Global J. Environ. Sci. Manage. 8(4): 473-484, Autumn 2022, Serial #32

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

ORIGINAL RESEARCH PAPER

Water resources carrying capacity before and after volcanic eruption

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ARTICLE INFO

Article History:
Received 04 September 2021
Revised 11 December 2021
Accepted 16 January 2022

Keywords:
Mount Merapi
Spatial-gridded model
Water availability
Water needs

DOI: 10.22034/gjesm.2022.04.02

ABSTRACT

BACKGROUND AND OBJECTIVES: Water resources carrying capacity is dynamic and can be influenced by catastrophic volcanic eruptions. The eruption of Mount Merapi in 2010 changed the landscape and community livelihoods due to the redistribution of a large volume of volcanic materials. This study aims to analyze water resources carrying capacity before and after the major 2010 eruption of Mount Merapi.

METHODS: The value of water resources carrying capacity is derived from that of water availability and the domestic water needs per capita per year. The model uses a grid of 100 x 100 meter cells to determine the spatial distribution of water resources carrying capacity in Krasak watershed, and this analysis considers the years 2008, before the eruption, and 2021, after the eruption. The population distribution data have been previously mapped by referring to statistical data and land use at the village level, while water availability is calculated considering rainfall, potential evaporation rate, and runoff.

FINDINGS: Water resources carrying capacity in Krasak watershed has undergone changes related to the distribution of volcanic material and human activities. The water resources carrying capacity for both periods experienced a surplus, although there has been an average decrease of 331.50 cubic meters per year for each grid cell. Water resources carrying capacity analysis shows a decline, especially in the midstream and downstream. Based on T-Test, there are significant changes in the water resources carrying capacity at 2008 and 2021 (p-value 0.047 and 95% confidence level).

CONCLUSION: Water resources carrying capacity increased only in some locations that occurred ecosystem succession after the eruption, although areas near the peak are decreased by sand and stone mining. The spatial-gridded model proved capable of analyzing this phenomenon.

NUMBER OF REFERENCES
60

NUMBER OF FIGURES
3

NUMBER OF TABLES
4

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Note: Discussion period for this manuscript open until January 1, 2023 on GJESM website at the “Show Article”.

INTRODUCTION

Mount Merapi is an active volcano located in Central Java and the Special Region of Yogyakarta, Indonesia. Its volcanic edifice is surrounded by 10 rivers flowing to Indian Ocean in the south (Ville *et al.*, 2015; Anna *et al.*, 2016; Gob *et al.*, 2016). Merapi acts as a rain catchment area and contributes to surface water and shallow groundwater resources that meet the various needs of the surrounding community. Merapi is the most active volcano in Indonesia. Its "Merapi type" eruption is characterized by dome creation and destruction producing Pyroclastic Density Currents (PDCs) (Priatna and Kadarsetia, 2007). Basaltic-andesite lava of Merapi volcano was formed next to the subduction zone of Eurasian and Indo-Australian plates. The Eurasian plate is a continental plate type predominately composed of silica-aluminium (Si-Al) material, whereas the Indo-Australian plate is an oceanic plate with a composition of primarily silica-magnesium (Si-Mg) (Verstappen, 2010; Wang *et al.*, 2019). The interaction between these plates causes Merapi's eruptions to be divided into effusive and explosive phases, occurring alternately (Carr *et al.*, 2020). The last major eruption of Mount Merapi occurred in 2010 when volcanic ash spread up to thousands of kilometres from its crater through the air (long-range transport) (Wu *et al.*, 2019). The surrounding landscape changed drastically due to the sedimentation of pyroclastic materials and post-eruptive lahars. The Indonesian government made structural mitigation strategy to manage the cold lahar material using the 264 Sabo Dams, on the main rivers originating from Mount Merapi (Sukatja and Alfianto, 2017). The volcanic ash carried by the wind generally did not receive much attention in term of disaster mitigation because government focused on evacuating as many people as possible. Therefore, volcanic ash deposited on top soil, which damaged vegetation and caused changes in land use/cover through ecosystem succession. This phenomenon was classified as a post-disaster impact (Sutomo, 2013; Yudistira *et al.*, 2020). Ecosystem changes have a further impact, especially by decreasing the water resources carrying capacity (WRCC). Population growth and landscape changes, as signs of rural-to-urban transformation (urbanization–industrialization), have caused a decline in WRCC, thus worsening water crises (Sunardi *et al.*, 2020). The downward trend of WRCC is linearly related to socioeconomic structural changes that encourage increased water consumption and the release of wastewater into the environment. Ecosystem degradation amid the threat of climate change has become a barrier to recover water resource provisions (Cheng *et al.*, 2018; Yang and Yang, 2021). Declining WRCC is an implication of reduced vegetation cover and an increase in uncontrolled bare land, especially in areas close to population growth centres (Bangyou *et al.*, 2011; Dede and Widiawaty, 2020). Therefore, analysis of WRCC associated with Merapi can provide an important lesson about ecosystem dynamics and their impact on disaster-prone communities. WRCC analysis generally uses non-spatial approaches based on population, weather and climate, and socioeconomic and environmental data (Widodo *et al.*, 2015). Using geospatial approaches, WRCC study can surpass administrative boundaries from local scale to national scale (Lv *et al.*, 2021). The WRCC is obtained from the difference in values of water availability and the annual population's water demand in the study area based on spatial grids, especially in 2008 (pre-eruption) and 2021 (post-eruption). Few WRCC studies ignore geospatial aspects. It is only formulated by tabular data and even if using geospatial analysis, the analysis does not refer to ecoregions (eg. watersheds) and spatial grids. This study aims to analyse the WRCC in the Krasak watershed before and after the major eruption of Mount Merapi of Indonesia in 2010. This study would be useful for disaster mitigation, especially for determining new settlements and quantifying the socioeconomic activities of relocated population in detail.

MATERIALS AND METHODS

Study area and data acquisition

This study is based on a hypothesis that WRCC may change due to massive volcanic eruptions. Krasak watershed located at southwest of Mount Merapi, Indonesia. Administratively, Krasak watershed belonged to two provinces, i.e. Central Java and the Special Region of Yogyakarta in which there were three regencies, eight sub-districts, and 21 villages covering an area of 35.48 km^2. Krasak watershed was chosen as an appropriate location for WRCC research because it was an affected area

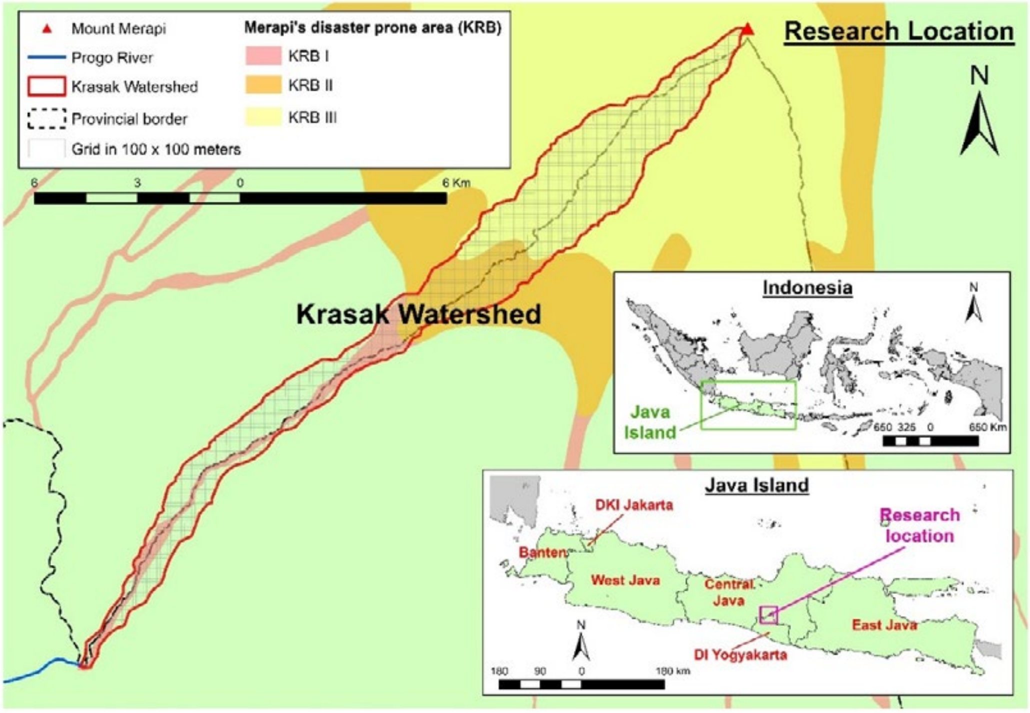

Fig. 1: Geographic location of the study area of Krasak watershed, in Indonesia (Mount Merapi is upstream and Kali Progo where is downstream of the watershed in Indonesia)

Table 1: Parameters for water resources carrying capacity

Variable	Parameter	Data source
Water availability	Rainfall	Annual rainfall
	Runoff	Rainfall intensity, land use-runoff capacity, and slope
	Potential evaporation	The geographical latitude and average temperature
Water needs	Population distribution	Population and land use data

covering three level of volcanic prone areas (KRB) during Merapi eruption in 2010 (Utami *et al*., 2018). Krasak watershed was inhabited by 28,081 people as of 2021 and possessed a complete database from previous studies (Umami *et al*., 2015; Maharani *et al*., 2016; Ikhsan *et al*., 2019b). Krasak watershed was divided by grids of 100 x 100 m to facilitate the analysis and aggregation of various parameters, as shown in Fig. 1. This analysis used the entire area of Krasak watershed, thus sample data refers to the population sample design. The grid size actually would refer to the unit of population density calculation in person per square kilometer, but the regulation of spatial data in Indonesia (Regulation of the Head of the Indonesian Geospatial Information Agency Number 3 of 2016 concerning Technical Specifications for the Village Maps) has required WRCC analysis to becomes more detailed – from 1 x 1 km to 100 x 100 m. The spatial-gridded approach differs from previous WRCC studies that were based on administrative regions of different sizes, even though the units were uniform in the legally formal context (Hastoyuando *et al*., 2020). The WRCC analysis used four parameters, i.e. rainfall, runoff capacity, potential evaporation rate, and spatial distribution of population. These parameters contributed to form variables for water availability and annual water demand (Table 1).

WRCC data processing and analysis

The WRCC calculation considered the water availability and the individual consumption per year. The WRCC value used volumetric units (m^3), with positive values indicating a surplus and negative values indicating a water resource deficit (Brontowiyono *et al.*, 2009; Tariq *et al.*, 2015; Yang *et al.*, 2019; Nikiel and Eltahir, 2021). This water requirement was not classified for agricultural activities because farmers generally provided their irrigation water from rivers and historical Mataram ditches coming from adjacent watersheds. Rainfall was derived from spatial interpolation using observational data from Governmental agencies such as Meteorology, Climatology and Geophysics Agency of Indonesia (BMKG), Indonesian Ministry of Public Works and Public Housing, and Indonesian Ministry of Agriculture. Furthermore, the runoff data were used as coefficient values for each land use type (Kodoatie and Sjarief, 2010; Tarigan, 2018; Asdak, 2020), shown in Table 2. Potential evaporation for the WRCC model was obtained from Blaney–Craddle method (Gotardo *et al.*, 2016; Mendoza and Peña, 2021). Calculation for the WRCC was presented using Eq. 1, and the analysis of the water availability was governed by Eqs. 2 to 4.

$$WRCC = WA - NW \quad (1)$$

Where WRCC is the water resources carrying capacity, WA is water availability, and NW represents the water needs per capita. This equation uses metres as international standard units using Eqs. 2 to 4.

$$WA = P - R - ET - \Delta S \quad (2)$$

$$R = 0.278 \times C \times P \times A \quad (3)$$

$$ET = p(0.46 \times T + 8.13) \quad (4)$$

Where, P is precipitation, R is runoff capacity, E is evapotranspiration, and S is the change in water storage. The parameter S for Krasak watershed was neglected because there is no significant surface reservoir in this area. Moreover, C is the runoff coefficient for each land use type, A is the catchment area, p is the annual average daytime percentage, and T is the annual average temperature.

Water needs were strongly influenced by the population and regional development characteristics, i.e. rural, urban, and peri urban. The spatial distribution of the population was useful in this analysis to understand the details. Therefore, a grid model as part of spatial approaches should be considered (Raju, 2004; Siljander, 2010; Widiawaty, 2019). In the case of Krasak watershed, land use data from the Indonesian Ministry of Environment and Forestry and population data from the Indonesian Central Statistics Agency were used for this model. Population distribution was tied to land use and regional characteristics, which required weighting (Bielecka, 2005; Mennis, 2009; Khomarudin *et al.*, 2010), as shown in Table 3. A spatial water needs analysis was performed using Eqs. 5 and 6. T-Test is used to compare the WRCC changes due to Merapi's eruption (Lohe *et al.*, 2015; Medina and Toledo-Bruno, 2016; Widiawaty *et al.*, 2020).

$$NW = Pop \times Wy \quad (5)$$

$$Pop_i = (Si / \sum ASi) \times Wi \times Pop \quad (6)$$

Where NW is the water needs per capita, Pop is the population, Wy represents the annual water needs per capita, Pop_i is the population in polygon i, Si is the area of polygon i, $\sum$ ASi is the total area of land use type i and Wi is the weight of land use type i.

RESULTS AND DISCUSSION

Merapi is an active stratovolcano in Indonesia

Table 2: Runoff coefficient (C) for land use types

Land use	C	Land use	C
Secondary forest	0.15	Bare land	0.60
Industrial forest (plantation)	0.47	Dryland farming	0.40
Bushes and shrubs	0.22	Dryland farming mixed with shrubs	0.20
Settlement	0.70	Rice field	0.52

Table 3: Weight (W) for land use types

Land use	W	Land use	C
Secondary forest	0.00	Bare land	0.00
Industrial forest (plantation)	0.03	Dryland farming	0.05
Bushes and shrubs	0.01	Dryland farming mixed with shrubs	0.02
Settlement	0.79	Rice field	0.10

Table 4: Land use in 2008 and 2021

Land use	Area (km^2)		Gain and loss	
	2008	2021	Km^2	%
Secondary forest	0.14	2.70	2.56	1826.04
Industrial forest (plantation)	3.38	0.53	−2.85	−84.37
Settlement	7.79	7.92	0.12	1.56
Dryland farming	13.33	7.28	−6.04	−45.34
Dryland farming mixed with shrubs	0.11	6.08	5.98	5649.67
Rice field	4.03	3.69	−0.33	−8.30
Bushes and shrubs	0.30	3.33	3.04	1022.07
Bare land	6.41	3.95	−2.47	−38.48

with its highest peak reaching 2930 m above sea level. Statictically, small eruptions occur every 2–3 years and larger eruptions occur every 10–15 years (Hapsari *et al.*, 2020). During its major eruption in 2010, Krasak watershed received 10.8 million m^3 of pyroclastic materials. This was the third largest after those of the Gendol watershed (24 million m^3) and Pabelan watershed (20.8 million m^3) (Kusumawardani *et al.*, 2017). Krasak watershed, located to the southwest of Mount Merapi, has been affected by 21 eruptions between the 18th and 21st centuries AD (Umaya *et al.*, 2020). The succession of ecosystems in Krasak watershed is a recurring event. The community continues to live in harmony with Mount Merapi, illustrated in part by its consistent population growth. WRCC analysis in Krasak watershed is important because it is related to the sustainability of water resources management in volcanic areas. Krasak watershed has an average elevation of 732.92 m above sea level (min: 114.48 m; max: 2871.34 m). Eleven years after Merapi's 2010 eruption, the changes in land use are characterized by increased scrub and reduced industrial forest (plantations) (Table 4). These changes are related to the pyroclastic flows (*Wedus Gembel* in Javanese), sand mining, and ecosystem succession initiated by pioneer vegetation (Utami *et al.*, 2021a, 2021b). Although Krasak watershed has a very high annual rainfall (2332–3102 mm/year), changes in land use have an impact on runoff flow and infiltration capacity, which is higher downstream than up- and midstream (Ikhsan *et al.*, 2019a). This condition affects shallow groundwater recharge at Yogyakarta-Sleman Groundwater Basin, which has become the main resource of water for residents, especially for household needs. A WRCC deficit will therefore lead to many cones of depression (Mulyadi *et al.*, 2020).

The water needs after Merapi eruption have increased due to population growth, especially at mid- and downstream of Krasak watershed. Many dryland farms have been turned into new settlements, taking up a larger area than during the post-eruption relocation as the population of Krasak watershed increased by 4.92 percent from 2008 to 2021. The regional status as a disaster-prone area has not affected people's desire to stay there because Merapi has an abundance of natural resources. These conditions have high economic value for tourism, agriculture, and animal husbandry (Priyanti and Ilham, 2011; Widodo *et al.*, 2014; Napsiah *et al.*, 2016). Global climate change, which increases the temperature, also affects the potential evapotranspiration. Krasak watershed has a threat of water loss due to these changes. In 2008, the average air temperature reached 25.90°C, and eleven years later, it increases to 27.22°C. Potential

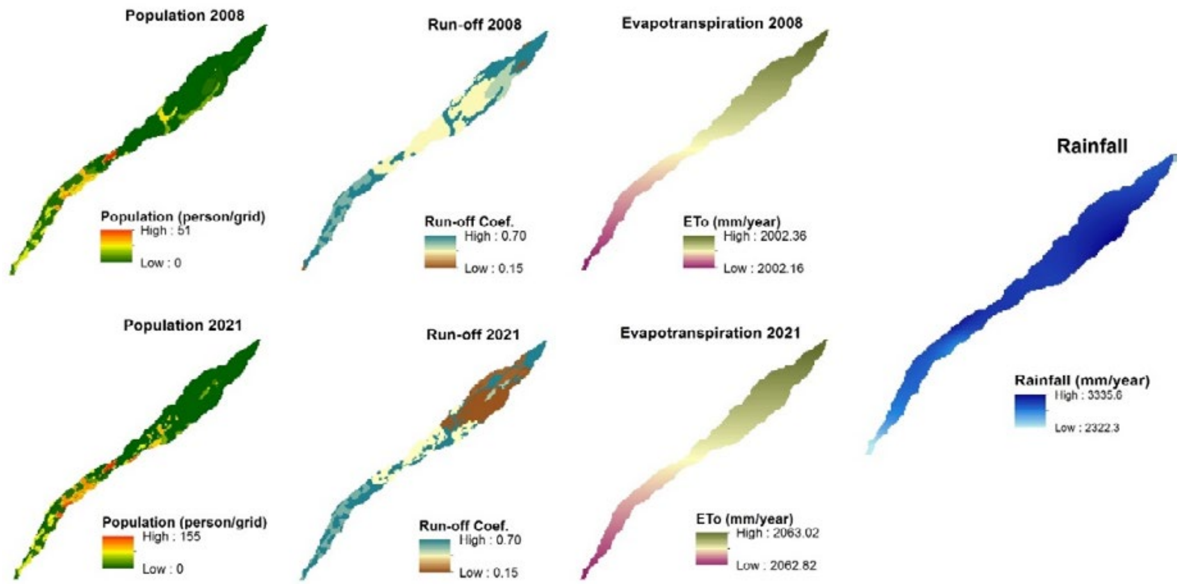

Fig. 2: Changes in WRCC parameters (rainfall is assumed to be constant according to the data span over less than 30 years)

evapotranspiration also increases significantly from 5.49 mm/day, to 5.65 mm/day for each unit area. Population growth, ecosystem changes, and increasing evapotranspiration are the main factors reducing WRCC in Krasak watershed (Fig. 2).

The population over the 13 years increases by only 1316 people, which is relatively small when compared with Indonesian average annual population growth ranging from 1.00 percent to 2.00 percent (Oey-Gardiner and Gardiner, 2013). If each resident needs 80 litres or 0.08 m^3 water per day, according to the criteria of the IMPWPH (2018) for rural areas, then each individual needs 29.20 m^3 water per year in total. It will continue to increase along with the rural-to-urban transformation of the landscape in Krasak watershed. The WRCC analysis ignored local discharges from springs due to endogenous and exogenous energy activities in the folds, faults, and weathering of rocks. There was a grid expansion of the WRCC deficit 10 years after the eruption, especially in the groundwater discharge zone close to Krasak River estuary where the confluence zone with the Progo River is located (Fig. 3). The community's water needs increased by 4.91 percent, from 781.601 m^3 (2008) to 819,973 m^3 (2021). Non-spatial WRCC calculations do not use grid units. However, Krasak watershed still has an overall surplus of more than 21 million m^3 per year. The WRCC surplus is more spread out in the recharge and transition zones, which are rarely inhabited by residents. However, between the years before Merapi's eruption in 2010, there is a significant decrease in WRCC at the transition (midstream) and discharge (downstream) of Krasak watershed. The statistical test showed this significant difference with p-value of 0.047 and 95% confidence level. Individual consumption (population growth) and ecosystem succession illustrate that WRCC is very dynamic. Therefore, these results accept the hypothesis that WRCC has a strong interaction with Merapi's eruption. Although in the initial period after the eruption, it brought losses to the landscape and communities affected by volcanic materials, a few years later, this phenomenon gave a blessing because it could rejuvenate the landscape and fertilize the soil that increasing the environmental carrying capacity (Fiantis et al., 2019), including the WRCC.

A largest surplus was found in the upstream, which has been overgrown by vegetation, while the middle has started to experience pressure on water availability. The WRCC surplus of more than 5,000 m^3 per grid was decreased. Even in 2021, it has spread to the upper reaches near Merapi's peak. The WRCC

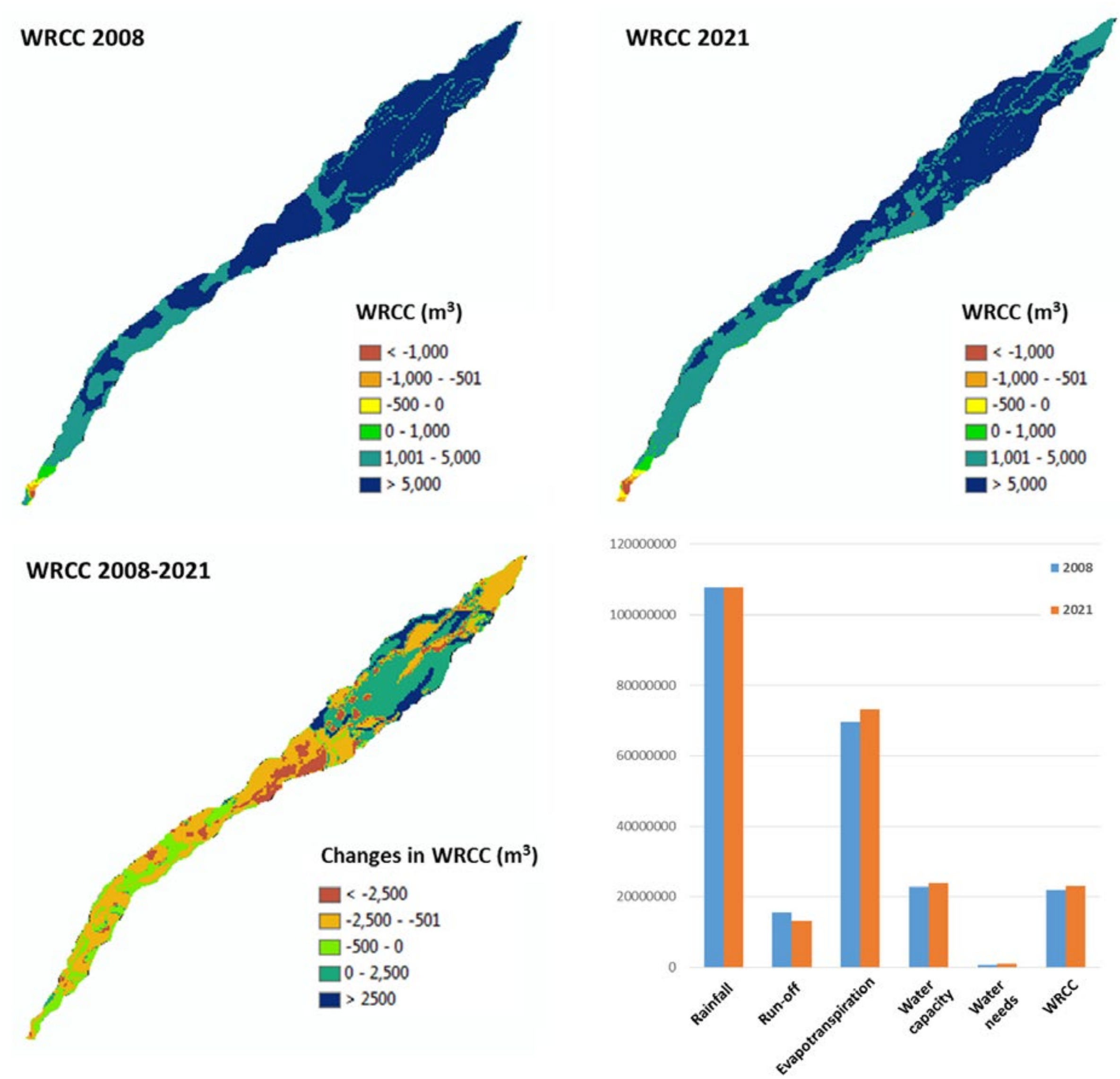

Fig. 3: WRCC Changes in Krasak Watershed (There are significant changes in surplus and deficit areas based on T-Test with p-value 0.047 and 95% confidence level).

at the peak experienced a decline of 331.50 m^3 per year for each grid cell. This phenomenon occurred on the west side of Krasak watershed, specifically in the Bebeng River segment. In this segment, there are many sand mining activities and the prices of these commodities are very high, in a linear relationship with the qualities (Sulaiman, 2008; Miller, 2021). Bebeng River segment serves 480 m^3 of volcanic sand per day, this certainly increased due to demand-driven during the rapid development on Java Island (Pangestu and Darmono, 2014). Different conditions are found on the eastern side (Krasak River segment), which is relatively greener because it is less exploited by traditional sand mining by the local community and receives less lahar flows (Lavigne, 2000). In Krasak River segment, which is steeper with many springs exposed to the ground, the topography is considered as limiting factor preventing similar exploitation. The spatial-gridded model also shows that the east side has a very high annual WRCC (more than 5,000 m^3 per grid), it looked constant tendency to increase in intervals 0–2,500 m^3 per grid. The directional change of dominant eruptive material slide on the west side (Bebeng River segment), makes WRCC in the Krasak River segment relatively more preserved with clear water. Merapi eruption has changed the environmental carrying capacity both directly and indirectly. From this study, conservation and rehabilitation efforts are needed to maintain the watershed ecosystem thus the carrying capacity is not exceeded due to population pressure, land management, and natural resources exploitation, even though some areas of Krasak watershed belong to Mount Merapi National Park (Hartono, 2006; Thorburn, 2012).

CONCLUSION

WRCC in Krasak watershed was changed both before and after Mount Merapi eruption. Grid-based WRCC analysis shows a decline, especially in the midstream and downstream areas. WRCC at the peak occurred a decline of 331.50 m^3 per year for each grid cell. An increase in WRCC occurred only in some locations that experienced ecosystem succession after the 2010 eruption, although areas near the peak experienced a decrease due to sand mining. WRCC changes in Krasak watershed occurred significantly based on the results of T-Test (p-value 0.047 and 95% confidence level). Population growth and the economic attractiveness of pyroclastic materials from Mount Merapi are threats that need to be anticipated by governments, communities, and other stakeholders, as some locations have experienced a decline in WRCC. From this study, Merapi eruptions can increase WRCC through ecosystem succession, but also indirectly encourage various anthropogenic activities which potentially reduce WRCC in the transition and recharge zones. Without proper monitoring and management in the volcano ecosystems, it is not impossible that WRCC dynamics will decline due to unsustainable landscape. Mount Merapi has two cycles of eruption, small and large, efforts to be aware of large eruptions are very meaningful to know changes in the landscape that have impacts on land use, livelihoods, and population distribution as parameters that affect WRCC. This study has limitations in evapotranspiration measurement which is only based on numerical calculations (potential evapotranspiration), not using actual evapotranspiration. The WRCC model has the potential for further development, particularly it is able to include other parameters such as shallow groundwater, microclimate, river systems, and shallow groundwater resources.

AUTHOR CONTRIBUTIONS

M. Dede made the project plan, collected the data, processed and interpreted the data, performed WRCC model, prepared the manuscript text, and manuscript edition. S.B. Wibowo collected the data and prepared the manuscript text. Y. Prasetyo prepared the manuscript text. I.W. Nurani commented on the data. P.B. Setyowati performed the literature review. S. Sunardi made the work plan, collected the data, prepared the manuscript text, and manuscript edition.

ACKNOWLEDGEMENT

This study was funded by Hibah Riset Universitas Padjadjaran (HRU) in 2021 with contract number [1959/UN6.3.1/PT.00/21], under program of PPKI Research Collaboration of Indonesian Ministry of Education, Culture and Higher Education. The authors also thank to Millary Agung Widiawaty (Research Center for Nuclear Energy System-National Nuclear Energy Agency of Indonesia 'BATAN') for the valuable discussion in developing this model.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percentage
∑ ASi	Total area of land use type i
A	Catchment (area)
C	Runoff coefficient
E	Evapotranspiration
Eq	Equation
Eqs	Equations
Fig	Figure
IMPWPH	Indonesian Ministry of Public Works and Public Housing
km	Kilometer
km^2	Square kilometer
KRB	*Kawasan rawan bencana Merapi* (Merapi's disaster prone area)
m	Meter
m^3	Cubic meter
NW	Water needs per capita
P	Precipitation
p	Annual average daytime percentage
Pop	Population
Pop_i	Population in polygon i
R	Runoff capacity
S	Surface reservoir
Si	Area of polygon i
T	Annual average temperature
W	Weight for land use types
WA	Water availability
Wi	Weight of land use type i
WRCC	Water resources carrying capacity
Wy	Annual water needs per capita

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HOW TO CITE THIS ARTICLE

Dede M.; Wibowo, S.B.; Prasetyo, Y.; Nurani, I.W.; Setyowati, P.B.; Sunardi, S., (2022). Water resources carrying capacity before and after volcanic eruption. Global J. Environ. Sci.Manage., 8(4): 473-484.

DOI: 10.22034/gjesm.2022.04.02

url: https://www.gjesm.net/article_249013.html