

Research Article

Water productivity simulation for irrigated farmlands in the Brantas River Basin

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Abstract: Simulation of land and water management for the irrigated farmlands has become an interest to answer how agricultural productivity is related to the water use in a river basin. This research was undertaken in the Brantas River Basin in Indonesia, involving a modelling process with the virtual water concept as a tool to analyze water productivity. The research simulated the agricultural water demand and provided the results of the virtual water content of paddy and maize, based on the available farming land, water availability, cropping pattern and climatological conditions of the respective hydrological years of 1997 and 2011 as a benchmark. After which projections were made based on the low rainfall scenario for the years 2021 to 2025. The research concluded that the presence of excess irrigation in the tropical climates hinders the increase in agricultural productivity, and therefore, the irrigation in the Brantas River Basin needs to be improved by, among others, selecting plants with higher water productivity, developing water-sensitive cropping patterns, and water conveyance savings.

Keywords: *agriculture water use, Brantas River Basin, farming land, irrigation, virtual water content*

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Introduction

Indonesia is blessed with sufficient rainfall, thus forming a large freshwater supply (Pawitan et al., 2013). This abundant availability provides various agrohydrological advantages, including the ease by which wetland farming activities can be carried out and the growing season which can last throughout the year in many places. So far in Indonesia, precipitation in the form of rain has always been the main source of fulfilling water needs, especially for agriculture in various places.

Globally, wetland farming activities and growing seasons are adequately maintained throughout the year, and providing water through irrigation is a common effort on many occasions (Connor et al., 2011). Providing irrigation to meet

the agricultural water needs has efficiently become a broad policy (WB, 2011) although this increase in efficiency does not solve the water crisis (FAO, 2017; Grafton et al., 2018).

This contradiction has a paradoxical impact because the use of irrigation tends to increase (Scott et al., 2014) and agricultural activities are becoming accustomed to using large amounts of water (Molden et al., 2007; Berbel et al., 2015). This problem also occurs in Indonesia as a result of the intensification of agriculture extensively carried out since the beginning of the agricultural revolution (Pasandaran and Rosegrant, 1995; Rosegrant et al., 1998).

Currently, various studies on the use of irrigation in couple with water in the form of moisture stored in the soil have been carried out

in areas with semi-arid or dry climates and limited water supplies in order to increase agricultural productivity (Rockström et al., 1998; Pandey et al., 2000; Oweis and Hachum, 2006; Liu and Savenije, 2008; Zhang et al., 2019). However, this kind of research in the humid-tropical areas, like Indonesia, is still limited to theoretical studies (Bulsink et al., 2010; van Noordwijk et al., 2016).

Various reports show that agricultural management in Indonesia utilizing water in abundance has reduced water productivity, considering that the large precipitation in this country is still accompanied by irrigation so that the water used by agriculture becomes inefficient. Researches by Sayekti et al. (2017) and Lestari et al. (2018) have provided a preliminary insight on this phenomenon in a specified watershed in East Java, namely the Brantas River Basin.

The question raised in this research is: What is the relationship between the agricultural productivity, on the one hand, and the water used for rice and maize cultivation processes, on the other, based on an optimization model developed for the farming land in a watershed, in this case, the Brantas River Basin? This research aimed to answer this question by determining the factors determining the water necessity to explain the water uptake by rice and maize in relation to the availability of farming land within the basin.

Materials and Methods

This research developed a mathematical model to replicate the real agrohydrological conditions at the river basin level to answer the relationship between land and water use, regarding the existing agricultural activities. This model was utilized to simulate the agricultural water use (AWU) and the sources whereby the demand was fulfilled and the virtual water content (VWC) of the simulated crops was calculated. The model was a mathematical function to optimize variables through an iterative process.

This research used the virtual water concept from Allan (2003) as a tool to analyze the water productivity within the Brantas River Basin, in East Java. Virtual water is the consumed volume of water used to produce a unit of agricultural commodity or service for humans, even though it does not physically appear in the final product or service rendered (Hoekstra and Hung, 2002). Research at the local level using this tool is useful for designing policies in managing water availability (Aldaya et al., 2019; Novoa et al., 2019; Xu et al., 2019) and the optimization of cropping patterns and water availability for agriculture (Lee et al., 2018; Van Huynh et al., 2019; Elbeltagi, 2020).

Data in this research were collected from the East Java Water Resources Office, Jasa Tirta I Corporation and the Meteorological Agency of East Java. The acquired data included irrigated farming land, the irrigation discharge, rainfall and climatological information. The research was conducted from the beginning of 2019 up to early 2020.

The model involved in this research was based on solving a set of equations. The AWU informs the volume of water needed to cultivate specific commodities within a certain area, and shows how much agricultural sector had or will utilize the current water potential in a river basin, which is defined by Chapagain and Hoekstra (2004):

$$AWU = \sum_{c=i}^n CWU[c] \dots\dots\dots (1)$$

where: CWU denotes the crop water use as the water demand to fulfil CWR over a specific period (m³); [c] denotes the certain agricultural commodities that are planted, from i = 1 ton.

CWU is directly related to the evapotranspiration at the farm level, and to optimize the land use in relatedness to the water availability within a particular river basin, the following equation was used:

$$CWU[c] = CWR[c] \times A[c] \dots\dots(2)$$

where: CWR denotes the crop water requirement (m³ /ha); and A denotes the planted area for certain crop [c] in a year (ha).

CWR is the cumulative water demand to fulfil the plant's evapotranspiration starting from the seedling stage until to the harvest, computed under certain climatic conditions, where sufficient soil moisture is available from precipitation and irrigation, thus not limiting the plant growth and yield (Allen et al., 1998). CWR is obtained by the Penman-Monteith equation and informs the evapotranspiration of a crop over a certain cultivation time.

For a specific river basin where water availability is considered to be entirely derived from surface water sources, the equation (1) is subject to be:

$$AWU \leq BWR - EFR \dots\dots\dots(3)$$

where: BWR denotes total water flow in the river basin for the given year (m³/year); EFR denotes minimum total flow to maintain the river environment (m³/year). On the other hand, the VWC having the units of m³/t¹, was calculated by the equation from Hoekstra and Hung (2002):

$$VWC = \frac{CWR}{Y} \dots\dots\dots (4)$$

where: CWR denotes the crop water requirement (m^3/ha); and Y denotes the yield of agricultural commodities planted (t/ha).

The model in this research aimed at maximizing the crop productivity by taking into account the water and land availability, including the possible sharing between the blue and green water sources to fulfil the objective. In consideration of equation (1) and equation (3), the optimization equation used was as follows:

$$\text{Max}\{f(\text{AWU}[c] + \text{LP} - \text{IR} - \text{R} \pm \text{GF})\} \dots (5)$$

where: Max f denotes the goal of the optimization equation to minimize wasted water; AWU denotes agricultural water use ($m^3/year$) for the irrigated area (A) within the boundary of $a < A < b$; LP denotes the water requirements for land preparations ($m^3 \text{ year}^{-1}$) for the farming area (A) within the boundary of $a < A < b$; IR denotes irrigation water ($m^3 \text{ year}^{-1}$) in accord to A; R denotes the effective rainfall ($m^3 \text{ year}^{-1}$) in accord to A; and GF denotes displacement (flux) of green water to and from nature.

The limit set for this model was used to maximize A (land area) within the boundary $a \leq A \leq b$, by utilizing as much blue water as possible from irrigation (I) and effective rainfall (R) to meet the agricultural water needs (AWU) in the

river basin. If $(\text{AWU}[c] + \text{LP}) < (\text{L} + \text{R})$ then the variable $G > 0$, so the value of G represents the absorption of humidity (green water) from nature.

This research problem was answered by utilizing the VWC concept in a model developed in accordance with the following flow chart (Figure 1). The model was used to optimize the cropping pattern in accordance to the limited farming land within the basin, maximizing the available blue water, and thereto incorporating the blue water and green water as an agriculture water source.

The hydrological description of this research was determined by the basic year representing the situation of the Brantas River Basin. For this purpose, the 37-year annual rainfall data (1982-2018) of the basin were analyzed using the Weibull and Basic Year distribution method. The hydrological reliability was set at 80% and was found to be equivalent to the year 2011, with an annual rainfall that stood at 1,643 mm, representing the basin's basic year, and another dry year (1997) was taken into consideration for the modelling, in order to obtain a further understanding of the basin's hydrological impact in the farming optimization process. Furthermore, the optimization was carried out using the model for the respective years of 1997 and 2011 as a verification method.

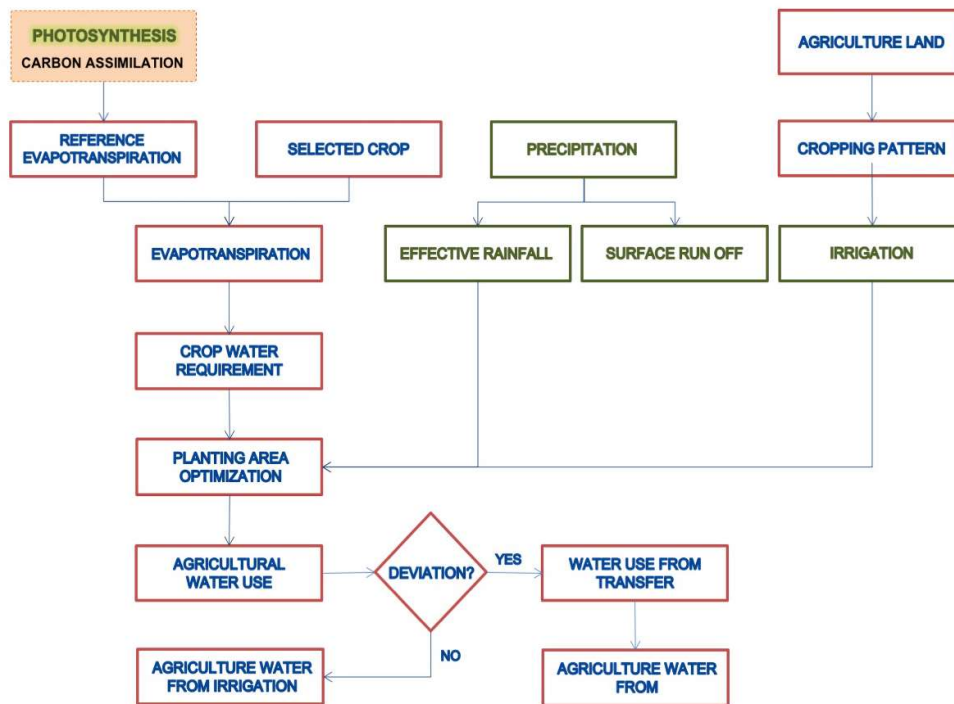


Figure 1. Flow chart of the research.

After the model is deemed adequate, the process is continued by using the model to calculate the intended AWU, planting area and VWC of the year 2021 to 2025. The rainfalls for the years 2021 to 2025 were forecasted using the generalized space-time autoregressive (GSTAR) approach, while the ET characteristics were calculated using the climate data of 2011, while the irrigation was designed with the combination at a 65% reliability for the rainy season and a 35% reliability for the dry season.

Results and Discussion

Results

The answer of the research problem has given the light into the role of how fulfilling the AWU at basin level will be important to secure the agricultural sector. Through computing the CWR in accordance to Penman-Monteith approach (Allen et al. 1998), the AWU was simulated for the entire agricultural land in the Brantas River Basin using equation (1) and equation (5), and the results are presented as follows. An important issue that surfaces within the Brantas River Basin is the decline of the total irrigation area due to land use change in the basin. The survey result showed that the irrigated farming land was 135,235 ha in 1997 and has declined to 123,177 ha (2011), thus making the total loss close to 9%. Based on this condition,

the optimization process has considered the decline as an important threshold while simulating the agriculture activity based on the available water supply within the basin. The optimization process shows that AWU can be fulfilled from rain and irrigation, as both resources are available in sufficient quantities. Based on the planted area, it is known that the crop intensity is stable even though the farming land decreases every year due to the reduced agricultural land.

The optimization results also provide the optimum planted area in the Brantas River Basin for paddy and maize crops. The optimization results consistently suggest planting more paddy than maize, during the dry year (1997), near the dry year (2011), and future low rainfall scenario (2021-2025). Optimization of the future low rainfall scenario, recommends a paddy planting area of approximately 140% compared to the planted area of maize (Table 1).

The optimization results also enlighten to the regarding deficits arising from the unavailability of irrigation or effective rain at exactly the right time during the cropping season. This deficit can be seen in the optimization carried out in the low rain scenario in 2021-2025. Optimization has confirmed in advance that all the available water potentials, both irrigation and rain, can be effectively utilized throughout the year, and seeks to prevent crop failure due to depletion of moisture in the soil until it reaches the wilting point.

Table 1. Agriculture water use and effective rainfall (AWU in mm) and optimized farming area (in hectares) as optimized for the Brantas River Basin.

No	Year	Optimization Results in the form of AWU and Planted Area						
		1997	2011	2021	2022	2023	2024	2025
1	AWU	450.0	432.0	454.2	454.4	452.6	453.0	450.8
2	Effective rainfall	778.0	1,509.0	580.2	488.8	480.9	508.6	436.5
3	Paddy	211,829	203,796	179,740	180,497	165,841	191,811	191,804
4	Maize	167,556	146,135	139,456	136,944	149,863	122,174	120,841
5	Total area	379,385	349,931	319,197	317,441	315,704	313,986	312,285

Although there were no crop failures, the modelling shows a deficit at certain periods throughout the year, which arises when the AWU is not properly met by irrigation or effective rain that moisturizes the soil. This deficit is still within the limit that can be met by the transfer (flux) of available moisture kept in the soil.

This deficit is actually a terminology where sufficient water that must be added in a timely manner to maintain soil moisture within the field capacity range within the irrigated farming lands. The average deficit for 2020-2025 for the low rain scenario is around 33% of the total AWU used by

agricultural activities in the Brantas River Basin (Figure 2). Even small, this indicates that irrigation has not been properly provided to meet the needs of the cropping pattern.

The optimization results also prove that the VWC from paddy and maize produced in the optimization process is related to climatic conditions. Dry climatic conditions have been shown to increase water use as evapotranspiration and evaporation from the water surface or from the ground increases, and if agricultural productivity falls, overall water productivity will decrease and in fact increase the VWC.

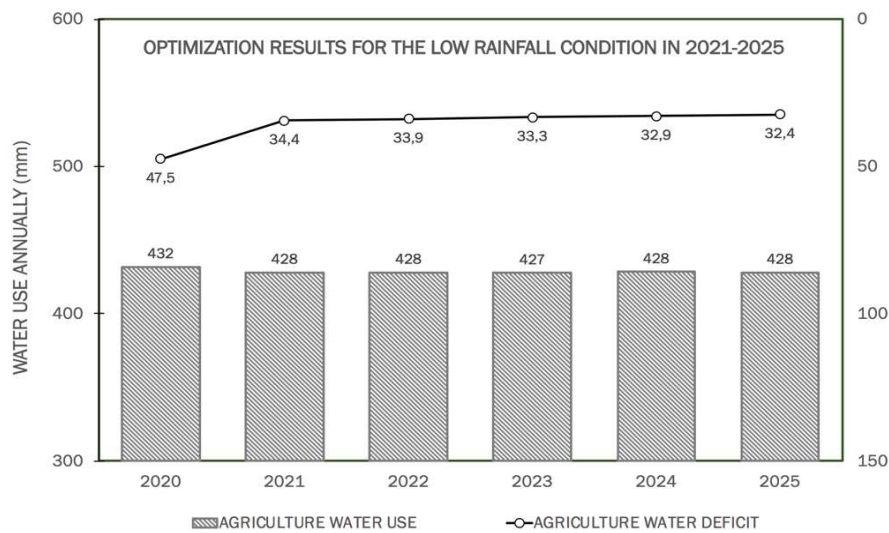


Figure 2. Optimization results of the low rainfall condition for the year 2021 to 2025.

During the driest year in the simulation (1997) VWC for unhusked rice and maize increases to 838 m³/t and 1,494 m³/t, respectively. However, during the low rainfall years, and assuming the year 2011 as a climate benchmark for computing the evapotranspiration, the VWC of both unhusked rice and maize remains considerably in average at 720 m³/t¹ and 1,250 m³/t for the optimized years of 2021 to 2025 (Table 2).

Table 2 Virtual water content of unhusked paddy and maize obtained from the optimization process (in m³ /t).

No	Optimized Year	Virtual Water Content	
		Unhusked Rice	Maize
1	1997	838	1,494
2	2011	717	1,050
3	2020	720	1,270
4	2021	724	1,218
5	2022	716	1,240
6	2023	723	1,206
7	2024	712	1,266
8	2025	724	1,237

Discussion

Paddy as type C3 and maize as type C4 involve different carbon assimilation processes which accordingly affect the amount of VWC for each respective crop product. This research confirms the argument of Rockström (2003) that the evapotranspiration of food crops in the tropical climate is highly related to the efficiency of the

photosynthetic process involved. Considering that the C4 plants in tropical environments have a higher productivity per unit of water use than the C3 plants in the sub-tropics.

As the C4 plants have about twice the carbon assimilation per unit of evapotranspiration compared to that of the C3 plants, and the rate of this assimilation in a given climatic condition is determined by the magnitude of the vapour pressure deficit due to the evapotranspiration in the plant, food crops with less efficient photosynthetic pathways when cultivated in the sub-tropical climatic conditions are implied to be able to thrive only when compensated by a more humid atmosphere, meaning that a lower vapour pressure promotes transpiration.

Based on this analogy, it can be concluded that paddy as a C3 crop is preferable when the humidity in the air is adequate and there is sufficient water, for example, during the rainy season. Meanwhile, when the humidity drops so that the vapour pressure decreases, it is advisable for irrigated land in the Brantas watershed to prioritize planting C4 types such as maize, as it reduces the overall water use.

Apart from selecting plants with higher water productivity, another problem in the process of optimizing the agricultural sector in the Brantas River Basin is the cropping patterns, which in this research are less sensitive to the real evapotranspiration requirements. This problem is known to have occurred for a long time (SUDP, 1997) and is still an issue that continues to be researched at the Brantas river basin (Sayekti et al., 2017; Lestari et al., 2018).

This research was successful, for example, in showing that the cropping pattern at the beginning of the dry season, which usually starts at the end of June or early July, will result in an increase in the need for agricultural water during the peak of the dry season occurring at the end of August and in early November (Figure 3). As recommended by other researchers (Wahida, 2005; Muhtadi and Iksan, 2017), accuracy is more required in the Brantas River Basin to determine the right cropping patterns and adjusting irrigation needs

during the dry season. The optimization process shows that increasing the maize area at the beginning of the dry season, which is planted without taking into account the available moisture in the soil has the potential to cause a deficit. This deficit can be seen in the scenario with a limited rainfall of the years 2021 to 2025. This deficit can be reduced by controlling the area of the maize crop and replacing it with paddy planted in a water-efficient manner, and withholding continuous irrigation practices.

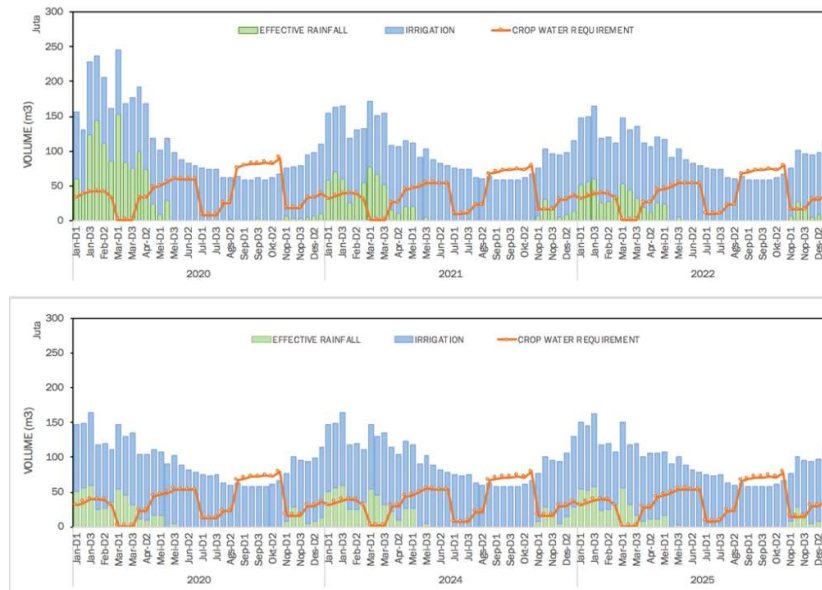


Figure 3. Effective rainfall, irrigation and crop water requirement for the optimized years of 2021 to 2025.

Mankin et al. (2017) have warned that various deficits of this kind are a threat to the agricultural sector in the future, especially due to climatological uncertainty caused by climate change. If this deficit is to be reduced and the risks are to be managed, then structural and non-structural mitigation should be carried out. Levidow et al. (2014) suggest that mitigation efforts in dealing with the risk of water shortage for agriculture are closely related to the changes in farming behaviour and procedures. Irrigation inefficiency is often due to a long-standing habit at the farmer level.

If the structural methods are taken by physically establishing a drought reserve, then this effort will certainly require water storage either in the form of adding new reservoirs or by increasing the capacity of the existing reservoirs, by elevating the dam-crest or dredging the reservoir. The cost of the implementation of these actions needs to be accurately calculated as it is costly. In confirmation with, among others, L'vovich and White (1990),

Gordon et al. (2003), Van der Zaag and Carmo-Vaz (2003), Rockström (2003), and Molden et al. (2007), this research also shows the importance of combining effective rain and irrigation in ensuring agricultural success in the Brantas River Basin in that the provision of irrigation in an agricultural optimization process must address only the deficits that arise in especially, and consider the importance of precipitation as the source of soil humidity. The optimization process for 2021 to 2025 shows that AWU can be fulfilled both from effective rain and irrigation, but the thickness of irrigation for each planting area in the Brantas River Basin exceeds the requirements (Figure 4). This research results confirmed that the low efficiency of wetland farming in the tropics can be caused by the inefficiency: (1) in the main intake structures, dividing the structures and the irrigation networks causing water loss in the water supply process; and (2) at the field level, namely in the plots where the agricultural activities are conducted.

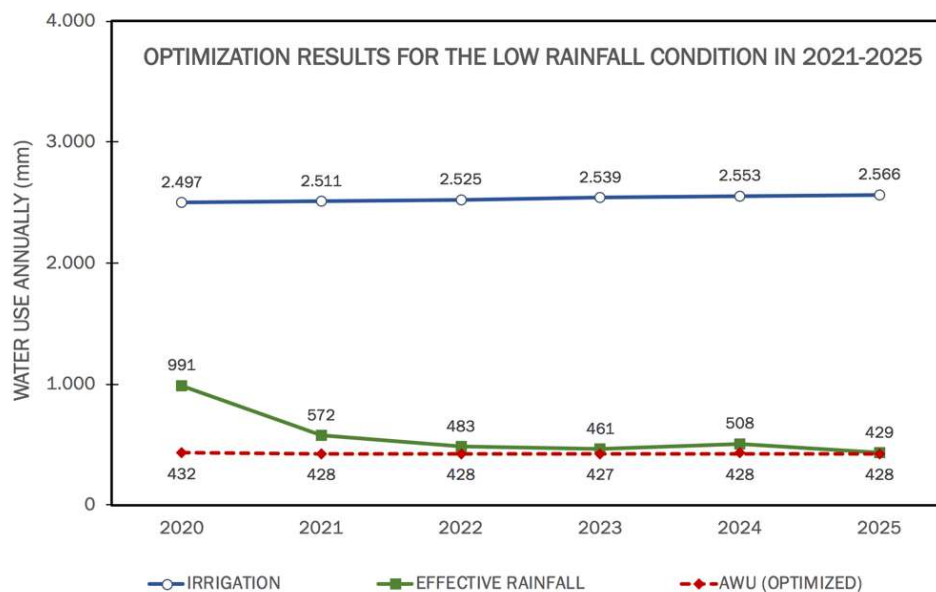


Figure 4. Irrigation supply, effective rainfall and agriculture water use for the optimized years of 2021 to 2025.

The research also confirms that the agricultural performance improves with the improvement of irrigation efficiency, which can be improved by means of increasing water productivity, as expected by Falkenmark and Lannerstad (2005). For humid-tropical areas, water savings can be allocated for other uses, such as for the environmental flows in the rivers. Confirming Chapagain et al. (2011) and other researchers up to Simons et al. (2020), this research shows that improvements in the irrigation networks management, crop rotation to endorse water savings, restrictions on activities outside the licensed irrigation issued by the irrigation manager, and dynamic cropping patterns according to water availability, must be implemented and will be a game-changer in the future of irrigation at the Brantas river basin.

Conclusion

In answering the relationship between the agricultural productivity and the water use in the cultivation processes for rice and maize-based on the optimization model developed, it is concluded that optimization using linear programming has successfully tested and determined the factors at the river basin level affecting the agricultural productivity. Modelling has explained the phenomena that shape crop water needs and how their fulfilment at the river basin's level involves both precipitations (rain) as the main source of

soil humidity and irrigation as a complementary source to satisfy the agriculture water demand. Furthermore, the research shows that the presence of excess irrigation in the tropical climates hinders the increase in agricultural productivity. The results of the optimization show that the method of providing irrigation in the Brantas River Basin needs to be improved by, among others, selecting plants with higher water productivity, developing water-sensitive cropping patterns and water conveyance savings. This study also confirms that virtual water content is a tool for assessing agricultural productivity.

References

- Aldaya, M.M., Custodio, E., Llamas, R., Fernández, M.F., García, J. and Ródenas, M.Á. 2019. An academic analysis with recommendations for water management and planning at the basin scale: a review of water planning in the Segura River Basin. *Science of the Total Environment* 662: 755-768.
- Allan, J.A. 2003. Virtual water: the water, food, and trade nexus useful concept or misleading metaphor? *Water International* 28(1): 4-11.
- Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. Crop Evaporation (Guidelines for Computing Crop Water Requirement). FAO Irrigation and Drainage Paper No. 56, Roma, Italia.
- Berbel, J., Gutiérrez-Martín, C., Rodríguez-Díaz, J.A., Camacho, E. and Montesinos, P. 2015. Literature review on rebound effect of water saving measures and analysis of a Spanish case study. *Water*

- Resources Management* 29: 663-678, doi: 10.1007/s11269-014-0839-0.
- Bulsink, F. Hoekstra, A.Y. and Booij, M.J. 2010. The water footprint of Indonesian provinces related to the consumption of crop products. *Hydrology and Earth System Sciences* 14: 119-128, doi: 10.5194/hess-14-119-2010.
- Chapagain, A.K. and Hoekstra, A.Y. 2004. Water Footprints of Nations. Volume I: Main Report. UNESCO-IHE Value of Water Research Report No. 16, Delft, The Netherlands.
- Chapagain, T., Riseman, A. and Yamaji, E. 2011. Achieving more with less water: alternate wet and dry irrigation (AWDI) as an alternative to the conventional water management practices in rice farming. *Journal of Agricultural Science* 3(3): 3-13.
- Connor, D., Loomis, R. and Cassman, K. 2011. Water management in irrigated agriculture. *Crop Ecology: Productivity and Management in Agricultural Systems*. Cambridge University Press. Pp 384-410, doi: 10.1017/CBO9780511974199.019.
- Elbeltagi, A., Deng, J., Wang, K. and Hong, Y. 2020. Crop Water footprint estimation and modeling using an artificial neural network approach in the Nile Delta, Egypt. *Agricultural Water Management* 235, doi: 10.1016/j.agwat.2020.106080.
- Falkenmark, M. and Lannerstad, M. 2005. Consumptive water uses to feed humanity: curing a blind spot. *Hydrology and Earth System Sciences* 9: 15-28, doi: 10.5194/hess-9-15-2005.
- FAO. 2017. Does improved irrigation technology save water? A review of the evidence. Food and Agriculture Organization., doi: 10.13140/RG.2.2.35540.81280.
- Gordon, L., Dunlop, M. and Foran, B. 2003. Land cover change and water vapour flows: learning from Australia. *Philosophical Transactions Royal Society London B* 358: 1973-1984, doi: 10.1098/rstb.2003.1381.
- Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S.A., Wang, Y., Garrick, D. and Allen, R.G. 2018. The paradox of irrigation efficiency. *Science* 80: 361-372, doi: 10.1126/science.aat9314.
- Hoekstra, A.Y. and Hung, P.Q. 2002. Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade. Value of Water Research Report Series No.11. UNESCO-IHE, Delft, The Netherlands.
- L'ovich, M.I. and White, G.F. 1990. Use and transformations of terrestrial water systems.. In: Turner II, B.L., Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T. and Meyer, W.D. (eds), *The earth as transformed by human action*. Cambridge University Press, Cambridge, UK.
- Lee, S.H., Choi, J.Y., Yoo, S.H. and Mohtar, R. 2018. Water footprint for Korean rice products and virtual water trade in a water-energy-food nexus. *Water International* 43(6): 871-886.
- Lestari, W.S., Suprayogo, D. and Prijono, S. 2018. Irrigation System Vulnerability Analysis with Resilience Index in the Irrigation Area of the Brantas River Basin. *Agri-tech* 38(4): 413-423 (in Indonesian).
- Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M. and Scardigno, A. 2014. Improving water-efficient irrigation: prospects and difficulties of innovative practices. *Agricultural Water Management* 146: 84-94.
- Liu, J. and Savenije, H.H.G. 2008. Food consumption patterns and their effect on water requirement in China. *Hydrology and Earth System Science* 12: 887-898, doi: 10.5194/hessd-5-27-2008.
- Mankin, J.S., Viviroli, D., Hoekstra, A.Y., Horton, R., Smerdon, J. and Diffenbaugh, N.S. 2017: Influence of internal variability on population exposure to hydroclimatic changes. *Environmental Research Letters* 12(4), 044007, doi:10.1088/1748-9326/aa5efc.
- Molden, D., Oweis, T.Y., Pasquale, S., Kijne, J.W., Hanjra, M.A., Bindraban, P.S., Bouman, B.A.M., Cook, S., Erenstein, O., Farahani, H., Hachum, A., Hoogeveen, J., Mahoo, H., Nangia, V., Peden, D., Sikka, A., Silva, P., Turral, H., Upadhyaya, A. and Zwart, S. 2007. Pathways for increasing agricultural water productivity, dalam *Water for Food, Water for Life, a Comprehensive Assessment of Water Management in Agriculture*. Earthscan and International Water Management Institute, London. pp 279-310.
- Muhtadi, M.I dan Iksan, M.Y.M. 2017. Efficiency of Water Supply in the Brantas Delta Irrigation Area (Mangetan Kanal Irrigation Network) to Get the Optimal Planting Pattern Using A Linear Program. Thesis, Institut Teknologi 10 November Surabaya. Indonesia (in Indonesian).
- Novoa, V., Ahumada-Rudolph, R., Rojas, O., Munziaga, J., Sáez, K. and Arumi, J.L. 2019. Sustainability assessment of the agricultural water footprint in the Cachapoal River Basin. *Ecological Indicators* 98: 19-28.
- Oweis, T. and Hachum, A. 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. *Agricultural Water Management* 80: 57-73, doi: 10.1016/j.agwat.2005.07.004.
- Pandey, R.K., Maranville, J.W. and Admou, A. 2000. Deficit irrigation and nitrogen effects on maize in a Sahelian environment: grain yield and yield components. *Agriculture Water Management* 46: 1-13, doi: 10.1016/S0378-3774(00)00073-1.
- Pasandaran, E. and Rosegrant, M.W. 1995. Irrigation investment in Indonesia: trend and determinants. *Jurnal Agro Ekonomi* 14(1): 1-26.
- Pawitan, H., Adidarma, W., Hatmoko, W., Hadihardaja, I.K., Kodoatie, R.J., Putuhena, W.M., Sitompul, A.T.M., Sumiarsih, N.M., Sari, Y.C., Faridz, E. and Radhika. 2013. Water Tread Air and Indonesia's Water Supply Strategy. Directorate General of Water Resources, Ministry of Public Works, the Republic of Indonesia (in Indonesian).
- Rockström, J. 2003. Water for food and nature in drought-prone tropics: vapour shift in rain-fed agriculture. *Philosophical Transactions Royal Society London B* 358: 1997-2010, doi: 10.1016/S0022-1694(98)00176-0.
- Rockström, J., Jansson, P. and Barron, J. 1998. Seasonal rainfall partitioning under run on and runoff

- conditions on sandy soil in Niger; on-farm measurements and water balance modelling. *Journal of Hydrology* 210: 68-92, doi: 10.1016/S0022-1694(98)00176-0.
- Rosegrant, M.W., Kasryno, F. and Perez, N.D. 1998. Output response to prices and public investment in agriculture: Indonesian food crops. *Journal of Development Economics* 55(2): 333-352, doi: 10.1016/S0304-3878(98)00039-X.
- Sayekti, R., Purwati, E. and Ismojo, M.D. 2017. Simulation of water use index (IPA) for saving of irrigation water in Sonosari and Pakis of Malang Regency. *Jurnal Teknik Pengairan* 8(2): 241-251, doi: 10.21776/ub.pengairan.2017.008.02.10 (in Indonesian).
- Scott, C., Vicuña, S., Blanco-Gutiérrez, I., Meza, F. and Varela-Ortega, C. 2014. Irrigation efficiency and water-policy implications for river basin resilience. *Hydrology Earth System Sciences* 18: 1339-1348, doi: 10.5194/hess-18-1339-2014.
- Simons, G.W.H., Bastiaanssen, W.G.M., Cheema, M.J.M., Ahmad, B. and Immerzeel, W.W. 2020. A novel method to quantify consumed fractions and non-consumptive use of irrigation water: application to the Indus Basin Irrigation System of Pakistan. *Agricultural Water Management* 236: 1-14, doi: 10.1016/j.agwat.2020.106174.
- SUDP. 1997. *Surabaya River Improvement and Pollution Control Project*. Final Report Volume 4 Annex F. Surabaya Urban Development Program (SUDP). IBRD Loan 3726-IND SURIPCAPS.
- van der Zaag, P. and Carmo-Vaz, A. 2003. Sharing the Incomati waters, cooperation and competition in the balance. *Water Policy* 5: 340-368, doi: 10.2166/wp.2003.0021.
- van Huynh, C., Scheltinga, C.T. van, Pham, T.H., Duong, N.Q., Tran, P.T., Khanh-Nguyen, L.H., Pham, T.G., Nguyen, N.B. and Timmerman, J. 2019. Drought and conflicts at the local-level: establishing a water sharing mechanism for the summer-autumn rice production in Central Vietnam. *International Soil and Water Conservation Research* 7(4): 362-375, doi: 10.1016/j.iswcr.2019.07.001.
- van Noordwijk, M., Kim, Y.S., Leimona, B., Hairiah, K. and Fischer, L.A. 2016. Metrics of water security, adaptive capacity, and agroforestry in Indonesia. *Current Opinion on Environmental Sustainability* 21: 1-8, doi: 10.1016/j.cosust.2016.10.004.
- Wahida. 2005. Estimation of Technical Efficiency Level of Rice and Palawija Farming in Brantas River Waters: Application of the Stochastic Production Frontier Approach. Thesis, Institut Pertanian Bogor (IPB), Indonesia (in Indonesian).
- WB. 2011. East Java Growth Diagnostics, Identifying the Constraints to Inclusive Growth in the Indonesian Second-Largest Province. World Bank, REDI and Government of East Java. World Bank.
- Xu, M., Wang, X.M., Sun, T., Wao, H., Li, X.M. and Kang, S.C. 2019. Water balance change and its implications to vegetation in the Tarim Basin Central Asia. *Quaternary International* 523: 25-36, doi: 10.1016/j.quaint.2019.06.011.
- Zhang, X.X., Liu, J.G., Zhao, X., Yang, H., Deng, X.Z., Jiang, X.H. and Li, Y.P. 2019. Linking physical water consumption with virtual water consumption: methodology, application and implications. *Journal of Cleaner Production* 228: 1206-1217, doi: 10.1016/j.jclepro.2019.04.297.