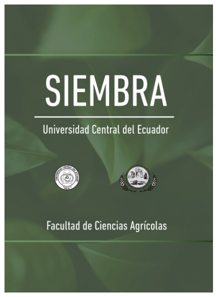
Determination of difference in flow distribution in the quantification of the hydric demand for land use. Case study Tumbaco's irrigation channel, Pichincha, Ecuador



Determinación de la brecha hídrica en la distribución de caudales a partir de la cuantificación de la demanda hídrica por uso de suelo. Estudio de caso del canal de riego Tumbaco, Pichincha, Ecuador

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Abstract

In Ecuador, the administration, operation, and maintenance of irrigation systems are the responsibility of water irrigation boards. These organizations distribute water resources facing different problems related to unknown water demands of crops and other specific system parameters, which creates an imbalance between offer and demand. This research proposes the development of a methodology to estimate water requirements in the Tumbaco irrigation canal, to optimize the use of this resource. The methodology incorporates variables such as cultivable land area, crop type, edaphic(land) factors, and climate conditions, to accurately quantify flow rates that should be delivered to the sectors directly influenced by the canal. The proposed methodology is adaptable to various territories, and different water application strategies have been considered according to each system's reality. Among the main results, it was found that the current irrigation of the branches that make up the canal is higher than the actual demand. For the Alangasí-La Merced branch, a requirement of 28.80 l s ha^{-1} was established, which compared to the flow delivered by the irrigation board, it was observed that 247.22% more water is distributed than necessary. Similar overestimation results were found in all other branches analyzed: Chichipata 241.66 l s ha^{-1} (+44.83%), Churoloma branch 132.79 l s ha^{-1} (+35.55%), El Pueblo branch 97.3 l s ha^{-1} (+54.16%), Ilaló branch 220.83 l s ha^{-1}(+44.91%), La Viña 68.34 l s ha^{-1} (+119.49%), and San Blas 20.13 l s ha^{-1} (+496.12%). The developed methodology can be applied to manage large-scale sustainable water management programs and as a water resource management model. It can also serve as a baseline for establishing econometric models in the collection of irrigation water consumption fees.

Keywords: irrigation, land use, optimization of water, hydric demand, evapotranspiration.

Resumen

En Ecuador, la administración, operación y mantenimiento de sistemas de riego se encuentra gestionada por juntas de usuarios, las cuales distribuyen el recurso hídrico enfrentando diferentes problemáticas relacio-

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nadas con el desconocimiento de la demanda hídrica de los cultivos y condiciones propias del sistema, lo cual crea una brecha entre la oferta y la demanda. Esta investigación propone el desarrollo de una metodología de cálculo del requerimiento hídrico en el canal de riego Tumbaco, con la finalidad de optimizar este recurso, mediante la incorporación de variables de superficie de tierra cultivable, tipo de cultivo, factores edáficos y climáticos para cuantificar adecuadamente los caudales que deben ser entregados en los diferentes sectores de influencia directa del canal. La metodología propuesta es adaptable a diversos territorios y han sido consideradas diferentes estrategias de aplicación de agua, de acuerdo con la realidad de cada sistema. Entre los principales resultados se obtuvo que la irrigación de los ramales que conforman el sistema se encuentra sobreestimada; en el caso del ramal Alangasí-La Merced se establece un requerimiento de 28,80 l s ha^{-1}. Al compararlo con el caudal entregado por la junta de riego, se observa que se distribuye un 247,22 % más de lo necesario, el ramal Chichipata 241,66 l s ha^{-1} con +44,83 %, ramal Churoloma 132,79 l s ha^{-1} +35,55 %, ramal El Pueblo 97,3 l s ha^{-1} +54,16 %, Ilaló 220,83 l s ha^{-1} +44,91 %, La Viña 68,34 l s ha^{-1} +119,49 % y San Blas 20,13 l s ha^{-1} +496,12 %. La metodología desarrollada se puede aplicar para gestionar programas de manejo sustentable de agua a gran escala y como modelo de gestión del recurso hídrico, así como servir de línea base para establecer modelos econométricos en la recaudación de tarifas de cobro por consumo de agua de riego.

Palabras clave: riego, uso de suelo, requerimiento hídrico, optimización de agua, evapotranspiración.

1. Introduction

Climate change and human activities have contributed to the scarcity of freshwater worldwide (Huang et al., 2021). Irrigation has been one of the most water-intensive productive activities, as it accounts for over 70% of global freshwater withdrawals (FAO, 2020), which puts pressure on water resources (Wang et al., 2016).

Latin America is no exception, as the region also faces pressure on water resources, with irrigated agriculture increasing from 8 million to 52 million hectares in 2016, implying a continuous extraction of water in the region (Villalobos et al., 2017).

Irrigation in Ecuador involves high water consumption, as the government authorizes a daily constant flow of 682.50 m^3 s^{-1} for consumptive water use, with irrigation consuming a flow of 560.9 m^3 s^{-1}, representing 82 % of the authorized flow. Therefore, irrigation becomes the activity with the highest consumptive use (Ministerio del Ambiente, Agua y Transición Ecológica [MAATE], 2021). The water distribution is not optimal, as irrigation boards, responsible for providing water to their communities, allocate uniform flows for all agricultural production units (UPA), regardless of area, type of crop, or irrigation method (Instituto Interamericano de Cooperación para la Agricultura [IICA], Fundación Colegio de Postgraduados en Ciencias Agrícolas, San Luis Huexotla [Fundación COLPOS], Programa de Cambio Climático, Recursos Naturales y Gestión de Riesgos Productivos [PCRG], y Eje Transversal Innovación y Tecnología [ETIT], 2017). This results in over-irrigation and under-irrigation, combined with inefficiency in water management by farmers due to several factors, including the type of water conveyance, from intake to inadequate application time in furrow, sprinkler, or drip irrigation systems at the community level, which further exacerbates the problem (Cercado Damiany, 2022).

The information presented highlights the relationship between the supply and demand of water related to various anthropogenic activities in Ecuador, with an emphasis on agricultural production. By identifying possible excesses in water delivery to farmers or deficits in water distribution to different production systems, it is possible to identify a water gap in an area or irrigation system, which will allow for the establishment of strategies for the proper management of water resources (Leiva-Zelada & Zelada-Muñoz, 2024).

It is estimated that there are around 4,000 irrigation users in the Tumbaco parish, for whom agriculture is the main subsistence economic activity (GAD Tumbaco, 2020). Agricultural development has been favored in this area, as it features a vast expanse of flat topography with a diversity of climates and soils, which helps crops grow optimally.

The Tumbaco irrigation system does not have a flow distribution across its different branches based on the water requirements of the crops, which directly affects agricultural activities in the area (Ortiz et al., 2021). This article aims to validate and implement a methodology for quantifying water requirements based on land use in the Tumbaco irrigation canal to determine whether the flow authorized by the Tumbaco Irrigation Board is optimal in relation to the calculated required flow. Over-irrigation is identified in the seven branches that make up the Tumbaco irrigation system.

2. Materials and Methods

The study area is located in Tumbaco, Quito canton, Pichincha province, at coordinates 0°12′48″S 78°24′03″W. The Tumbaco irrigation system consists of a main canal, with a length of 21.76 km, and seven branches (Figure 1), which are: Alangasí-La Merced branch 3.83 km, Ilaló branch 13.65 km, Chichipata branch 8.63 km, Churoloma branch 6.95 km, El Pueblo branch 8.16 km, La Viña branch 4.36 km, and San Blas branch 2.99 km (GAD Tumbaco, 2015). Different types of water conveyance systems are present: cement-covered, piping, or earthen, as well as various types of irrigation systems, such as furrows, drip, and sprinkler (Ortiz et al., 2021).

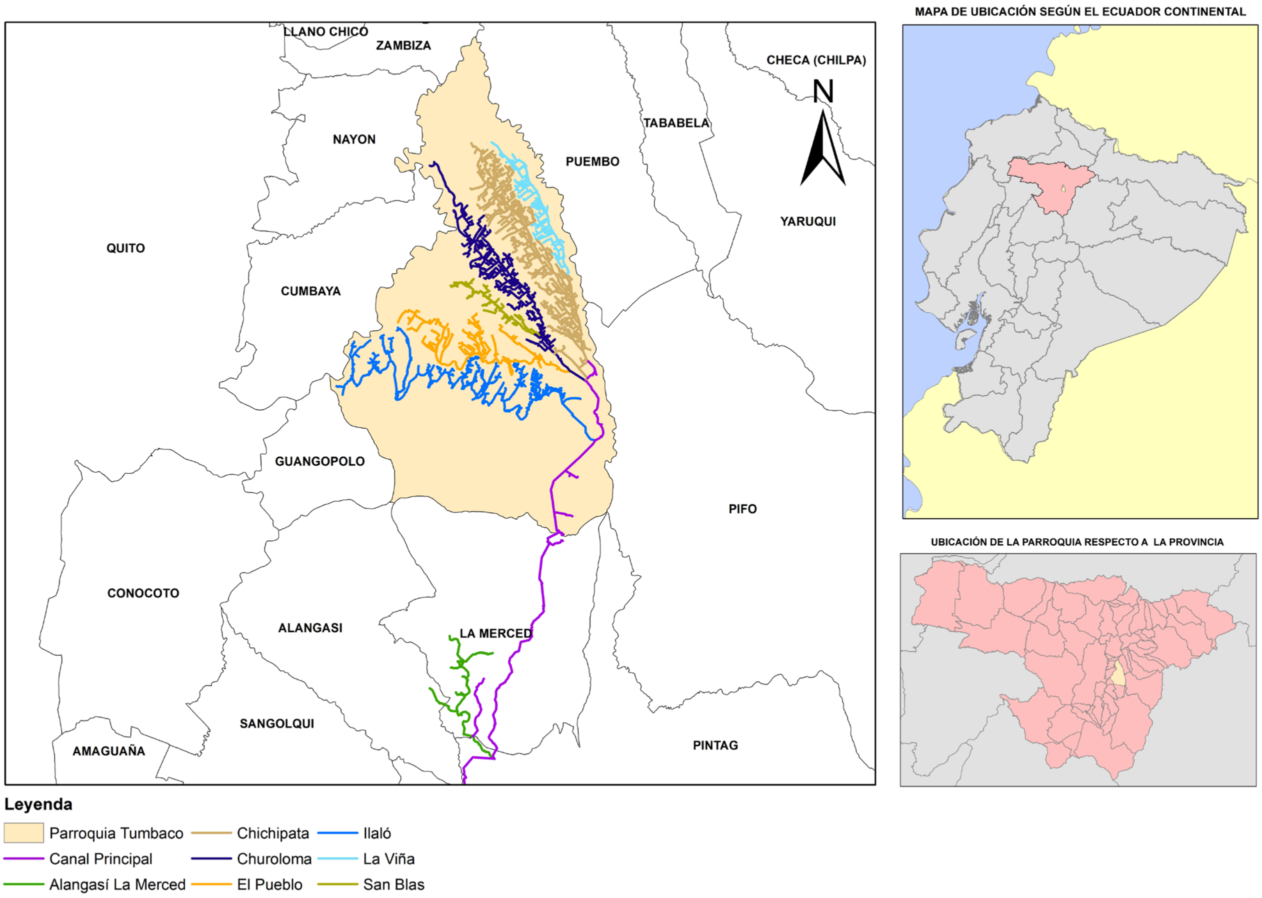

Figure 1. *Dynamics of water distribution in the Tumbaco irrigation system.*

2.1. Land use

A land-use recategorization was carried out using the cadastral data compiled in 2016 for each of the seven branches that form part of the Tumbaco irrigation canal (Aguirre Escobar, 2017; Andrade Betancourt, 2018; Chasiluisa Yanchatuña, 2017; Cisneros Vaca, 2018; Estévez Cadena, 2017; Maigua Barreno, 2017; Montecé Calderón, 2018; Ochoa Ortega, 2017; Tipantiza Chicaiza, 2020). This recategorization determined that the main crops in the study area are: grass, avocado, maize, vegetables, citrus, tomato, fruit trees, alfalfa, short-cycle crops (beans, broad beans, potatoes), and forest (conifers, eucalyptus). This process was supported through the interpretation of satellite images (Landsat) from 2016.

2.2. Crop coefficient

The quantification of water demand for irrigation management purposes is carried out using the crop coefficient (Guerra et al., 2015); this coefficient determines the relationship between crop evapotranspiration and reference evapotranspiration (Allen et al., 2006).

Globally, the information generated by FAO Bulletin N.º 56 is used, which establishes reference parameters. However, several local studies determine different ranges of Kc data due to local influencing factors, such as cultivar variety, climate, crop evapotranspiration (Guerra et al., 2015), as well as changes in vegetation and land cover (Allen et al., 2006). For this reason, it is necessary to use a coefficient adapted to the study area, if available (Espinosa & Rivera, 2016).

Table 1 shows the coefficient values for each crop. For crops not included in the estimated values in the publication, a literature review was conducted, such as for forests with conifer species (Allen et al., 2006) and eucalyptus (Alves et al., 2013), obtaining an average value of 0.91 for forests, as the land use in these categories is mixed.

For fruit species, two types are considered: stone fruits and pome fruits, with Kc values of 1.15 and 1.2, respectively, resulting in an average of 1.18. The short-cycle category includes crops like beans with an average Kc of 1.05, broad beans with 1.15, and potatoes with 1.15, yielding an average Kc value of 1.12.

Table 1. Main crops identified with Kc in the Tumbaco irrigation system.

Corp type	Initial Kc	Medium Kc	Final Kc	Autor
Eucalyptus forest	-	0,91	-	Alves et al. (2013) and Allen et al. (2006)
Grass	0.90	0.95	0.95	
Avocado	0.60	0.85	0.75	
Corn	-	1.2	0.60-0.35	
Vegetables	0.70	1.05	0.95	
Citrus	0.75	0.70	0.70	Allen et al. (2006)
Tomato	-	1.15	0.70-0.90	
Fruit trees	-	1.18	-	
Alfalfa	0.40	0.95	0.90	
short cycle	-	1.12	-	

2.3. Analysis of climate information

Atmospheric conditions, such as radiation, temperature, humidity, and wind speed, influence the evapotranspiration process (Allen et al., 2006). Precipitation and temperature lead to sudden changes in ET, as a relationship between these variables has been determined (Kuzay et al., 2022).

For this study, databases were generated for the following climatic variables: temperature (°C), precipitation (mm), wind speed m $s^{-1,}$ sunshine hours, evaporation (mm), and relative humidity (%), over a 31-year period from 1990 to 2021. These data were obtained from the Tumbaco ordinary climatological station, managed by INAMHI, and processed using the climatol function for homogenizing different meteorological variables and climatological indicators (Adeyeri et al., 2022).

2.4. Effective precipitation estimate

Effective precipitation [*Pe*], compared to total precipitation [P], more accurately expresses the amount of water that crops can use productively (Tigkas et al., 2016). Effective precipitation is influenced by various factors, such as the amount of irrigation, crop characteristics, soil, and rainfall (Ali & Mubarak, 2017). Therefore, it is important to establish an optimal model for its calculation. The method recommended by the Soil Conservation Service of the United States Department of Agriculture [USDA-SCS] was used to estimate effective precipitation, expressed in equation [1] (Dastane, 1978).

$$Pe = P / 125 (125 - 0.2 P) \quad [1]$$

2.5. Reference evapotranspiration estimate

Four methods were selected for calculating reference evapotranspiration: 1. Thornthwaite, 2. FAO Penman-Monteith, 3. Hargreaves-Samani, and 4. Evaporation tank. The first three are considered indirect methodologies derived from physical analyses, while the fourth is considered a direct measurement method. The selection was made based on the availability of climatic variables and taking into account the most widely accepted quantification methodologies in water resources studies in Ecuador. For calculating reference evapotranspiration, depending on the methodology used, climatic information related to temperature (°C), precipitation (mm), wind speed $ms^{-1,}$ evaporation (mm), and relative humidity (%) from the 1990-2021 period at the La Tola meteorological station, located in the study area, was considered.

2.5.1. Thornthwaite Ecuation

Thornthwaite has been widely used in Ecuador for calculating water balances in the Andean region for pastures (Franco Puco, 2018), in páramo ecosystems (Guamán Caballero & Rodas Velarde, 2022), and in micro-basins in the Amazon region (Poma & Usca, 2020).

The fundamental equation of the model (equation [2]) is based on the mean monthly temperature, with a correction index based on altitude. The heat index is calculated from the mean air temperatures, obtaining the annual heat index [*I*], determined as the sum of twelve monthly heat index values for theoretical months of 30 days and 12 hours of sunlight per day (Thornthwaite, 1948).

$$ETo = 1{,}6\left({}^{10Tef}/_{I}\right)^{a} \qquad [2]$$

Where, I = Annual heat index (Dlouhá et al., 2021), Tef = Effective temperature (°C), $a = 0{,}49 + 0{,}0179I – 0{,}000077I^2 + 0{,}000000675I^3$.

2.5.2. FAO Penman-Monteith equation

The FAO model calculates evaporation based on several input variables, such as air temperature, wind speed, heat storage, and net radiation (Dlouhá et al., 2021), using the FAO Penman-Monteith formula (equation [3]) (Allen et al., 2006). This method is recommended for determining reference evapotranspiration for the Tumbaco valley (Ortiz & Chile, 2020), as the necessary data for the model's optimal performance is available.

$$ETo = \frac{0{,}408\Delta(Rn-G)+ Y\frac{900}{T+273}U_2(e_s-e_a)}{\Delta+Y(1+0{,}34U_2)} \qquad [3]$$

Where, ETo = Potential evapotranspiration mm day^{-1}, Rn = Net radiation on the crop surface MJ m^{-2} day^{-1}, G = Heat flow in the ground MJ m^{-2} day^{-1}, Δ = Vapor pressure curve slope kPa°C^{-1}, Y = Psychometric constant kPa°C^{-1}, T = Average temperature °C, U_2 = Wind speed measured at 2 m height m s^{-1}, Es = Saturation vapor pressure kPa, ea = Real steam pressure kPa.

2.5.3. Hargreaves-Samani equation

The Hargreaves-Samani equation (equation [4]) (Hargreaves & Samani, 1985) is a reliable and widely used method for estimating ETo over daily periods (Pérez-Leira et al., 2018), as similar values to those obtained by the Penman-Monteith method are found in the Andean region (Espinosa et al., 2023). This method is used in Ecuador as a starting point for agricultural and forestry studies (Cárdenas Torres, 2021). The equation requires temperature and solar radiation data, making it an appropriate method for areas lacking information on wind speed and relative humidity (Morales-Salinas et al., 2017).

$$\text{ETo}=0{,}0023*KT*Ra*(T+17.8)*(T_{max} - T_{min})\text{^}0{,}5 \qquad [4]$$

Where, ETo = Potential evapotranspiration mm day^{-1}, Ra = Incoming shortwave solar radiation mm d^{-1}, T_{max} = Maximum temperature °C, T_{min} = Minimum temperature °C, KT = 0.162 for internal regions and 0.19 for coastal regions.

2.5.4. Class A Evaporimeter Tank Equation

The evaporation tank is an instrument for quantifying water demand. This method is very useful for improving irrigation management efficiency, as it can be used by any producer in different regions due to its low cost in the case of alternative tanks (Neves et al., 2022). It has been successfully used to estimate reference evapotranspiration by observing the evaporation loss from a water surface and applying empirical coefficients to relate the tank evaporation to *ETo* (equation [5]) (Allen et al., 2006). For the local calibration of the dimensionless tank coefficient *Kp*, the calibrated value for Tumbaco generated in 2018 was used (Ortiz et al., 2018).

$$ETo=Kp*ECA \quad [5]$$

Where, *ETo* = Reference evapotranspiration mm day^{-1}, mm $month^{-1}$, *Kp* = Dimensionless tank coefficient, *ECA* = Tank water evaporation mm day^{-1}, mm $month^{-1}$.

2.6. Evapotranspiration sensitivity analysis

It is used to estimate the adjustment relationship between the calculated reference evapotranspiration values obtained by indirect methods (Penman-Monteith, Thornthwaite, & Hargreaves-Samani) and to determine the best methodology that aligns with a direct measurement method (evaporation tank), which was previously calibrated to estimate reference evapotranspiration in the Tumbaco valley (Moreno Romero, 2023; Ortiz et al., 2018). For this purpose, the simple linear regression model (equation [6]) was applied, which measures the linear relationship between two variables.

The result will determine whether there is a significant correlation between variables (Boslaugh, 2008). The absolute value [*r*] establishes the significance relationship; thus, a value of 0.1 is classified as low, a value of 0.3 as medium, and a value greater than 0.5 as high (Cohen, 1988).

$$r = \frac{\Sigma(x-\bar{x})(y-\bar{y})}{\sqrt{\Sigma(x-\bar{x})^2\Sigma(y-\bar{y})^2}} \quad [6]$$

2.7. Water balance

The water balance integrates climatic variables to determine irrigation requirements in order to design and plan water availability in a specific area (Espinosa et al., 2011). The calculation uses a monthly accounting of precipitation and potential evapotranspiration, with the goal of establishing the evolution of water on a monthly basis, determining whether there is evapotranspiration, if it is retained in the soil reserve, or if there is a deficit or excess of water (equation [7]) (Thornthwaite & Mather, 1957).

$$P\text{-}ER(\pm \Delta\ Alm)\text{-}Exceso=0 \quad [7]$$

Where, *P* = Water supply due to precipitation, *ER* = real evapotranspiration, *Alm* = Soil water storage.

2.8. Calculation of water requirements and determination of characteristic flows

2.8.1. Water requirement

It was obtained by applying equation [8] proposed by FAO in 1990 (Allen et al. 2006).

$$ETc=ETo*Kc \quad [8]$$

Where, *ETc* = Crop evapotranspiration mm $month^{-1}$, *ETo* = Reference evapotranspiration mm $month^{-1}$, *Kc* = Crop coefficient. Own coefficient of each dimensionless crop.

2.8.2. Monthly net requirement

It is established by equation [9] proposed by Brouwer et al. (1985).

$$N\ H\ M = ETc - Pe \quad [9]$$

Where, *MNR* = Monthly net requirement mm $month^{-1}$, *ETc* = Crop evapotranspiration mm $month^{-1}$, *Pe* = Effective precipitation.

2.8.3. Gross requirement

To calculate the gross requirement, an application efficiency of 75 % belonging to sprinkler irrigation was considered (Burt et al., 1997; Soil Conservation Service, 1985). In the case of areas with drip systems, the efficiency considered is 90% and in the case of drip irrigated areas, 50% is considered (Brouwer et al., 1985b; MINAGRI, 2015a; Soil Conservation Service, 1985), using equation [10]. These efficiencies were identified according to the irrigation systems present in the study area (MAATE, 2021), need in addition to being related to the conduction efficiency study of the Tumbaco irrigation system published by Ortiz et al. (2021).

$$NB = \frac{NND}{Efa} * 100 \quad [10]$$

Where, GR = Gross requirement mm day^{-1}, DNR = Daily net requirement mm day^{-1}, Efa = Efficiency of irrigation water application according to the type of irrigation.

2.8.4. Nominal flow per crop

The minimum required flow for each crop was quantified for all months of the year to identify the month with the highest water demand using equation [11]. The GR is expressed in mm day^{-1}; therefore, 1 mm is equivalent to 1 liter per m² per day to convert NB into flow rate.

$$Qc = \frac{NB * 1\frac{l}{m^2} * \frac{10000m^2}{1ha}}{dia * \frac{24h}{1\,dia} * \frac{3600s}{1\,hora}} \quad [11]$$

Where, Q_c = Nominal flow per crop l s^{-1} ha^{-1}, GR = Gross requirement mm day^{-1}.

2.8.5. Necessary flow for each branch

Once the critical flow was determined according to the month of greatest demand for each of the crops, it was extrapolated across the area of this crop, for which the equation [12] was applied.

$$Q_r = Q_c * S \quad [12]$$

Where, Q_r = Flow per branch l s ha^{-1}, Q_c = Crop flow present in the area l s ha^{-1}, S = Arable area ha.

3. Results and Discussion

3.1. Land use

The development of agriculture in the Tumbaco parish is directly influenced by the irrigation canal, benefiting from diverse climates and soil types that support the implementation and diversification of various crops.

The potential irrigation area has an extensive flat topography, which has facilitated the establishment of traditional agriculture. The main cultivated crops (Table 1) include maize (*Zea mays*), tomato (*Solanum lycopersicum*), bean (*Phaseolus vulgaris*), potato (*Solanum tuberosum*), avocado (*Persea americana*), cherimoya (*Annona cherimola*), peach (Prunus persica), guaba (Inga edulis), tree tomato (Solanum betaceum), lemon (Citrus limon), mandarin (*Citrus reticulata*), lettuce (*Lactuca sativa*), cabbage (*Brassica oleracea var. capitata L.*), radish (*Raphanus sativus*), celery (*Apium graveolens*), forested areas, and grasslands, as confirmed by several studies (Espín Mayorga, 2015; MAATE, 2021; Tipantiza Chicaiza, 2020). The identified crops are generally found in medium and large plots. Table 2 presents the land use coverage for each branch of the irrigation canal. To simplify the information, the crops have been grouped, as shown in Table 2.

Table 2. Different types of crops by surface area (ha).

Crop type *	Alangasí La Merced	Chichipata	Churoloma	El Pueblo	Ilaló	La Viña	San Blas
Avocado	0.5	10.8	3.4	10.9	13.1	2.1	0.3
Alfalfa	-	1.6	0.6	0.3	0.9	0.1	-
Forest	14.4	29.2	14.3	20.6	79.6	7.6	3.7
Short cycle	1.3	40.7	18.6	13.6	38.4	6.7	2.7
Citrus	0.2	15.8	3.3	10.3	10.5	2.3	1.2
Fruit trees	-	23.3	6.4	4.7	8.4	4.6	0.7
Vegetables	0.9	2.2	2.2	1.1	2.1	0.7	
Corn	1.2	27.0	9.8	2.3	10.7	4.8	0.4
Grass	18.3	143.1	104.5	61.4	113.8	55.6	16.6
Tomato	-	0.3	0.2	-	-	-	-
TOTAL	36.9	293.9	163.3	125.0	277.6	84.7	25.5

***** The land use groupings are based on the following list of crops: corn, tomatoes, beans, potatoes, fruit trees (avocado, custard apple, peach, guava, tree tomato), citrus (lemon, mandarin), vegetable gardens (lettuce, cabbage, radish, celery, etc.).

3.2. Effective precipitation

Table 3 identifies that the critical months of precipitation are July with 13.3 mm and August with 17.5 mm, while the months with the highest effective precipitation are March with 100.1 mm and April with 93.3 mm, which is consistent with previous studies (Calderón Baños, 2014).

Table 3. Effective rainfall for Tumbaco.

Months	Precipitation (mm)	Effective precipitation (mm)
January	69.7	61.9
February	79.2	69.2
March	125.1	100.1
April	114.1	93.3
May	68.1	60.7
June	27.7	26.5
July	13.6	13.3
August	18	17.5
September	46.8	43.3
October	108.3	89.5
November	107.9	89.3
December	77.8	68.1
Total	**856.3**	**732.6**

3.3. Reference evapotranspiration

The determination of reference evapotranspiration in Ecuador primarily focuses on analyzing four physically based methodologies and one direct measurement method. The main question regarding the application of one method over another is the accuracy of the obtained results (Figure 2), as values may vary depending on the number of meteorological variables involved in the calculation. Depending on the implemented method, the results may create either a positive or negative differential in water demand, a topic of discussion among various public institutions. For instance, the *Plan Nacional de Gestión Integrada de los Recursos Hídricos* uses the Penman-Monteith methodology (Changjiang Institute of Survey, Planning, Design, and Research

[CISPDR], 2016), while the Instituto Nacional de Meteorología e Hidrología [INAMHI] determined that the Penman-Monteith and Thornthwaite methods show similar trends under Ecuador's environmental conditions (Hargreaves & Samani, 1985; Ortiz et al., 2018; Snyder et al., 2005).

The FAO Penman-Monteith method is widely recommended worldwide due to its higher accuracy, as it incorporates more climatic variables into its analysis. However, this also represents its main limitation in practical application (Djaman et al., 2019; Rodrigues & Braga, 2021). The Thornthwaite and Hargreaves-Samani models do not consider wind speed variables, which suggests that they underestimate *ETo* values in July and August, directly affecting the evapotranspiration rate (Ortiz & Chile, 2020). These types of statements can be subjective if the trend of each of the results or the sensitivity with respect to a direct estimation method, such as the type A tank, is not analyzed.

Figure 2 shows that the lowest *ETo* values were obtained using the Thornthwaite method, with an average of 1.41, followed by Hargreaves-Samani at 1.75, the evaporation tank at 3.08, and the highest value recorded using FAO Penman-Monteith at 5.43. The variation in results is primarily due to the different climatic variables each model considers in its calculations (Espinosa & Rivera, 2016; Ortiz et al., 2018; Romero-Palomares et al., 2019; Thornthwaite, 1948).

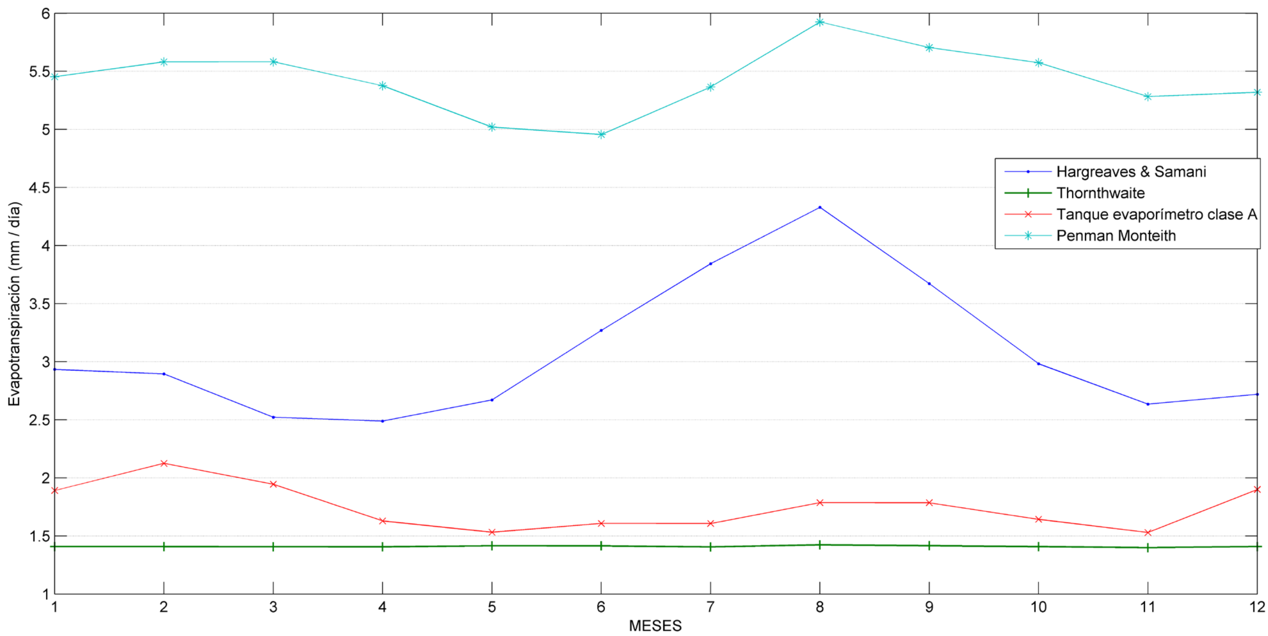

Figure 2. Distribution of values obtained for different evapotranspiration models (Thornthwaite, Hargreaves, Penman-Monteith and Type A tank).

3.4. Sensitivity analysis of evapotranspiration models

To analyze the variations in the comparison of results obtained from the proposed evapotranspiration methods in this study, their sensitivity was estimated concerning a direct estimation method using the coefficient of determination. This analysis was conducted considering that the Tumbaco area has a meteorological station providing comprehensive climate data, managed by INAMHI, with over 30 years of recorded information.

When comparing the results obtained from the Class A evaporation tank with the Thornthwaite method, the determination and correlation values were higher. This indicates better performance than the FAO Penman-Monteith and Hargreaves-Samani methodologies, as illustrated in Figure 3.

This analysis was conducted to determine an appropriate estimation methodology when meteorological data availability is limited for the proper implementation of a method. By doing so, uncertainty in obtaining results can be minimized. Similar analyses have been carried out in other countries, demonstrating that each methodology can be adapted to specific areas based on their geographic, climatic, and, in some cases, topographic conditions (Hargreaves & Samani, 1985; Ortiz et al., 2018; Snyder et al., 2005; Trezza).

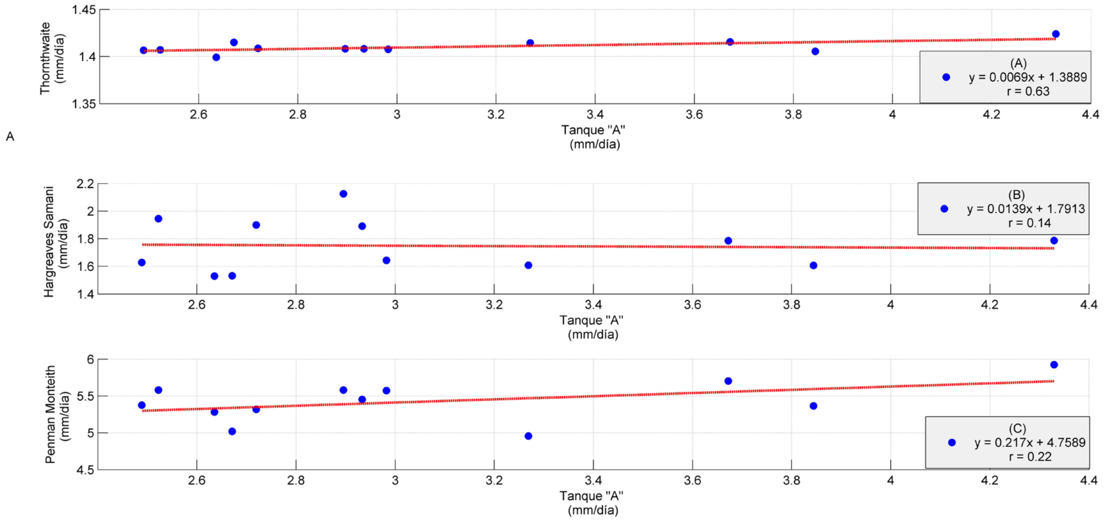

Figure 3. Regression model for the evaporation model (Eto) **(**a). Tank vs Thornthwaite; (b) Tank vs. Hargreaves-Samani; (c) Tank vs. Penman-Monteith. R^2.

3.5. Water balance

The Tumbaco region experiences a water deficit (Figure 4) from June to September, with the highest value recorded in August at 116.2 mm. Water storage in the soil occurs in October and November, while surpluses are observed in March and April. These surpluses can be expressed as runoff for surface flow analysis. Soil water reserves are utilized in December, January, February, and May to compensate for water loss due to evapotranspiration, which aligns with other water management and dynamics models (Carrera-Villacrés et al., 2019).

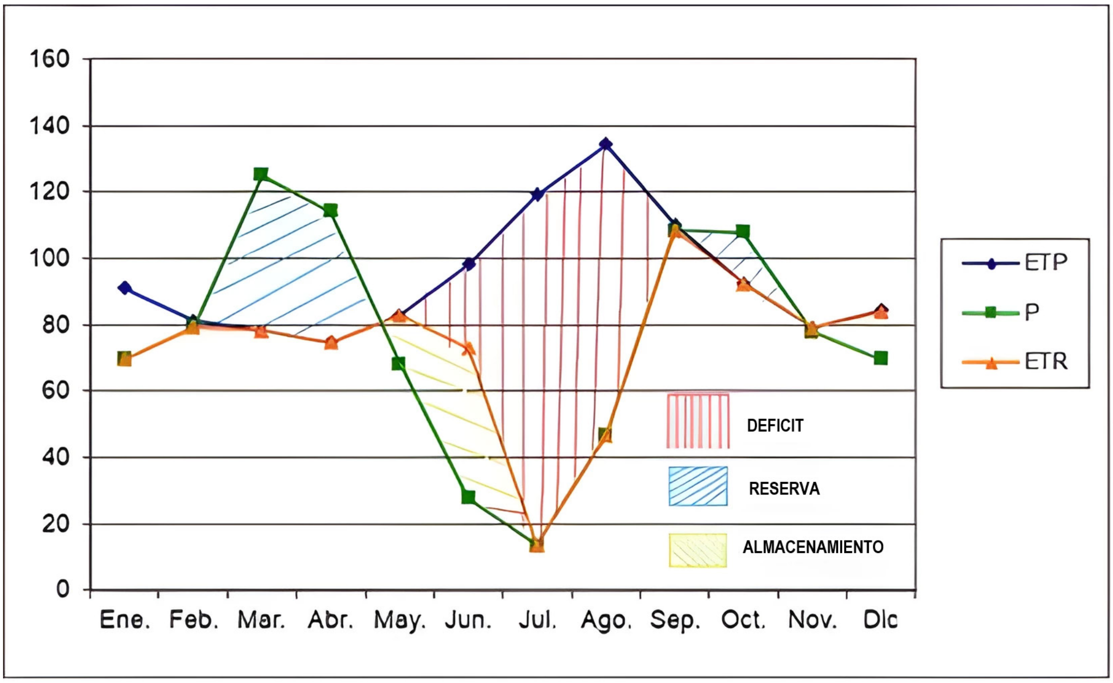

Figure 4. Water balance from the Tumbaco area.

3.6. Water balance

The nominal flow rates in l s ha^{-1} are established based on the critical month with the highest daily evapotranspiration (August) for the main crops present in each branch of the SRT (Table 4).

Table 4. Nominal flow calculated by branches.

Crops	Alangasí	Chichipata	Churoloma	El Pueblo	Ilaló	La Viña	San Blas
Avocado	0.36	7.44	2.33	7.54	9.04	1.47	0.20
Alfalfa	-	1.25	0.50	0.22	0.67	0.06	-
Forest	10.73	21.72	10.64	15.32	59.33	5.69	2.76
Short cycle	1.24	38.13	17.42	12.71	35.97	6.30	2.54
Citrus	0.11	8.74	1.82	5.67	5.82	1.29	0.64
Fruit trees	-	23.13	6.35	4.62	8.37	4.61	0.67
Vegetables	0.80	1.89	1.95	0.97	1.86	0.62	-
Corn	1.24	27.24	9.09	2.28	10.81	4.87	0.37
Grass	14.33	111.87	81.64	47.96	88.97	43.43	12.95
Tomato	-	0.26	0.24	-	-	-	-
Total (l s ha^{-1})	**28.80**	**241.66**	**132.79**	**97.3**	**220.83**	**68.34**	**20.13**
Delivered Flow Rate (l s ha^{-1})	**100.00**	**350.00**	**180.00**	**150.00**	**320.00**	**150.00**	**120.00**
Gap %	**247.22**	**44.83**	**35.55**	**54.16**	**44.19**	**119.49**	**496.12**

By comparing the flow rate assigned by the Tumbaco Irrigation System's water users' association, it is established that over-irrigation exists in all branches. For example, the Alangasí-La Merced branch exceeds the required amount by 247.22 %, Chichipata by 44.83 %, Churoloma by 35.55 %, El Pueblo by 54.16 %, Ilaló by 44.91 %, La Viña by 119.49 %, and San Blas by 496.12 %. This aligns with the findings of Ortiz et al. (2021), who assessed the water distribution efficiency in the seven branches of the Tumbaco irrigation system and identified over-irrigation in six branches and under-irrigation in one. Their study reported an over-irrigation of +589.7 % in Alangasí-La Merced, under-irrigation of -26.4 % in Chichipata, over-irrigation of +67.7 % in Churoloma, +122 % in El Pueblo, +14 % in Ilaló, +171.5 % in La Viña, and +62.1 % in San Blas. These discrepancies can be addressed by regulating flow rates towards secondary canals and from secondary to tertiary networks, as they directly impact water distribution efficiency at the canal network level (Calderón Baños, 2014; MINAGRI, 2015; Ortiz et al., 2021).

The presented values differ due to numerous factors such as changes in land use, the number of users, and fluctuations in agricultural surface area. However, there is a clear pattern of unequal water distribution, which is linked to the lack of hydraulic infrastructure as well as the modernization of existing systems (Espinosa & Rivera, 2016; IICA et al., 2017; Ortiz et al., 2021).

4. Conclusions

For the Tumbaco area, the use of the Thornthwaite indirect evapotranspiration estimation method is recommended when sufficient information on other climatic variables is unavailable. As demonstrated, the Penman-Monteith method tends to overestimate monthly values compared to the direct estimation method, such as the Class A Evaporation Pan, which aligns with findings from other studies in nearby irrigation areas (Tacuri Lalangui, 2023; Yánez León, 2023).

The water flow authorized by the Tumbaco Irrigation Board is not optimal, as over-irrigation was identified in all seven branches of the irrigation system. Specifically, the Alangasí-La Merced branch receives 247.22 % more water than necessary, Chichipata 44.83 %, Churoloma 35.55 %, El Pueblo 54.16 %, Ilaló 44.91 %, La Viña 119.49 %, and San Blas 496.12 %. These findings align with the efficiency analysis of water distribution conducted on the irrigation canal and its different branches (Ortiz et al., 2021).

The developed methodology serves as a foundation for sustainable water management, the creation of water resource management models for various irrigation systems nationwide, and support for public institutions responsible for water distribution in agricultural, community, or business projects. This ensures the appropriate allocation of water according to its intended use and land coverage.

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Author contributions

- Jefferson Francisco Cando Bautista: investigation, writing – original draft.
- Jorge Andrés Espinosa Marín: conceptualization, methodology, writing – review & editing
- Wellington Augusto Bastidas Guevara: supervision.
- Carlos Lenin Montúfar Delgado: resources.

Ethical implications

Ethics approval not applicable.

Conflict of interest

The authors declare that they have no affiliation with any organization with a direct or indirect financial interest that could have appeared to influence the work reported.

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