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Incorporating rainwater harvesting systems into the design of green infrastructure, alongside constructed wetlands and fishponds

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Abstract
In rural areas grappling with recurring water scarcity during dry periods, the imperative for water conservation becomes evident. This research centers on Green Infrastructure (GI), showcasing its substantial potential for better water management practices, specifically in the realms of rainwater harvesting and greywater treatment. We implemented an integrated household-scale rainwater harvesting system (RWH) coupled with greywater processing using a constructed wetland (CW). The constructed wetland, filled with sands and gravels and adorned with Napier grass (Pennisetum purpureum), served as a filtration medium for both greywater and rainwater before channelling them into a fishpond. The project was conducted at the ITB research station in Haurngombong village, Pamulihan sub-district, Sumedang, West Java. The project exemplified an effective synergy between the RWH system and a constructed wetland for greywater treatment, benefiting both plant irrigation and fishpond utilization. The demonstrated approach holds significant potential added value for communities, serving as a reservoir for crop irrigation, supporting fish farming, and facilitating greywater treatment through an integrated aquaponic system.

Keywords:
Constructed Wetland;
Fish Pond;
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INTRODUCTION

In rural areas where water scarcity is a common issue during the dry season, especially in the absence of river irrigation canals and soils with high porosity, water conservation measures become imperative. Rainwater harvesting (RWH) is a practice that involves collecting run-off from impervious surfaces for later use. Traditionally, this includes gathering rain from roofs, which is directed through gutters into downspouts and then stored in various vessels. Rainwater collection systems range from simple rain barrels to elaborate cisterns capable of meeting the entire household demand [1].

RWH stands out as a promising alternative water source, as rainwater can be easily collected and utilized without extensive treatment for non-potable purposes. However, the economic feasibility of these systems is not always guaranteed [2].

Besides rainwater, people in rural areas also can obtain water from grey water. Grey water is defined as urban wastewater which includes water derived from baths, showers, hand basins, washing machines, dishwashers, and kitchen sinks while excluding effluents from toilets [3][4]. Grey water which is typically discharged into ditches, actually can be effectively repurposed by diverting it to constructed wetlands adorned with economically valuable plants like Napier grass (*Pennisetum purpureum*), a valuable feed source for cattle. This sustainable practice not only mitigates water wastage but also contributes to the cultivation of a valuable feed source for cattle.

The focus of this research is on Green Infrastructure (GI) which holds significant potential in transforming water management practices, particularly in the areas of rainwater or stormwater management and wastewater treatment. Addressing stormwater runoff is a key concern in contemporary urban environments. This occurs when domestic/municipal wastewater, urban runoff, and stormwater are all directed into the same pipe network, ultimately leading to an end-of-the-pipe centralized wastewater treatment plant. The introduction of GI in this context can offer a modern perspective and valuable solutions to enhance water management practices [5, 6, 7].

Research on GI and Buildings in Indonesia is limited. GI involves environmentally friendly infrastructure through spatial planning. It encompasses both natural systems and engineered solutions designed with conservation principles to provide functions and benefits for human life. The core of this concept emphasizes multifunctionality, sustainability, and resource efficiency by integrating diverse natural environmental features [8].

Since climate change is expected to worsen these events, the incorporation of GI holds the promise of strategically utilizing diverse ecosystem services. Consequently, this approach can more efficiently mitigate the negative impacts of climate change in urban areas [9].

Green buildings encompass various stages including design, construction, and operation, focusing on conserving resources such as energy, land, water, and materials. They aim to reduce pollution, protect the environment, and create indoor spaces that promote health and comfort for occupants [10, 11, 12].

The illustration in Figure 1 depicts a comprehensive rainwater collection system. While certain components displayed are essential, not all the listed elements are obligatory. Nevertheless, incorporating all these components contributes to the development of a highly efficient and nearly maintenance-free harvesting system.

Rainwater that is not stored in the RWH can be utilized in constructed wetlands (CWs). In the past few decades, various types of water, including stormwater, polluted river water, urban runoff, mine drainage, industrial effluent, domestic sewage, and agricultural wastewater have all been treated extensively using CWs, a green treatment technology that resembles natural wetlands [13, 14, 15].

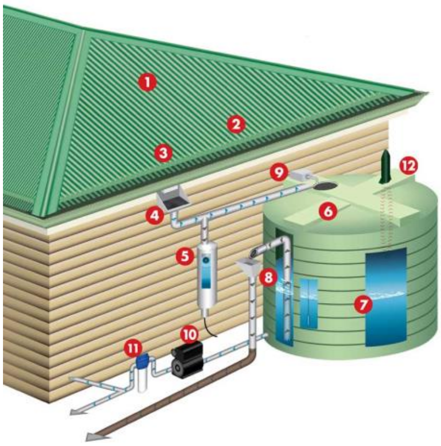

Figure 1. A comprehensive rainwater collection system.

Notes: 1. Roof Surface, 2. Gutter Protection Screening, 3. Gutter., 4. Rain Head, 5. A First-Flush Diverter, 6. Tank Screen, 7. Rainwater Tank, 8. Insect Proof Flap Valve, 9. Auto-Fill System, 10. Pump System, 11. Irrigation Filter, 12.A Water Level Indicator [9].

In urban and peri-urban areas, the application of constructed wetlands (CWs) for stormwater management is both feasible and promising [16, 17].

Presently, ongoing research is focused on evaluating diverse treatment technologies to pinpoint those demonstrating the utmost effectiveness. Among these, constructed wetlands (CWs) emerge as one of the most promising solutions [18].

This paper explores the integration of a rainwater collection system with greywater processing in CWs and fishponds, on a household scale. The plant used for the phytoremediation process is Napier grass (*Pennisetum purpureum*). The project, was conducted at the ITB research station in Haurngombong village, Pamulihan sub-district, Sumedang district.

METHOD

In this study, we built two RWH systems, the first system (RWH-1) captured rainwater from one wooden house and integrated it with two CWs and a fishpond. In the second system (RWH-2) rainwater was captured from two green houses and one office building. Besides that, we also created an aquaponic system in fishpond of RWH-2.

Materials

The materials used in this work are building materials which include: sands, cements, gravels, bricks, iron rods, PVC pipes and gutters. For hydroponic installation we also used a water pump.

RWH-1 Installation

In this project, an RWH model was constructed in a wooden house. In this house, the roof's cross-sectional area measures 70 m^2, and the gutter's total length spans 20 m (Figure 2). The system channels the rainwater into two plastic drums with a combined volume of 400 liters. Each plastic drum is equipped with a water faucet at the bottom, facilitating convenient utilization of the stored water [16].

CWs with Napier Grass and a fishpond

The CWs consist of CW-1 and CW-2, were built to treat grey water and also received water from RWH-1. Both CWs were constructed with bricks and cement. The depth and slope of excavation of the CWs and fishponds have considered the type of soils and their consistency (shear strength) to produce stable excavated CWs. Napier Grass, commonly cultivated as animal feed, is planted in both wetlands, initially comprising 100 clumps each (Figure 3).

The fishpond is 6 m wide, 7 m long, and has a depth of 1.2 m (Figure 4). It is equipped with an input channel directly connected to CW-2. The water entering this fishpond has undergone a filtering process in CW-1 and CW-2, ensuring that it is sufficiently safe for fish farming or for use in watering plants. This integration of a filtering process contributes to maintaining water quality within the fishpond.

RWH-2 Installation

The RWH-2 installation covering water catchment area from two greenhouses (GH-1 and GH-2) and one office building with a pond as rainwater storage (Figure 5). The size of the pond is 10 x 8 x 1.5 m^3. This system was completely separated from RWH-1 system.

Figure 2. A design of harvested rainwater (RWH-1) with collecting drums at a wooden house. The water also channeled to CW-1, CW-2 and a fishpond

Figure 3. Technical design of a tiered constructed wetlands (CWs) with a fishpond. The source of the water is from rainwater and grey water

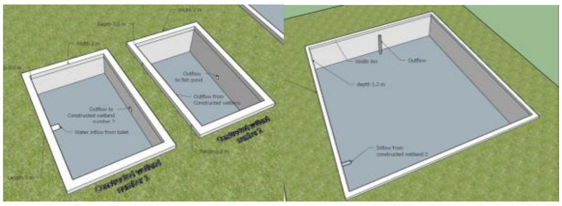

Figure 4. Dimensions of CW-1, CW-2, and a Fishpond

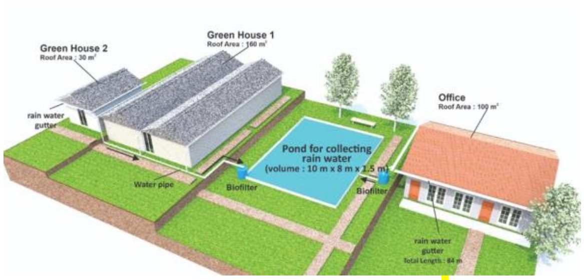

Figure 5. RWH-2 installation [16]

Aquaponic models related to ponds

The rainwater reservoir was equipped with a hydroponic system employing a series of PVC pipes. PVC frames are affixed to light steel racks. An electric pump facilitates the conveyance of pool water into parallel pipes on each level, ensuring uniform distribution of water and nutrients (Figure 6)

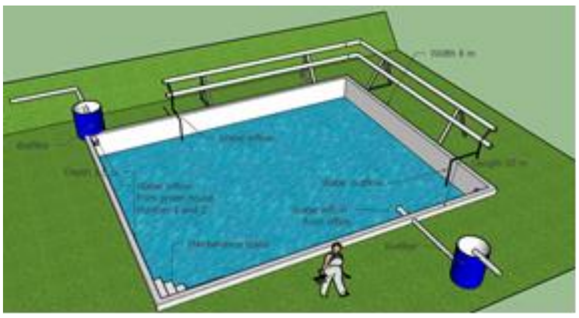

Figure 6. Technical Design of a RWH Pond with a Hydroponic System

RESULTS AND DISCUSSION

RWH Installation

The RWH-1 system integrated into the wooden house. Any surplus discharge triggers an automatic redirection of water. This excess water seamlessly flows through pipes into a tiered CWs situated in front of the wooden house, serving as wastewater treatment ponds (Figure 7).

Constructed wetlands with Napier Grass and fishpond.

Constructed wetlands come in various types, and one notable design criterion is the method of water flow, such as the constructed wetland with subsurface flow. Due to their low cost-energy consumption, simple use, and superior performance, subsurface flow constructed wetlands (SSCWs), which are artificial systems planted with aquatic macrophytes, are now recognized as an environmentally friendly and sustainable environmental biotechnology for a variety of wastewater treatments [21, 22, 23].

The construction of the tiered constructed wetlands serves the purpose of filtering wastewater (greywater) originating sourced from bathrooms, specifically addressing the soap used for washing or bathing. This filtration process is implemented before the water enters the holding pond, preventing contamination of the surrounding water or soil. It's important to highlight that black water is directed to the septic tank separately.

The incorporation of CW as filtering wastewater causes the constructed wetland as municipal wastewater, subsurface CW are frequently employed as secondary and tertiary treatment stages for domestic applications, serving individual houses or households as well as municipal purposes, catering to clusters of houses or community sewage treatment [24].

CW-1 and CW-2 share the same dimensions in terms of width and length, both measuring 2 m in width and 3 m in length. However, they differ in depth. CW-1 has a depth of 0.6 m, whereas CW-2 was 0.8 m.

Figure 7. Drums for collecting rain water in the wooden house

This intentional difference in depth facilitates the automatic flow of water from CW-1 to CW-2 within the system (Figure 8).

The CW-1 initiates the filtering process as the wastewater passes through a layer of gravel, followed by a layer of sand and plant roots. The filtered water then proceeds to the CW-2, undergoing a similar filtration process. Ultimately, the treated water flows into the fishpond, creating a comprehensive and environmentally conscious wastewater management system.

CWs operate based on natural materials and processes, involving interactions among essential system components: substrate media, plants, wastewater, and naturally occurring microorganisms. Because CWs limit the use of non-renewable materials like concrete and steel and instead rely on gravel, soil, and plants, they inherently hold significant in-country value [25].

In CW-1, there is an input channel that receives wastewater from the bathroom and runoff water from the rainwater storage barrel of the wooden house. Subsequently, the water exits through the output channel, directed towards CW-2. From CW-2, the water further exits through its output channel, ultimately reaching the fishpond. This systematic flow helps manage and treat the water as it progresses through the constructed wetland and subsequent pond.

The fish cultivated in the ponds include tilapia and nilem fish. To assist in waste management from the filtering processes in CW-1 and CW-2, water hyacinth is intentionally cultivated in the fishpond. This aquatic plant helps absorb remaining waste, contributing to water purification. Furthermore, the fishpond is outfitted with a water circulation system and a filter system that mirrors the design of the rainwater reservoir. This integrated system ensures effective water circulation and maintains the quality of water within the fishpond, creating a conducive environment for the cultivation of tilapia and nilem fish (Figure 9).

Figure 8. Tiered Constructed Wetland with napier grasses

Figure 9. The current constructed fishpond with floating water hyacinth

CWs designed for treating stormwater or addressing combined sewer overflow (CSO) primarily aim to capture and retain peak flows. This is accomplished by reducing the load of suspended solids through filtration and diminishing soluble and particulate pollutants via adsorption and biological degradation processes [26].

Aquaponic model related to pond

The availability of rainwater harvesting pond can not only be used to raise fish for consumption or recreation, but can also be used to irrigate plants either by conventional watering or by using a hydroponic system. The combination of aquaculture and hydroponic is known as aquaponic. Pipes for growing plants hydroponically (aquaponics) are placed on the edge of the pond (Figure 10). Water for growing plants is taken from the pond water using an electric pump.

The gutters have the capacity to accommodate a total of 120 plant individuals. This system is designed with the objective of harnessing nutrients derived from fish waste and residual feed present in the pond water, fostering a sustainable and integrated approach to plant cultivation.

RWH system is becoming more essential in the sustainable stormwater management toolkit [27]. However, a heightened focus on the environmental and life cycle impacts of this system [28] underscores the need for precise designs.

Figure 10. Pond with Hydroponic System

This imperative arises not only to minimize initial expenses but also to curtail the materials employed in system fabrication. Additionally, it aims to mitigate the costs and resource demands associated with system installation and maintenance [29].

The presence of CW suggests that this system also hold promise for enhancing urban water quality by effectively eliminating micro-pollutants such as pharmaceuticals, personal care products, antiseptics, and similar substances [30].

The installment of aquaponic system also play role in absorbing minerals in water, thus helping in cleaning the water. Another alternative approach involves utilizing CWs for the development of green roofs, which entails constructing roofs with a vegetated surface. Research indicates that this method can effectively control indoor temperatures, mitigate urban heat-island effects, serve as a carbon sink, and offer a variety of ecological services [31][32].

Another approach also to create floating island for treatment of grey water which can be installed in a variety of urban water bodies and ponds without necessitating substantial infrastructure. This makes them an efficient, sustainable, and cost-effective water purification solution, simultaneously fostering terrestrial and aquatic habitats for wildlife and augmenting ecological diversity [33, 34, 35].

Catchment Capacity of a Rainwater Storage System

Catchment capacity of our rainwater storage system can be calculated based on assumption that 1 mm of rainfall in an area of 1 m^2 is equivalent to 1 L of stored water, and the formula for roof catch capacity is [36]:

$$\textit{Roof capacity (L)} = \textit{rainfall level (mm) x roof surface area } (m^2) \quad (1)$$

The summary of calculation can be seen in the following Table 1. The average monthly rainfall in Pamulihan Sub- district (source: LAPAN, 2021, personal communication) is 123.6 mm per month. Meanwhile, for RWH-2, total roof area of system 2 is 56 m^2, and the roof catch capacity is 6,921.6 L/month. With the total volume of catchment ponds 49,200 L, the length of filling time is 7.1 months.

From two rainwater storage systems, we calculated water catchment area and length of filling time with simple operation. For RWH-1, total roof area of System 1 is 260 m^2. With average monthly rainfall 123.6 mm/month, the roof catch capacity is 32,136 L/month. With total volume of storage reservoir 120,000 L, the length of filling time is 3.7 months.

The highest rainfall in Sumedang is in January with an average rainfall of 267 mm per month, so the filling time is only 1.7 months at RWH-2 and 3.3 months on RWH-1 (Figure 11). During months with heavy rainfall, if the water is not used, it will surpass its storage capacity and be infiltrated into the soil of the surrounding area. While for six months (May to October) the rainfall is only below 100 mm per month, so RWH-1 cannot be fully charged, it will only be charged as much as 40% and on RWH-2 it will be loaded as much as 77%.

During the peak of the rainy season, the reservoir will be filled with water to its maximum capacity within 4 to 5 days. The total volume of this fishpond, if used to water plants on an area of 6x6 m², is enough to water the plants every day (morning and evening) for 3 months during the dry season. This is also the case for the first pond, without refilling.

For comparison, the calculations on Roof Top Rainwater Harvesting (RRWH) carried out by [38] calculated water available from roof with data from total roof area, average rainfall, and rooftop coefficient (Table 2). In that case, the rooftop coefficient used was 0.7, while in our case the rooftop coefficient was considered 1. The difference in coefficients is due to difference in sensitivity levels that depend on characteristic of gutter surface.

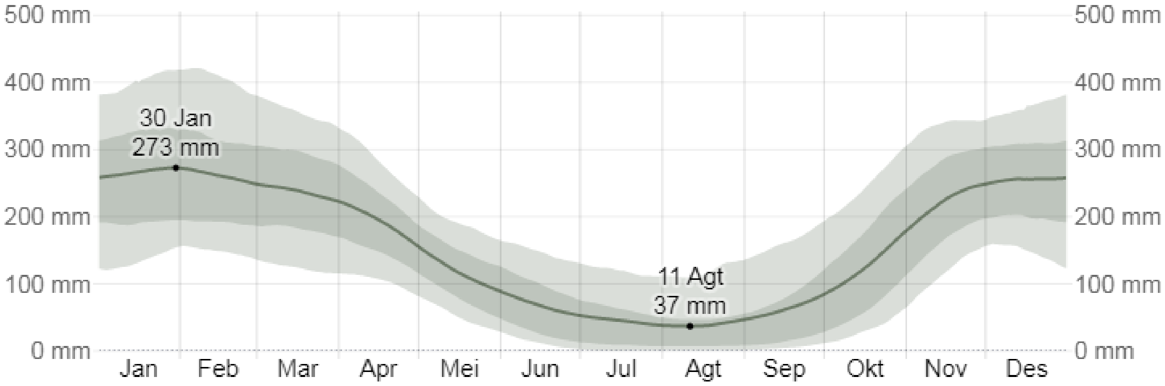

Figure 11. Average of Rainfall in Sumedang in a year. Source WeatherSpark.com [37]

Table. 1 Calculation for water catchment area at Rain water harvesting system at Haurngombong Farm

System	Installation	Size (m²)	Total Water Catchment Area (m²)	Roof catch capacity (L/month)	The size of Pond/ CW (m³)	Capacity of collected water (m³)	Length of filling time (months)
RWH-1	Wooden House Roof	8 x 7	56	6,921.6	CWs (3x2x0.5) + (3x2X0.7)	7.2	7.1
Total Roof area for RWH-1			56		Fishpond (7x6x1)	42	
						49.2	
RWH-2	GH-1 Roof	16 x 10	160	32,136	Fishpond 10 x 8 x 1.5	120	3.7
	GH-2 Roof	6 x 5	30				
	Office Roof	10 x 7	70				
Total Roof area for RWH-2			260				

Table 2. Calculated Area and Amount of Water [38]

No	Roof Name	Calculated Area (m2)	Water Available (W=Tx640x0.70) (Liters)	Tank Capacity (Liters)
1.	Park Prime Hotel	2027.23	908199.04	950000
2.	Hostel	714.75	320208	375000
3.	Collage	1923.64	861790.72	900000
4.	91 Mall	513.38	220004.24	275000
5.	House	598.5	268128	300000
6.	Hospital	794..42	355900.16	400000

CONCLUSION

There is diverse array of models for rainwater harvesting installations, spanning various combinations with fishpond, constructed wetlands, and aquaponic systems, each varying in scale. Based on the project conducted in the ITB garden in Haurngombong village, Sumedang, which focused on creating ponds, CW and installing RWH on a small scale and at a relatively low cost, there is great potential for communities to adopt and utilize this approach. This not only serves as a water reservoir for crop irrigation but also facilitates fish farming, grey water wastewater treatment, and integration with aquaponic systems. Encouragingly, community involvement in such projects could be significantly enhanced through financial assistance from the government, universities engaged in community service programs, or support from social institutions. This collaborative effort could promote sustainable water management practices and benefit both the community and the environment.

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