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QUANTIFYING WATER BALANCE OF SUBAK PADDY FIELD BASED ON CONTINUOUS FIELD MONITORING

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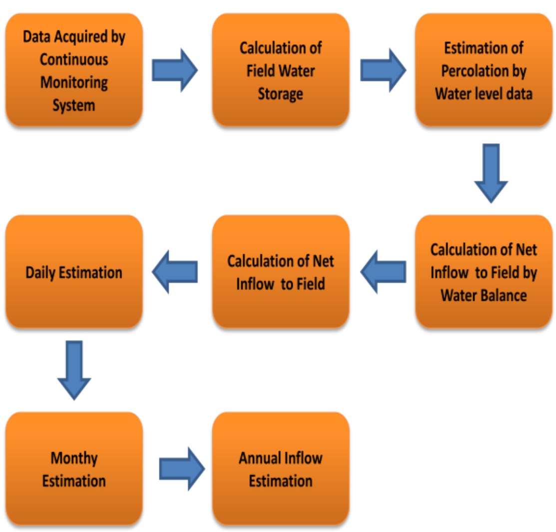
Graphical abstract



Abstract

Subak had been known as superior and sustainable water management system in Bali's paddy field, and had a long history as an interesting topic for study. Water management in Subak is more or less based on religious practices and the philosophy of the harmony among God, human and nature, that ensures equity and sufficiency of water diversion. Traditionally there is no water regulation in the meaning of gate operation as most Subak has their own water source from definite location, and fixed system was used for water diversion that defined portion of water discharge and not quantity. In this study, field monitoring system had been set up to continuously observe the water balance components such as: rainfall, evapotranspiration, percolation, field water status. With the available data, water balance equation can be used to obtain net inflow, which in this case only minimum, median and maximum for each particular month. These values were used to summarize total annual net inflow to the field, which ranges from 4575 to 7419 mm. This is accounted as total water use for rice production at the site and generally it can be concluded as the amount of water required to sustain the present paddy field of the Subak.

Keywords: Local framework, IWRM, continuous monitoring, irrigation

1.0 INTRODUCTION

Subak is a traditional irrigation system in Bali Province, Indonesia, managed by farmers autonomously, had a long history since 1071 AD and still exists up to these days. Water management in Subak is based on religious practices and the philosophy of the harmony among God, human and nature, that ensures equity and sufficiency of water diversion. Farmers as subak member feel their interests to have been served and result in harmony and togetherness atmosphere within the subak irrigation system. This has been going on since the system was established.

General and detailed rules for implementing it are included in the subak awig-awig and perarem (bylaws). A subak system can be broadly subdivided into four mayor components: (a) the main structure (weir/inlet structure); (b) the main canal, with the function of conveying the irrigation water from the main structure upstream to the last rice field downstream; (c) the irrigation canals, with the function of distributing the irrigation water to the rice fields; and (d) the drainage facilities, including the small on-farm drains up to the big drains and rivers, serving several subak irrigation systems. Traditionally there is no water regulation by mean of gate operation and fixed system was used for water diversion that defined portion of irrigation water called tektek in some areas. Tektek is amount of water necessary for one-season irrigation of paddy field with an area up to about 1 ha; other terms with the same meaning are kecoran or tanding.

Our study is focusing on subak managed paddy field in Saba watershed in Buleleng regency, northern part of Bali as part of water management research project in the area. In this study, field monitoring system had been set up to continuously observe the water balance components such as: rainfall, evapotranspiration, percolation, field water status. The information is being used to quantify the water balance and water use of one paddy field under Subak management, with objectives to determine the amount of water that should be provided in order to sustain Subak paddy fields.

2.0 MATERIAL AND METHODS

The main method that was applied in this study is continuous remote monitoring based on weather station, soil monitoring system and quasi real-time monitoring system "Field Network System (FNS) [10], [12]. The monitoring system had been installed to continuously observe and records weather variables: rain, solar radiation, air temperature, air relative humidity, wind speed, air pressure and also ultra-violet index and wind direction. Additionally reference evapotranspiration is also obtained by standardized FAO Penmann-Monteith methods [3] using the measured data. Soil monitoring system uses sensors which simultaneously measure soil moistures, soil temperatures, soil EC, water level, water temperature, water EC and soil potential, and then being recorded by data logger. All acquired data is then downloaded by FNS and uploaded to the server, along with picture taken on the day.

Table 1 enlists variables which are recorded by the monitoring system, which are used in this paper. In this case, 3 sensors were used at three different depths of 5, 10 and 30 cm for measurement of θ, EC and Ts as shown in Figure 1. Water level sensor, which is also measures water temperature and water EC was installed in a 2" diameter pit at 50cm depth. Soil potential sensor was installed at the 30 cm depth of soil. EM50, 5TE, CTD and MPS-2 are the type of data logger, soil sensors, water level sensor and soil water potential sensor.

2.1 Location and Soil

Observation was focused on mid-stream of Saba watershed area in Buleleng Regency, Bali Province, Indonesia. The site is located at coordinate S 8°16'16.43"; E 114°58'2.87", having elevation of 200m above sea level near Titab river, and therefore although the field is a member of Subak Bukit Pulu, from here it is referred as Titab field (Figure 1). Monitoring station was installed at a roughly 300m^2 areas of paddy field plot. Irrigation to the field is taken directly from the subak's irrigation channel.

Soil properties information is required for Titab paddy field hydrology analysis. The physical properties of textures, porosity, densities, permeability as well as water retention were obtained through laboratory analysis of undisturbed soil samples taken from the field. These properties are shown by the following Figure 2. Water retention curve was modeled based on [14] soil water retention model.

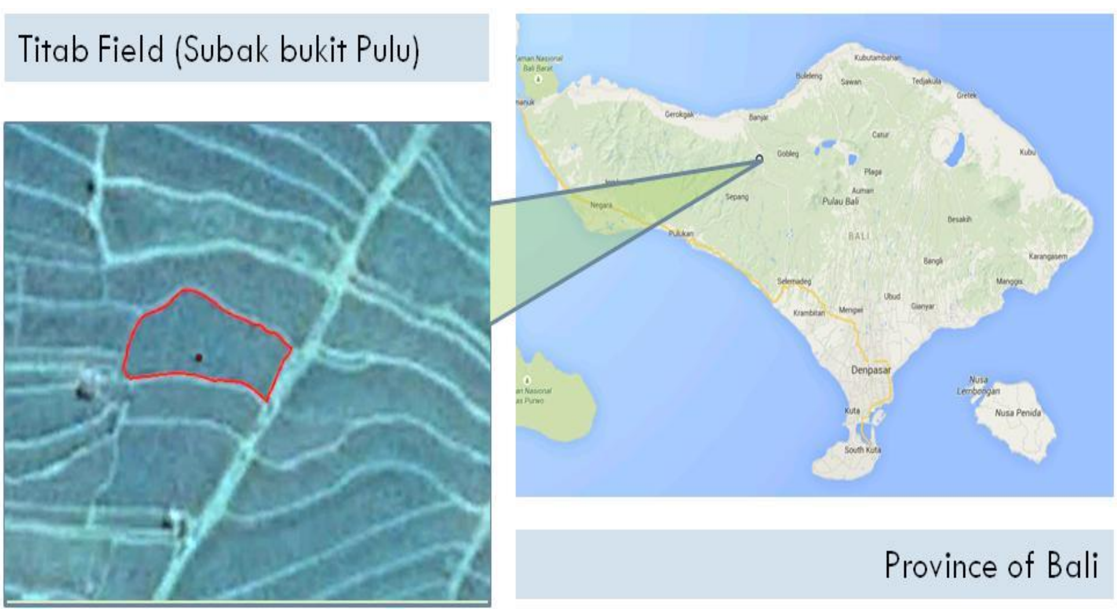


Figure 1 Location: Titab Field, Saba Watershed

Table 1 Monitoring variables

Variable	Symbol	Unit
Rain fall	R_f	mm
Solar radiation	S_r	W/m^2
Air Temperature	T_a	^{o}C
Relative humdity	RH	%
Wind speed	u	m/s
Air pressure	Pa	hPa
Evapotranspiration	ET	mm
Soil water content	θ_i ; i : sensor number	cm^3/cm^3
Soil electro-conductivity	EC_i ; i : sensor number	mS/cm
Soil temperature	T_{si} ; i : sensor number	^{o}C
Water level (height of water level above sensor)	WL ;	mm

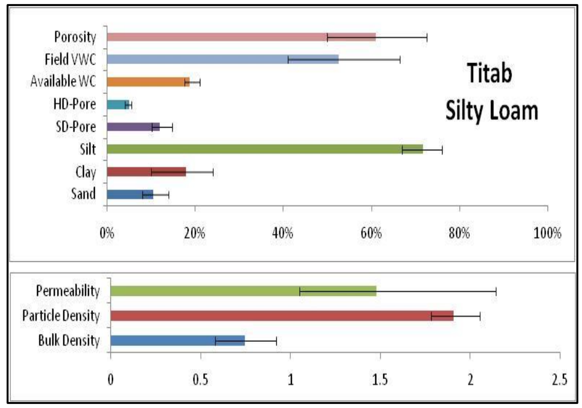


Figure 2 Soil Physical Properties

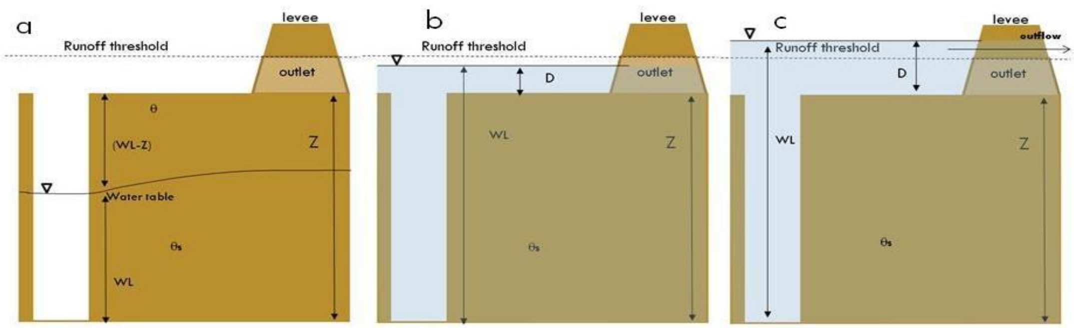


Figure 3 Field condition determined by water level: a. Non-flooding, b. Flooding, c. Flooding with run-off

2.2 Water Level

Water level (WL) is one of the most important variables in the observation since it indicates the conditions of the field i.e. water table depth, standing water height and whether there is inflow and or outflow. During non flooding period, water table will decrease below the soil surface which indicates water depletion from the field through ET, percolation (P) and seepage. When water table increases, the field is receiving either rainfall and/or inflow (I_f) that can consists of irrigation (I), subsurface flow (seepage from upper), rainfall generated inflow (surface runoff that run into irrigation canals).

As water level increase over the run off threshold (e.g. the height of outlet), outflow (O_f) through the outlet occurs. If water level is increasing below this threshold and no rain (R_f = 0) is recorded, it means the field is receiving irrigation water, assuming subsurface flow from upper field is negligible. At condition in which If, R_f and O_f is zero, the decreasing of WL is equal to percolation (P) if seepage can be neglected. Figure 3 depicts the mentioned conditions in which the respective analysis can be conducted.

2.2 Percolation

Percolation can be estimated by using Darcy's flow model for example as proposed by [8] to estimate percolation losses in paddy fields with a dynamic soil structure, or by percolation test. Methods of field percolation test for rice field are explained in [1], which requires the field to be puddled. Other measurement can be done in simple way as described in [6] for drained soil. All methods suggested measurement of water level during the test, which in our observation is continuously measured. Water level data can be used to estimate the percolation when water level is decreasing when I_f and O_f do not occur, because of their uncertainty confuses the water level changes measurement. Percolation is calculated as decrease of water level divided by time, regarding the contribution of ET and rain.

$$P = -\left(\frac{(WL_t - WL_{t-1})}{\Delta t} - ET + R_f\right) \; ; WL_t < WL_{t-1} \quad (1)$$

During the observation, it was difficult to separate between percolation and seepage or subsurface outflow from the field. Therefore the variable P in this case represents both percolation and seepage.

2.3 Field Water Storage

Field water (FWS) is a term used in this paper to describe the total amount of water that is stored at the field in water depth equivalent (mm). FWS consists of soil water content (θ, cm^3/cm^3) in a soil column Z (mm) and standing water depth (D, mm) during flooding period, where WL>Z and D =WL-Z.

Soil's water saturation zone and unsaturated zone are determined by water level. When it is below soil column depth (Z, mm) it is termed as water table, where soil below this depth is considered as saturation condition with soil water content θ_s equal porosity, and water storage in this zone can simple be calculated as WL x θ_s. In unsaturated zone, water storage is calculated by multiplying θ by the unsaturated zone's thickness (Z-WL).

The following equation is used to calculate and observe the changes of FWS to represent change in water storage in water balance equation. The term ΔFWS is equivalent with the sum of changes surface storage ΔS and subsurface storage ΔSS which was used by [5].

$$FWS\begin{cases} WL\,\theta_s + D & ;WL > Z \\ WL\,\theta_s + (Z - WL)\,\theta & ;WL < Z \end{cases} \qquad (2)$$

$$\Delta FWS = FWS_t - FWS_{t-1} \qquad (3)$$

2.4 Water Balance

Variants of paddy field's water balance equation can be found in [5], [7] and [9], which all consider rainfall, evapotranspiration, lateral in- and out-flows (irrigation, seepage, drainage), vertical flow (percolation, capillary flow) and changes of water storage at the field. Paddy field water balance equation that is used in this study had been governed to simplify the calculation using available monitoring data, as follows.

$$(I_f - O_f) = ET + P + \Delta FWS - R_f \qquad (4)$$

As mentioned previously the value of I_f consists of irrigation, surface and subsurface flow to the field, and O_f consists of runoff through outlet as no outflow by means of surface run off.

2.5 Calculation Process

Measurement sampling period is set at 30 minutes, where weather station as well as soil monitoring system measure and record data to their memory. In this study, calculation of water balance was conducted on daily basis and raw 30minutely data should be converted into daily values. Data were calculated into their average, minimum, maximum, total or accumulation values depending on the nature of the variables.

Temperatures, humidity, moisture, wind speed, pressure and water level were calculated into their average values, with additional minimum and maximum values for temperatures. Beside of its daily average value, water level value measured at the same time during the observation is also used for the calculation of *FWS*.

Daily values of evapotranspiration and rainfall were obtained by summing their data in the respective day. Solar radiation should be separately by integration of the solar radiation curve during the day to obtain its total. FWS, in the other hand should be estimated every 30min, taking into account soil moisture and water level, before it is converted into daily value.

3.0 RESULTS AND DISCUSSIONS

3.1 Rainfall and Evapotranspiration

Rainfall data and reference ET were obtained by using weather station from January 2013 to May 2015 without measurement failure. Daily values of Rf and ETo were summarized in Figure 4 where variation of rainfall and evapotranspiration as well as dry-wet periods, can be observed. According to the data, dry seasons were between July and November, where R_f is less and ET seems to be higher.

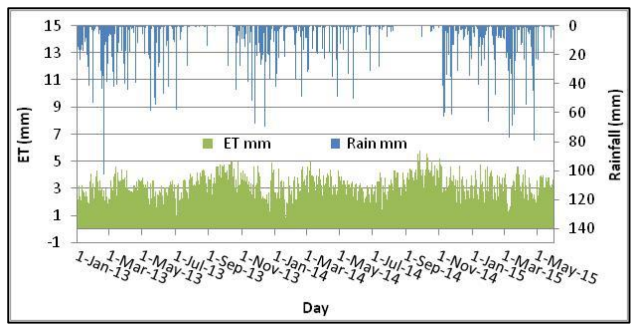


Figure 4 Rainfall and Evapotranspiration

3.2. Water Level and Field Water Storage

Figure 5 shows water level and soil moisture measured by sensors and field water storage (FWS) calculated based on them. There were no measurement of water level during January-March 2013 and during December 2013-March 2014 there was measurement failure in water level measurement. Within these periods FWS could not be calculated based on the data. Consequently, during these months water balance could not be closed. Soil was mostly at saturation state especially during cropping season which is normally 3 times in a year. This is shown by soil moisture data that was 0.6 cm^3/cm^3, which at saturation condition. Figure 5 shows that the field had never experienced water scarcity during the observation period.

3.3 Percolation

Percolation was estimated by observing water level data, considering the conditions mentioned previously, and average value was taken as the maximum percolation. Percolation is assumed to occur when soil moisture is higher than field water capacity. Whenever this condition is satisfied, the average percolation value was taken as half hour percolation rate and was used in water balance calculation.

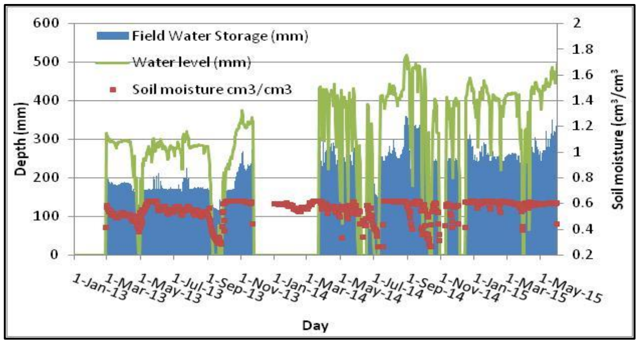


Figure 5 Water level, field water storage and soil moisture

Averaged percolation obtained for year 2013, 2014 and 2015 are 0.6 mm/h, 1 mm/h and 1 mm/h. This values are equal 14.4 to 24 mm per day assuming 24 hours of continues paddy fields flooding. Comparing to soil permeability data, which average is around1.5 cm per hour, percolation rate is lower. This is considered as normal since hardpan at the bottom of the field prevents deep percolation through it.

Percolation found in this case is higher than expected rice field percolation in Indonesia, but as mentioned previously that the value includes seepage. Water that is seeping out from the levee of upper field to its lower adjacent field is commonly found at the terraced paddy like at the site. It is known that seepage is often being captured and reused by downstream field [4], and this could be an indication of unintentional water re-use in Subak field.

3.4 Water Balance

Water balance calculation based on the observation data is presented in Figure 6 to Figure 8, where monthly values of R_f, ET, P, ΔFWS (dFWS in the figures) and Q are plotted in the charts. The notation Q is the net inflow which is equal to I_f-O_f . These values were concluded from daily values of the variables to their respective months. Missing data of P, dFWS and Q are due to measurement failure and could not be taken into account for water balance calculation. Further analyses of these missing information are not covered in this paper.

The figures show the variation of net Q in the year 2013, 2014 and the first 5 months o f 2015. There were increases of net Q during period of July to August, which is also within the dry season. According to local information July is the end of second harvesting and August is the starting of third cropping season of the year. As not much rain water wetting the field, more water has to be flown from irrigation channel and thus increase the net Q.

In the month of April there was increasing in net Q and also increase in FWS in April to May 2013, this is the second cropping season start. Increase of FWS is not seen in April 2014 but net Q seems to have been slightly increased which is a sign of irrigation. Although this is at the end of wet season in Bali, the quantity of rainfall is lower than the previous year according to recorded rainfall data.

Total inflow of individual years could not be completely clarified due to measurements failure that caused incomplete annual summary. In the effort to summarize net Q, the minimum, median and maximum quantity of inflow of the same month is used to obtain their min, med and max annual accumulation (Figure 9).

Here, annual net inflows to the field ranged from 4575 to 7419 mm, which with the current paddy plot are equal to 1372 to 2226 m^3 of water.

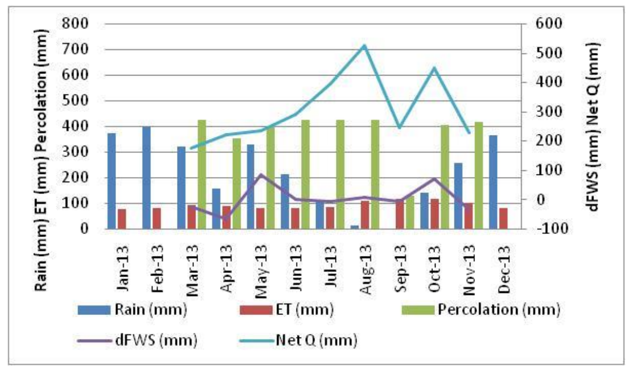


Figure 6 Water balance year 2013

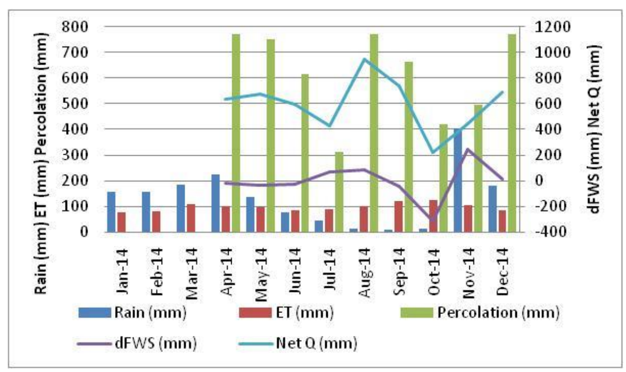


Figure 7 Water balance year 2014

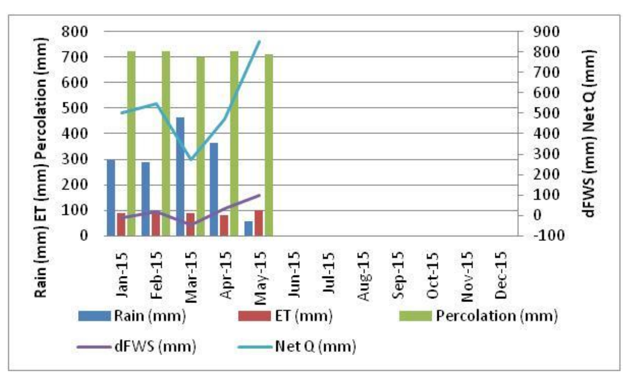


Figure 8 Water balance year 2015 (until May)

3.5 Water Productivity

Water productivity is a term that is used to describe the productivity of a unit volume of water to produce amount of product mass. It can be measured with respect to irrigation amount, total inflow, depleted water or process-depleted water as explained by [11]. In this study, water productivity is described by using accumulation of net inflow since there are uncertainties in water balance components that have to be clarified later. This can be explained as the amount of water that flows into and stored the field, after which it will be devised into increase of soil moisture or/and water level, percolation and seepage, evaporation and transpiration, and biological processes. In other words, if this amount of water is available for the field then it can sustain as it is at present in term of water sufficiency.

Normally, paddy field in the area has 3 cropping seasons, assuming the productivity of 4.5 t/ha for each harvest (average Subak Bukit Pulu's productivity) water productivity can be estimated between 0.18 to 0.30 kg/m^3. This value is lower than the range of rice crop water productivity by found by [14] which is between 0.6 and 1.6 kg/m^3. However the definition was 'the marketable crop yield over actual evapotranspiration' that in our case is one part of water use in rice production.

Improving water productivity is a need as there is demand for increased grain production. The high water productivity value should be associated with preferable yields i.e. about 80% of the highest yields to imply efficient use of water resources for crop management [2]. It is a challenge to determine crop water productivity of the site with various definitions and followed by improving water productivity for the future work.

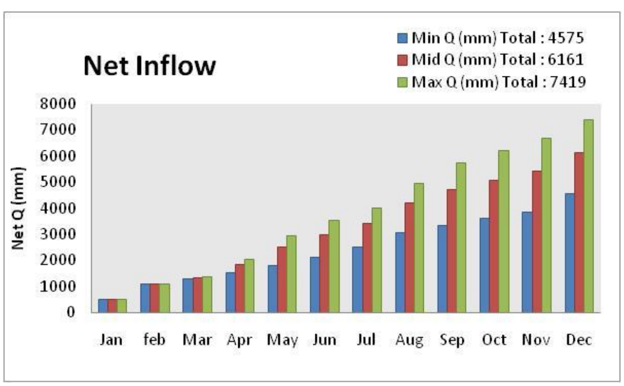


Figure 9 Accumulation of net inflow (I_f-O_f)

4.0 CONCLUSION

Weather data was collected by continuous measurement without measurement failure from January 2013 to May 2015. Rainfall and evapotranspiration data derived from this observation can be used in water balance calculation. Soil monitoring system could not supply complete required measurement data in the early of 2013, end of 2013 and first 3 months of 2014. Thus water balance equation had not been completed for these periods.

With the available data, water balance equation can be used to obtain net inflow, which in this case only minimum, median and maximum for each particular month. These values were used to summarize total annual net inflow to the field, which ranges from 4575 to 7419 mm. This is accounted as total water use for rice production at the site and generally it can be concluded as the amount of water required to sustain the present paddy field of the Subak.

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