It is expected by South Johor Earth Region that Wilayah Iskandar will face water shortages after 2025. Hence, a new source of water needs to be identified to meet the demand. LSRWH is a promising alternative for exploring the abundant rainfall in the tropic. It can simultaneously solve the most pressing water security issues in urban areas— water shortage and flash flood. Followings are the gap identified on rainwater harvesting system design and optimization.

1) Small-scale rainwater harvesting has gained importance as the government started to include legislation that new buildings have to take into account on how they deal with run-off water. However, small-scale rainwater harvesting has some drawbacks; one of it is the storage size. In a small-scale system, during a heavy downpour, the collection system may not be able to hold all rainwater which ends up flowing into drains and rivers.

2) Total outsourced water supply should be determined while planning the water supply system. It is important to know the exact amount of outsourced water supply for a specific daily time period, instead of a monthly time period. The optimal storage tank size can be determined if the best time to supply outsource water has been known. In addition, considering a bigger time period may lead to oversized storage tank system.

3) Recent studies had focused on small-scale systems. Since most of the systems applied were small-scale systems, the spatial location for storage tank system was not included in designing the rainwater harvesting system. Optimal spatial location involves determining the location of storage tank system to be installed. For a large-scale system, spatial location determination is one of the main factors in designing and optimizing rainwater harvesting systems. Hence, the limitation of the small-scale can be overcome through this research.

A LSRWHS involves a comprehensive system planning and design, covering rainwater source collection (roof) to the storage, sizing the storage tank system, distribution, and spatial location system. Hence, this research aims to develop a planning model to determine the optimal storage tank sizing system of rooftop collection, the best time to supply outsourced water utility and optimal spatial location to meet the regional supply-demand distribution network.

1.3 Objectives of the Study

The objective of this study is to develop an optimization model for systematic design and planning to determine the optimal sizing and network design for LSRWHS to meet the regional supply-demand distribution at minimum cost.

In order to achieve the ultimate goal, three specific objectives are included in this research:

1) To develop a new numerical technique (graphical technique) to determine the optimal storage tank size system and the best time to supply outsourced water utility.
2) To develop a mathematical model for optimal storage tank size to satisfy consistent water demand.
3) To develop a spatial planning and scheduling system for a large-scale rainwater harvesting unit to satisfy inconsistent water demand, along with the optimal location. Planning and scheduling system covers how the system will supply water if the rainwater is not enough to meet the demand, and the best time to supply outsourced water utility.

1.4 Scopes of the Study

This study is conducted on a rainwater harvesting system in Wilayah Iskandar, Johor Malaysia. This study focuses on a large-scale rainwater harvesting system. The relevant process data was extracted from the rainfall data and roof area in Nusajaya, Johor to produce a set of base case data. Sensitivity analysis is conducted to establish the current performance of the system and to determine the location and size of the storage tank for rainwater harvesting. An optimization software package, GAMS is used to carry out the optimal design of rainwater harvesting system and optimal location for the system in Nusajaya, Johor Malaysia. The models for optimum large-scale rainwater harvesting system are coded in optimization software, General Algebra Modelling System (GAMS) version 23.2 and solved with CPLEX solver.

To achieve the intended research objective, some of the scopes are carried out as following:

1. Literature review and analysis on the current water issues and research gap in rainwater harvesting system in the aspect of development, process optimization and designing system.

2. Collecting rainfall data of 20 years from Jabatan Pengairan dan Saliran Negeri Johor.

3. Developing an optimization model with General Algebra Modelling System (GAMS) software for mathematical modeling and numerical analysis by applying the pinch analysis concept.

4. Targeting and selecting the potential location to install the storage tank system in Nusajaya as a case study due to the land availability.

5. Performing sensitivity analysis on case studies to evaluate economic and technical performances of the model system.

1.5 Significance of the Study

The optimum large-scale rainwater harvesting system can act as an aid system to the optimal design of a storage tank, as well as scheduling and planning for the water distribution system. Although this study focuses in Wilayah Iskandar, Johor, it also can be implemented throughout Malaysia or any country. In this study, scheduling and planning for a rainwater harvesting system is developed by using a mathematical model to meet the water demand at minimum cost. Scheduling and planning term was referring to the best time to supply rainwater and the optimum volume of rainwater that should be supply to the demand side. Large-scale rainwater harvesting system can reduce the dependence and demand of public water supply which comes from a dam reservoir. Hence, it can also contribute in overcoming water shortage problems that is forecasted to happen in 2025 by fully utilizing a rainwater harvesting system when rainwater is available and save water from the dam reservoir. The idea is to only use water from the reservoir during prolonged drought and when rainwater is not available. The expenses can be minimized since rainwater is freely accessible in Malaysia and the cost for installing this system is much more economical comparing to the new dam reservoir. By doing so, it can also delay water shortage problems in the future.

On the other hand, this study is **unique** because

- It deals with tropical rainfall which behaves very differently from the temperate rainfall.
- Establishment of community-based LSRWHS in urban areas that enables companies to sell treated water to main water distributors
- Simultaneously address water shortage and flood problems as the two most pressing water security issues

1.6 Thesis Outline

Overall, this thesis consists of 7 chapters. Chapter 1 gives an introduction to the research background, objectives, scopes and contribution to rainwater harvesting system. Chapter 2 on the other hand, describes the role of the rainwater harvesting system towards the community, state-of-art and the fundamentals of rainwater harvesting system optimization and modeling, as well as the literature to provide better understanding on rainwater system related works and technology. Chapter 3 describes the general and detailed methodology of this study, including both numerical analysis, as well as mathematical modeling. Chapter 4, 5, and 6 present the development of the optimization technique and the results generated based on case studies. Chapter 4 discusses the numerical analysis of the system while serving as a fundamental understanding on the operation of rainwater harvesting system prior to the development of a mixed integer linear programming (MILP) model. Chapters 5 discusses the MILP mathematical model which will be compared with the numerical analysis technique for the validation, while Chapter 6 performs a model for the selection of optimal location for rainwater harvesting system that can accommodate the limitations of economic factor when sizing the rainwater storage tank system. Finally, Chapter 7 summarizes all chapters, and recommends possible future works to improve or extend the findings from this study.

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