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**THESIS:**  
**RAINWATER HARVESTING SYSTEM (RWHS) AS  
POTENTIAL ADAPTATION STRATEGY FOR  
WATER, SANITATION AND HYGIENE (WASH) IN  
THE VIETNAMESE MEKONG DELTA:  
A CASE OF BINH DAI, BEN TRE**

Author:

**Nguyen, Huu Minh Tri**



Supervisor(s):

**Dr.-Ing. Jens-Uwe Wiese**

**Dr. Doan Van Binh**

Water Technology, Reuse and Management Master Program  
of  
Technische Universität Darmstadt  
and  
Vietnamese – German University

**December 13<sup>th</sup>, 2022**



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## TABLE OF CONTENTS

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<b>TABLE OF CONTENTS</b> .....	i
<b>ACKNOWLEDGEMENT</b> .....	i
<b>AFFIDAVIT</b> .....	i
<b>LIST OF ABBREVIATIONS AND ACCRONYMS</b> .....	I
<b>LIST OF FIGURES</b> .....	II
<b>LIST OF TABLES</b> .....	III
<b>ABSTRACT</b> .....	1
<b>1. INTRODUCTION AND LITERATURE REVIEW</b> .....	3
<b>1.1 INTRODUCTION</b> .....	3
1.1.1 Climate Change and Salinity Intrusion .....	3
1.1.2 Water Scarcity .....	4
1.1.3 Research Objective .....	8
<b>1.2 LITERATURE REVIEW</b> .....	9
1.2.1 Salinity Intrusion Mechanism: Behaviors, Causes, and Effects .....	9
1.2.2 Precipitation Trends in VMD .....	12
1.2.3 Rainwater Harvesting Systems and Practices .....	16
<b>2. DATA AND METHOD</b> .....	24
<b>2.1 Study Area</b> .....	24
2.1.1 Ben Tre .....	24
2.1.2 Binh Dai District .....	26
<b>2.2 Data Collection</b> .....	27
<b>2.3 Method</b> .....	29
2.3.1 Rainwater Assessment .....	29
2.3.2 Water Quality Analysis and System Design .....	31
2.3.3 Cost-benefits Analysis .....	33
<b>3. RAINWATER ASSESSMENT</b> .....	36
<b>3.1 Rainwater Quantity Assessment</b> .....	36
3.1.1 Findings: Water Consumption and Sufficiency .....	36
3.1.2 Dataset Selection and Bias Correction .....	39
<b>3.2 Rainwater Quality Assessment</b> .....	49
3.2.1 Current Rainwater Harvesting Practices .....	49
3.2.2 Rainwater Quality Aspects .....	52

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4. RAINWATER HARVESTING SYSTEM.....	54
4.1 Rainwater Harvesting and Guiding Principle.....	54
4.2 Catchment, Conveyance, and Storage Module.....	59
4.2.1 Catchment Consideration .....	59
4.2.2 Conveyance Consideration .....	61
4.2.3 Storage Consideration .....	63
4.3 Treatment Module .....	71
4.3.1 Available Rainwater Treatment Technology.....	71
4.3.2 Treatment Recommendation.....	75
4.4 Overall Design.....	76
5. COST-BENEFIT ANALYSIS AND RECOMMENDATION .....	79
5.1 Cost-benefit Analysis .....	79
5.1.1 Cost and Benefit Breakdown.....	79
5.1.2 Present Value, Payback Period, and Benefit-cost Ratio .....	82
5.2 Discussion and Recommendation.....	85
5.2.1 Perceived Investment Willingness.....	85
5.2.2 Climate Change Contingency.....	88
5.2.3 Expandability and Future Outlooks.....	91
5.3 Conclusion.....	92
<b>REFERENCES</b> .....	95
<b>APPENDIX</b> .....	107

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## AFFIDAVIT

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Thesis Statement pursuant to § 22 paragraph 7 of General Examination Terms (GET) of the Technische Universität Darmstadt

I herewith formally declare that I, Nguyen Huu Minh Tri, have written the submitted thesis independently pursuant to § 22 paragraph 7 of General Examination Terms of the TU Darmstadt. I did not use any outside support except for the quoted literature and other sources mentioned in the paper. I clearly marked and separately listed all of the literature and all of the other sources which I employed when producing this academic work, either literally or in content. This thesis has not been handed in or published before in the same or similar form.

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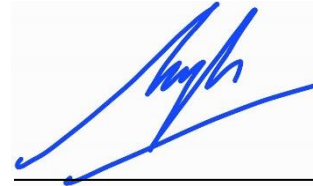
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## LIST OF ABBREVIATIONS AND ACCRONYMS

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AME: Absolute Mean Error

CDCF: Cumulative Discounted Cash Flow

CDR: Climate Data Record

COD: Chemical Oxygen Demand

CSS: Cloud Classification System

DCF: Discounted Cash Flow

DPR: Driver, Pressure Response

DPSIR: Driver, Pressure, State, Impact, Response

GAC: Granular Activated Carbon

GsMaP: Global Satellite Mapping of Precipitation

GSO: General Statistics Office of Vietnam

ITCZ: Intertropical Convergence Zone

MF: Microfiltration

NCF: Net Cash Flow

NF: Nanofiltration

NPV: Net Present Value

OECD: Organisation for Economic Co-operation and Development

PDIR: Precipitation Estimation – Dynamic Infrared Rain Rate

PERSIANN: Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks

PP: Polypropylene

PV: Present Value

R<sup>2</sup>: Coefficient of Determination

RO: Reverse Osmosis

RSME: Root Square Mean Error

RWH: Rainwater Harvesting

RWHS: Rainwater Harvesting System

SDG: Sustainable Development Goal

SODIS: Solar Disinfection

SOPAS: Solar Pasteurization

UF: Ultrafiltration

UN: United Nations

UV: Ultraviolet

VMD: Vietnamese Mekong Delta

WASH: Water, Sanitation, and Hygiene

WB: World Bank

WBG: World Bank Group



## LIST OF FIGURES

Figure 1-1: Salinity Intrusion in VMD. A: Salinity Intrusion Severity in Areas by Years. B: Channel Depth Changes of Hau and Tien River between 1998 and 2008. C: Salinity Trends from Three Stations. Figure Retrieved from: Loc et al., 2021a .....	4
Figure 1-2: Annual Rainfall Distribution in Coastal Provinces in Vietnamese Mekong Delta. Figure Retrieved from: Dang et al., 2020 .....	6
Figure 1-3: Thesis Concepts for RWHS based on DPSIR framework .....	8
Figure 1-4: Thesis Research Framework .....	9
Figure 1-5: Common Rainwater Storage Used in the VMD .....	14
Figure 1-6: Main Sources of Drinking Water Between 2010 – 2020 in the Vietnamese Mekong Delta. Figure Constructed using data from GSO, 2022 .....	21
Figure 2-1: (a) Mekong Delta Provinces and River Networks; (b) Ben Tre Province and Binh Dai District; (c) Selected Communes for Survey and Research .....	24
Figure 2-2: Framework for quantitative assessment method .....	29
Figure 2-3: Framework for qualitative assessment method .....	31
Figure 2-4: Method framework for RWHS design .....	31
Figure 2-5: Framework for financial sustainability analysis .....	33
Figure 3-1: Annual (a) CDR precipitation surface; and (b) Corrected precipitation surface .....	44
Figure 3-2: Monthly Distribution of Corrected Precipitation .....	45
Figure 3-3: Linear Correction Observation Based on (a) Rainfall Time Series Between Gauge and Satellite Data; and (b) Correlation Between Gauge (Y) and Satellite (X) Datum Series .....	47
Figure 3-4: Setups of Rainwater Harvesting System at Survey Sites .....	49
Figure 4-1: Depth Filtration Mechanisms. Figure retrieved from Tchobanoglous (2014) .....	74
Figure 4-2: Capacity of filtration techniques .....	76
Figure 4-3: Concept design for (a) side-to-side horizontal storage placement; and (b) vertical stack .....	78
Figure 5-1: Aggregated Perception Affinity for Selected Aspects of RWHS: Quantitative sufficiency (QS), cost efficiency (CE), environmental sustainability (ES), self-sufficiency (SF), affordability (AF) .....	86
Figure 5-2: Percentage of (a) Household Willing to Upgrade, and (b) Household Willing to Implement by Income Bracket .....	86
Figure 5-3: Inferred Investment Aggregated by Income Bracket .....	87
Figure 5-4: Automatic Slow Release Valve Mechanism of First Flush Device. Figure Retrieved from GreenCo Water (n.d.) .....	91

## LIST OF TABLES

Table 1-1: Recent study on prominent drivers for intensifying salinity intrusion. (1) sea level rising (SLR); (2) land subsidence (LS); (3) riverbed incision (RI); (4) sandmining (SM); (5) Groundwater extraction (GE); (6) hydropower dams (HD) .....	10
Table 1-2: Rainwater Quality Index and Allowable Ranges for Potability .....	15
Table 1-3: Benefits of RWHS implementation around the world as sustainable practices .....	18
Table 1-4: RWHS legislation and incentive in the world.....	19
Table 1-5: Examples of RWHS implementations and designs in the world .....	20
Table 2-1: Data checklist for thesis objectives .....	28
Table 3-1: Frequency for Primary Water Source among Response (Single Response) .....	36
Table 3-2: Frequency for Secondary Water Sources among Responses (Multi Responses).....	36
Table 3-3: Perceived Sufficiency on Primary Water Source Quantity and Quality .....	37
Table 3-4: Harvested Rainwater Uses at Study Area .....	37
Table 3-5: Monthly Water Consumption.....	38
Table 3-6: Water Consumption Details by Area .....	38
Table 3-7: Summary of Open-Source Satellite Dataset Considered for Selection .....	39
Table 3-8: Correlation between Satellite-based Dataset (Observed) and Gauge-based Precipitation (Expected). Note: yellow highlight indicate highest in row; orange highlight indicate second highest in row.....	40
Table 3-9: Absolute Mean Error (AME) between Satellite-based Dataset (Observed) and Gauge-based Precipitation (Expected). Note: yellow highlight indicate lowest in row; orange highlight indicate second lowest in row .....	40
Table 3-10: Correlation Root-Mean-Squared Error (RMSE) between Satellite-based Dataset (Observed) and Gauge-based Precipitation (Expected). Note: yellow highlight indicate lowest in row; orange highlight indicate second lowest in row.....	41
Table 3-11: Cumulative annual rainfall of rain gauge, PERSIANN-CDR, and bias corrected PERSIANN-CDR daily precipitation datasets at the gauge location .....	42
Table 3-12: Extrapolated rainfall at survey sites .....	45
Table 3-13: Monthly Rainfall of Available Gauge Station in the VMD .....	49
Table 3-14: Rainwater harvesting practice frequency among surveyed household system .....	50
Table 3-15: Basic treatment practices among surveyed household.....	51
Table 3-16: Rainwater Quality Result from Lab Testing in Reference to National and WHO Guideline. Note: Parameters exceeding guidelines are highlighted yellow .....	52
Table 4-1: Summary of RWHS typification.....	55
Table 4-2: Summary of surveyed system parameters.....	56
Table 4-3: RWHS guiding principle for design.....	57
Table 4-4: Efficiency factor of different catchment materials. Source of data from <sup>1</sup> Gould (2015) and <sup>2</sup> Zhu and Liu (1998).....	59

Table 4-5: Graded characteristics of storage materials: (1) Longevity (LG); (2) Availability (AV); (3) Transportability (TP); (4) Maintenance (MT); (5) User Workability (DIY); (6) Cost; and (7) Carbon Footprint. Retrieved from source: Nazif et al. (2021) .....	64
Table 4-6: Scenario-based Water Balance Table Arranged by Hydrological Season: Wet Season (June to November); and Dry Season (December to May) .....	67
Table 4-7: Iterative Catchment Adjustment .....	70
Table 4-8: Iterative Consumption Optimization.....	71
Table 4-9: Pros and cons of treatment techniques .....	74
Table 4-10: Summary of selected recommendations for system components.....	77
Table 5-1: Input Variables.....	80
Table 5-2: Annual Benefits of Proposed RWHS for Optimized Scenario .....	81
Table 5-3: Capital Costs of Proposed RWHS Using Optimized Scenario .....	82
Table 5-4: Annual Costs of RWHS for Optimized Scenario.....	82
Table 5-5: Present Value Tabulation for Optimized Scenario.....	83
Table 5-6: Material-based Cost–Benefit Tabulation for Optimized Scenario.....	83
Table 5-7: Capital Costs of Proposed RWHS Using Optimized Scenario and Contingency Consideration...	89
Table 5-8: Annual Costs of RWHS Using Optimized Scenario and Contingency Consideration .....	89
Table 5-9: Present Value Tabulation Using Optimized Scenario and Contingency Consideration .....	89
Table 5-10: Cost–Benefit Tabulation Using Optimized Scenario and Contingency Consideration (Plastic Material Only) .....	89

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## ABSTRACT

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Under the impact of climate change and the rising sea level, saltwater intrusion, or salinity intrusion, is limiting freshwater sources in coastal provinces in Vietnam. Particularly, the Vietnamese Mekong Delta (VMD) has been experiencing some of the worst droughts and salinity intrusion in the past decades due to the compounded effects of anthropogenic flow alteration, groundwater extraction, land subsidence, and rising sea level. As a result, water scarcity is increasingly pressuring the local populace to find alternative freshwater sources aside from surface water and groundwater. Rainwater harvesting is one of such alternative practices which have been studied and utilized throughout the world in both developed and developing nations.

However, rainwater harvesting practices in the VMD are spontaneous with ad-hoc implementation and neglected by the local government despite its proven effectiveness around the world if harnessed optimally and efficiently. This thesis aims to achieve two main objectives: (1) the assessment of the implementation feasibility of rainwater harvesting systems (RWHS) (given environmental, socio-economic, and institutional conditions) as a potential strategy for integrated water management; and (2) the design and technical considerations of RWHS in the study area – Binh Dai district, Ben Tre province. Particularly, specific tasks inherent to achieving the objectives involve (a) rainwater assessment in both quality and quantity which will be the basis for (b) RWHS technical consideration and concept layout; (c) cost-benefit analysis of the proposed RWHS; and (d) potential recommendations for policy and expansion of uses.

Given the current mean water demand surveyed among households, a complete rainwater supply given mean catchment is not possible, which necessitates further estimation of optimal demand that locally available rainwater supply could realistically (hydrologically and economically) accommodate. Quantitative analysis of rainwater showed that given the average catchment area 28.8 m<sup>2</sup> per individual household and an average pluvial regime of 1917 mm annually with primary rainfall concentration from May to November, harvestable rainwater can only optimally accommodate a monthly consumption of 3.89 m<sup>3</sup> per household with a recommended storage tank capacity of 18.64 m<sup>3</sup>. Qualitative assessment of rainwater exhibits elevated concentration of Cadmium and micro-organism contaminations that requires adsorption and disinfection process as treatment, thus indicating the treatment modules needed for addressing the issues. For materials, it was determined that galvanized steel for catchment and PVC for conveyance modules (pipes, gutters, downspout, etc...) were most appropriate, while storage unit option could potentially be between steel and plastic depending on costs and, subsequently, economic feasibility.

The cost-benefit analysis accounts for overall profitability via present value estimation and related indicators. Particularly, RWHS with steel storage exhibits a net present value (NPV) of -24,549,665 VND, and a benefit-cost ratio (BCR) of 0.8. Comparatively, plastic-based RWHS exhibits an NPV 7,138,362 of and BCR 1.1, which makes it the more economically suitable options of the ideal material selection, especially given the low-medium socio-economic condition in the study area. These economic indicators showed that RWHS implementation for accommodatable (optimized) water demands given system consideration and layout is only

economically feasible if storage material, which accounts for a significant quantity of capital costs, is plastic (polyethylene).

Furthermore, cross-analysis using cost-benefit technique and socio-economic analysis from survey result showed gaps between household economic capacity and willing-to-pay for RWHS implementations. Specifically, only 40% of respondents are willing to further improve rainwater harvesting capability despite mean surveyed storage capacity is only at 10.1 m<sup>3</sup>, which is approximately 84.6% below the calculated optimal storage of 18.64 m<sup>3</sup>. The majority of responses willing to invest (75%) is categorized under the low-medium monthly income bracket (5-10 million VND/month) which is also the category most likely to invest more on RWHS implementation (average 12.5 million VND/month) compared to responses belonging to monthly income bracket of 1-5 million (8 million VND/month) and 10-20 million (10 million VND/month). However, given the investment capitals of plastic-based RWHS (45,522,037 VND or ~1827 €), there is a gap in willingness-to-pay comparative to actual investment cost at market price, which could be mitigated with the recommended minimum monetary incentive starting at 4,626,638 VND/year continuously for 10 years of the proposed lifespan to breakeven with investment cost. Taking into account future increase in rainfall as a result of climate change, recommendation of a contingent storage increase by 20% is also recommended at the cost of raising minimum subsidy to 5,269,761 VND/year for 10 years. An additional recommendation for temporally variable implementation of modular storage capacity is proposed in the event of subsidy infeasibility. However, dynamic cost-benefit analysis of such an alternative cannot be evaluated simply by static valuation method and would be subject to future study like other research aspects where limitations were present.

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# 1. INTRODUCTION AND LITERATURE REVIEW

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## 1.1 INTRODUCTION

### 1.1.1 Climate Change and Salinity Intrusion

Vietnam is one of the most vulnerable countries to climate change in the world (World Bank Group [WBG], 2019), and the Vietnamese Mekong Delta (VMD), which covers a wide area of approximately 40,816 km<sup>2</sup> including 13 provinces: An Giang, Bac Lieu, Ben Tre, Ca Mau Can Tho, Dong Thap, Hau Giang, Kien Giang, Long An, Soc Trang, Tra Vinh, Tien Giang, Vinh Long (General Statistics Office of Vietnam [GSO], 2020a), is indicated as particularly at risk for extreme climatic alteration (Chaudhry & Ruysschaert, 2008). The VMD serves as the primary drivers for a robust and flourishing agricultural, industrial, and service sectors in Vietnam, which supports the livelihood of 18% (17.5 million) of its population (GSO, 2020a) and accounts for 17% of the national GDP (Sagris et al., 2017). Evidently, the VMD is dependent on the ecohydrological services provided by the Lower Mekong basin, which underlines significant consequences derived from potential changes in hydrological conditions in the delta. Specifically, consequences are inherently exhibited via variably unpredictable spatial and temporal distribution of water-related disasters, namely flood, drought, and salinity intrusion (Quinn et al., 2010), which can induce cascading environmental and socio-economic disasters in form of water land subsidence, mass migration, and economic paradigm shift (Khong et al., 2020; Loc et al., 2021b; Minderhoud et al., 2018; Minderhoud et al., 2020).

Despite the geographic features that facilitates social and economic development in the VMD region, trends in climatic phenomena, which exhibit rising sea level and severe meteorological pattern changes, have impacted coastal population via intensification of flooding, tidal inundation, and saltwater intrusion (Toan, 2014). Given the current status of the region, it is predicted that sea level is expected to increase by 30 centimeters (cm) by 2050, which will likely impact frequency of El Nino events near the coastline of the VMD (Sagris et al., 2017). As a result, intensity of storm, floods, drought, and salinity intrusion is expected to elevate accordingly, which further debilitate the coastal communities, especially the VMD, with dry land losses, water-borne diseases, water-energy nexus deficits, and loss of water availability (Sagris et al., 2017; Wong et al., 2014). In particular, extreme changes in precipitation, as a symptom of climate change, not only cause severe flooding in wet seasons, but also prolonged drought during dry seasons, which significantly deteriorates the local ecosystems and human welfare (Wong et al., 2014) within the VMD.

Among climate driven water-related disasters, it has been found that more commonly visible wet disasters, such as floods, are less economically impactful compared to dry disasters, such as drought which can propagate salinity intrusion and cascade additional damage in both tangible and intangible forms during a prolongs period (Damania et al., 2017). Furthermore, the intensification of salinity intrusion is also attributes to land-use changes and poor management of anthropogenic activities (Figure 1-1) (Eslami et al., 2021; Eslami et al., 2019; Loc et al., 2021a; WBG, 2019) conducted by local residents. For example, groundwater extraction is a common practice accommodating the rising water demand as population and development advance. However, such common practices can leave long-term impact on soil integrity on a large scale and increase subsidence risk by a significant margin (Minderhoud et al., 2017; Minderhoud et al., 2020). In a similar

manner, uncontrolled groundwater extraction has also been found to lower water tables, which enable inland propagation of seawater, exacerbate salinity intrusion of both surface and groundwater, and results in further decrease in water availability (An et al., 2014; Xiao et al., 2021). Another notable factor that aggravates salinization in the VMD is sandmining, which starves necessary sediments to maintain downstream riverbed integrity (Eslami et al., 2019), which causes an increase in seawater differential pressure propelling inland. Most significant of all anthropogenic impacts are upstream hydropower dams that were observed to trap sediments within reservoirs, which increase salinity intrusion as a consequence of alterations in discharge, water level, and riverbed incision in downstream VMD (Binh et al., 2020a). Consequently, anthropogenic activities have driven geohydrological changes to characteristics in the VMD that decrease water accessibility and usability to downstream users and infrastructural distributors, thus impacting water security of VMD. Despite examined anthropogenic activities being a product of the need for development and economic advancement, it has inadvertently reduces livelihood opportunities, provision of food, and water, sanitation and hygiene (WASH) especially in combination with extended drought during dry seasons (Khong et al., 2020; D. D. Tran et al., 2021). Moreover, current anthropocentric productivity could increase salinity intrusion by 10-27% in affected provinces with another 6-19% increase attributed to rising sea level is projected (Eslami et al., 2021), which elevates the urgency for sustainable water resource management in the VMD.

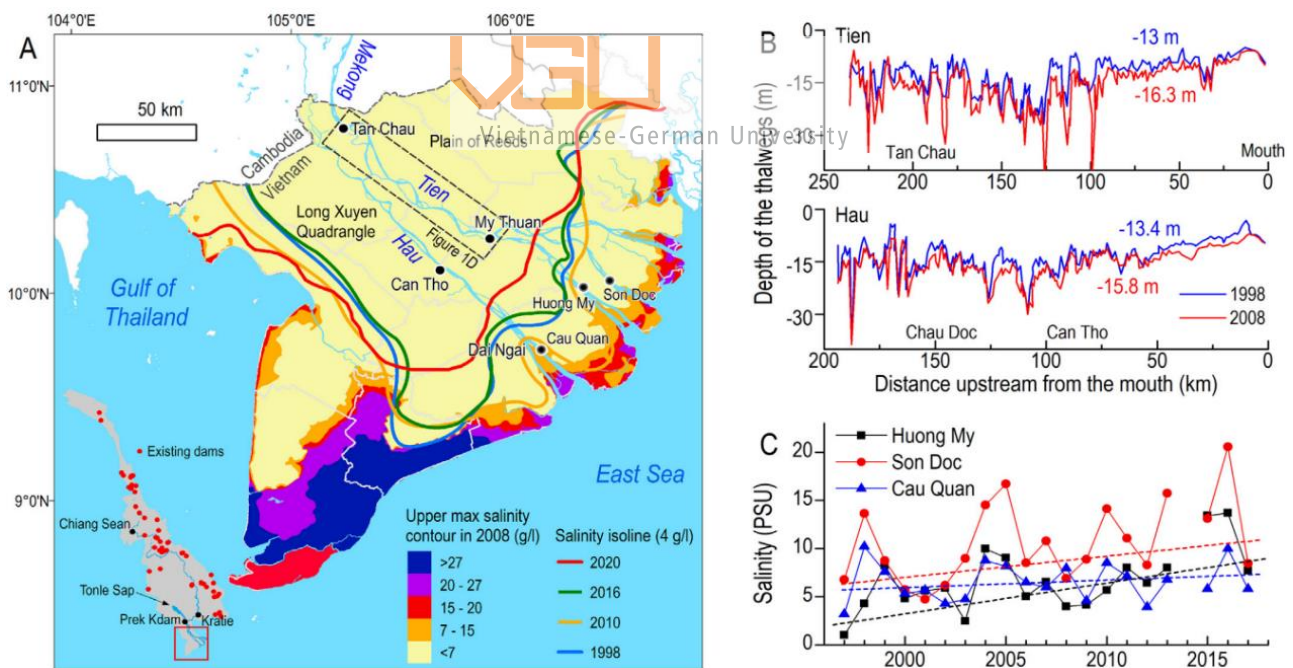


Figure 1-1: Salinity Intrusion in VMD. A: Salinity Intrusion Severity in Areas by Years. B: Channel Depth Changes of Hau and Tien River between 1998 and 2008. C: Salinity Trends from Three Stations. Figure Retrieved from: Loc et al., 2021a

## 1.1.2 Water Scarcity

### 1.1.2.1 Water Stress in Vietnam

Approximately 57% of the water resource in Vietnam is available within the 8% of the Mekong River that resides within the country and forms the VMD, which quantitatively translates to a potentially high availability of 500 billion cubic meters ( $m^3$ ) or 9434  $m^3$  per capita. However, as a downstream country,

Vietnam has little control over two-thirds of its water resource flow, which places its internal water renewal rate at 4200 m<sup>3</sup> per person – lower than Southeast Asia average of 4900 m<sup>3</sup> per person (WBG, 2019). To compound the issue, water in forms of precipitation and run-off are highly seasonal commodities with unpredictable frequency due to the increasing effect of climate change.

Economic development is water intensive. Hydropower and irrigation contribute to a significant proportion of water usage in Vietnam. Specifically, water is used for the benefit of over 7500 hydro-structures (dams and reservoirs) and 4 million hectares (ha) of irrigated land, all of which provides and ensures the livelihood and welfare of the population therein (WBG, 2016; WBG, 2019). Particularly, distribution for water priority indicates an 81% for agriculture, 11% for aquaculture, 5% for industry, and 3% for municipal purposes (WBG, 2019). Additionally, water significantly contributes to economic development via inland canal transportation, which accounts for 48% of the national tonnage (Blancas & El-Hifnawi, 2014).

However, given the constraints on water resource acquisition and renewability, a growing agricultural economy with shifting interests in industrial and service sector is proving to be tax for its water resource priority. Despite the abundance of water, water stress across Vietnam, especially in the VMD, is experiencing unsustainable level of surface and groundwater extraction (Minderhoud et al., 2017; Xiao et al., 2021) especially during dry seasons (Damania et al., 2017). Given low renewability compounded by the rising water consumption from developmental demands, water stress will inevitably disrupt social order and impact local economy (WBG, 2019). In the event that nothing is done to limit consumption patterns via (a) population control, (b) controlled and planned development, and (c) consumption behavior changes, water demand is projected to rise 30% by 2030 and consequences will be devastating during dry season for four major basins in Vietnam, namely the Red – Thai Binh, Mekong, Dong Nai and the South East River Cluster (SERC) river basins (Sagris et al., 2017).

#### **1.1.2.2 Water Accessibility in the Vietnamese Mekong Delta**

The context of natural disaster and water stress in Vietnam paint a picture of unfortunate necessity, in which water is essential for all livelihoods in most river basins, but rapid development and subsequent overexploitation are its own inhibiting factor in regards to sustainable development and water management. In other words, policy and practices of development in the VMD enable rapid economic prosperity while it is also the reason for hydrological degradation that sequentially inhibits development in the region (WBG, 2019). The current circumstances of water scarcity demonstrate a systematic environmental degradation caused by climate change, which snowballed into salinity intrusion and drought. Particularly, water supply distribution for agriculture, industry, and domestic utilization in the VMD are most vulnerable to drought and salinity intrusion (T. Ha et al., 2018; WBG, 2016). Due to frequent shortages of freshwater in salinized areas in the VMD, users are shifting to groundwater extraction. Additionally, contamination in fresh surface water is not strictly salt contents, but also the elevated level of both organic and inorganic pollutants discharged by increasing agricultural and industrial activities, which sequentially impact acquisition of potable and drinkable water. Consequently, groundwater is currently the dominant source for freshwater supply although its viability is diminishing (An et al., 2014; T. Ha et al., 2018; Minderhoud et al., 2017; Minderhoud et al., 2020), which suggests changes in water management policies or sustainable alternatives can be derived.



Fundamentally, land-use planning and water resources are intrinsically related because surface water is an easily accessible source of stream resources for agriculture, forestry, industry, and domestic utilization. Therefore, water availability affects land utilization (hydropower, agriculture, aquaculture, industry, etc.) and, as a consequence, land utilization now affects water quantity and quality in the VMD (T. N. Le et al., 2018). Therefore, research has postulated that effective hydrological regime management starts with appropriate land-use planning. According to Calder (2012), activities associated with development, such as afforestation, urbanization, or aggressive irrigation, have been linked to changes in hydrological conditions and ecological integrity, especially in developing countries. It is also believed that worldwide rapid development and globalization are significant disruptors to the global hydrological cycle, which subsequently contributes to climate change phenomena similar to soil degradation, erosion, and land subsidence. As a result, water supply for all purposes is restricted, although domestic water uses, which indicates WASH status within the VMD communities, will most likely be influential on other productivity sectors due to its intrinsic linkage to basic survivability.

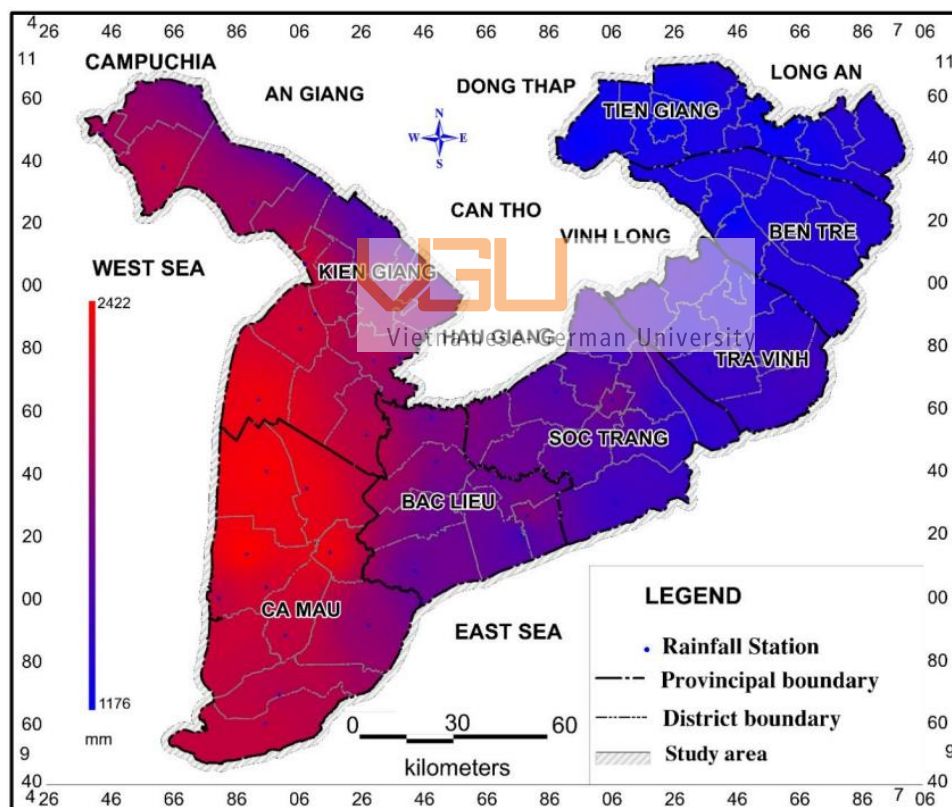


Figure 1-2: Annual Rainfall Distribution in Coastal Provinces in Vietnamese Mekong Delta. Figure Retrieved from: Dang et al., 2020

Typically, domestic water sources in the VMD are primarily surface water and groundwater. However, the condition of salinity intrusion in recent years, especially for seven coastal provinces (Figure 1-2), has significantly reduced the viability of surface water as a domestic water source (T. A. Tran et al., 2021). Specifically, due to the effects of climate-driven rising sea level and drought coupled with anthropogenic activities (hydropower dams, sandmining, groundwater extraction, etc...), the VMD has seen significant changes to its hydrological regimes and morphological characteristics, which have been noted to induce

changes to the hydrology and amplify salinity intrusion of downstream delta (Eslami et al., 2019). Moreover, hydro-morphological effects on water supply are usually not reflected in the official statistics that assess the living standard of the people. As a result, water scarcity is often downplayed by domestic reports. For example, it was highlighted that water access via tap water in the VMD has risen by 20% between 2010 – 2020, thus assessed water accessibility is no longer a top priority (GSO, 2020b). Additionally, the only problem cited was surface water pollution which is only a fraction of the nuances that impact water quality and, subsequently, water supply. In contrast, field survey by UN (2020) reported that people within VMD provinces such as Kien Giang, Tra Vinh, and Ben Tre particularly experienced severe water shortage due to salinization of water sources which also contaminate tap water supply, making it unreliable despite its availability.

Simultaneously, freshwater sources in underground aquifers are proven to only provide short-term supply with devastating long-term consequences. Particularly, decades of excessive extraction of groundwater for domestic uses have seen strong correlation with exacerbation of drought, saltwater intrusion and climate change effects within VMD (Eslami et al., 2021; Thilakarathne et al., 2017; Xiao et al., 2021), which potentially leads to further saline contamination in water supply system (United Nations [UN], 2020). Furthermore, long-term groundwater extraction is linked to large-scale land subsidence in the VMD, which also exacerbates the effects of sea level rising and salinity intrusion (Loc et al., 2021a; Minderhoud et al., 2018; Minderhoud et al., 2017; Minderhoud et al., 2020). Decades of unregulated development can destroy groundwater, but it takes ten times the period for groundwater table to recover; even then it is not guaranteed to recover completely as observed in the cases of some developed countries (Hiscock & Bense, 2021). Ultimately, proliferation of groundwater extraction only serves to exacerbate salinity intrusion and sea level rising already deteriorating surface water and groundwater in terms of water-soil environment, which has unfortunately experience a decline in trends since 2014 (GSO, 2020b).

### 1.1.2.3 Necessity for Alternatives

Restricted freshwater accessibility due to salinization of both surface water and groundwater is escalating water scarcity in VMD. As a result, the demand for sustainable alternative water source is increasing. Currently, many provinces in VMD employ a variety of community-funded rainwater storage system to supplement, or replace, their dependence on centralized water supply (Özdemir et al., 2011). Rainwater storage innovation is significant because studies have shown that communities were able to leverage the high annual rainfalls between 1100 – 2450 mm of VMD to supplement freshwater demand in dry seasons with rainwater collected during wet seasons (Dang et al., 2020; Mekong River Commission [MRC], n.d.). However, studies have also shown that quality of rainwater collected from roofs in VMD is poor, with high COD, traces metals and coliform concentration (Wilbers et al., 2013). So far, research has indicated rainwater as a promising and abundant source of freshwater despite its low drinkability and storage capability due to potential organic contaminants within the context of a tropical climate. Concerningly, many of the harvest and storage systems lack rudimentary treatment which highlights potential public health issues within VMD communities (UN, 2020). Although rainwater is a common alternative for water supply, little research has been done on its practices in VMD and its community-funded nature, which indicates an absence of necessary government program to incentivize modernization of these improvised system and improve WASH conditions for

community development (Özdemir et al., 2011). Furthermore, there has not been any research that seeks to modernize the highly haphazard nature of current ad-hoc rainwater apparatus in VMD considering the local efficiency and quality of rainwater (Özdemir et al., 2011; Wilbers et al., 2013).

Drought and saline water intrusion not only impact long-term sustainability of the region by impacting water scarcity, but also raise concerns of WASH vulnerability (Mekong Delta Plan [MDP], 2013; D. D. Tran et al., 2021; T. A. Tran et al., 2021). Given future salinity hazard and constraints regarding surface and groundwater, rainwater utilization as a potential long-term strategy for WASH is necessary. However, the potentials of a modern and affordable Rainwater Harvesting System (RWHS) in VMD are not well examined, which necessitates further research on its geographical feasibility, optimization, and potential economic benefits to evaluate potential for integrated water management in VMD.

The necessity for this area of research can be represented by the Driver-Pressure-State-Impact-Response (DPSIR) analysis framework (Figure 1-3), which examines the drivers, pressure, state, impact, and response loop for conditional phenomena. The framework serves as a comprehensive extension to the DPR framework derived by the OECD, which basically creates connections between socio-economic, socio-technical, socio-ecological, and socio-political elements as cause-and-effect relational interaction to characterize the necessity of RWHS for WASH capacity development in order to achieve goal 6 (Clean water and sanitation) and goal 11 (Sustainability cities and communities) of the Sustainable Development Goals (SDGs) conceived by the United Nations Council.

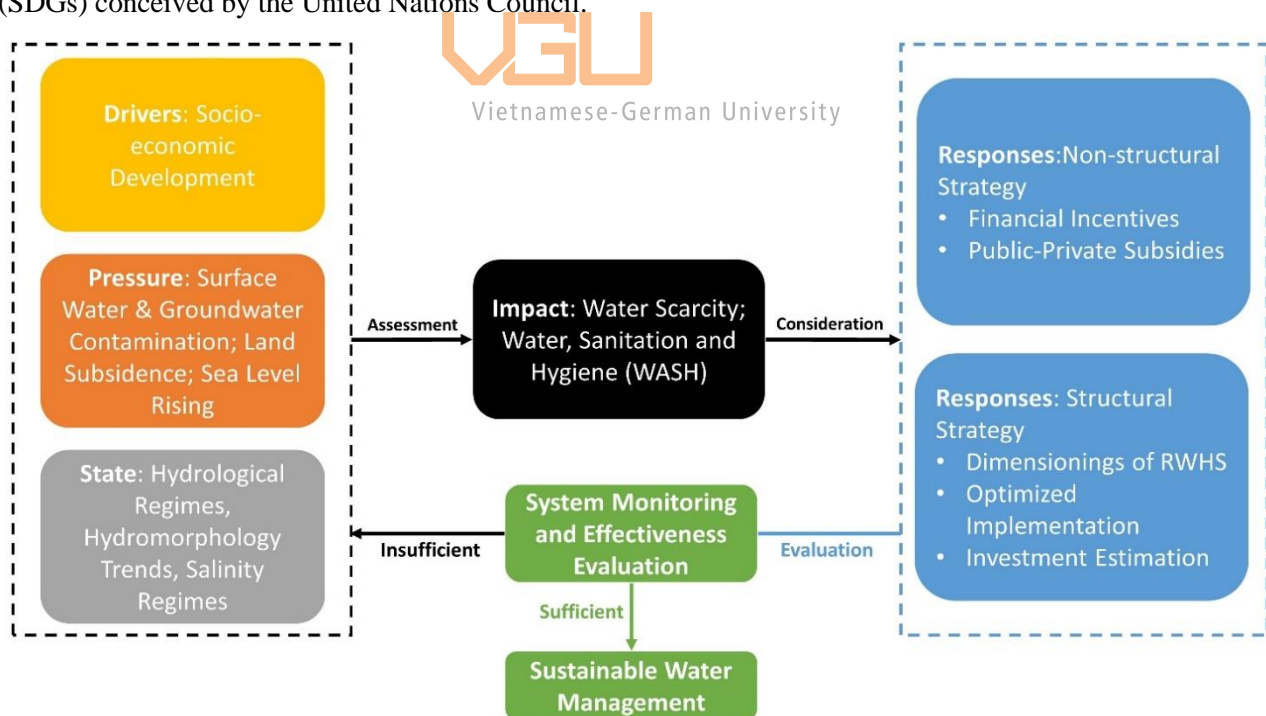


Figure 1-3: Thesis Concepts for RWHS based on DPSIR framework

### 1.1.3 Research Objective

The overall objective of this research is (1) the assessment of implementation feasibility and transferability of RWHS as a potential strategy to integrated water management at the study area; and (2) the technical aspects of a RWHS in the study area. Particularly, specific goals to achieve the objectives are (a)

rainwater assessment; (b) RWHS concept designs and considerations; (c) cost-benefit analysis of RWHS; and (d) potential recommendations for policy and expansion of uses. In order to complete each goal necessary for the achievement of the objectives, components tasks are conceived to modularize and manage thesis progress appropriately. The framework to achieve these objectives is illustrated in Figure 1-4.

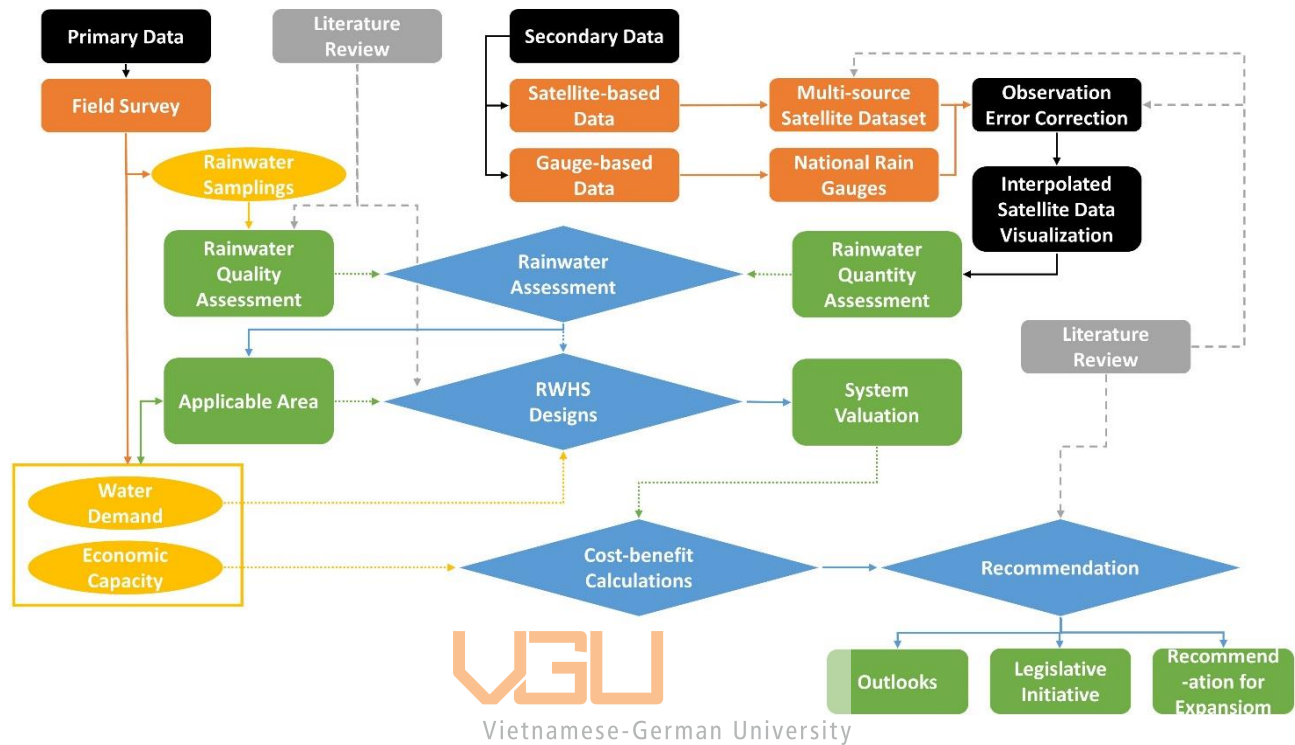


Figure 1-4: Thesis Research Framework

## 1.2 LITERATURE REVIEW

### 1.2.1 Salinity Intrusion Mechanism: Behaviors, Causes, and Effects

VMD, with a total area of 4 million ha, is considered mostly flat and low-lying land with an average elevation of 1 meter (m) above sea level (Toan, 2010). Resultingly, the region is heavily susceptible to tidal variations that propagate saltwater inland, causing salinity intrusion. By estimate of the Southern Institute of Water Resource Research (SIWRR), annual flooding affects around 2 million ha, which enables seasonal salinity intrusion to impact approximately 44% (1.7 million ha) of VMD (Toan, 2010). Alarmingly, such annual trend only shows that salinity intrusion in VMD will progress a maximum of 27% by 2030 (Eslami et al., 2021). The circumstance is critical due to the fact that VMD is the largest producer of rice in Vietnam. Specifically, the region has consistently produced more than 23 million tons of rice paddy between 2015 and 2020, which contributes to more than 50% of the national rice production and around 85% of annual rice exports (GSO, 2020a). It can be estimated that the salinization of water used for irrigation will likely induce a loss between 2.5 – 4 tons per hectare, which translates to roughly 18 – 30% loss in total paddy yield (Khai et al., 2018). Besides agricultural impact, increasing salinity concentration among coastal region is reported to be a contaminant in the piped water supply, impacting water access of 20,000 people in Kien Giang and potentially hundred of thousands more within VMD (UN, 2020). Given the importance of freshwater to the

lives people and their livelihood, it is necessary to understand the mechanism and effects that salinity intrusion has on the communities and ecosystem.

Studies have suggested that there are mainly six main drivers (Table 1-1), through which three main mechanisms for intensifying salinization of water resources in VMD is enabled – (1) hydrological dynamics between the river and the sea; (2) geomorphological dynamics between upstream and downstream; and (3) Interaction between anthropogenic factors and hydro-morphological conditions. The combination of all three mechanism can significantly impact the freshwater flow and water level necessary to counterweight seawater pressure (Khong et al., 2020; Loc et al., 2021a; Loc et al., 2021b).

Table 1-1: Recent study on prominent drivers for intensifying salinity intrusion. (1) sea level rising (SLR); (2) land subsidence (LS); (3) riverbed incision (RI); (4) sandmining (SM); (5) Groundwater extraction (GE); (6) hydropower dams (HD)

SN	Source	Driver						Study and Findings
		SLR	LS	RI	SM	GE	HD	
1	(Binh et al., 2021)	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	The study investigated the correlation between riverbed incision and worsening salinity intrusion. Findings suggested that riverbed incision impact water level during dry season, which is also the period when salinity intrusion is at its peak, thus exacerbating the disaster.
2	(Binh et al., 2020b)	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	The study investigated and modelled the impact of upstream hydropower in Upper Mekong Delta on the hydro-morphological regimes in Lower Mekong Delta. Findings suggested that hydraulic structures like hydropower dams and reservoirs impact sediment load that causes riverbed incision in Lower Delta. Riverbed incision correlates with the reduction in water level during dry season, which increases salinity intrusion.
3	(Binh et al., 2020a)	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	The study investigated the long-term impact on flow regimes in the VMD as a result of riverbed incision and anthropogenic factors such as hydropower dams and sandmining. Findings suggested that both sandmining and hydropower dams act as contributing factors to downstream sediment starvation and subsequent riverbed incision. Riverbed incision is postulated to be a driver that exacerbate water resource salinization in the region.
4	(Eslami et al., 2019)	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	The study assessed anthropogenic factors such as hydropower dam development and sandmining in relation to tidal conditions and salinity intrusion via barotropic model. Findings suggested anthropogenic factors amplify tidal conditions and salinity intrusion as a consequence of upstream sediment load reduction.
5	(Loc et al., 2021a)	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	The study focuses on analysis and mathematical estimation of impacts from contributing factors to worsening salinity intrusion: sea level rising, land subsidence, sandmining, and hydropower dams. Findings suggested underlying factors are responsible for worsened tidal amplification of 1.5 – 2 cm/year, which correlates to increased backwater effect.

6	(Mai et al., 2018)	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	The study modelled conditions within the VMD to determine contributing factors to salinity intrusion. Findings suggested that salinity intrusion progress is indeed sensitive to sea level rising and hydropower dam conditions.
7	(Minderhoud et al., 2017)	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	The study modelled the impact on land subsidence as a result of 25 years of groundwater extraction practices. Findings estimated subsidence of roughly 18 cm over the research period, which translates to 1 – 2.5 cm subsiding area per year.
8	(Trieu & Phong, 2015)	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	The study modelled the impact of sea level rising and increasing saline water concentration on aquaculture (Pangasius). Findings suggested that aquaculture will experience a shrinkage in viable land due to Pangasius tolerance to saltwater.
9	(Vu et al., 2018)	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	The study modelled the impact of sea level rising and its impact on agricultural productivity. Findings suggests that sea level rising will push salinization 50 – 60 km inland, meaning an additional 30,000 ha of agricultural land will have water saline concentration greater than 4 g/l and a greater yield loss for rice paddies.
10	(Xiao et al., 2021)	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	The study modelled the impact of global climate change on inland saltwater contamination and groundwater aquifers. Findings suggests that climate change and the resulting sea level rising causes salinization of groundwater, which is also exacerbated by local groundwater extraction practices.

The first mechanism describes that process of saltwater intrusion via inward pressure caused by difference in water level between the rising sea and the river mouth (Khong et al., 2019). Essentially, sea level rising as a consequences of climate change has caused a height-based differential pressure that impacts the hydrological regimes of VMD and allows saltwater to intrude. The Mekong River has a high historical flow reaching 65,000 m<sup>3</sup>/s observed during the rainy season of 1939, and a consistent low flow between 1000 to 2500 m<sup>3</sup>/s during the dry season since 1960 (Toan, 2010). Due to low flow, which indicates low upstream pressure, rising sea level is able to exert higher pressure and diffuse higher gradient of salinity into river mouth. In addition, high variation in seasonal discharge is associated with the low topographical feature of the region to induce a natural vulnerability to flood-prone ecosystem during dry season (Toan, 2010). Despite its susceptibility to flood stressors, only 3% of the basin area is considered flood-prone during the dry season, to which cultivational benefits was assessed to outweigh the potential impact of flooding and flood-propagated salinity intrusion. As a result, with increasing flooding and salinity intrusion, the approach of “adaptive cohabitation with floods” is popular among coastal provinces such as Kien Giang, Long An, Tien Giang, and Ben Tre (Toan, 2014). Specifically, this strategy of adaptive cohabitation usually involves utilization of large hydraulic structures such as sluice gates and embankments for flow regulations, which, by extension, controls flood and salinity intrusion during both wet and dry seasons, although not completely successful. In some other

cases, non-coastal provinces like Dong Thap and An Giang with the uses of sluice gates and embankment are able to thoroughly stop floods and salinity intrusion (Toan, 2010).

The second mechanism denotes the process of sediment load alteration in the downstream via upstream dam and reservoir development. Primarily, dam development has significant impact on the sediment transportation process and riverbed formation according to a study that modelled different scenarios to observe the hydrological regimes in the lower Mekong including VMD under the effects of hydraulic structures such as embankments and dikes (Binh et al., 2020a). The research found that high presence of hydraulic structures demonstrated a more defined flow regime alteration over a 36-year period when compared to low or no development scenarios. Particularly, dam development and flow regimes have been noted to be negatively correlated with downstream sediment load, which starve the river of essential materials to compensate for riverbank erosion and riverbed incision (Binh et al., 2020a; Binh et al., 2020b; Binh et al., 2021; Eslami et al., 2019). Consequently, riverbed incision has been linked to decreases in water level in research area (Binh et al., 2020a; Binh et al., 2020b; Binh et al., 2021; Loc et al., 2021a), which changes hydrological dynamics between the river and sea. In other words, dam-induced sediment load reduction causes riverbed incision, which acts as a contributing factor to water level alterations and, with respect to the first mechanism, intensified salinization of inland freshwater.

Finally, the third mechanism links excessive anthropogenic interference within VMD to the exacerbation of hydrological regime alterations and sediment supply in VMD basin. In particular, two of the most notable drivers of anthropogenic disruptions are groundwater extraction (Loc et al., 2021a) and sandmining (Eslami et al., 2019), which are known drivers for land subsidence (Minderhoud et al., 2017) and river incision (Binh et al., 2020a; Binh et al., 2020b; Binh et al., 2021; Eslami et al., 2019). Ultimately, anthropogenic mechanism serves as negative amplifier for previous mechanisms.

## **1.2.2 Precipitation Trends in VMD**

### **1.2.2.1 Precipitation Quantity: Intensity and Distribution of Rainfall**

The climate in VMD is characterized by Southeast tropical monsoonal behavior with annual precipitation ranging from 1400 – 2400 mm, 80 – 90% of which is concentrated in its wet season; specifically, the onset of wet season is in May, which peaks between August – September and ceases in November (United Nations Environment Programmes [UNEP], 2009). Monsoon is defined by a wind system that seasonally reverse its flow, thus bringing changes to the intensity and distribution of regional precipitation. In VMD, monsoon circulation commonly advances into land via the sea via a wind channel called the southwest monsoon (Dang et al., 2020). Southwest monsoon is bolstered by the Intertropical Convergence Zone (ITCZ) which is a near-equatorial region where trade winds from the northeast and southeast converges. The phenomenon advances into land from the sea, which carries an abundance of rainfall into the VMD during wet seasons (Dang et al., 2020). Despite a large volume of rainfall formation during this period, southwest monsoon is periodic, which means that precipitation fluctuates in intermittent waves throughout the season, making forecasting and projection difficult. In October, high pressure formation over the Asian continents forces the ITCZ south, which moves subtropical pressure east. The changes atmospheric pressure causes southwest

monsoon to reverse direction and form northeast monsoon, which slowly ends the rainy season in November (Dang et al., 2020).

Prediction of rainfall during wet seasons can be difficult due to the intermittent nature of precipitation and the variety of local conditions in VMD (Acharya & Bennett, 2021; Y. Hu et al., 2019), which indicates the variable onset and cessation dates of wet season in the different provinces of the VMD. In practice, start dates and end dates of the rainy season are usually inferred based on rainfall monitoring, which demonstrate latency in comparison the formation and dissipation of the southwest monsoon (Acharya & Bennett, 2021). Dang et al. (2020) estimated that annual rainfall in the VMD averages at around 1860 mm, with the west coast benefitting from higher rainfall concentration (2247 mm highest) compared to the east coast and inland (1439 mm lowest) (Figure 1-2). Another study calculated that monthly precipitation during the wet season averages 250 mm and less than 20 mm during the 4 – 5 dry months (Ross et al., 2022). Given the volume of rainfall across the VMD, harvesting potential of rainwater could average 45.5 billion m<sup>3</sup> annually, which translate to a 4900 m<sup>3</sup> per capita per year – more than half of the potential supply by the Mekong River at 9434 m<sup>3</sup> (WBG, 2019).

During the dry months, rainfall is still assessed to be adequate at 107 mm per month, with highest registered rainfall in Kien Giang and Ca Mau at 156 mm and 136 mm respectively; studies found that historical rainfall in the dry season even reach an average of 411 mm (Dang et al., 2020). Overall, precipitation during dry months signifies sufficient and accessible source of freshwater, serving as an essential component to RWHS application for mitigation of salinity-driven water shortage. However, current precipitation condition might experience alterations in the short-term, mid-term, and long-term due to climate change. For instance, studies have found that west VMD (Kien Giang and Ca Mau) will have decreased precipitation by an estimated average of 5.8% (65.5 mm) and 8.2% (19.7 mm) during the wet and dry season respectively (Sun et al., 2021). In addition, Kien Giang and Ca Mau will also experience less consecutive rainy days and less 10 – 100 mm rainy days. In contrast, the east coast will experience a significant increase of approximately 55.8% (134.6 mm) and 15.7% (19.2 mm) during its wet and dry season respectively, which would likely increase consecutive precipitation days, and along with it, the likelihood of flood (Sun et al., 2021). Overall, projection of precipitation demonstrated negative changes for the west coast, but the east coast (Ben Tre, Tien Giang, Tra Vinh, Vinh Long) will benefit from the increased precipitation and RWHS viability which can mitigate potential flood risks.

#### **1.2.2.2 Precipitation Quality: Effects of Contamination and Guidelines for Rainwater**

While rainfall in the VMD is abundant to satisfy water demands in the dry and wet season, rainwater is susceptible a variable source of contamination. As such, rainwater will need treatment along with its application, the degree of which depends on the quality of local rainwater. In principle, rainwater harvesting collects rainfall before it makes contact with the ground from roofs, which intuitively implies a safer option compared to surface water and groundwater. However, there are a few factors contributing to the composition of rainwater, such as airborne particulate dissolved chemical (nutrients, trace heavy metals, organic compounds) and microbiological composition. Particularly, studies have found that rainwater is not entirely safe for direct consumption as there are still public health risks associated with its atmospheric and airborne



pathways, as well as system-based contamination (i.e. storage and catchment factors) (Lim & Jiang, 2013). For example, contaminated rainwater is linked to causes for bacterial infection that leads to diarrheas (Salmonella, Campylobacter), pneumonia (Legionella), botulism (Clostridium), and tissue helminths (Lye, 2009). Another case in Australia demonstrated that roof-contaminated and storage-contaminated rain is associated with outbreaks of diarrheas and pneumonia (Ahmed et al., 2010). As a result, consequences of unsafe rainwater consumption serve as a warning for the conventional perception that rainwater is clean. However, in despite the potential health risks, it still represents one of the simplest and intuitive form of green technology that is easily transferrable globally to alleviate water scarcity. Therefore, comprehension of potential health risks and pathways of contamination in rainwater can be consequential to the accessibility of water, especially in developing countries and rural areas where water treatment and distribution facilities are unavailable. Furthermore, water connection does not equate consistency, areas in the VMD reported present of piped water networks, but performance is often insufficient to meet demands due to saline contamination and degrading infrastructure (UN, 2020; WBG, 2019). As such, identifying and understanding in-situ pathways constituting contamination for potability and risk assessment are critical for implementation, operation, and evaluation of RWHS, the details of which will be discussed in subsequent section under technical considerations. In addition, understanding the determinants of rainwater quality and its impact on public health can provide valuable information as policy instruments to improve rainwater quality and public health measures.



Figure 1-5: Common Rainwater Storage Used in the VMD

There is a lack of defining indices or specifications for potable rainwater in Vietnam. Instead, there are national regulations on the quality of drinking water and standards for rainwater monitoring, all of which do not explicitly accounts for potability in rainwater. For example, under Law No. 55/2014/QH13 on Environmental Protection, Circular No. 24/2017/TT-BTNMT on Environmental Monitoring Technique and Circular No. 32/2011/TT-BTNMT on Technical Guidelines for Rainwater Quality Monitoring were issued by the Ministry of Natural Resources and Environment (MONRE). Upon examination, it was determined that either of these documents mentioned rainwater in any potable capacity. Instead, Circular No. 32/2011/TT-

BTNMT defined the objective for rainwater quality monitoring in Vietnam as followed: (1) Assessment of rainwater quality for the purpose of regional pollution control; (2) Assessment and monitoring of spatial and temporal accumulation of rainwater acidification; (3) Assessment of rainwater quality status and trends; and (4) Fulfillment of managerial requirements in environmental protection. Specifically, Section 5, Article 21 of Circular No. 24/2017/TT-BTNMT, which defines the parameters necessary to rainwater quality monitoring are “temperature, pH, EC, TDS, meteorological parameters,  $\text{Cl}^-$ ,  $\text{F}^-$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$ ,  $\text{SO}_4^{2-}$ ,  $\text{NH}_4^+$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ”, which indicates rainwater quality monitoring is only valid within the context of climate change and environmental protection. Furthermore, National Standard QCVN 01-1:2018/BYT on Technical Guideline in Water Quality for Domestic Purpose, issued by the Ministry of Health (MOH), limits its scope of application to water manufacturing activities involving the extraction of surface water and groundwater, with no specific mention of application for rainwater, although it can be for the purpose of academic research. As such, current legislative has not explicitly considered rainwater an integral part of its water resource management policy despite the enormous potentials of rainwater. However, given the context of rainwater quality monitoring in the VMD, several studies have extrapolated keys determinants for potability on rainwater in the VMD from Vietnamese national regulations and reputable organizations such as the World Health Organization (WHO) (Bui et al., 2021; Förster, 1999; Gwenzi et al., 2015; Thuy et al., 2019; Wilbers et al., 2013), which is summarized in Table 1-2.

Table 1-2: Rainwater Quality Index and Allowable Ranges for Potability

Parameter	Units	National Guideline	WHO Guideline	Description of Significance
pH	-	6 – 8.5	6.5 – 8.5	pH, or the potential of Hydrogen, measures concentration of hydrogen ions in water, which can be used to determine the acidity or basicity within water environment (Snoeyink & Jenkins, 1980).
Turbidity	NTU	2	5	Turbidity represents the indication of suspended or dissolved particles within rainwater, which could be a pathogenic risk as it can consists of fine organic matter, fine inorganic matter, soluble organic compounds, and microorganisms (Snoeyink & Jenkins, 1980).
Total Dissolved Solids (TDS)	mg/L	1000	1000	TDS indicates the dissolved concentration of colloidal as well as inorganic and organic substances in rainwater. Its assessment is primarily similar to that of turbidity.
Nitrite	mg/L	0.05	3	Nitrate ( $\text{NO}_3^-$ ) and Nitrite ( $\text{NO}_2^-$ ) are core components within the nitrogen cycle which refers to the conversion and circulation of organic nitrogen within the environment. These parameters serve as potential nutrients for the development of algae development which can toxify rainwater in storage.
Nitrate	mg/L	2	50	
Arsenic	mg/L	< 0.01	< 0.01	Heavy metals are toxic for human health. Exposure pathway is primarily through drinking water. Some heavy metals (arsenic, mercury, lead), which can bioaccumulate in the body, are carcinogenic with variable other associated chronic diseases.
Mercury	mg/L	< 0.001	< 0.006	
Lead	mg/L	0.01	0.01	
Cadmium	mg/L	< 0.003	< 0.003	

Iron	mg/L	< 0.3	0.3	Total coliform and E. coli serve as the most basic and affordable microbial indicators for harmful pathogens in water quality assessment. It is one of the most basic sanitary tests for potable water.
Zinc	mg/L	< 2	< 4	
Nickel	mg/L	0.07	0.07	
Chromium	mg/L	0.05	0.05	
Total coliform	CFU/100 mL	< 3	< 1 – 27	
E. coli	CFU/100 mL	< 1	< 1 – 4.48	

### 1.2.3 Rainwater Harvesting Systems and Practices

#### 1.2.3.1 Technical Considerations

In a modern rainwater collection system, components consists of (1) collection ; (2); conveyance (3) storage; (4) treatment; and (5) distribution (Ross et al., 2022). Collection and conveyance components consist of a catchment element and transportation network. Dimensional considerations for collection and conveyance units primarily rely on precipitation availability and capacity of storage units. Primary considerations for treatment units are flow capacity, which entails the necessary retention for adequate in-line treatment and output volume necessary for distribution needs. Distribution system vary from simple to complex – simple outlet valves to piped networks connecting to household utilities – those design can be determined and adjusted based on the need and budget of users.

Rainwater is increasingly becoming a source of freshwater alternatives for areas with limited access in both developed and developing countries around the world. However, due to the autonomous nature of rainwater harvesting and varying degree of regulations depending on national capacity, rainwater can be viewed as public health hazard due to its potential as contamination carriers from the environment. As such, one of the most important metrics to evaluate effectiveness of a RWHS design is its output quality of potable water. Input quality is mainly assessed via the degree, or lack thereof, of contamination in collected rainwater, which typically stems from environmental conditions and component materials. Particularly, collection and storage components are most susceptible to contamination via roofing and container materials.

Roofing contamination can happen by two main pathways – direct atmospheric deposition or organic debris which is fauna and flora in origin. Alternatively, leakage from material that comprise the catchment area as a result of degradation contains particulate and dissolved matter, which contribute to considerable contamination to roof runoffs. Studies have shown that metals with during exposure to environmental conditions and runoffs can leak dissolved metal particulates into liquids. Potential dissolved metal leakage are copper via clay or concrete tiles, zinc and cadmium via zinc gutters and galvanized metal roofing, and lead or mercury via asphalt materials (Despins et al., 2009; Förster, 1999; Galster & Helmreich, 2022; Van Metre & Mahler, 2003). However, there are studies, in contrast, that observed insignificant changes in trace dissolved metals in metal and asphalt roofs (Hart & White, 2006), which indicates location-based and, possibly, climate-based disparity between results on contamination sources in rainwater catchment roof (Campisano et al., 2017).

While not as visible as a contaminant source, rainwater storage units if ill-maintained can create an environment that facilitate hazardous growth. Particularly, storage contamination can occur when bio-chemical

conditions within storage units facilitate latent development elements toxic to human health and harmful to maintenance conditions of system. For example, rainwater is naturally acidic, which can create environment that enable microorganism growth (Sánchez et al., 2015). However, in some studies, it is revealed that prolonged storage of rainwater in concrete tanks is beneficial. Specifically, it serves to promote retention time and, thus, contact time of collected rainwater with concrete materials, which raises potassium and calcium concentration. As a result, alkalinity of stored rainwater is reportedly higher than its initial measurement, which was observed to inhibit growth of coliform bacteria (Campisano et al., 2017; Despins et al., 2009; Sánchez et al., 2015; Scott & Waller, 1987). In addition, increase storage time remove contamination via sedimentation, which remove a significant number of suspended particles of both organic and inorganic sources with minimal risk of re-suspension (Dissanayake & Han, 2020; Owusu-Boateng & Gadogbe, 2015; Spinks et al., 2005). In comparison, metal and plaster (polyethylene) cisterns present problematic leachate into stored rainwater. For metal tanks, contamination reflects the same issue with that of metal roofs, where potential trace metals of lead and copper can be imparted in higher concentration depending on storage duration (Despins et al., 2009; Hart & White, 2006). Polyethylene-based cisterns introduce an emerging issue with microplastic fibers. There are studies that mentioned that rainwater storage in plastic cisterns indicate concern of organic contaminants (Despins et al., 2009). However, there is a lack of study that specifically investigate the leakage of microplastics in RWHS despite recent studies demonstrating that polyethylene can leak up to 5000 fibers per liter given acidic condition (Mortula et al., 2021).

### 1.2.3.2 Rainwater Harvesting Systems in the World

Rainwater harvesting technology is not novel, it is only underutilized due incapability to streamline implementation process and scale. Another obstacle to rainwater utilization rate is its autonomy, or decentralization, which requires high degree of regulatory framework to effectively enforce public health code. This section will review (1) RWHS benefits under selected international practices and strategies (Table 1-3); (2) RWHS legislative initiatives around the world (Table 1-4); and (3) RWHS application and design in selected case studies around the world (

Table 1-5).

On a global scale, the definition of RWHS refers to direct collection of rainwater using catchment, conveyance, and storage apparatus for potable and non-potable purposes. Research regarding RWHS has increased at an exponential rate over the past two decades as water shortage around world is increasingly putting pressure on the global water economy. Specifically, RWHS is seen by the scientific community as a provider for sustainable and cost-effective water (Hafizi Md Lani et al., 2018), which can reduce piped water use by 18 – 53% in addition to energy and operational costs (Lucas et al., 2010). RWHS are increasing in trends among developed countries like the United States of America, Canada, and Australia, despite it also being the source of controversy (Despins et al., 2009; Ross et al., 2022; Thomas et al., 2014). However, due

to availability of modern technology and improved living standards, controversial concerns are purely perception-based not fact-based (Reyneke et al., 2020). Approaches that utilize RWHS are assessed to be practical regardless of scale of implementation with few limitations in forms of environmental and system requirements (Matos et al., 2013; Musz-Pomorska et al., 2020). As a result, application of RWHS can provide multi-faceted benefits that satisfy the pillars of sustainability. Specifically, RWHS-driven improvements represent the binding essence of technology in harmonizing crucial aspects of human development in the world, namely the environment, economy, and society (Table 1-3).

Table 1-3: Benefits of RWHS implementation around the world as sustainable practices

Countries	Benefits	Sustainability Dimensions			Source
		Environmental	Social	Economic	
Malaysia	Implementation of RWHS at study site could decrease piped water demand by 34% and flood peak by 10%.	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	(Shaaban & Appan, 2003)
Korea	Modelled RWHS implementation would reduce flooding by 10%	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	(K. Kim & Yoo, 2009)
Uganda	RWHS implementation alleviated water shortage, improve local water management, and reduce water-related health conditions.	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	(Baguma & Loiskandl, 2010)
Jordan	RWHS reduced dependence on surface and groundwater and improves health risk related to water shortage.	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	(Abdulla & Al-Shareef, 2006; Khaleq & Dziegielewski, 2006)
Nigeria	RWHS increased availability of water used for local production, consumption, and irrigation.	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	(Aladenola & Adeboye, 2010)
Australia	Households implementing RWHS experienced low water-related spending, which reduced water demands and delayed additional development of water infrastructure	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	(Coombes et al., 2002; Tam et al., 2010)
Canada	Pilot site of RWHS demonstrated reduced peak flood and increased water conservation, which promoted alternative domestic water sources.	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	(Farahbakhsh et al., 2009)
UK	Utilization of RWHS resulted in reduced peak water demand as well as peak flood at implemented site.	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	(Fewkes, 2012)
USA	RWHS supplemented water needs for areas with low water accessibility, improving local WASH conditions.	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	(Jones & Hunt, 2010)

Regarding the legislative aspect of RWHS, several countries around the world has initiatives that encourage and directly incentivize adoption of RWHS. For example, Germany introduced rebates and tax exemptions for implementation of RWHS (Herrmann & Schmida, 2000), while Spain and Belgium requires new buildings to implement RWHS if certain roof sizes are met (Domènech & Saurí, 2011). In East Asia, Japan offers subsidies and loans necessary for rural development of RWHS (Furumai et al., 2008), while

Taiwan is progressing its RWHS guidelines as its first of many steps in sustainable water development (Cheng et al., 2006). In Africa, developing countries such as Uganda and Jordan are both making initiatives in the integration of RWHS as core value in their water management policy, demonstrated by Uganda with its provision of incentives in finance and building materials (Baguma & Loiskandl, 2010). Overall, RWHS legislation is making steady progress among developed countries and developing countries (Table 1-4), which indicates a universal growing concern for shortage of centralized freshwater distribution.

Table 1-4: RWHS legislation and incentive in the world

Country	Legislative Initiative	Source
Taiwan	Initiative considers rainwater as alternative source of domestic water that can be harnessed via RWHS and issues guidelines on implementation of RWHS.	(Cheng et al., 2006)
Japan	Government legislation supports installation of RWHS via financial aids and low interest loans.	(Furumai et al., 2008)
Australia	A maximum of 500 AUD in rebate value is issued by the government for households interested in implementation of RWHS.	(Rahman et al., 2012)
Uganda	Financial subsidy and materials necessary for implementation of RWHS are provided by government in rural areas.	(Baguma & Loiskandl, 2010)
Jordan	Rainwater and RWHS are core integration for water resource management policy in the government.	(Khaleq & Dziegielewski, 2006)
Spain	Legislation mandates implementation of RWHS in new buildings with garden area meeting requirement thresholds.	(Domènech & Saurí, 2011)
Belgium	Legislation mandates implementation of RWHS in new buildings with total roof area exceeding 100 m <sup>2</sup> .	(Domènech & Saurí, 2011)
Germany	Buildings implementing RWHS are exempted from stormwater taxes.	(Herrmann & Schmida, 2000)
Brazil	Initiative promoted RWHS programme installing more than one million rain storage cisterns in areas with semi-arid climate.	(Domènech & Saurí, 2011)
USA	State government of Texas issues rebates and tax exemption for implementing rainwater harvesting practices.	(Domènech & Saurí, 2011)

Application of rainwater is categorized into three main group: (1) primary use, covering drinking and cooking, hygiene, laundry, toilet, and outdoor use; (2) secondary use, covering drinking and cooking, hygiene use; and (3) tertiary use, covering laundry, toilet, outdoor use (Thomas et al., 2014). RWHS designs and prototypes around the world have been assessed to be well-received by users, with no evidence of acute health hazard presented in any study. RWHS satisfaction has been achieved throughout various studies that were examined, which indicates the flexibility of rainwater harvesting given the diversity in RWHS form factors globally (

Table 1-5). Notably, Ross et al. (2022) proposed a comprehensive system valued roughly between 25,000 – 45,000 AUD (~15,000 – 30,000 USD) for implementation at community-level in rural regions of Australia and Vietnam – the proposed developing country counterpart. With a consistent performance of 4 – 50 m<sup>3</sup>/day, service capacity is able to provide for approximately 200 – 1000 users in rural communities for primary use in Vietnam, while Australia will have a lower service parameter due to higher water use per capita. However, it is important to noted that implementation costs and public perception still constitute a significant probability of RWHS acceptability, which makes RWHS optimization all the more important.

Table 1-5: Examples of RWHS implementations and designs in the world

Country	Scope of Implementation	Application and Capacity	Catchment Material	Storage Material	Treatment Method	Reference
United States	Residential Household	Primary use: 50 – 75 m <sup>3</sup> capacity. Secondary use: 10 – 20 m <sup>3</sup> capacity	Metal; asphalt shingle; clay/concrete tiles.	Polyethylene; galvanized steel; seamless aluminum	First-flush; in-line UV treatment; batch chlorination (very rare)	(Thomas et al., 2014)
Canada	Residential Household	Secondary & Tertiary use: N/A	Metal; asphalt shingle	Plastic (polyethylene); concrete	First-flush; in-line UV treatment; heat tank; sand filtration; fine mesh filtration (20 micrometers - μm)	(Despins et al., 2009)
Australia	Residential Community	Primary use: 365 m <sup>3</sup> capacity	N/A	Galvanized steel	pH neutralizer; mesh filtration; heavy metal filtration; UV sterilizer	(Ross et al., 2022)
Poland	Residential Household	Primary use: 7 – 9 m <sup>3</sup> capacity	Metal; clay tiles	Polyethylene (overground); Concrete (underground)	Mechanical (sedimentation); Mesh filtration	(Musz-Pomorska et al., 2020)
Portugal	Commercial Building	Secondary & Tertiary use: 250 – 325 m <sup>3</sup> capacity	ethylene tetrafluoroethylene	Polyethylene	N/A	(Abdulla & Al-Shareef, 2006; Matos et al., 2013)

### 1.2.3.3 Rainwater Harvesting in VMD: Status and Shortcomings

As previously discussed, salinity intrusion is one of the leading causes to the degradation of surface water and groundwater in VMD. However, it is far from the only one. While surface water faces inorganic and organic contamination from open latrine and debris (UN, 2020), groundwater contains trace dissolved metals in addition to arsenic contamination (K. P. Nguyen & Itoi, 2009). In 2006, rainwater use as primary water sources (23%) alongside lakes, rivers (25%), and wells (26%) (GSO, 2008). However, rainwater, despite its availability, were slowly overtaken by both surface water and groundwater as the most used sources for potable water in the form of private taps and drilled pump wells (GSO, 2020b). Over the past decade, rainwater utilization has fluctuated in the period between 2010 and 2020 as piped water and drilled pump well become popular (Figure 1-6). Despite advancement in surface and groundwater technology, rainwater remains the third primary source of water for local residents with only traditional sedimentation methods (Özdemir et al., 2011), which indicates a general perception of consistency in regional rainwater quality. Nevertheless, current practices in rainwater utilization may vary between regions and occasional cases of contamination due to improper treatment and storage technique during dry season.

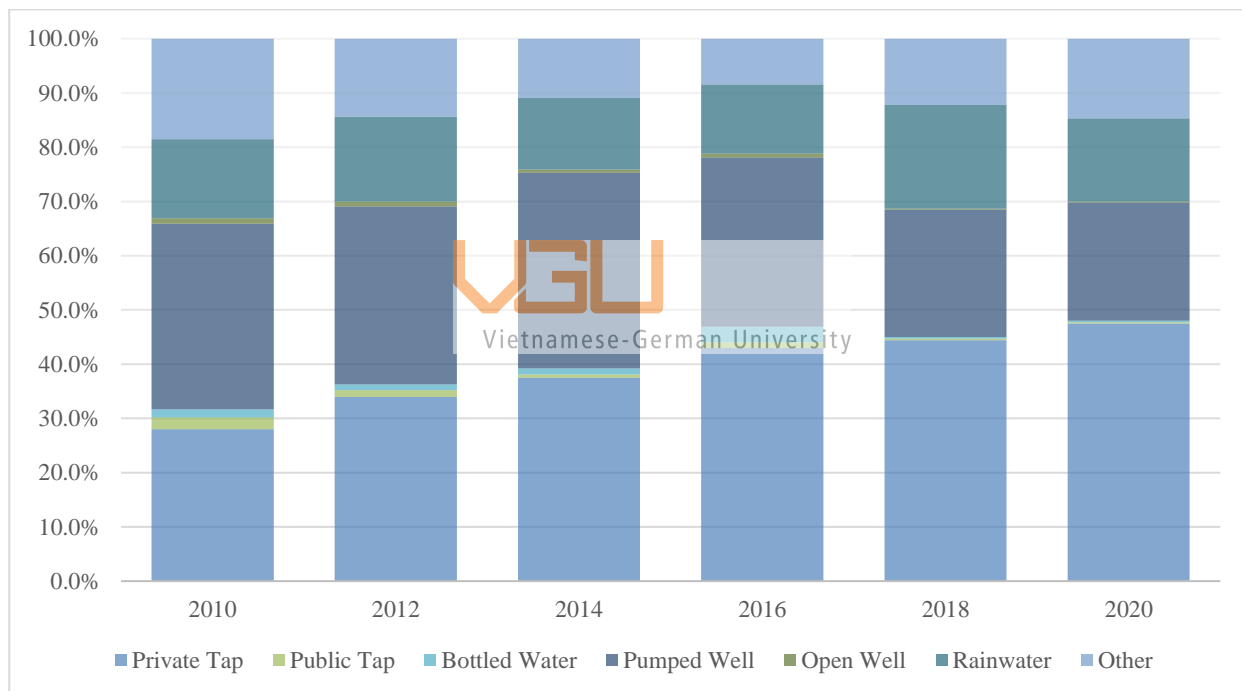


Figure 1-6: Main Sources of Drinking Water Between 2010 – 2020 in the Vietnamese Mekong Delta. Figure Constructed using data from GSO, 2022

There are still gaps in research regarding rainwater harvesting in Southeast Asia, especially in Vietnam, which is indicated by a disparity in integrated rainwater harvesting research. Specifically, previous studies seem one-dimensional by focusing mostly on water quality, health impact, and technical aspects (Ross et al., 2022; Sánchez et al., 2015; Semaan et al., 2020; Thuy et al., 2019; Wilbers et al., 2013); and studies regarding perception and awareness of rainwater harvesting as a sustainable practice are most often neglected (de Sá Silva et al., 2022; Islam et al., 2011). However, in the implementation of RWHS, there is a social and economic components that are usually overlooked, which can introduce a skewed perspectives to rainwater harvesting in general (de Sá Silva et al., 2022). For example, acceptability and perception of rainwater



harvesting as a sustainable practice is mostly not a concern for local users of rainwater; instead, utilization of rainwater in the area is driven by basic needs and desperate necessity rather than an awareness of the environment, which can potentially be neglected once piped water and groundwater are available (Islam et al., 2011).

A balanced and integrated research into technical, economic, social and environmental impact is essential to rainwater harvesting proliferation in VMD, which is also the biggest shortcoming for RWHS research. Specifically, taking into account the sustainable principle of rainwater harvesting, primary barriers to rainwater harvesting in Vietnam can be demonstrated via three dimensions: technical barriers, social barriers, and economic barriers.

Technical barriers mainly manifest in the form of hydrological conditions and availability of data (a) poor water quality; (b) drought during dry season; and (c) lack of precise data at regional level. Poor water quality suggests a high concentration of organic and inorganic particulate contaminants, which can be mitigated with proper scientific understanding of maintenance process. However, constraint regarding viable period for harvest significantly reduce the potentials for rainwater utilization. As a region within the tropical monsoon zone, VMD not only has high annual precipitation, but it also has high seasonal variability with high precipitation during wet season and extreme drought during dry season, which affects design consideration for RWHS (Mekong River Commission, n.d.). In term of domestic utilization, current RWHS in VMD are characterized by limited catchment area and storage capacity, which would be suitable if precipitation was consistently periodic in an annual cycle (Thuy et al., 2019). However, given the actual circumstance, there is a possibility that current domestic RWHS are not able to harness and maximize rainfall collection. For example, Thuy et al. (2019) reported that residential-scale rainwater harvesting is frequently hampered by limitation of catchment roofs and storage tanks, which failed to deliver sufficient water supply for annual uses. Consequently, the majority of surveyed households in that study reported shortage of rainwater throughout the six-month dry season. Özdemir et al. (2011) also observed that storage capacity is the most significant barrier to rainwater gathering and that around one-third of households in the Mekong Delta region lack access to water during the dry season.

Furthermore, drawbacks in data availability can impact the planning and design phase of a RWHS. Analysis of hydrological conditions and technical performance determine capacity for RWHS to effectively sustain rainwater supplementation during dry season. However, meteorological data, such as rainfall data, is essential for visualizing RWHS feasibility and performance due to its direct correlation to the sizing necessary for operational costs or benefits of the catchment area and storage cistern. For example, cistern capacity can be overestimated given availability of only average monthly rainfall, which can be optimized via more precise daily reporting of precipitation (D. C. Nguyen & Han, 2017).

Social barriers constitute challenges with both the people and the government. Rain harvesting is an autonomous coping mechanism of local residents during severe water shortage in the past (Özdemir et al., 2011). It is common for a lack of social knowledge regarding RWHS to be prevalent in urban area, notably when surface-based and ground-based water extractions for centralized water systems are increasingly widespread, which leads to a side effect of expressed disapproval for rainfall utilization (Y. Kim et al., 2016).

Negative impression of RWHS originates from two main causes: (1) previous failures in RWHS implementation; and (2) poor rainwater quality as a result of perceived air pollution. However, properly treated rainwater in effect RWHS has demonstrated its safety for human consumption in Vietnam (Dao et al., 2017), which indicates an urgent need for improved education regarding rainwater utilization for the public, professionals, and policymakers. Fortunately, rural areas are more likely to have favorable attitudes toward rainwater due to chronic water shortage as a result of natural disasters (flood, drought and salinity intrusion) or poor utility infrastructures, which instills a sense of necessity and resourcefulness. In fact, there is a considerable number of impromptu practices regarding rainwater collection as a result of local social knowledge and autonomous coping mechanisms in Vietnam (Bui et al., 2021; Özdemir et al., 2011; Thuy et al., 2019). Overall, education and social engagement for rainwater harvesting are still in working progress for the majority in Vietnam.

Institutional framework on rainwater harvest is also another challenge in the social dimension. Rainwater is legally regarded an essential source for domestic water supply as stated in Law No. 17/2012/QH13 on Water Resources, in which rainwater use is encouraged throughout Article 4, 39, 41, and 54. However, the legislation provides ambiguous information concerning the technical specificity on rainwater harvesting structures. For instance, MONRE issued Circular No. 32/2011/TT-BTNMT providing only guidelines on rainwater quality without expressly identifying the objective for utilizing rainwater. Given the growing water shortage from population growth and development in VMD, there is an urgent need for additional legal framework for rainwater harvesting and RWHS to ensure that public health and safety can be upheld. Specifically, these additions should be made by MOH and The Ministry of Construction (MOC). MOH has no guideline on rainwater quality standard and no specification on its uses or potability, all the while having guidelines on drinking water standards without the inclusion of rainwater. In addition, there are no public programs that support people financially in RWHS development and construction which is usually conducted and funded wholly by NGOs and volunteering (UN, 2020). However, that is also a problem in itself because of the lack of regulations on quality control of structure and construction specific for RWHS. Therefore, MOC needs to have specific technical guidelines concerning RWHS for household water supply. Social supports, especially from authoritative figures, can have strong impact on the acceptability and implementation of RWHS in VMD. For example, Baguma & Loiskandl (2010) found that socio-economic status is indicative of RWHS acceptability. Instead, governmental subsidies for up-front costs were observed to have a stronger correlation to adoption of rainwater harvesting in Uganda. Overall, the legal framework in Vietnam encourages rainwater use but does not incentivize its proliferation and implementation nor does the legal framework provide people with all guidelines on technical specificities including quality, dimensioning, and capacity.

Finally, economic barriers describe the limited fiscal capacity of local residents. While it is discussed that social supports are indicative of acceptability of rainwater harvesting in some case studies, economic capacity and capitals are the core for adoption in the absence of governmental subsidies. The initial investment cost is the greatest barrier to entry for RWHS. Approximately forty percent of households sampled in Binh Dai district, Ben Tre reportedly cannot afford the initial cost of RWHS as a one-time payment, despite preferring rainwater as a primary water source. Nguyen and Han (2014; 2017) estimated that household-level rainwater

storage of 2 m<sup>3</sup> in capacity would individually cost between 200 – 400 USD – eight times higher the monthly per capita income. Moreover, maintenance costs can discourage proper upkeep for RWHS, which can result in poor water quality from organic and inorganic particle formation as previously discussed.

## 2. DATA AND METHOD

### 2.1 Study Area

#### 2.1.1 Ben Tre

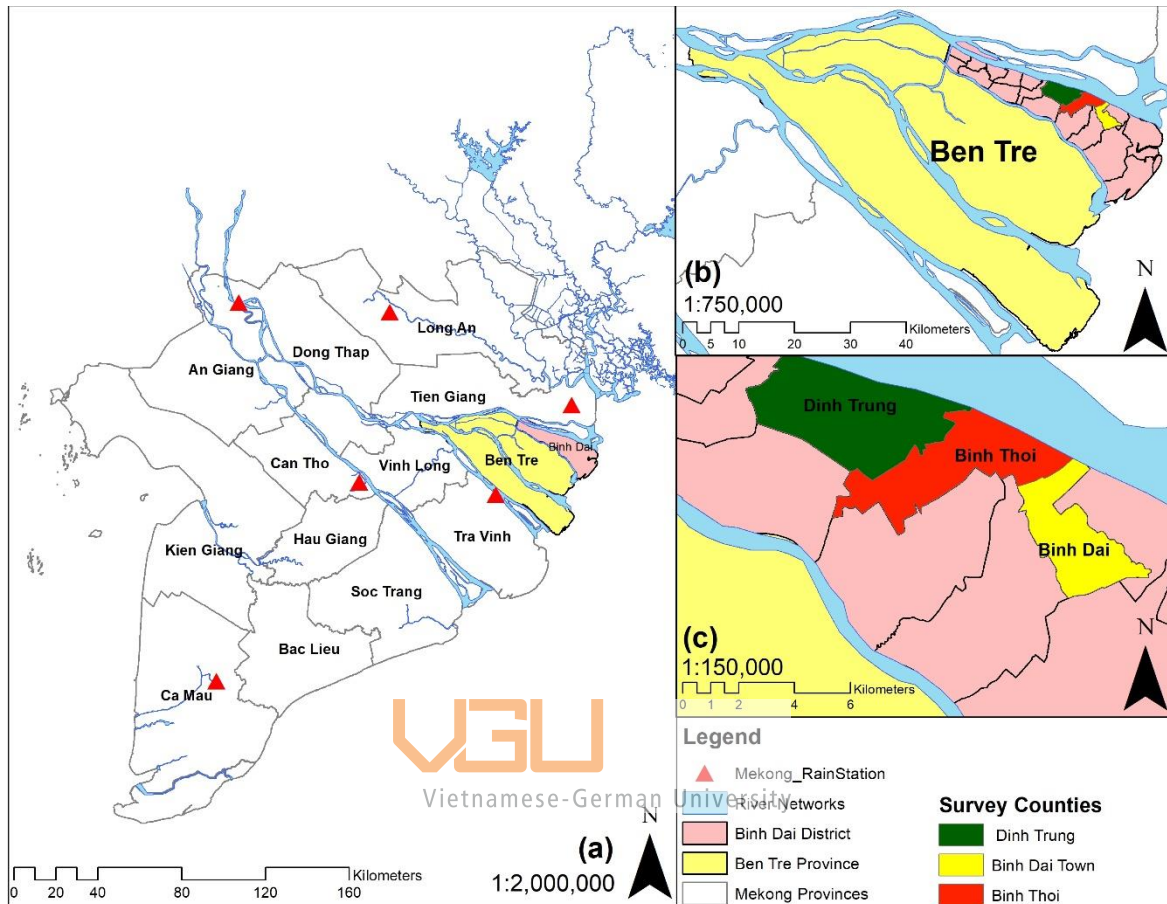


Figure 2-1: (a) Mekong Delta Provinces and River Networks; (b) Ben Tre Province and Binh Dai District; (c) Selected Communes for Survey and Research

### Topography

In general, Ben Tre mostly has plain terrain, averaging 1–2 m above sea level. While Ben Tre has the highest points (usually sandy mounds) reaching 3–5 m above sea level, its lowest points are at 0.5 m, notably in the district of Thanh Phu and Binh Dai. A large percentage of the landmass in Ben Tre is light woodlands with mangrove forest ecosystem along the coastline. However, with the progressing rate of environmental degradation in Ben Tre, the coastal ecosystem that contribute to the attenuation of coastal flooding and salinity intrusion is deteriorating, which introduced issues of fresh water deficit for productions in recent years (T. C. S. Nguyen et al., 2013).

### River System and Hydrological Characteristics

The Mekong River is the Ben Tre 12th longest river in the world, which provides a plethora of hydrological benefits regions within its basin. Ben Tre is located in the lower Mekong River that flows into the East Sea (South China Sea), which benefits the are greatly via provision of intricate water networks. Ben Tre has an interlaced network of rivers with a total length of approximately 6,000 km, which boasts highest

national river density in the country (2.7 km/km<sup>2</sup>) (V. K. Le et al., 2013). The Lower Mekong River splits into two main rivers before reaching the ocean – the Tien and Hau river. The Tien River, before pouring into the sea, splits into four branches, creating the fan-shaped border that defines the three islands (Bao, Minh, and An Hoa) of the province with a combined coastline of 65 km. These distributaries are Co Chien River (80 km), Ham Luong River (70 km), Ba Lai River (55 km), and My Tho River (90 km). All rivers have a common direction of Northwest - Southeast, all flowing into the East Sea with wide estuaries. With such an extensive network of inland streams, irrigation and navigation within the province is convenient, which enables agriculture to be the largest economic sector within the province.

The hydrological regime in Ben Tre province is dominated by the semi-diurnal tide as a result of the effects from the river networks, the low-lying elevation, and the East Sea (V. K. Le et al., 2013). The Lower Mekong River has three main tributaries essential to the flows in Ben Tre province, namely Ham Luong, Co Chien and Cua Dai rivers. This provides the province with an abundance of upstream flow that could exhibit a peak discharge of 15,000 m<sup>3</sup>/s in to the East Vietnam Sea (V. K. Le et al., 2013). In contrast, dry season would experience low discharge that enables drought and, subsequently, saline intrusion in the coastal regions of the VMD in general and Ben Tre province in particular (MDP, 2013). Consequently, about 70% of coastal areas in Ben Tre province at risk for freshwater deficit in the dry season (T. S. Le et al., 2021).

Changes in the hydrologic patterns in the VMD have been found in some recent studies that impact regional sedimentation, leading to hydrogeological changes to riverbed (i.e. flow regime alteration and riverbed incision) (Binh et al., 2020a; Eslami et al., 2019). In particular, Binh et al. (2020a) observed a decrease in the water level in the dry season in recent years, while (Eslami et al., 2019) identified a increase in the tidal amplification (i.e. tidal amplitude in the rivers is going up by 2 cm/year) in the VMD. Studies have observed that most of these potentially adverse changes to the hydrological regime are attributed to anthropogenic activities, such as sand mining, and upstream hydro-impoundment developments, and climate change (Loc et al., 2021a). As a result, the increasing intensity of salinity intrusion has begotten the loss of water security and, subsequently, local livelihoods (Loc et al., 2021b).

## Climate

Ben Tre is located in the sub-equatorial monsoon tropical climate, although it is not affected by the tropical monsoon season, which is mostly attributed to its latitude ranging only between 9 – 10° North while most Pacific monsoon channels occur around 15° North. The wind mode seasonally has two main modes of operation: northeast monsoon (obstruction wind) and southwest monsoon. The northeast monsoon operates from December to April next year, characterized by drought. The southwest monsoon operates from May to November, characterized by elevated temperature and humidity. Between the two southwest and northeast monsoon seasons are two transition periods with wind direction changing in November and April. Therefore, the climate is seasonally differentiated into the rainy season (May to October), and the dry season (November to April). During the rainy season, southwest wind influences the high humidity and rainfall cumulatively reaching 1250 – 1500 mm throughout the season, which accounts for 94 – 98% of annual rainfall while off-season rainfalls accounts for the remaining percentage. The temperature is consistent throughout the year with an average annual temperature between 26°C to 27°C. Monthly average temperature is always above 20°C

with a monthly differential range between 3 – 4oC. The number of sunshine hours reaches over 2,300 hours/year.

The climatic conditions in Ben Tre have both positive and negative effects, especially under the impact of climate change and persistent geo-political water security issues (Eslami et al., 2021; M. T. Nguyen et al., 2019). On the positive side, sunlight, temperature, and humidity are all climate-driven factors that bolster the productive capacity of agriculture, husbandry, and aquaculture. However, the same factors that benefits the region are also contributors to the presence of pests and fungi year-round. Moreover, with the increasing prevalence of drought and salinity intrusion within the VMD and Ben Tre, shortage of freshwater for all purposes are becoming inevitable (M. T. Nguyen et al., 2019)

### **Socio-economic**

According to the General Statistics Office of Vietnam (2020a), Ben Tre relies on three main economic sectors for development – (1) agriculture, fishery, and forestry; (2) industry, product manufacturing (hand-crafted), and infrastructure construction; and (3) commercial services and tourism. Sector one accounts for 60% of regional GDP with an estimated growth of 5 – 6% annually, followed by sector two – a projected fast growing sector currently taking up 14% of regional GDP. Sector three experiences the lowest GDP growth (7%) but diversification and subsidy are ongoing to develop all sectors equally. In recent years, salinity intrusion has significantly impact freshwater availability in the area, leading to declining trends in water dependent sectors such as sector one and sector two.

#### **2.1.2 Binh Dai District**

Binh Dai district is located on one of the main three island of Ben Tre – An Hoa island – located in the northeast of Ben Tre province; bordering Chau Thanh district to the west; east by the sea; bordering My Tho river in the north, separated from Tien Giang province; The south borders the Ba Lai River, separating it from Giong Trom and Ba Tri districts. Administratively, the district includes Binh Dai town and 19 communes: Tam Hiep, Long Dinh, Long Hoa, Phu Thuan, Chau Hung, Vang Quoi Tay, Vang Quoi Dong, Thoi Lai, Phu Vang, Loc Thuan, Dinh Trung, Phu Long, Binh Thoi, Thanh Tri, Dai Hoa Loc, Binh Thang, Thanh Phuoc, Thua Duc, Thoi Thuan.

Binh Dai often suffers from salt water intrusion into the communes in the middle of the island such as Dinh Trung and Binh Thoi. Primary livelihoods in the region includes agricultural (gardening, farming) and aquacultural (shrimp farming) productions. Binh Dai is one of the three coastal districts of Ben Tre province with available potential due to the favorable nature of the 27-km coastline, the interlaced system of rivers and canals, forming an ideal ecological environment not only to develop fisheries in all three areas of salt, brackish and freshwater, but also create favorable conditions for the development of fisheries. Significantly, some of the industrial productions in coconut-based handicrafts, seafood processing, ice production, and freshwater production.

Given the context of surface water salinization, recent research in Vietnam has suggested that the chronic salinization of surface water will not only impact key industries in Ben Tre, but also lower the community resilience in coastal districts of the province via reductions in tap-based drinking (T. S. Le et al., 2021). One of the reasons cited was the rate of tap water propagation in the Mekong Delta has plateaued as

freshwater supply from streams is increasingly limited; and the fact that saline tap water has also been reported as a consequence of the lack of saline treatment in standard water treatment facilities. As previously mentioned, Binh Dai is among regions with the lowest elevation above sea level, which increases its risks to salinity intrusion and drought significantly. In Ben Tre, rate of tap water use for drinking is below 50%, with rainwater accounting for 19.1% of drinking water source, and commercial freshwater accounts for 12.2% (GSO, 2020b). It should be noted that dependence on commercial freshwater also becomes one of the weak links leading to exacerbation in water-based resilience due to its economic unsustainability under the presumption that the monthly income per household in Ben Tre only averages around 3.5 million VND (~150 USD). As such, rainwater becomes an available and easily accessible source of freshwater, which requires further assessment in harvesting practices. For this thesis, the study area focuses on Binh Dai district in Ben Tre, specifically within three communes that was observed and predicted to be salinized the most within the province according to Loc et al. (2021a) – Dinh Trung, Binh Thoi, and Binh Dai Town. To further consolidates, the reason of significance for the chosen sites, further insights will be provided under the assessment of rainwater quantity and quality, and RWHS cost-benefit analysis therein.

## 2.2 Data Collection

**Primary data** collection will mainly be done through field survey which comprises of two main components – rainwater sampling and questionnaire interview. Both components were conducted at the same corresponding survey sites. Collected rainwater samples at interviewed sites were examined in laboratory using selected drinkability parameters in Table 1-2. Interviews will be conducting via a structured questionnaire (Appendix I), which will be designed based on the need for data presented in Table 2-1.

The questionnaire is divided into 4 main sections: General water use; rainwater perception and practices; technical consideration of current RWHS; and socio-economic details. Each of the section correspond to specific data analysis need. For instance, general water use and rainwater perception are quantitative and qualitative indicators that could provide insights necessary for the optimal determination of rainwater catchment and storage as well as viability of the system in terms of social acceptability and necessity in the study areas. Questions regarding technical aspect investigate information that reveals current materials of existing system and treatment practices common among locals. Finally, socio-economic questions will attempt to determine the household size that existing systems accommodate. Social and economic results will also be used to assess correlation between economic capacity and behavioral affinity to

**Secondary data** collection will primarily utilize datasets collected from open-source repository and available data with access from reputable research institute in Vietnam. For instance, rain gauge, historical salinity concentration, and historical groundwater level data will be accessed with permission from government agency such as the Southern Institute of Water Resource Planning (SIWRP) and researchers. Satellite data will be collected from open-source databases made available by the Center for Hydrometeorology and Remote Sensing (CHRS) in the USA. For cross-reference purposes on rainwater quality, secondary data obtained from literature will also be incorporated into findings in relevant chapters of the thesis. Purpose and necessity of each data item will be described in Table 2-1.

Table 2-1: Data checklist for thesis objectives

Data Type		Purpose and Use	Data Source	Acquisition Type	
				Primary	Secondary
Gauge-based Rainfall Data		Gauge-based rainfall will be used as a controlled, or observational, rainfall trends. has limited access, which does not provide enough data points for rainfall interpolation and visualization.	Research Institute	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Satellite-based Rainfall Data		Open-source satellite-based rainfall primarily will be used as data points for interpolation and visualization after observational correction based on gauge-based data.	Literature and Open-source repository	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Rainwater Quality Sampling		To determine the necessary treatment processes for collected rainfall, samples of rainwater at survey sites will be collected and analyzed using chosen parameter in literature review. Additionally, analyzed samples can be cross-referenced with studies conducted in the area previously for discussion.	Literature and Field Survey	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Water Demand Survey		Besides data on precipitation availability and rainwater quality, RWHS design will also need information on habitual water consumption of households at specific study site to better optimize the storage and catchment	Field Survey (Questionnaire) and Official Statistics	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Socio-economic Survey	Awareness	As previously mentioned, one of the social barriers to RWHS in Vietnam is local awareness and understanding of the significance in rainwater harvesting practices	Field Survey (Questionnaire)	<input checked="" type="checkbox"/>	<input type="checkbox"/>
	Economic Capacity	RWHS can be significant investment as several studies have pointed out, which can be a barrier to local residents. Survey economic capacity can provide a better overview of the capacity and willing for RWHS implementation in the population, which will serve as indications for overall RWHS acceptability.			
	Investment Willingness				
	Social Acceptability				



## 2.3 Method

### 2.3.1 Rainwater Assessment

#### 2.3.1.1 Quantitative Assessment

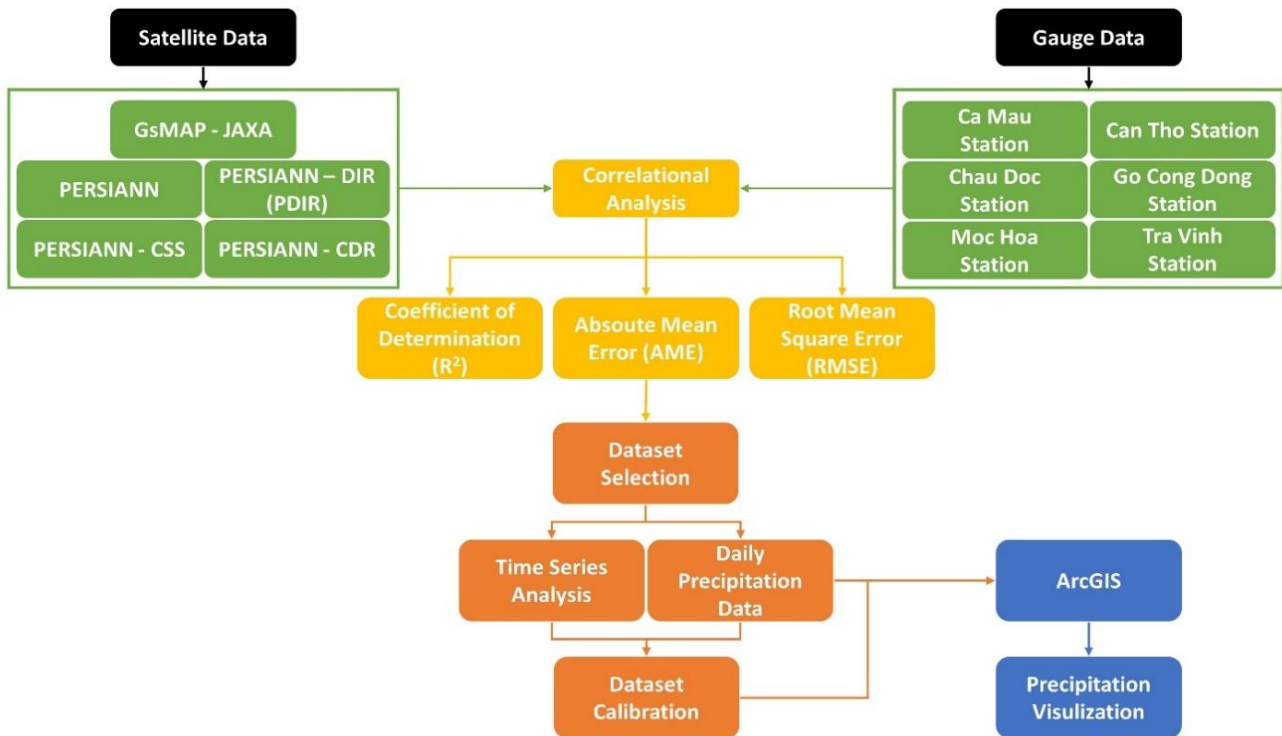


Figure 2-2: Framework for quantitative assessment method

Rainwater assessment will mainly focus on not only quantitative but also qualitative conditions of rainwater in the study area. Quantitative assessment will begin with the analysis of daily precipitation data retrieved from selected satellite-based precipitation datasets at coordinates corresponding to available rain gauge station collected. There are a total of eighteen rain stations installed in the VMD, and of those rain stations, only six were available for thesis research. As such, gauge-based data, which represents the most accurate historical precipitation in the VMD, is limited by its available data points. As a result, visualization of precipitation using interpolation algorithms will produce a significant margin of error, which is the reason for satellite-based data sets having a crucial role in quantitative assessment.

Satellite-based precipitation visualization are based on a combination of remote-sensing technique and machine learning to evaluate data retrieved from satellites around the globe. These datasets are available at multiple online repositories, which varies in techniques and resolutions. Given the variable satellite dataset available, selection and calibration of a single dataset are necessitated.

Figure 2-2 illustrated methodology used to select appropriate satellite datasets for analysis. First, correlational analysis will be conducted using compiled satellite-based databases and available rain gauge data. Statistical indicators used for analysis are Coefficient of Determination ( $R^2$ ), Absolute Mean Error (AME), and Root Mean Square Error (RMSE), which will provide overview of data consistency and deviation between gauged-based data and each satellite-based datasets at the corresponding rain gauge station. Formula for statistical indicators are presented as followed:

$$R^2 = 1 - \frac{SSR}{SST} = 1 - \frac{\sum_{i=1}^n (S_i - G_i)^2}{\sum_{i=1}^n \left( S_i - \frac{\sum_{i=1}^n S_i}{n} \right)^2} \quad (1)$$

$$AME = \frac{|\sum_{i=1}^n S_i - G_i|}{n} \quad (2)$$

$$RSME = \sqrt{\frac{\sum_{i=1}^n (S_i - G_i)^2}{n}} \quad (3)$$

Where *SSR* stands for Sum Squared Regression; *SST* stands for Sum Squared Total; *i* is the variable at corresponding data point *i*; *n* is the number of non-missing data points; *S<sub>i</sub>* = Actual observational satellite-based time series; *G<sub>i</sub>* is the expected gauge-based time series.

Expected selected datasets will have a relatively high *R<sup>2</sup>* with low *AME* and *RMSE* calculations, indicating its deviation from observed gauge data is minimal. After selection, dataset will be calibrated using a non-parametric statistical correction method. Corrected datasets will be used as input data for ArcGIS to interpolate and generate a raster of precipitation intensity across the spatial variation in the at the study area. Using this output, specific precipitation at specific survey point can be extracted using the coordinate recorded at each interview point in the study area.

Many methods exist for bias correction within expected dataset using observed datasets, of which the complexity, accuracy, and required skills also scale proportionally. Machine learning is rapidly becoming a superior, albeit vastly more complex, tool essential to the estimation, prediction, and correction of rainfall on surfaces. While regression, deterministic, and geostatistical relies on assumption of spatial and relational variability to estimate rainfall, machine learning is data-driven, which reduces its dependency on mathematical formulas and increases its capability in processing nonlinear relations meaning accuracy depends on training cycles between input and output (Q. Hu et al., 2019). At present, successful application of rainfall estimations and corrections are limited to some machine learning algorithms, most prominent of all is the the Artificial Neural Network (ANN) that is foundational to PERSIANN-based rainfall datasets; others includes association rule mining (Teegavarapu et al., 2009), fuzzy inference (Kajornrit et al., 2016). Ziarh et al. (2021) also demonstrated use of complex rainfall correction via machine learning algorithms that operates based on Category and Regression Tree (CART) model, or Random Forest (RF) model. In some studies, rainfall corrections were performed using statistical factor. For instance, methods for rainfall corrections via a multiplicative bias factor derived from a General Circulation Model (GCM) were proposed with consistent results (Bhatti et al., 2016; Ines & Hansen, 2006). In another study, Katiraie-Boroujerdy et al. (2020) conducted rainfall bias correction using Empirical Cumulative Distribution Function (ECDF or CDF), of rainfall data from multiple controlled (rain gauge) and observed datapoints across selected spatial quantile, which facilitate correction with the best possible accuracy given nonparametric spatial correction.

### 2.3.1.2 Qualitative Assessment

Qualitative assessment will focus on the concentration and existence of various parameters significant to the drinkability of collected rainwater, which is based on reviews of literature relevant to the conditions in the VMD. The evaluation process is depicted in Figure 2-3. Intended measurement of parameters in rainwater

samples will indicate the concentration of existing constituents in rainwater samples, which will be referenced with the allowable ranges specified in National Standard QCVN 01-1:2018/BYT and WHO guideline (Table 1-2). Using the index and guideline, parameters that do not meet the safety threshold will necessitate treatment processes for concentration regulation of constituents.

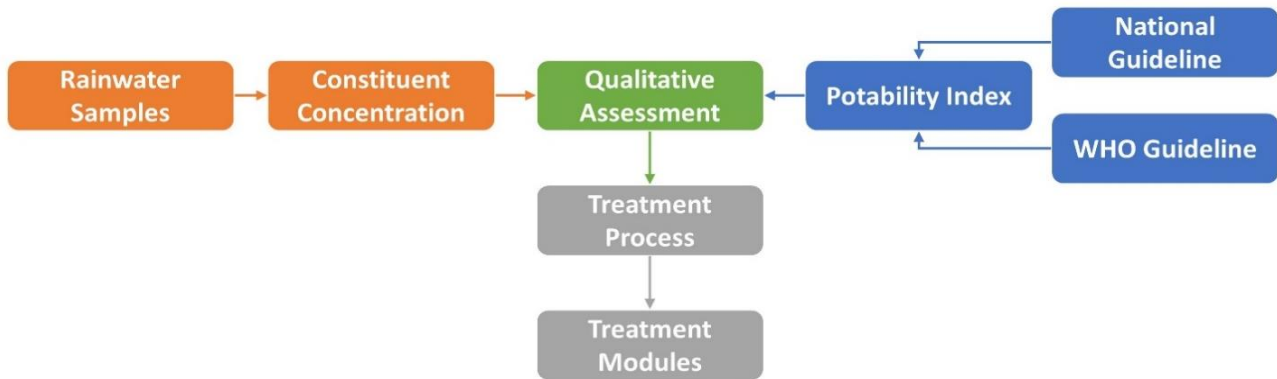


Figure 2-3: Framework for qualitative assessment method

### 2.3.2 Water Quality Analysis and System Design

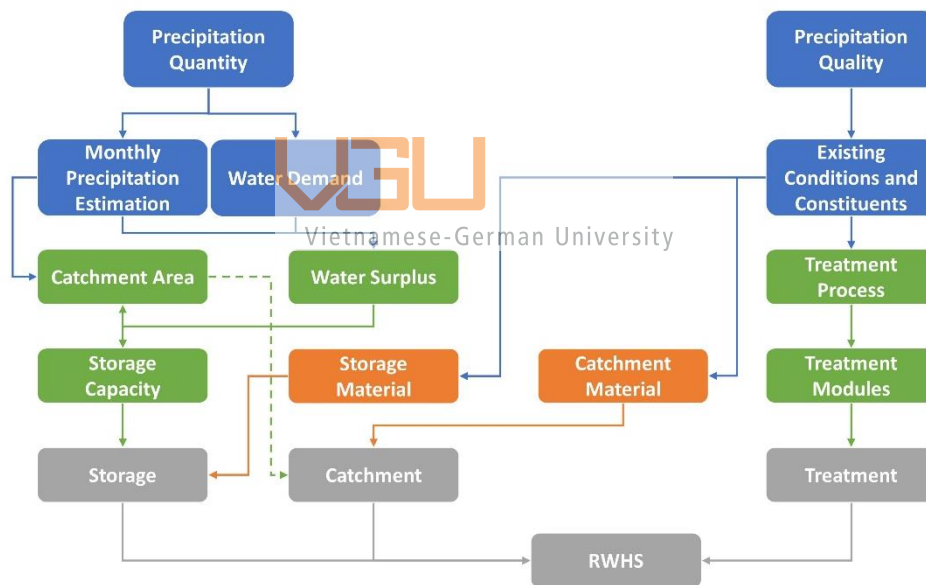


Figure 2-4: Method framework for RWHS design

Core parameters that will be tested includes physio-chemical properties such as pH, turbidity (NTU), TDS (mg/L), nitrite (mg/L), nitrate (mg/L); heavy metals arsenic (mg/L), mercury (mg/L), lead (mg/L), cadmium (mg/L), nickel (mg/L), chromium (mg/L); and microorganism indicators – total coliform (CFU/100mL) and E.coli (CFU/100mL). All parameters were tested in the lab.

Colony-forming unit (CFU) of E.coli and coliform is determined via implantation on agar-based bacteriological media on a petri dish, which will be incubated at  $36 \pm 2^{\circ}\text{C}$  for  $21 \pm 3$  hours according to the Vietnamese national standard for water quality sampling and microbiological analysis TCVN 8880:2011 (ISO 19458:2006). All equipment and chemicals used for experimentations were provided by the Vietnamese-German University whom environmental lab was available for thesis research.

As physio chemicals parameters, pH and TDS are measured using Horiba Laqua F-74 Benchtop Dual Channel pH/Ion/Conductivity/Resistivity/Salinity/TDS Meter. Turbidity is measured using Hanna Portable Turbidimeter HI98703. Heavy metals will be bulk tested using the High-Resolution Continuum Source Atomic Absorption Spectrometer for Flame and Hydride (contrAA 300 - Analytik Jena GmbH)

Nitrate in rainwater samples will be determined via spectrometric method. Analytical process for nitrate starts with 25 ml of rainwater sample, then adds 0.5 ml of sodium azide ( $\text{NaN}_3$ ) solution (0.5 g/L) and 0.2 ml of acetic acid (1.05 g/ml). The mixture will be dried via heat evaporation, then add 1 ml of sodium salicylate ( $\text{C}_7\text{H}_5\text{NaO}_3$ ) solution (10 g/l) before drying again. Next, add 1 ml of concentrate sulfuric acid ( $\text{H}_2\text{SO}_4$ ) solution (1.84 g/ml) and let settle for ten minutes before adding 10 ml of water and 10 ml of 50 g/l concentration of EDTANA solution ( $(\text{CH}_2-\text{N}[\text{CH}_2\text{COOH}]\text{CH}_2\text{COONa})_2 \cdot 2\text{H}_2\text{O}$ ). Finally, add 4 ml more water, and measure the absorbance of nitrate in the solution using the Shimadzu UV-1800 Spectrophotometer at 415 nm.

Similarly, nitrite determination via spectrometric method starts the preparation of chromogenic solution, which includes: 800 ml of distilled water, 100 ml of 85% phosphoric acid ( $\text{H}_3\text{PO}_4$ ), 10 g of sulfanilamide ( $\text{C}_6\text{H}_8\text{N}_2\text{O}_2\text{S}$ ), and 1 g of N-(1-naphthyl)-ethylenediamine di-hydrochloride ( $\text{C}_{10}\text{H}_7\text{NHCH}_2\text{CH}_2\text{NH}_2 \cdot 2\text{HCl}$ ). Then, add water to make up to a total of 1000 ml in volume. For analysis, add and mix 2 ml of the chromogenic solution into 50 ml of rainwater solution (adjust to pH between 5 and 9). After ten minutes, the absorbance of nitrite in the solution can be determined at 543 nm.

System design will be based on the literature-based and data-based analysis of rainwater availability and quality within VMD. In addition, field survey data on water use of residents at study area will be incorporated into the technical considerations for appropriate designs that accommodate the general demand in the study area. As illustrated in Figure 2-4, with a general estimation of monthly rainfall and water demand in the study area, a simplified water balancing table can be established, which will contribute to the sizing and dimension of the catchment area and the storage capacity. For rainwater quality, identification of existing constituents and the overall concentration threshold serves as an indicator for necessary treatment considerations for household implementation. Rainfall quality will also serve as a factor to refine the material selection phase of the RWHS as pertained to aforementioned discussion. Overall, rainwater quantity and quality at the study site are important basis on which the conceptual design of household-level RWHS is designed.

### 2.3.3 Cost-benefits Analysis

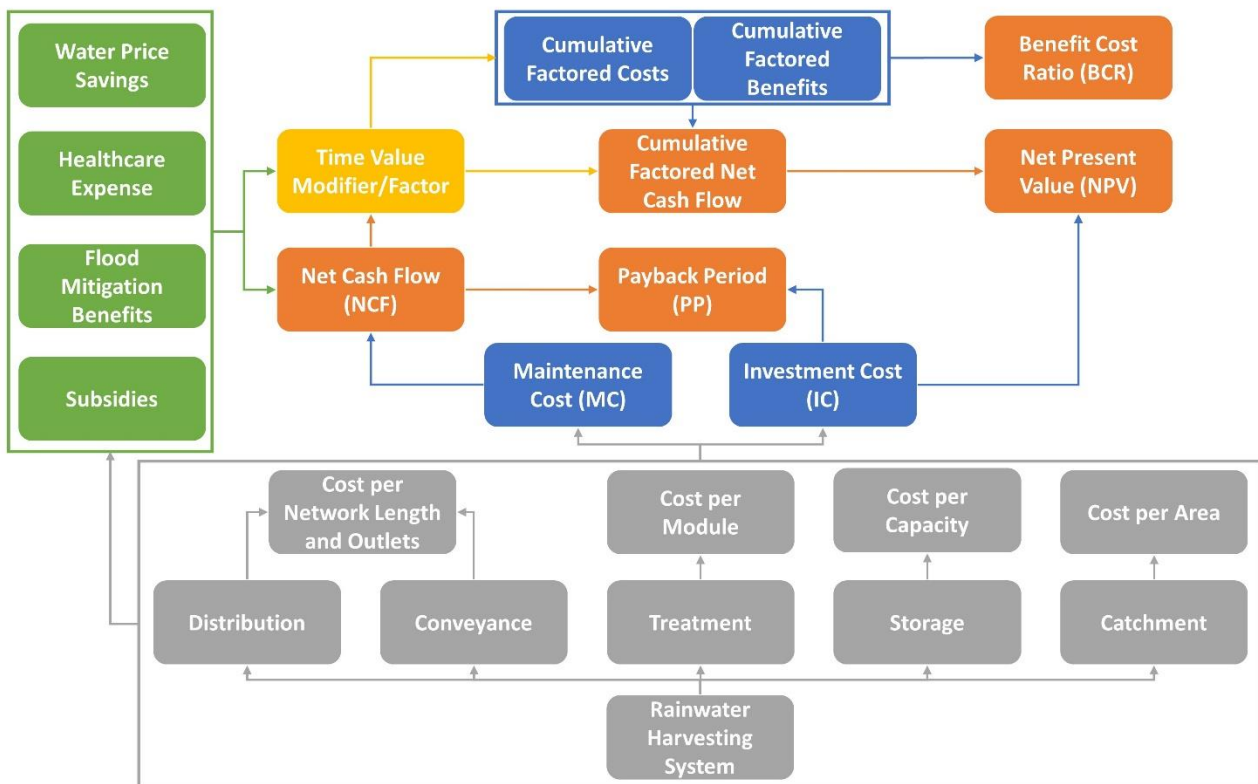


Figure 2-5: Framework for financial sustainability analysis

Cost-benefit Analysis serves to assess the long-term financial sustainability of RWHS and identify barriers need addressing through policy instrument. For this analysis, two main indicators determine the economic feasibility of RWHS implementation in the area – benefit-cost ratio (BCR) and net present value (NPV), which can be mathematically derived using collected data and hypothesized figures as illustrated in Figure 2-5. BCR basically weight the benefits provided against the costs incurred by the system which serves as a justification basis for implementation. However, BCR only accounts for the operational period of the system, and does not indicate the overall profitability of the system that accounts for discounted profits in comparison to initial investment cost. NPV represents net gain or loss of a project by accounting for the total profits adjusted to present value and the present investment cost, thus acting as a determinant for project feasibility.

The implementation of RWHS will impose not only investment costs (IC) on households, but also maintenance costs for continual operation. In economic assessment, capital costs represent the initial investment necessary for implementation, which are usually unaffected by annual discount rate. Continuous costs are recurring expenses required for continual operation of a system, such as maintenance cost, component replacement cost, and operation cost (power, water, etc.) over the estimated life span of the system. While replacement cost and operation cost (power consumption) can be estimated depending on available local economic market, overall maintenance cost varies case-by-case and system-by-system; most of the time, Khastagir and Jayasuriya (2011) determined that maintenance costs for RWHS is primarily relevant to the

upkeep of on-site storage units, which is estimated by 0.5 USD (normalized 12,500 VND) for each cubic meter available in storage system, and the total proposed lifespan:

$$[Annual\ Maintenance\ Cost] = 12,500 \frac{VND}{m^3} \times [Proposed\ Storage\ Capacity]m^3 \times [Lifespan] \quad (4)$$

Capital cost can be determined using the initial investment in the first year of implementation, which does not subject it to the annual changes in discount rate – a value necessary for calculation of present value of future cash flow. In contrast, continuous cost is subjected to future economic fluctuation, which makes a discount rate necessary to reflect the present value (PV) of continuous cost in the future, which can be calculated via fixed present maintenance cost and discount rate at year t given interest rate i:

$$Annual\ PV\ Maintenance\ Cost = [Annual\ Maintenance\ Cost] \times \frac{1}{(1+i)^t} \quad (5)$$

$$Total\ Cost = [IC] + [PV_{\Sigma} Maintenance] + [PV_{\Sigma} Replacement] + [PV_{\Sigma} Operation] \quad (6)$$

The system will also provide a set of indirect but tangible recurrent financial benefits that alleviate expenditure burden on households in the form of mitigated municipal and private water service pricing. Similarly, RWHS mitigate the continual cost associated with use of municipal or private water services post-implementation during its lifespan, whose PV should be considered and determined via the equation below:

$$Total\ PV\ Benefits = \sum_t^T [Municipal/Private\ Water\ Pricing] \times [Household\ Water\ Demand] \times \frac{1}{(1+i)^t} \quad (7)$$

These annual costs and benefits offset each other, which can be used to calculate the annual net cash flow (NCF) for households that implemented RWHS. Given the known IC from the structure and material selection of RWHS, NCF can be used to calculate a flat payback period (PP) to roughly indicate the breakeven period, which can also be an estimator of the necessary lifespan of the system. This stage can be expressed via the following formula:

$$NCF = [Annual\ Benefits] - [Annual\ Maintenance\ Costs] \quad (8)$$

$$PP = \frac{IC}{NCF} \quad (9)$$

However, PP merely indicates a linear breakeven point in a vastly complicated economic system with many parameters unaccounted for, such as inflation, interests, and depreciation. Essentially, the income in the future may hold a different value in the future due to the impact of fiat currency fluctuation. This means that projected incomes and costs in the future needs to be converted to present value via a modifier. Given each year (t) of the expected total RWHS operational lifetime (T) with an effective interest rate (i), there is a corresponding time value modifier or annual discount rate (annuity factor) that impact the annual benefits and costs:

$$Annuity\ Factor = \sum_t^T \frac{1}{(1+i)^t} = \frac{(1+i)^T - 1}{(1+i)^T \cdot i} \quad (10)$$

Assuming that annual operation cost and annual income remains constant throughout the total years of operation, annual present value for benefits and costs can be derived by application of annuity factor, which can be used to calculate the BCR using the following formula:

$$BCR = \sum_{t=1}^T \frac{PV_{Benefit}}{PV_{Cost}} \quad (11)$$

Subsequently, discounted cash flow (DCF) for each operating year can be determined and summed to identify the cumulative DCF (CDCF), which can be used for NPV determination via the following formulas:

$$CDCF = \sum_{t=1}^T \frac{Annual\ incomes}{(1+i)^t} - \sum_{t=1}^T \frac{Annual\ costs}{(1+i)^t} \quad (12)$$

$$NPV = CDCF - IC \quad (13)$$



### 3. RAINWATER ASSESSMENT

#### 3.1 Rainwater Quantity Assessment

##### 3.1.1 Findings: Water Consumption and Sufficiency

Surveys collected 20 randomized responses distributed across the study area regarding the quantitative aspects of water use, which includes preferred water as well as the adequacy of the centralized water supply. Responses revealed that primary water source is predominantly tap water, or central water supply, at 65% while rainwater as a primary water source is only preferred in 4 cases (20%) of responses (Table 3-1). During interview, it was observed that households have varying degree of access to central supply line. For those with full access, supplemental water sources such as rainwater remains an essential contingency for most households (84.2%), the cause of which was reportedly cited to saline contamination in tap water source (45% reported). For descriptive statistics of perceived sufficiency on water supply quantity and quality, refer to Table 3-3. As a result of risks associated with stability and safety of tap water sources, supplemental water source is most commonly rainwater as reported by 16 cases (84.2%), followed by bottled water at 26.3% (Table 3-2). Although bottled water is noted as a secondary source in the absence of tap water access at interview sites, responses indicates that it is not a frequent occurrence as services for non-potable fresh bottled water, or tank water in local term, is expensive (at 100,000VND/m<sup>3</sup>, 910% higher than state water pricing), which reflects the need for reliable central water supply in these areas with water pricing generally regulated by the municipal water authority at the listed rate of 9,900 VND/m<sup>3</sup> since 2016 (Ben Tre Water Supply and Sewage [BEWACO], 2016). Regarding rainwater use (Table 3-4), 9 responses indicated use for consumption; 12 responses indicated use for showering and hygiene, and 16 responses indicated use for other purposes such as flushing, laundry, and outdoor (gardening).

Table 3-1: Frequency for Primary Water Source among Response (Single Response)

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Tap Water	13	65.0	65.0	65.0
	Drilled Well	2	10.0	10.0	75.0
	Bottled Water	1	5.0	5.0	80.0
	Rainwater	4	20.0	20.0	100.0
	Total	20	100.0	100.0	

Table 3-2: Frequency for Secondary Water Sources among Responses (Multi Responses)

Note: Multi Responses Statistics Can Indicate Higher Sampling Number (N) Than Sample Size Collected due to Repeating and Overlapping Responses, leading to Percent of Cases higher than 100		Responses		Percent of Cases
		N	Percent	
Secondary Water Source	Secondary Water Source: Tap Water	4	15.4%	21.1%
	Secondary Water Source: Drilled Well	1	3.8%	5.3%



	Secondary Water Source: Bottled Water	5	19.2%	26.3%
	Secondary Water Source: Rainwater	16	61.5%	84.2%
<b>Total</b>		<b>26</b>	<b>100.0%</b>	<b>136.8%</b>

Table 3-3: Perceived Sufficiency on Primary Water Source Quantity and Quality

Primary Water Source Quantity					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Sufficient	15	75.0	75.0	75.0
	Insufficient	5	25.0	25.0	100.0
	<b>Total</b>	<b>20</b>	<b>100.0</b>	<b>100.0</b>	
Primary Water Source Quality					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Sufficient	11	55.0	55.0	55.0
	Insufficient	9	45.0	45.0	100.0
	<b>Total</b>	<b>20</b>	<b>100.0</b>	<b>100.0</b>	

Table 3-4: Harvested Rainwater Uses at Study Area

Drinking and Cooking					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Yes	9	45.0	45.0	45.0
	No	11	55.0	55.0	100.0
	<b>Total</b>	<b>20</b>	<b>100.0</b>	<b>100.0</b>	
Showering and Hygiene					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Yes	12	60.0	60.0	60.0
	No	8	40.0	40.0	100.0
	<b>Total</b>	<b>20</b>	<b>100.0</b>	<b>100.0</b>	
Other Purposes (toilet, laundry, outdoors, etc.)					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Yes	16	80.0	80.0	80.0
	No	4	20.0	20.0	100.0
	<b>Total</b>	<b>20</b>	<b>100.0</b>	<b>100.0</b>	

Categorically, monthly water consumption is classified into four range that reflects the water consumption brackets that is shown in Table 3-5. Specifically, water consumption in the study area varies between 2 – 20 m<sup>3</sup> per month with an average that 7.5 m<sup>3</sup> per month with a standard deviation of 4.5 m<sup>3</sup>. There

are outlier responses citing higher than 15 m<sup>3</sup> per month use water for service business purpose as well, which could potentially skew mean consumption in the area. To correct the skewness, households noted to operate in-house businesses were excluded (2 cases), which corrected mean consumption to 5.75 m<sup>3</sup> per month – a less skewed figure given the median pre- and post-correction of 6 and 5.5 respectively. Full details on water consumption and household specifics can be consulted in Table 3-6.

Table 3-5: Monthly Water Consumption

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	< 5 m <sup>3</sup>	6	30.0	30.0	30.0
	5-10 m <sup>3</sup>	8	40.0	40.0	70.0
	10-15 m <sup>3</sup>	4	20.0	20.0	90.0
	>15 m <sup>3</sup>	2	10.0	10.0	100.0
	Total	20	100.0	100.0	

Table 3-6: Water Consumption Details by Area

Area	People in Household	Total Water Consumption (m <sup>3</sup> )	Water Rate (thousand VND/m <sup>3</sup> )	Monthly Water per Capita (m <sup>3</sup> /person)	Monthly Bill (thousand VND)
Dinh Trung	2	4	9.9	2	39.6
Dinh Trung	4	3	9.9	0.75	29.7
Dinh Trung	4	2	9.9	0.5	19.8
Dinh Trung	5	5	9.9	1	49.5
Dinh Trung	5	6	9.9	1.2	59.4
Dinh Trung	3	5	9.9	1.7	49.5
Binh Thoi	4	5	9.9	1.25	49.5
Binh Thoi	4	20	9.9	5	198
Binh Thoi	4	16	9.9	4	158.4
Binh Thoi	4	10	9.9	2.5	99
Binh Thoi	5	10	9.9	2	99
Binh Thoi	5	5	9.9	1	49.5
Binh Dai	5	10	9.9	2	99
Binh Dai	5	6	9.9	1.2	59.4
Binh Dai	6	6	9.9	1	59.4
Binh Dai	4	7	9.9	1.75	69.3
Binh Dai	3	4	9.9	1.3	39.6
Binh Dai	4	5	9.9	1.25	49.5
Binh Dai	5	12	9.9	2.4	118.8
Binh Dai	5	8	9.9	1.6	79.2
<b>Mean</b>	4	7.45		1.77	73.75
<b>Standard Deviation</b>	1	4.48		1.08	44.33
<b>Median</b>	4	6		1.5	59.4
<b>Mode</b>	4	5		2	49.5

### 3.1.2 Dataset Selection and Bias Correction

#### 3.1.2.1 Satellite Dataset Selection

The development and launch of the Television and IR Observation Satellite in 1960 provided the basis and facilitated the future of meteorological satellite systems (Kidd, 2001). Many satellite datasets for rainfall and precipitation current exist on a worldwide scale, including CMORPH (Joyce et al., 2004); GsMAP (Ushio & Kachi, 2010); TRMM Multi-satellite Precipitation Analysis (TMPA) (Huffman et al., 2007); and the Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN) (Hong et al., 2004; Hsu et al., 1997; Sadeghi et al., 2019; Sorooshian et al., 2000).

Table 3-7: Summary of Open-Source Satellite Dataset Considered for Selection

Satellite Dataset	Available Period	Resolution	Available Frequency	Algorithm	Reference
PERSIANN	2000–present	0.25° x 0.25°	Hourly	Artificial Neural Networks	(Hsu et al., 1997)
PERSIANN-CDR	1983–present	0.25° x 0.25°	Hourly	Artificial Neural Networks	(Ashouri et al., 2015)
PERSIANN-CSS	2003–present	0.04° x 0.04°	Hourly	Artificial Neural Networks	(Sorooshian et al., 2000)
PERSIANN-PDIR	2000–present	0.04° x 0.04°	Hourly	Artificial Neural Networks	(Nguyen et al., 2020)
GSMaP	2000–present	0.1° x 0.1°	Hourly	Kalman filter mode	(Ushio & Kachi, 2010; Ushio et al., 2009)

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PERSIANN is a satellite system that utilizes satellite infrared imaging and surface-based data as input for an artificial neural network that constantly generates and updates precipitation-related within its designated scale (0.25° x 0.25°). Its primarily algorithmic data sources are primarily from the Geostationary Meteorological Satellite (GMS), GridSat-B1 IR satellite specifically, and Automated Meteorological Data Acquisition System (AMeDAS) for satellite and ground-based data respectively (Hsu et al., 1997). The system is flexible with the possibility for inputs that expands, or overhaul, its scale, parameter, and characteristic within different temporal and spatial precipitation observations. For instance, the PERSIANN Climate Data Record (PERSIANN – CDR) incorporates a historical record of multiple climate datasets, which provides insight into longer precipitation time series (1983 – present) within the same spatial scale (Ashouri et al., 2015). Another derivative of PERSIANN system is the PERSIANN Cloud Classification System (PERSIANN – CCS), which utilizes atmospheric temperature and passive microwave mapping from satellites to integrate its parameters into the system via cloud cluster analysis and cloud segmentation algorithm, which updates the system with a finer pixel dataset (0.04° x 0.04°) at the same frequency intervals (Hong et al., 2007).

The Global Satellite Mapping of Precipitation, or GSMaP, was a project developed under the sponsorship of the Japan Science and Technology Agency between 2002 – 2007 to produce a microwave radiometer algorithm for the visualization of a global precipitation map. By manipulating the motion vector of infrared cloud imagery and using Kalman filtering as the core algorithm, GSMaP\_MVK precipitation map is

created with one of the finest resolution pixels ( $0.1^\circ \times 0.1^\circ$ ) (Ushio & Kachi, 2010). In addition, GSMaP\_MVK\_RT, which renders precipitation data in near real-time, is also created for visual indicators of the temporal propagation of global precipitation.

Each system and dataset present a different algorithm-based methodology for precipitation visualization (i.e. resolution, data approximation, temporal variability, spatial variability, etc...), which was consolidated and extensively examined by (Maggioni et al., 2016). For quantitative assessment in this thesis, dataset candidates (Table 3-7) consisted of the open-source repository available for direct access by the Center of Hydrometeorology and Remote Sensing (CHRS), which mainly includes PERSIANN-derived and GSMaP datasets. For GSMaP, only CSV file formats are available for public use. Daily time series are extracted from within pixel raster available for many of the PERSIANN-based datasets via ArcGIS built-in value extraction function, which was then re-formatted into CSV for consistent analysis and comparison with the GSMaP dataset. Multi-datasets analysis was conducted within the same temporal and spatial boundary. Specifically, precipitation data from selected datasets were retrieved from overlapping coordinates as selected six rain stations available within the year 2020. The selection process among selected datasets will be conducted as described in section 2.3.1.1, the results of which are presented in Table 3-8, Table 3-9, and

Table 3-10.



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Table 3-8: Correlation between Satellite-based Dataset (Observed) and Gauge-based Precipitation (Expected). Note: yellow highlight indicate highest in row; orange highlight indicate second highest in row

Coefficient of Determination ( $R^2$ )	PERSIANN	CDR	CSS	PDIR	GsMAP
Ca Mau	0.2792	0.4045	0.209	0.2792	0.3512
Can Tho	0.2165	0.1594	0.1875	0.2165	0.1712
Go Cong Dong	0.0569	0.0973	0.0847	0.0569	0.0956
Moc Hoa	0.1356	0.1524	0.145	0.1356	0.1391
Tan Chau	0.0938	0.1073	0.1114	0.0938	0.1063
Tra Vinh	0.0723	0.1167	0.1413	0.0722	0.0279

Table 3-9: Absolute Mean Error (AME) between Satellite-based Dataset (Observed) and Gauge-based Precipitation (Expected). Note: yellow highlight indicate lowest in row; orange highlight indicate second lowest in row

Absolute Mean Error (AME)	PERSIANN	CDR	CSS	PDIR	GsMAP
Ca Mau	1.84	1.07	0.33	1.84	1.11
Can Tho	1.14	1.00	3.30	1.14	1.63
Go Cong Dong	0.59	1.09	1.99	0.59	0.64
Moc Hoa	0.83	0.78	3.36	0.83	0.04
Tan Chau	1.10	1.54	2.70	1.10	0.52

Tra Vinh	5.50	0.40	1.36	0.97	0.67
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Table 3-10: Correlation Root-Mean-Squared Error (RMSE) between Satellite-based Dataset (Observed) and Gauge-based Precipitation (Expected). Note: yellow highlight indicate lowest in row; orange highlight indicate second lowest in row

Root-Mean-Squared Error (RMSE)	PERSIANN	CDR	CSS	PDIR	GsMAP
Ca Mau	14.00	12.81	15.63	14.00	14.61
Can Tho	10.83	10.63	15.11	10.83	16.74
Go Cong Dong	14.07	12.66	16.81	14.07	14.34
Moc Hoa	13.45	12.29	17.83	13.45	14.20
Tan Chau	13.19	12.12	15.02	13.19	13.97
Tra Vinh	13.83	12.35	14.67	13.52	23.01

As indicated in previous sections, the statistical criteria for the selection of the satellite dataset are based on  $R^2$ , AME, and RMSE, where the selected dataset is expected to have a relatively high  $R^2$  with low AME and RMSE calculations among other candidate datasets. In Table 3-8, the highest and second highest  $R^2$  values are highlighted post-calculation for each datapoint, which illustrated the PERSIANN-CDR dataset presenting the highest recurrence for the highest  $R^2$  value (Ca Mau, Go Cong Dong, and Moc Hoa), and co-leading the highest recurrence for the second highest  $R^2$  value (Tan Chau and Tra Vinh) with the GSMaP dataset (Ca Mau and Moc Hoa). The calculation indicates that PERSIANN-CDR presented the highest degree of correlation at the same concurrent datapoints as the gauge-based rain station data, while other datasets showed minimal correlation when compared to expected gauge data.

In Table 3-9, the statistical category of AME presents the measure of errors between paired datasets (expected and observed data) exhibiting precipitation in this case. Similar to the previous analysis, the lowest and second lowest value within the table is highlighted. Evidently, the PERSIANN-CDR datasets exhibited two lowest values (Can Tho and Tra Vinh) and two second lowest values (Ca Mau and Moc Hoa). In contrast, GSMaP, as the second best performing candidate, only exhibited two highest values (Moc Hoa and Tan Chau) and one second highest value (Go Cong Dong). The result demonstrated that the mean deviation for daily precipitation value between PERSIANN-CDR and rain gauge station is the lowest among datasets, thus indicating a higher resemblance to expected rain gauge data.

In

Table 3-10, RSME represents the mean quadratic differences between a precipitation estimator (expected data) and observed precipitation data. In this statistical category, PERSIANN-CDR was determined

to exhibit the lowest value at all data points, which indicated that its mean quadratic precipitation value deviation from the rain gauge data is the least among candidate datasets.

Given the statistical calculation, it is indicated that PERSIANN-CDR precipitation data performs relatively well compared to other datasets. In this case, PERSIANN-CDR data met the most selection criteria using rain gauge data as an estimator. Thus, PERSIANN-CDR precipitation data was selected for primary use in data correction, visualization, and subsequently, precipitation datapoint extraction at survey sites.

### 3.1.2.2 Interpolative Correction and Rainfall Map Building

For bias correction in this thesis, only precipitation data and spatial coordinates were available for use with no associated parametric attribute (i.e. elevation, soil conditions, moisture, etc...). As a result, complex machine learning algorithm, which is parameter-focused, is not feasible for corrective application in the study. In addition, parameter-based statistical methods that involve the partial implementation of GCM were not viable. Instead, cumulative distribution function (CDF) will be considered for statistical correction due to its non-parametric requirement.

A CDF is an expression of the distribution probability of a variable within a given dataset. Basically, CDF delineates the sum of the probability density function that is possible within the sampled and available expected and observed dataset (Abramowitz & Stegun, 1964). Under normal distribution circumstances, the calculation for CDF can be determined given the determination of Error Function (EF), which can be calculated as the upper limit integration of x (highest value) in a spatially variable dataset, the mean ( $\mu$ ), and the standard deviation ( $\sigma$ ). In this case, CDF is represented as the area under the normal distribution of real number values smaller or equal to x. Once CDF was derived for both expected and observed datasets using Equations 9–10, PERSIANN-CDR daily rainfall bias correction can be performed using Equation 11 (Katirae-Boroujerdy et al., 2020), the result of which is processed via IBM SPSS Statistics 25 and summarily shown in Table 3-11.

$$EF(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \quad (14) \text{ (Abramowitz \& Stegun, 1964)}$$

$$CDF(x; \mu, \sigma^2) = \frac{1}{2} \left[ 1 + EF\left(\frac{x - \mu}{\sigma\sqrt{2}}\right) \right] \quad (15) \text{ (Abramowitz \& Stegun, 1964)}$$

$$P_{CDR-BC} = CDF_G^{-1} [CDF_{CDR}(P_{CDR})] \quad (16) \text{ (Katirae-Boroujerdy et al., 2020)}$$

Table 3-11: Cumulative annual rainfall of rain gauge, PERSIANN-CDR, and bias corrected PERSIAN-CDR daily precipitation datasets at the gauge location

Cumulative Annual Rainfall in 2020 (mm/year)			
	Gauge	CDR	Bias Correction
Ca Mau	2394.90	2004.86	2392.04
Can Tho	1660.40	2027.69	1661.71
Go Cong Dong	1822.60	2222.12	1823.41
Moc Hoa	1871.30	2228.34	1869.25
Tan Chau	1551.30	2114.53	1550.26
Tra Vinh	2011.40	1866.11	2012.17

Using corrected data as input, a z-value (precipitation) raster can be produced via built-in spatial interpolation functions within ArcGIS 10.8 software. As one of the most often common and essential functions in GIS, spatial interpolation techniques for spatial query and spatial data visualization within the application of environmental science. Some of the available ArcGIS methods for spatial interpolation such as Inverse Distance Weighting (IDW), spline, and geostatistical models (Kriging methods) present different analysis algorithms that can produce results appropriate for different research contexts. As a result, it is necessary to explore the mechanism of some common methods and determine the most suitable method for precipitation interpolation and visualization.

According to Childs (2004), IDW and spline are considered deterministic interpolations which generate values based on the degree of similarity and distance for smoothness. IDW mainly relies linear weighting algorithm as a fitting mechanism for datapoint determination based on cell values and gaps. The weighting of each cell is expressed as a function of the distance from locations of known inputs. Greater distance exerts less influence and accuracy on the output of cell values. Hence, the density of available data points can highly influence output expressions targeted value in cells. Spline is a more geometric-based estimation method that uses mathematical functions to smooth the curvature of a surface by creating connections between input datapoints. The spline can be applied in regularized or tension form. Regularized spline method uses multi-level derivatives to the third degree (slope, rate of change in slope, rate of change within rate of change in slope) to optimize surface connections. Tension spline method only utilize derivatives to the second degree, which results in smoother outputs at the expense of computation time. Ideally, both spline variations are used for predicting and identifying geological formations or anomalies such as ridges or valleys; temperature estimation is also a common application for this method. In summary, spline optimizes curved surface connections between all input datapoints into a smooth surface and estimates values on surface connections drawn, while IDW uses distance-based cell weightings to determine the output values and does not intercept input data points.

Another useful technique is the kriging method, which estimates cell values via combined analysis of correlation, trend, and weighting methodology. This makes kriging a powerful tool for geostatistical modelling within the application of environmental, health, and geochemical science (Childs, 2004). Particularly, it was noted to be a viable technique for rainfall interpolation alongside IDW and spline (Earls & Dixon, 2007). Basically, kriging evaluates the distance and direction to use a reference weighting to reflect a spatial correlation between all input datapoints. In addition, based on the radial distance categorized in the computed search radius option (fixed or variable), dynamic functions can be applied for a cluster of datapoints or all datapoints to generate cell surface values. As a general rule in kriging, estimated values cannot exceed input values and generated surfaces, like IDW, do not passthrough input datapoints. There are several types of kriging, but ordinary and universal kriging are basic and essential for spatial interpolation references. Ordinary kriging is the most common application of the technique where its functions do not account for trends (i.e., constant mean of input data in the area) whereas universal kriging does. Childs (2004) suggested that kriging is most appropriate in tasks where spatially corrected bias value (z-value) and distance correlation (point-based coordinates) are available.

In one study, Meng et al. (2013) assessed the performance of seven GIS interpolation techniques including deterministic techniques (IDW, spline, radial basis function), univariate kriging (ordinary kriging, universal kriging, cokriging), and a multivariate kriging (regression kriging) technique. Results from the study showed that regression kriging performed better than other interpolations in terms of geo-spatial Pearson correlation factor, Bayes factor, MAE, and RMSE, followed by cokriging, ordinary/universal kriging, and the three deterministic interpolation techniques. The study noted that although univariate kriging performance was better than deterministic interpolation, the difference was slight and should not be treated as an indication of superiority. In the context of precipitation, Earls and Dixon (2007) compared rainfall interpolation variances



via multi-configurations for both deterministic and geostatistical techniques to determine the best technique that produces unique variant outputs most correlated to actual gauge rainfall datapoints; thereby, identifying the configuration of exponential semivariogram and variable search radius of 12 points in ordinary kriging to be the best approach given the goal of research. Ly et al. (2013) also suggested that geostatistical interpolation techniques are preferable to deterministic techniques for daily, monthly, and annual rainfall modelling.

Given the extent of studies done on rainfall interpolation within the context of GIS, this thesis opted to utilize the geostatistical technique for the interpolation of corrected rainfall. Specifically, monthly and annual modelling of corrected rainfall input could be conducted using the configuration of exponential semivariogram and variable search radius of 12 points in ordinary kriging as a preferred option as noted by (Earls & Dixon, 2007). The output extent will be within the VMD. The generated model has a resolution of  $0.001^\circ \times 0.001^\circ$ , which was refined using ArcGIS built-in clip function using the VMD polyline as clipping extent. Assessment for monthly and annual rainfalls in the VMD and study area are shown in Figure 3-2 and Figure 3-1, and site-specific rainfall extracted from the generated surface is shown in Table 3-12.

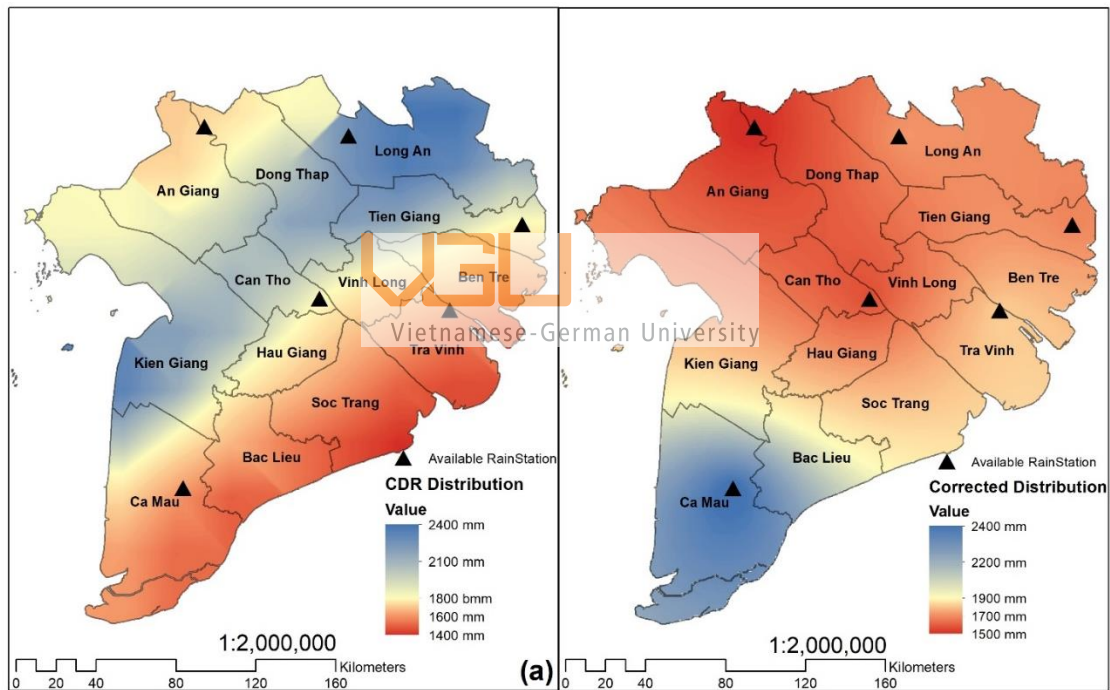


Figure 3-1: Annual (a) CDR precipitation surface; and (b) Corrected precipitation surface

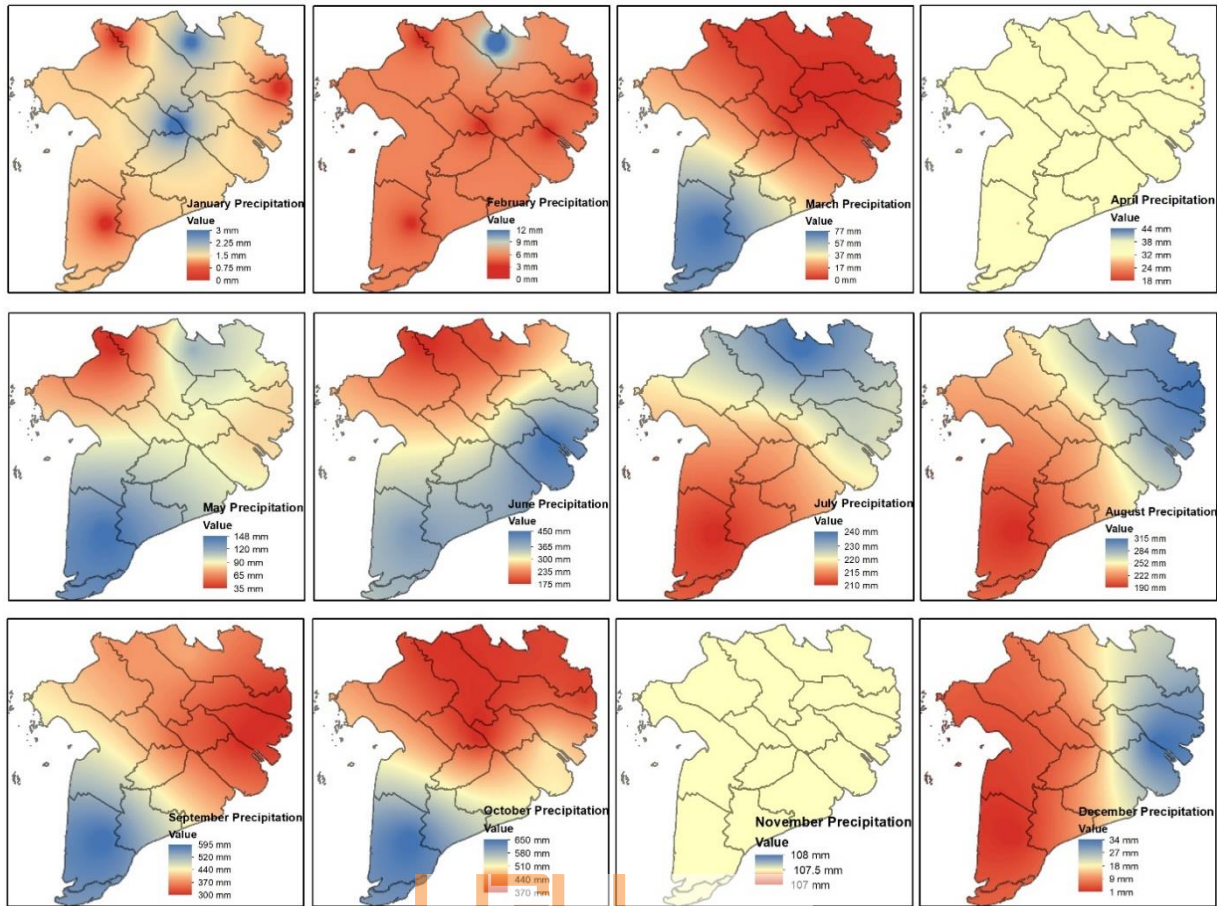


Figure 3-2: Monthly Distribution of Corrected Precipitation

Table 3-12: Extrapolated rainfall at survey sites

Site Code	Rainfall (mm)												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2008 01 (DT)	0.509	1.40 8	0.04 9	31.83 4	84.88 1	363.47 4	227.48 8	309.31 2	300.49 8	422.30 8	107.47 5	30.06 7	1879.30 5
2008 02 (DT)	0.491	1.37 5	0.23 8	31.83 4	84.68 5	362.35 5	227.37 6	309.79 8	300.53 2	421.06 0	107.47 5	30.03 8	1877.25 6
2008 03 (DT)	0.473	1.33 2	0.17 1	31.83 4	84.69 8	360.51 8	227.39 2	310.15 2	300.44 8	419.00 5	107.47 5	29.93 0	1873.42 9
2008 04 (DT)	0.483	1.36 2	0.33 5	31.83 4	84.59 9	361.79 4	227.32 2	310.00 7	300.59 2	420.49 1	107.47 5	30.01 8	1876.31 3
2008 05 (DT)	0.501	1.40 4	0.40 7	31.83 4	84.59 6	363.59 2	227.30 7	309.64 2	300.71 0	422.54 9	107.47 5	30.12 0	1880.13 9
2008 06 (DT)	0.509	1.43 4	0.68 8	31.83 4	84.47 8	364.15 1	227.19 4	309.59 5	301.12 5	423.59 0	107.47 5	30.15 9	1882.23 3
2008 07 (BT)	0.526	1.47 4	0.76 8	31.83 4	84.49 0	365.85 9	227.18 0	309.21 5	301.29 9	425.62 4	107.47 5	30.25 2	1885.99 6
2008 08 (BT)	0.506	1.43 3	0.79 5	31.83 4	84.43 3	363.54 8	227.14 8	309.72 1	301.31 2	423.15 3	107.47 5	30.12 4	1881.48 1

2008 09 (BT)	0.485	1.38 8	0.82 4	31.83 4	84.37 7	361.29 0	227.11 6	310.21 1	301.33 7	420.74 5	107.47 5	29.99 8	1877.08 1
2008 10 (BT)	0.503	1.43 8	1.01 3	31.83 4	84.37 1	362.37 2	227.06 2	309.90 3	301.77 3	422.43 0	107.47 5	30.04 7	1880.22 2
2108 01 (BT)	0.504	1.44 5	1.12 5	31.83 4	84.35 4	361.80 1	227.02 2	309.96 0	302.04 8	422.14 7	107.47 5	30.00 5	1879.72 1
2108 02 (BT)	0.485	1.38 8	0.82 4	31.83 4	84.37 7	361.29 0	227.11 6	310.21 1	301.33 7	420.74 5	107.47 5	29.99 8	1877.08 1
2108 03 (BD)	0.521	1.48 0	1.09 5	31.83 4	84.39 6	363.98 7	227.04 9	309.51 5	301.98 2	424.41 7	107.47 5	30.13 1	1883.88 2
2108 04 (BD)	0.538	1.51 9	1.17 9	31.83 4	84.42 3	365.58 0	227.03 5	309.12 6	302.20 0	426.39 0	107.47 5	30.21 2	1887.51 2
1208 05 (BD)	0.554	1.55 4	1.26 6	31.83 4	84.45 1	367.15 2	227.02 0	308.73 7	302.42 8	428.34 6	107.47 5	30.29 1	1891.10 9
2108 06 (BD)	0.523	1.49 7	1.32 1	31.83 4	84.37 7	362.79 3	226.97 2	309.60 6	302.57 4	423.85 7	107.47 5	30.03 9	1882.86 8
2108 07 (BD)	0.554	1.56 1	1.37 9	31.83 4	84.44 3	366.48 6	226.98 1	308.79 3	302.72 5	427.99 7	107.47 5	30.24 1	1890.46 9
2108 08 (BD)	0.570	1.60 2	1.58 4	31.83 4	84.47 6	367.31 6	226.92 8	308.44 0	303.29 7	429.58 5	107.47 5	30.26 1	1893.36 8
2108 09 (BD)	0.584	1.63 1	1.67 7	31.83 4	84.51 2	368.77 6	226.91 1	308.04 9	303.56 0	431.46 1	107.47 5	30.32 9	1896.80 1
2108 10 (BD)	0.584	1.63 1	1.67 7	31.83 4	84.51 2	368.77 6	226.91 1	308.04 9	303.56 0	431.46 1	107.47 5	30.32 9	1896.80 1
<b>Avg.</b>	0.520	1.46 8	0.92 1	31.83 4	84.49 6	364.14 6	227.12 7	309.40 2	301.76 7	424.36 8	107.47 5	30.12 9	1883.65 3
<b>Std. Dev.</b>	0.034	0.09 0	0.49 9	0.000	0.136	2.537	0.172	0.678	1.017	3.714	0.000	0.123	6.936
<b>Max</b>	0.584	1.63 1	1.67 7	31.83 4	84.88 1	368.77 6	227.48 8	310.21 1	303.56 0	431.46 1	107.47 5	30.32 9	1896.80 1
<b>Min</b>	0.473	1.33 2	0.04 9	31.83 4	84.35 4	360.51 8	226.91 1	308.04 9	300.44 8	419.00 5	107.47 5	29.93 0	1873.42 9

From the results of interpolative correction, it can be observed that the rainfall pattern between the satellite dataset and corrected dataset in Figure 3-1 is quite different from each other, which indicates a high margin of error during interpolative outputs using CDF-based corrected dataset. In Figure 3-2, significant margin of error can also be observed via visual anomalies in January, February, April, and November, which is symptomatic of the six limited gauge datapoints over a large geographic area such as the VMD (more than 40,000 km<sup>2</sup>). In addition, due to few available rain gauge data serving as reference points, distance-weighted interpolation produces relatively homogenous values regardless of geographical variations as seen in Table 3-12. For these reasons, even though interpolative correction can be a viable option, given the scale of the VMD and limited access to rain gauge data, it would be more accurate to examine alternative and simpler corrections for the specific study area in Ben Tre. Given more access to rainfall gauge datapoints, more comprehensive rainfall mapping in the VMD and interpolation can be conducted with relatively higher accuracy in the future study.

### 3.1.2.3 Linear Correction and Aggregation of Closest Rain Gauge Data Points

As a result of the concerns posed by interpolative correction given limited access to rainfall data, a more linear method of correction is adopted to assess the possibility of use comparatively to interpolative correction. Particularly, a linear correction will produce a correlational trend between aggregated data of available gauge stations and selected satellite datasets based on time series precipitation time series observation (Figure 3-3).

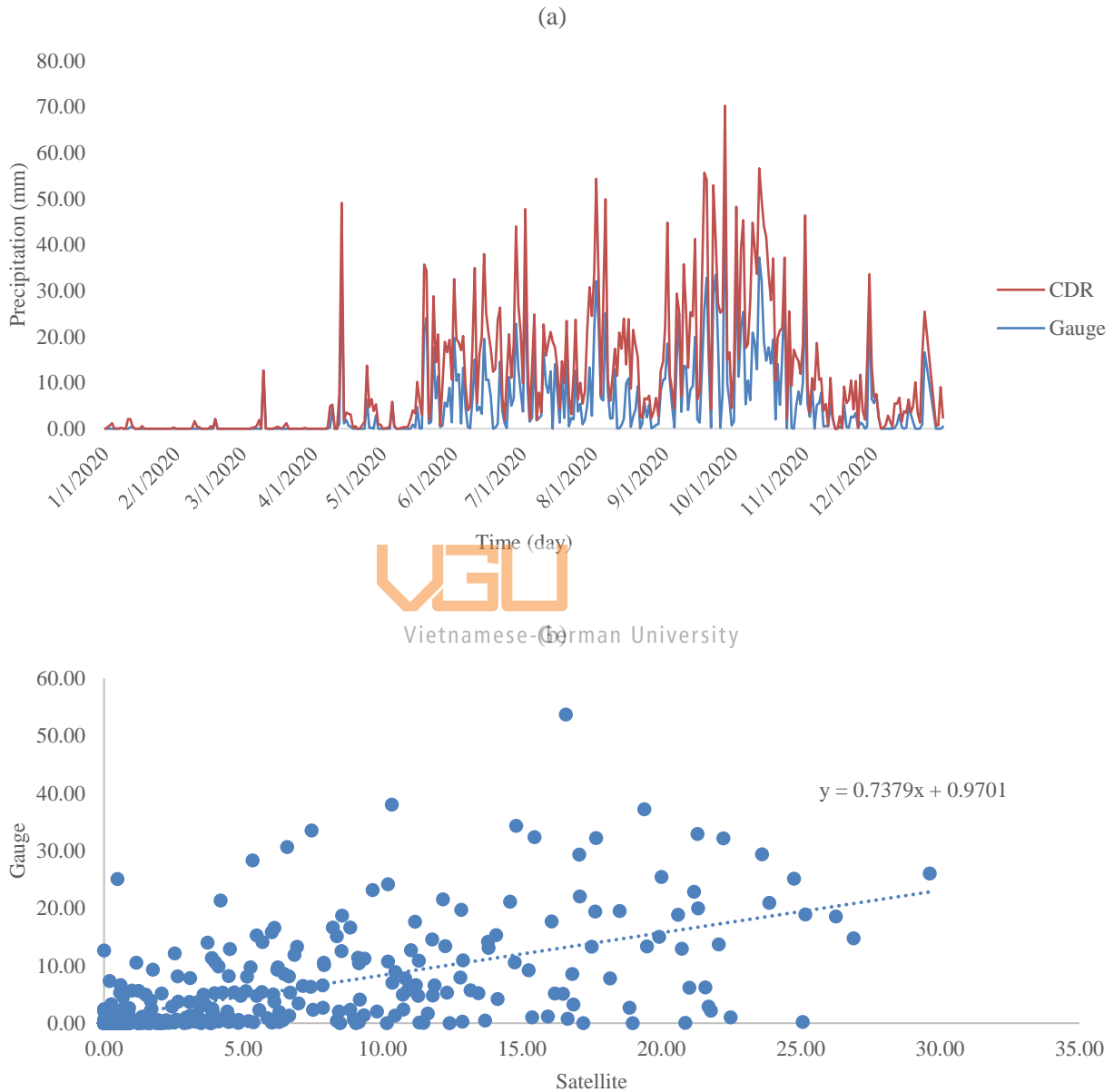


Figure 3-3: Linear Correction Observation Based on (a) Rainfall Time Series Between Gauge and Satellite Data; and (b) Correlation Between Gauge (Y) and Satellite (X) Datum Series

However, one significant disadvantage of this correction method is that it universally downscales satellite data relative to gauge data across the time series, not dynamically correct rainfall data based on gauge pattern. Evidently, this can be observed from the linear correlation trendline expressed as:  $y = 0.7379x + 0.970$ , which implies actual rainfall can be estimated in an unknown datapoint if the satellite pixel value is applied to this 'modifier'. However, this proves to be problematic as it encounters the same limitation as the previous

method, which is limited by available datapoints. Particularly, the aggregated time series used in the process of formulating Figure 3-3 only accounts for the six accessible gauge data, which could potentially indicate a lack of geographical variants necessary to be statistically representative of the VMD. Due to the linearity of this correction method, uneven distribution of precipitation pattern between satellite and gauge data is universally downscaled, which suggested that value exceeding the gauge threshold can be corrected with relative accuracy while value already lower than the gauge threshold will be exacerbated, creating a one-dimensional correction whose applicability across the VMD is unclear due to real unknown rainfall distribution patterns. Downscaling precipitation data is a common practice in environmental science, especially for bias correction in satellite or remote-sensing datasets, which presents imprecise measurements across the coarse spatial resolution. However, such techniques are conducted dynamically (usually with the assistance of a machine learning algorithm), while statistical linear downscaling can often lead to the same distribution errors with a lower-value dataset, hence providing no changes to concerns of inaccuracy (Abdollahipour et al., 2021).

As a result, it is difficult to overcome the error margin via interpolative correction and linear downscaling within remote-sensing rainfall datasets given the scope of methodology (statistical-focused) and limited accessibility to official rainfall data in the VMD. One potential and most straight-forward way of estimating local rainfall is the aggregation of real measured data from datapoints relatively as close to the study area as possible. This means that the relative determination of rainfall in the surveyed areas will be estimated using the average of 2 – 3 rainfall time series closest to the survey points. Studies conducted in data-limited areas of Australia determined that a small number of available gauges near or within the study area could be more reliable than an abundance of satellite-based data. Particularly, Stephens et al. (2022) first attempted to utilize satellite data for implementation in hydrological modelling, which was unsuccessful due to the persistence of variable errors in the satellite dataset despite an effort to filter it via correction algorithms and models. Further transference of research application concepts in some areas of Vietnam also confirmed previous findings in Australia. The dilemma of satellite data uses stems from a lack of rain gauge data which is also the factor that limit reference data necessary for appropriate satellite data correction. Hence, the studies have proposed that satellite data used in the data-sparse area do not facilitate accurate hydrological assessment more than a few actual measured datapoints, and that gauge data, however little, is recommended over satellite data. Finally, the studies also suggested that future development of satellite data products should address accuracy via improved spatial resolution and precipitation timing (Stephens et al., 2022).

On this basis, it can be posited that aggregation of rainfall data from Tra Vinh station and Go Cong Dong station (highlight grey in

Table 3-13), which are 40 km and 20 km from the Binh Dai district respectively, can be more representative of rainfall assessment at the surveyed areas than satellite products. The drawback of such

aggregation is that neither spatial nor temporal distribution of rainfall can be assessed and visualized, leaving primarily statistical tabulation of daily rainfall consolidated into monthly quantification in

Table 3-13.

Table 3-13: Monthly Rainfall of Available Gauge Station in the VMD

Date	Monthly Rainfall Data (mm)						Aggregation of Highlighted Stations
	Ca Mau Station	Can Tho Station	Go Cong Dong Station	Moc Hoa Station	Tan Chau Station	Tra Vinh Station	
Jan	0.00	2.20	0.00	2.00	0.00	0.80	0.40
Feb	0.10	0.00	0.00	12.40	0.00	0.00	0.00
Mar	76.30	0.00	0.00	0.00	0.00	0.00	0.00
Apr	15.20	59.20	1.60	73.30	114.10	60.30	30.95
May	107.90	83.40	155.20	92.00	97.70	165.90	160.55
Jun	284.40	218.10	288.40	189.20	79.90	320.60	304.50
Jul	187.10	274.20	248.60	125.70	135.70	361.40	305.00
Aug	227.30	154.50	316.60	231.10	184.10	181.70	249.15
Sep	589.60	396.70	322.40	436.80	416.30	287.30	304.85
Oct	638.50	302.90	357.60	551.80	385.40	433.60	395.60
Nov	196.90	111.10	105.60	108.40	74.50	162.90	134.25
Dec	71.60	58.10	26.60	48.60	63.60	36.90	31.75

### 3.2 Rainwater Quality Assessment

#### 3.2.1 Current Rainwater Harvesting Practices

From observation, the current RWHS implemented at survey sites is simple, yet sufficient. The system consists of a tilted roof serving as the catchment area, under which there is a small gutter connected to a detachable downspout to transport rainwater down directly into storage units (Figure 3-4). The placement of components or downspout piping network varies between household surveyed, but the principle remains the same. Given this impression, recommendations for RWHS would take into consideration this principle, upon which improvements can be built and expanded for a sustainable solution.



Figure 3-4: Setups of Rainwater Harvesting System at Survey Sites.

As part of the rain quality assessment from among surveyed households for the purpose of RWHS modular considerations, inquiries on the current setup of surveyed households are conducted to provide an overview of rainwater harvesting practices in the study area. These inquiries will investigate the current catchment (roofing) material used for rainwater catching; the total catchment area used for rainwater harvesting; the storage materials used in the study area; the storage capacity used for annual withdrawal; and the piping system for delivery into storage or household utilities.

Table 3-14: Rainwater harvesting practice frequency among surveyed household system

		Roofing Material			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Brick Tiles	0	0.0	0.0	0.0
	Thatched Roof	0	0.0	0.0	0.0
	Corrugated Metal	15	75.0	75.0	75.0
	Fibro Cement	5	25.0	25.0	100.0
	Total	20	100.0	100.0	
		Catchment Area			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	< 20 m <sup>2</sup>	6	30.0	30.0	30.0
	20-40 m <sup>2</sup>	12	60.0	60.0	90.0
	40-60 m <sup>2</sup>	2	10.0	10.0	100.0
	Total	20	100.0	100.0	
		Storage Material			
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Polyethylene	5	25.0	25.0	25.0
	Concrete	13	65.0	65.0	90.0
	Ceramic	2	10.0	10.0	100.0
	Total	20	100.0	100.0	
		Capacity of Storage			
		Frequency	Percent	Valid Percent	Cumulative Percent

Valid	<5 m <sup>3</sup>	8	40.0	40.0	40.0
	5-10 m <sup>3</sup>	5	25.0	25.0	65.0
	10-15 m <sup>3</sup>	3	15.0	15.0	80.0
	>15 m <sup>3</sup>	4	20.0	20.0	100.0
	Total	20	100.0	100.0	
<b>Gutters &amp; Downsprout Material</b>					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Aluminum	2	10.0	10.0	10.0
	PVC	18	90.0	90.0	100.0
	Total	20	100.0	100.0	

Responses on current rainwater practices revealed that the majority of households surveyed in the Dinh Trung county, Binh Thoi county, and Binh Dai township mainly utilize corrugated metal for rainwater harvesting (75% of cases) whereas fibro cement utilization only constitutes 25% of responses. Rainwater catchment area inquiries revealed that approximately 60% of responses reported available catchment areas between 20 – 40 m<sup>2</sup>, 30% with less than 20 m<sup>2</sup> available roof catchment area, and 10% with more than 40 m<sup>2</sup> of the catchment area.

In terms of a storage facility, the most common material for storage units is concrete, which is favored in 13 cases (65%) of collected responses followed by polyethylene (plastic) at 25%. Installation mode for all storage units is direct placement on property ground with detached lids for coverage, which is reportedly the cheaper option compared to a stand or elevation frame. For storage capacity, available capacity at surveyed households is the indication of the capability of the facility to store sufficient rainwater from the wet season for use during the dry season, which lasts 5-6 months with high risks of drought and saline intrusion. Approximately 8 cases (40%) reported a total storage capacity of below 5m<sup>3</sup>, among which 3 cases reported sufficient quantity due to limited reliability on rainwater, whereas others struggle with rainwater management during the dry season to sufficiently sustain domestic entirely on rainwater. For cases belonging to the upper brackets with more than 10 m<sup>3</sup> for the total storage area, it is reported that rainwater sufficiency is met in most cases, and some even claimed abundance in some cases.

For delivery components, all cases in surveyed areas reported limited use of piping networks directly feed into household utility systems. In surveyed cases, all households prefer direct retrieval of rainwater from the storage unit for use instead of a networked approach. As a result, piping systems at surveyed sites are simple in design and material, only accounting for the small gutter that collects rainfall from tilted roofs into downspouts connecting directly to storage units. In that context, 18 cases (90%) reported PVC as the material that made up the gutters and downspouts in the systems, and only 2 cases utilize the more expensive aluminum as the material of these components.

Table 3-15: Basic treatment practices among surveyed household



<b>Frequency of Fundamental Treatment Utilized among Responses</b>			
<b>(Multi Responses Statistics Can Indicate Higher Sampling Number (N) Than Sample Size Collected due to Repeating and Overlapping Responses, leading to Percent of Cases higher than 100)</b>			
	Responses		Percent of Cases
	N	Percent	
Basic Treatment: Nothing	0	0.0%	0.0%
Basic Treatment: First Flush	18	24.0%	90.0%
Basic Treatment: Storage Cleanup	8	10.7%	40.0%
Basic Treatment: Tank Coverage	18	24.0%	90.0%
Basic Treatment: Gravity Sedimentation	18	24.0%	90.0%
Basic Treatment: Boiling	13	17.3%	65.0%
Total		100.0%	385.0%

In Table 3-15, fundamental and common practices for treatment in the study area are illustrated based on multi-response inquiries. It is reported that most households (18 cases out of 20) do not use any form of disinfection (chlorination or UV) or filtration apparatus for rainwater in case of consumption. However, only 13 households (65%) reported using rainwater for cooking, and drinking purposes, all of which cited boiling as the essential step needed before consumption. Prior to boiling and consumption, other rudimentary measures were common and widely applied for rainwater before use, which are first-flush (90%), storage unit coverage (90%), and gravity sedimentation. Storage cleanup appears to be sparsely applied where only 40% of responses indicate active practices for this measure. In addition, all cases did not report regular quality test, even for those that prefer rainwater as a primary drinking source. Despite the lack of precautions measures, all cases reported no major adverse health effects in the recent five years, which possibly only indicates an insignificant dosage of contaminants that can trigger an acute reaction and not an indication of a safe drinking water source prior to treatment. Overall, common local measures are passed among communities as a means of making it as safe as possible without additional expenditure on top of the cost for RWHS. Understanding and awareness regarding the risks in rainwater are only partially understood.

### 3.2.2 Rainwater Quality Aspects

Table 3-16: Rainwater Quality Result from Lab Testing in Reference to National and WHO Guideline. Note: Parameters exceeding guidelines are highlighted yellow

Parameter	Units	National Guideline	WHO Guideline	Study Area Samples
pH	-	6 – 8.5	6.5 – 8.5	5.8 – 6.7
Turbidity	NTU	2	5	0.248 – 1.008
Total Dissolved Solids (TDS)	mg/L	1000	1000	0.943 – 85.120
Nitrite	mg/L	0.05	3	0.005 – 0.055
Nitrate	mg/L	2	50	0.124 – 1.256
Arsenic	mg/L	< 0.01	< 0.01	ND

Mercury	mg/L	< 0.001	< 0.006	ND
Lead	mg/L	0.01	0.01	ND
Cadmium	mg/L	< 0.003	< 0.003	0.002 – 0.009
Nickel	mg/L	0.07	0.07	ND
Chromium	mg/L	0.05	0.05	ND
Total coliform	CFU/100 mL	< 3	< 1 – 27	13 – 643 (one sample >1000)
E. coli	CFU/100 mL	< 1	< 1 – 4.48	0 – 140

Water quality determination results are illustrated in cross-reference to the guideline for domestic and potential drinking water use from both WHO and the Vietnamese national standard (Table 3-16). In this respect, physio-chemical properties of 16 rainwater samples collected from household storage units do not pose any risk as parameters are within the guideline threshold of both guidelines. Specifically, pH in rainwater samples ranges from 5.8 – 6.7 – a slightly acidic value, which is common for rainwater. For turbidity, samples measured range between 0.248 – 1.008 NTU (within the guideline threshold), which indicates low particulate and colloidal presence. It is important to note that low turbidity could be attributed to the effect of first-flush widely applied in the community and the retention time rainwater had resided within storage units, which allows for varying degrees of sedimentation to take place before sampling on the surface layer of stored rainwater to occur. Although freshly collected rainwater could provide a more accurate environmental reading for turbidity testing, in-situ rainwater collected from household storage units reflects a more practical assessment of rainwater that would be used for domestic purposes directly among surveyed households.

Heavy metals are of significant concerns because of the long-term high impact these elements can inflict on public health. Although acute poisoning of these heavy metals is possible, the dosage is usually so high that it would be unnatural for some of the naturally occurring metals in water sources. Pathologically, heavy metals can be introduced into stored rainwater via atmospheric aerosol and roof-attached atmospheric contamination (dust) (Förster, 1999; Galster & Helmreich, 2022; Lye, 2009; Sánchez et al., 2015). The attribute that makes heavy metals particularly hazardous is their capacity to bioaccumulate in the body, weakening bodily systems and functions. Most notably, arsenic is considered one of the most contaminants in water sources due to its ability to propagate long-term illnesses such as cancer and skin lesion; associate, but less visible diseases are also identified to be diabetes, cardiovascular, and cognitive disability in infants (Ratnaik, 2003). Rainwater quality test indicates that 16 samples collected from households have neglectable trace amounts of heavy metals (listed as Not Detected [ND]). However, cadmium exhibit slight elevation ranging between 0.002 – 0.009 – a range that exceeds the threshold of 0.003 set by both guidelines.

Two others abnormalities in the quality test results that exceed the safety threshold for both guidelines are microbiological contamination of coliform and E.coli. Although, contamination can be a concern, coliform and E.coli contamination from roof-based rainwater harvesting can be common, especially so in urban areas

(Ahmed et al., 2010; Sánchez et al., 2015). One study of rain harvesting in Hanoi, Vietnam found that stored rainwater collected from brick tiles for an elementary rainwater harvesting system exhibited coliform between 0 – 78,000 CFU/mL and E.coli between 0 – 3,200 CFU/mL (Dao et al., 2017). Nevertheless, it is highly recommended that microbiologically contaminated water or rainwater be disinfected prior to use given the potential health hazard.

As shown in Table 3-16, only cadmium and microorganism parameters significantly exceed that of the national and WHO guidelines. As a result, it is recommended that technical suggestions for RWHS treatment quality be considered in addition to the estimation of storage capacity and analysis of materials selection. Furthermore, to maintain the relatively sustainable and low-cost nature of existing RWHS, recommendations in the following section will primarily focus on aspects relating to the catchment, storage, and treatment within the RWHS.

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## 4. RAINWATER HARVESTING SYSTEM

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### 4.1 Rainwater Harvesting and Guiding Principle

The degree to which RWHS is implemented depends on the scale and purpose for which production is undertaken. For this reason, it is helpful to understand the different classifications of RWHS. Criteria used to classify RWHS are storage method, catchment types, and scale. Given this condition, an integrated classification by Tuinhof et al. (2012) and S. Singh et al. (2022) determined that there are four main groups for the RWHS concept: Macro-catchment system, micro-catchment system, floodwater harvesting, and domestic harvesting.

Floodwater harvesting is the largest system designed primarily for agricultural consideration. Basically, this system stores rainwater in the channel for crop irrigation. The method is conceived so that ephemeral channel flow from runoffs is retained for continuous irrigational recharge for crops, and vegetation, which also serves to periodically replenish groundwater water. By using a channel as a storage medium, a catchment for this floodwater harvesting can span several kilometers. This system is particularly significant for agriculture-oriented arid regions where evaporation exceeds precipitation during dry seasons, which forces maximization of large-scale rainwater retention during massive flood events from heavy rainfall during wet seasons.

The second largest type of system, the macro-catchment harvesting system, utilizes mountains, hills, or slopes as natural catchments for runoff collection. In this system, sources of potential runoff are variable. For example, runoffs from saturated soils, concrete, and the compacted surface can be funneled and collected via direct diversion of surface water flow onto cultivated areas (foot of hills or flatland) where it is available for non-potable processes and uses. Domestic application for macro-catchment is sparse, but possible if implemented for use on a community-level consumption. However, feasibility can be variable and transferability is geographically dependent. Alternatively, diversion can connect to industrial storage facilities, or artificial retention structures, such as barriers, can be installed to impede flow and form small rainwater reservoirs.

Micro-catchment harvesting collects rainwater using smaller scale catchment via rills and runoff sheets compared to macro-catchment, but with the same flow diversion mechanism. Storage of rainwater in micro-catchment harvesting is typically adjacent to the targeted zone of application, whether for small-scale agricultural or communal purposes within a medium group of households – a neighborhood. For agriculture, storage is near the root zone of vegetation areas for direct use; multiple storage fields connected to the same catchments can alternate between vegetation ponds, acting as a passive reservoir that supplements hydration and moisture for the soil. For domestic use within a neighborhood, flow diversion directly connects to enclosed (usually underground) storage units where varying degrees of treatment are required before for potable or non-potable use. Micro-catchment harvesting is mostly optimized for agronomic crop rotation due to its boost to soil fertility management.

Domestic harvesting denotes the storage of rainwater of the smallest scale. In this category, there are two primary sub-type for domestic RWHS, namely the roof-based system and pond-based system. These

systems are among the most prominent and most utilized in both developed and developing countries where water security requires improvement for domestic purposes, such as hydration, sanitation, gardening, and coolants (Zabidi et al., 2020). Roof-based domestic RWHS can be implemented for private, public, or commercial. Basically, rainfall is captured using roof areas as catchments with 80 – 85% effective rainfall capture rate (Gould, 2015; Oweis et al., 2012). Roof-based systems are most prominently observed in tropical and subtropical countries and regions, such as the Lower Mekong Delta in Vietnam, where collected rainfall can be used for domestic uses such as sanitation, hygiene, and even cooking and drinking in areas with unreliable tap water access – circumstance similar to that of many VMD provinces and Ben Tre (particularly Binh Dai district) (Dao et al., 2017; Özdemir et al., 2011; Thuy et al., 2019; Worm, 2006). Pond-based RWHS relies on sloped surfaces (paved or compacted) or plastic sheets as a catchment for rainwater. For optimal collection, slopes are combined with ridges to maximize retention capacity. The permeability of sloped surfaces is also a factor in collection efficiency as it is proportional to possible rainwater volume collected. Basically, a pond-based system operates similarly to urban retention ponds designed to store stormwater at a certain capacity to mitigate flood risk via passive soil infiltration; the difference is the minimization of permeability of collection ponds so that flows can be diverted to connected storage units above or below ground (Zabidi et al., 2020).

Table 4-1: Summary of RWHS typification

Types of RWHS		Catchment Size	Scale	Application	Characteristics
Floodwater harvesting		1 – 50 km <sup>2</sup>	Region	Agriculture	Rainfall is harvested via (a) natural flooding events or spate overflow from rivers and gullies; and (b) impounded water in the valley floor. Harvested water is diverted into one central spillway or two parallel spillways as arterial channels that distribute water to adjacent fields. Floodwater harvesting can promote constant soil-water exchange and self-fertilization (via sediment build-up) to enhance appropriate crop growth, thereby leading to a highly productive rainwater harvesting system.
Macrocatchment harvesting		0.1 – 4 ha	Community (or industry)	Agriculture– Industry– Domestic	Harvested rain from rill flows and overland flow. Flow diversion via hillsides, pasture, forests, and roads into storage fields or facilities, which enables direction provision of water for crops, or settlements after appropriate treatment.
Microcatchment harvesting		500 – 1000 m <sup>2</sup>	Neighborhood	Agronomy– Agriculture– Domestic	Harvested rain from rill flows and overland flow. Runoff is stored directly in the field or in the enclosed storage unit for further distribution to crops and residential areas.
Domestic Harvesting	Roof-based	10 – 100 m <sup>2</sup>	Household	Domestic	Rainfall is harvested via the roof of private and public buildings. Harvest rainwater is diverted through a conveyance system of gutters and downspouts towards storage units where the provision of rainwater can be

					conducted via direct withdrawal, or an integrated utility system.
	Pond-based	10 – 100 m <sup>2</sup>	Household	Domestic	Rainfall is harvested via plastic sheets or inwardly sloped surfaces (usually paved or concrete) to form ponds. Harvested rainfall is diverted into overground or underground storage that enables provision throughout the household for domestic use.

As discussed in chapter 3, rainwater harvesting in the study area is mainly observed to be roof-based, mainly used for domestic use (non-potable and potable). The system is simple and comprises similar components described in the characteristic of roof-based domestic harvesting; particularly the sloped roof under which installed gutters collect rainwater into downspouts connected to storage facilities. Based on information collected on overall system parameters available for each household in the surveyed area (Table 4-2), it is observed that all catchment areas are also under 100 m<sup>2</sup> in size, with a local average of 28.8 m<sup>2</sup>. Given this condition, it is assessed that most harvesting systems in the study area belong to the category of roof-based domestic harvesting systems, and system design will be considered under this assumption. In addition, besides integrated sustainability principles to be discussed in the following paragraph, the design philosophy of the system will also emphasize the aspects of maintenance difficulty, transferability, and ease of use.

Table 4-2: Summary of surveyed system parameters

Area	Available Catchment (m <sup>2</sup> )	Storage Capacity (m <sup>3</sup> )	Storage Material	Storage Cost (million VND)	Installation	Cost per unit storage (million VND/m <sup>3</sup> )
Dinh Trung	36	10	Polyethylene	18		1.8
Dinh Trung	37.5	20	Concrete	44		2.2
Dinh Trung	18	2	Concrete	5		2.5
Dinh Trung	50	50	Concrete	120		2.4
Dinh Trung	31.5	12	Polyethylene	25		2.08
Dinh Trung	45	18	Ceramic	30		1.67
Binh Thoi	30	14	Concrete	30		2.14
Binh Thoi	44	8	Concrete	10		1.25
Binh Thoi	35.5	20	Concrete	45		2.25
Binh Thoi	20	1	Concrete	2		2
Binh Thoi	22	10	Concrete	25		2.5
Binh Thoi	36	6	Concrete	10		1.67
Binh Dai	20	8	Concrete	15		1.875
Binh Dai	16.5	1	Concrete	1.5		1.5
Binh Dai	35	1	Concrete	2		2
Binh Dai	20	5	Polyethylene	10		2
Binh Dai	10	2	Polyethylene	4		2
Binh Dai	16	2	Polyethylene	5		2.5
Binh Dai	38.5	10	Concrete	30		3
Binh Dai	15	2	Concrete	3		1.5

Mean	28.8	10.1	-	21.7	2.04
Standard Deviation	11.6	11.3	-	26.95	0.42
Median	30.75	8	-	12.5	2
Mode	20	2	-	30	2

RWHS promotes sustainability via the collection and storage of surplus rainfall at a specific catchment area. This allows users to create freshwater availability whenever and wherever a water shortage occurs. Basically, rainwater harvesting increases water availability via the mutually beneficial reduction of rainfall runoffs and maximization of its retention, or trappings, in storage units. In this respect, rainwater harvesting can supply households or communities with enough freshwater to overcome surface and groundwater insufficiency as a consequence of pollution or saltwater intrusion in coastal regions of the Binh Dai district. According to S. Singh et al. (2022), storage of rainwater for domestic, agricultural, and forestry purposes indirectly enhances the water replenishment rate for surface and groundwater at specific time intervals via periodic soil-water infiltration. As a result, rainwater harvesting can also improve groundwater quality via the promotion of vegetation growth and periodic dilution.

Given the aim and need for RWHS, the designed proposal for existing RWHS aims to preserve the nature of sustainability. This includes consideration of the environmental, economic, and social aspects associated with RWHS presented in Table 4-3.

Table 4-3: RWHS guiding principle for design

Aspects	Criteria	Guiding Principles	Component Consideration
Social	Health and Safety	A sufficient RWHS can contribute to the improvement of the public within the region of implementation. Since tap water is not drinkable in Vietnam due to concerns of trace chlorine dosage, users are recommended to boil water before consumption like they do rainwater. Long-term consumption of chlorinated water poses a significant health risk to consumers (Morris, 1995), which could potentially serve as facilitation for rainwater endorsement.	Treatment modules serve as one of the most crucial components of RWHS for quality control. While practices such as first flush, and material consideration in a catchment, storage, and conveyance modules are important elements in the mitigation of contaminants, the final treatment that ensure the drinkability of rainwater.
	Community Empowerment	As previously mentioned, the use of tap water for drinking in Ben Tre is less than 50% (GSO, 2020b). This is due to the water supply coverage capability within the Mekong Delta. As a result, reliance on surface and groundwater withdrawal is still prevalent. However, these activities are being threatened by the increasing intrusion of saltwater as a result of climate change, thus increasing water scarcity, which is one of the	Catchment and storage will be the main components that determine rainwater surplus available for consumption in the context of domestic activities, or production such as agriculture and forestry. Assessment of implementation feasibility and design of

		<p>reasons why communities started harvesting rainwater. Rainwater harvesting represents self-sufficiency and household independence. In addition, a sufficiently large enough rainwater harvesting system can also promote sustainable agriculture via the provision of irrigation water (de Sá Silva et al., 2022), thereby promoting sustainable livelihood to communities, especially in rural areas.</p>	
Environmental	Emission Capacity	<p>RWHS has been tested to be more efficient in energy use in comparison to conventional centralized supply in terms of energy use and manufacturing life cycle costs. Chang et al. (2017) were able to determine that an urban RWHS emits about 0.14 – 0.16 kgCO<sub>2</sub>-eq/m<sup>3</sup>, which is 0.27 – 0.29 kgCO<sub>2</sub>-eq/m<sup>3</sup> less than a conventional water supply system in Korea. In America, a life cycle analysis by Ghimire et al. (2014) also determined that RWHS components emit 0.41 kgCO<sub>2</sub>-eq/m<sup>3</sup> compared to 0.85 kgCO<sub>2</sub>-eq/m<sup>3</sup> observed in conventional systems.</p>	<p>Each component that makes up the operational function of RWHS emits a certain degree of carbon footprint. In terms of energy use, treatment modules will likely contribute to the majority of emissions in an RWHS. In a conventional water supply, a complex system of pressurized pumps is attributed to high energy use. Emission consideration will primarily be accounted for in the design of treatment modules. However, the design will not prioritize optimized energy consumption over health risks to users of RWHS.</p>
	Water-energy saving	<p>As a result of increased water availability from rainfall, freshwater self-sufficiency is increased due to the implementation of RWHS. Subsequently, the needs for a central water supply is reduced. Dang et al. (2020) estimated that the VMD has an average rainfall potential of 43 m<sup>3</sup> per capita annually (approximately 119 liters per capita daily). In particular, the study also estimated Ben Tre average potential rainfall at 1858 mm annually, 264 mm of which is off-season rainfall during the dry season. In the context of Ben Tre province, the overall potential would be equivalent to at least 31.86 m<sup>3</sup> per capita annually, or 87 liters per capita daily (Dang et al., 2020). Not only will potential rainfall availability reduce central water supply use, but it will also reduce energy use as well. For reference, a study conducted in China found that water conservation for domestic and agricultural purposes via RWHS, reduce water use by 75.8 m<sup>3</sup> per household annually, which corresponds to a decrease of 138.6 kWh in energy use,</p>	<p>Water saving is one of the most basic environmental functions to which RWHS contributes. The component that primarily attributes to this contribution is storage capacity. The volume of rainfall stored is proportional to the reduction of the central water supply, thereby reducing energy consumption. As such, storage capacity design will be determined via a water balancing table aggregating known precipitation extract in rainwater quantitative assessment; the available rainwater volume collectible given average household catchment area; average water demand surveyed.</p>



		equivalent to 21.3% of the annual energy use of studied households (Jiang & Li, 2013).	
Economic	Financial sustainability	Long-term economic sustainability Measures and maintenance processes for the RWHS will incur certain recurrent costs to the finance of users. Therefore, it is important to review the cost of investment in comparison to the economic value and its return potential in the long term given the implementation of RWHS.	For economic aspects, all components proposed in the design will be reviewed from commercially available products, which allows for an approximate price estimation in the most recent time. Using certain calculated indicators, economic sustainability can be determined.

## 4.2 Catchment, Conveyance, and Storage Module

### 4.2.1 Catchment Consideration

Roof catchment areas within the study area, and most likely in Binh Dai district in general are variable on a case-by-case basis as observed in Table 4-2. Variability in roof catchment areas will also impact water availability potential, thus changing storage capacity design on a case-by-case basis. Therefore, the roof catchment area is standardized based on the average roof catchment in Table 4-2 at 28.8 m<sup>2</sup>. Instead, catchment considerations primarily focus on material selection for catchment areas, which mainly concern two aspects: collection efficiency and potential contamination risk.

#### 4.2.1.1 Collection Efficiency

Collection efficiency, also known as runoff coefficient, is the ratio of rainwater that runs off a roof catchment surface to rainwater that falls onto the catchment surfaces. Collection efficiency is one of the most important factors in rainwater catchment calculations as it accounts for rainwater loss as a result of material hardness, porosity, permeability, etc. in the form of spillage, leakage, infiltration, evaporation, and surface wetting, all of which reduces potential rainwater harvest to enter storage units. Gould (2015) suggested that a maximized system using corrugated metal sheets or tiles can reach achieve an efficiency between 90 – 95%. However, the study also postulated that long-term operation efficiency will be lower due to substantial losses from (a) gutter overflow or debris blockage, especially during torrential rains, and (b) precipitation that occurs in snow or hail form during strong wind conditions. As such, the majorly used material of corrugated metal in the study can ideally reach up to 95% efficiency, but realistically 85% is the standard efficiency under weather conditions and roof erosion (Gould, 2015). Collection efficiency for other materials used for both roof-based and pond-based systems can be referenced from Table 4-4.

Table 4-4: Efficiency factor of different catchment materials. Source of data from <sup>1</sup>Gould (2015) and <sup>2</sup>Zhu and Liu (1998)

Roof Catchment (Roof-based)		Ground Catchment (Pond-based)	
<sup>2</sup> Clay tile (Handmade)	0.24 – 0.31	<sup>2</sup> Concrete lined	0.73 – 0.76
<sup>2</sup> Clay tile (Industrial)	0.30 – 0.39	<sup>2</sup> Cement soil mix	0.33 – 0.42
<sup>2</sup> Cement tile	0.62 – 0.69	<sup>2</sup> Buried plastic sheet	0.28 – 0.36
<sup>1</sup> Corrugated steel	0.90 – 0.95	<sup>2</sup> Compacted loose soil	0.13 – 0.19

#### 4.2.1.2 Materials

There are two main types of roofing materials used for rainwater harvesting in the study area according to survey results: fibro cement and corrugated metal (Table 3-14). Fibro cement, also known as asbestos cement, is a composite material commonly used in the construction industry for sturdy, non-flammable, flexible, and low-cost properties – characteristics primarily attributed to its mineral component, asbestos. This is because cementitious matrix exhibited subpar mechanical performance without the reinforcement of a fibrous material which significantly enhances the overall resistance of the matrix (Campopiano et al., 2009). There is a variety of asbestos used as a material component in industrial production, but there are two main types: serpentine (chrysotile, curly-shaped crystal), and amphibole (needle-shaped crystal). Flat and corrugated asbestos cement sheets are produced via the incorporation of asbestos into the mixing processing of cement with a percentage varying between 10 – 16% based on the final purpose. Asbestos is also known for causing chronic life-threatening diseases such as lung fibrosis (asbestosis), pleural mesothelioma, peritoneal mesothelioma, and lung cancer (Boffetta, 1998; Osinubi et al., 2000), indicating that primary exposure pathway is via inhalation. Normally, asbestos fiber within fibro cement is mostly inert, which means that good maintenance can limit the spontaneous release of asbestos particulate fibers into the air. However, erosion as a result of exposure to environmental conditions is inevitable, which raises asbestos's status as a hazardous material that requires international prohibition. Unfortunately, Vietnam is not part of the 44 countries that ban use of asbestos in construction and industrial production (Bahk et al., 2013). According to National Decree 09/2021/NĐ-CP on Management of Building Materials, chrysotile asbestos, commonly referred to as white asbestos, continues as the primary component for the production of asbestos-containing materials in Vietnam. In recent decades, Harrison et al. (1999) and Osinubi et al. (2000) found that potential alternatives such as p-aramid, cellulose, and polyvinyl alcohol (PVA) have been developed and compared to asbestos-containing products with mixed results. Particularly, it was found that while fiber-cement mix of alternatives yield greater durability over time, which release less particular fiber into the environment in the short term but overall particulate fiber released over the total lifespan of product is equivalent to that of asbestos cement regardless. In the end, asbestos remains one of the most economically and mechanically efficient mineral in the construction industry in spite of the potentially hazard for both producers and users because alternatives are still unable to entirely mitigate health risk while exhibiting a higher cost-output ratio.

In contrast, metal is one of the safer options despite the potential health risks. For example, metal sheet roofing can be a source of metal ion contamination in collected rainwater; particularly, variant metal roofing sheeting can impart traces of its metal components into rainwater under poorly maintained conditions (i.e. rust or erosion) (Ahmed et al., 2010; Galster & Helmreich, 2022; Lim & Jiang, 2013; Lye, 2009). Besides metal roofing, sources of heavy metal contamination in rainwater is attributed to air pollution in urban areas where the concentration of emitted pollutants is diffused into the local atmosphere for precipitation to pick up (Sánchez et al., 2015). In more rural areas, such as Ben Tre province and Binh Dai district, rainwater contamination from urban pollution is less significant, although still possible. Within the context of this thesis, contamination regarding heavy metals will focus on cadmium contamination as per the results of the rainwater quality assessment in chapter 3. In Australia, Chubaka et al. (2018) found that the most likely cadmium contamination pathways are material-based and atmosphere-based. In particular, clay tiles were discovered to

have a higher association with elevated cadmium in comparison to metal and concrete roofs (almost no association); and atmospheric aerosol was also attributed to elevated cadmium in the region. Given the context of metal roofing as the most common roofing in the area, it can be postulated that metal roofing is not likely to be the source of cadmium contamination observed in rainwater samples, which makes metal a better candidate material for standard rainwater harvest catchment than asbestos cement. Despite the carcinogenic and chronic health risks associated with cadmium exposure, treatment of cadmium in rainwater is simple, compact, and more manageable than air purification for particulate asbestos, which will be elaborated further in the corresponding section of this chapter.

In summary, for catchment consideration in the context of this thesis, the current primary material of corrugated metal sheets as catchment roofing should continue to be the standard practice in the study area, and possibly the region, which would satisfy the design principle of transferability, environmental (85% of runoff collection rate), and social aspects (health and safety) discussed previously.

#### **4.2.2 Conveyance Consideration**

Each household has a different design that requires different variants of piping networks if integrated utility is to be considered. As such, to standardize design for the highest transferability, it is more practical to maintain the minimalistic nature of the current conveyance system commonly used by local users. This means that while gutters and downspouts are still significant consideration to roof-based design and consideration, integrated distribution will not be accounted for and conveyance consideration will focus on (a) material used to minimize cost and risk of contamination, (b) general placement for direct withdrawal, and (c) gutter, downspout, debris mesh and splash guard from roof to storage.

##### **4.2.2.1 Materials**

Generally, conveyance components are estimated to cost between 5 to 15% of the total cost based on variable local prices and conditions of materials (Gould, 2015). Material options for gutters and downspouts can vary between metals (aluminum, galvanized steel), plastic, cement, wood, and bamboo. While wood and bamboo are viable and relatively sustainable choices, due to their organic nature, permeability, bioaccumulation, decay, and deterioration under direct environmental contacts can reduce collection efficiency and introduce contaminants into rainwater in storage, risking the health and safety of users. As such, the remaining choices would be either plastic (specifically PVC plastic) or metal (aluminum, or galvanized steel), both of which exhibit a similar characteristic of sturdiness and water resistance. Therefore, the criteria that determine the final material choice generally are the economic, environmental, and health-related properties of these materials. In terms of health and safety, both materials have a very high degree of resistance to environmental changes, and the lifecycle of both can last for more than 50 years (Recio et al., 2005). For metals such as aluminum and galvanized steel, proper maintenance will reduce the risks of heavy metals being imparted into the rainwater supply. Concerns surrounding PVC toxicity primarily derive from the manufacturing process where manufacturing additives and byproducts can cause adverse health risks such as cancer; however, under its stable commercial form, it can last up to 100 years under no maintenance conditions (Akovali, 2012). In fact, it was also noted PVC is more resistant to corrosion and oxidation than steel (Bergman, 2000), which means that PVC is more unlikely to impart any adverse physiochemical

characteristics into rainwater supply under normal conditions, thereby reducing environmental and maintenance costs, and extending the average RWHS 10-year life span (Akovali, 2012; Gould, 2015).

Furthermore, the option of metal, aluminum and galvanized steel also displayed a differential affinity for rainwater harvesting. For example, aluminum was observed to have a better performance against corrosion in an acidic rainwater condition than galvanized steel, making it a more desirable option for metal (3 – 4.34 pH) (Abdulkarim et al., 2009). Similarly, corrosive resistance in PVC has been sufficiently adequate that it is popularized in sewage piping (Akovali, 2012). Environmentally, Recio et al. (2005) found that one PVC window manufacturing lifecycle consumed between 1730 – 1780 kWh and emitted 730 – 742 kgCO<sub>2</sub>-eq while one aluminum window averaged between 3244 – 4413 kWh (87.5 – 147.9% higher) and 1418 – 1935 kgCO<sub>2</sub>-eq (94.3 – 160.8% higher) in comparative power consumption and carbon emission respectively. Based on the assessment that metal is generally more environmentally costly to manufacture than PVC, an inference on commercial pricing between the two materials can also be derived. Overall, it can be observed that decades of experimentation and material manufacturing have shown that the benefits and versatility of PVC outweigh its risks, which, in context to risks and costs posed by metal materials, makes it the better choice environmentally, economically, and socially as material for the conveyance system.

#### 4.2.2.2 Optimal Placement and Sizing

The role of water transportation is singular, yet enormous to the cohesion and efficiency of the entire RWHS. Conveyance components can easily be as much of a weak link as it is a significant cohesion factor between catchment, storage, and treatment modules. Gutters and downspouts placement is essential to factor to maximizing the collection efficiency of rainwater catchment as broken or impaired gutters and pipes often limit the capability of the entire system to adequately collect, store, and treat rainwater for use. As such, regular maintenance of conveyance is recommended to keep it clean of debris.

Alternatives for catchment-storage water transportation are available in many forms around the world. Gould (2015) described the roof glides observed in Bermuda, cement channels in rural China, and even wooden or scrap metal sheets are often a common makeshift technique to divert water from roof to storage among poorer developing countries. Despite the international variety, gutters and downspouts are still considered the most popular in both the developed and developing world because it enables the highest ideal collection efficiency of up to 90%, but long-term normal condition stabilizes the figure between 80 – 85%. It should be noted that collection efficiency is not a separate factor from the one introduced in the previous discussion on catchment consideration; rather, collection efficiency is the collective factor derived by the study on the normal operation of a well-designed catchment and conveyance system (Gould, 2015).

A sufficient conveyance and delivery design that utilize the full capacity of the catchment area should account for the following variables within its system: (a) water flow; (b) inflow protection; (c) first-flush valve; (d) overflow optimization; and (e) outflow optimization.

Water flow facilitation is important because it ensures the effectiveness of the collection process. For instance, a horizontal gutter is usually not recommended as it creates unnecessary retention in the gutter and does not utilize the freely available gravity. Instead, a sloped gutter, preferably at a 1:100 gradient, is recommended in most cases (Gould, 2015). Additionally, gutter size is also crucial to the effective water flow

of a design system. Due to spatial and temporal variability of rainfall, gutter sizing according to precipitation is difficult, therefore gutter size is generally estimated based on an available catchment area of the targeted household, which is at least 1 cm<sup>2</sup> of the gutter cross-section for every 1 m<sup>2</sup> of catchment area (Gould, 2015). However, to account for overflow during torrential rainfall, it is also recommended to estimate the gutter cross section with a compensatory factor of 1.3. Managing constant water flow during rain via management of spillage from rainfall overshooting gutter is also an important aspect of concern. In this case, a 30-cm-width sheet can be installed as a ‘splash guard’, the upper half of which is nailed to the roof, while the lower half is angled and bent to be hung over the edge of the roof by 2 – 3 cm. Furthermore, the splash guard also enables two alternative modifications to the gutter system: (a) the gutter can now be suspended from the splash guard instead of being fitted in an attached bracket to the side of the house; and (b) the gutter can be best optimized with a V-shaped cross-section to prevent not just water over-shooting but also under-cutting, which would lead to loss of considerable water potential.

Inflow protection is recommended to prevent debris with potential contaminants to infiltrate storage and continue propagating impurities in the collected rainwater matrix. To do this, a 5-mm mesh is to be installed, angled at a minimum of 60° from the x-axis of the gutter, and placed at least 3 cm from the downspout.

First-flush is one of the most basic and crucial steps in contaminant prevention. As discussed in previous chapters, the first flush can mitigate a significant (85%) concentration of incoming contaminants common within the first few rainfalls of the season (Martinson & Thomas, 2009). To effectively implement, the storage inlet should be perpendicular to the downspout, creating a three-way intersection where a manual valve can be installed, allowing first-flush rainwater to follow the downspout and bypass the storage inlet down to the ground or a small-sized container corresponding to the first-flush volume. According to the Texas Water Development Board (2005), the estimation of first-flush volume is generally calculated as 0.41 liters per square meter of the catchment area, which, in the context standardized 28.8 m<sup>2</sup> catchment in the study area, was calculated to be 11.81 liters of diverted rainwater. However, Gould (2015) cautions that an average household should divert at least between 20 – 24 liters given the standard size of detached houses (in Australia), or overcompensate with a 1.3 multiplier factor.

Overflow and outflow optimization basically prevent the so-called “dead storage” which describes wasted storage below and above inadequately placed outflow and overflow respectively. Essentially, the overflow pipe connection should be placed at the highest point on the side of the storage unit so that no filler air space is left. Similarly, the outflow is recommended to be placed at the lowest relative point of storage units to ensure sufficient water head for all available supply in storage and prevent static storage below the point of outflow.

## 4.2.3 Storage Consideration

### 4.2.3.1 Materials

With roof-based domestic harvesting, storage tanks or cisterns generally consume the majority of the budget for the system. In some cases, the treatment module can also be expensive, but in most cases, storage is the most expensive component due to the large volume requirement for long-term water use. In addition,

storage unit pricings are variable depending on the region, materials, and capacity of the component. Different culture has had a different material adaptation of rainwater storage such as earthenware (India), pottery (Africa, Southeast Asia), vinyl-line sheet (Hawaii), and stone, concrete, brick, and galvanized steel in the central United States (Nazif et al., 2021). Determining the size of storage depends on many variables, mainly concerning local rainfall season, actual water demand, and catchment area, all of which will be elaborated on in the following sub-section. The main consideration in the determination of tank material depends on the placement and budget.

Placement of storage can be above or below ground depending on soil condition, temperature variability, and associated costs. Some materials are more appropriate only for above ground (vinyl-lined sheet, fiberglass) while others can be implemented for both types (polyethylene) depending on the chemical and mechanical properties of the material (corrosive resistance, thermal expandability, tensile strength, leachability, etc.). However, due to the sheer amount of material available for consideration, preliminary criteria should be established to narrow down selections. Understanding necessary information regarding available alternatives is crucial to selecting the most suitable material that complies with the fundamental and sustainable principle of RWHS design. Assessment from research conducted by Shah et al. (2016) and Nazif et al. (2021) can be illustrated via score-based differences between storage materials, including longevity, availability, transportability, maintenance requirement, handling difficulty for a household to build and repair themselves (DIY), cost, and carbon footprint (Table 4-5). Availability and transportation are elective assessment factors, which means that their weight can vary depending on the geographic scope of the local market and the personal preferences of households or designers implementing RWHS. This means those selection criteria will place a higher emphasis on longevity, maintenance, workability, cost, and carbon footprint. These factors are graded on a scale from 1 to 5, with 1 being very undesirable and 5 being very desirable.

Table 4-5: Graded characteristics of storage materials: (1) Longevity (LG); (2) Availability (AV); (3) Transportability (TP); (4) Maintenance (MT); (5) User Workability (DIY); (6) Cost; and (7) Carbon Footprint. Retrieved from source: Nazif et al. (2021)

Material		LG	AV	TP	MT	DIY	Cost	Carbon Footprint	Total	Justification
Wood		3	2	4	3	2	2	4	20	(Nazif et al., 2021)
Stone		5	2	1	3	3	2	4	20	(Nazif et al., 2021)
Plastered tires		5	2	1	4	4	5	3	24	(Nazif et al., 2021)
Fiberglass		4	4	4	1	1	2	4	20	(Nazif et al., 2021)
Cement/Concrete		4	3	1	4	3	2	2	19	(Shah et al., 2016)
Ferro-cement		4	3	1	4	4	3	2	21	(Shah et al., 2016)
Metal	Aboveground	5	4	4	4	1	3	3	24	(Shah et al., 2016)
	Underground	5	4	3	4	1	1	3	21	(Shah et al., 2016)

Polyethylene	Aboveground	4	5	5	3	1	4	4	26	(Shah et al., 2016)
	Underground	5	4	5	1	1	1	4	21	(Shah et al., 2016)

Based on material reviews within the table, wood is the only material that performed inadequately relative to other materials. However, it should be noted that Table 4-5 is formulated based on assumptions of common rainwater harvesting practices without consideration for specific socio-economic and geo-economic availability and circumstances in variable regions. For instance, it was assessed that plastered tires as a storage material is the most desirable given the exclusion of elective assessment factors (Nazif et al., 2021). However, the most commercially available household water tank in Vietnam is polyethylene and stainless galvanized steel (locally known as inox steel) based on oral responses from interviewees. In fact, it was noted that residents are predisposed to a certain cost-associated material hierarchy that starts with concrete as the cheapest, followed by plastic or polyethylene, and ends with inox steel as the most expensive and ideal storage material, which can be partially observed in storage market price reported in survey responses. This revelation means that ferro-cement and cement are only potentially expensive if labor cost is involved. Fortunately, cement is assessed to be relatively workable by households, meaning households can build projects by themselves with less labor-associated cost, although labor cost for more complex excavation of underground storage is not as easily waived as above-ground labor. Therefore, within the context of the study area in Vietnam, cement, polyethylene, and metal are materials with the highest availability. In comparison, between cement, polyethylene, and metal, it can be observed that cement enable households to build storage by themselves and mitigate labor cost and value-added cost from the preassembled storage tank from less workable material such as steel and polyethylene. Raw material cement is also cheap and requires minimal maintenance with high longevity. As previously in chapter 2, concrete storage also serves as a passive pH neutralizer due to the presence of lime component, which mitigates the risks of microorganism development under an acidic environment (Campisano et al., 2017; Despins et al., 2009; Sánchez et al., 2015; Scott & Waller, 1987). However, this neutralization benefit only applies to rainwater with pH between 3 to 4, given that the pH collected within the study area measured at around 5.8 – 6.7 (for both concrete and polyethylene containers), the benefit seems redundant and unnecessary. In addition, the process of neutralizing rainfall acidity via slow corrosion of concrete containers (in the context of minimal maintenance) poses risks to health, safety, household economics, and the ability to secure water supply in the long term. As a result, cement does not provide enough of a net benefit to social convenience to justify the high socio-economic and environmental externality (carbon footprint) risks. In contrast, metals and plastic not only exhibit high longevity and provide the same health and safety benefit, without user workability potential, but also offer high transportability; all the while maintaining relatively medium (metal) to low (polyethylene) environmental impact in the form of carbon emission (Shah et al., 2016). Furthermore, given the concept of the overall system (Figure 4-3), aboveground implementation for metal and polyethylene would best suit the design, economic, and environmental requirements stated in previous design principles. In summary, potential candidate materials

under consideration are both polyethylene and metal, the reason for which is to provide a more complete picture in terms of actual cost-benefit analysis in the next chapter.

#### 4.2.3.2 Dimensioning

For efficient storage volume, the determination of size will utilize the Rippl method which allows for a calculation of compensatory storage volume required to ensure sufficient water supply given the pluvial regime, demands, and roof area (Matos et al., 2013; Silva & Maia, 2021). Although Matos et al. (2013) noted that arithmetic-based methods introduce variable uncertainties in the determination of storage sizing given pluvial regime, the Rippl method demonstrated itself to be accurate, albeit under two main limitations: (a) data sampling error (i.e. reliance on water demand consumption survey); and (b) the coarse discretization of time. However, coarse discretization of time can be mitigated by using finer temporal indicators such as daily (instead of monthly) availability of rainwater given a normalized catchment area. Basically, the method involves water balancing between the inflow (collectible rainfall) and outflow (demand) given current catchment conditions, which would output the water supply storage necessary to store the highest rainwater surplus (positive value).

This can be done via the use of eight columns shown in Table 4-6. Within the scope of this study, only rainwater storage will be considered, which means scenarios presenting a deficit in column 8 would suggest that the conditions of supply and demand are impractical, or requires adjustments either from the supply side (structural expansion) or from the demand side (consumption limitation).

In Table 4-6, **column 1** depicts the time through a year; **column 2** shows the monthly precipitation averaged between all extracted data points in Table 3-12 of chapter 3; and **column 3** shows the constant monthly first flush volume necessary to ensure the minimal risk of contamination from roof debris accumulation, which is estimated based on the principle of 0.41 liters of the first flush per square meter of the catchment area, multiplied by a compensatory factor of 1.3. It is calculated as  $\frac{0.41 L}{m^2} \times \frac{m^3}{1000 L} \times 28.8 m^2 \times 1.3 = 0.02 m^3$

**Column 4** refers to the average monthly consumption for individual households. From the result reported in the survey, the self-reported monthly household consumption averaged around  $7.5 m^3$ . Given that the average household size in the study area is 4 people per household, this average translates to a consumption rate of  $1.875 m^3$  per person per month (or 62.5 liters per person per day). For reference, studies on water consumption from 286 cities in China discovered a consumption rate of 70 liters per capita per day, noting that rural areas often experience lower water consumption for drinking and hygiene, but higher water use for drinking, hygiene, and outdoor combined (Beal et al., 2013; Fan et al., 2017). In India, it was noted that the average consumption rate in a rural area can rise to as high as 117 liters per capita per day, which translate to roughly 67.14% higher than domestic rural consumption (O. Singh & Turkiya, 2013). The field survey also indicated that water utilization varies between households in Binh Dai, but there are indications that rainwater is used for all drinking, hygiene, and outdoor use. Therefore, average consumption reported includes drinking, hygiene, and outdoor use as the first water use scenario (i.e., scenario 1), which introduces the need for different scenarios in water – namely, drinking and hygiene use as scenario 2, and drinking use as scenario 3. As a



result, under the assumption that outdoor use for water can increase water use by as much as 67.14%, it can be calculated that the average water use without outdoor use in the study area be 37.4 liters per capita per day or 4.5 m<sup>3</sup> month per average household of 4 people as the monthly water consumption for scenario 2. Similarly for scenario 3, under the assumption that the average potable water consumption is 5 liters per capita per day, the determination of monthly water consumption only for drinking can be estimated to be 600 liters per average household of 4 people;

**Column 5** shows the standardized catchment area previously determined to be 28.8 m<sup>2</sup>, and **column 6** depicts the available monthly volume given catchment and monthly precipitation, which is obtained via the multiplication of monthly rainfall (column 2), catchment area (column 5), and an efficiency factor of 0.85, then subtracted by the first-flush volume in column 3:  $Monthly\ rainfall\ (mm) \times \frac{(m)}{1000\ (mm)} \times 28.8\ (m^2) \times 0.85 - 0.02\ (m^3)$ . **Column 7** expresses the difference between monthly consumption (column 4) and monthly available volume (column 6) (i.e. column 6 subtracted by column 4), with a negative value indicating a deficit due to relatively rainwater supply being lower than demand, and rainwater surplus for a positive value.

Finally, **column 8** shows the total accumulated difference from column 7, where the lowest negative value represents the highest water demand not met given the available water supply from the catchment and pluvial regime. In contrast, the highest positive number indicates a surplus in rainwater supply. As such, the value of the highest positive numbers serves as the optimal storage size necessary to ensure sufficient rainwater harvesting given rainwater supply from catchment and rainfall regime. Within the scope of this study, only rainwater storage will be considered, which means scenarios presenting a deficit (negative values) in column 8 would suggest that the conditions of supply and demand are impractical, or requires adjustments from either supply side (structural expansion) or demand side (consumption limitation).

Table 4-6: Scenario-based Water Balance Table Arranged by Hydrological Season: Wet Season (June to November); and Dry Season (December to May)

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8
Month	Average Monthly Precipitation (mm)	First Flush Volume (m <sup>3</sup> )	Monthly Consumption Demand (m <sup>3</sup> )	Catchment Area (m <sup>2</sup> )	Monthly Volume of Rainwater (m <sup>3</sup> )	Monthly Consumption Balance (m <sup>3</sup> )	Cumulative Consumption Balance (m <sup>3</sup> )
<b>Scenario 1</b>							
Jun	304.50	0.02	7.50	28.80	7.44	-0.06	-0.06
Jul	305.00	0.02	7.50	28.80	7.45	-0.05	-0.11
Aug	249.15	0.02	7.50	28.80	6.08	-1.42	-1.53
Sep	304.85	0.02	7.50	28.80	7.45	-0.05	-1.58
Oct	395.60	0.02	7.50	28.80	9.67	2.17	0.59
Nov	134.25	0.02	7.50	28.80	3.27	-4.23	-3.64
Dec	31.75	0.02	7.50	28.80	0.76	-6.74	-10.38
Jan	0.40	0.02	7.50	28.80	-0.01	-7.51	-17.88
Feb	0.00	0.02	7.50	28.80	-0.02	-7.52	-25.40
Mar	0.00	0.02	7.50	28.80	-0.02	-7.52	-32.91
Apr	30.95	0.02	7.50	28.80	0.74	-6.76	-39.67

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8
Month	Average Monthly Precipitation (mm)	First Flush Volume (m <sup>3</sup> )	Monthly Consumption Demand (m <sup>3</sup> )	Catchment Area (m <sup>2</sup> )	Monthly Volume of Rainwater (m <sup>3</sup> )	Monthly Consumption Balance (m <sup>3</sup> )	Cumulative Consumption Balance (m <sup>3</sup> )
May	160.55	0.02	7.50	28.80	3.91	-3.59	-43.26
<b>Scenario 2</b>							
Jun	304.50	0.02	4.50	28.80	7.44	2.94	2.94
Jul	305.00	0.02	4.50	28.80	7.45	2.95	5.89
Aug	249.15	0.02	4.50	28.80	6.08	1.58	7.47
Sep	304.85	0.02	4.50	28.80	7.45	2.95	10.42
Oct	395.60	0.02	4.50	28.80	9.67	5.17	15.59
Nov	134.25	0.02	4.50	28.80	3.27	-1.23	14.36
Dec	31.75	0.02	4.50	28.80	0.76	-3.74	10.62
Jan	0.40	0.02	4.50	28.80	-0.01	-4.51	6.12
Feb	0.00	0.02	4.50	28.80	-0.02	-4.52	1.60
Mar	0.00	0.02	4.50	28.80	-0.02	-4.52	-2.91
Apr	30.95	0.02	4.50	28.80	0.74	-3.76	-6.67
May	160.55	0.02	4.50	28.80	3.91	-0.59	-7.26
<b>Scenario 3</b>							
Jun	304.50	0.02	0.60	28.80	7.44	6.84	6.84
Jul	305.00	0.02	0.60	28.80	7.45	6.85	13.69
Aug	249.15	0.02	0.60	28.80	6.08	5.48	19.17
Sep	304.85	0.02	0.60	28.80	7.45	6.85	26.02
Oct	395.60	0.02	0.60	28.80	9.67	9.07	35.09
Nov	134.25	0.02	0.60	28.80	3.27	2.67	37.76
Dec	31.75	0.02	0.60	28.80	0.76	0.16	37.92
Jan	0.40	0.02	0.60	28.80	-0.01	-0.61	37.32
Feb	0.00	0.02	0.60	28.80	-0.02	-0.62	36.70
Mar	0.00	0.02	0.60	28.80	-0.02	-0.62	36.09
Apr	30.95	0.02	0.60	28.80	0.74	0.14	36.23
May	160.55	0.02	0.60	28.80	3.91	3.31	39.54

From Table 4-6, it can be observed that the storage capacity needed given demand, catchment area, and collectible rainwater is quite large for scenarios one and two. The table was arranged according to the hydrological seasons of rainy (June to November) and dry (December to May) seasons in the VMD to indicate a seasonal consecutive monthly surplus in column 7 for comparison against the deficit during the dry season, which will enable the determination construction and completion time window. Determination of the onset of seasonal consecutive monthly surplus (Table 4-6) also serves as an indication for the timeline of implementation completion and operation initiation. For example, the onset of consecutive surplus for scenario 2 and scenario 3 starts in June and ended in October, which means that implementation of RWHS should start at the beginning of the dry season (November or December) and be complete by the start of the rainy season (June) so that collection cycle can initiate according to the local pluvial regime.

Regarding the determination of rainwater storage, as previously mentioned, the Rippl method indicates that while the lowest negative number in column 8 represents the water deficit rainwater is unable to accommodate demand, thus suggesting a separate water supply tank to compensate for such deficit. In contrast, given a similar principle, the absence of a demand deficit in column 8 indicates a sufficient supply of rainwater given demand, where the highest rainwater surplus is expressed as the minimum storage sizing for rainwater supply. This would suggest that only the scenario where column 8 has no negative number is eligible for a complete transition from tap water to rainwater use, in which case only scenario 3 satisfies this requirement. For scenarios 1 and 2 to eliminate the existing water deficit in the study area, an increased monthly available rainwater in column 6 is necessitated, which requires a structural expansion to the supply side as mentioned before (i.e. increase of catchment area and first-flush volume as a function of catchment area). Using iterative adjustments of the catchment in scenario 1 and scenario 2 (Table 4-7), it can be observed that the preservation of current water consumption demand for scenarios 1 and 2 necessitates an increase in the catchment area to 55.5 m<sup>2</sup> and 33.5 m<sup>2</sup> respectively. However, this would require design individualization for many of the households in the study area, and it can pose a significant obstacle in the form of property space and local spatial planning policy, all of which is beyond the generalized design scope of this thesis. Furthermore, upon cross-comparison given the data collected in Table 4-2, the requirement of 55.5 m<sup>2</sup> and 33.5 m<sup>2</sup> could not be met by 100% and 60% respectively of the 20 households surveyed in the study area, which means that changes to the catchment area would suggest a significant undertaking in addition to mentioned obstacles. Overall, catchment expansion, while a potential avenue for rainwater harvesting optimization, poses unknown variables concerning physical and institutional, which serves as a limitation to the thesis, but also presents promising outlooks for future studies.

As a result, it would be more realistic to optimize possible water consumption given the physical conditions in the study area. From initial results, it is observed that scenario 3 did not pose any cumulative deficit throughout the entire hydrological year, which met the technical criteria for scenario-based viability. However, scenario 3 only indicates the bare minimum of water use for survival (i.e. drinking and cooking) which only allows for 5 liters per capita per day. Given the physical parameters in the study area, this is sub optimal as the highest surplus value (39.54 m<sup>3</sup>) representing rainwater storage far exceeded the total annual consumption demand of 7.2 m<sup>3</sup> (0.6 m<sup>3</sup> per month in column 4). This indicates an excessive amount of stored rainwater that has no full use as most of it would overflow comes the following rainy seasons.

During the period when rainwater is supplied and consumed, the monthly surplus balance fluctuates but will always be a function of demand, which means that the highest cumulative surplus will always reflect the minimum rainwater storage needed for the given pluvial regime, and, as such, can be lower than total annual demand. Additionally, the total surplus is significantly higher than the total deficit, which implies room for optimization on possible demand capacity for rainwater use given rainwater availability – preferably demand lower than scenario 2 and higher than scenario 3.

Via iterative adjustments, Table 4-8 illustrated that consumption demand of 3.89 m<sup>3</sup> (46.68 m<sup>3</sup> annual consumption threshold) is exhibited to be the most viable water use plan to maintain cumulative water surplus without wastage, indicated by surplus reaching as close to zero as possible in April or May when surplus should

be almost depleted so that rainwater collection cycle can start anew in the following hydrological year. Demand optimization can be further optimized and adjusted dynamically based on the relative ratio of demand to water source diversity. This means that consumption can vary monthly based on specific environmental or social characteristics as long as it is within the annual demand threshold of 46.68 m<sup>3</sup>. However, further optimization of this degree would require extensive data collection and algorithm-based calculation to be implemented, which the thesis is unable to perform currently. In summary, using scenario basis as an initial calculation for storage sizing, optimized consumption demand of 3.89 m<sup>3</sup>/month and, subsequently, minimum rainwater storage are determined to be 18.64 m<sup>3</sup> given the physical and environmental conditions at the study area (Table 4-8); the reason the highest surplus being indicative of minimum, or expandable, rainwater storage is in consideration to uncertainties of meteorological patterns (i.e. climate change) in the future to compensate for increased precipitation intensity especially under the circumstance that current storage determination is based only on historical precipitation. Such contingent considerations will be further explored in the next chapter.

Overall, a complete technical and financial optimization of RWHS is necessary to determine the hydrological and economical feasibility. For economic assessment, as the optimized scenario served as a technical optimization for the system to be operationally feasible within current physical and environmental conditions, a cost-benefit analysis will then mainly be conducted for only that scenario to determine whether such technical sizing is economically feasible in addition to its technical feasibility.

Table 4-7: Iterative Catchment Adjustment

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8
Month	Average Monthly Precipitation (mm)	First Flush Volume (m <sup>3</sup> )	Monthly Consumption Demand (m <sup>3</sup> )	Catchment Area (m <sup>2</sup> )	Monthly Volume of Rainwater (m <sup>3</sup> )	Monthly Consumption Balance (m <sup>3</sup> )	Cumulative Consumption Balance (m <sup>3</sup> )
<b>Scenario 1: Catchment Adjusted 1</b>							
Jun	304.50	0.03	7.50	55.50	14.34	6.84	6.84
Jul	305.00	0.03	7.50	55.50	14.36	6.86	13.69
Aug	249.15	0.03	7.50	55.50	11.72	4.22	17.92
Sep	304.85	0.03	7.50	55.50	14.35	6.85	24.77
Oct	395.60	0.03	7.50	55.50	18.63	11.13	35.90
Nov	134.25	0.03	7.50	55.50	6.30	-1.20	34.71
Dec	31.75	0.03	7.50	55.50	1.47	-6.03	28.67
Jan	0.40	0.03	7.50	55.50	-0.01	-7.51	21.16
Feb	0.00	0.03	7.50	55.50	-0.03	-7.53	13.63
Mar	0.00	0.03	7.50	55.50	-0.03	-7.53	6.10
Apr	30.95	0.03	7.50	55.50	1.43	-6.07	0.04
May	160.55	0.03	7.50	55.50	7.54	0.04	0.08
<b>Scenario 2: Catchment Adjusted</b>							
Jun	304.50	0.02	4.50	33.50	8.65	4.15	4.15
Jul	305.00	0.02	4.50	33.50	8.67	4.17	8.32
Aug	249.15	0.02	4.50	33.50	7.08	2.58	10.90
Sep	304.85	0.02	4.50	33.50	8.66	4.16	15.06
Oct	395.60	0.02	4.50	33.50	11.25	6.75	21.81
Nov	134.25	0.02	4.50	33.50	3.80	-0.70	21.11
Dec	31.75	0.02	4.50	33.50	0.89	-3.61	17.50

Jan	0.40	0.02	4.50	33.50	-0.01	-4.51	12.99
Feb	0.00	0.02	4.50	33.50	-0.02	-4.52	8.47
Mar	0.00	0.02	4.50	33.50	-0.02	-4.52	3.96
Apr	30.95	0.02	4.50	33.50	0.86	-3.64	0.32
May	160.55	0.02	4.50	33.50	4.55	0.05	0.37

Table 4-8: Iterative Consumption Optimization

Optimization Scenario							
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8
Month	Average Monthly Precipitation (mm)	First Flush Volume (m <sup>3</sup> )	Monthly Consumption Demand (m <sup>3</sup> )	Catchment Area (m <sup>2</sup> )	Monthly Volume of Rainwater (m <sup>3</sup> )	Monthly Consumption Balance (m <sup>3</sup> )	Cumulative Consumption Balance (m <sup>3</sup> )
Jun	304.50	0.02	3.89	28.80	7.44	3.55	3.55
Jul	305.00	0.02	3.89	28.80	7.45	3.56	7.11
Aug	249.15	0.02	3.89	28.80	6.08	2.19	9.30
Sep	304.85	0.02	3.89	28.80	7.45	3.56	12.86
Oct	395.60	0.02	3.89	28.80	9.67	5.78	18.64
Nov	134.25	0.02	3.89	28.80	3.27	-0.62	18.02
Dec	31.75	0.02	3.89	28.80	0.76	-3.13	14.89
Jan	0.40	0.02	3.89	28.80	-0.01	-3.90	11.00
Feb	0.00	0.02	3.89	28.80	-0.02	-3.91	7.09
Mar	0.00	0.02	3.89	28.80	-0.02	-3.91	3.19
Apr	30.95	0.02	3.89	28.80	0.74	-3.15	0.04
May	160.55	0.02	3.89	28.80	3.91	0.02	0.06

### 4.3 Treatment Module

#### 4.3.1 Available Rainwater Treatment Technology

Rainwater can potentially be the medium for a variety of inorganic and organic contaminants, which prompts the development of a wide variety of treatment technologies to counteract its adverse effect. One technique in Australia popularizes the use of a first-flush device to divert 0.8 – 3.5 mm of rainfall at the onset rainy season; the reason for this, as mentioned in the previous section, is due to the observed phenomenon of exponential reduction in contaminants such as suspended particles, organic pollutants, and even trace metals (Förster, 1999). Studies have also shown that pollutant concentration in first-flush improves substantially in all indicative parameters with a discharge rate of 40 – 190 liters per 100 square meters (Kus et al., 2010). Another study in Nigeria also revealed that first flush volume contains 2 to 3 times the contaminants concentrations compared to post-flush rainwater (Adeniyi & Olabanji, 2005). This method is a highly recommended practice across most studies conducted on rainwater quality as it reduces health risks significantly for the cost of a small rainwater volume neglectable to the overall pluvial regime (Despins et al., 2009; Gwenzi et al., 2015; Martinson & Thomas, 2009; Sánchez et al., 2015), which the thesis will definitively incorporate into its design.

Aside from first-flush practices, heat treatment is also another effective way to treat bacteriological aspects of rainwater, possibly in a hot water tank between 50 – 70°C. Studies found that hot water can remove most of the pathogenic elements found within particularly contaminated rainwater samples, reducing it by 2

log (99%) to around 166 CFU/100ml coliform concentration, 20 CFU/100ml of which is E.coli (Coombes et al., 2000), which is significant in spite of it being higher than recommended WHO international guidelines (< 27 CFU/100ml for coliform and < 4.48 CFU/100ml for E.coli). A. T. Spinks et al. (2003) also experimentally observed that heating rainwater sample to 60°C for 5 minutes can reduce up to 5 log (99.999%) in E.coli concentration. Despite the potential of heat treatment, accumulated power consumption can be high, making it more suitable as a precaution practice for freshly drawn water from storage.

Treatment strategies involving technology depend on a variety of options, ranging from chlorination (Keithley et al., 2018; Lantagne et al., 2008; Lantagne et al., 2010), ozonation (S. A. Ha et al., 2013), filtration (Jordan et al., 2008; R.-H. Kim et al., 2005), solar disinfection (SODIS) (Amin & Han, 2009; Strauss et al., 2016), and solar pasteurization (SOPAS) (Dobrowsky et al., 2015; Strauss et al., 2016). Although treatment efficiency and user workability of these unique technologies exhibited variability (Hamilton et al., 2019), the determination of the optimal selection for treatment technologies will ultimately depend on cost, management difficulty, and water accessibility, among others (Hunter et al., 2010). Therefore, the development of appropriate treatment strategies accounts for health parameters, efficiency indicators, and economical effectiveness given the context of developing countries.

Among these technologies, SODIS are novel concepts primarily implemented in Africa, South America, and parts of Asia with approximately five million daily users (McGuigan et al., 2012), which is indicative of its characteristic of affordability and sustainability among portable water purification techniques. At its essence, SODIS operational condition is simple, transparent water containers are placed under direct contact with sunlight, inducing a UV exposure environment to water contents within the containers and disinfecting pathogenic elements therein. Under a full sunlight regime, water samples require contact time between 6 – 8 hours for a 50.6% to 75.22% decrease in Legionella bacteria (Strauss et al., 2016). Under cloudy conditions, it can take up to 48 hours for the complete disinfection process, which can be time-consuming and requires complicated logistical management to organize the disinfection cycle and constant water consumption. Operating on a similar but slightly modified technique, SOPAS is a continuous cycle form of SODIS that requires specific apparatus to cycle water contents through multiple arrays of simultaneous tubes configured at different temperatures induced by UV radiation. In other words, while SODIS uses only direct UV radiation as its primary treatment process, SOPAS uses UV radiation as both a direct and indirect mechanism to disinfect with UV while accumulating and raising the temperature necessary for pasteurization, which yielded a 94.7% Legionella reduction; additionally, both SODIS and SOPAS are capable of yielding more than 99% of disinfection for E. coli and other heterotrophic bacteria (Strauss et al., 2016).

In principle, all microbial treatment processes such as chlorination, ozonation, and UV (including SODIS and SOPAS) attempt to alter or damage the cell membrane of pathogenic elements, disabling and inactivating all pathogenic functions safe for consumption. However, the difference between techniques is not solely based on treatment efficiency but also on residual effects (which contribute to lasting insurance of disinfection for health and safety) and the user-friendly operation. For instance, chlorination involving the use of chlorine or chlorine compounds that can chemically inactivate pathogens, which it leaves behind residuals that can continuously inactivate bacteria, albeit at the risk of potentially generating carcinogenic by-products.

Therefore, precise dosage done by professionals is a necessity, which negates its potential to be safe and user-friendly. Similarly, ozonation involves ozone ( $O_3$ ) which is a highly reactive oxygen species created from the common dioxygen ( $O_2$ ) via many methods, all of which involve the input of catalytic energy in specific configurations to induce advanced oxidation process for inactivating pathogens, which makes it non-user-friendly. Overall, both SODIS and SOPAS are the most economical both being operated based on the principle of sterilization via UV radiation, which has the energy to directly inactivate microbial elements by altering cellular integrity, or indirectly by creation of reactive oxygen species that oxidize microbial cells (ozonation) (Nelson et al., 2018). Additionally, an increase in temperature (above  $45^\circ\text{C}$ ) as water molecules absorb the UV radiation also contribute to faster deterioration of microbial cell membrane (McGuigan et al., 2012). However, the issue with UV-based treatment is its lack of residual effect for possible re-contamination, which means treated water needs to be packaged in a specific way to prevent contact with air-borne contaminants, or consume immediately post-treatment. In the case of water treatment for drinking, this issue could almost be entirely neglected as water is withdrawn for drinking purposes will almost always be consumed immediately. As such it can be argued that for microbiological treatment, UV treatment and its variants such as SODIS and SOPAS, are some of the most cost-effective treatment techniques in the field.

Filtration is also an important treatment technique that addresses the physio-chemical aspects of treatment, unlike previously mentioned techniques that primarily focus on microbial and bio-chemical treatment. The basis for filtration relies on the porosity of a barrier surface to physically block and reject particles from the passage. In principle, two primary filtration techniques are available among its modern variants, namely depth filtration and surface filtration. Depth filtration involves the removal of particulate suspended matters from an aqueous environment by passing the liquid through a granular medium such as anthracite and silica sand, which is commonly a pretreatment for finer filtration processes such as activated carbon adsorption, membrane filtration, and UV treatment. Common medium filtration operates based on the mechanisms of (a) straining, which means particles larger than the pore size of the medium from passing and smaller particles are trapped by chance contact; (b) sedimentation, which means the medium provides the surface for particles that deviate from flow streamlines to settle on; (c) Interception, which means particles are intercepted by filter medium on contact; (d) adhesion, which means particles intercepted will adhere to medium (Van de Waals force), creating cumulative layers of particle that prevent further particles from the passage; and (e) flocculation, which means large particles formed by velocity gradient are removed by one or more of the previously mentioned mechanisms (

Figure 4-1) (Tchobanoglous, 2014; Yao et al., 1971).

Surface filtration involves passing the liquid through a fine porous septum (sieve) to remove suspended particulates via various mechanisms depending on its sub-classification: screen filtration (physical separation); cake filtration (cumulative physical separation); and cross-flow filtration (adsorption). Depending on the porous medium used for filtration, a wide range of physio-chemical and, in the case of the finer membrane, biological contaminants. Each treatment techniques provide benefits as well as drawback associated with its implementation, which are summarized in Table 4-9.

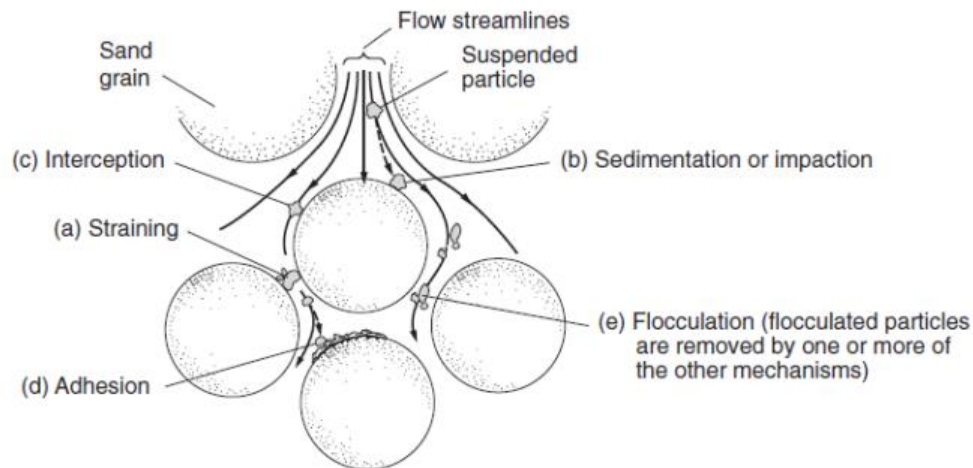


Figure 4-1: Depth Filtration Mechanisms. Figure retrieved from Tchobanoglous (2014)

Table 4-9: Pros and cons of treatment techniques

Treatment Classification	Subcategory	Pro	Con
Filtration	Sand/Silica	- Can provide a slight improvement in the microbiological and physiochemical characteristics of rainwater.	- Cannot remove viruses. Filtration time, temperature, and oxygen level greatly impact the variability of performance.
	Activated Carbon	- Can provide heavy metals remediation via adsorption depending on the granular levels of filter media. - Can improve aesthetic (turbidity) and taste and remove odors.	- Cannot remove pathogens (bacteria and viruses).
	Reverse Osmosis	- Can remove microorganisms, trace minerals, heavy metals, and chemicals in the water with high efficiency.	- Can be very expensive depending on system configurations - Require prefiltration to maximize efficiency in addition to separate drainage and power supply.
	Membrane	- Can remove bacteria, sediment, and heavy metals depending on pore sizes.	- Can be expensive depending on membrane layer configurations. - Require prefiltration and cannot remove viruses.
UV Disinfection		- Can remove pathogens effectively (bacteria, viruses, and protozoa) with minimal maintenance. - Relatively affordable.	- Require power supply. - No residual effect. - Treated water needs to be used right after treatment to avoid re-contamination.
Chlorination		- Can remove pathogens. - Can provide continuous removal for extended period residual effect.	- Chlorinated water poses significant health risks in the long-term. - Can produce carcinogenic by-products.



		- Require high operational skill to determine the appropriate dosage, therefore not accessible to average persons.
Ozonation	- Can remove pathogens (bacteria, parasites, etc.). - Produce fewer chemical by-products.	- By-products are positively carcinogenic - No residual effect. - Treated water needs to be used right after treatment to avoid re-contamination.

### 4.3.2 Treatment Recommendation

Within the assessed parameters of rainwater quality (Table 3-16), coliform, E.coli, and cadmium are the main considerations for the determination of water treatment modules. Given the previous discussion, treatment of bacterial elements can be done by most techniques in Table 4-9, but the most foolproof, in terms of user-friendliness, technique is considered UV as it requires minimal operational skills and does not risk by-product toxicity like chlorination and ozonation. In addition, the UV treatment apparatus is flexible and capable of standalone implementation, or supplementary implementation in subsequence to other treatment processes (i.e. filtration) to maximize treatment effectively. Regarding the specification of the UV source, R.-H. Kim et al. (2005) found a 0.3 log reduction (50%) and 0.5 log reduction (66.6%) in a total coliform sample under a low-intensity UV lamp (5.4W) for 5 minutes and 60 minutes respectively. In addition, it was noted that using a 5-mm and 1-mm membrane filters pre-UV phase can increase general removal efficiency to 78% and 98% respectively, and bacterial removal to 80% and 90% respectively. Jordan et al. (2008) found that a higher intensity UV output (22W) can yield up to 2 log reduction (99%) per cycle. In Vietnam, commercially available or imported UV treatment tubes can be found with specifications ranging between 29W to 55W, the choice of which will be the 29W UV lamp for cost-effectiveness.

Regarding Cadmium and future potential risks, a plethora of processes is capable of remediating parametric elevation of heavy metal, including adsorption, precipitation, membrane filtration, and ion exchange; however, filter-based adsorption has been noted as particularly cost-effective against its complex and expensive competitors (Karnib et al., 2014). Specifically, adsorption is often most effective in the removal of heavy metals, organic pollutants, and dye from polluted wastewater (Tangjuank et al., 2009). Imamoglu and Tekir (2008) noted that activated carbon, silica, and graphene are effective adsorbents capable of purifying highly polluted water sources. In particular, granule activated carbon (GAC) performed relatively well against a combination of organic and inorganic pollutants due to its high contact surface between 500 – 1500 m<sup>2</sup> per gram and high porosity, which justified its common use in various removal of heavy metals, including lead, copper, zinc, chromium, nickel, cadmium, among others organic contaminants (Bhatnagar et al., 2013; Liu et al., 2010; Tangjuank et al., 2009). On removal efficiency, Karnib et al. (2014) were able to establish GAC adsorption removal rates in relation to variable concentrations of the contaminant in aqueous solutions. Particularly for cadmium, initial concentrations of 30, 50, 100, and 200 mg/L have observed removal rates of 86%, 84%, 70%, and 66.1%, which exhibited similar removal tendency to other heavy metals tested (i.e. lead, chromium, nickel). This indicates a disproportional relation between removal rates and concentrations, meaning higher concentration tends to overwhelm the filter and lead to lower removal rate while lower

concentration allows more effective operation and higher removal. Removal of heavy metals via interactive chemical mechanisms (in filter-based medium adsorption) often result in better removal compared to convention filtration because of the small size fraction cadmium, chromium ( $<0.22 \mu\text{m}$ ) and other heavy metals (lead and cooper:  $< 0.22 \mu\text{m}$ ; nickel:  $<0.22\text{--}0.45 \mu\text{m}$ ) (Vymazal, 1989). For effective surface-based filtration techniques on heavy metals, it is necessary to utilize fine pores filtration such as ultrafiltration (UF) which is capable of removing particles between  $0.004 - 0.1$  (Cheryan, 1998; Wijmans & Baker, 1995). Alternatively, nanofiltration (NF) and reverse osmosis (RO) technique as the most recent innovations, remove dissolved solutes in liquid via a non-porous semipermeable membrane that induces pressure-driven diffusion, in which NF preferably separate divalent ions and organic contaminants from the liquid phase and RO purifies water to the highest degree (Figure 4-2) (Cui et al., 2010; Van der Bruggen, 2018). The application of these technologies is often industrial in scale for the process objective of seawater desalination, brackish water desalination, water softening, and complete drinkable water reuse from all types of water. Fine filtration techniques like UF, NF, and RO are undoubtedly effective in the removal of both biological and physio-chemical contaminants in a liquid environment, but their commercial costs are exponentially proportional to their performance as well, which would not be ideal for a relatively reasonably priced domestic implementation.

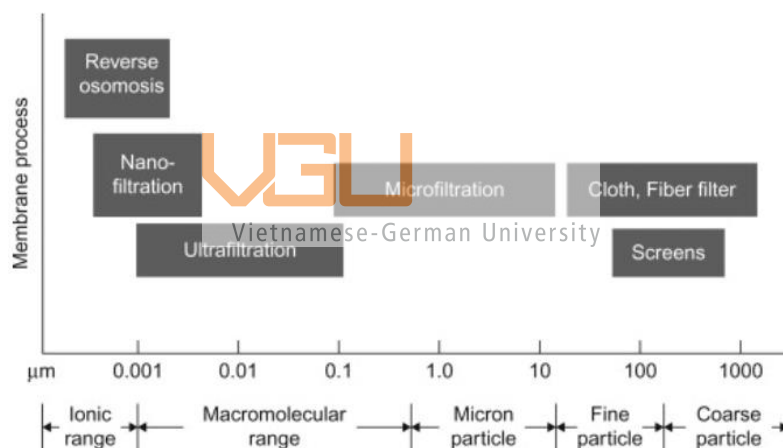


Figure 4-2: Capacity of filtration techniques

Extrapolating from reviewed studies, the optimal arrangement of treatment modules to maximize drinkable rainwater quality would be a multiphase filtration starting with a  $5 \mu\text{m}$  polypropylene (PP) filter, followed by a sequence of GAC filter and  $1 \mu\text{m}$  PP filter, and finished with a 29W UV lamp.

#### 4.4 Overall Design

With the review and analysis of available aspects relating to the design of individual modules of the RWHS, a summary of relevant parameters can be reviewed in

. Given the determined parameters for a general RWHS for implementation in the study area, it is necessary to also specify the placement necessary for the optimization of water flow, treatment, and consumption, the concept schematic of which is illustrated in Figure 4-3. Regarding catchment placement, it was previously mentioned various type of catchment and placement are possible depending on the scale and

type of RWHS. For roof-based domestic RWHS as established, the roof of a local household will typically serve as rainfall catchment areas as well. Placement of the conveyance module including the gutter and downspout is positioned directly below the catchment; a debris mesh angled at 60° from the gutter bed and placed at least 3 cm from the downspout is optimal for debris removal. At the midpoint of the downspout, a valve is installed, splitting into two pipes, one leading straight down into a first-flush container, the other is connected to storage units. For storage placement, storage containers can be configured in two ways, side-by-side horizontal and vertical stack configuration depending on the availability of the placement area. For horizontal placement, overflow pipes connect storage units from the highest positions of each container and exit from the last unit to overflow freely into the ground. For vertical configuration, units are stacked on top of one another via a compact frame and connected to each other from the lowest position of upper units to the highest position of lower units; free overflow is placed at the highest position of the highest unit in the stack to ensure maximum storage capacity. Finally, treatment modules connect to all units at their lowest position in horizontal placement configuration, which would be connected to a tap for direct withdrawal. For vertical configuration, treatment module will be connected at the lowest point of the bottom unit, and, subsequently, can be withdrawn from a water tap.

Table 4-10: Summary of selected recommendations for system components

Module	Criteria	Parameter	Unit
Catchment	Material	Metal	-
	Area	28.8	m <sup>2</sup>
	Efficiency Factor	0.85	-
Conveyance	Material	PVC	-
	Gutter and pipe cross-section	40	cm <sup>2</sup>
	Gutter mesh	5	mm
	Gutter splash guard	30 (5-6 cm bent)	cm
	Slope gradient	0.01	-
	Compensatory factor	1.2	-
Storage	Material	Polyethylene	-
	Sizing: rainwater supply	18.64 (Table 4-8)	m <sup>3</sup>
	Sizing: first-flush	20	Liter
Treatment	Physio-chemical Treatment: 3-step filtration	5 µm PP filter GAC filter 1 µm PP filter	-
	Microbial Treatment: UV lamp filter	29	Watt

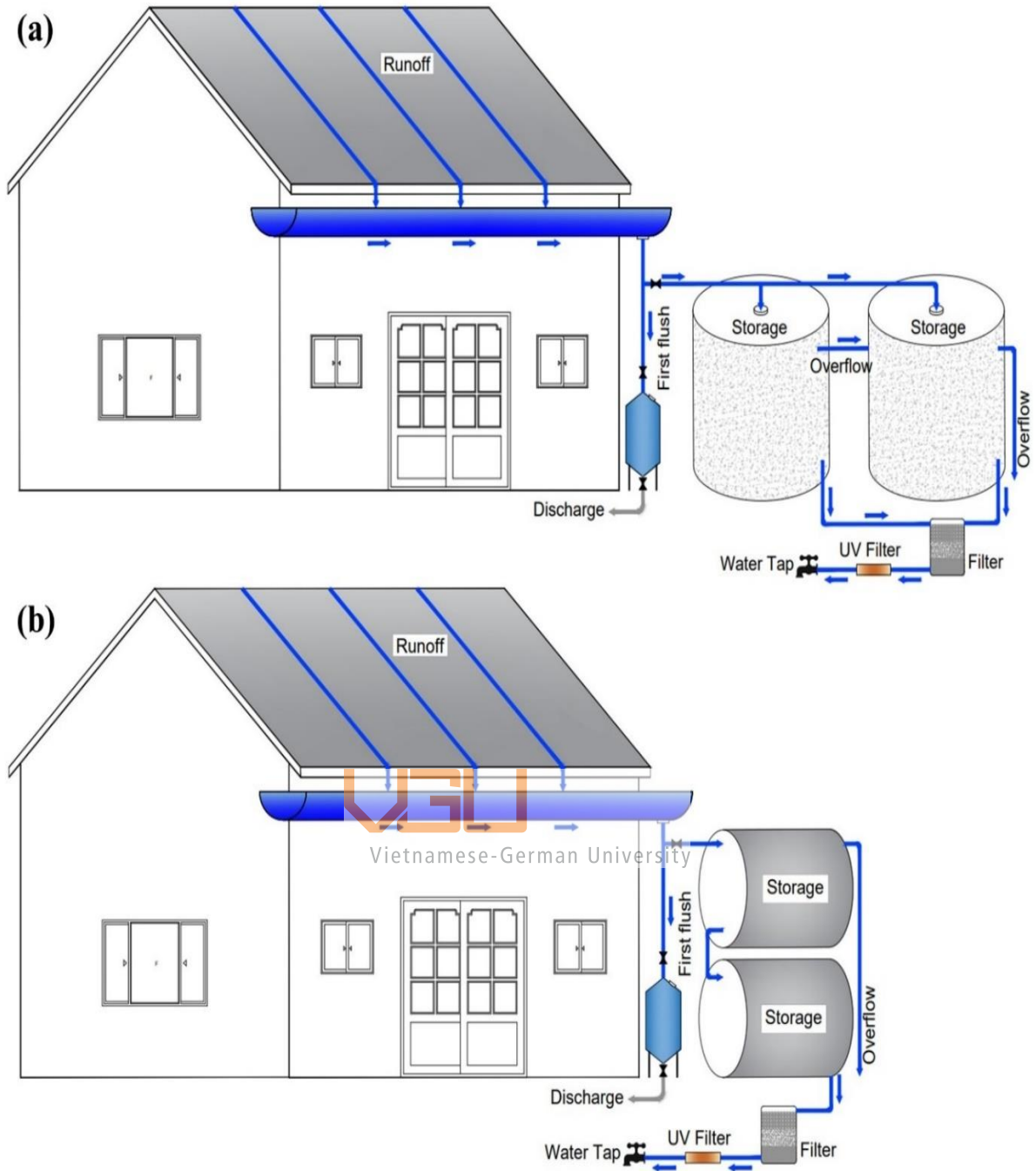


Figure 4-3: Concept design for (a) side-to-side horizontal storage placement; and (b) vertical stack

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## 5. COST-BENEFIT ANALYSIS, RECOMMENDATION, AND CONCLUSION

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### 5.1 Cost-benefit Analysis

#### 5.1.1 Cost and Benefit Breakdown

##### 5.1.1.1 Variables and Annual Benefit Quantification

Before calculation for economic viability via net present value and benefit-cost ratio can be conducted, evaluation of input parameters is necessary to define the scope of calculation and facilitate calculation processes. Some of these parameters can be determined based on survey and literature basis (i.e. interest rate, lifespan, power consumption), while others are arithmetic (discounted or annuity factor) and inferential (i.e. benefit quantification) determination (Table 5-1). The purpose of the inferential analysis is the derivation of previously unquantifiable values via connecting co-factors (potential RWHS benefits quantified by the cost of various water service use during an independent time frame).

Particularly, inferential assumptions are made based on self-reported responses from the field survey and the limitation of case specificity within the boundary of a concept design. As a result, some assumptions can produce a margin of error, and may not be representative of the actual market prices in the study area due to normalization and case-based variations. For instance, electricity pricing in Vietnam is calculated based on consumption brackets and designated types of municipalities. There are six monthly consumption brackets: 0 – 50, 51 – 100, 101 – 200, 201 – 300, 301 – 400, and >400 kWh, which determine incremental prices for higher usage, especially for incremental regional level (rural, town, city, etc.). Since the study area is rural, the power consumption of treatment devices and the resulting monthly electricity bills are determined based on that pricing. However, this consumption does not take into account the overall power consumption due to difficulty in estimating the monthly energy demand of individual households. This means that the combined consumption of RWHS and household utilities can potentially place pricing in a higher bracket, resulting in higher costs. In order to eliminate uncertainty, this is normalized under the condition that RWHS is a separate operating entity from the household, which enables estimation of its monthly operational consumption and electricity pricing based on brackets.

Another major assumption necessary for benefit quantification is monthly water source dependency in the context of the worst-case scenario during the dry season with severe drought and saline contamination in tap water. This assumption pertains to the assumption of potable water need elaborated above (Table 4-6) in scenario 3 of storage dimensioning, and homogenous use of water source throughout the designated seasonal period. Unlike the solar energy incentive scheme, which enables a direct income stream via energy generation, rainwater collection can't be a tradable product that can supplement the municipal water supply for payment. As such, benefit quantification in this case primarily concerns the mitigated cost that would have been otherwise incurred on households in the study area without the implementation of RWHS.

Based on responses in the questionnaire, it is reported that tap water is only fully viable during the wet season between May to November during severe drought episodes. In some cases, tap water is also viable within the first and, possibly, second months of the dry season as drought has not set in and the salinization effect is minimal. However, for the remaining duration of the dry season, survey responses reported that

salinization will be severe, making tap water not drinkable. As a result, private water services are often contacted for the provision of both non-potable and potable monthly water for the price of 100,000 VND/m<sup>3</sup> and 3,750,000 VND/m<sup>3</sup> respectively during the last 4 months of the dry season (910% and 3779% higher than municipal water pricing at 9,900 VND/m<sup>3</sup>). This is not always going to be the case, as water sources are diverse and dynamically interchangeable depending on the socio-economic circumstances in the study area, but for the worst-case anticipation and benefit maximization, a seasonal designation for uniform monthly use of water sources is necessary. Given that condition, monetary benefits of RWHS can be quantified as a function of consumption demand, pricing of water sources, and total source-dependent months (Table 5-2).

Table 5-1: Input Variables

Assumption			
Information	Value	Unit	Justification
Interest Rate	4	%	Ross et al. (2022)
Proposed RWHS Lifespan	10	(year)	Assumption based on lifespan review for storage systems and average RWHS lifespan (Gould, 2015)
UV lamp lifespan	8,000	(hour)	Specification according to the device supplier
UV filter Power Consumption	0.029	(kWh/hour)	Specification according to the device supplier
RWHS Annual Operation	365	(days/year)	-
RWHS Monthly Operation	30	(days/month)	-
RWHS UV Operation	24	(hour/day)	-
RWHS Monthly Power	20.88	(kWh/month)	<50kWh/month, electricity rate for rural area adjusted to 1,403 VND/kWh
Municipal Power Pricing	1,403	(VND/kWh)	(Southern Power Corporation [EVN SPC], 2022)
Municipal Water Service	9,900	(VND/m <sup>3</sup> )	(Ben Tre Water Supply and Sewage Joint Stock Company [BEWACO], 2016)
Private Water Service (Non-potable)	100,000	(VND/m <sup>3</sup> )	Local water service based on survey responses
Private Water Service (Potable)	3,750,000	(VND/m <sup>3</sup> )	(Vinh Hao Water, n.d.)
Municipal Water Service: Rainy Season	6	(months)	Assumption based on responses of worst-case scenario reported from surveys.

Municipal Water Service: Dry Season	2	(months)	
Private Water Service (Non-potable): Dry Season	4	(months)	
Private Water Service (Potable): Dry Season			

Table 5-2: Annual Benefits of Proposed RWHS for Optimized Scenario

Water Saving Source	Dry Season	Wet Season	Monthly Household Demand	Cost per Unit	Annual Benefit per Source
Municipal Water Service (outdoor, non-potable, and potable)	2 months	6 months	3.89 m <sup>3</sup> /month	9,900 VND/m <sup>3</sup>	308,088 VND
Private Water Service (non-potable)	4 months	-	3.29 m <sup>3</sup> /month	100,000 VND/m <sup>3</sup>	1,316,000 VND
Private Water Service (potable)			0.6 m <sup>3</sup> /month	3,750,000 VND/m <sup>3</sup>	9,000,000 VND
Total Annual Benefit					12,354,000 VND

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### 5.1.1.2 Capital Costs and Annual Cost

Using the design basis proposed in the previous chapter, relative capital costs can be estimated by section. Accounting for conveyance length, gutters length on both sides of the roof (each 4-5 meters) connecting to one downspout (1-2 meters) with junction, inflow, overflow, and outflow (1-2 meters) would be at least around 15 meters in length. For other components, storage unit quantity depends on scenario-based storage capacity derived; UV lamp filter and activated-carbon filtration and comprising of the treatment module will only account for one unit quantity each, which needs to be replaced annually to maintain filtration and disinfection efficiency. Given the context of current energy price, market price, and commercially available options for each component, the capital costs of proposed RWHS and its subsequent annual costs can be estimated (

Table 5-3 and Table 5-4). Capital cost determination for steel and plastic storage, as aforementioned, is primarily for the purpose of comprehensive analysis and open choice.

Particularly, annual costs are recurrent costs as a result of necessary maintenance fees, operation fees (from energy use), and replacement costs for treatment module, of which (a) operation cost remains constant due to unchanged power specification of UV filter module; (b) replacement cost remains constant due to unchanged quantity of module; and (c) only maintenance cost changes due to formulation as a function of different storage capacity in different scenarios.



Table 5-3: Capital Costs of Proposed RWHS Using Optimized Scenario

Section	Item	Supplier	Unit Quantity	Cost per Unit (VND/unit)	Cost per Section (VND)
Rainwater Collection	Gutter and downspout (m)	Ton PVC (2022)	15	80,000	1,200,000
Rainwater Storage tank	Inox Storage Tank (m <sup>3</sup> )	Son Ha (2022a)	18.64	4,000,000	74,560,064
	Plastic Storage Tank (m <sup>3</sup> )	Son Ha (2022b)	18.64	2,300,000	42,872,037
Rainwater Treatment	UV lamp steriliser (29W)	Aqualife (2022a)	1	750,000	750,000
	3-phase activated carbon filtration	Aqualife (2022b)	1	700,000	700,000
Total Capital Cost (Steel)					77,210,064
Total Capital Cost (Plastic)					45,522,037

Table 5-4: Annual Costs of RWHS for Optimized Scenario

Category	Cost per Source	Unit
Operation Cost	351,536	(VND/year)
Maintenance Cost	2,330,002	(VND/year)
UV Replacement Cost	750,000	(VND/year)
Filter Replacement Cost	700,000	(VND/year)
Total Annual Costs	4,131,538	(VND/year)

### 5.1.2 Present Value, Payback Period, and Benefit-cost Ratio

According to Gould (2015), the average lifespan of RWHS is at least 10 years given the consideration for material deterioration and maintenance, which will serve as the baseline for time value calculation. Given that the interest rate of 4% is constant throughout 10 years of operation, the annuity factor is basically the cumulative sum of a discount factor for each year proposed for the lifespan of RWHS, which can be calculated via equation 10:

$$Annuity\ Factor = \sum_t^T = 1 \frac{1}{(1+i)^t} = \frac{(1+i)^T - 1}{(1+i)^T * i}$$

$$Annuity\ Factor = \frac{(1+0.04)^{10} - 1}{(1+0.04)^{10} * 0.04} = 8.11$$

Assuming that the total cost from the operation, maintenance, and annual income remains constant over the proposed 10 years lifespan in the optimized scenario, the total cost can be determined using equation 6:

$$Total\ Cost = [Scenario - based\ Capital\ Costs] + \sum_{t=1}^{10} \frac{[Total\ Annual\ Costs]}{(1+0.04)^t}$$

Similarly, CDCF, NPV, and BCR, all of which indicate the overall difference between annual benefits, annual costs, and capital costs over 10 years, can be calculated using equation 11, 12, and 13.

$$CDCF = \sum_{t=1}^{10} \frac{[Total Annual Benefits]}{(1 + 0.04)^t} - \sum_{t=1}^{10} \frac{[Total Annual Costs]}{(1 + 0.04)^t}$$

$$NPV = [CDCF] - [Capital Costs]$$

$$BCR = \frac{\sum_{t=1}^{10} \frac{[Total Annual Benefits]}{(1 + 0.04)^t}}{\sum_{t=1}^{10} \frac{[Total Annual Costs]}{(1 + 0.04)^t} + \frac{[Total Annual Costs]}{(1 + 0.04)}}$$

Table 5-5: Present Value Tabulation for Optimized Scenario

Optimization Scenario							
Year	Annual Benefits	Annual Costs	NCF	CNCF	Discount Factor	DCF	CDCF
1	10,624,088	4,131,538	6,492,550	6,492,550	0.96	6,242,837	6,242,837
2	10,624,088	4,131,538	6,492,550	12,985,101	0.92	6,002,728	12,245,565
3	10,624,088	4,131,538	6,492,550	19,477,651	0.89	5,771,854	18,017,418
4	10,624,088	4,131,538	6,492,550	25,970,201	0.85	5,549,859	23,567,277
5	10,624,088	4,131,538	6,492,550	32,462,752	0.82	5,336,403	28,903,680
6	10,624,088	4,131,538	6,492,550	38,955,302	0.79	5,131,157	34,034,837
7	10,624,088	4,131,538	6,492,550	45,447,852	0.76	4,933,805	38,968,642
8	10,624,088	4,131,538	6,492,550	51,940,403	0.73	4,744,043	43,712,685
9	10,624,088	4,131,538	6,492,550	58,432,953	0.70	4,561,580	48,274,265
10	10,624,088	4,131,538	6,492,550	64,925,503	0.68	4,386,134	52,660,399
NPV <sub>steel</sub>							-24,549,665
NPV <sub>plastic</sub>							7,138,362
PP <sub>steel</sub>							11.89
PP <sub>plastic</sub>							7.01

Table 5-6: Material-based Cost–Benefit Tabulation for Optimized Scenario

BCR – Steel Storage						
Effect	Year	Time Value (VND)	Discount Factor	Annuity Factor	Net Present Cost (VND)	Net Present Benefit (VND)
System Capital Cost	1	77,210,064	0.96		74,240,446	
Maintenance Cost	1-10	2,330,002		8.11	18,898,403	
Operation Cost	1-10	351,536		8.11	2,851,269	
Replacement Cost	1-10	1,450,000		8.11	11,760,799	
Municipal Water Cost	1-10	308,088		8.11		2,498,870
Non-potable Private Water Cost	1-10	1,316,000		8.11		10,673,939
Potable Private Water Cost	1-10	9,000,000		8.11		72,998,062
<b>Total Present Value</b>					<b>107,750,918</b>	<b>86,170,871</b>
<b>Benefit-Cost Ratio</b>					<b>0.8</b>	

BCR – Plastic Storage						
Effect	Year	Time Value (VND)	Discount Factor	Annuity Factor	Net Present Cost (VND)	Net Present Benefit (VND)
System Capital Cost	1	45,522,037	0.96		43,771,189	
Maintenance Cost	(1-10)	2,330,002		8.11	18,898,403	
Operation Cost	(1-10)	351,536		8.11	2,851,269	
Replacement Cost	(1-10)	1,450,000		8.11	11,760,799	
Municipal Water Cost	(1-10)	308,088		8.11		2,498,870
Non-potable Private Water Cost	(1-10)	1,316,000		8.11		10,673,939
Potable Private Water Cost	(1-10)	9,000,000		8.11		72,998,062
<b>Total Present Value</b>					<b>77,281,661</b>	<b>86,170,871</b>
<b>Benefit-Cost Ratio</b>					<b>1.1</b>	

Results shown in Table 5-5 and Table 5-6 indicate that using steel as the material for storage in the optimized scenario is economically unfeasible regardless of the material selection as economic adjustment. This is exhibited via a negative NPV value for metal material selection, which signifies that the overall net benefits of RWHS cannot overcome the sum of the present valued total annual cost and initial capital cost given the expected lifespan of 10 years of the proposed RWHS. This does not necessarily indicate a lack of annual benefits over annual costs. In fact, Table 5-5 shows that total annual benefits are higher than total annual costs, resulting in an annual positive revenue in the form of NCF. A net negative NPV only indicates feasibility in terms of breakeven or profitable possibility specifically within the context of the proposed lifespan of 10 years. As a result, even with a positive annual NCF, it would take too long to break even the lifespan of the RWHS is already exceeded, which necessitates total or majority replacement of RWHS components as additional costs, further reducing the overall NPV as well. This can be observed via a PP value larger than 10 and a BCR value less than 1. The PP value roughly indicates the operational time required to reach breakeven with capital costs for RWHS, which means that a lower PP value indicates a higher profitable time period given annual benefits; therefore, a lower PP value translates to higher NPV. In the metal storage option, PP was higher than 10 years, which exceeded the expected lifespan of the RWHS, leading to negative NPV as no actual revenue streams are being generated until the breakeven threshold is reached within the proposed 10 years. PP is only a relative range of the breakeven threshold as its value is subject to a margin of error due to its being a function of NCF (an annual constant) not DCF (an annual dynamic value). Therefore, the precise determination of PP should be manually examined. For instance, the capital costs for steel- and plastic-based RWHS are 77,210,064 VND and 45,522,037 VND respectively (

Table 5-3), in which the capital costs for a steel storage system exceeded the final CDCF of 52,660,399 VND at year 10, which validated the estimated PP value. For plastic storage RWHS, while the initial PP value roughly estimated the breakeven threshold at year 7, actual CDCF accounting for the discount rate only exceed the initial capital cost at year 9 (48,274,265 VND). The result offset the estimated PP by 2 years (the higher the interest or inflation rate, the higher the offset), but still within the expected lifespan and profitable NPV of 7,138,362 VND at the end of the system lifecycle, which indicated a 343.91% profit increase compared to steel storage alternative NPV of -24,549,665 VND.

BCR indicates the ratio between net annual benefits and net costs throughout its lifespan, a value less than 1 indicates an inability for the benefits provided to compensate the overall costs incurred during the proposed 10 years, thereby making the implementation of RWHS using galvanized steel storage system unviable for the optimized scenario. Overall, having optimized the proposed RWHS hydrologically, economic assessment serves as an indicator for economic optimization to further determine the final material selection for storage components, the result of which indicated that polyethylene or plastic storage units are more economically viable than steel given the hydrologically optimized conditions.

## 5.2 Discussion and Recommendation

### 5.2.1 Perceived Investment Willingness

Given calculations of capital and economic feasibility of the RWHS implementation in the study area, it is also important to examine the social aspect of RWHS, which mostly pertains to the acceptability of interviewees within the survey area and perceived RWHS cost concerning the actual cost.

Questionnaires used during the field survey included exploratory questions designed to gauge interest in the RWHS implementation via five main statements (questions 2.1.6 – 2.1.11 in Appendix I) to which degree of agreement is reported. The statements represent five different perception aspects concerning the RWHS implementation, namely: quantitative sufficiency, cost efficiency, environmental sustainability, self-sufficiency, affordability, and institutional priority. Quantitative sufficiency observes the perceived supply of rainwater among responses specifically to determine if interviewees are interested in the complete replacement of the water supply with the RWHS supply. Cost efficiency relates to the perception of cost-to-performance perception, which correlates to the perception of affordability given that perceived cost-to-performance. Depending on the state of water shortage during the dry season, such cost-related perception can shift to prioritize implementing RWHS regardless of cost perception, which relates to an awareness of less dependency on municipal supply and a proactive perception to implement RWHS (self-sufficiency).

Environmental sustainability denotes the perception of interviewees to perceive RWHS as a factor that contributes to the overall environmental sustainability in terms of the hydrology of the area, or as merely a means to an end – prevention of water shortage and dehydration. Institutional priority expresses the perception of institutional engagement regarding rainwater harvesting practices and water shortage issues. The aggregated result (Figure 5-1) shows that positive responses tend to gravitate toward aspects of cost-efficiency, self-sufficiency, and affordability; while the perception of quantitative sufficiency, environmental sustainability, and institutional priority remains relatively neutral. The affinity for such socio-economic driven perception

emphasizes the circumstances of a low socio-economic dynamic and constant water shortage from salinity intrusion in coastal areas of rural VMD (Khong et al., 2020; Tran et al., 2022; D. D. Tran et al., 2021).

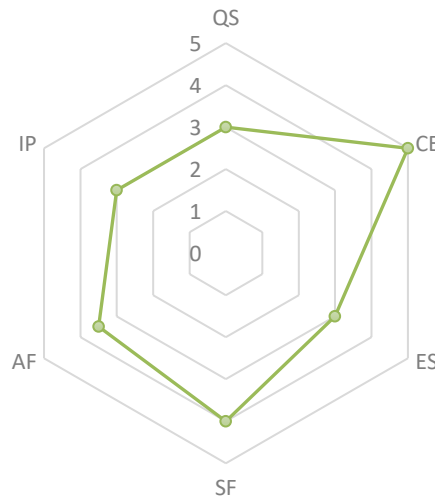


Figure 5-1: Aggregated Perception Affinity for Selected Aspects of RWHS: Quantitative sufficiency (QS), cost efficiency (CE), environmental sustainability (ES), self-sufficiency (SF), affordability (AF)

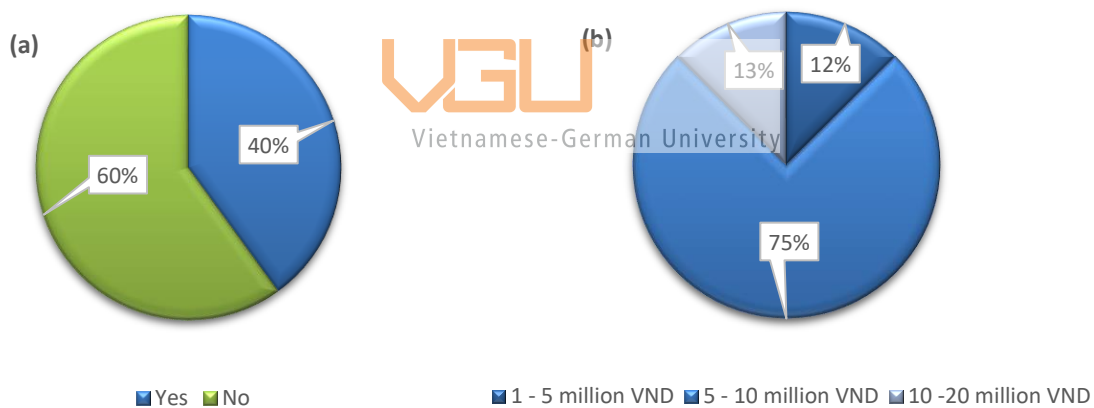


Figure 5-2: Percentage of (a) Household Willing to Upgrade, and (b) Household Willing to Implement by Income Bracket

In addition to perception-based analysis, additional direct inquiries showed that only 40% (out of 20 responses) of participants are willing to implement or expand RWHS. Of those 40%, approximately 12%, 75%, and 13% account for the monthly income bracket of 1-5 million VND, 5-10 million, and 10-20 million respectively. This indicates that the majority of respondents willing to implement RWHS can be categorized as medium-low income to the GSO (2020a). Based on this result, the questionnaire continues inquiring about the specific amount of economic support respondents would be willing to invest given their willing attitude toward implementation, the average of which is suggested to be around 12,250,000 VND, which is approximately 500 USD (or 475€) as of 2022. This is the inferred cost, or willingness-to-pay, of non-governmental entities (private households) for expenses incurred by environment-related issues that limit local livelihoods. Further breakdown of economic composition within willing households revealed that there is a

trend of economic capacity – characterized by incremental monthly income bracket – being proportional to increasing willing-to-pay quantity (Figure 5-3), which can be compared to actual valuation indicators (capital costs and NPV) for the purpose of progressive incentive inversely proportional to economic capacity (higher subsidy for lower-income status).

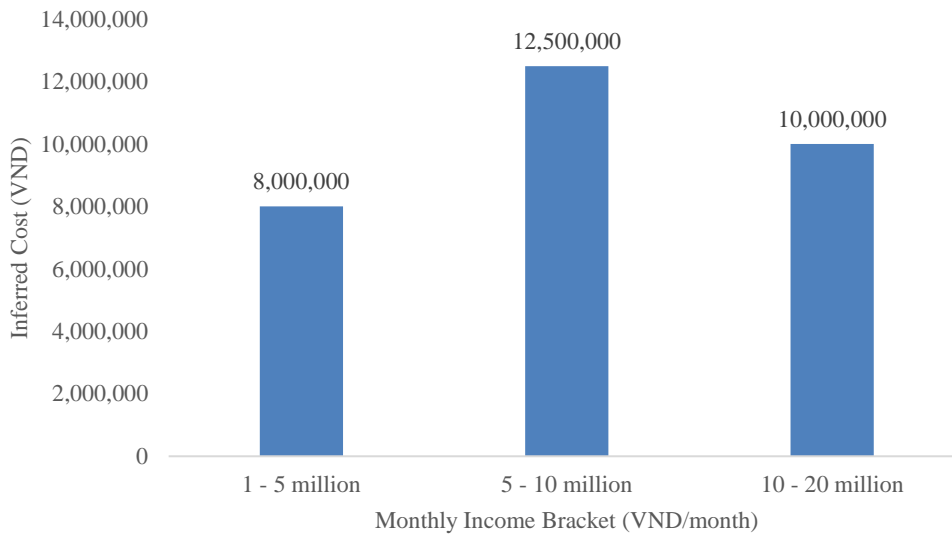


Figure 5-3: Inferred Investment Aggregated by Income Bracket

Particularly, a discussion comparing capital cost, NPV, and BCR indicators to a perceived willingness among households in the surveyed area can also identify gaps in local policy regarding water management and infrastructure investment. Moreover, assessing perceived willingness among locals can provide a clear comprehension of actual willingness to contribute to the environment- and water-related concerns, thus better equipping policymakers with information important for future risk reduction and incentive plans if needed (Khong et al., 2019). On this basis, differences between capital costs and willing-to-pay quantity based on the monthly income category can be roughly estimated. This can be performed using the annuity factor calculated above. Calculation breakdown of NPV indicators requires the determination of CDCF, which can be modularized as different between cumulative discounted costs and cumulative discounted benefits. For instance, the cumulative discounted benefit is the sum of each annual benefit multiplied by the respective annual, which can be expressed in the form of a total sum of annual benefits multiplied by the annuity factor because the annuity factor represents the total sum of the annual discount factor. Assuming that the difference between inferred valuation and actual valuation of capital costs represents the cumulative present value payable, then additional annual benefit as an annual subsidy, or annual incentive, for 10 years can be estimated by dividing that difference to the annuity factor using monthly income category of one (1-5 million VND), two (5-10 million VND), and three (10-15 million VND) as followed:

$$\begin{aligned}
 \text{Category 1 Subsidy} &= \frac{\text{Capital Cost (Plastic)} - \text{Category 1 Inferred Cost}}{\text{Annuity Factor}} \\
 &= \frac{45,522,037 - 8,000,000}{8.11} = 4,626,638 \text{ VND/year}
 \end{aligned}$$

$$\begin{aligned}
 \text{Category 2 Subsidy} &= \frac{\text{Capital Cost (Plastic)} - \text{Category 2 Inferred Cost}}{\text{Annuity Factor}} \\
 &= \frac{45,522,037 - 12,500,000}{8.11} = 3,302,2037 \text{ VND/year} \\
 \text{Category 3 Subsidy} &= \frac{\text{Capital Cost (Plastic)} - \text{Category 3 Inferred Cost}}{\text{Annuity Factor}} \\
 &= \frac{45,522,037 - 10,000,000}{8.11} = 4,380,029 \text{ VND/year}
 \end{aligned}$$

These calculations present a general frame of reference necessary for policy maker to establish a monetary baseline for socio-economic support, especially when these calculations are subjected to sampling errors from self-reported income values. For instance, such sampling errors are evident in the willing-to-pay quantity exhibited by category 3 income earners, which resulted in a higher (and unfair) subsidy for the highest income bracket compared to income category 2. To eliminate such errors, significantly more samplings are required to be representative of the study area – something that future studies can look into. Given the current circumstances, it would be more equitable to consider the subsidy for category 1 income to be minimal for poorer households and decrease the baseline subsidy as income class increases. Exploration of the socio-economic capacity of households in relation to water availability and cost-to-water ratio in the study area enables an understanding of risks and potentials for institutional and mitigation investment. To that end, an understanding discrepancy between inferred valuation and actual valuation not only provide a comprehensive economic overview for policymakers, but also an overview of public education gaps that can be remediated through an awareness campaign, which can be a cheaper alternative to incentive plans.

### 5.2.2 Climate Change Contingency

Regarding climate change, expandability and contingency will facilitate future implementation feasibility within the context of climate change which is characterized by extreme increases in rainfall during the rainy season within a short period, or drought during the dry season. As the system sizing is determined retroactively as opposed to proactively, meaning that the scope of research only considers past precipitation and not future forecasting, which can introduce uncertainties that would not be representative of climate change projection (Trenberth et al., 2003). Particularly, Clausius–Clapeyron relation elaborates that precipitation intensity can experience an increase of 7% per degree Celcius increase in global temperature (Allen & Ingram, 2002; Ingram, 2016) which is reported to have increased by 0.95 – 1.2°C between 2011 – 2020 and is projected to increase at higher rate in the following decades (Pörtner et al., 2022). Given this information, it can be roughly inferred that precipitation increase in the following decades can exceed 10%. In preparation for increased precipitation as a result of climate change, a mitigative factor of 1.2 can be introduced to the rainwater storage as opportunity for additional rainwater harvesting and accommodate higher optimized demand. To elaborate, this would entail a compensatory increase of 20% for the calculated storage tank volume based on the hydrologically optimized scenario, which would increase the original 18.64 m<sup>3</sup> to 22.37 m<sup>3</sup> to cope with the expected increase of more than 10% in future rainfall caused by climate change. This increase proactively. Following this storage sizing contingency for climate change, subsequent changes to the economic valuation process are also required to evaluate contingent adjustment, specifically for capital costs and overall

annual costs. Using a similar economic assessment method as indicated in the methodology of chapter 3 to calculate valuation indicators such as NPV and BCR in chapter 5, analysis for such contingency will also be conducted the process and result of which are detailed in Table 5-7, Table 5-8, Table 5-9, and Table 5-10).

Table 5-7: Capital Costs of Proposed RWHS Using Optimized Scenario and Contingency Consideration

Section	Item	Supplier	Unit Quantity	Cost per Unit (VND/unit)	Cost per Section (VND)
Rainwater Collection	Gutter and downspout (m)	Ton PVC (2022)	15	80,000	1,200,000
Rainwater Storage tank	Inox Storage Tank (m <sup>3</sup> )	Son Ha (2022a)	22.37	4,000,000	89,472,077
	Plastic Storage Tank (m <sup>3</sup> )	Son Ha (2022b)	22.37	2,300,000	51,446,444
Rainwater Treatment	UV lamp steriliser (29W)	Aqualife (2022a)	1	750,000	750,000
	3-phase activated carbon filtration	Aqualife (2022b)	1	700,000	700,000
Total Capital Cost (Plastic)					54,096,444

Table 5-8: Annual Costs of RWHS Using Optimized Scenario and Contingency Consideration

Category	Cost	Unit
Operation Cost	351,536	(VND/year)
Maintenance Cost	2,330,002	(VND/year)
UV Replacement Cost	750,000	(VND/year)
Filter Replacement Cost	700,000	(VND/year)
<b>Total Annual Cost</b>	<b>4,131,538</b>	<b>(VND/year)</b>

Table 5-9: Present Value Tabulation Using Optimized Scenario and Contingency Consideration

Optimization + Contingency Scenario							
Year	Annual Benefits	Annual Costs	NCF	CNCF	Discount Factor	DCF	CDCF
1	10,624,088	4,597,538	6,026,550	6,026,550	0.96	5,794,760	5,794,760
2	10,624,088	4,597,538	6,026,550	12,053,100	0.92	5,571,884	11,366,644
3	10,624,088	4,597,538	6,026,550	18,079,650	0.89	5,357,581	16,724,225
4	10,624,088	4,597,538	6,026,550	24,106,200	0.85	5,151,520	21,875,745
5	10,624,088	4,597,538	6,026,550	30,132,750	0.82	4,953,385	26,829,130
6	10,624,088	4,597,538	6,026,550	36,159,300	0.79	4,762,870	31,591,999
7	10,624,088	4,597,538	6,026,550	42,185,849	0.76	4,579,683	36,171,682
8	10,624,088	4,597,538	6,026,550	48,212,399	0.73	4,403,541	40,575,223
9	10,624,088	4,597,538	6,026,550	54,238,949	0.70	4,234,174	44,809,397
10	10,624,088	4,597,538	6,026,550	60,265,499	0.68	4,071,321	48,880,718
<b>NPV<sub>plastic</sub></b>							<b>-5,215,726</b>

Table 5-10: Cost–Benefit Tabulation Using Optimized Scenario and Contingency Consideration (Plastic Material Only)



Effect	Year	Time Value (VND)	Discount Factor	Annuity Factor	Net Present Cost (VND)	Net Present Benefit (VND)
System Capital Cost (Plastic)	1	54,096,444	0.96		52,015,812	
Maintenance Cost	(1-10)	2,796,002		8.11	22,678,084	
Operation Cost	(1-10)	351,536		8.11	2,851,269	
Replacement Cost	(1-10)	1,450,000		8.11	11,760,799	
Mitigated Municipal Water Cost	(1-10)	308,088		8.11		2,498,870
Mitigated non-potable Private Water Cost	(1-10)	1,316,000		8.11		10,673,939
Mitigated potable Private Water Cost	(1-10)	9,000,000		8.11		72,998,062
<b>Total Present Value</b>					<b>89,305,964</b>	<b>86,170,871</b>
<b>Benefit-Cost Ratio</b>					<b>0.96</b>	

The result only calculated only for plastic material as the economically feasible material given the optimized capacity, which would increase the contingent consideration, hence making the steel alternative even less feasible. Estimation showed a 20% increase in the optimized capacity for consideration of climate change can potentially impact the economic feasibility of implementation. Not only will NPV indicators go negative, but BCR will also be less than 1, which indicates a breakeven threshold at zero for NPV. Given the context that less than 50% of respondents in the survey are willing to implement RWHS, if plastic storage is economically unfeasible under the contingency consideration, then additional subsidy necessary to breakeven is recommended for the purpose of maintaining RWHS approval, which adds up to the income-based subsidy previously recommended in section 5.2.1 pertaining to acceptability and willingness-to-pay gap subsidy. Similarly, additional subsidy to breakeven can be calculated via the absolute value of negative NPV as the present value needed to be annually subsidized via the annuity factor:

$$\text{Contingency Breakeven Subsidy} = \frac{|NPV|}{\text{Annuity Factor}} = \frac{5,215,726}{8.11} = 643,123 \text{ VND/year}$$

Using this contingent subsidy in addition to the category 1 income-based subsidy above, the total minimum subsidy needed would total 5,269,761 VND/year (~205 €/year) throughout the lifespan of the system (10 years), which can be a significant amount of subsidy that requires prior policy initiative and appropriate financial structuring to be enabled – something that local government in rural Vietnam is not equipped to do. Given the estimation that incentives for plastic storage would be this significant of an endeavor, steel storage implementation would be even more unfeasible. Alternatively, smart management of RWHS as an incrementally growing and expandable system is also a potential avenue for exploration.

### 5.2.3 Expandability and Future Outlooks

There are many ways to adapt and modify RWHS to fit the need of local characteristics. For instance, a proposal of RWHS implementation in this thesis suggested the use of a manual valve for the first flush because local respondents have indicated such practices as common in the study area. However, manual operation can introduce certain operational errors, leading to insufficient or redundant diversion of monthly first-wave rainfall. This is one of the limitations of material and product sources available in Vietnam. In the United States, European countries, and Australia, first flush diverters are often mentioned as an automatic process that can be done via the implementation of an appropriately sized reservoir with a floatable blocker under the junction valve. As the pre-determined volume of first rainwater fills the reservoir, the floatable blocker rises to block the inlet and enable flow to be diverted to the storage inlet instead. The contaminant-laden rainwater in the reservoir is then discharged via a slow-release valve connected underneath (Figure 5-4). While it is a simple concept, its market presence has not made an appearance in Vietnam, which potentially opens opportunities for the market though it is outside the scope of research for the thesis.

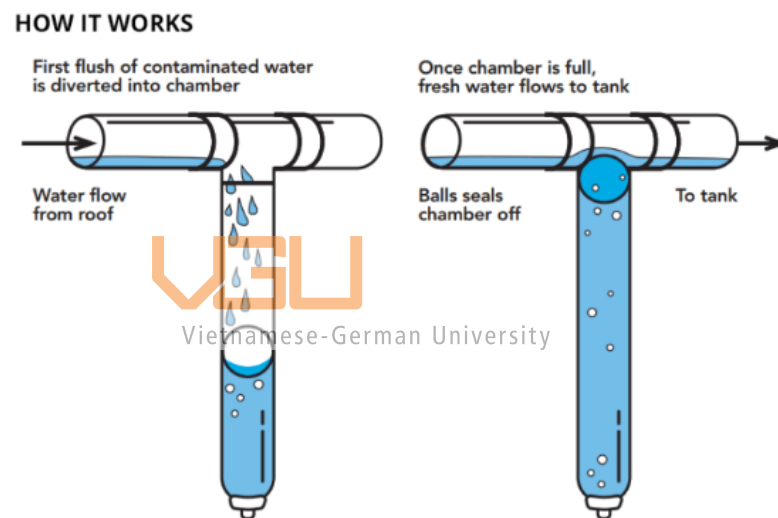


Figure 5-4: Automatic Slow Release Valve Mechanism of First Flush Device. Figure Retrieved from GreenCo Water (n.d.)

Expandability also pertains to the ability to slowly upgrade the system over time in case there a lack of subsidy and economic capacity to fully implement the proposed RWHS. In this context, previously suggested scenario 3 becomes relevant as a scenario used to establish the baseline to optimize supportable demands and storage given the rainfall regime. Scenario 3 was previously overlooked in favor of the optimized scenario when considering the highest and most efficient use of collectible rainwater given rainfall and catchment availability. Scenario 3 is proposed to be able to only fulfill the most basic need for survival (drinking and cooking), which would have resulted in a significant wasted potential as water surplus was not being fully consumed before April or May to renew the rain harvesting cycle in accordance to the hydrological season in the VMD. As proposed, storage for RWHS can comprise several connected units in an either horizontal or vertical configuration. Using this modularity, a single small unit that accommodates the annual drinking and cooking needs of households to ensure basic access to fresh water in the worst-case scenario.

In scenario 3, if the highest cumulative water surplus determines the storage size, then the capacity requirement would be too large for so little monthly consumption, which was why optimization is necessary.

As a result, it would be more appropriate to size the storage by the total annual consumption need in scenario 3 according to the  $0.6 \text{ m}^3$  monthly consumption, which would be  $7.2 \text{ m}^3$ . Using this storage input, capital costs for both steel and plastic materials are estimated to be 31,450,000 VND and 19,210,000 VND respectively. Subsequently, NPV for both steel- and plastic-based systems are respectively 20,021,617 VND and 32,261,617 VND, while BCR is estimated to be 1.4 and 1.8.

On preliminary examination, economic indicators showed that in the case of incremental storage implementation, steel-based RWHS become available as a feasible option based on household preference, albeit with a lower return margin than that of a plastic system. This method of implementation can support the RWHS adoption rate for households lacking in finance, which can also boost the acceptability of RWHS in the study area and, possibly, the VMD. Additional research is, however, needed as separate capital costs, annual costs, and annual benefits are subject to more dynamic change as its implementation is not confined within a static lifespan for a uniformly constructed system. Nevertheless, incremental expandability with a satisfactory economic threshold has a potential outlook, not only for raising the RWHS adoption rate, but also for building water-related resilience and long-term water capacity in the study area.

### 5.3 Conclusion

The objective of this thesis comprises two main objectives: (1) the assessment of the implementation feasibility and transferability of RWHS as a potential strategy for integrated water management in the study area; and (2) the technical and economical considerations of RWHS in the study area. Particularly, specific goals to achieve the objectives are (a) rainwater quantity and quality assessment; (b) RWHS designs and configurations; (c) cost-benefit analysis of RWHS; and (d) potential recommendations for policy and expansion of uses.

Regarding rainwater assessment, rainfall quantity and quality were examined. For quantitative assessment, the limited availability of high-accuracy rain gauge data leads to an exploration of various statistical correction methods for use on remote-sensing satellite datasets to fill data discrepancies. However, the reliability of statistical satellite bias correction methods is inversely proportional to the number of gauge stations available in the study area, thus making statistical correction subject to a significant margin of error. While more accurate rainfall determination can be performed via advanced machine learning algorithms, such methods are novel and inaccessible to the study. Ultimately, prior research has shown that in areas where gauge data is limited, the use of aggregated limited gauge data was proven to be more representative in a study area than any satellite-corrected rainfall dataset. On that basis, aggregated rainfall was used as a representation of precipitation in the surveyed area for compatible storage sizing and, subsequently, cost-benefit analysis. In terms of quality assessment, rainwater samples exhibit parameters within the allowable thresholds safe for consumption, except for the heavy metal Cadmium and microbiological contamination (coliform and *E. coli*).

Based on prior rainwater assessment, RWHS design and configurations mainly concern the determination of catchment, storage, conveyance, and treatment. Catchment aggregation among surveyed households represents the uniform catchment of the study area to reduce the need for case-based determination of storage using the Rippl method. Using the Rippl method, which accounts for a uniform catchment area and rainfall regime determined in rainwater quantitative assessment, storage sizing can be estimated via water

balancing between consumption scenarios and available monthly rainwater volume. Scenario-based storage sizing established that proposed scenarios proposed either provide not enough surplus or too much surplus compared to the consumption demand, which necessitates hydrological optimization of demand given available rainwater volume. For instance, given a mean rainfall of 1917 mm per year with distribution primarily concentrates between May to November, the surveyed mean water demand of  $7.5 \text{ m}^3$ , cumulative rainwater and consumption balance would only have a maximum surplus of  $0.59 \text{ m}^3$  during the rainy, which will not be enough to supplement the lack of freshwater during potential drought during the dry season. On the other hand, if demand were to be reduced to bare survival basis (drinking and cooking) with on a monthly consumption of  $0.6 \text{ m}^3$  such as scenario 3, then maximum surplus of  $39.54 \text{ m}^3$  would be redundant for such a minimal demand. Therefore, optimized demand of  $3.89 \text{ m}^3/\text{month}$  and storage sizing of  $18.64 \text{ m}^3$  were the most ideal baseline to efficiently use rainwater during the rainy season while cumulatively store enough rainwater to be used up in the dry season so that the collection cycle can restart anew in the next hydrological cycle.

Given the quality assessment of rainwater samples, the treatment process needed was heavy metal adsorption and microbiological disinfection, the most cost-to-effectiveness corresponding modules of which were three-phase GAC filtration and in-line UV disinfection lamp. The general layout concept is top-down, emphasizing on the efficient flow of rainwater while minimizing contaminants and particles from entering the orientable storage layout (vertical and horizontal).

The optimized demand and storage capacity established the bulk of the capital costs necessary in addition to conveyance and treatment module costs. Further quantification of continual annual benefit and annual cost enables the calculation of present value indicators (NPV and BCR) via the determination of NCF, DCF, and subsequently CDCF. Cost-benefit analysis shows that among the option of steel and plastic storage tanks, only plastic material satisfies the criteria of the present value indicators. Cost-benefit analysis can be used as the basis for further consideration on environmental, institutional, and management aspects of the RWHS implementation.

In terms of materials, galvanized steel for catchment, PVC for conveyance, and plastic (polyethylene) or steel storage tanks are determined to be the most appropriate material given the guiding principle of the concept design. Alternative material selection for storage unit was for the consideration of variety and user options in term of preference. However, NPV for plastic and steel are 7,138,362 VND and -24,549,665 VND respectively; and BCR for plastic and steel are 1.1 and 0.8 respectively. Given the economics of material selection for storage post-assessment determined that only plastic storage were the economically viable for the system design given economic conditions established. In addition, given the willingness-to-pay responses in the study area, inferred cost and actual cost gap also indicate that the proposed system should be implemented under a subsidy of 4,626,638 VND per year for 10 years (duration of system lifespan) so that households are incentivize to proactively adopt RWHS to increase water resilience in the region.

Taking into account climate change and a potential increase in rainfall, a compensatory factor of 1.2 can raise the contingent storage at the expense of raising capital costs and introducing a net present deficit in cost-benefit analysis. This means that in order to effectively implement RWHS, institutional incentive, in the form of financial instrument, is advised to subsidize between 4,626,638 – 5,269,761 VND depending on

income-based willingness-to-pay and climate change consideration. Such financial aid can support the population with water management issues in areas where drought and salinity intrusion are prevalent, while simultaneously increasing the attractiveness of RWHS implementation and improving water-related resilience locally. However, such financial aid per household is not an insignificant quantity, which limits its generalized implementation, especially for a rural developing region such as Ben Tre.

Throughout the thesis, several limitations are noted to be better remediated for future outlook in addition to expanded topic outlook. Particularly, the lack of data transparency limited the accessibility of rain gauge data in the VMD, which serves as an uncertainty margin regarding determination of the rainfall regime necessary for the RWHS sizing process. Sampling size was also a notable shortcoming as socio-economic questionnaire and rainwater assessment sampling were paired, which means increasing sample size would also increase the resources, budget, labor, and time spent on fieldwork. As a result, socio-economic analysis presents certain errors due to relatively few datapoints, particularly with respect to willingness-to-pay and economic capacity structure in the study area. Therefore, these limitations serve as a basis to facilitate further research to overcome previous shortcomings.

In conclusion, given the best possible access to data and equipment for fieldwork, rainwater assessment was conducted as a basis for best design consideration among RWHS variables. Based on the sustainability principle, the best design consideration outcome serves as input parameters for cost-benefit analysis, which determined that RWHS is viable as a water management strategy only if water consumption demand remains at 3.89 m<sup>3</sup> per household with the implementation of a plastic-based storage system; and given better research, advanced consideration pertaining to capacity forecasting, climate change, institutional incentives, and temporally modularized implementation can become feasible in the area as discussed above.

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## APPENDIX

### Appendix I: Questionnaire on Water Use and Rainwater Harvesting Practice

<b>1. General Water Use</b>		
1.1. What is your primary source of freshwater? <input type="checkbox"/> Municipal water (piped/tap water) <input type="checkbox"/> Drilled pumped well <input type="checkbox"/> Constructed well <input type="checkbox"/> Bottled water <input type="checkbox"/> Rainwater		1.2. What are your supplemental sources of freshwater? <input type="checkbox"/> Municipal water (piped/tap water) <input type="checkbox"/> Drilled pumped well <input type="checkbox"/> Constructed well <input type="checkbox"/> Bottled water <input type="checkbox"/> Rainwater
1.3. What is your monthly water consumption? Specific: _____ Category: <input type="checkbox"/> <5 m <sup>3</sup> <input type="checkbox"/> 5-10 m <sup>3</sup> <input type="checkbox"/> 10-15 m <sup>3</sup> <input type="checkbox"/> >15 m <sup>3</sup>		
1.4. Is your current primary water source sufficient in term of quantity? <input type="checkbox"/> Yes <input type="checkbox"/> No		1.5. Is your current primary water source sufficient in term of quality? <input type="checkbox"/> Yes <input type="checkbox"/> No. Specify: _____
1.6. What is your monthly water bill?		
1.7. Is salinity intrusion an issue for water acquisition during dry season and drought? <input type="checkbox"/> Yes. Is alternative water provision service available? <input type="checkbox"/> Municipal provision: Free <input type="checkbox"/> Private provision. Specify: _____ VND/m <sup>3</sup> <input type="checkbox"/> No	1.8. Is salinization impacting groundwater quality? <input type="checkbox"/> Yes <input type="checkbox"/> No	1.9. Is salinization impacting water quality of municipal supply (tap water)? <input type="checkbox"/> Yes. Contamination period: <input type="checkbox"/> 6 months <input type="checkbox"/> 4 months <input type="checkbox"/> <3 months <input type="checkbox"/> No
1.10. Are there any increases in health concerns during dry season? <input type="checkbox"/> Yes <input type="checkbox"/> No		
<b>2. Rainwater Perception and Practices</b>		
<b>2.1. Perception</b>		
2.1.1. Do you think that rainwater is an easily accessible source of water? <input type="checkbox"/> Yes <input type="checkbox"/> No		
2.1.2. Between rainwater, municipal water, and other sources of water, which do you prefer best? Why? <input type="checkbox"/> Municipal water (piped/tap water) <input type="checkbox"/> Drilled pumped well <input type="checkbox"/> Constructed well <input type="checkbox"/> Bottled water <input type="checkbox"/> Rainwater Why? _____		
2.1.3. Are you satisfied with your current harvested rainwater in term of quantity? <input type="checkbox"/> Yes <input type="checkbox"/> No		2.1.4. Are you satisfied with your current harvested rainwater in term of quality? <input type="checkbox"/> Yes <input type="checkbox"/> No
2.1.5. Do you perceive your current rainwater quality to be safe compared to other sources of water? <input type="checkbox"/> Yes <input type="checkbox"/> No		
<b>Please state your agreement to the following statement (1 least agreed – 5 most agreed):</b>		
2.1.6. Rainwater harvesting should be the primary source of freshwater in the region		<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5



2.1.7. Rainwater harvesting is a cost-effective supply of freshwater		<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5
2.1.8. Rainwater harvesting is a sustainable practice that helps the environment		<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5
2.1.9. Rainwater harvesting enable self-sufficiency for your household		<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5
2.1.10. Rainwater harvesting should have cheaper affordable treatment technology		<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5
2.1.11. Rainwater harvesting should be considered a priority for water management policy		<input type="checkbox"/> 1 <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5
<b>2.2. Practices</b>		
2.2.1. What was your motivation for practicing rainwater harvesting? <input type="checkbox"/> Salinity intrusion - drought <input type="checkbox"/> Environmental sustainability <input type="checkbox"/> Ineffective centralized water supply <input type="checkbox"/> Self-sufficiency		
2.2.2. What is the cost for your current system?		
2.2.3. Do you use harvested rainwater for drinking and cooking? <input type="checkbox"/> Yes <input type="checkbox"/> No		
2.2.4. Do you use harvested rainwater for showering and hygiene? <input type="checkbox"/> Yes <input type="checkbox"/> No		
2.2.5. Do you use harvested rainwater for non-potable purposes (toilet, laundry, outdoors, etc.)? <input type="checkbox"/> Yes <input type="checkbox"/> No		
<b>2.3. Technical Consideration</b>		
2.3.1. What best describe your roofing materials? <input type="checkbox"/> Corrugated metal <input type="checkbox"/> Fibro Cement <input type="checkbox"/> Brick tiles <input type="checkbox"/> Thatched roof <input type="checkbox"/> Not Sure	2.3.2. What is your total roof catchment area of your? Specific: _____ Category: <input type="checkbox"/> < 20 m <sup>2</sup> <input type="checkbox"/> 20 – 40 m <sup>2</sup> <input type="checkbox"/> 40 – 60 m <sup>2</sup> <input type="checkbox"/> 60 – 80 m <sup>2</sup> <input type="checkbox"/> > 100 m <sup>2</sup>	
2.3.3. What best describe your current rainwater storage materials? <input type="checkbox"/> Galvanized Steel <input type="checkbox"/> Polyethylene (plastic) <input type="checkbox"/> Concrete <input type="checkbox"/> Ceramic <input type="checkbox"/> Not Sure	2.3.4. What is the capacity of your current rainwater storage? Specific: _____ Category: <input type="checkbox"/> <5 m <sup>3</sup> <input type="checkbox"/> 5-10 m <sup>3</sup> <input type="checkbox"/> 10-15 m <sup>3</sup> <input type="checkbox"/> >15 m <sup>3</sup> <input type="checkbox"/> Not Sure	
2.3.5. Which type of storage tanks are you currently? <input type="checkbox"/> On elevated stand <input type="checkbox"/> On ground <input type="checkbox"/> Buried below ground <input type="checkbox"/> Constructed Well-Hybrid	2.3.6. How do you access harvested rainwater from storage tanks? <input type="checkbox"/> Direct withdrawal <input type="checkbox"/> Valved outlet <input type="checkbox"/> Integrated Utility Network	
2.3.7. What best describe your current gutters and downspouts materials <input type="checkbox"/> Aluminum <input type="checkbox"/> Other _____ <input type="checkbox"/> PVC <input type="checkbox"/> Not sure		
2.3.8. Do you utilize any rudimentary method to eliminate contaminants prior to usage? <input type="checkbox"/> No <input type="checkbox"/> Cloth/mesh screening <input type="checkbox"/> First-flush <input type="checkbox"/> Tank sedimentation <input type="checkbox"/> Tank interior cleanup <input type="checkbox"/> Boiling water <input type="checkbox"/> Tank coverage <input type="checkbox"/> Alum or other coagulants		
2.3.9. Do you utilize any filtration treatment method? <input type="checkbox"/> No <input type="checkbox"/> Yes: <input type="checkbox"/> GAC filtration <input type="checkbox"/> Cartridge filtration <input type="checkbox"/> Membrane filtration		
2.3.10. Do you utilize any other treatment method? <input type="checkbox"/> No <input type="checkbox"/> Yes:		



<input type="checkbox"/> In-line UV <input type="checkbox"/> In-line chlorination <input type="checkbox"/> Batch chlorination	
2.3.11. How often do you test your collected rainwater for contamination? <input type="checkbox"/> Never <input type="checkbox"/> Semi-annually <input type="checkbox"/> Monthly <input type="checkbox"/> Annually <input type="checkbox"/> Bi-monthly <input type="checkbox"/> Bi-annually	
2.3.12. Have you ever experienced any health issues related to the consumption of harvested rainwater? <input type="checkbox"/> Yes. Specify: _____ <input type="checkbox"/> No	
<b>3. Socio-economic Details</b>	
3.1. How many people are in your household?	
3.2. What is the highest level of education in your household?	
<input type="checkbox"/> No education <input type="checkbox"/> Elementary <input type="checkbox"/> Secondary <input type="checkbox"/> High School	<input type="checkbox"/> Vocational <input type="checkbox"/> University <input type="checkbox"/> Master <input type="checkbox"/> PhD or higher
3.3. What is your average annual household income? Specific: _____	
Category: <input type="checkbox"/> < 1 million VND <input type="checkbox"/> 20 – 30 million VND <input type="checkbox"/> 1 – 5 million VND <input type="checkbox"/> 30 – 50 million VND <input type="checkbox"/> 5 – 10 million VND <input type="checkbox"/> > 50 million VND <input type="checkbox"/> 10 – 20 million VND <input type="checkbox"/> Not sure	
3.4. If you are able, would you upgrade your RWHS? If yes, how much are you willing to pay for the upgrade? <input type="checkbox"/> No <input type="checkbox"/> Yes. Specify: _____	
 Vietnamese-German University	