Community-Based Rainwater Harvesting in Intramontane Basins: An Inventory Approach for Sustainable Water Management

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Abstract

Intramontane basins filled with fluviolacustrine alluvium are often characterized by diverse wetland ecosystems, including ponds, swamps, paleo-channels, lakes, agricultural fields, and floodplains. The water quality in these areas varies significantly, influencing its suitability for domestic use and ecological sustainability. Due to the low availability of groundwater resources, community-based rainwater harvesting plays a crucial role in water management. Traditional and communal ponds, primarily used for rainwater storage, serve as vital water sources, particularly in non-porous alluvial terrains. This study proposes a rainwater harvesting model utilizing an inventory-based approach, incorporating a large community pond with provisions for replenishment from nearby water bodies such as rivers, streams, lakes, or channels. The model aims to enhance water availability for domestic consumption while ensuring sustainability in water-scarce regions.

Keywords: Rainwater harvesting, intramontane basin, alluvial plains, water quality, community pond.

Introduction

Access to safe and sufficient water for personal and domestic purposes is a fundamental human right, as emphasized by Yannopoulos et al. (2019). However, despite this recognition, nearly 40% of the global population continues to struggle with water scarcity, facing difficulties in securing an adequate supply to meet their daily needs (Henry et al., 2015). Water scarcity remains a pressing concern, particularly in developing and underdeveloped nations, where limited infrastructure and inadequate water management systems exacerbate the problem (Farook et al., 2006). Recognizing the critical importance of water accessibility, the United Nations included Clean Water and Sanitation as its sixth Sustainable Development Goal (SDG 6) in 2019, aiming to ensure the availability and sustainable management of water resources for all (UN, 2019). Nonetheless, even in developed countries, water conservation efforts, such as rainwater harvesting (RWH) and reuse, have been actively promoted through regulatory frameworks and policies as a means of enhancing water supply resilience (Raimondi et al., 2023).

Rainwater harvesting has emerged as a crucial component of sustainable water resource management, playing a pivotal role in improving water security and reducing dependence on traditional water sources (Aklan et al., 2023). The effectiveness of an RWH system is primarily determined by factors such as the storage capacity of the system, the catchment area, and the intensity and frequency of rainfall. Historically, one of the most prevalent traditional RWH techniques involved the utilization of ponds for water collection and storage. Ponds, as an alternative water supply system, have demonstrated significant potential in addressing water shortages, particularly in regions with erratic rainfall patterns (Zabidi et al., 2020). Areas situated within intramontane basins filled with alluvium of fluviolacustrine origin are particularly suitable for pond-based RWH systems. Such regions are often characterized by wetlands comprising ponds, swamps, paleo-channels, lakes, agricultural fields, and floodplains, which naturally facilitate water retention and storage (Zabidi et al., 2020).

Water resource management strategies often involve optimizing the utilization of available water bodies to maximize benefits while minimizing operational costs. In this context, inventory management principles can be applied to water storage and distribution systems to enhance efficiency (Dutta and Choudhury, 2017). An effective inventory system for water supply should incorporate mechanisms to maintain adequate stock levels in reservoirs, ensuring a consistent and uninterrupted supply of water to consumers. Consider a community pond of substantial size, designed with appropriate dimensions to capture and store a significant volume of rainwater and freshwater during both the rainy and dry seasons. If the pond is located in an intramontane basin with alluvial deposits, a well-structured water management system can be implemented to maintain the minimum required water levels. This can be achieved by integrating supplementary water sources such as nearby rivers, streams, and lakes through a dedicated supply system. The sustainability of such a system necessitates an economic model wherein revenue generated from individual households benefiting from the additional water supply is allocated to cover operational expenses. These expenses may include water purification costs, wages for maintenance personnel, utility costs, transportation charges, and the ongoing maintenance of the community pond. The water collection mechanism from external sources may be implemented through two primary methods: (i) direct pipeline connections between the pond and nearby water bodies, and (ii) transportation using water tankers equipped with pumps and necessary infrastructure.

In areas surrounding a community pond, numerous households stand to benefit from rainwater harvesting. Rainwater collected within the pond, along with rooftop harvesting by individual households, can supplement existing water supply systems to bridge the gap between the actual demand and the water provided by government or agency-operated supply schemes. While not all households may adopt rainwater harvesting techniques, those that do often utilize various storage tanks made from materials such as plastic, iron, cement concrete, earthenware, and rubber. Among these, plastic storage tanks are widely preferred due to their durability, ease of cleaning, portability, space efficiency, and resistance to seismic activities. A well-established estimation model suggests that one litre of water can be collected per square meter of catchment area under a 1 mm rainfall condition, illustrating the potential of large-scale rooftop rainwater harvesting in urban and rural settings. Despite various water supply schemes implemented by governments and public agencies, many fail to meet the total water demand for household and non-potable purposes throughout the year. Effective inventory management in water supply systems requires careful consideration of both holding and setup costs. Holding costs typically include expenses related to chemical treatment, labour wages, fuel, repair, and maintenance, whereas setup costs encompass initial investments in infrastructure, depreciation, and interest charges on capital investment.

Leakages in the Inventory System

One of the critical challenges in any inventory system is the occurrence of leakages, which refers to the loss of stored resources while the quality remains unchanged over a specified period. In water inventory systems, leakages can significantly impact operational efficiency by increasing minimum operational costs and reducing the optimal quantity available for distribution (Tomba and Geeta, 2008; 2010). Water leakage can arise due to poor maintenance, aging infrastructure, or inefficient distribution networks. Such losses ultimately affect the profitability and sustainability of water supply systems, necessitating periodic inspections and preventive measures to mitigate leakage-related inefficiencies. Moreover, water demand fluctuates depending on seasonal variations, weather conditions, and household usage patterns. Non-potable domestic water requirements, such as for washing, cleaning, and irrigation, tend to vary throughout the year. Consequently, ensuring a robust inventory system that accounts for these fluctuations is essential for maintaining an adequate and reliable water supply. By addressing issues related to water loss, optimizing storage capacity, and implementing sustainable water management practices, communities can work towards achieving long-term water security and resilience in the face of growing water challenges.

Methodology and Terminologies used:

The inventory model can be developed under two situations

(a) when there is sufficient rain ($k > r$) and

(b) when there is no rain or insufficient rain ($k \leq r$)

where k units per unit time and r units per unit time indicate the supply rate and the demand rate. Rainfall data of a particular area of study will show the availability of rainwater for harvesting during rainy season, dry and poor season etc.

Terminologies

i) C_1: Holding cost per unit per unit time.

ii) C_2: Shortage cost per unit per unit time.

iii) C_3: Set up cost per operational run.

iv) r : Average demand rate of water for domestic use in the area.

v) k: Supply rate of harvested rainwater (Random) or supplemented water (Discrete)

vi) r_1: Leakage rate (very small) assumed in the system

Other terminologies used in developing the model:

a) q: Quantity of rainwater harvested through the pond or supplementation of water from nearby water sources using a specific water supply system.

b) Q: Capacity of water in the community pond above the minimum water level.

c) N: Number of households having different members around the community pond for which regular water supply is to be ensured,

d) V: Storage capacity of the community pond having a specific length (l metres), breadth (b metres) and Depth (d metres) = (l* b*d) cubic metre

e) W: The Catchment area or rooftop space available near the Community Pond

f) C_r: Runoff coefficient (due to evaporation, absorption to the soil etc.)

First let us assume that shortages (C_2) are not allowed in the system. During rainy days, the supply of water in the community pond is random in nature i.e. depends upon rainfall phenomenon in the area of study. If the supply rate (rain water) is greater than the demand rate (k > r), the water level will increase until it reaches the maximum capacity, Q, the capacity of the pond excluding minimum level of water to be preserved in the community pond satisfying Q < V. Model formulation has been considered in two ways:(a) without the provision of leakages (b) with the provision of leakages.

Model Formulation under three situations

(i) Leakage occurs during supply period, time t_1 and demand period, time t_2.

(ii) Leakage occurs during time t_1 only.

(iii) Leakage occurs during time t_2 only.

Model 1: Leakage occurs during supply period, time t_1 and demand period, time t_2 but without shortages.

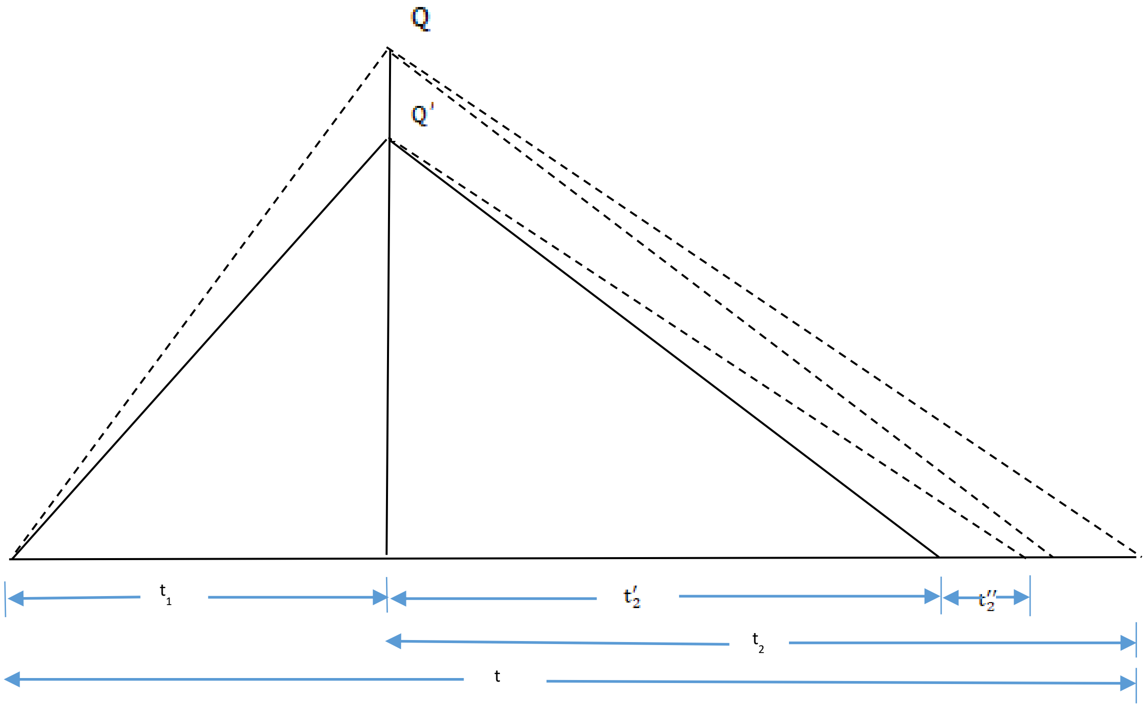

Figure 1: Involving leakage during time t_1 and t_2

Let us assume that shortages are not allowed in the system but leakage exists in the community pond or in the supply system. Let k (> r) be the rate of water harvested or supplied per unit time. The rainwater harvesting is random in nature, depending upon rainfall available in the specific area of study which is normally high in rainy days and low to very low during off season which gives two situations of (i) k > r when supply rate (rainfall) exceeds demand rate and (ii) k ≤ r when supply rate is less than or equal to demand rate.

If q is the amount of water supplied or harvested through the community pond, having specific size (length, breadth and depth) the collection/production will continue till the maximum capacity is achieved, (say) at time t_1.

Therefore, $q = kt_1$ and $q = r(t_1 + t_2) = rt$ [1]

where, $t = t_1 + t_2$ represents the operational run time

If Q is the water level (without leakage) at the moment of production/rainwater collection is completed,

then $Q = q - rt_1 = q - r\frac{q}{k} = q\left(1 - \frac{r}{k}\right)$ [2]

Holding cost per operational/production run = $C_1 \frac{1}{2} Qt = \frac{1}{2} C_1 q \left(1 - \frac{r}{k}\right)t$

Hence, the total cost per run of time t = $\frac{1}{2} q\, C_1 \left(1 - \frac{r}{k}\right)t + C_3$ [3]

∴ The total cost per unit time = $\frac{1}{2} C_1 q \left(1 - \frac{r}{k}\right) + C_3 \frac{r}{q}$ [4]

Let $r_1 > 0$ and $k - (r + r_1) > 0$. If Q' is the water level at the moment of the production/collection of rainwater is stopped (i.e. at the end of time t_1 with leakage).

Then $Q' = q - (r + r_1)\, t_1 = q\left(1 - \frac{r + r_1}{k}\right)$ [5]

Quantity lost due to leakage in time $t_1 = Q - Q' = r_1 t_1 = \frac{q r_1}{k}$ [6]

If the leakage is not detected at the end of time t_1, then quantity Q' reduces to zero in time t_2' at a rate of $(r + r_1)$ units per unit time

$\therefore Q' = (r + r_1)\, t_2'$ where $t_2' < t_2$ [7]

i.e. $t_2' = \frac{q}{(r + r_1)}\left(1 - \frac{r + r_1}{k}\right)$ [8]

Again, if the leakage is detected at the end of time t_1, quantity Q' reduces to zero in time t_2'' at a rate of r units per unit time.

$\therefore Q' = r\, t_2''$ [9]

From [7] and [9], we get $(t_2'' - t_2')r = r_1 t_2'$

Quantity loss with leakage in time $t_2 = (t_2'' - t_2')r = \frac{q\, r_1}{r + r_1}\left(1 - \frac{r + r_1}{k}\right)$ [10]

∴ The total amount of quantity loss due to leakage in a run if the leakage is not detected at the end of time $t_1 = \frac{q\, r_1}{k} + \frac{q r_1}{r + r_1}\left(1 - \frac{r + r_1}{k}\right) = \frac{q\, r_1}{r + r_1}$ [11]

Actual quantity available = $q - \frac{q r_1}{r + r_1} = \frac{qr}{r + r_1}$ [12]

Additional cost (due to leakage) in time $t_1 = \frac{1}{2} C_1 (Q - Q') t_1 = \frac{1}{2} C_1\, r_1 \left(\frac{q}{k}\right)^2$ [13]

Additional cost with leakage in time $t_2 = \frac{1}{2} C_1 (t_2'' - t_2') Q' = \frac{1}{2} \frac{C_1\, r_1}{r\,(r + r_1)} q^2 \left(1 - \frac{r + r_1}{k}\right)^2$ [14]

Total additional cost in one run = $\frac{1}{2} C_1 r_1 \left(\frac{q}{k}\right)^2 + \frac{1}{2} \frac{C_1\, r_1}{r\,(r + r_1)} q^2 \left(1 - \frac{r + r_1}{k}\right)^2$ [15]

Total additional cost per unit time = $\frac{1}{2} \frac{C_1 r\, r_1 q}{k^2} + \frac{1}{2} \frac{C_1\, r_1 q}{(r + r_1)} \left(1 - \frac{r + r_1}{k}\right)^2$ [16]

Adding [4] and [16], we get the total cost per unit time

$$C(q) = \frac{1}{2} C_1 q \left(1 - \frac{r}{k}\right) + C_3 \frac{r}{q} + \frac{1}{2} \frac{C_1 r\, r_1 q}{k^2} + \frac{1}{2} \frac{C_1\, r_1 q}{(r + r_1)} \left(1 - \frac{r + r_1}{k}\right)^2 \quad [17]$$

For minimum value of $C(q)$, using $\frac{dC(q)}{dq} = 0$ and $\frac{d^2 C(q)}{dq^2} > 0$, we get

$$q^* = \left[\frac{2C_3\, r\, k^2 (r + r_1)}{C_1 k (r + r_1)(k - r) + C_1 r\, r_1 (r + r_1) + C_1\, r_1 (k - r - r_1)^2}\right]^{\frac{1}{2}},\ t^* = \frac{q^*}{r + r_1} \quad [18]$$

And minimum cost is given by

$$C_{min} = \frac{1}{2} C_1 q^* \left(1 - \frac{r}{k}\right) + C_3 \frac{r}{q^*} + \frac{1}{2} \frac{C_1 r\, r_1 q^*}{k^2} + \frac{1}{2} \frac{C_1\, r_1 q^*}{(r + r_1)} \left(1 - \frac{r + r_1}{k}\right)^2$$

∴ With leakage, the minimum cost increased.

If $r_1 \to 0$, then $q^* = \left[\frac{2C_3}{C_1}\left(\frac{r\,k}{k - r}\right)\right]^{\frac{1}{2}}$, $t^* = \frac{q^*}{r}$ and $C_{min} = \left[2C_1 C_3 r \left(1 - \frac{r}{k}\right)\right]^{\frac{1}{2}}$

Model II: Leakage occur during the supply period, time t_1 (without shortage)

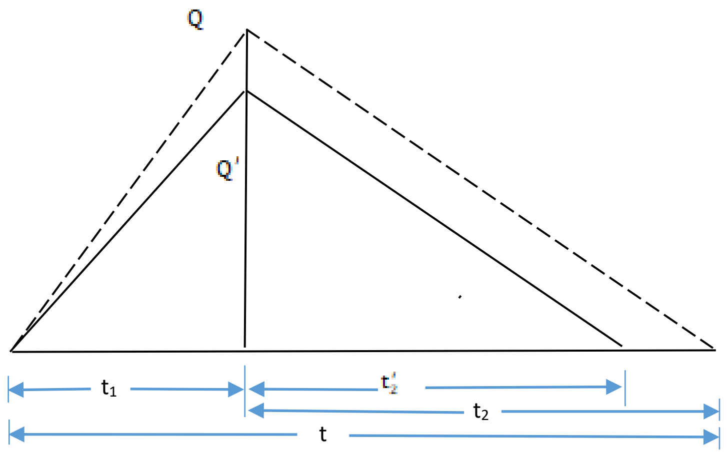

Figure-2: Involving leakage during time t_1 only

Here, the quantity q reduces to zero in time $(t_1 + t_2')$

And $(t_1 + t_2') = \frac{q}{k} + \frac{Q'}{r} = \frac{q(k-r_1)}{kr}$

Additional cost with leakage in time $t_1 = \frac{1}{2}(Q - Q')t_1C_1 = \frac{1}{2}C_1 r_1 \left(\frac{q}{k}\right)^2$

Since the leakage is detected at the end of time t_1

Therefore, total cost per unit time $C(q) = \frac{1}{2}C_1 q\left(1 - \frac{r}{k}\right) + C_3\frac{r}{q} + \frac{1}{2}\frac{C_1 r r_1 q}{k^2}$

For minimum value of $C(q)$, using $\frac{dC(q)}{dq} = 0$ and $\frac{d^2C(q)}{dq^2} > 0$, we obtain

$$q^* = \left[\frac{2C_3 r k^2}{C_1(k^2 - kr + r r_1)}\right]^{\frac{1}{2}}, \qquad t^* = \frac{q^*(k-r_1)}{kr} \text{ and } C_{min} = \frac{1}{k}\left[2C_1C_3 r(k^2 - kr + r r_1)\right]^{\frac{1}{2}}$$

If $r_1 \to 0$, then $q^* = \left[\frac{2C_3}{C_1}\left(\frac{rk}{k-r}\right)\right]^{\frac{1}{2}}$, $t^* = \frac{q^*}{r}$ and $C_{min} = \left[2C_1C_3r\left(1 - \frac{r}{k}\right)\right]^{\frac{1}{2}}$

Model-III: Leakages occur after supply period, time t_1 (without shortage)

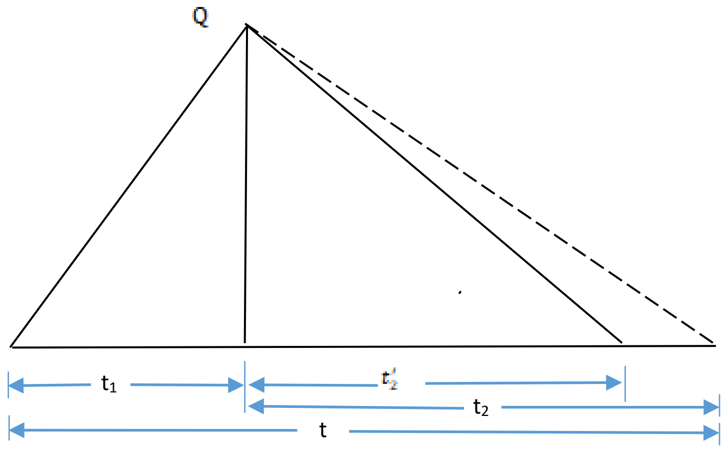

Figure-3: Involving leakage during time t_2 only

Here the quantity q reduces to zero in time ($t_1 + t'_2$) as shown in figure-3.

And $t_1 + t'_2 = \frac{q(k+r_1)}{k(r+r_1)}$

Additional cost in time $t_2 = \frac{1}{2} C_1 (t_2 - t'_2) Q = \frac{1}{2} C_1 (t_2 - t'_2) q \left(1 - \frac{r}{k}\right)$

Now, $t_2 - t'_2 = \frac{q\, r_1 (k-r)}{rk(r+r_1)}$

Therefore, additional cost in time $t_2 = \frac{1}{2} \frac{C_1\, r_1 (k-r)^2}{r(r+r_1)} \left(\frac{q}{k}\right)^2$

Total cost per unit time $C(q) = \frac{1}{2} C_1 q \left(1 - \frac{r}{k}\right) + C_3 \frac{r}{q} + \frac{1}{2} \frac{C_1 r_1 q (k-r)^2}{k^2 (r+r_1)}$

For minimum value of $C(q)$, using $\frac{dC(q)}{dq} = 0$ and $\frac{d^2 C(q)}{dq^2} > 0$, we get

$$q^* = \left[\frac{2C_3\, r\, k^2 (r+r_1)}{C_1 (k-r)\{k(r+r_1) + r_1 (k-r)\}}\right]^{\frac{1}{2}}, \qquad t^* = \frac{q^*(k+r_1)}{k(r+r_1)}$$

And $C_{min} = \frac{1}{k}\left[\frac{2C_1\, C_3\, r\,(k-r)(kr + 2k\, r_1 - r r_1)}{r + r_1}\right]^{\frac{1}{2}}$

If $r_1 \rightarrow 0$, then $q^* = \left[\frac{2C_3}{C_1}\left(\frac{r\,k}{k-r}\right)\right]^{\frac{1}{2}}$, $t^* = \frac{q^*}{r}$ and $C_{min} = \left[2C_1 C_3 r \left(1 - \frac{r}{k}\right)\right]^{\frac{1}{2}}$

Special Condition for k ≤ r: When the rainfall (supply) rate is less than or equal to the demand rate (k ≤ r), filling of fresh water from the nearby river or stream or channel should be made so as to maintain the minimum water level in the community pond.

The situation gives $t_1 \rightarrow 0$ and $t_2 \rightarrow t$ as such the quantity q (or Q) reduced to zero in time t.

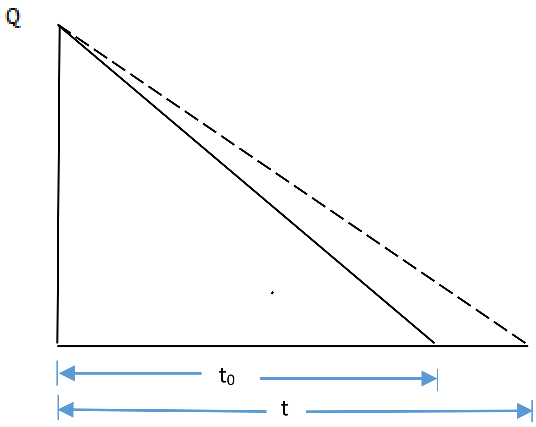

Figure-4: Involving leakage with no or very low less rainfall

Now, average total cost $= \frac{1}{2} C_1 q + \frac{C_3}{t} = \frac{1}{2} C_1 q + \frac{C_3 r}{q}$

If $r_1 > 0$, then q reduces to zero in time t_0 $(t_0 < t)$

therefore $q = (r + r_1) t_0$

Now, $r t - (r + r_1) t_0 = 0$ i.e $t - t_0 = \frac{r_1 q}{r(r + r_1)}$

Average additional cost incurred $= \frac{1}{2} (t - t_o) C_1 q \frac{1}{t} = \frac{1}{2} \frac{C_1 r_1 q}{r + r_1}$

Therefore, total average cost $(C) = \frac{1}{2} C_1 q + \frac{C_3 r}{q} + \frac{1}{2} \frac{C_1 r_1 q}{r + r_1}$

For finding the minimum value of C, using $\frac{dC}{dq} = 0$ and $\frac{d^2C}{dq^2} > 0$, we get

$q^* = \left[\frac{2C_3 r (r + r_1)}{C_1 (r + 2r_1)}\right]^{\frac{1}{2}}$, $t^* = \frac{q^*}{r + r_1}$ and minimum cost, $C_{min} = \left[\frac{2C_1 C_3 r (r + 2r_1)}{r + r_1}\right]^{\frac{1}{2}}$

If $r_1 \rightarrow 0$, then $q^* = \left[\frac{2C_3 r}{C_1}\right]^{\frac{1}{2}}$, $t^* = \frac{q^*}{r}$ and $C_{min} = [2C_1 C_3 r]^{\frac{1}{2}}$

This represents the general model.

Thus, when k ≤ r, the water level will not be raised and therefore need to be supplied using the device, installed for the plan. The holding cost consist of chemicals cost, labour charges, fuel expenses, repair and maintenance etc. while the setup cost should have the provisions of depreciation and interest charges on fixed assets.

Illustrated Example; Study area and Calculation Procedure:

Study area: The valley areas of Manipur (a state of India) cover with alluvial soil where underground water and tube well facility is not available successfully. Rainwater harvesting is done in most of the community ponds constructed from time to time by the then kings of Manipur or the Government of Manipur. Though sufficient rainfall is received in the valley areas of Manipur during monsoon season, water flows down through the rivers of Imphal, Iril, Nambul, Thoubal, Kongba, Maklang etc. leading to bigger rivers on its way to the sea or ocean. Rainfall in Manipur valley is normally above 180 mm per month from May to September of every year. Dry season in this area is from October to April normally. Average rainfall data (in mm) for the last 10 years (2012-2021) as recorded by ICAR, Lamphelpat, Imphal West District of Manipur is shown in table 1 below:

Minimum average rainfall during rainy season is 180mm per month. Water available in the nearby river, lake, and stream are found to be fresh and suitable for human consumption as well as flora and fauna ecology (Laishram and Kshetrimayum, 2018).

Table 1: Monthly Rainfall (in mm) in Imphal West District, Manipur

Mth/ Yr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2012	26.4	6.00	73.2	151.3	102.3	213.8	209.0	113.0	180.4	161.5	88.3	0.00
2013	0.00	1.70	31.8	83.6	335.1	135.5	254.1	414.3	291.3	90.30	0.00	1.40
2014	0.00	31.2	28.0	47.5	277.3	385.0	85.00	263.9	106.7	29.00	0.00	0.00
2015	46.0	17.0	21.3	213.4	60.00	309.6	418.2	254.9	178.5	124.0	13.3	0.40
2016	10.1	35.8	66.8	215.4	377.3	205.3	328.6	119.8	221.5	198.3	66.2	5.80
2017	3.7	19.4	250.6	273.3	230.9	319.8	396.8	319.3	259.2	242.6	7.5	116.3
2018	7.8	10.6	70.2	91.9	212.3	365.7	214.7	180.8	27.9	119.1	0.4	24.3
2019	3.4	20.3	36.0	77.6	87.1	181.4	202.6	62.9	253.7	159.8	38.7	13.6
2020	65.8	13.3	12.1	102.8	148.6	307.4	270.8	205.7	229.9	165.8	104.9	0.0
2021	6.6	7.5	55.6	54.8	118.7	228.5	220.1	248.0	2.8.9	77.7	2.0	70.9
Total	**170.4**	**162.8**	**645.6**	**1311.6**	**1899.6**	**2652**	**2599.9**	**2182.6**	**1958**	**1368.1**	**321.3**	**232.7**
Mean	**17.0**	**16.2**	**64.5**	**131.1**	**189.9**	**265.2**	**259.9**	**218.2**	**195.8**	**136.8**	**32.1**	**23.2**

Source: Statistical Handbook of Manipur 2021

Calculation Procedure

Capacity of community pond: V = (lbd) cubic metre or lbd *1000 cubic litre [i]

Q represents quantity of water above minimum water (reserved) level of the Pond and Q < V.

If x_i is the number of families/households having h_i members, then the total number of persons in the area enjoying the community pond is

$$N = \sum_{i=1}^{n} x_i h_i \text{ and the average family size } \bar{N} = \frac{\sum_{i=1}^{n} x_i h_i}{\sum_{i=1}^{n} x_i} \quad [ii]$$

Table 2: Runoff coefficient for different catchments

Type of catchment		Runoff coefficient
Roof catchment	(i) Tiles	0.8-0.9
	(ii) Corrugated metal sheets	0.7-0.9
Ground surface Coverings	(i) Concrete	0.6-0.8
	(ii) Brick pavement	0.5-0.6
Untreated ground catchment	(i) Rocky natural catchment	0.2-0.5
	(ii) Soil on slopes less than 10 %	0.1-0.3

Source: A Handbook on Rainwater Harvesting in the Caribbean

Water harvested through the community pond

= Rainfall (in mm) * Area of the community pond (sq. m) [iii]

And water harvested through the catchment area or rooftop connected to the pond

= Rainfall (mm) * catchment area (sq. m) * C_r [iv]

where C_r is the runoff coefficient due to evaporation, absorption to the soil etc.

For some catchment surfaces general runoff coefficient are given in table 2.

Total water harvested through the community pond and catchment area

= Rainfall * (Area of Community Pond + Catchment area/rooftop * C_r) [v]

Since shortages are not allowed, the water is to be filled using supplementation system immediately so as to maintain uninterrupted water supply.

Example1 : A community pond in the valley area of Manipur having the length 60 m, breadth 50m and depth 1.5 metres is considered for providing additional water to 100 individual households having the average of 5 persons per family with the average additional demand of 10 litres per head per day. The holding cost is INR 0.001 per litre/day and set up cost is INR16000 and revenue collected from individual households be INR 200 per month. If there is a leakage at a rate 500 lit per day, determine the optimal quantity, optimal time and minimum cost per run.

Solution: The water level available at the beginning at any position will raise with harvested rainwater (satisfying $k > r$) till it reaches the maximum capacity of the community pond in time t_1. Since the additional demand of water for domestic use continues and the maximum level reduces to minimum level in time t_2. If the rainfall ceases or not satisfied (k > r) then water level will not increase further, then steps to fill fresh water from nearby water sources should be taken up immediately.

Now, V= Volume of the community pond

= 60*50*1.5 cu m = 4500 cu m = 4500*1000 litres.

Q = Volume of water above minimum water level= 60*50*(1.5-0.4) cu m = 3300 cu m.

where 0.4 m is the minimum water level.

r = Estimated Demand rate for 100 families having 5 members in each family consuming 10 litres per head per day = (100*5*10) litres/day =5000 litres/day

=150000 litres/month

r_1 = leakage rate = 500 litres/day = 15000 litres/month

k = Water harvested through the community pond and catchment area per month during rainy season

= Rainfall * (Area of Community Pond + Catchment area/rooftop * C_r)

= 180mm * (3000+1000*0.85)sq.m = 693000 litres/month

C_1 = INR 0.001 per lit/day = INR 0.03per litres/month and C_3 = INR 16000

For without leakage condition

$q^* = \left[\frac{2C_3}{C_1}\left(\frac{r\,k}{k-r}\right)\right]^{\frac{1}{2}}$ = 451883.71 litres, $t^* = \frac{q^*}{r}$ = 3.01 months

And $C_{min} = \left[2C_1C_3r\left(1-\frac{r}{k}\right)\right]^{\frac{1}{2}}$ = INR 10622.20

Case I: With leakage during supply period (t_1) and demand period (t_2)

$$q^* = \left[\frac{2C_3\, r\, k^2(r+r_1)}{C_1k(r+r_1)(k-r)+C_1 r\, r_1(r+r_1)+C_1\, r_1(k-r-r_1)^2}\right]^{\frac{1}{2}} = 431674.28 \text{ litres.}$$

$$t^* = \frac{q^*}{r+r_1} = 2.64 \text{ months.}$$

$$C_{min} = \frac{1}{2}C_1q^*\left(1-\frac{r}{k}\right) + C_3\frac{r}{q^*} + \frac{1}{2}\frac{C_1 r\, r_1 q^*}{k^2} + \frac{1}{2}\frac{C_1\, r_1 q^*}{(r+r_1)}\left(1-\frac{r+r_1}{k}\right)^2$$

= INR 11004.77

Case II: With leakage during supply period, t_1 only.

$$q^* = \left[\frac{2C_3\, r\, k^2}{C_1(k^2-kr+r\,r_1)}\right]^{\frac{1}{2}} = 450538.77 \text{ litres.} \quad t^* = \frac{q^*(k-r_1)}{kr} = 2.93 \text{ months}$$

and $C_{min} = \frac{1}{k}\left[2\,C_1C_3\, r(k^2-kr+r\,r_1)\right]^{\frac{1}{2}}$ = INR 10653.91

Case III: Leakage occur during demand period, t_2 only

$$q^* = \left[\frac{2C_3\, r\, k^2(r+r_1)}{C_1(k-r)\{k(r+r_1)+r_1(k-r)\}}\right]^{\frac{1}{2}} = 436601.24 \text{ litres.}$$

$$t^* = \frac{q^*(k+r_1)}{k(r+r_1)} = 2.70 \text{ months}$$

And $$C_{min} = \frac{1}{k}\left[\frac{2C_1\, C_3\, r\,(k-r)(kr+2k\, r_1 - rr_1)}{r+r_1}\right]^{\frac{1}{2}} = \text{INR } 10994.01$$

Special condition when k ≤ r

$$q^* = \left[\frac{2C_3\, r\,(r+r_1)}{C_1(r+2r_1)}\right]^{\frac{1}{2}} = 382970.84 \text{ litres}, \quad t^* = \frac{q^*}{r+r_1} = 2.32 \text{ months}$$

and minimum cost, $$C_{min} = \left[\frac{2C_1 C_3\, r\,(r+2r_1)}{r+r_1}\right]^{\frac{1}{2}} = \text{INR } 12533.59$$

If $r_1 \to 0$, then $$q^* = \left[\frac{2C_3\, r}{C_1}\right]^{\frac{1}{2}} = 400000 \text{ litres}, \quad t^* = \frac{q^*}{r} = 2.66 \text{ months}$$

and $$C_{min} = [\,2C_1 C_3\, r\,]^{\frac{1}{2}} = \text{INR } 12000$$

From this example we see that the involvement of leakage in the system increase the minimum cost and decrease the supply duration.

Discussion and Conclusion

The study explores the potential of a community pond in the Manipur Valley as a supplementary water source for domestic use, particularly for 100 households, each consisting of five members with an additional daily water demand of 10 litres per person. The pond, with dimensions of 60 meters in length, 50 meters in breadth, and 1.5 meters in depth, serves as a rainwater harvesting structure with a substantial storage capacity. The economic analysis includes a holding cost of INR 0.001 per litre per day, an initial setup cost of INR 16,000, and a revenue collection of INR 200 per household per month. However, operational inefficiencies, particularly leakage at a rate of 500 litres per day, pose challenges to the optimal utilization of the stored water. The study systematically investigates the optimal quantity of water, the ideal replenishment time, and the minimum cost per supply cycle to ensure an efficient and sustainable distribution system.

The fluctuations in the availability of water in the pond depend on both natural and anthropogenic factors. During periods of sufficient rainfall, the water level rises and reaches its maximum storage capacity within a specific timeframe. However, due to continuous domestic consumption and potential leakage, the water level gradually declines until it reaches the minimum threshold required for effective utilization. If rainfall is inadequate or ceases altogether, the natural replenishment process is hindered, necessitating the use of alternative water sources to maintain supply. The intricate balance between rainfall-dependent harvesting, daily consumption rates, and leakage significantly influences the pond’s sustainability as a reliable water source. Understanding the interplay of these factors is critical for optimizing water resource management and ensuring long-term usability. The analysis of different operational scenarios highlights the significant impact of leakage on water availability and associated costs. In an ideal situation without leakage, the system operates efficiently, leading to prolonged supply duration and reduced operational costs.

However, when leakage occurs during both the supply and demand periods, the overall water supply duration is considerably shortened, and the financial burden increases. Even if leakage is restricted to either the supply or demand phase, it still negatively affects the efficiency of storage and leads to higher expenses. In extreme scenarios where rainfall fails to meet consumption demands, the water supply duration is further reduced, leading to escalated costs. The findings indicate that proactive leakage management strategies are essential to optimizing water distribution, minimizing costs, and ensuring a sustainable water supply.

This research emphasises the importance of utilizing existing community ponds, which have historically played a pivotal role in water resource management across major villages in the Imphal Valley. Constructed over different periods by both past rulers and the government, these ponds have immense potential for sustainable water conservation. Traditionally, they have been used for agricultural, domestic, and communal activities. However, changing climatic patterns and increasing population pressures necessitate a reassessment of their functionality. This study seeks to integrate these historically significant community ponds into modern rainwater harvesting systems, thereby enhancing their utility in addressing the additional water requirements of surrounding households. A key aspect of this research is the development of a strategic approach to optimizing rainwater harvesting through existing community ponds. By ensuring effective collection, storage, and equitable distribution, the study provides a framework for sustainable water conservation. Given the increasing pressure on conventional water sources, repurposing these ponds as rainwater harvesting reservoirs can play a crucial role in addressing water scarcity and improving overall water security. The feasibility of such an initiative depends on several factors, including storage capacity, seasonal rainfall variability, and necessary infrastructural upgrades to maximize efficiency. Furthermore, the study highlights the critical impact of system inefficiencies, particularly water leakage, on both operational performance and economic sustainability. Unchecked leakage leads to significant water loss, reduces the effective storage period, and increases financial costs associated with maintenance and water supply. By identifying key sources of leakage and assessing their impact on the system, this research provides practical recommendations for reducing water loss, improving storage efficiency, and ensuring an uninterrupted supply of harvested rainwater. Addressing these inefficiencies will not only enhance the financial viability of community pond management but will also support the broader goal of sustainable water resource utilization.

The present study provides valuable insights into the optimization of community ponds as sustainable rainwater harvesting structures. By addressing key challenges such as leakage, operational costs, and storage efficiency, it offers a comprehensive approach to improving domestic water availability. The findings contribute to the formulation of improved water conservation policies and encourage active participation from local communities in preserving and utilizing their traditional water resources. Effective management of these community ponds has the potential to significantly enhance water security, mitigate supply shortages, and ensure long-term sustainability in water resource management across the Imphal Valley.

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