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Future Water Availability in the Asian Monsoon Region: A Case Study in Indonesia

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In the Asian monsoon region, which has distinct rainy and dry seasons, the water cycle will be accelerated by global warming, leading to more intense rainfall and long-term drought. The growing population in Indonesia will require increased food production in the future, and the floods and droughts induced by global climate change will affect agricultural production directly and indirectly through soil erosion and/or changes in carbon and nutrient dynamics in soil. Therefore, evaluation of spatial and temporal distributions of available water is necessary to manage water resources effectively. In this study, we predicted the future water availability in the Citarum River basin of West Java. A distributed water cycling model was developed and applied to analyze the water balance in the basin, and a dam operation model was combined with this model to calculate water storage in the reservoirs. According to our analyses, rainfall intensity is expected to lessen in 2046–2055, with rain falling more equally throughout the year and with mid-range amounts of rainfall continuing for longer periods as compared to 1996–2005. The drought period in 1996–2005 was 632 days over 10 years, but in 2046–2055 it is predicted to increase to 881 days. The predicted frequency of flooding increased from two times in 1996–2005 to five times in 2046–2055. These results show that water will become difficult to obtain in the future, and water scarcity and competition among water users will become severe. Our analyses of two irrigation districts showed that the one with water regulation facilities is expected to have more stable water availability in the face of climate change conditions than the one with no such facilities. Thus, it is necessary to construct more water regulation facilities to improve the resilience of the Citarum watershed to water scarcity.

Key words: climate change, hydrological model, water scarcity

Introduction

Global climate change is causing severe flooding and droughts around the world, and few regions exist where river basins and aquifer systems are not being impacted. Among other factors, the intensification of agriculture is contributing to deforestation and desertification. At present, 70% of the water in river basins and aquifer systems is withdrawn for agricultural use in the world (Bouman *et al.*, 2000). Increased water use associated with agriculture and urbanization is leading to high rates of groundwater use, as well as

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changes in storage infrastructure and new conveyance networks. Despite these improvements, climate change increases the uncertainty associated with the future availability and variability of freshwater resources and may even lead to permanent desertification of certain regions of the world (Gallee *et al.*, 2004; Hagos and Cook, 2007).

The impacts of floods and droughts in many areas will have to be managed more frequently than in the 20th Century. For example, in the Asian monsoon region with distinct rainy and dry seasons, the water cycle will be accelerated as global warming proceeds, leading to more intense rainfall and long-term drought. In addition, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) examined the impact of climate change on food production and predicted that in low-elevation regions, particularly in tropical regions with dry and rainy seasons, a rise of just 1–2℃ in regional temperatures will lower crop productivity and increase the risk of famine. In Indonesia, an increase in food production is needed to meet the demands of the growing population. However, the floods and droughts predicted as a result of global climate change will affect agricultural production directly and indirectly through soil erosion and changes in the carbon and nutrient dynamics in soil.

The Citarum River basin of West Java is a region known for its highly palatable rice. However, sediment accumulation and eutrophication have become serious issues in downstream reservoirs, due to the inflow of waste water from urban areas and fertilizer components from hilly upland fields into the river. In this study, we investigated the future availability of water in the Citarum watershed by using a distributed type of rainfall-runoff model.

Materials and Methods

Study Area

The Citarum River is the largest river in West Java, having a length of 350 km and catchment area of 6000 km^2 (Fig. 1). Annual mean precipitation varies from 1600 to 2800 mm/year. In this basin, 70% of the annual precipitation falls during the rainy season from November to March. Bandung city is located along the upstream reach of the Citarum River, and the river has three large dams: Saguling dam in the upstream reach, Cirata dam in the middle reach, and Jatiluhur dam in the downstream reach. Table 1 lists the char-

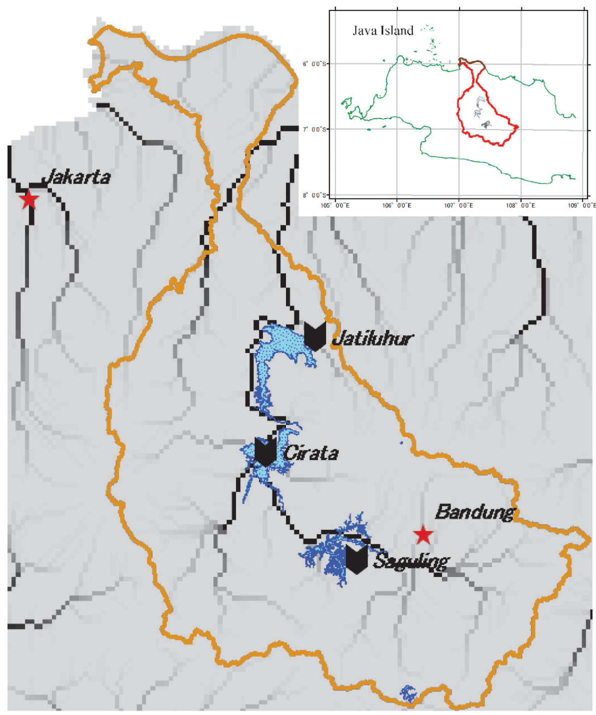

Fig. 1. Map showing the Citarum River basin and the dams at Saguling, Cirata, and Jatiluhur

Table 1. Characteristics of the three reservoirs in the Citarum River Basin, West Java, Indonesia, in 1996

Characteristics	Saguling Reservoir	Cirata Reservoir	Jatiluhur Reservoir
Catchment area (km^2)	2283	4061	4500
Dam height (m)	99	125	96
Volume (million m^3)	603	1927	2448
Purpose	Electricity	Electricity	Multiple/irrigation
Surface area (ha)	4869	6200	8200
Effective volume (million m^3)	598.4	784.9	1869
Installed capacity (turbins×MW)	700 (4×175)	1000 (8×125)	180 (6×30)

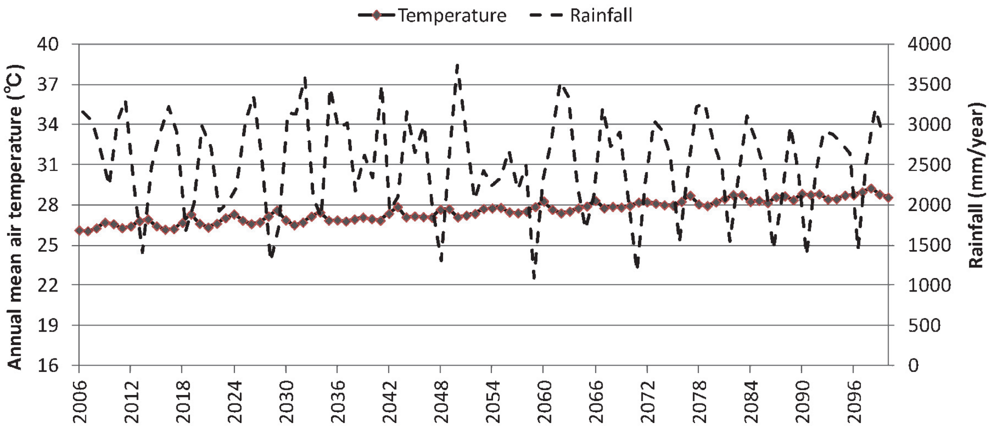

Fig. 2. Predicted annual mean air temperature and rainfall from 2006 to 2100

acteristics of the Saguling, Cirata, and Jatiluhur reservoirs. The Citarum River is the most important river in West Java, supplying water for Bandung and Jakarta City, with 80% of domestic water in Jakarta being withdrawn downstream of the Jatiluhur dam (Loebis and Syamman 1993; Fares 2003). The land uses in the Citarum River basin are paddy (35%), plantation (25%), forest (23%), urban (12%), and water (5%). Land-use change in the upper Citarum basin, which was caused by deforestation, was the main cause of soil erosion (Saroinsong *et al.* 2007).

In this study, we used the Model for Interdisciplinary Research on Climate (MIROC5) these values were estimated with a general circulation model (GCM) with a spatial resolution of 1 degree, and the generated data were corrected for bias errors. Figure 2 shows the predicted annual mean air temperature and rainfall from 2006 to 2100 based on MIROC5 (rcp8.5) output at Bandung City (http://pcmdi9.llnl.gov/esgf-web-fe/). The model predicts that the air temperature will increase gradually by more than 3℃ during the period, whereas the trend of annual rainfall will not change significantly. For example, the 10-year average rainfall values are predicted to be 2170 mm/year for 2021–2030, 2258 mm/year for 2046–2055 and 2198 mm/year for 2091–2100.

Rainfall-Runoff Model

To evaluate the impact of future climate change on water availability in the Citarum watershed, a distributed water cycling model was developed and applied to analyze the water balance in the basin. TOPMODEL was employed for the rainfall-runoff analysis. Such a distributed model can include the spatial distribution of topography, land use, and soil characteristics. Therefore, TOPMODEL is widely used for hydrological characteristic analysis, water management, water quality analysis, and future forecasting.

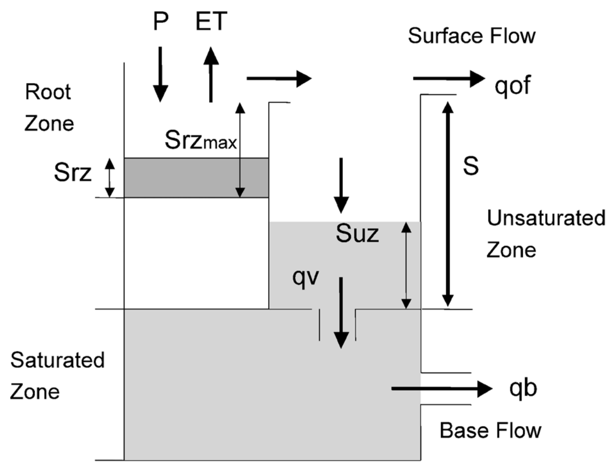

Fig. 3. Conceptual structure of the water cycle as estimated by TOPMODEL. P represents the amount of precipitation that enters the system, and ET represents water loss due to evapotranspiration.

TOPMODEL was proposed by Beven and Kirkby (1979) based on the contributing area concept in hill slope hydrology. This model is based on the exponential transmissivity assumption, which leads to a topographic index $\ln(a/To/\tan b)$, where a is the upstream catchment area draining across a unit length, To is the lateral transmissivity under saturated conditions, and b is the local gradient of the ground surface. Figure 3 illustrates the conceptual structure of the water cycle as estimated by TOPMODEL. TOPMODEL includes three soil layers: the root zone, unsaturated zone, and saturated zone. Water content of the root zone and unsaturated zone are calculated by distributed parameters, whereas water content of the saturated zone is normally calculated by lumped parameters. Because TOPMODEL requires only three parameters (i.e., m, To, and Srz_{max}), the model is easy to link with GIS data (for details, see Ao *et al*., 1999; Nawarathna *et al*., 2001). In addition, a dam operation model was combined with TOPMODEL to calculate water storage in the reservoirs (Hanasaki *et al*., 2007).

Discharge is composed of overland and base flow, and the saturation deficit controls the discharge from a local area. The local saturation deficit is determined from the local topographic index relative to its average value λ. Thus, the topographic index is the critical controlling factor in runoff generation and is a function of topography and soil type.

Over an entire area, the average saturation deficit $D(t+1)$ is determined by using the following equation:

$$D(t+1)=D(t)-Qv(t)+Qb(t) \tag{1}$$

where $D(t)$ is the previous average saturation deficit, $Qv(t)$ is infiltration to groundwater from the unsaturated zone at time t, and $Qb(t)$ is the base flow discharge from groundwater to stream over all grids at time t.

The average saturation deficit $D(t)$ is distributed to the local saturation deficit $S(i,t)$ at grid cell i and time t according to the magnitude of the local topographic index relative to its average λ, as follows:

$$S(i,t)=D(t)+\{m\times[\lambda-\ln(a/to/\tan b)]\} \tag{2}$$

where m is the decay factor of lateral transmissivity with respect to the saturation deficit in meters.

Rainfall on the grid cell i at time t first enters the root zone, and the storage in the root zone $Srz(i,t)$ changes as follows:

$$Srz(i,t)=Srz(i,t-1)+P(i,t)-ET(i,t) \tag{3}$$

where P is precipitation and ET is evapotranspiration.

The excess of root zone storage $Srz(i,t)$ then enters the unsaturated zone, and its storage $Suz(i,t)$ is calculated as follows:

$$Suz(i,t)=Suz(i,t-1)+Srz(i,t)-Srz_{\max}(i,t) \tag{4}$$

where $Srz_{\max}$ is the maximum storage capacity of the root zone.

Overland flow from grid cell i at time t $qof(i,t)$ is estimated as follows:

$$qof(i,t)=Suz(i,t)-S(i,t) \tag{5}$$

Groundwater discharge (i.e., base flow) is considered to be a semi-steady process depending on the saturation deficit. The hydraulic gradient is assumed to be parallel to the ground surface. Groundwater discharge from grid cell i at time t is determined as follows:

$$qb(i,t)=To\cdot\exp[-S(i,t)/m]\cdot\tan b \tag{6}$$

The discharge from grid cell i at time t to the stream is the sum of $qof(i,t)$ and $qb(i,t)$.

Results and Discussion

By using TOPMODEL, the water balance in the Citarum basin was calculated at a resolution of 1 km × 1 km. Calculated river discharge was in good agreement with the amounts observed at Cirata station from 1993 to 2006 (Fig. 4). Figure 5 shows calculated versus observed water storage at Cirata reservoir from 1993 to 2006.

Evaluation of Available Water Resources in the Future

By using the MIROC5 dataset, future changes in discharge from the Citarum River were evaluated. Figure 6 shows decadal rainfall and calculated river discharge at the Cirata dam station for the periods 1996–2005 and 2046–2055. Rainfall intensity is expected to lessen in 2046–2055, with rain falling more equally throughout the year and with mid-range amounts of rainfall continuing for longer periods as compared to 1996–2005. The river discharge is expected to be altered a great deal in response to such rainfall changes. For example, the drought period during which river discharge was less than $100\,m^3/s$ in 1996–2005 was 632 days over 10 years, but in 2046–2055 it is predicted to increase to 881 days over 10 years. This increase in the drought period was also affected markedly by evapotranspiration. Potential evapotranspiration was calculated from air temperature data by using the Thornthwaite method (Thornthwaite 1948). The runoff ratio, which is the ratio of total river discharge to total rainfall, decreased from 0.65 in 1996–2005 to 0.59 in 2046–2055. In the case of flooding (i.e., discharge more than $500\,m^3/s$), the frequency increased from two times in 1996–2005 to five times in 2046–2055. These results show that water will become difficult to obtain in the future, and water scarcity and competition among the water users will be-

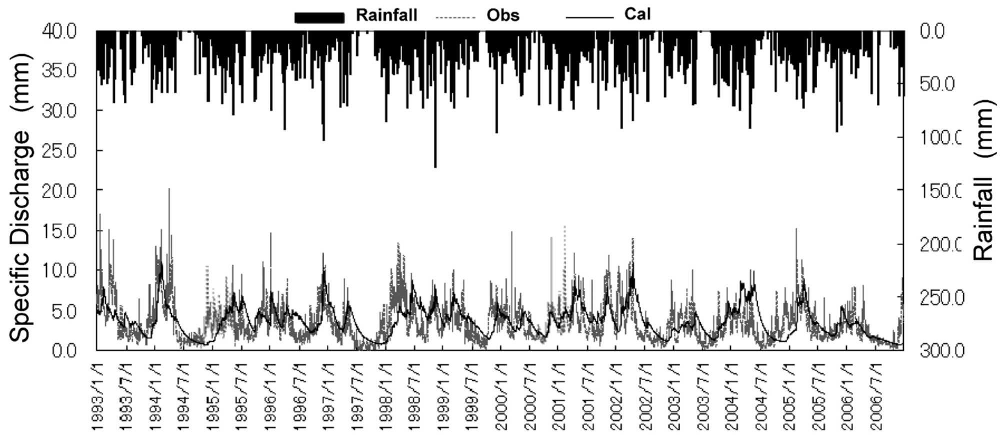

Fig. 4. Rainfall and calculated and observed river discharge at Cirata station from 1993 to 2006

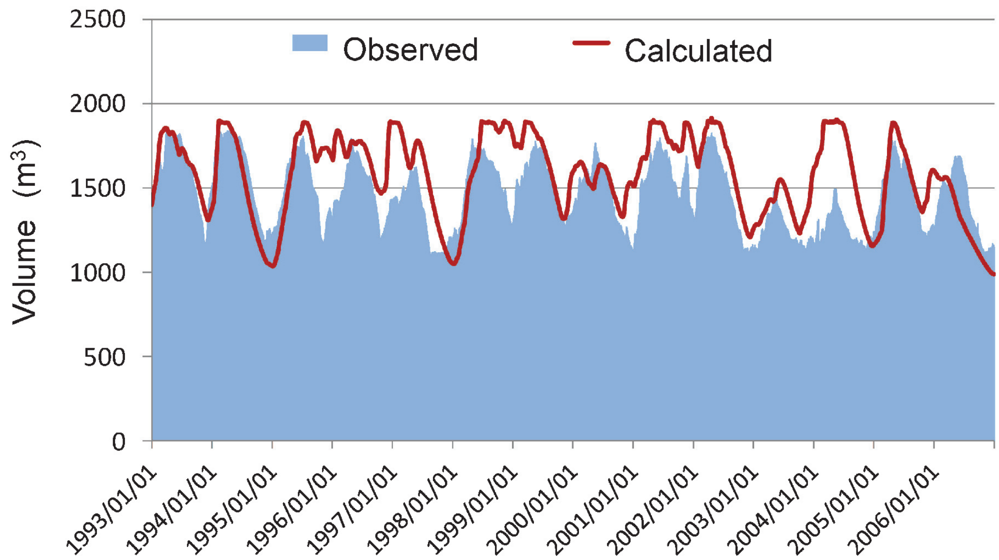

Fig. 5. Comparison of calculated and observed water storage at Cirata reservoir from 1993 to 2006

come severe.

In the Citarum River basin, the main water user is the agricultural sector (BBWSC 2011). Much water is needed for food production, especially in paddy fields, and the availability of water is strongly affected by natural weather conditions. From 1990 to 2008, the average amount of water available from the Citarum River was 7.65×10^9 m^3/year, and the agricultural sector used more than 70% (5.52×10^9 m^3/year) of the total. With this amount of water, farmers can cultivate irrigated paddies 2.1 times per year, on average.

In the next analysis, we made the simplifying assumption that water demand will remain constant from 1996 to 2055. Figures 7 and 8 show the river water discharge versus water demand at the point of intake in the Cihea Irrigation District (5844 ha) and Jatiluhur Irrigation District (128,000 ha), respectively. The numbers of water shortage days, when river discharge is lower than water demand, were estimated as (all values per decade): 638 days (1996–2005), 1632 days (2021–2030), and 990 days (2046–2055) in the Cihea Irrigation District and 67 days (1996–2005), 651 days (2021–2030), and 110 days (2046–2055) in the Jatiluhur Irrigation District. Upstream of the Cihea Irrigation District, there are no water regulation facilities, so that water availability in the future is predicted to become more vulnerable. In contrast, there are three large-scale dams upstream of the Jatiluhur Irrigation District, so that the amount of water is expected to be more stable than at Cihea.

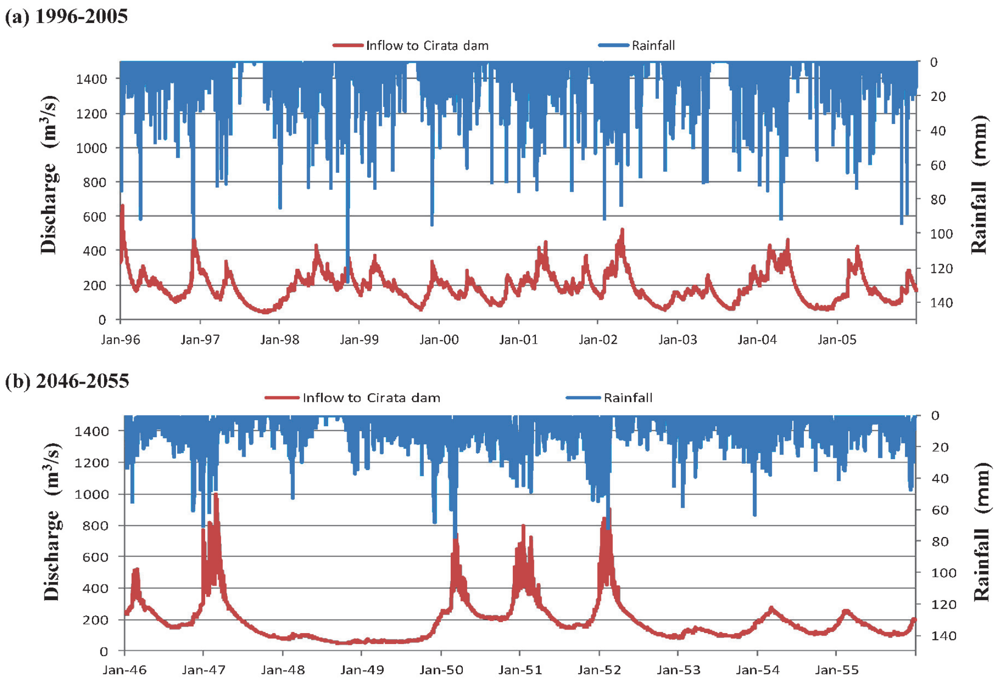

Fig. 6. Decadal rainfall and calculated river discharge at Cirata station in (a) 1996–2005 and (b) 2046–2055

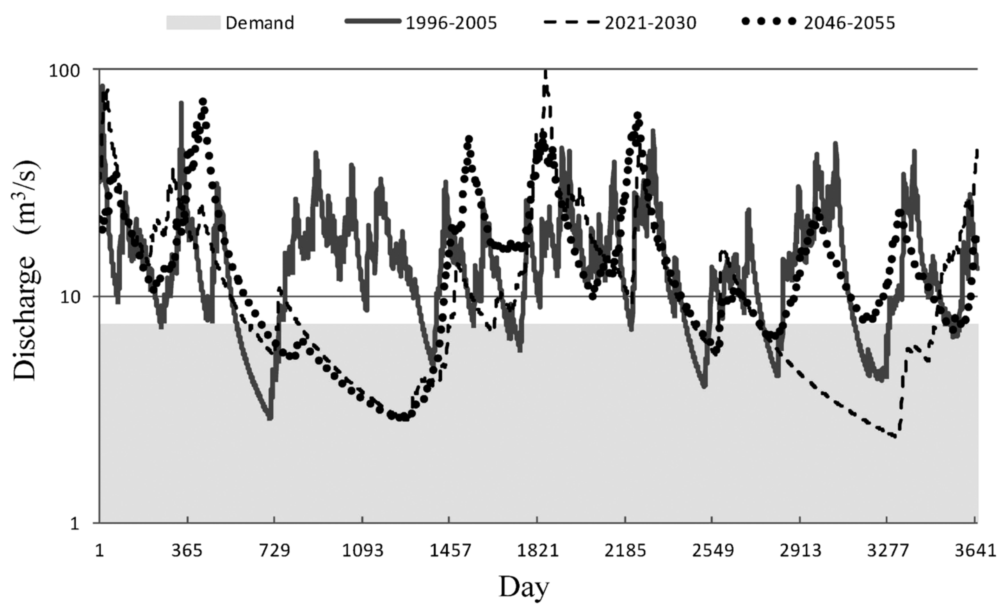

Fig. 7. Comparison of river water discharge and water demand in the Cihea Irrigation District, which has no water regulation facilities

Conclusion

In this study, a rainfall–runoff model was developed and applied to the Citarum River basin to evaluate future changes in water availability. According to MIROC5 GCM data, the air temperature in this region will significantly increase and evapotranspiration will be accelerated. Therefore, the total amount of water flowing in the river will decrease, especially during the dry season. Although the annual rainfall amount is

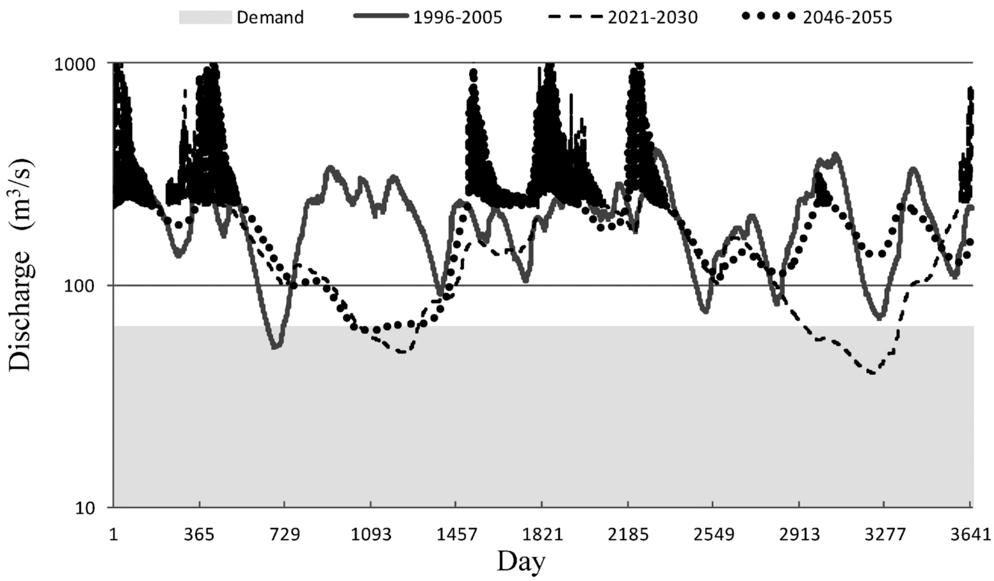

Fig. 8. Comparison of river water discharge and water demand in the Jatiluhur Irrigation District, which has three large-scale dams upstream

expected to remain fairly stable in the future, rainfall intensity will lessen, with rain falling more equally throughout the year and with mid-range amounts of rainfall continuing for longer periods as compared to the current situation. These results indicate that less water will be available in the future, such that water scarcity and competition among water users will become severe. Among the two irrigation districts analyzed, the one with water regulation facilities is expected to have more stable water availability in the face of climate change than the one with no such facilities. Thus, it is necessary to construct more water regulation facilities to improve the resilience of the Citarum watershed to water scarcity.

Acknowledgments

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References

Ao, T., Ishihira, H., Takeuchi K. 1999. Study of distributed runoff simulation model based on block type Topmodel and Muskingum-Cunge Method. Annual Journal of Hydraulic Engineering, 43, 7–12.

[BBWSC] Balai Besar Wilayah Sungai Citarum. 2011. Profil BBWSC (in Indonesian).

Beven, K.J., Kirkby, M.J. 1979. A physically based, variable contributing area model of hydrology. Hydrol. Sci. Bull. 24 (1), 43–69.

Bouman B.A.M. and T.P. Tuong 2000. Field water management to save water and increase its productivity in irrigated lowland rice, Agricultural water management, 1615, 1–20.

Fares, Y.R. 2003. Water resources management in tropical river catchments. J. Environ. Hydrol. 11 (14), 1–11.

Gallee, H., Moufouma-Okia, W., Bechtold, P., Brasseur, O., Dupays, I., Marbaix, P., Messager, C., Ramel, R., Lebel, T. 2004. A high-resolution simulation of a West African rainy season using a regional climate model. J. Geophys. Res. 109, D05108. DOI:10.1029/2003JD004020.

Hagos, S.M., Cook, K.H. 2007. Dynamics of the West African monsoon jump. J. Climate 20, 5264–5284.

Hanasaki, N., Utsumi, N., Yamada, T., Shen, Y., Bengtsson, M., Kanae, S., Otaki, M., Oki, T. 2007. Development of a global integrated water resources model for water resources assessments under climate change. Annual Journal of Hydraulic Engineering, JSCE, 51, 229–234.

Intergovernmental Panel on Climate Change 2007. IPCC Fourth Assessment Report: Climate Change 2007 (AR4).

Loebis, J., Syamman, P. 1993. Reservoir operation conflict in Citarum river basin management. IAHS Pub. 213, 455–459.

Nawarathna, N.M.N.S.B., Ao, T.Q., Kazama, S., Sawamoto, M., Takeuchi, K. 2001. Influence of human activity on the BTOPMC model runoff simulations in large-scale watersheds. 29th IAHR Congress Proc. Theme a, 93–99.

Saroinsong, F., Harashina, K., Arifin, H., Gandasasmita, K., Sakamoto, K. 2007. Practical application of a land resources information system for agricultural landscape planning. Landscape and Urban Planning 79, 38–52.

Thornthwaite, C.W. 1948. An approach toward a rational classification of climate. Geograph. Rev. 38, 55–94.