OPTIMAL WATER SHARING FOR SUSTAINABLE WATER RESOURCE UTILIZATION IN CICATIH-CIMANDIRI WATERSHED, SUKABUMI, INDONESIA[1]

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ABSTRACT

To date, agricultural water management in Indonesia has developed since ancient times merely for rice cultivation. Later on, the East Indian Company VOC in the early 1700s, initiated the irrigation scheme with canalization. The Netherlands Colonial Government then institutionalized irrigation development with the establishment of Public Work in 1845 that has been the sole authority to develop irrigation in the country until now. In the early years of national development, numerous constructions of dams and diverted weirs were the main civil works in developing modern irrigation mostly with financial supports from international donors. The objective of irrigation development was to increase rice production by intensifying cropping season from one to two or even three times a year. However, later on complexities has arisen as rice demand increases while trend of agricultural land conversion is unavoidably faster, and in the other side, water availability has been fluctuating in a manner that is more difficult to handle since it is also linking to climate change phenomenon. Nowadays, effective water management in agriculture is even more crucial not only for supplying water in a right volume and time but to make sure that water is readily available for other daily necessities. This paper gives a highlight of water management in agricultures currently conducted in Indonesia, and proposes a throughout optimum solutions based on a concept of optimum water sharing to find a robust agricultural water management for sustainable development of rice production. Herewith, we present a case study on how the concept of optimum water sharing is introduced among stakeholders in Cicatih-Cimandiri watershed in Sukabumi, West-Java.

Keywords: agriculture, rice, irrigation, water management, climate change, optimal water sharing

INTRODUCTION

To date, agricultural water management in Indonesia has developed since the ancient times merely for rice cultivation. As reported by Hasan *et.al* (2010), the East Indian Company VOC in the early 1700s initiated the irrigation scheme with canalization projects mainly to expand rice paddy fields in the country. The Dutch Colonial Government then established a Public Works Department in 1854, which was then becoming the sole authority to develop irrigation in the country. To note, the Brantas River Dam was the first modern water reservoir completed in 1920, which is still functioning until these days. When the Japanese authorized the country, planted areas of paddy fields doubled and reached 3.3 million hectare resulting in rice surplus.

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In the early years of national development (1960s-1990s), numerous constructions of dams and diverted weirs were the main civil works in developing modern irrigation mostly with financial supports from international donors. These times the irrigation development aimed to increase rice production by intensifying cropping season from one to two times or even more in a year. Later on complexities has arisen as a demand for rice increases with population while trend of agricultural land conversion is unavoidably faster, and in the other side, water availability has become uncertain that might link o climate change phenomenon. The present government anticipates the situation, which among other effort is to expand irrigated paddy fields outside Java Island. At present time, the irrigated paddy fields amounts to 7.5 million hectare but only 11% out of it receives fresh water for reservoirs whilst the rests gets diverted water from river weirs (Hasan *et.al.* (2010).

Nowadays, effective water management in agriculture is even more crucial not only for supplying water in a right volume and time but to make sure that water resource is readily available for other daily necessities of the stakeholders. In the studied location, in example, the available water resource is mainly shared by four categories, such as 1) the environments, 2) domestics, 3) agricultures, 4) industries including drinking water industries, which use the water as the raw material. With the expansion of population and economic development and with realizing the limitation of water resource then agriculture has to minimize its use of water but at the same time has to increase its yield, or it ought to increase the so-called water productivity. Accordingly, agriculture has to find an effective way to reduce water use in order not to jeopardize yield. Recently, intermittent irrigation is a promising option to reduce the water use that has wide attention worldwide (Dong, 1999; Massey, 2009; Setiawan, *et.al.,* 2011). When it is applied to SRI[4] Paddy Fields water productivity increased significantly (Uphoff and Kassam, 2011; Hasan and Sato, 2007; Lin *et.a.*, 2011; Setiawan, *et.al.*, 2011). In consequence, in this study this is taken into account in trying to minimize water use in the rice production.

This paper describes a concept to optimize the use of water resource that be shared by stakeholders for multipurpose activities, which a main focus to find a reasonable proportion of water use for a long period. We conducted a case study in Cicatih-Cimandiri watershed in Sukabumi, West-Java.

CONCEPTUAL APPROACH

In this study, we define water sharing as a utilization scheme of water resource by water users in a watershed. A watershed is a water catchment area that collects rainwater, and part of the water flow on the soil surface, which then it concentrates into a river and/or reservoirs and the part of the water may enter into the deeper layers of the soil and occupy aquifers. As for maintaining healthy environment, a reasonable quantity of the water resource should be conserved in the watershed.

Available Water Resources

Based on the water balance equation in the watershed the apparently available water resource is as follows:

Eq. 1: $$\frac{\Delta S}{\Delta t} = \alpha_R R - \alpha_{ET} ET_a - Q$$

Where, S is water storage in the soil profile, R is rainfall, ET_a is the actual evapotranspiration, Q is

[4] SRI stands for the System of Rice Intensification.

surface runoff or river discharge, α is correction factor, and t is time. In order to conserve the water in the soil surface then the gradient of water storage is to minimize in such a way so the equation becomes:

Eq. 2: $$\frac{\Delta S}{\Delta t} = 0 \rightarrow \; Q = \alpha_R R - \alpha_{ET} ET_a$$

The following equation expresses the apparently available water:

Eq. 3: $$Q_{AW} = \begin{cases} Q - Q_{mn} & Q > Q_{mn} \\ 0 & Q \leq Q_{mn} \end{cases}$$

Where, Q_{AW} is the available water resource and Q_{mn} is a recorded minimum river discharge in a period under consideration.

In this study, water users comprises four categories, which based on the priority are: 1) Domestics; 2) Agricultures; 3) General Industries; and 4) Water Industries. The general industry uses the water as supporting material whilst the water industry uses the water as raw material.

Available Water Supply

Since water for domestics is prerequisite then the available water supply distributed to the other water users becomes:

Eq. 4: $$Q_T^S \geq Q_{AW} - Q_P^D$$

Where, superscripts *S* and *D* indicate supply and demand, respectively, and subscripts *T* and *P* indicate Total and Population, respectively. The total available water supply delivered to the three activities should meet the following equation:

Eq. 5: $$Q_T^S \geq Q_T^D = Q_{AG}^D + Q_{GI}^D + Q_{WI}^D$$

Where, subscripts *AG*, *GI* and *WI* indicate Agriculture, General Industry and Water Industry, respectively.

Water Demand for Domestics

Daily water need for domestics varies with place, human age and activity in the range of 80-185 liter/capita (BAPPENAS, 2006). Redjekiningrum (2011) used its averaged value 144 liter/capita to calculate daily water demand of the population in the studied location. Furthermore, Redjekiningrum (2011) estimated population using the following Verhults model:

Eq. 6: $$P = P_\infty \left[1 + \left(\frac{P_\infty}{P_o} - 1\right) e^{-\gamma t}\right]^{-1}$$

Where, *P* is population, subscripts∞ and o indicate infinity and initial, respectively, γ is a fitted parameter, and t is time. The following equation calculates the domestic water demand:

Eq. 7: $$Q_P^D = 144P$$

Water Demand for Agricultures

Water demand for agriculture or in this case is paddy field represented by the following yield function (Allen, *et.al.*, 1990):

Eq. 8: $$\left(1 - \frac{Y_a}{Y_m}\right) = \beta\left(1 - \frac{ET_a}{ET_m}\right)$$

Where, Y and ET are Yield and evapotranspiration, respectively; β is water-yield sensitivity coefficient; and subscripts a and m indicate actual and maximum values, respectively. The water-yield sensitivity coefficient shows different values for different water management. Setiawan, *et.al* (2011) reports the real value varied with water management but in a small range with its averaged value is about 1.285. The following equation can represent water demand of agriculture:

Eq. 9: $$Q_{AG}^D = (1 + \delta) \sum_i^{ni} ET_a$$

Where, δ is water losses in percentage, i and ni are index and number of planting seasons in a year. Irrigation water losses from tertiary canal to the paddy field varied in a wide range depending on types of climates, canal, water management, etc. In the studied area, water loss is intermediate about 35% mainly due to evaporation, seepage and deep percolation.

Water Demand for General Industries

General industry consists of small, medium and big industries each of which has different water demand. Water demand for each industry could be obtained from secondary data and its trends in the future can be estimated in example using an extrapolation model. The following equation calculates water demand for general industry in the studied location:

Eq. 10: $$Q_{GI}^D = \sum_j^{nj} Q_{GI,j}^{D}$$

Where, j and nj are index and number of industry (nj=3).

Water Demand for Water Industries

Water industries that use the water as raw material mainly tap clean water springs. These will reduce river discharge since naturally the spring water flow into the river in the downstream. Water demand for each water industry could be obtained from secondary data and its trends in the future can be estimated in example using an extrapolation model. The following equation calculates water demand for general industry in the studied location:

Eq. 11: $$Q_{WI}^D = \sum_k^{nk} Q_{WI,k}^{D}$$

Where, k and nk are index and number of water industry.

Optimal Water Sharing

The first priority of the optimal water sharing is to allocate a reasonable quantity of water to produce sufficient food or rice for the population with less water. This means to apply more efficient water management. The second priority is to allocate supporting for the general industries, and the third priority is to allocate water as raw material to water industries. The following equation expresses a system of linear equations that used to find the optimal allocation of the water:

Objective Function:

Eq. 12: $$0 \leq \epsilon = \left| Q_T^S - Q_T^D \right| \leq TOL$$

Where, ε is absolute error and *TOL* is error tolerance.

Constraint Functions:

Eq. 13: $$Q_{AG}^D \geq Q_{AG,mn}^D$$

Eq. 14: $$Q_{AG}^D = Q_{CF}^D + Q_{IT}^D + Q_{SF}^D$$

Eq. 15: $$A_{AG}^D = A_{CF}^D + A_{IT}^D + A_{SF}^D$$

Eq. 16: $$A_{CF}^D = \alpha_{CF} A_{AG}^D;\ A_{IT}^D = \alpha_{IT} A_{AG}^D;\ A_{SF}^D = \alpha_{SF} A_{AG}^D$$

Eq. 17: $$\alpha_{CF} + \alpha_{IT} + \alpha_{SF} = 1$$

Eq. 18: $$Q_{GI,mn}^D \leq Q_{GI}^D < \left(Q_T^S - Q_{AG}^D \right)$$

Eq. 19: $$Q_{WI,mn}^D \leq Q_{WI}^D < \left(Q_T^S - Q_{AG}^D - Q_{GI}^D \right)$$

Where, *A* is the area of paddy fields. Subscript *mn* indicates the minimum water demand. Subscripts *CF* is for a conventional paddy field with Continuous Flooding, *IT* is for a conventional paddy field with Intermittent Irrigation, and *SF* is for SRI[5] paddy field with Shallow Flooding, and α are proportional coefficients, or changing parameters that need to determine through an optimization process.

A BRIEF OF DESCRIPTION OF THE WATERSHED

Geographics

The geographic location of Cicatih-Cimandiri Watershed (Figure 1) is E: 106°39’8’’-106°57’30’’ and S: 6°42’54’’-7°00’43’’. The watershed has five sub-watersheds with the total area is 52,979 ha. The elevation varies from 200 to 3000 m from the sea level. The land slope varies and about 68% of the land is mostly flat (0-20%).

There are 15 administrative districts within the watershed. Figure 2 shows 6 sub-watersheds along with the river networks in the watershed. As presented in Table 1, the total area of the watershed is about 53 thousand hectares.

[5] System of Rice Intensification

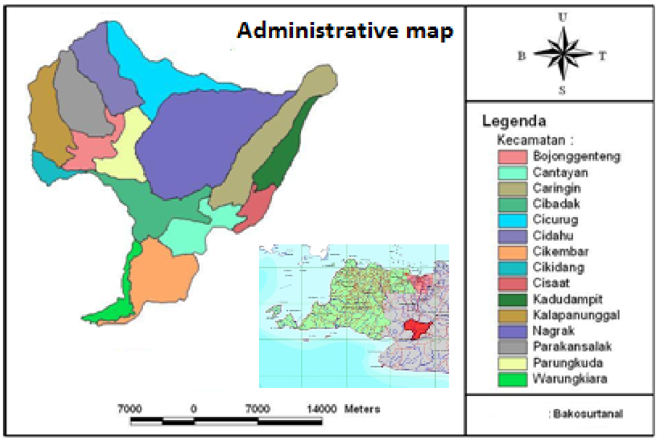

Figure 1 Districts (15) in Cicatih-Cimandiri Watershed of Sukabumi Regency

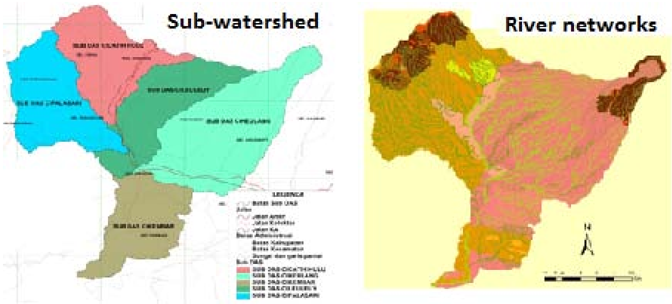

Figure 2 Sub-watersheds (5) and river networks

Table 1 Sub-watersheds and their areas

No	Sub-watershed	Area (ha)	Fraction
1	Cicatih Hulu	9,939	19%
2	Cipalasari	9,306	18%
3	Ciheulang	15,911	30%
4	Cileuleuy	9,234	17%
5	Cikembar	8,589	16%
	Total	52,979	

Table 2 Land uses and their changes with time

No	Land uses	Area (ha)			Fraction			Changes
		1991	2001	2008	1991	2001	2008	1991-2008
1	Primary forests	9,715	9,024	9,019	18%	17%	17%	-7%
2	Secondary forests	935	782	566	2%	1%	1%	-39%
3	Industrial zones	35	45	55	0%	0%	0%	57%
4	Mining zones	254	246	250	0%	0%	0%	-2%
5	Mixed farms	8,902	9,467	9,766	17%	18%	18%	10%
6	Uplands	13,643	14,282	13,392	25%	27%	25%	-2%
7	Settlements	2,135	2,218	2,232	4%	4%	4%	5%
8	Plantation	3,388	3,616	4,438	6%	7%	8%	31%
9	Paddy fields	13,943	13,533	13,521	26%	25%	25%	-3%
10	Bushes	340	104	101	1%	0%	0%	-70%
11	Water bodies	217	215	212	0%	0%	0%	-2%
12	Bare lands	67	42	22	0%	0%	0%	-67%
		53,574	53,574	53,574	100%	100%	100%	

Table 3 Parameters of the Yield Function (Eq. 8)

Parameters	Conv-CF	Conv-IT	SRI-SF
β	1.285	1.288	0.963
ETm	2500	2500	1269
Ym	8.816	13.071	10.386

Climates and Hydrology

Based on Mann-Kendal method, rainfall and Evapotranspiration have shown significant decrease during the period of 1990-2008 (Redjekiningrum, 2011), which effected to the decrease of water discharge and water storage in the soil layers. During this period, water balance have shown negative gradient of water storage.

Figure 3 shows daily accumulation of rainfall and potential evapotranspiration that is averaged in the period 2000-2008. In the average, the watershed has an annual excess of water amounted to 1500 mm, which means having abundant water resources. The both accumulative values show the fifth degree of polynomial curves. Rainfall season may begin in the middle of August and last until March of the next year. It also means that drier season begin from March up to the middle of August.

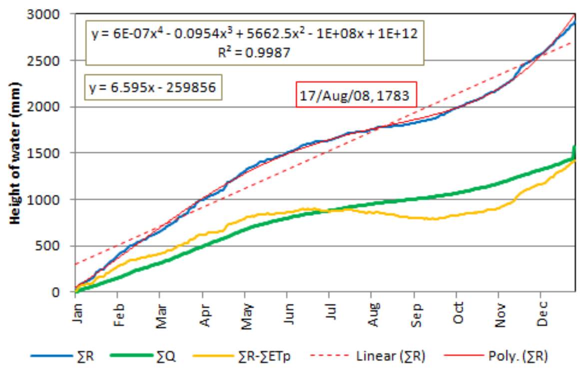

Figure 3 Accumulative rainfall and evapotranspiration

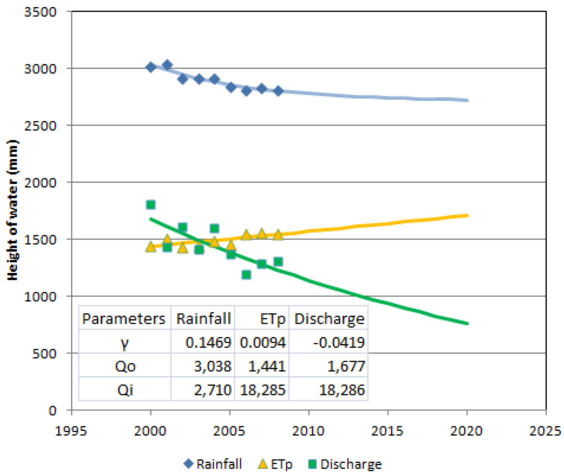

Figure 4 Rainfall, evapotranspiration and river discharge

Figure 4 shows rainfall, evapotranspiration and river discharge, and their trends such as estimated by Eq. 6. Rainfall has has been decreasing whilst evapotranspiration is on the contrary. In the consequences, river discharge has shown a sharp decrease.

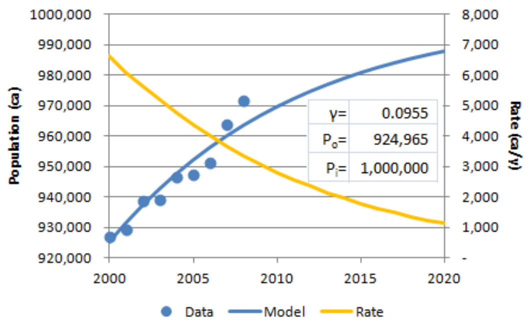

Figure 5 Population and its rate

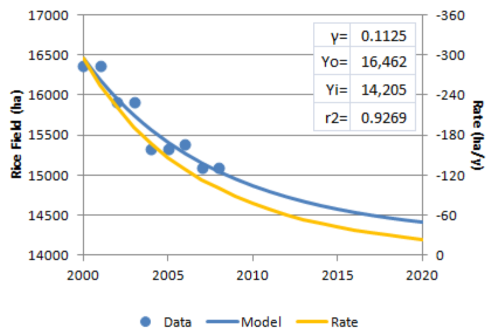

Figure 6 The area of paddy fields and its rate.

Population

Figure 5 shows population and its increasing rate and their projection estimated by Eq. 6. Population is still increasing but its rate is decreasing with time. After leveling off in the future, population would reach 1 million.

Paddy Fields

Figure 6 shows the area of paddy fields and its rate and their projection estimated by Verhults' model. The area of paddy field is decreasing and after leveling off in the future, it would reach 14.2 thousand hectares.

WATER DEMANDS AND AVAILABILITY

Water demands

Figure 7 (left) shows the minimum rice demand by the population in order to attain self-sufficient based on the annual consumption of 132 kg/capita. Divided by the area of paddy such such as described in Figure 6, Figure 7 also shows the expected productivity or yield with increase with time due to the increase of population and the decrease of the area of paddy fields. Initially, the expected productivity is 5.87 ton/ha and then it reaches 7.16 ton/ha in 2020. These values are higher than commonly attained in the range of 5.98 ton/ha to 6.47 ton/ha[6]. Thus, it is clear that to attain self-sufficient a second cultivation is necessary or applying proper techniques to improve land and water productivities.

Figure 7 (right) shows water demand (calculated with Eq. 8) for paddy fields with different available techniques. The first one is a conventional paddy field applying Continuous Flooding (CF), the second one is a conventional paddy field with Intermittent Irrigation (IT) and the third one is the System of Rice Intensification with Shallow Flooding (SRI-SF). Setiawan, *et.al* (2011) and Gardjito (2011) reported data and parameters of the Eq. 8 as summarized in Table 3. It is clear that SRI-SF gives the higher results in term of water productivity followed successively IT and CF.

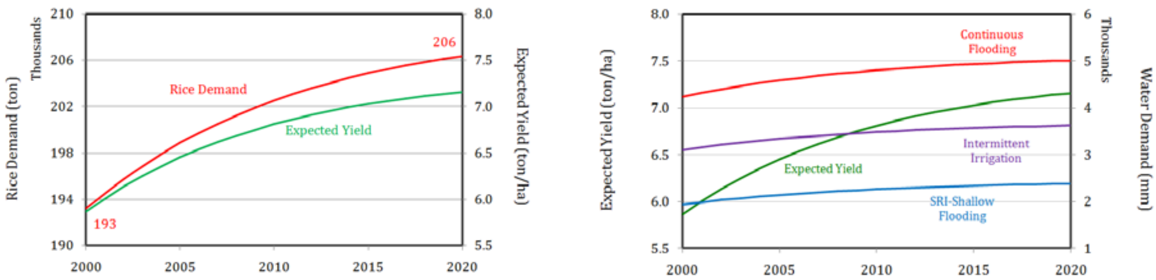

Figure 7 Rice demand and expected land productivity (left), and agricultural water demand (right).

Figure 8 shows water demands for paddy fields, the environments, domestics, general industries and water industries. Water allocated for the environments are to maintain spring water, ground water and minimum river discharge. Redjekiningrum (2011) has reported the availability of surface water, spring water and ground water by means of data inventory and simulated using Tank Model (Setiawan *et.al* (2003); Setiawan, *et.al*, 2007). The water demands for paddy field and the environments are extremely higher than those for the domestics, general industries and water industries. It seems that future water demands of those three items cannot hamper agricultural water demands. On the contrary, excessive uses of water for agricultures may threaten the others. In this regards, applying a proper water management in the agricultural side is becoming very important.

[6] BPS Sukabumi

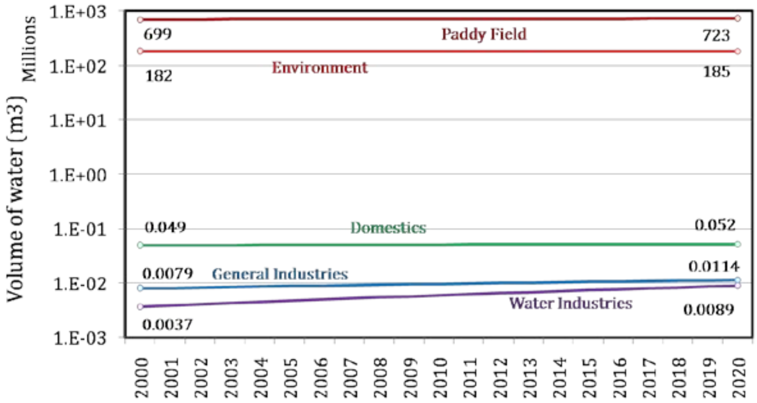

Figure 8 Overall Water Demands

Water Availability

Figure 9 shows available water resources from rainwater minus evapotranspiration, water spring, ground water and surface water. R-ETp decreases gradually because of the fact that the rainfall has depleted whilst potential evaporation has become higher during 2000-2008 (see Figure 2).

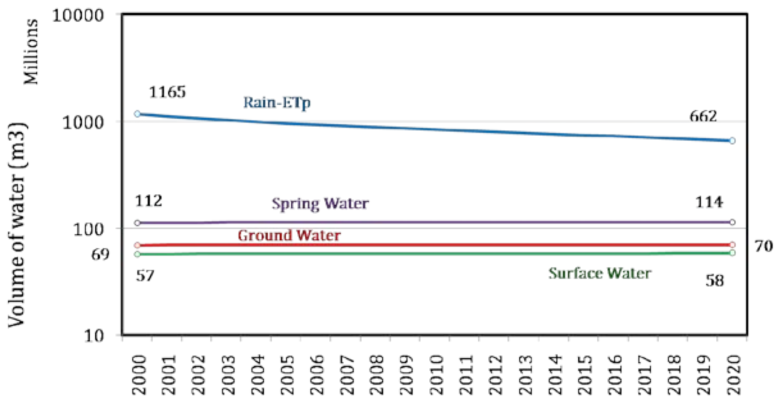

Figure 9 Available Water Resources

Figure 10 shows the available water resource and water demands for three different water managements, such as the conventional paddy field with continuous flooding, the conventional paddy field with intermittent irrigation and the System of Rice Intensification with applying shallow flooding. Since the paddy field with continuous flooding consumes the largest water then its gap with the available water declines sharply and both lines would have met around and beyond 2009. It is then advisable started from 2009 to apply other methods of irrigation, which are more water efficient. The intermittent irrigation is the simpler ones since it only gives water within a certain time interval then stops for another time interval. In the intermittent irrigation, it is common to give a standing water on the soil surface over 5-10 cm then leaves it to decrease for 7-10 days (Dong, 1999; Lin *et.al*, 2011, Massey, 2009). The system of rice intensification with shallow flooding is also advisable to apply since it gives multiple advantages not only enabling to produce more rice with less water but also among others contributing on carbon emission reduction (Hadi et.al, 2010).

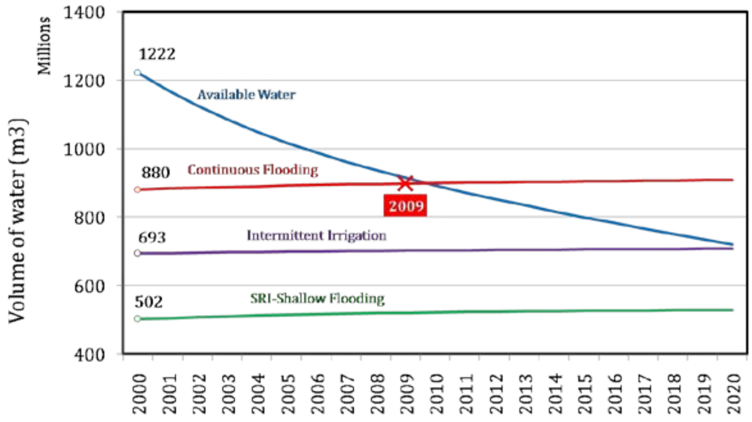

Figure 10 Available Water Resources and Water Demands

Optimal Water Sharing

As described previously, under the present cultivation of paddy fields with continuous flooding the availability of water is at stake for other water users in the watershed. It is then necessary to carry out preemptive measures to apply more water efficient practices of paddy field cultivation. One possible measure is to apply optimal water sharing as previously suggested by Redjekiningrum (2011). In this report, the water sharing could give certainty to all water users that for a long period of time water would be available even though rice cultivated in two seasons by gradually applying SRI paddy fields in combination with the other ones, such as intermittent irrigation.

Figure 11 shows one possible solution to secure the water supply for a longer period until 2020 in which three different irrigation methods combine in an optimal proportion. Under this scenario, the water supply can meet the demand side until 2020 in which, such as shown in Figure 12, the area of paddy fields with continuous occupies 44%, the paddy field with intermittent irrigation occupies 34.7% and SRI paddy field with shallow flooding occupies 9.3%. Thus, to get a longer term sustainable water supply than the increase of areas that apply intermittent irrigation and/or SRI with shallow flooding is very important.

CONCLUDING REMARKS

This paper has described an approach to attain optimal water sharing based on a priority to obtain self-sufficiency of rice in a watershed. The watershed was Cicatih-Cimandiri located in Sukabumi regency. Up to this time, the watershed has a problem with water scarcity since it has experienced a tremendous change of land uses and water availability tends to decrease due to less annual rainfall from time to time. The water was still available for water users but after 2009, a tougher competition of water use among water users has begun and thus, it needs preemptive measure be taken in a right time. One important measure is applying a more water efficient paddy fields that can produce more yields with less water, i.e., by gradually introducing intermittent irrigation and SRI with shallow flooding. This paper has shown the optimization method enable to determine a suited combination of irrigation methods to meet the objective on achieving self-sufficiency of rice production.

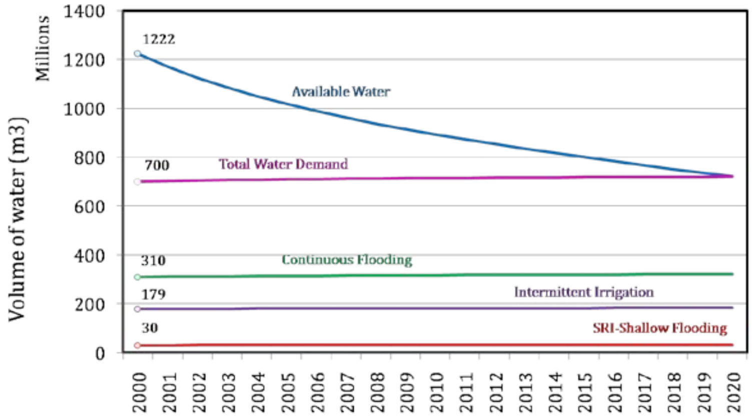

Figure 11 One alternative solution for an optimal water sharing

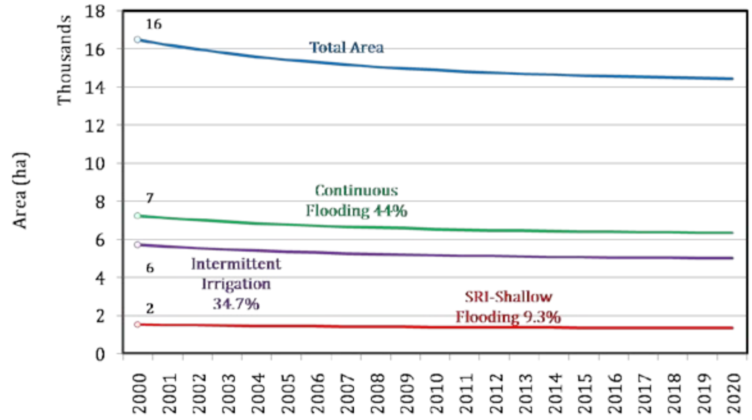

Figure 12 Areas of paddy fields under one alternative solution

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