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Methodological Framework

Water Productivity Assessment Framework for Aquaculture Pond Systems: Physical, Nutritional, and Economic Dimensions

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1. Introduction

Aquaculture has been the primary engine driving the increase in the global aquatic food supply for over three decades, accounting for 53% of global aquatic animal production and over 59% of production for human consumption(FAO 2026) Despite the increasing contribution of aquaculture to global seafood production and economic activity, the sector is often regarded as a controversial and potentially unsustainable industry. Aquaculture has been widely criticized for its potential environmental impacts, including water pollution, habitat degradation, biodiversity loss, and pressure on natural resources.(Afewerki et al. 2023). There is also continued concern regarding the potential negative social impacts associated with aquaculture. For instance, Golden et al. (2017) argue that aquaculture may have limited contributions to food security in nutritionally vulnerable countries, while (Beveridge et al. 2013) suggest that the sector tends to prioritize species and product forms that are primarily targeted at urban middle-class consumers and international markets. Furthermore, the contribution of aquaculture to employment and livelihood opportunities has also been questioned.(Belton et al. 2020). Existing studies have examined water consumption, water-footprint estimation, and water productivity in aquaculture using different methodological approaches and system boundaries (Symeonidou & Mente, 2024).

To address this gap, this paper presents the Water Productivity Assessment Framework (WPAF), which evaluates physical, economic, and nutritional water productivity by relating production, economic value, and nutritional outputs to water use. This report primarily aims to develop a methodological framework and practical assessment tool to evaluate water productivity in closed production systems (such as farm ponds), where we can measure and quantify water inputs with reasonable accuracy. The framework provides a systematic approach to assessing water productivity using three distinct parameters, allowing for a multidimensional evaluation of water use in production systems. Its primary audience includes researchers, technical practitioners, and project teams seeking to assess water productivity using a consistent and replicable methodology. The framework supports empirical assessments, provide a method to standardize data collection and computations, which would enable comparisons across similar closed production systems where the necessary data are available.

The framework (as illustrated in Figure 1) assesses physical, economic, and nutritional outputs relative to water leading to assessing the input use efficiency of different farm ponds. Assessing aquaculture water productivity through production, economic, and nutritional dimensions offers a more comprehensive framework for understanding resource-use efficiency and sustainability. Together, these three indicators provide a broader assessment of water productivity by examining the physical output, nutritional value, and economic returns generated from water use. Their combined application to aquaculture systems helps assess how effectively water resources support fish production, food and nutrition security, and farmers' economic benefits. It also helps examine how species composition and diversification influence physical, nutritional, and economic water productivity.

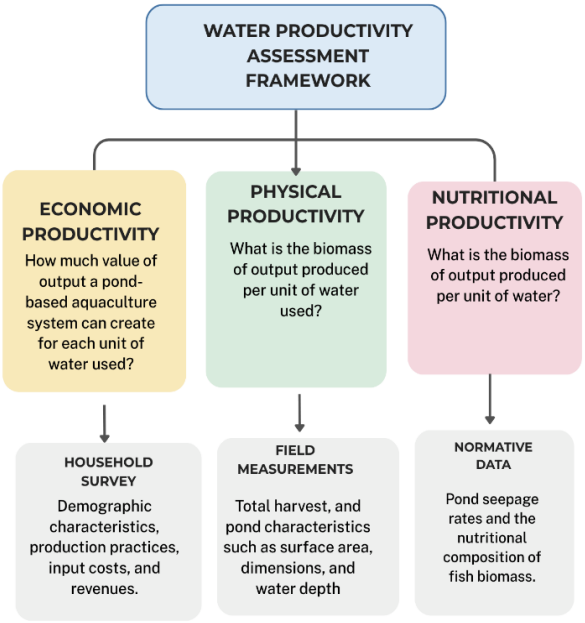


Figure 1. Conceptual framework for the Water Productivity Assessment Framework

Source: Author's creation using Canva.

The framework adopts a hybrid methodological approach that combines a baseline household survey (see Annexure II) with a normative data framework. Primary data collected through random stratified sampling (details in Annexure I) structured questionnaires administered by trained enumerators and supplemented by field observations includes - household survey (information on demographic and socioeconomic characteristics), production practices, input costs, and revenues. In parallel, field observations record key production parameters, including fish stocking profiles, total harvest, and pond characteristics such as surface area, dimensions, and water depth.

This framework (WPAF) applies to closed-system aquaculture ponds to determine the water productivity by integrating household socioeconomic survey, pond-level observations, and water-use data specified in the framework. The application involves collecting the required data on inputs, costs, revenues, pond characteristics, stocking and harvest, and water use. These data are used to quantify water use and calculate the proposed indicators of economic, physical, and nutritional water productivity. The resulting indicators are comparable across ponds or production systems to assess differences in water productivity and identify the factors associated with variation in productivity.

Primary data collection provides site-specific empirical evidence regarding farm operational parameters, yield outputs, and economic performance. However, evaluating overall resource productivity also requires quantifying other specific variables that cannot be easily or directly captured through field observations and household surveys alone. These include pond seepage rates associated with different soil types and the nutritional composition of fish biomass. To address this challenge, the framework uses a normative data approach, using established values reported in peer-reviewed literature and other authoritative sources. These reference values serve as standardized parameters for estimating environmental and nutritional outcomes. To translate these combined datasets into meaningful metrics, the framework applies standard equations. The framework integrates primary field measurements with secondary reference parameters using established equations. A limitation of this approach is that normative values derived from secondary sources may not fully reflect local production conditions, since they originate from different geographical and research contexts. Furthermore, because these data originate from studies conducted by other researchers, the assessment has limited control over the quality and consistency of the original measurements (Sindin 2017).

Despite these limitations, the normative data approach offers several practical advantages. It avoids the substantial time, cost, and technical requirements associated with long-term environmental monitoring and laboratory-based nutritional analyzes, enabling a more efficient assessment process (Pederson et al. 2020). In addition, the use of established scientific reference values provides a standardized basis for comparison across production systems, improving the transparency, scalability, and replicability of the framework. By integrating primary field data with normative reference parameters, the framework enables the estimation of physical, nutritional, and economic water productivity across smallholder aquaculture systems. The assessment of water productivity helps evaluate how effectively aquaculture systems use water resources to achieve fish production, economic gains, and nutritional advantages. By assessing physical, economic, and nutritional outputs relative to the volume of water used, this approach provides a broader understanding of aquaculture performance beyond total fish output alone. It enables comparisons of water productivity among farming households, highlighting differences in the efficiency of water use. This integrated approach is particularly relevant in smallholder aquaculture systems, where water availability, production practices, and household livelihood objectives influence the benefits generated from fish farming.

Aims and objectives of the framework:

This report aims to develop a practical and field-applicable framework for assessing the physical, nutritional, and economic water productivity of ponds. More specifically, this methodological framework addresses three objectives:

1. Define appropriate indicators for assessing physical, nutritional, and economic water productivity at the pond level, relative to the volume of water used for fish production.
2. Establish data requirements and standardized data collection procedures for obtaining the farm-level information needed to apply the framework, including production, input costs, water use, and revenue.
3. Develop a transparent and adaptable assessment methodology that applies under different pond-farming conditions, while acknowledging current methodological limitations and identifying priorities for field-level validation.

2. Aquaculture Water Productivity Assessment

To assess how effectively water resources support fish production and the benefits derived from it, this framework considers three complementary dimensions of water productivity: physical, nutritional, and economic water productivity (Aklakur et al. 2026; Mohanty et al. 2014). These dimensions are considered together because the quantity of fish produced alone does not fully capture the contribution of water to food production, nutrition, and farmers' livelihoods. This is particularly important in aquaculture, where freshwater scarcity and competition for water among agriculture and other sectors increase the need to use available water resources efficiently (Mohanty et al. 2017). Physical water productivity measures the weight of harvestable fish produced per cubic meter of water consumed, indicating the production output supported by water use. However, fish yield alone does not reflect the nutritional benefits of the harvest. Nutritional water productivity therefore assesses the quantity of protein and other selected nutrients produced per cubic meter of water consumed, capturing the nutritional contribution of fish production. Economic water productivity measures the financial return generated per cubic meter of water consumed, reflecting the economic benefits derived from water use. This dimension is important because higher fish yields do not necessarily translate into greater economic returns when production costs and market prices vary.

2.1 Physical Water Productivity (PWP):

As shown in Equation (1), Physical Water Productivity (PWP) measures the weight of fish harvested (kg) per cubic meter of total water supplied to the pond during a farming cycle (Aklakur et al. 2026; Mohanty et al. 2014). Total fish output refers to the net weight of all fish harvested, while total water supplied includes the initial pond filling, subsequent water additions to compensate for evaporation and seepage losses, and effective rainfall. The measure based on total water supplied is used as the primary indicator because it relates fish production to the total water input required to operate the pond. A complementary measure, calculated using consumptive water use (CWU) as the denominator (Equation 2), assesses fish yield relative to the water consumed or depleted during production. Depending on the water accounting approach, CWU may include evaporation, seepage into the surrounding soil, and water retained in the harvested fish biomass. Calculating both indicators provides complementary perspectives on water productivity: the first reflects fish output relative to total water supplied, while the second relates fish output to consumptive water use.

$$PWP = \frac{Total\ Yield\ of\ Fish\ in\ kg}{Total\ Volume\ of\ Water\ Used\ in\ m^3} \quad (1)$$

$$PWP = \frac{Total\ Yield\ of\ Fish\ in\ kg}{Volume\ of\ Consumptive\ Water\ Use\ m^3} \quad (2)$$

Variables

- **Total yield of fish (kg):** The combined weight of all fish harvested from the pond over the full production cycle.
- **Total volume of water used (m³):** All the water received by the pond, including its initial water volume, rainfall and runoff entering the pond during the production cycle, and additional water added by farmers (e.g., pumped water), as defined in detail below.

Where the data comes from

- **Fish yield:** The total weight of fish harvested is recorded in kilograms at each partial and final harvest (Survey Question 2.21).
- **Water volume:** Calculated using the initial pond water volume based on on-site measurements of pond dimensions and depth, additional water added by farmers (e.g., pumped water, Survey Question 2.16), and rainfall (Survey Question 3.1) and runoff estimated as explained later in this section (Survey Question 2.19).

Unit

Result is expressed in kilograms of fish per cubic meter of water (kg/m³).

The following section explains how the total weight of fish harvested throughout the complete culture cycle and the total volume of water used during the production cycle are calculated by combining the measurements recorded from each relevant production event.

Total Yield of Fish (kg): Partial harvesting of fish usually begins around three months after stocking and continues at regular intervals, either fortnightly or monthly, depending on farm management practices. During each partial harvest, fish that have reached marketable size are collected using a seine net, while smaller fish are returned to the pond for further growth. The remaining fish are harvested at the end of the culture period, usually after six months.

Because fish are harvested at different times during the culture cycle, the total fish production includes all fish harvested from the pond, not only the final harvest as calculated in Equation (3). Enumerators record the quantity of fish harvested during each harvest event reported by the farmer, including both partial and final harvests. The quantities from all harvests are then added to obtain the total fish yield for the production cycle, using the harvest records collected through Survey Question 2.21. This approach is applicable to all pond-based aquaculture production systems, including monoculture and polyculture, as it accounts for the quantities of fish harvested during all partial and final harvest events, irrespective of the species cultured or the harvesting practices adopted.

$$\sum_{i=1}^{n} H_i = H_1 + H_2 + \cdots + H_n \qquad (3)$$

where:

- H_i = Total weight of fish harvested during the i th harvest event (kg), including both partial and final harvests.
- n = total number of harvest events in the culture cycle

Total volume of water used (m^3):

Total water use is the total amount of water that enters the fishpond during the farming season. This includes rainwater that falls directly into the pond, rainwater running in from surrounding land, groundwater seeping in, and any extra water pumped or added by the farmer as expressed in Equation (4). In simple terms, it counts every drop of water that comes into the pond from both nature and farm management. (Boyd et al. 2007; Mohanty, 2015). Groundwater seepage into the pond is not included as a separate term in Equation (4). The direction of lateral seepage (i.e., groundwater entering or leaving the pond through the pond bed and surrounding embankments) depends on the relative levels of the groundwater table and the pond water surface. Water seeps out of the pond when the groundwater table is lower than the pond water level, and into the pond when it is higher (Kam and Hoanh 2007; Coche and Muir 1992). In a pond water budget model for Bangladesh, Sylhet is a low-lying, flood-prone area with shallow groundwater (mean depth of 1.1 m below the ground surface). Even so, the groundwater table was generally lower than the pond water level, and exceeded it only when the pond was drained and being refilled, by up to 0.3 m. The resulting rise in pond water level was only about 17 mm over a one-week interval, which was small compared with the outflow losses simulated where the water table lies below the pond bottom, as at most other stations (Kam and Hoanh 2007). On this basis, the framework treats seepage as a net loss (Equation 16) and does not separately account for groundwater inflow, which is a reasonable assumption where groundwater inflow is minimal.

$$\begin{aligned} &Total\ volume\ of\ water\ used\ (m^3) \\ &\quad = Initial\ volume\ of\ water\ (m^3) + Precipitation\ volume\ (m^3) + Surface\ runoff\ volume\ (m^3) \\ &\quad + Additional\ water\ pumped\ by\ the\ farmer\ (m^3) \end{aligned} \qquad (4)$$

Initial volume of water (m^3):

The initial volume of water used in the calculation is determined using the following formula. It represents the total volume of water retained in a pond at the beginning of the culture cycle. It is calculated as the product of the pond's average surface area (m^2) and its average water depth (m) as expressed in Equation (5). Surface area is measured across the water-land boundary at full capacity, and the depth is measured from the water surface to the pond bottom. This starting volume acts as a baseline, making it easy to track any water lost through evaporation and seepage or any extra water added to the pond during the culture cycle.

$$Initial\ volume\ of\ water\ (m^3) = Average\ surface\ area\ (m^2)\ x\ Depth\ (m) \qquad (5)$$

To accurately quantify total water volume for the on-site assessment, the pond's surface area and average depth are calculated systematically from its shape and size.

As shown in Figure 2, pond surface area measurements are taken directly on site, and the surface area is calculated using Equation (6) for square ponds and Equation (7) for rectangular ponds:

$$A\ (m^2) = Side\ (m) \times Side\ (m) \quad (6)$$

$$A\ (m^2) = Length\ (m) \times Width \quad (7)$$

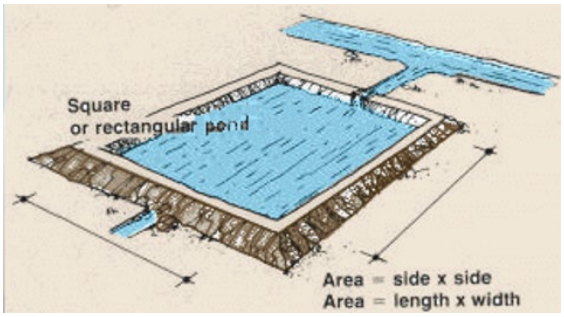


Figure 2.Measurement of pond surface area

Source: FAO 1998

To calculate the average water depth:

As shown in Figure 3, according to FAO 1998, when assessing a small pond with a regular shape and a constant bottom slope that is already filled, on-site depth measurements are taken directly from the water surface.

Measurements: The enumerator wades safely into the water and uses a calibrated bamboo sounding pole or graduated rod (marked at regular centimeter intervals) to take direct vertical measurements. The pole is pushed straight down until it meets the firm pond bed at four symmetrical points across the basin. The mathematical average of these four distinct readings represents the final operational average water depth (FAO 1998).

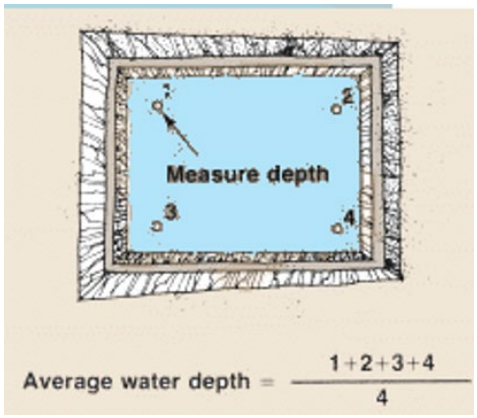


Figure 3.Measurement of average water depth

Source: FAO 1998

Where the pond has a multilevel bottom, measurements are taken at the midpoint and at points on either side to ensure accuracy, as shown in Figure 4. Measuring the average water depth allows for a more accurate estimation of the total water volume in the pond, according to Equation (8). This reduces errors, especially in small ponds, and gives a better estimate of the total water available.

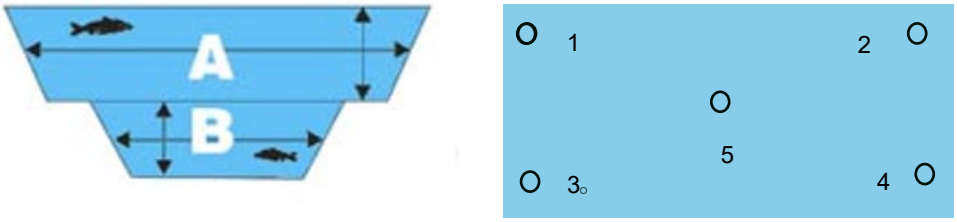


Figure 4. Measurement of the average water depth in a multilevel pond bottom

Source: Author's creation

$$Average\ water\ depth = \frac{1+2+3+4+5}{5} \quad (8)$$

Data on pond length, width, and water depth are collected through Survey Question 2.20 and used in Equation (8) to estimate the initial water volume.

Precipitation Volume (m3):

Precipitation is measured using a rain gauge at the farm. Where on-farm measurements are unavailable, precipitation records from the nearest weather station are used (Sharma et al. 2013) to estimate how much rainwater enters the pond (Krisnayanti et al. 2019). Precipitation is usually measured as the quantity of water falling over a one square meter area, it is measured in millimeters. To estimate the actual amount of rainwater entering the pond, this rainfall depth is converted into the volume of water in cubic meters (m^3) as expressed in Equation (9). Rainfall data are collected through Survey Question 3.1 and used to calculate the precipitation volume.

$$Precipitation\ volume\ (m^3) = \frac{Rainfall\ depth(mm)}{1000} \times Surface\ area\ (m^2) \quad (9)$$

Variables

- **Rainfall depth (mm):** total rainfall recorded over the culture period, from a rain gauge or from the nearest weather station data.
- **Surface area (m^2):** the pond's surface area, calculated earlier.

Why divide by 1000

Precipitation is measured in millimeters (mm) and is converted to meters (m) before the water volume is calculated. Dividing the precipitation depth by 1,000 converts millimeters to meters (1 m = 1,000 mm).

Runoff (m3):

Method 1:

In addition to rain falling directly into the pond, water can also enter the pond from the surrounding land. This water is called surface runoff and mainly comes from rainwater flowing over the ground into the pond. (Quagliolo et al.2021). The total runoff volume (m^3) is calculated by multiplying the total area of land draining into the pond (catchment area, m^2) by the estimated runoff depth (m). The USDA Soil Conservation Service Curve Number (SCS-CN) method is used to estimate how much rainfall runs off. This method considers the type of land cover, soil type, and how wet the soil is before the rainfall. To calculate the runoff accurately, the total area of land that drains water into the pond (catchment or watershed) is identified using a Digital Elevation Model (DEM).

The land area from which rainwater flows into the pond is identified using a Geographic Information System (GIS). A Digital Elevation Model (DEM) is used to identify the direction in which water naturally flows, because

water generally flows from higher land to lower land. Unlike satellite images, which mainly show land cover and water bodies, a DEM shows the elevation of the land and helps identify the areas that drain water into the pond.

Depending on the available data, either the Shuttle Radar Topography Mission (SRTM) DEM (30 m resolution) or Advanced Land Observing Satellite ALOS PALSAR DEM (12.5 m resolution) is used to identify the land area that drains water into the pond (catchment or watershed area). The catchment area is delineated using water-flow analysis tools in QGIS or ArcGIS (Grove et al. 1998).

The amount of surface runoff (Q) is estimated using the USDA Soil Conservation Service Curve Number (SCS-CN) method. This method estimates how much rainwater flows over the land and enters the pond after a rainfall event. It considers the type of land cover, soil type, and the wetness of the soil before the rainfall. This method is also useful for estimating runoff in areas where direct runoff measurements are not available (Shrestha 2003).

The land use/land cover (LULC) and soil type maps are combined in GIS to assign a Curve Number (CN) to the catchment area (Grove et al. 1998). The CN value indicates how much rainfall is likely to become surface runoff for different combinations of land use and soil type. CN values range from 0 to 100, where a higher value indicates that a greater proportion of rainfall is likely to flow as runoff under normal soil moisture conditions.

The standard SCS-CN empirical framework calculates storm runoff using the following mathematical formulation according to Equation (10) (Smithers 2012).

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad (10)$$

where:

Q = Direct surface runoff depth (mm)

P = Total rainfall depth (mm) for the event, from the nearest weather station.

S = Potential maximum retention after runoff begins- how much water the catchment's soil and land cover can hold before runoff starts. (mm), Calculated from the Curve Number as S=25400/CN-254.

I_a = All lose before runoff begins. (Initial abstraction (mm), which accounts for surface storage, interception, and infiltration prior to runoff.

Rainfall depth data (P, in mm) are acquired from the nearest active meteorological station.

Where the data comes from.

- **P:** Rainfall depth is acquired from the nearest meteorological station.
- **CN (and hence S):** derived in GIS from the intersection of land-use/land-cover and soil-type layers over the catchment.

Using the Curve Number (CN) map created from the land use and soil type maps, the potential maximum amount of water that the soil can hold (S) is calculated. The calculation is carried out using the Raster Calculator tool in GIS.

The runoff values from each GIS pixel are combined to obtain an average runoff depth for the entire watershed. This average runoff is expressed in millimeters (mm). To calculate the total runoff water volume in cubic meters (m^3), the average runoff depth is first converted from millimeters to metres. The total runoff volume (V) is then calculated by multiplying the average runoff depth (m) by the total catchment area (m^2) as expressed in Equation (11).

$$Runoff\ volume\ (m^3) = Average\ runoff\ depth\ (m) \times Catchment\ area\ (m^2) \qquad (11)$$

Method 2:

Although the SCS-CN method provides a more detailed, physically informed approach to estimating surface runoff by incorporating land use/land cover, soil characteristics, and antecedent moisture conditions, its application requires DEM data, spatial datasets, GIS software, and technical expertise. These requirements may make the method difficult to implement directly during smallholder pond surveys, particularly where detailed spatial data are unavailable. Farmers and field enumerators may also find it challenging to delineate catchment areas and perform GIS-based runoff calculations. Therefore, the SCS-CN method is applied where suitable spatial data and GIS expertise are available, while a simplified runoff coefficient method is used as an alternative when these resources are unavailable. This method estimates runoff volume using the catchment area, rainfall

depth, and a runoff coefficient representing the proportion of rainfall that becomes surface runoff (Muruganandam et al. 2012). The runoff coefficients corresponding to different land-use types, slope classes, and soil textures are presented in Table 1.

The estimated surface runoff volume is calculated using the following equation (12).

$$Vr = \frac{C \times A \times P}{1000} \qquad (12)$$

where;

Vr= Estimated surface runoff volume (m^3)

C = Runoff coefficient (dimensionless, ranging from 0 to 1), representing the proportion of rainfall that becomes surface runoff, depending on catchment characteristics such as land cover, soil type, and slope.

A= Catchment area (m^2), representing the total land area from which surface water drains towards the pond.

P= Total rainfall depth (mm) during the selected rainfall event or assessment period.

Where the data comes from.

Values for the runoff coefficient are obtained from Table 1 based on catchment characteristics.

Catchment area data are extracted from Survey question 2.18 and survey question 2.19 using mobile GIS application records.

Rainfall depth is obtained from the nearest meteorological station (Survey Question 3.1).

Table 1.Runoff coefficients for different land-use types, slope classes, and soil textures

Topography & Vegetation	Slope (%)	Sand	Silt	Clay
I. Forest Land	Flat (0–5)	0.10	0.30	0.40
	Rolling (5–10)	0.20	0.35	0.50
	Hilly (10–30)	0.30	0.50	0.60
II. Pasture Land	Flat (0–5)	0.10	0.30	0.40
	Rolling (5–10)	0.10	0.36	0.55
	Hilly (10–30)	0.20	0.42	0.60
II. Cultivated Land	Flat (0–5)	0.30	0.50	0.60
	Rolling (5–10)	0.40	0.60	0.70
	Hilly (10–30)	0.50	0.72	0.82

Source: Muruganandam et al. 2012

Simple field steps for farmer-level catchment measurement

The catchment area contributing surface runoff to each aquaculture pond is estimated using a smartphone-based GPS area measurement application (Matheswaran and Ali 2023). The surrounding land area from which rainfall runoff flows into the pond is identified by the farmer and enumerator. The boundary of the identified catchment area is recorded using a GPS-enabled smartphone application, such as

1 https://play.google.com/store/apps/details?id=lt.noframe.fieldsareameasure&hl=en&gl=US&pli=1 or
2 https://apps.apple.com/us/app/gps-fields-area-measure/id1123033235

The catchment area is then calculated by the application from the recorded boundary and expressed in square meters. The mapped boundary is verified by the farmer by checking visible drainage pathways and field features to ensure that only land contributing runoff to the pond is included. If the catchment boundary cannot be clearly identified in the field, GIS-based watershed delineation is used as a supplementary method.

2.2 Nutritional water productivity (NWP)

Nutritional Water Productivity (NWP) was originally developed for crop production systems to assess the nutritional output generated per unit of water used (Renault and Wallender 2000). Although it has primarily been applied to agricultural crops, its extension to aquaculture provides a methodological contribution by applying a nutrition-oriented water productivity concept to aquatic food production systems. This is particularly relevant because fish provide high-quality protein, energy, essential fatty acids, and important micronutrients, including vitamins and minerals. Assessing NWP therefore allows the nutritional contribution of fish production to be considered alongside the water resources required to produce it, complementing assessments that focus primarily on physical yield, economic returns, or water footprint indicators (Symeonidou and Mente 2024).

The NWP framework retains the principle of expressing nutritional output per unit of water use but requires adjustments to reflect differences between crop production and aquaculture. In both systems, nutritional output is estimated from the quantity of harvested produce and its nutrient composition. However, the appropriate water-use denominator depends on the production system and the purpose of the assessment. In crop-based applications, water use is commonly represented by actual evapotranspiration, whereas aquaculture requires water-use measures appropriate to pond production. Accordingly, this framework adapts the framework by replacing crop yield with fish production and applying aquaculture-specific water-use measures while retaining nutrient output as the basis for assessing nutritional productivity. Nutritional productivity is assessed for individual nutritional components, including energy and macronutrients such as protein and fat, as well as micronutrients such as vitamin A, iron, zinc, phosphorus, and calcium. For each component, total nutritional output is estimated using the quantity of each fish species harvested during the culture cycle and its corresponding nutrient composition. This allows the assessment to move beyond the question of how much fish is produced per unit of water to examine how much nutritional value that water supports.

In this framework, NWP is calculated using two denominators, as presented in Equations (13) and (14), respectively: total volume of water use and consumptive water use (CWU). Total volume of water use is used as the primary denominator because it relates nutritional output to the overall volume of water supplied to the pond during the culture cycle and is more practical to estimate in smallholder aquaculture systems. Consumptive-water-based NWP is calculated as a complementary indicator to assess nutritional output relative to water consumed or depleted during production. The two measures provide different perspectives on nutritional water productivity: the primary indicator reflects nutritional output relative to total water input, while the complementary indicator relates it to consumptive water use.

For each pond, the total output of each nutritional component is calculated by summing the contributions of all fish species harvested, based on their respective yields and nutrient composition. These estimates combine localized fish production data with species-specific nutrient profiles obtained from recognized food composition tables (Table 2) (Drastig et al. 2023). Nutrient values are expressed on a consistent edible-portion and weight basis, according to the source data, to ensure comparability between production and nutritional estimates. The resulting nutritional outputs are divided by the respective water-use denominators to calculate separate NWP values for each component, capturing the combined nutritional contribution of all species in the polyculture system. Nutrient composition can vary with species, diet, natural food availability, environmental conditions, season, reproductive stage, and fish age and size. Where locally representative nutrient composition data are unavailable, published values are treated as estimates, and this limitation is acknowledged when interpreting the results. This approach provides a basis for comparing the nutritional water productivity for aquaculture ponds across different nutrients while recognizing the need for further field-level validation.

$$NWP = \frac{Y_1 \times NC_1 + Y_2 \times NC_2 \ldots \ldots Y_n \times NC_n}{V_T} \quad (13)$$

$$NWP = \frac{Y_1 \times NC_1 + Y_2 \times NC_2 + \ldots \ldots + Y_n \times NC_n}{V_C} \quad (14)$$

Variables

- Y_1, Y_2, ..., Y_n = Total yield of each fish species (kg)
- NC_1,NC_2…. NC_n = Nutrient content - the amount of a specific nutrient per kilogram of fish (e.g. grams of protein per kg), taken from Table 2.
- V_T = Total volume of water used(m^3)
- V_c = Total volume of water Consumed (m^3)

Where the data comes from

The total yield of fish (Survey Question 2.21) and total volume of water (Survey Question 2.20) are the same as defined in PWP. Fish yield and water volume are obtained from the pond's own records (From the Survey); nutrient content is obtained from the standard nutrient-composition reference in Table 2, matched to the species harvested.

The nutrient composition values of selected carp and SIS species, including macronutrients and essential micronutrients are presented in Table 2. These published values are used to estimate the nutritional water productivity of the SIS carp polyculture system as an example.

Table 2. Nutrient profile of selected species of carp and SIS

	Nutrient content per 100 g raw edible parts										
	Macronutrients					Essential Micronutrients					
Fish Species	**Crude Protein (g)**	**Crude Fat (g)**	**Total Metabolizable Energy (kJ)**	**Ash /Total Mineral Matter (g)**	**Total-Omega-3 Polyunsaturated Fatty Acids (g)**	**Ca (mg)**	**P (mg)**	**Fe (mg)**	**Zn (mg)**	**Vitamin A (µg/100g)**	**Vitamin B 12(µg/100 g)**
Catla catla	14.9	0.7	267	1.0	0.41	210	260	0.83	1.1	4.54	1.3
Labeo rohita	18.9	1.1	363	1.1	0.188	960	210	2.5	1.5	3.39	5.05
Cirrhinus mrigala	18.2	3.0	422	1.0	0.237	51	119	0.98	1.0	6.76	5.57
Ctenopharyngodon idella	15.2	1.1	341	1.1	0.296	54	190	0.46	0.91	15.6	-
Amblypharyngodon mola	14.7	4.6	412	1.0	0.545	1400	700	19	4.2	134	5.9
Systomus sarana	17.4	3.92	417.0	1.98	0.239	159	-	0.743	0.81	30.2	-
Mystus gulio	17	5.25	-	1.04	0.279	171	220	1.13	1.22	19.5	-
Heteropneustes fossilis	20.5	0.6	384	1.0	0.144	230	270	1.7	1.6	14.2	2.0
Clarias magur	14.87	7.09	-	3.74	25.56	222.36	129.42	2.20	0.68	13.6	-

Source: Ara et al. 2006; Bogard et al. 2015; Chetia 2020; Mohanty et al. 2016; Nayak et al. 2015; Vlieg et al. 1991; Wheal et al. 2016

Consumptive water use (CWU):

CWU includes the possible outflows such as evaporation (E), seepage from the pond into the surrounding soil (S), and water contained in the harvested fish biomass ($W_{biomass}$) as expressed in Equation 15 (Mohanty 2015; Mohanty et al. 2014). Furthermore, Consumptive water use refers to the portion of water supplied to an aquaculture pond that is effectively removed from the pond system through processes that reduce the amount of water available for continued use. Thus, CWU provides an estimate of the water that is actually consumed or removed from the aquaculture system rather than simply measuring the total amount of water entering the pond. This distinction is important because water supplied to a pond may not necessarily be consumed; some water may remain within the pond or leave the system through non-consumptive pathways. By accounting for evaporation, seepage, and water retained in harvested biomass, CWU provides a more representative measure of the water requirement associated with fish production. The total consumptive water use is therefore calculated as:

$$CWUm^3 = E + S + W_{biomass} \quad (15)$$

where,

CWU is the total consumptive water use (m^3)

E is evaporation loss (m^3),

S is seepage loss (m^3),

$W_{biomass}$ is the volume of water contained in the harvested fish biomass (m^3).

Water loss by seepage (S):
Seepage is the movement of water from the pond into the surrounding soil. In earthen aquaculture ponds, water can potentially be lost through two main pathways: vertically through the pond bottom and horizontally through the pond dikes or embankments. However, the relative importance of these pathways depends on the construction and physical characteristics of the pond. In undrainable earthen ponds with thick mud embankments, structural drainage leaks are assumed to be negligible. Therefore, horizontal infiltration is minimal. In this framework, seepage loss is estimated primarily as vertical water movement through the pond bottom.

Over time, seepage rates naturally decrease as settling organic matter seals the soil pores at the bottom. The amount of water that seeps through the bottom of a pond depend mainly on the type and condition of the soil. Sandy and sandy-loam soils have larger spaces between soil particles, so water can move through them more easily and usually have higher seepage rates. Clay soils have smaller and tightly packed spaces, so they allow less water to pass through and usually have lower seepage rates. Seepage can also change as the pond is used. In a newly constructed or newly dug pond, seepage may be higher because the soil pores at the bottom are still open. As the pond is used for aquaculture, fine soil particles and organic matter settle at the bottom and form a layer that reduces water movement into the soil. Therefore, the seepage rate applied to a pond account for both the soil condition and how long the pond has been in use.

The total volume of water lost to seepage over a culture cycle is calculated using Equation (16):

$$Total\ seepage\ (m^3) = \frac{Daily\ seepage\ rate\ (mm/day)}{1000} x\ Pond\ area\ m^2 \times Culture\ period\ (days) \quad (16)$$

Table 3 below gives the rate of seepage losses in millimeters per day (mm/day) from various soil types (in the natural state) needed to calculate pond seepage losses over a period (FAO 1998). The seepage rates presented in the following table represent typical water-loss rates associated with different soil types under natural conditions and are used to estimate seepage losses over the culture period. These values provide a standardized basis for estimating seepage where site-specific measurements are unavailable. However, actual seepage may vary depending on soil texture, compaction, pond age, sediment accumulation, water depth, and other site-specific conditions

Table 3. The rate of seepage losses in millimeters per day (mm/day) from various soil types

Natural soil type	Seepage losses (mm/day)
Sand	25.00 - 250
Sandy loam	13.00 - 76
Loam	8.00 - 20
Clayey loam	2.50 - 15
Loamy clay	0.25 - 5
Clay	1.25 - 10

Source: FAO 1998.

Soil type is recorded through Survey Question 2.3 and used to select the corresponding seepage rate from Table 3.

Water loss by evaporation (E):

Evaporation is the loss of water from the pond surface into the air as water vapor. It is an important part of water use in aquaculture because water continuously leaves the exposed pond surface during the culture period. The amount of evaporation is affected by several factors, such as sunlight, air temperature, wind speed, air humidity, and pond water temperature. Therefore, evaporation can vary between different locations and months and can cause a considerable amount of water loss, especially during hot and dry periods.

This framework uses satellite data to estimate water loss through evaporation from small ponds, farm dams, tanks, and similar water bodies, usually smaller than a few hectares. It estimates evaporation on a monthly basis without requiring measurements directly from the pond. The main advantage of this method is that evaporation can be estimated across the framework area without continuous field measurements from individual ponds. Satellite data provide information about the pond surface and environmental conditions, which can be combined with weather information to estimate the amount of water lost through evaporation.

The evaporative water-loss depth is then converted into the actual volume of water lost from an individual pond by considering its surface area, as shown in Equation (17).

$$Evaporated\ volume\ (m^3) = \frac{E}{1000} \times A \quad (17)$$

where:

Evaporative water-loss depth (E, mm)

A = pond surface area (m²)

Evaporation from an open pond depends on the balance of energy at the water surface. Sunlight and heat from the atmosphere provide energy to the pond surface, and this energy is shared among different processes. The net radiation absorbed by the water is divided between the energy used for evaporation, the heat transferred from the water to the air, and the heat stored in the pond water. Equation 18 below is used to calculate the net radiation.

$$Rn = \lambda E + H + Gw \qquad (18)$$

where:

Rn = net radiation

λE = latent heat flux (evaporation)

H = sensible heat flux

Gw = water heat-storage flux

Because ponds are small, they have some important differences from large lakes and vegetated land. Pond water reflects only a small amount of sunlight (low albedo, about 0.05–0.08) and has a high ability to emit heat (emissivity about 0.99). The water surface temperature can be different from the air temperature, so heat may move either from the water to the air or from the air to the water. Also, because small ponds are surrounded by dry land, wind and dry air can increase evaporation, known as the "oasis effect." Therefore, evaporation is also affected by the size of the pond and the surrounding land conditions.

The framework is modular and consists of three layers:

a. Pond detection and characterization (water extent and area)
b. Estimation of energy balance and atmospheric drivers
c. Application of evaporation models and reconciliation of outputs

Each method first estimates the energy used for evaporation (latent-heat flux). This is then converted into the depth of water evaporated using the latent heat of vaporization. The evaporation is added together to get the total monthly evaporation, and this value is then combined with the pond area to calculate the total volume of water lost through evaporation.

Table 4 summarizes the input variables required by the framework and their respective roles in estimating evaporation and associated water loss. Table 5 lists representative open-access datasets for each data category. The framework is not tied to any of them; equivalent national or commercial products may be substituted, and the choice of dataset depends on the size of the ponds being studied (finer optical resolution is needed for smaller ponds).

Table 4. List of input variables

Variable	Role in the framework	Data category
Air temperature	Vapor pressure, slope Δ, longwave, sensible heat	Climate reanalysis
Humidity / dewpoint	Actual vapor pressure, vapor-pressure deficit	Climate reanalysis
Wind speed	Aerodynamic / wind-function term	Climate reanalysis
Incoming shortwave radiation	Net shortwave (with water albedo)	Reanalysis or solar-geometry estimate
Incoming longwave radiation	Net longwave balance	Reanalysis or derived from T, humidity
Atmospheric pressure	Psychrometric constant γ	Reanalysis or elevation-based
Water-surface temperature Tw	Longwave loss; sensible heat (EB route)	Satellite thermal infrared
Water extent / area A	Pond delineation; volume conversion	Optical satellite (water index)
Water depth d	Heat-storage term	Surveyed / assumed parameter
Surface elevation	Pressure; terrain context	Digital elevation model

Source: Author's creation.

Table 5. Data sources

Dataset (example)	Provider	Resolution	Supplies
ERA5-Land / AgERA5	ECMWF/ Copernicus C3S	~9 km, hourly–daily	Air & dewpoint temperature, wind, radiation, pressure
Landsat 8/9 C2 L2	USGS / NASA	30 m optical, 100 m thermal	Albedo, water index, water-surface temperature
Sentinel-2 MSI	ESA / Copernicus	10–20 m	Finer water delineation for very small ponds
MODIS (MOD/MYD)	NASA LP DAAC	250–1000 m, daily	Frequent reflectance / LST where coarseness is acceptable
Copernicus DEM / SRTM	ESA / NASA	30–90 m	Elevation for pressure and terrain
JRC Global Surface Water	EC JRC	30 m	Water occurrence / permanence to locate ponds
CHIRPS (optional)	UCSB / USGS	~5 km	Precipitation, if a fuller water balance is sought

Source: Author's creation.

Processing workflow:

- Ponds are delineated from cloud-masked optical composites using a water index, and the surface area of each pond is computed.
- Water-surface temperature is retrieved from the thermal band over the water mask, and water albedo and emissivity values are assigned.
- Atmospheric drivers are assembled from reanalysis data, the psychrometric terms are computed, and incoming radiation is derived.
- Net radiation over water and the heat-storage term are computed.
- At least two evaporation models (e.g., Penman open-water and the energy-balance residual) are applied.
- The estimates are reconciled and accumulated to a monthly evaporation depth (E), which is multiplied by the pond area to obtain the evaporated volume.
- Per-pond maps and tabular summaries (water mask, Tw, E in mm, volume in m^3) are exported.

Limitations:

The accuracy of estimates is affected by the spatial and thermal resolution of satellite imagery, particularly for very small ponds. Additional uncertainty arises from approximating the heat-storage term, using coarse-resolution reanalysis data, and the need for regional calibration of the wind function. The framework estimates evaporation only and does not account for seepage, inflow, abstraction, or direct precipitation.

Validation:

The following approaches are recommended for validating the evaporation estimates where suitable reference data are available:

- Comparison with observed water-level decline during rain-free periods after accounting for seepage and abstraction.
- Direct flux measurements (e.g., eddy covariance, Bowen-ratio energy balance, or scintillometer observations), where available.
- Comparison with nearby Class-A pan evaporation records using appropriate pan coefficients.
- Agreement between the paired evaporation models as an internal quality check.
- Sensitivity and uncertainty analysis of key parameters (e.g., water depth, albedo, wind function, and heat-storage term).
- Benchmarking against published open-water evaporation estimates or operational products (e.g., FAO WaPOR). (Allen et al. 1998; De Bruin 1978; Finch and Calver 2008; McFeeters 1996; McJannet et al. 2012, 2013; Muñoz-Sabater et al. 2021; Pekel et al. 2016; Sinclair 2019; Xu 2006)

As an alternative method, evaporation depth is estimated using the Penman method based on the evaporation records collected through survey question 3.1.

The total volumetric water loss through evaporation (m³) for the months the pond is in use is calculated by multiplying the evaporation depth by the pond's surface area, as shown in Equation (19).

$$Total\ evaporation\ loss\ (m^3) = Corrected\ evaporation\ depth\ (m)\ x\ Pond\ area\ (m^2) \quad (19)$$

A small amount of water is removed from the pond along with the harvested fish. This water loss is approximately 0.75 m³ (Boyd et al. 2007) for every tonne of fish harvested and is generally considered very small. This is a negligible amount (Mohanty 2015; Mohanty et al. 2014). Therefore, this water loss is not included in the consumptive water use calculation in this framework.

2.3 Economic water productivity:

Economic water productivity indicates how much value of output an economy can create for each unit of water used. Gross Total Water Productivity (GTWP) measures the gross monetary value of fish production per cubic meter of water used (USD/m³), whereas Net Total Water Productivity (NTWP) measures accounting profit per cubic meter of total water used (USD/m³). Net Consumptive Water Productivity (NCWP) measures accounting profit per cubic meter of consumptive water use (USD/m³). Together, these indicators provide complementary assessments of the gross monetary value and accounting profit generated relative to water use, rather than a comprehensive assessment of overall farm profitability or full economic profit. To assess water-use efficiency from different economic perspectives, three indicators are calculated, these are the Gross Total Water Productivity (GTWP), as shown in Equation 20, Net Total Water Productivity (NTWP), as shown in Equation 21, and Net Consumptive Water Productivity (NCWP), as shown in Equation 22. These indicators are calculated in USD per cubic meter of water used or consumed, as appropriate. Any values reported by farmers in local currency are subsequently converted to USD using the Standard exchange rate (Aklakur et al. 2026; Mohanty 2015). GTWP represents the gross economic value generated per unit of total water used, whereas NTWP considers the net economic return after deducting production costs. NCWP further relates the net economic return to the amount of water consumed through processes such as evaporation and other consumptive losses. Together, these indicators provide a comprehensive assessment of the economic efficiency of water use in aquaculture

$$Gross\ \ total\ economic\ productivity = \frac{Total\ economic\ value\ of\ the\ product\ (USD)}{Total\ volume\ of\ water\ used\ (m3)} \quad (20)$$

$$Net\ \ total\ economic\ productivity = \frac{Total\ economic\ value\ of\ product - Production\ cost\ (USD)}{Total\ volume\ of\ water\ used\ (m3)} \quad (21)$$

$$Net\ \ total\ economic\ productivity = \frac{Total\ economic\ value\ of\ product - Production\ cost\ (USD)}{Volume\ of\ consumptive\ water\ use\ \ (m^3)} \quad (22)$$

where the total volume of water used (Survey Question 2.20) and the volume of consumptive water use are defined separately in the framework, with consumptive water use calculated using Equation (15). In this framework, economic water productivity is evaluated by quantifying the production costs, gross income, and net income, of each aquaculture production unit. The economic water productivity indices are calculated using conventional, established methods, as described below (Aklakur et al. 2026).

The economic performance of aquaculture can vary with farming practices, production costs, market access, and the types of fish produced. Where information on the gender of the household head and or the person responsible for aquaculture production and financial decision-making is available, economic water productivity indicators can also be disaggregated by gender. GTWP, NTWP, and NCWP can be compared between male and female managed headed production units, as appropriate. This analysis can identify gender-related differences in economic value and accounting profit per unit of water and explore whether differences in access to productive resources, inputs, labor, markets, or financial decision-making are associated with economic water productivity. Results are interpreted in relation to the sample size and the specific gender variable used, without attributing observed differences to gender alone. Below is a practical example of how changes in aquaculture practices can influence farmers' economic outcomes and livelihoods, highlighting the importance of evaluating the economic benefits of aquaculture and giving a practical example of gender-related differences in economic outcomes.

A practical example of economic evaluation in aquaculture

In Kheyadaha Wetland in the East Kolkata Wetlands, West Bengal, India, where 250 farmers transitioned from exotic fish farming, including African magur (Clarias gariepinus), to indigenous fish farming. Ghosh et al. (2026) reported that the average annual profit before the intervention was USD 2,390 per farmer (at INR 88/USD), while the average annual income following the intervention reached USD 5,910 per farmer. Average annual income among men increased from USD 2,390 to USD 5,910, while that among women increased from USD 1,250 to USD 3,520. These improvements were attributed to low-cost feed production, value-added products, and strengthened market linkages (Ghosh et al. 2026).

Production cost (USD):

Production cost represents the total monetary expenditure required to produce fish during a complete culture cycle. As explained in Equation 23, it includes both the recurring costs required for day-to-day production and the expenditure associated with establishing the production system.

$$Total\ cost\ of\ production\ = Operational\ cost(USD) + Capital\ expenditure\ (USD) \quad (23)$$

Operational cost (USD):

Operational cost refers to the recurring expenses directly associated with the operation and management of the aquaculture system during a culture cycle. In this framework, operational costs include pond preparation, fish seed/fingerling procurement and transportation, feed, fertilizers/manure, lime, medicines and disease treatments, fuel/electricity for aeration or pumping, labor, pond protection and maintenance, lease rent, transportation, interest on capital/loans, and other miscellaneous expenses. These data are collected through questions on pond preparation, seed procurement, feeding and input use, pond protection and maintenance, labor activities, and other/miscellaneous costs. (Pond preparation cost: survey question 2.8, Transport cost and seed procurement cost: survey questions 2.9, Pond Protection & Maintenance Cost: survey questions: 2.12, Other / Miscellaneous Costs: survey questions 2.13, Input cost: survey questions 2.11)

Labor costs are estimated separately for each aquaculture activity based on the total person-days, number of laborers, and daily wage rate as shown in equation 25. The cost for each activity is calculated by multiplying the total person-days by the corresponding daily wage rate. Family labor is valued using an appropriate imputed wage rate, while hired labor is valued using the actual wage rate paid. The overall labor cost is calculated by summing the value of family labor and hired labor costs as shown in equation 24, using the labor activity and labor cost summary questions (survey questions 2.14 and 2.15).

$$Total\ labor\ cost = Family\ labor\ cost + Hired\ labour\ cost \quad (24)$$

$$Labor\ cost = Person\ days \times Daily\ wage\ rate \times Number\ of\ laborers \quad (25)$$

Capital expenditure (USD):

Capital expenditure represents the initial investment made to establish the aquaculture production system, including pond excavation, embankment construction, infrastructure, machinery, and equipment. These investments generally provide benefits over multiple production cycles rather than being incurred repeatedly during each cycle. Capital costs are annualized over the expected useful life of each asset. The annualized cost is then allocated to each production cycle according to the cycle's duration, with the useful life and annualization period determined separately for each asset. For assets used across multiple cycles within a year, the annualized cost is allocated across those cycles to avoid charging the full annual cost to each cycle. The expected useful life of each asset and the method used to annualize and allocate capital costs are documented. The initial capital investment data are collected through survey question 2.24.

Income

Gross income (USD):

Income represents the monetary value generated from fish harvested during a complete culture cycle and is assessed through two components: gross income, which represents the total revenue from fish sales, and net income, which represents the amount remaining after deducting the total production cost from gross income. Therefore, gross income indicates the total revenue generated from fish sales, but it does not represent the actual profit because production costs have not yet been deducted as shown in Equation 26. Data on total quantity of fish harvested and average price per kg are collected through survey question 2.21. The quantity harvested, harvest size, and the corresponding market price are recorded separately for each fish species at each partial harvest, allowing the total value of production to be calculated by summing the values of all harvested species across all harvest events. This approach accommodates differences in market prices among species and supports its application to any aquaculture production systems.

$$\begin{aligned} &Gross\ Income\ (USD) \\ &\quad = Quantity\ of\ each\ fish\ species\ harvested\ at\ each\ partial\ harvest\ (kg) \\ &\quad \times Corresponding\ price\ per\ kg\ at\ that\ Harvest \end{aligned} \quad (26)$$

Net Income/Net profit (USD):

Net income is defined as the total revenue generated from aquaculture minus the total production cost incurred during the complete culture cycle as shown in Equation 27. Total production cost includes all fixed and variable costs associated with aquaculture production (Magna et al. 2023). In this framework, net income is interpreted as accounting profit, calculated by deducting the production costs included in the assessment from gross income. It does not represent full economic profit because the opportunity cost of owned resources, particularly land used for aquaculture, is not included. Consequently, the resulting measure reflects the financial surplus after the costs accounted for by the framework rather than the return after accounting for all opportunity costs.

$$Net\ income = Gross\ income - Total\ production\ cost \quad (27)$$

3. Applications and Intended Use of the Framework

The framework is applied to compare water productivity across ponds, species combinations and management practices. It is used to identify opportunities to improve fish production, nutritional output and economic returns per unit of water used or consumed. Comparing these indicators helps identify potential synergies and trade-offs between economic returns, nutritional benefits and water use efficiency in aquaculture systems.

The framework is intended for use by researchers, aquaculture practitioners, fisheries extension officers and policymakers to support the evaluation and improvement of aquaculture production systems. It can help identify suitable species combinations and management practices that improve water resource use efficiency while enhancing fish production, nutritional contributions and economic benefits. The results may also help farmers and development organizations identify practices that provide greater benefits from limited water resources.

Furthermore, the framework could contribute to water allocation decisions between aquaculture and other sectors, such as agriculture and domestic water supply, when combined with comparable cross-sectoral data, environmental water requirements and livelihood considerations. By expressing physical, nutritional and economic outputs in relation to water use, it provides a basis for assessing the value of water in aquaculture and comparing its multiple benefits with those of alternative water uses. Overall, the framework is intended to support evidence-based decision-making for more efficient, sustainable and equitable water resource management.

4. Limitations and Planned validation

4.1 Limitations

The framework has yet to be validated using field data from a defined sample of farms. Consequently, its performance and the applicability of its indicators across diverse geographical contexts and production systems remain to be established.

Several inputs are estimated rather than measured at the pond, which introduces uncertainty:

- Rainfall and evaporation data come from the nearest weather station or from coarse-resolution gridded and satellite products, which may not reflect conditions at individual ponds. Rainfall varies over short distances, and monthly totals miss short, intense storms, which can strongly affect the SCS-CN runoff estimates.
- Runoff is estimated from runoff coefficients based on catchment characteristics.
- Seepage is estimated from standard values for each soil type.

These values are approximations and may differ from actual conditions at individual ponds.

Nutritional water productivity is estimated from nutrient values published in other studies, not from laboratory analysis of fish from the assessed ponds. Fish nutrient content varies with feed, plankton density and natural food, water quality, fish size and age, and season. Published values may therefore not reflect the fish actually produced in these ponds.

4.2 Planned validation

The validation of the framework is planned in India Sundarbans, where small fish and carp polyculture production system is being promoted as a targeted intervention. The validation will involve 30–35 ponds purposively selected from a particular agroecology with direct field measurements under real-world smallholder farming conditions. This will not be statistically representative of pond aquaculture in general. In particular, the standard seepage, runoff and evaporation values may perform quite differently in other settings, such as arid or semi-arid regions, upland or lateritic soils, or areas with deep groundwater, and in other production systems or species combinations. Before the framework is applied in other agroecological zones or production systems, it should be validated again there, using locally measured data and the stratified random sampling approach described in Annexure I.

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5. Conclusion

This framework presents the Water Productivity Assessment Framework (WPAF) for assessing water productivity across closed aquaculture production systems where water as an input can be measured and quantified with reasonable accuracy. The framework provides a systematic approach to assessing water productivity using three distinct parameters, allowing for a multidimensional evaluation of water use in production systems. Its primary audience includes researchers, technical practitioners, and project teams seeking to assess water productivity using a consistent and replicable methodology. The framework is designed to support future empirical assessments, facilitate standardized data collection and analysis, and enable comparisons across production systems where the necessary data are available. This framework addresses an important gap by developing a standardized framework for assessing aquaculture water productivity at the farm level across three complementary dimensions: economic water productivity, nutritional water productivity, and physical water productivity. It combines a baseline household survey and field measurements. Each indicator is expressed per cubic meter of water used. This report emphasizes that high fish yield alone is insufficient to assess overall farm performance. Aquaculture productivity also depends on the species composition, which influences nutrient production, as well as production costs and market prices, which together determine economic water productivity. It also depends on how much water is consumed through evaporation, seepage and harvested biomass, as distinct from total water use. The WPAF gives researchers and development practitioners a transparent, replicable and scalable way to compare how much fish, nutrition, and income each unit of water produces across different ponds, species combinations, and management practices. This report presents the method and its tools but no applied results. The framework needs to be tested using data from a representative sample of farms, and its estimates need to be validated against field measurements to assess its reliability and practical applicability.

6. References

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7. Annexure

Annexure I: Sampling Framework

Sampling design and sample size;

WPAF is meant for closed or semi-closed pond systems where water inputs can be measured with reasonable accuracy. Users define the study area to suit their objectives. It should be broadly uniform in climate, mainly rainfall and evaporation regime, and should contain enough ponds of the systems being compared. If an assessment covers more than one agro-climatic zone, each zone should be treated as a separate stratum or analyzed separately. The proposed framework recommends the use of stratified random sampling to enhance the generalizability of the approach.

Sampling frame: a complete list of eligible ponds in the study area, built from fisheries or agriculture department records, local administrative or producer-organization lists, or a quick listing survey where no such records exist.

Strata: ponds are grouped by the characteristics that most affect water use and productivity:

(a) production system: extensive, improved extensive, semi-intensive (Survey Question 2.1)

(b) main water source: groundwater, rainfed or runoff, combined (Survey Question 2.5)

(c) where relevant, soil texture class (Survey Question 2.3), because seepage, and therefore water use, depends heavily on soil type.

Users can change these strata to fit local conditions, as long as each pond falls into exactly one stratum.

Selection: ponds are drawn at random within each stratum. The sample can be allocated in proportion to stratum size, or equally across strata when comparing them is the main aim. Small strata can be oversampled or merged.

Sampling units: The unit of analysis is the pond in one complete production cycle, from stocking to final harvest (Survey Question 1.17). All water, yield, nutrient and economic quantities are calculated for each pond and cycle, so the water productivity indicators can be compared directly. The household or pond operator is the respondent and supplies the management, cost and revenue information. If a household runs more than one pond, one pond is chosen at random so that observations from the same household aren't correlated. Ponds that share water (for example, connected ponds) are treated as a single sampling unit.

Proposed sample size: The main outcome is the mean water productivity (e.g., PWP in kg/m³) within each stratum. To estimate a stratum mean within a relative margin of error e as shown in the following Equation 27:

$$n_0 = (z \times \frac{CV}{e})^2 \quad (27)$$

Assuming a coefficient of variation (CV) of about 0.5, which reflects the large variation between farms in pond systems, with z = 1.96 (95% confidence) and e = 0.10, this gives $n_0 \approx 96$ ponds per stratum. Where the stratum population is small, the sample size should be adjusted using the following Equation 28:

$$n = \frac{n_0}{(1+\frac{n_0}{N})} \quad (28)$$

To compare strata, the sample per stratum needed to detect a 25% difference in mean water productivity is shown in the following Equation 29:

$$n = 2(z_1 - \frac{\alpha}{2} + z_1 - \beta)^2 \times \frac{CV^2}{\Delta^2} \quad (29)$$

With 80% power, α = 0.05, CV = 0.5 and Δ = 0.25, this gives about 63 ponds per stratum. We therefore recommend:

- at least 30 ponds per stratum for descriptive estimates
- about 60–65 ponds per stratum for statistical comparisons between strata
- plus 10–15% extra to cover non-response and incomplete harvest records.

The total sample therefore depends on how many strata are defined. The CV should be re-estimated from pilot data (Section 4) and the sample size recalculated.

Annexure II: Baseline Survey

The purpose of this survey is to understand how households in this area manage their fishponds, how much water they use, and the production, costs and income from fish farming, so that the water productivity of fishponds can be assessed. We want to gather information on your household, your fishpond and your fish farming practices, including the species you raise, the water you use, your harvest, and your input costs and income from fish farming. This information will help us assess how much fish, nutrition and income each unit of water produces in fishponds, and identify ways to improve the productive and efficient use of water in fish farming. Your participation is crucial in helping us design better interventions to support sustainable livelihoods and improve the overall well-being of the community. The discussion will require **about 90 minutes.**

All the data that we gather from you will be used for research purposes only and the same will remain confidential. Your identity will also not be revealed to anyone. You have been selected to participate in the framework and sharing whatever you know will help to explore possible improvement of livelihood in this region. **Your participation is completely confidential and voluntary.** Your responses will not be quoted as individual responses in the report, but as a summary of all respondents. **There are no right or wrong answers to the questions,** we are simply interested in your opinion. You have the right to refuse to discuss any issue/question if you feel uncomfortable about it or even discontinue with the interview if you feel so. **If you permit us, we will proceed with the interview.**

Note: - Primary respondent should be the head of the household.
Note: - Fields labelled (USD) indicate that a monetary value is required; the USD label is indicative only. Record all amounts in local currency, as reported by the respondent. Conversion to USD is carried out during data analysis using the standard exchange rate.
I thank you in advance for accepting to participate in the framework.

Do you agree to participate and answer this questionnaire? (Yes = 1, No = 0)

If the respondent answers 'Yes', proceed with the interview. If the respondent answers 'No', thank them and move to the next household.

Section 1: Pond Identification, Ownership and Household Socio-economic Characteristics		
Part A: Pond Identification, Location and Ownership Information		
1.1	**Name of the Interviewer**	……
1.2	**Capture the location of the pond (taken at the pond embankment)**	
1.3	**Pond latitude (decimal degrees)**	……
1.4	**Pond longitude (decimal degrees)**	……
1.5	**Pond elevation (m above sea level)**	……
1.6	**GPS accuracy (m)**	……
1.7	**Administrative unit, level 1 (e.g., province / state / region)**	……
1.8	**Administrative unit, level 2 (e.g., district / county)**	……
1.9	**Administrative unit, level 3 (e.g., sub-district / commune / village)**	……
1.10	**Name of the household head** *(Lastname, First Name)*	……
1.11	**Contact number** *(If the respondent does not want to share the contact number, please write 88, if he/she does not have a phone write 98)*	……
1.12	**HH unique ID**	……
1.13	**Pond ID (as assigned in the sampling frame)**	……
1.14	**Pond size (as reported by the respondent)** **Local unit** **Conversion factor to m²** *Note: Pond area used in the calculations is based on on-site measurements (Equations 6–7). The respondent-reported pond size is collected for cross-checking purposes only.*	…… …… ……
1.15	**Ownership type (owned / leased / shared)**	……
1.16	**Lease rent, if applicable (USD)**	……
1.17	**Production cycle / season (start date – end date)**	……
Part B: Household Demographic Characteristics and Livelihood Profile		
1.18	**How many members do you have in your household?**	No …… (Specify number)

1.19	**What are the main livelihood sources of this household?** *(Select up to 3, rank by importance)*	**Code** **Livelihood** **Rank (1=main)** 1 Aquaculture ___ 3 Agriculture (crops) ___ 4 Livestock ___ 5 Vegetable farming ___ 6 Floriculture/horticulture ___ 7 Wage labor (agriculture) ___ 8 Wage labor (non-agriculture) ___ 9 Small business/trade ___ 10 Migration/remittances ___ 11 Government/private job ___ 12 Other: _____ ___
1.20	**How many members are involved in aquaculture for their livelihoods as their primary or secondary occupation?**	.....
1.21	**Gender of household head**	1 ☐ Male 2 ☐ Female 3 ☐ Other
1.22	**Education of household head**	00 ☐ No formal education 01 ☐ Primary education 02 ☐ Lower secondary education 03 ☐ Upper secondary education (or equivalent) 04 ☐ Tertiary education (degree or equivalent) 05 ☐ Vocational or technical education 06 ☐ Other (specify)
1.23	**Age of household head involved in aquaculture**	.....
1.24	**How many years are you involved in aquaculture?**	.....

Section 2: Farming characteristics and economics of production

Part A: Farming Characteristics and Management Practices

2.1. **How would you classify your aquaculture system? (Select one)**

1 ☐ Traditional/extensive (auto-stocking, no feed, no planned harvest)
2 ☐ Improved traditional/modified extensive (low stocking, basic management, occasional feeding)
3 ☐ Semi-intensive (higher stocking, regular feeding, higher inputs)

2.2 **Years of aquaculture operation: _____**

2.3 **Soil type:**
1 ☐ Sand
2 ☐ Sandy loam
3 ☐ Loam
4 ☐ Clayey loam
5 ☐ Loamy clay
6 ☐ Don't Know

2.4 **Pond infrastructure availability:**
1 ☐ Perimeter dykes / raised embankments
2 ☐ Groundwater well (tube well / borehole / dug well)
3 ☐ Rainfall and surface runoff (rainwater harvesting)
4 ☐ On-site mechanical aerator(s) – paddle wheel

2.5 **Main water source:**
1 ☐ Groundwater pumping
2 ☐ Rainfall and surface runoff (rainwater harvesting)
3 ☐ Combined groundwater pumping and rainwater harvesting

2.6 Do you monitor any water quality parameters?
1 ☐ Yes
2 ☐ No
If yes, ask the following question
Which water quality parameters do you monitor and record their measured values? (Select all that apply)
1 ☐ pH: _____
2 ☐ DO: _____
3 ☐ Temperature: _____
4 ☐ Ammonia: _____

2.7 Cropping pattern:
1 ☐ Single crop (single stocking-single harvesting)
2 ☐ Multiple crops (multiple stocking and multiple harvesting)

Part B: Production Costs and Resource Use

2.8 **Do you follow pond preparation practices?**
1 ☐ Yes
2 ☐ No

If yes, ask the following question
Which of the following practices do you follow, and what is the cost of each practice?

Pond preparation practices	Pond preparation cost (Pre-stocking)
Dewatering / pond drying cost (USD)	
Liming before stocking – type & quantity	

Liming cost (USD)	
Basal manuring / fertilizer before stocking – type & quantity	
Basal manuring / fertilizer cost (USD)	
Predatory / weed fish removal cost (USD)	
Pond bund / embankment repair cost (USD)	
Any other pre-stocking cost (specify)	
Total pond preparation cost (USD)	

2.9

What fish species do you cultivate, and what were the procurement costs for fish seeds/fingerlings in the last production cycle?
Note: If multiple ponds are present, please repeat the question for each one.

Fish Species	Number of Production Cycles per Year	Source	Weight of fingerlings/fries stocked per cycle (kg, approx.)	Size (cm)	Rate per kg (USD)	Date of stocking	Total cost (USD)
	_____	◯Natural ◯Fingerling/Fry ◯Both					
	_____	◯ Natural ◯ Fingerling/Fry ◯ Both					
	_____	◯ Natural ◯ Fingerling/Fry ◯ Both					

Transport cost of seed / fingerlings (USD): _____
Total seed procurement cost (USD) (Seed cost + Transport Cost) (USD): _____

2.10

Feeding practice: (Select all that apply)

Type of feed use?	Total quantity of feed used during the culture cycle (kg)

If feeding is practiced (i.e., any option other than "No feeding"), ask the following:
Feeding frequency:
1 ☐ Daily
2 ☐ Alternate days
3 ☐ Occasional

If feeding frequency is selected as Daily, ask the following
Do you follow timely feeding intervals?
1 ☐ yes
2 ☐ *No*
If Yes: What are the feeding times? _____

2.11

Input use (select all that apply):

Supplementary feed – type(s) used	
Total feed quantity used (kg)	
Total feed cost (USD)	
Fertilizer / manure applied during culture _type & quantity	
Fertilizer / manure cost (USD)	
Lime applied during culture – quantity	
Lime cost during culture (USD)	
Medicine / disease treatment cost (USD)	

	Fuel / electricity for aeration or pumping (USD)	
	Total input cost during culture (USD)	

2.12 **Pond Protection & Maintenance Cost**

Net for bird / predator protection – cost (USD)	
Fencing / guarding structure cost (USD)	
Net / equipment repair cost (USD)	
Other maintenance cost (specify) (USD)	
Total protection & maintenance cost (USD)	

2.13 **Other / Miscellaneous Costs**

Transport cost (other than seed procurement Ex: Market Trasport cost) (USD)	
Lease rent of pond, if not included in Section A (USD)	
Interest on capital / loan, if any (USD)	
Depreciation of equipment (nets, boats, pumps, etc.) (USD)	
Any other cost (specify) (USD)	
Total other / miscellaneous cost (USD)	

2.14

Labor Activity	Total person-days	Rate per person per day (USD/day)	Number of Laborers	Total cost
Pond preparation				
Stocking of fingerlings				
Feeding and manuring				
Routine care and maintenance (embankment, net repair)				
Guarding / watchman				
Harvesting				
Marketing, sorting and carrying				
Other (specify)				

2.15 **Overall, labor cost summary**
Cross-check with labor entered in question 2.14; enter combined totals here.

Family labor used (total person-days)	
Imputed wage rate for family labor (USD/day)	
Value of family labor (USD)	
Hired labor used (total person-days)	
Wage rate for hired labor (USD/day)	
Value of hired labor (USD)	
Total labor cost (USD)	

2.16 Did you add or exchange water during the culture cycle (top-up, exchange)?
1 ☐ Yes
2 ☐ No

If yes, complete the table below.

month	Type/model of water pump	Actual water discharge rate	Approx. pump hours per time	No of Times water added/ Exchanged per day	Method (pump, gravity/both)	Approx. water-level increase each time (cm/inches, if known)

Note: * Ask only if a pump is used. Record approximate values where exact information is not available. Do not require the farmer to provide water depth in mm or pump discharge unless the farmer knows this information. If the farmer does not know the discharge rate but can identify the pump manufacturer and model, record the manufacturer,

model, and outlet size so that the rated discharge can be obtained from the manufacturer's specifications or another reliable source, where available.

Part C: Pond Characteristics and Physical Measurements

2.17

Number of ponds: ____

Shape of the pond

1 ☐ Rectangular
2 ☐ Square
3 ☐ Irregular (sketch attached)

2.18

During heavy rain, does water from the surrounding land flow into the pond?
1 ☐ Yes
2 ☐ No

Total catchment area draining to the pond (m²)
Note: Walk or draw the catchment boundary with the mobile GIS app. Record the area of the land that drains into the pond, not the pond itself.
Method code:
1 = GPS-enabled smartphone application, Android
2 = GPS-enabled smartphone application, iPhone/iOS

Pond	Method	Catchment area (m²)

2.19

Land use, slope and soil texture of the catchment
Note: Visit the area surrounding each pond and observe the catchment area. Record the dominant land use, slope, and soil texture of the surrounding area for each pond.

Land use code: 1 = Forest, 2 = Pasture, 3 = Cultivated, 4 = Other (specify)
Slope code: 1 = Flat (0–5%), 2 = Rolling (5–10%), 3 = Hilly (10–30%)
Soil code: 1 = Sand, 2 = Silt, 3 = Clay

pond	**Land use (code)**	**Slope (code)**	**Soil texture (code)**

2.20

Total water spread area (m^2) and depth (m):

Note: Measure pond length and width (m) using a measuring tape. Measure water depth at four evenly distributed points and midpoint using a graduated pole/rod (marked at regular centimeter intervals) and record the average depth (m).

Pond	**Surface area**			**Depth (m)**						**Total water volume (m^3)**
				1	**2**	**3**	**4**	**5**	**Average**	
	Length (m)	**Width (m)**	**Length x Width (m^2)**							
1										
2										
3										

Note: If multiple ponds are present, please repeat the measurements for each one.

Part D. Harvest, Production, and Revenue

2.21 **What is the average production and annual income from aquaculture by each species?**

Note: For each fish species, record the harvest weight (kg) for each harvest event. If multiple harvests occur, sum the weights from all harvests to calculate the total production (kg) for that species. Record the average sale price for each species. Total revenue is calculated automatically using total harvest weight and average sale price.

Species Name	Average size at harvest (cm)	Production Weight in quintals (kg)					Quantity sold	Avg. Price (USD/kg)	Total Revenue (USD) *(auto/computed)*	Mortality observed (%)
		H1	H2	H3	H4	Total				

Note: If multiple ponds are present, please repeat the question for each one.
If more than four harvest events are recorded, repeat the relevant section as required.
If the same species is harvested multiple times, record each harvest separately.
If no harvest of the same species has occurred multiple times, leave the additional fields blank.

How many kg of harvested fish is kept for home consumption?
Family consumption: _____ kg
Distributed among laborers or gifted to local community: _____ kg

Part E. Cost Allocation and Profitability Assessment

2.22 **Species-wise Cost of Production & Profitability**

Total pond preparation cost (from 2.8)	
Total input cost during culture, excluding any species-specific feed entered directly in (from 2.11) (USD)	
Total protection & maintenance cost (from 2.12) (USD)	
Total labour cost, (from 2.14) (USD)	
Total other / miscellaneous cost (from 2.13) (USD)	
Total common cost pool to be allocated (USD)	
Total quantity harvested, all species (kg) (from 2.20)	

2.23 **Species-wise Cost of Production & Profitability**

Species	Qty harvested (kg)	Share of total harvest (%) = this qty ÷ total qty	Direct seed cost (USD) [species-specific, from	Other direct cost, if any (USD) (e.g. species-specific feed)	Allocated share of common cost pool (USD) = J1 total × share %	Total cost for species (USD) = direct + other direct + allocated	COST OF PRODUCTION (USD / kg)	Selling price (USD / kg) [from I]	Profit / loss (USD / kg)

Total cost of production, all species combined (USD) (sum of J2)	
Total sales revenue, all species combined (USD) (from I)	
Net profit / loss, pond level (USD)	

2.24

Capital Cost

Instructions: List every durable asset (anything used for more than one production cycle) used for this pond, including assets shared with other ponds. Enter the original purchase or construction cost, not the annual cost.

Asset	Quantity	Year of purchase / construction	Original cost (USD)	Expected life (years)	Annual depreciation (USD)
Pond excavation / construction					
Land leveling / development					
Electricity connection					
Fencing					
Boat					
Harvesting / drag net					
Pump					
Aerator					
Other, specify					

Section 3: General data (Macro-level environmental data and local labor market rates)

3.1

Note: The enumerator must visit the local Sub-divisional Meteorological Station to obtain official data.

Nearest meteorological station

Name: _____

Distance from the pond (km): _____

Data source:

1 ☐ Meteorological Station
2 ☐ State agriculture department
3 ☐ Own Weather Station
4 ☐ Other

Part A

What type of evaporation monitoring data is available from the local meteorological station?

1 ☐ Penman Formula Method
2 ☐ Other (specify):
3 ☐ No data available

Month	Evaporation rates (mm)
1	
2	
3	
4	
5	
6	
Average	

Please complete the table by filling in the monthly evaporation rates in mm

Note: If data are available based on the previous question, fill in the corresponding column for the months the pond is actively in use (from Stocking to Harvest).

Part B

What type of precipitation monitoring data is available from the local meteorological station?

1 ☐ Standard Rain Gauge Method (Daily/Monthly Rainfall)
2 ☐ Other (specify):
3 ☐ No data available

Please complete the table by filling in the monthly rainfall (precipitation) in mm,
Note: If data are available based on the method selected in the previous question, fill in the corresponding column for the months the pond is actively in use (from stocking to harvest).

Month	**Precipitation in mm**
1	
2	
3	
4	
5	
6	
Average	

3.2

Note: The enumerator must verify the prevailing market wage rates by checking with the local government or village administration office, local labor contractors, or official regional minimum wage records.

Please record the daily wage rates for both male and female laborers. What is the average market rate (wage rate) for labor in this area per day?

Male labor rate (per day) ___

Female labor rate (per day) ___

Average working hours (per day) ___



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