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Integrated Exploitation of Rainwater and Groundwater: A Strategy for Water Self-Sufficiency in Ca Mau Province of the Mekong Delta

Dang Hoa Vinh [1], Dung Duc Tran [2,*], Dao Dinh Cham [3,4], Phan Thi Thanh Hang [3,4], Duong Ba Man [1], Danh Mon [1], Luu Hai Tung [1], Le Van Kiem [5], Thien Duc Nguyen [2] and Duong Thi Ngoc Tuyen [6]

1 HCMC Institute of Resources Geography, Tay Nguyen Institute of Scientific Research, Vietnam Academy of Science and Technology, Ho Chi Minh City 700000, Vietnam; dhvinh@hcmig.vast.vn (D.H.V.); dmon@hcmig.vast.vn (D.M.); lhtung@hcmig.vast.vn (L.H.T.)
2 Center of Water Management and Climate Change, Institute of Environment and Natural Resources, Vietnam National University Ho Chi Minh City, Ho Chi Minh City 700000, Vietnam; thienduc295@gmail.com
3 Graduate University of Science and Technology, Vietnam Academy of Science and Technology, Hanoi 100000, Vietnam; ddcham@ig.vast.vn (D.D.C.); hangphanvn95@gmail.com (P.T.T.H.)
4 Institute of Geography, Vietnam Academy of Science and Technology, Hanoi 100000, Vietnam
5 Southern Institute for Water Resources Research, Ho Chi Minh City 700000, Vietnam; kiemsiwrr@gmail.com
6 Department of Natural Resources and Environment of Ca Mau Province, Ca Mau 970000, Vietnam; tuyensotnmt@gmail.com
* Correspondence: dungtranducvn@yahoo.com

Abstract: Groundwater sources have been exploited excessively for numerous purposes worldwide, leading to increasingly severe depletion. However, the replenishment of groundwater sources has not usually been a focus in economically and socially underdeveloped countries and regions. In coastal provinces of the Vietnamese Mekong Delta (VMD), rural areas are facing difficulties in accessing fresh water due to shortages from the water supply plant and excessive use of groundwater, highlighting an urgent need for sustainable development solutions. Our study first conducted interviews with 200 households in Ca Mau Province of the VMD to identify the current situation and the challenges and obstacles of rainwater harvesting and to find sustainable and proactive solutions. We then analyzed daily rainfall data from 10 meteorological stations to construct four scenarios of the water balance method: (i) potential rainwater harvesting based on existing roof area; (ii) optimal scale of storage tank and catchments for different levels of water usage; (iii) tank scale utilizing rainwater entirely during the rainy season and basic needs during the dry season; and (iv) integrated water supply between rain and groundwater. The results showed that using rainwater entirely for domestic water supply requires large storage tank capacities, making these scenarios difficult to achieve in the near future. Our research introduces a novel integrated water supply approach to storing rain and groundwater that has demonstrated high effectiveness and sustainability. With existing tank capacities (0.8 m^3 per person), rainwater could only meet over 48% (14 m^3 per year) of the water demand while requiring 14.8 m^3 of additional groundwater extraction. With a tank capacity of 2.4 m^3 per person, ensuring rainwater harvesting meets basic demand, harvested rainwater could satisfy 64% of the demand, with artificial groundwater supplementation exceeding 1.79 times the required extraction, while excess rainwater discharge into the environment would be minimal. Our research results not only provide potential solutions for rainwater and groundwater collection to supplement sustainable domestic water sources for Ca Mau but also serve as an example for similar regions globally.

Keywords: rainwater; groundwater; harvesting; water balance; Mekong

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1. Introduction

Clean, fresh water is invaluable for human life and development. Hence, it is essential to safeguard human society from the impacts of water scarcity (i.e., droughts) or excess (i.e., floods), which could contaminate water quality and change its quantity [1]. The process of urbanization, coupled with population explosions, is driving up the increasing demand for clean water globally [2–4]. Meanwhile, climate change has increased its impacts by altering rainfall patterns, increasing temperatures, and negatively affecting water sources, leading to serious consequences for water security and causing severe livelihood disruptions, particularly for impoverished populations in particularly rural and coastal areas [5]. Despite the attention and research on water scarcity or excess and clean water issues [2,6–8], the consequences are escalating, demanding effective solutions, especially in poorer and developing countries and particularly in rural and coastal rural areas facing challenges such as climate change and sea-level rise driving environmental issues like salinity intrusion [9–11].

Groundwater (GW) is one of the most vital water sources in rural and coastal areas where accessing freshwater sources poses challenges [12]. However, GW extraction has been continuously increasing, reaching a rate of 1500 km^3 per year across countries worldwide [13], exceeding natural replenishment levels and causing significant global-scale impacts such as GW level depletion, land subsidence, and the contamination of aquifers [14–16]. Meanwhile, rainwater harvesting is perceived as a sustainable solution to obtain clean water at low costs and with minimal energy consumption [17,18], yet it remains an underappreciated water source. For instance, rainwater harvesting has been commonly applied in Australia and countries across Asia (i.e., Japan, China) and Africa (i.e., Botswana, Ethiopia, Kenya) [19]. Due to the unpredictable nature of rainfall in terms of onset, duration, and withdrawal, rainwater harvesting often faces challenges in meeting humans' water demands [20]. Therefore, GW and rainwater are considered important backup water sources with untapped potential, mostly during the dry season, and require management, protection, and renovation solutions.

Recognizing the importance of GW to meet future needs, the management, protection, and replenishment of GW resources are seriously considered [21]. Among management techniques, Managed Aquifer Recharge (MAR) has been globally implemented [22,23], treating GW as a reserve water bank and tightly managing aquifers to ensure replenishment. Several studies have outlined the benefits of MAR, not only for cost-effective water use but also for ensuring the secure stability of future water sources [24–26]. Water bank models, achievements, and challenges in MAR implementation have been introduced by Niazi et al. [27] and Arshad et al. [28], who suggested that GW utilization through MAR is more economical than surface water reservoirs, although the treatment costs are relatively high in cases of insufficient clean water sources for supplementation.

Ca Mau is the southernmost coastal province of the Vietnamese Mekong Delta (VMD) (Figure 1), where access to surface water sources during the dry season is challenging [29]. In the province, the primary water source for domestic needs is groundwater; however, it is currently facing severe depletion, evidenced by land subsidence (0.5 to 4 cm annually), declining water levels, and aquifer contamination [30,31]. In addition, the freshwater shortage has been exacerbating due to salinity intrusion caused by sea level rise driven by climate change [32]. According to Bruno et al. [33], climate change-induced sea level rise would inundate a substantial portion of the province, encompassing roughly 43% to 75% of its land area in the years 2030 and 2050, respectively. Thus, the abundant amount of rainfall within Ca Mau Province is considered a valuable resource that assists people in fulfilling their water needs. Rainfall on rooftops is deemed adequate to supply domestic water needs [20]; however, rainwater harvesting is currently limited across the province and does not fully utilize the available potential.

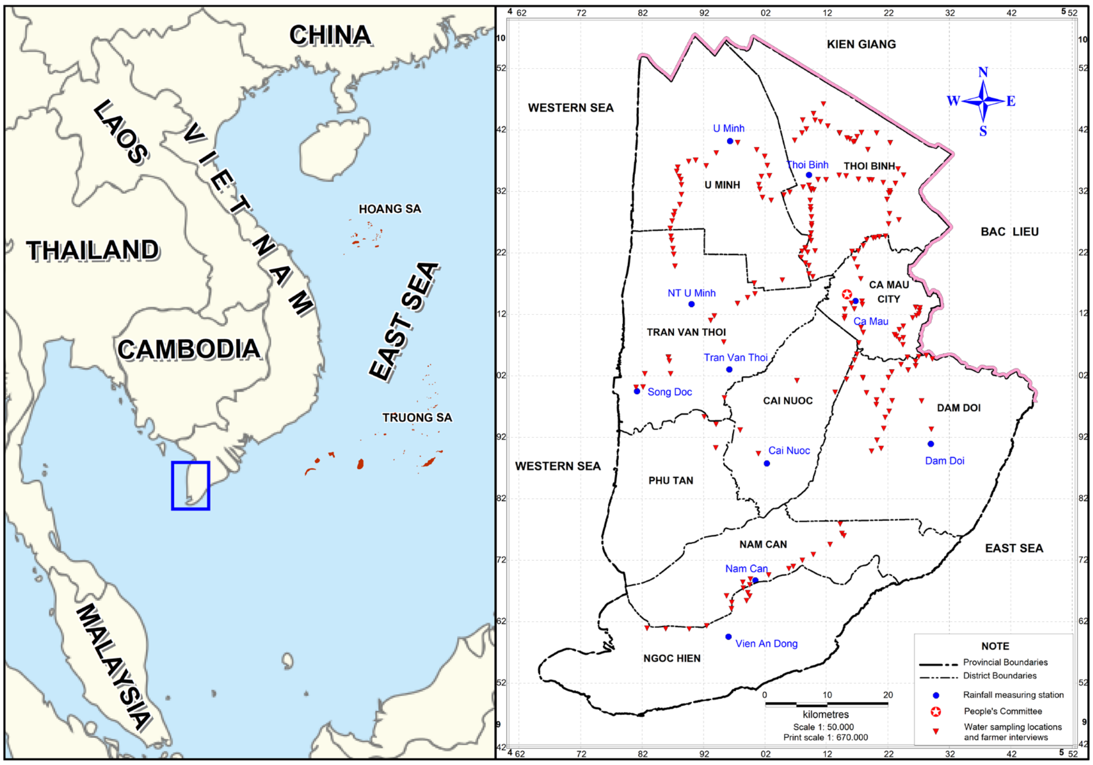

Figure 1. Map depicting the research area location of Ca Mau Province within the Mekong Delta, Vietnam (VMD) (**left**) and Ca Mau Province (**right**), illustrating provincial boundaries, districts, the locations of 10 rainfall monitoring stations, and 200 interviewing locations.

Recent studies have investigated the negative impacts of groundwater overexploitation, such as land subsidence in Ca Mau Province, and the need to sustain this resource [34,35]. Restricting groundwater usage while improving rainwater harvesting could alleviate depletion effects, but it remains underexplored in the province and most other coastal provinces in the VMD. In addition, our interdisciplinary approach, comprising a survey of 200 households and water balance calculations using rainfall data analysis from 10 meteorological stations in Ca Mau, aims to devise an integrated rainwater and groundwater strategy. This strategy considers rainwater (a renewable resource) as the primary water source, while groundwater becomes a backup source for cases of freshwater shortage [36]. The backup water source is protected and rejuvenated by artificially recharging groundwater, such as through MAR, using excess rainwater from its harvesting system. We hence address three main objectives, including (i) analyzing and evaluating the potential for rainwater harvesting (catchment and storage capacity), identifying obstacles, and assessing the willingness of the community to enhance rainwater harvesting; (ii) calculating rainwater harvesting options, implementation methods, and technical requirements; and (iii) quantifying excess rainwater in the system for artificial groundwater recharge. Our study offers a practical method and evidence for constructing an effective water storage strategy through rainwater harvesting to address freshwater shortages driven by salinity intrusion in the VMD provinces and similar regions globally, especially during the dry season.

2. Materials and Methods

2.1. Study Area and Data

Ca Mau covers nine (9) districts and is one of the seven (7) coastal provinces (i.e., Kien Giang, Bac Lieu) located in the Vietnamese Mekong Delta (Figure 1), with a total natural area of 5242.5 km^2, equivalent to 13.1% of the delta region's area and 1.58% of the national territory. It has a coastline stretching over 254 km, bordering both the East Sea and the West Sea, making it an advantageous location for seaport development. With a population of 1,194,476 people (2019), 73% settle in rural areas engaged in year-round brackish aquaculture (mainly shrimp) and paddy rice cultivation during the rainy season.

Annually, the dry season typically spans from January to May, while the rainy season extends from June to December. Fortunately, the province experiences an average annual rainfall of approximately 2247 mm. Nevertheless, many areas contend with a shortage of clean and fresh water during the dry season, leading many households to extract freshwater from underground aquifers. Located in a coastal zone, salinity usually intrudes further inland to affect aquaculture and agricultural activities across the province [32,33].

Daily rainfall data from 10 monitoring stations located within Ca Mau were provided by the Southern Regional Hydro-meteorological Center in Vietnam. To ensure consistency over time, the study selected a calculation timeframe for the entire dataset from 1989 to 2017. All the data used in the study were checked for reliability using the T-test method and tested for homogeneity using the one-sign analysis of variance [37]. After that, a statistical descriptive method was applied to determine the characteristics of the rainfall data. Details of the methods can be found in a previous study by Dang et al. [20].

2.2. Methods

2.2.1. Interview Survey

A survey of 200 households was conducted in April 2020 to mainly gather information on the current status of rainwater harvesting systems, the groundwater exploitation situation, and the obstacles they have faced (Figure 1, right map). We used stratified random sampling to interview households' heads. During the survey, three social groups, including poor households, middle-income households, and relatively affluent households, were selected as the main interview subjects. The purpose of dividing the households into the three various categories was to objectively understand the use of domestic water and rainwater collection practices within the communities. In addition, information about the perceptions of people with different economic capacities was expected to provide evidence supporting the feasibility of implementing a new rainwater harvesting strategy.

The interview questionnaires focused on clarifying key points, including general household information, domestic water usage and access to each water source, the current operation and maintenance status of rainwater harvesting systems, residents' perceptions and concerns about rainwater quality, and residents' readiness to increase rainwater harvesting capacity. These points were investigated in each interview, which took about 30 min to make sure they could address the research questions. Survey data were then input into Excel software 2016 version and processed for aggregation. Descriptive statistical methods were also employed to analyze the social characteristics of the surveyed group, water usage status, rainwater usage practices, perceptions of rainwater quality, and characteristics of rainwater harvesting systems. Our questionnaire can be found in the Supplementary Material.

2.2.2. Water Balance Calculations

Water balance calculations were used to assess the potential of rainwater and determine the amount of rainwater that can be harvested annually through existing catchment capabilities. Additionally, the minimum required rainwater catchment area and minimum tank capacity to meet usage needs were quantified. Subsequently, the excess rainwater in the specific calculated rainwater harvesting scenarios was determined to artificially refill groundwater.

The water balance equation is typically represented as a function of the amount of water in and out [38]:

$$W^t{}_i = W^t{}_{i-1} + W^c{}_i - W^o{}_i \ (m^3) \quad (1)$$

where

$W^t{}_i$ and $W^t{}_{i-1}$: the volume of water stored in the reservoir (m^3) in a given time period i, i − 1; The initial calculation period $W^t{}_1 = 0$;

$W^t{}_i \leq W^t$, where W^t is the capacity of the tank;
$W^c{}_i$: water volume entering the tank at time i (m^3);
$W^o{}_i$: volume of water discharged from the tank at time i (m^3).

Scenario 1: Evaluating the Potential for Rainwater Harvesting through the Existing Roof Area

This scenario aims to determine the amount of usable water that rainwater can provide through the existing rainwater catchment area. Here, the potential for rainwater harvesting is specified based on two conditions: (i) the storage tank capacity is unlimited and (ii) the catchment area is the existing average roof area (F) available to residents, which is 21.4 m^2 as per the Population and Housing Census Steering Committee of Vietnam [39].

The variables in Equation (1) include the following:

$W^o{}_i$: the water outflow from the storage tank or the amount of water used over the calculation period (day); $W^o{}_i$ = D/1,000, where D represents the water demand (L/person-day);

$W^c{}_i$ (the water volume entering the tank at time i) = $W^m{}_i$; the amount of rainwater collected through a catchment area during the period i (m^3) is determined via the following equation:

$$W^m{}_i = (X_i - A) \times F, \quad (2)$$

in which the variables are as follows:

X_i: the amount of rainfall at time i;
A: the amount of rainwater at the beginning of the rainfall event that needs to be discharged; in this study, A = 3 mm based on experience.

The water demand, D, was gradually tested to determine the maximum level at which there are no instances of the water reservoir running dry ($W^t{}_i \leq 0$). Afterward, the minimum capacity of the storage tank was re-evaluated to meet the previously determined maximum water demand (W^t—m^3).

Scenario 2: Determining the Minimum Roof Area/Size and Tank Capacity Requirements to Meet Water Demand Levels

The variables in Equation (1) at this time are as follows:

Water outflow from the storage tank:

$$W^o{}_i = W^d{}_i + W^x{}_i; \quad (3)$$

$W^d{}_i$: the water amount used during the calculated time period (day); $W^d{}_i$ = D/1000
$W^x{}_i$: the water amount discharged or overflowed during the calculated time period.
Equation (1) becomes the following:

$$W^t{}_i = W^t{}_{i-1} + W^c{}_i - W^d{}_i - W^x{}_i \ (m^3) \quad (4)$$

When $W^t{}_i \leq W^t$, then no water is discharged or overflowing, or $W^x{}_i = 0$;

When $W^t{}_i > W^t$, then the water will proceed to be discharged or overflow ($W^x{}_i > 0$).

The input information included the daily rainfall data from the observation stations; the calculated levels of water demand (D) are as follows: 3, 5, 15, 20, 30, 40, 50, 60, 70, 80, 90, and 100 L/person-day; the minimum roof area was determined as $F_{min} = D \times 365/X_{year}$, where X_{year} is the total average annual rainfall; and the minimum storage tank capacity was calculated using $W^t{}_{min} = D \times NRY$, where NRY is the maximum average number of consecutive non-rainy days in the year.

The roof area (F) and storage tank capacity (W^t) were calculated incrementally from small to large to ensure meeting the water demand without any instances of the storage tank running out of water ($W^t{}_i \leq 0$). The calculation resulted in the optimal roof area and storage tank capacity.

Scenario 3: Determining Tank Requirements for Maximum Use of Rainwater in the Rainy Season and Essential Water Needs in the Dry Season

This scenario utilized rainwater to fully meet the water demand throughout the year, requiring a relatively large storage tank capacity. The essential water demand was 15 L/person-day [39]. To accurately identify the transition from the rainy season to the dry season, which is challenging for most residents, our study used the criterion of water level in the storage tank to recognize the change in water usage demand; for example, when the water level in the tank was above 75%, it was used for full demand, and conversely, when the water level in the tank was below 75%, an essential water demand was set.

Equation (4) is applied, with the difference being the determination of the variable ${W^d}_i$: when ${W^t}_i > W^t \times 0.75$, then ${W^d}_i = D/1000$ (m^3), and when ${W^t}_i \leq W^t \times 0.75$, then ${W^d}_i = 0.015$ (m^3).

In this scenario, the roof area (F) is also 21.4 m^2/person. The calculation steps are similar to scenario 2.

Scenario 4 Integrating Rain and Groundwater

In this scenario, the tank capacity was specified from the results of scenario 3. Our objective was to maximize rainwater exploitation, just use groundwater when there was a shortage, and artificially supplement groundwater from excess rainwater. In case the tank ran out of water (${W^t}_i \leq 0$), the tank was then replenished from the supplementary water source (groundwater or other water source), and the excess rainwater source during the rainy season was used to maximize artificial groundwater recharge.

Whenever the storage tank ran dry, it was replenished with an amount of water equal to 50% of the tank's capacity (this result has been experimentally calculated across scenarios of 25%, 50%, and 75% replenishment, indicating that replenishing 50% each time the tank runs dry was suitable).

The artificial groundwater recharge method was applied as follows. During the permissible period for artificial groundwater recharge, when the water level in the storage tank exceeded 50% of the tank's capacity, the water in the tank automatically flowed into the artificial groundwater recharge well. The artificial recharge period started on 1 May each year and ended on 31 October, about 20 days before the end of the rainy season.

The following equation is considered:

$$ {W^c}_i = {W^m}_i + {W^{GW}}_i \quad (5) $$

${W^{GW}}_i$: the amount of water needed to be extracted from the groundwater when the storage tank runs dry (${W^t}_i \leq 0$).

$$ {W^o}_i = {W^d}_i + {W^{AR}}_i + {W^{OW}}_i \quad (6) $$

${W^{AR}}_i$: the amount of water artificially replenished into the groundwater during the period i;

${W^{OW}}_i$: the amount of water that needs to be discharged or overflowed during the period i;

Equation (1) is applied:

$$ {W^t}_i = {W^t}_{i-1} + {W^m}_i + {W^{GW}}_i - {W^d}_i - {W^{AR}}_i - {W^{OW}}_i \ (m^3) \quad (7) $$

This scenario aims to determine the amount of harvested rainwater used for domestic purposes, the amount of water that needs to be supplemented when there is a shortage, and the amount of rainwater needed for artificial groundwater recharge. We developed this scenario considering not only a technical assessment but also social and economic aspects.

In this scenario, the system consists of six main components (Figure 2): (i) a roof catchment for collecting rainwater, including gutters, debris swept/strainers, first flush diverters, and conduits with a bottom valve; (ii) a first storage tank for storing untreated water; (iii) a water treatment filtration system; (iv) a storage tank for treated water; (v) a groundwater extraction and recharge system with an inverted U-shaped structure, with a height equal to half of the tank height, and a groundwater extraction well integrated; and (vi) a groundwater extraction system, including extraction pumps and pipelines transferring water to the first storage tank. Rainwater collected from the roof catchment is stored in the first storage tank, treated through the filtration system, and transferred to the storage tank for distribution to users. Additional branches diverting water into the groundwater extraction well are installed along the pipeline leading water out of the storage tank. The inverted U-shaped structure ensures that the water level in the storage tank is maintained at 50%. During the permitted time, the check valve of the groundwater extraction and recharge system remains open and closes during the dry season. The groundwater extraction well is designed to also serve as a recharge well. Finally, the groundwater extracted from the well is transferred to the first storage tank for treatment and then sent to the storage tank for usage.

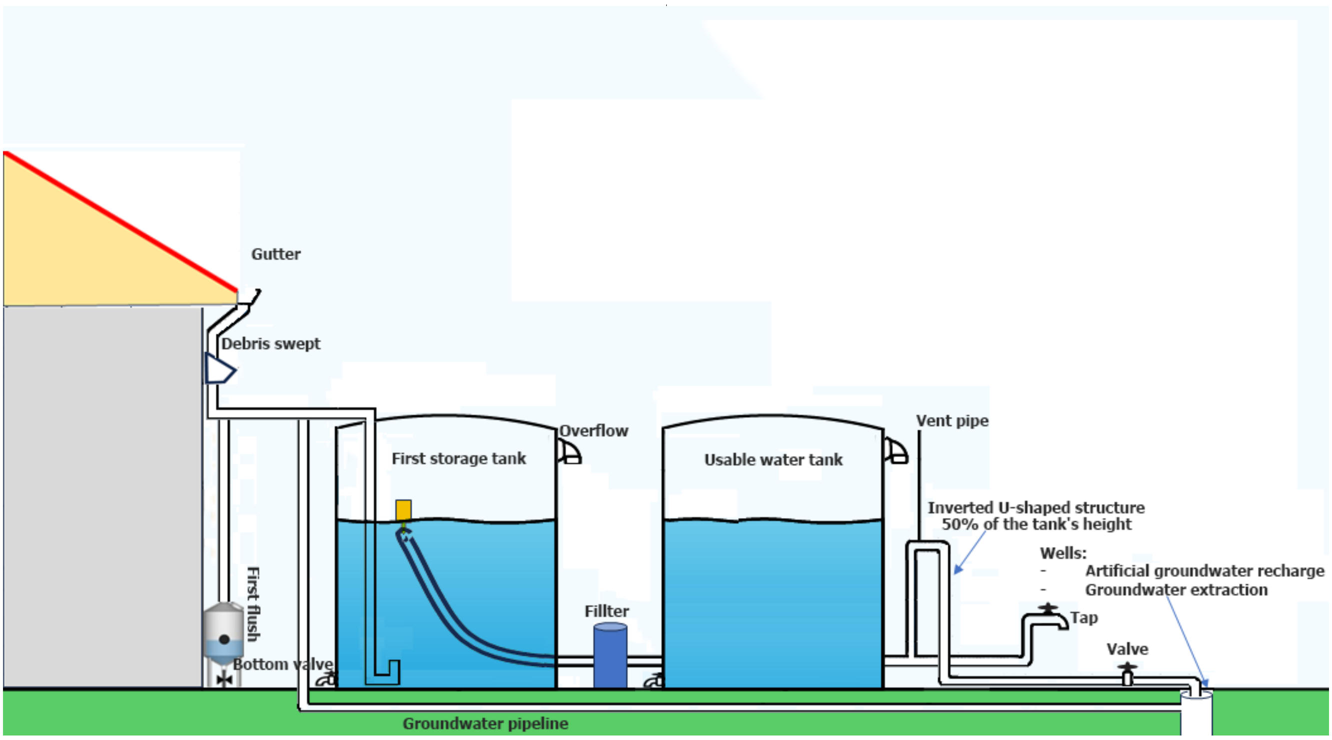

Figure 2. Rainwater harvesting system developed in the study, including artificial groundwater recharge and groundwater extraction, adopted from the website https://content.ces.ncsu.edu/mosquito-control-for-rainwater-harvesting-systems assessed on 31 December 2021.

3. Results and Discussion

3.1. Rainwater Harvesting for Domestic Use in Ca Mau Province

3.1.1. Interview Survey

The survey results show that residents in rural areas of Ca Mau Province use five different water sources, including tap water, groundwater, surface water, rainwater, and bottled water (Figure 3). On average, each household uses 2–3 different water sources.

Tap water in Ca Mau Province is supplied from water treatment plants under the Center of Clean Water and Environmental Sanitation in Rural Areas or from water supply companies. All these plants extract water from groundwater sources where the quality is good and abundant. Due to the uneven distribution of these plants and their placement in different areas, only 8% of households have access to this water source. Meanwhile, surface water is extracted from household ponds, lakes, or canals in areas with freshwater sources, but the quality is very poor, so only 2% of households can use it. Bottled water is quite commonly used by 53% of households due to its low cost. Our findings are similar to those in other regions of developing countries where surface freshwater is limited or affected by droughts and salinity intrusion [40,41].

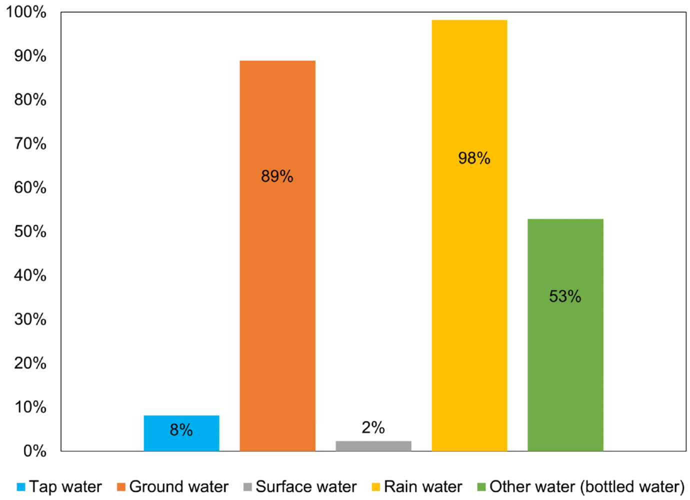

Figure 3. Five water resources for domestic usage in Ca Mau Province.

Rainwater and groundwater are the main sources of water for household purposes, which people harvest themselves on-site. Almost all residents (98%) use rainwater. Due to the convenience of groundwater, it is the preferred water source for 89% of the population, and households that do not use groundwater simply cannot access it.

Rainwater and bottled water are the main sources for drinking purposes, with rates of 59.1% and 31.8%, respectively, while other sources are less common (Figure 4). Rainwater is predominantly used for cooking, accounting for 49.3% of households, followed by groundwater at 47.1%. People rarely use rainwater for other purposes, mainly relying on groundwater for tasks such as washing food and kitchen utensils. Our survey results on water sources and usage patterns also indicate that rainwater and groundwater are the primary sources for household use. It is suggested that increasing the use of rainwater contributes to decreasing groundwater extraction.

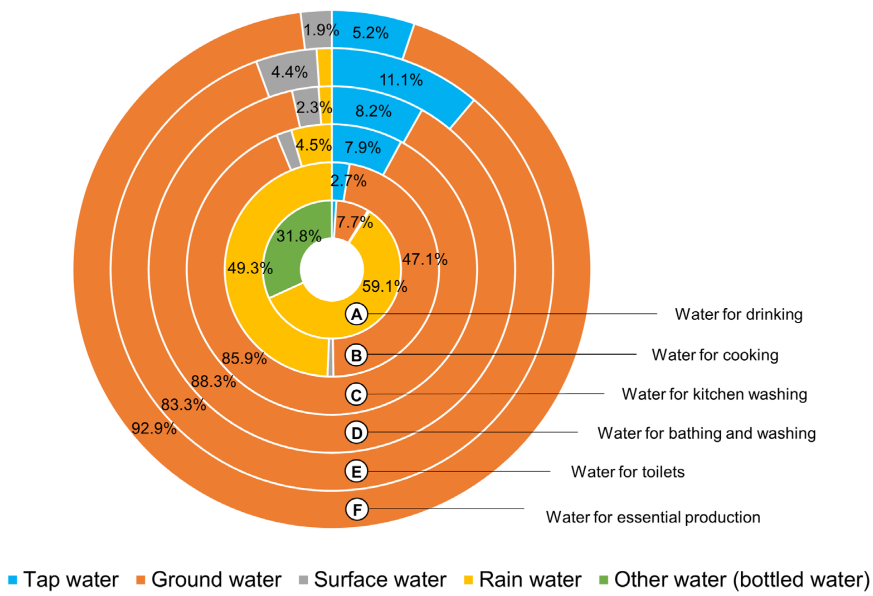

Figure 4. Percentage of residents using water sources for different purposes.

3.1.2. Existing Context of Rainwater Harvesting for Ca Mau Residents

In Ca Mau Province as well as others across the VMD, there are two common types of roof catchments, namely corrugated metal roofs (50.9%) and fiber cement roofs (49.7%), with nearly equal proportions (Figure 5). The average roof area per household is 77.24 m^2. Household types with roof areas ranging from 50 to 100 m^2 per household are prevalent (68.42%), while very small roofs (<30 m^2) or very large roofs (>200 m^2) are less common. On average, each household typically has around 3-4 individuals, resulting in an average roof catchment area of approximately 19.3 to 25.7 m^2 per person. The survey data are consistent with the results from the 2019 Population and Housing Census Steering Committee in Vietnam [39].

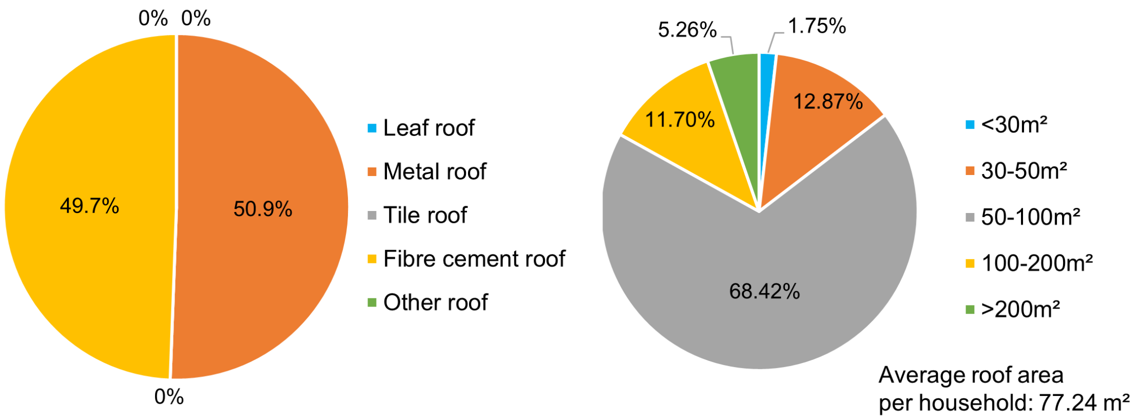

Figure 5. Characteristics of rainwater roofs in terms of material (**left**) and area/size (**right**).

The average storage tank capacity is 2.56 m^3 per household, with an average of about 0.64 to 0.85 m^3 of storage tank capacity per person (Figure 6). Commonly, households have storage tank capacities ranging from 1 to 3 m^3 (50.6%). The number of households with larger storage capacities (5 to 10 m^3) accounts for 5%, while those with very large capacities (>10 m^3) only make up 1.19%. The majority of residents primarily use water pots (48.52%) and prefabricated (44.52%) tanks.

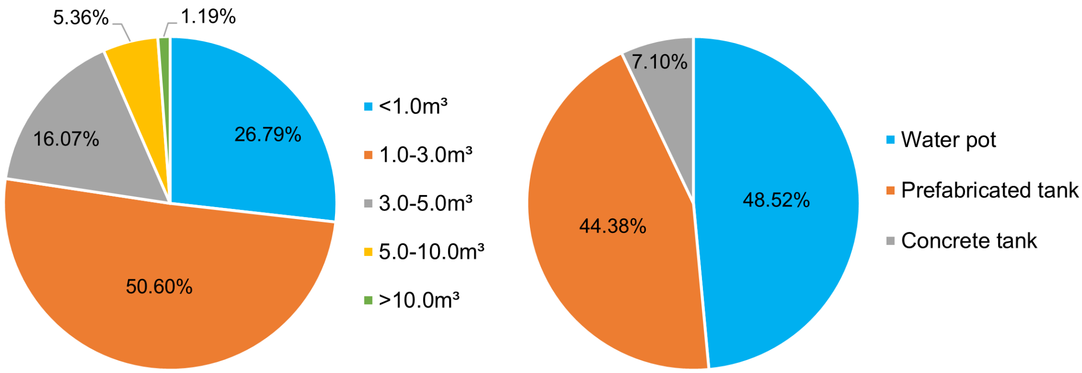

Figure 6. Characteristics of rainwater tanks in terms of capacity (**left**) and materials (**right**).

The primary purpose of rainwater harvesting is mainly for drinking and cooking, so residents do not have much motivation to increase rainwater storage when they already have enough water to use. Up to 84% of households responded that they do not want to increase their rainwater storage capacity. Among them, the main reasons are a lack of necessity (82%), a lack of funds (13%), and a lack of space for construction (5%).

Overall, rainwater is commonly used by residents in Ca Mau Province. However, the high installation costs of rainwater harvesting systems, along with the low direct economic efficiency [42–44], coupled with the ease of accessing piped water supply, have limited the increase in rainwater usage. Therefore, residents only harvest enough rainwater to meet their highest needs for drinking and cooking, with an estimated demand of about 2.5 to 3.0 L/person-day. Other needs with much larger volumes are mainly met from groundwater sources, which are currently under considerable pressure due to depletion.

3.2. Rainwater Potential and Rainwater Harvesting Scenarios

3.2.1. Rainwater Characteristics Related to Harvesting Capacity

Table 1 presents the statistical characteristics describing the annual rainfall and the greatest number of consecutive rainless days (or days with rainfall < 5 mm) based on data collected from 10 rainfall monitoring stations in Ca Mau Province. The rainfall amount characteristic reflects the potential, while the number of rainless days indicates limitations affecting rainwater harvesting.

Table 1. Statistical descriptive characteristics of annual rainfall data at 10 monitoring stations.

Station / Characteristic	Ca Mau	Cai Nuoc	Dam Doi	Nam Can	NT U Minh	Song Doc	Tran Van Thoi	Thoi Binh	U Minh	Vien An Dong	Average
Amount of Rainfall (mm)											
Average	2378	2148	1932	2329	2455	2353	2237	2363	2428	2149	2247
Median	2304	2115	1893	2250	2415	2381	2180	2336	2429	2114	2199
Max	3549	3151	2516	2964	3258	3406	3306	2885	3291	3385	2906
Min	1932	1554	1408	1781	1894	1695	1542	2014	1668	1024	1908
Standard deviation	306	365	314	316	365	359	381	252	360	467	236
Cv	0.13	0.17	0.16	0.14	0.15	0.15	0.17	0.11	0.15	0.22	0.11
Cs	0.72	0.28	0.37	0.75	0.33	0.23	0.45	0.32	0.01	0.22	1.43
Continuous days without rain (days)											
Average	77	96	107	101	87	84	86	82	82	108	91
Median	62	81	113	101	78	79	78	72	68	96	83
Max	153	174	171	187	162	150	158	138	171	185	141
Min	23	35	32	34	18	29	30	30	21	29	39
Standard deviation	39	45	38	44	41	38	36	36	41	39	33
Cv	0.50	0.47	0.36	0.43	0.47	0.45	0.42	0.43	0.50	0.36	0.36
Cs	1.18	1.03	0.46	0.02	0.64	0.36	0.69	0.83	1.05	0.90	0.78

The average annual rainfall in Ca Mau is 2247 mm/year and has remained stable over the years. With a natural area of 5242.5 km^2, the total rainfall in Ca Mau amounts to 11.78 billion m^3/year. The total population of Ca Mau in 2019 was 1,194,476 people, resulting in over 9600 m^3 of rainfall per person per year, which is close to the average in Vietnam (9434 m^3/person) and significantly higher than the average in Southeast Asian countries (4900 m^3/person) [45]. Even in the year with the least rainfall (1908 mm/year), there was still over 10 billion m^3 of rainfall (8158 m^3/person). This amount is 6.60 times higher than the total freshwater demand in Ca Mau [46]. The coefficient of variation (C_v) is low (0.11 to 0.22), indicating relatively stable annual rainfall in the province. Although we did not calculate the above values considering the impact factor of climate change, our results imply that climate change did not have much influence on the total rainfall amount, excluding the changes in rainfall patterns [9].

The average greatest number of consecutive rainless days or days with less than 5 mm of rainfall (NRY) across the entire province is 91 days (with a deviation of 33 days). The station with the shortest NRY is Ca Mau with 77 days, while the longest is Vien An Dong with 108 days. The coefficient of variation (C_v) is relatively high (0.36 to 0.50), indicating significant fluctuations in the NRY over time. The difference between the highest and lowest NRY values is substantial.

Overall, in the research area, the amount of rainfall can meet usage needs, but the challenge lies in the large and unstable NRY. The instability of the NRY makes it difficult to determine the required storage tank capacity.

3.2.2. Potential of Rainfall Harvesting

Table 2 shows that the amount of rainfall collected from existing rooftops can fully meet the water usage needs for household purposes in rural areas under the current conditions (60 L/person-day) as well as in the 2030 planning scenario (80 L/person-day) following Decision No. 2140/QD-TTg signed in 2016 by the Vietnam Prime Minister [47].

Table 2. Rainfall harvesting availability and requirement of tank volume based on current capacity of catchment roofs.

Station / Capacity	Ca Mau	Cai Nuoc	Dam Doi	Nam Can	NT U Minh	Song Doc	Thoi Binh	Tran Van Thoi	U Minh	Vien An Dong
Rainfall availability for harvesting (L/person-day)	130.0	113.3	106.5	110.7	127.5	114.9	130.1	125.1	134.0	122.8
Tank volume required (m^3)	68.3	43.9	63.3	33.2	33.2	47.9	44.6	49.8	42.8	75.9

The potential for rainwater harvesting can be expanded by increasing the roof catchment area. This expansion is achievable through various means: (i) repurposing the roofs of water storage tanks as additional catchment areas; (ii) installing awnings or canopies to extend the catchment surface; and (iii) utilizing mobile awnings for water collection. Consequently, the ability to increase rainwater harvesting is still possible. However, a significant obstacle to rainwater harvesting is the demand for large storage tank capacities (33.2–75.9 m^3 per household). The survey data indicate that the average storage tank capacity is 2.56 m^3 per household, corresponding to 0.64–0.85 m^3 per person, which is too small compared to the required capacity. Our results imply a positive policy change in rainwater harvesting for not only the VMD but also for any nation that encourages people to collect rainwater for storage through all means and provides robust programs for collecting rainwater at a larger scale for rural communities, especially those that have been strongly impacted by droughts and salinity intrusion.

3.3. Scale Requirements for Storage Tanks and Roof Catchments for Rainwater Harvesting Systems

3.3.1. Storage Tank and Roof Catchment Requirements for Different Water Supply Levels

Figure 7 illustrates the requirements for the storage tank capacity and roof catchment area to meet water supply needs. At the level of water demand for drinking, the requirements for the roof catchment area and storage tank capacity are very low, averaging 0.78 m^3 per tank and 1.27 m^2 for a demand of 5 L/person-day. With an average storage tank capacity of 2.56 m^3 per household (averaging 3–4 persons per household), rainwater harvesting can meet drinking water needs.

To ensure water supply for other basic needs such as basic sanitation and food and utensil washing, with a demand of about 15 L/person-day, the required storage tank capacity is 3.1 m^3 per person, averaging 9–12 m^3 per household. These types of tanks are typically made of concrete, with a cost of approximately 1–1.2 million VND per m^3 (equivalent to USD 40—45), a cost that is acceptable for households with moderate incomes. The roof catchment area requirement for cases exceeding 15 L/person-day is still relatively low, at only 3.58 m^2 per person, which is much smaller than the existing roof catchment area.

The existing roof catchment area of 21.4 m^2 per person can meet water supply demands, exceeding 80 L/person-day. This indicates that people do not currently need to increase their roof catchment areas for rainwater harvesting. However, to meet the demand for 80 L/person-day, a very large storage tank capacity is required, around 16 m^3 per person, corresponding to 48–64 m^3 per household. When following traditional solutions, many households cannot afford this.

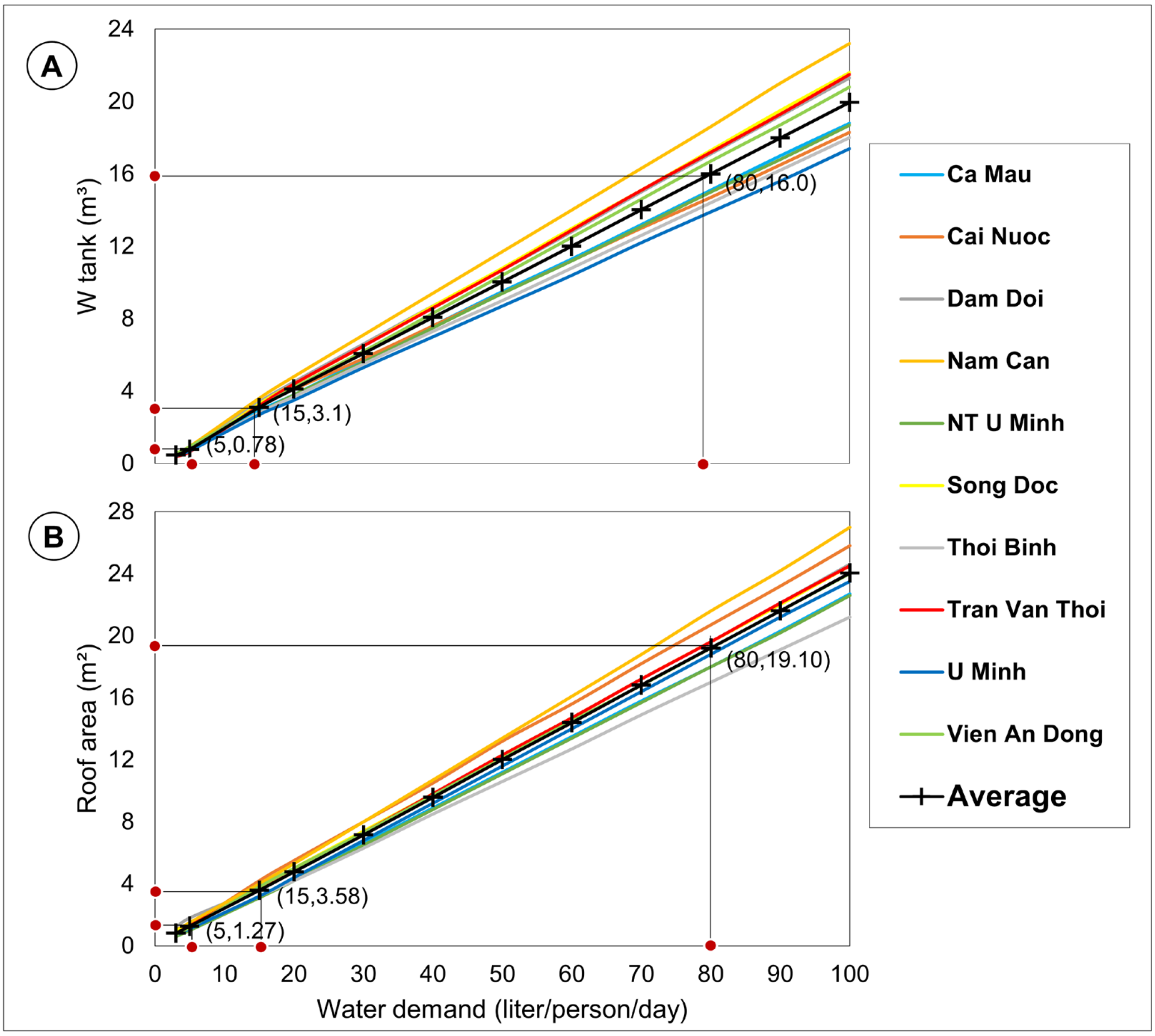

Figure 7. The requirement for the tank capacity (**A**) and the rainfall catchment area (**B**) to meet the water supply needs calculated based on the rainfall of 10 meteorological stations. The values from the red dots are the averages from 10 stations.

In general, the main difficulty is the requirement for large storage tank capacities in rainwater harvesting. Increasing storage tank capacities for rainwater use may present several obstacles, such as community needs, budget constraints, and space requirements for installation. The current average storage tank capacity only meets the water demand for drinking purposes at 5 L/person-day. However, a survey conducted in 2020 showed that about 5% of households have storage tank capacities ranging from 5 to 10 m^3, and 1% have capacities exceeding 10 m^3, which could enable rainwater harvesting to meet demands of 7 to 15 L/person-day. Therefore, rainwater harvesting systems should be divided into two types, respectively: (i) Rainwater harvesting for essential needs (maximum demand of 15 L/person-day), which requires a separate catchment area that is easy to clean to ensure high-quality water collection. Traditional storage tanks should be used, minimizing the risk of contamination during storage. (ii) Rainwater harvesting for additional needs (45 to 65 L/person-day) that utilizes all types of catchment areas and may involve improved storage tanks in the form of excavated ponds combined with waterproofing materials such as waterproof membranes. This is considered a long-term solution for rainwater harvesting systems, such as the Pond Harvesting System (PHS) and MAR, which are practiced in many countries [45].

One of the major reasons for reluctance to increase rainwater harvesting is that residents only perceive the need for enough water for drinking and cooking. Therefore, there is a need for awareness campaigns to encourage residents to increase their use of rainwater for other purposes. Additionally, there should be financial and technical support measures provided to help people increase their storage tank capacities.

3.3.2. Storage Tank Scale Required to Meet Basic Household Needs in the Dry and Rainy Seasons

The results indicate that the average storage tank capacity requirement is 2.4 m^3 per person, equivalent to 7.2–9.6 m^3 per household, to meet the essential water needs (Table 3). Increasing the demand to 80 L/person-day during the rainy season and 15 L/person-day during the dry season, the storage tank capacity requirement becomes 3.3 m^3 per person, equivalent to 10–13 m^3 per household. At these scales, residents are more likely to accept increasing the scale of rainwater harvesting. In reality, 6% of households already have storage tank capacities that can meet this demand. Hence, costs should be carefully analyzed to increase the possibility and willingness of residents to upscale their tanks under an integrated rainfall harvesting system, although the technical and social benefits are pointed out by our study. To make this level of storage tank more widely accepted and further disseminated, additional support from the government as well as various social organizations is needed in various forms, such as loans and capital subsidies for impoverished households.

Table 3. Tank volume required to meet essential water demand during the dry season and sufficient supply during the rainy season—the whole time series (holistic) regulation method (m^3/person).

Water Demand (Liter/Person/Day)	**15**	**30**	**60**	**80**	**100**
Station					
Ca Mau	2.5	3.0	3.4	3.5	3.6
Cai Nuoc	2.4	3.0	3.3	3.4	3.4
Dam Doi	2.9	3.4	3.8	3.9	4.0
Nam Can	2.8	3.3	3.6	3.7	3.8
NT U Minh	2.3	2.9	3.2	3.3	3.4
Song Doc	2.1	2.5	2.9	2.9	2.9
Thoi Binh	2.2	2.7	2.9	3.0	3.1
Tran Van Thoi	2.0	2.4	2.8	2.9	2.9
U Minh	2.1	2.5	2.9	3.0	3.0
Vien An Dong	2.8	3.3	3.6	3.8	3.8
Average	2.4	2.9	3.2	3.3	3.4

3.4. Integration of Rainwater Harvesting with Groundwater Usage and the Potential for Artificial Groundwater Recharge

This scenario is a promising solution which needs to be evaluated in terms of technical, economic, and social aspects. Building upon this, we technically examined the following: (i) the rainwater harvesting potential at different storage tank scales; (ii) the additional groundwater extraction required to meet the shortfall; and (iii) the potential use of surplus rainwater in the rainwater harvesting system to replenish groundwater. Specifically, the existing storage tank scales (0.8 m^3 per person), a storage tank meeting basic needs (2.4 m^3 per person), and a storage tank meeting maximum needs (3.4 m^3 per person) were analyzed. The excess water discharge, harvested rainwater, additional groundwater extraction needed, and rainwater available for groundwater replenishment were calculated for each scenario (Table 4).

Table 4. Synthesis of calculation results for tank scales (m^3/year).

Characteristic	Excess Rainfall Runoff			Rainwater Harvesting Volume			Groundwater Extraction Volume			Artificial Groundwater Recharge Volume		
Tank Volume (m^3)	0.8	2.4	3.4	0.8	2.4	3.4	0.8	2.4	3.4	0.8	2.4	3.4
Station												
Ca Mau	12.5	2.9	1.5	15.1	19.6	20.8	13.6	9.4	6.8	15.1	20.2	20.3
Cai Nuoc	12.8	3.4	1.8	13.0	17.6	18.6	15.8	11.4	11.2	13.4	18.2	18.7
Dam Doi	9.1	1.8	1.0	13.0	17.4	18.4	15.9	11.8	12.4	12.9	15.8	15.6
Nam Can	11.5	2.8	1.6	13.3	18.1	19.2	15.5	11.0	10.8	12.9	16.7	16.8
NT U Minh	14.8	3.6	1.6	14.8	18.9	20.4	14.0	10.2	8.0	15.5	22.6	23.1
Song Doc	11.2	2.4	1.2	13.4	18.3	19.6	15.3	10.7	12.4	12.6	16.5	16.4
Thoi Binh	13.1	2.6	1.1	14.6	19.5	20.7	14.2	9.6	11.2	15.4	21.1	21.4
Tran Van Thoi	11.8	2.5	1.1	13.8	18.5	19.7	15.0	10.5	9.6	14.5	19.0	19.2
U Minh	16.0	4.3	2.2	14.4	19.4	21.0	14.4	9.7	10.0	15.1	21.9	22.3
Vien An Dong	9.2	2.6	1.4	14.2	17.8	18.7	14.7	11.4	9.6	15.5	18.5	18.8
Average	12.2	2.9	1.5	14.0	18.5	19.7	14.8	10.6	10.2	14.3	19.0	19.3

In the case of the existing storage tank scale (0.8 m^3 per person), an average of 14 m^3 of rainwater is harvested, requiring 14.8 m^3 of additional groundwater extraction. Approximately 14.3 m^3 of rainwater can be used to replenish the groundwater, while the surplus rainwater amounts to 12.2 m^3 discharged into the environment. Overall, the integrated water usage solution has proven highly effective. Rainwater can meet more than 48% of the water demand, and the surplus rainwater available for groundwater replenishment is nearly equal to the additional groundwater extraction needed. This case demonstrates high efficiency under current conditions, but a limitation is the significant amount of surplus rainwater discharged into the environment. Additionally, the essential water supply needs to rely on groundwater of low quality during the dry season. Overall, this solution is beneficial for households lacking space to increase the scale of their storage tanks.

In the case of a storage tank capacity of 2.4 m^3 per person on average, approximately 18.5 m^3 of rainwater is harvested, requiring 10.6 m^3 of additional groundwater extraction. About 19.0 m^3 of rainwater can be used to replenish the groundwater, while the surplus rainwater amounts to 2.9 m^3 discharged into the environment. The harvested rainwater can meet 64% of the water demand, and the surplus rainwater available for groundwater replenishment is more than 1.79 times the additional groundwater extraction needed. The amount of surplus rainwater discharged into the environment is relatively small. These results indicate that this solution is highly effective and economically sustainable, representing a step towards achieving water self-sufficiency in rural areas.

In the case of maximum storage tank capacity (3.4 m^3 per person on average), approximately 19.7 m^3 of rainwater is harvested, corresponding to 10.2 m^3 of additional groundwater extraction. About 19.3 m^3 of rainwater can be used to replenish the groundwater, resulting in only 1.5 m^3 of surplus rainwater being discharged into the environment. This scenario is efficient in terms of utilizing rainwater and increasing the surplus rainwater available for groundwater replenishment while reducing the amount of additional groundwater needed. However, a storage tank capacity ranging from 2.4 to 3.4 m^3 per person is deemed appropriate because increasing the scale further does not enhance efficiency.

The scenario/method of integrating rainwater and groundwater has been implemented and tested by a research group at Tri Phai Primary School in Tri Phai commune, Thoi Binh district of Ca Mau Province. The system, which is illustrated in Figure 2, consists of two storage tanks with a capacity of 25 m^3 each, totaling 50 m^3, and a roof catchment area of 200 m^2. The groundwater extraction is conducted via a 49 mm diameter well reaching the Pleistocene aquifer at a depth of 100 m. This system provides water for the school and its

600 students. During the rainy season, the system adequately supplies water for the school. In the dry season, the system only provides drinking water for students (after treatment), while other needs such as sanitation and irrigation are met from the groundwater source. The flow rate of groundwater extraction reaches 900 L/h, and during the rainy season of 2022, the amount of extracted groundwater was 215 m^3, with no observed overflow from the system. The system considers rainwater as the primary water source prioritized for maximum utilization. Groundwater serves as a reserve source used in cases of water shortage, particularly during the dry season and drought years.

4. Conclusions

Millions of residents in the Vietnamese Mekong Delta (VMD), especially in Ca Mau Province, have relied on various water sources ingrained in their culture. Despite ample rainfall, efficient rainwater harvesting in Ca Mau falls short of meeting demands due to inadequate storage capacity and challenges like low awareness, high construction costs, and limited space. Our study uses data from 10 meteorological stations and interviews with 200 households to propose a sustainable water harvesting scenario. Emphasizing rainwater's importance, especially during dry periods, we stress the need to maintain large tank capacities for effective harvesting. Additionally, we advocate for integrating rainwater and groundwater systems to enhance water resource management and self-sufficiency. Based on the findings, two main conclusions are drawn:

- To satisfy the basic water supply requirement (15 L/person-day) from rainwater, each person needs an average tank capacity of 3.1 m^3 and a roof catchment area of 3.6 m^2. The roof catchment area requirement is not overly large but allows for adaptive operation and maintenance to ensure the harvesting of good-quality rainwater. In the scenario where all available roof catchment areas are utilized, a tank capacity of 2.4 m^3 per person can meet the basic water supply demand, and approximately 6% of households have achieved this. The scenario of utilizing rainwater entirely during the rainy season and meeting basic needs during the dry season demonstrates that the demand of 80 L/person-day during the rainy season and 15 L/person-day during the dry season can be met with a tank scale of 3.4 m^3 per person. These options could be flexibly selected for different areas with different economic conditions and water demands.
- The integrated water supply scenario of rain and groundwater demonstrates the highest effectiveness, even with the current rainwater tank size, nearly achieving water balance. At a tank scale of 2.4 m^3 per person, equivalent to 7.2 to 9.6 m^3 per household, 64% of rainwater can be utilized for domestic use. The supplementary artificial groundwater recharge exceeds the amount of groundwater extraction by 1.79 times, resulting in minimal surplus water discharge into the environment. The artificial groundwater recharge system is relatively simple and not expensive, involving the addition of inverted U-shaped structures and the adaptation of groundwater extraction wells to serve both extraction and recharge purposes. This approach offers sustainability and potential water independence across rural areas of the VMD. However, many challenges exist, such as the willingness of people and financial constraints, especially for the poor, to apply or transform this approach, which may prolong its widespread acceptance. This approach can also be applied in urban areas, directly saving water costs and indirectly mitigating urban flooding while replenishing groundwater, but it needs strong support from local authorities via long-term official programs.

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