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Research Paper

Assessment of Basin-scale Water Stress using Geographic Information System in Southeast Asian Countries with Megacities

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Abstract

Southeast Asian countries are facing unstable water resource situations, experiencing high water stress as a result in their river basins, particularly around large population cities. This research has assessed basin-scale water stress by estimating the amount of water resources and water use for all river basins in Indonesia, Thailand, the Philippines, Vietnam, and Malaysia. A simple water stress assessment methodology using a Geographic Information System revealed the basins vulnerable to high water stress around the capital areas in all five countries. The population ratio was under high-moderate and high water stress at 29.3% in Indonesia, 41.8% in Thailand, 31.9% in the Philippines, 43.3% in Vietnam, and 19.9% in Malaysia. The results imply that large populations depend on limited water resources. The basin-scale assessment conducted in this research could be used in support of the water resources management planning at an inter-basin scale aiming to neutralize water stress.

Keywords: Geographic Information System (GIS); Megacity; Southeast Asia; Water Resources Management; Water Stress

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1. Introduction

Among all types of water in the hydrosphere, only about 2.5% is available as freshwater (Shiklomanov and Rodda, 2003). Approximately 70% of freshwater exists as the ice sheets of the Antarctic, the Arctic, and mountain glaciers. Thus, water usage by humans depends on surface water and groundwater resources. Since water resources are limited, managing water resources, including water provision and quality management, to fulfill the water demand has become a fundamental issue, particularly in countries with megacities. This is defined as a city with a population exceeding 10 million (Suzuki, 2019) with a population increase and/or concentration and rapid urbanization (Biswas et al., 2005). The concept expressing the balance between water resources and withdrawal/use has been called water scarcity (Oki and Kanae, 2006; Wada et al., 2011). In the concept of water scarcity, water stress is the indicator that is linked to difficulties in water use and it is expressed by the use-to-availability ratio (Rockström et al., 2009). Water stress occurs when the water use exceeds the available water resources, i.e., volume, during a certain period (Munia et al., 2016). Water stress is considered to be high when the use-to-availability ratio is larger than 40% (Rockström et al., 2009).

The previous studies on assessing water stress have been done at the global, grid/pixel, or country levels. The global- and grid/pixel-level assessments allow us to identify the wide-scale hotspots with social issues, such as poverty and undernutrition, that could be driven by high water stress considering the international migration of people and water (Rockström et al., 2009). Country-level water stress assessment has been mainly used to evaluate food self-sufficiency under climate change and population growth situations (Rockström et al., 2009). For water resource allocation and management, on the other hand, the assessment of water stress at a basin scale is important because the conflict due to water resources would be led by the unfairness of water use between a basin's upstream and downstream (Munia et al., 2016). Cooperation as part of integrated water resource management could be governed by the stakeholders in a basin (Molle, 2009).

In Southeast Asia, major cities such as Jakarta in Indonesia, Bangkok in Thailand, Metro Manila in the Philippines, Ho Chi Minh City in Vietnam, and Kuala Lumpur in Malaysia are already/expected to be megacities with rapid economic development (Suzuki, 2019). Their water resource situations are unstable, occasionally experiencing drought and water shortages because of the monsoonal climate variation and increasing withdrawal of water. High water stress situations have been observed in Southeast Asian countries. The causes of high water stress varied and were, for example, due to climate conditions, such as the El Niño-Southern Oscillation (ENSO) (Wada et al., 2011), high water withdrawal by irrigation (Gheewala et al., 2014), and the deterioration of the water infrastructure (Douglass, 2010).

The studies on basin-scale water stress assessment in Southeast Asia have mainly focused on irrigation and/or agricultural water. For example, Gheewala et al. (2014) assessed the water stress caused by irrigation by considering the irrigation water requirements of multiple crops from 25 river basins in Thailand. The results revealed that the eastern basins of Thailand were under high water stress. A water stress assessment of 13 sub-basins in the Srepok River Basin lying between Vietnam and Cambodia was done by Ty et al. (2012). The research found out the upstream sub-basins faced severe water stress during the dry season under the scenarios considering climate and land use changes as well as population growth. Hanafiah et al. (2019) conducted an estimation of the water used for rice cultivation in 16 watersheds of Peninsular Malaysia and found a high water-stressed area, the northwestern basin, because of the low water availability. In these studies, some suggestions for water resource management, such as an improvement in crop productivity through good agricultural practices (Gheewala et al., 2014), the development of irrigation systems through water storage implementation (Ty et al., 2012; Gheewala et al., 2014), and the enhancement of water conservation and protection by education and demand management (Ty et al., 2012; Hanafiah et al., 2019), were made based on the results of the water stress assessment. Thus, the assessment of water stress will be the nugget of information used to discuss the necessity of proper water resource management in the direction of reducing water stress.

This research estimated the amount of water resources and water use and assessed the basin-scale water stress for all basins in the five candidate countries in Southeast Asia, specifically Indonesia, Thailand, the Philippines, Vietnam, and Malaysia. These countries have large cities that are already or expected to be megacities with rapid economic development. Water demand/use increases particularly in urban areas because of the population increase and economic activities. The water resource conditions vary because of the monsoon climate. Therefore, integrated water resource management, which considers the water environmental conditions in both the urban and surrounding areas, is needed to ensure a well-balanced, sustainable water supply as intended by Goal 6 of the Sustainable Development Goals (SDGs).

The novelty of this research was the use of the simple-as-possible method utilizing the Geographic Information System (GIS) to estimate the amount of water resources and water use so then water stress could be assessed in the data-scarce areas/basins in Southeast Asia. The previous studies reviewed above have used hydrological and climate models that require parameter calibration and bias correction for the models themselves alongside the local observation data. On the other hand, this research used only the GIS-based spatial information data and the functions packaged in the geoprocessing software. The comprehensive assessment of the basin-scale water stress revealed the basins vulnerable to water scarcity in each country. The methodology used in this research supports water resource management planning not only at a basin scale but at an interbasin scale, particularly around the urban river basins that are susceptible to the rapidly changing demand and varying water resources in Southeast Asia.

2. Study Area

The target area of this research consisted of five Southeast Asian countries, specifically Indonesia, Thailand, the Philippines, Vietnam, and Malaysia. These countries have a megacity or a large city that is expected to become a megacity. Ho Chi Minh City in Vietnam and Kuala Lumpur in Malaysia are projected to become megacities in 2026 and 2032, respectively (Suzuki, 2019; United Nations, 2019), in addition to the existing megacities of Jakarta in Indonesia, Bangkok in Thailand, and Metro Manila in the Philippines. In these areas, higher water stress situations are expected because of an increase in water demand/use under rapid economic development and unstable water resource conditions due to the monsoon climate.

Table 1 shows the general information including the demographic (population) and economic (gross domestic product (GDP)) statistics of the countries in the target areas. The populations have been increasing up to now as the population growth rate is positive across all countries. The urban population ratio has also been increasing. This means that the population has been concentrated in urban areas. The positive and almost constant GDP growth rates show that the economy of these countries is developing and expected to keep growing.

Table 1. Demographic and Economic Statistics of Indonesia, Thailand, the Philippines, Vietnam, and Malaysia

		Indonesia	Thailand	Philippines	Vietnam	Malaysia
Area (km^2)		1,910,931	513,140	300,000	331,236	330,621
Total population (*10^3, as of 2021)		276,362	69,951	111,047	98,169	32,776
Population density (per km^2, as of 2021)		152.6	136.9	372.4	316.6	99.8
Population growth rate (average annual %)	2010	1.3	0.5	1.7	1.0	1.9
	2015	1.3	0.4	1.7	1.0	1.4
	2021	1.1	0.3	1.4	1.0	1.3
Urban population (% of Total population)	2010	49.9	43.9	45.3	30.4	70.9
	2015	53.3	47.7	46.3	33.8	74.2
	2021	56.0	50.7	47.1	36.6	76.6
GDP: Gross domestic product (million US$)	2010	755,094	341,105	199,591	115,932	255,018
	2015	860,854	401,296	292,774	193,241	301,355
	2021	1,119,191	542,017	359,354	261,921	364,684
GDP growth rate (annual %, constant 2015 prices)	2010	6.2	7.5	7.6	6.4	7.4
	2015	4.9	3.1	6.1	6.7	5.1
	2021	5.0	2.4	5.9	7.0	4.3

Source: UNdata (http://data.un.org/)

3. Methods

3.1 Data Collection and Extraction

The data used for the basin-scale water stress assessment is listed in Table 2. In this research, the collected data for the assessment, the basin boundary, weather, and population, was on a global scale and able to be processed using the GIS. Therefore, the necessary data was extracted for the target area using the national border data. The data extraction and analysis in this research was conducted using the ArcMap 10.8 software. The national border information was obtained from the Global Administrative Area Database (GADM) Version 3.6. The GADM provided all country borders as polygon shapefiles. The country border information of the target areas, i.e., the five countries, was downloaded from the GADM website.

The information on the basin boundaries in each country was then extracted using the basin boundary and country border data. The Global Drainage Basin Database (GDBD) developed by the Center for Global Environmental Research at the National Institute for Environmental Studies in Japan was used as the basin boundary data of this research. The GDBD is comprised of six GIS-based data, that is, the drainage basin boundary, river network, discharge gauging station, natural lake, dam lake, and flow direction (Masutomi et al., 2009). For each basin extracted from the GDBD, the amount of water resources and water use were estimated to assess the water stress in the target area of this research.

This research set the year 2013 as the target assessment period for the case study due to the consideration of the comprehensive data availability. The rainfall and temperature data were obtained from the Climate Forecast System Reanalysis (CFSR) of the National Centers for Environmental Prediction (NCEP). The NCEP-CFSR has provided sub-daily weather data since 1979 (Fuka et al., 2013). This research collected daily rainfall and temperature data in 2013 using a 0.3125˚ spatial resolution and calculated the monthly and yearly values for each basin for use in the water stress assessment. The LandScan Global 2013 data provided by the Oak Ridge National Laboratory (Bright et al., 2014) was used to estimate the basin population in 2013. LandScan Global provided the global population distribution data representing the 24-hour average population with a spatial resolution of 30 arc-seconds (Oak Ridge National Laboratory, 2022). The whole data processing flow in this research is depicted in Figure 1. The details are explained in the following sections.

Table 2. Data Used in this Research

Data Type	Data Set	Source/Reference
National border	Database of Global Administrative Areas (GADM)	Global Administrative Areas
Basin boundary	Global Drainage Basin Database (GDBD)	Center for Global Environmental Research Masutomi et al. (2009)
Rainfall Temperature	Climate Forecast System Reanalysis (CFSR)	National Centers for Environmental Prediction (NCEP)
Population	LandScan Global 2013	Oak Ridge National Laboratory, Bright et al. (2014)

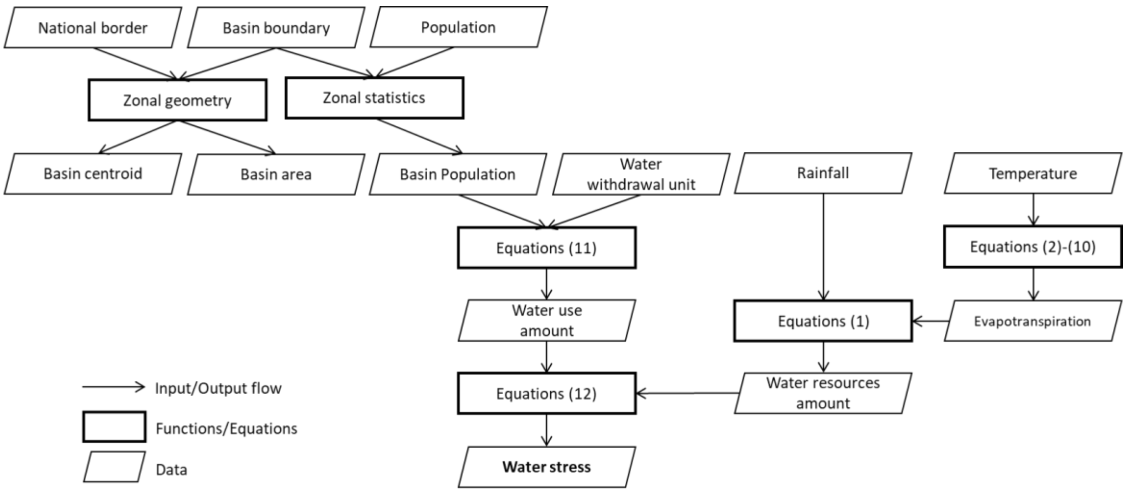

Figure 1. Data Processing Flow Chart of this Research

Source: Authors

3.2 Estimation of Basin-scale Water Resources Amount

3.2.1 Procedure for Water Resource Amount Estimation

This research used the concept of water resource amount as the theoretically available maximum water amount defined by the Japanese Ministry of Land, Infrastructure, Transport, and Tourism (2008). In this concept, the water resource amount is the maximum amount of water that can be used by humans. The water resource amount considers the precipitation/rainfall amount, evapotranspiration loss, and basin area and is estimated using Equation (1):

$$Wr = (P - E_{Ai}) \times Ba \times 1000 \quad (1)$$

Where Wr is the amount of water resources (m^3/year), P is the precipitation/rainfall amount (mm/year), E_{Ai} is the actual evapotranspiration amount (mm/year), and Ba is the basin area (km^2).

To follow Equation (1), the necessary data was drawn from the data shown in Table 2. The collected NCEP-CFSR global weather data, rainfall, and temperature, were set in an array with a 0.3125˚ spatial resolution covering the target area. In this research, the weather information was allocated to each basin based on the distance between the weather grids and the geometric centroid of each basin. The centroid of each basin was obtained from the GDBD boundary information. The nearest weather grid to the centroid of each basin was then calculated using the Near tool on ArcMap 10.8 before being selected as the representative weather station for the basin. The basin areas were calculated using the geoprocessing tool Zonal geometry, based on the GDBD. The estimation method of the actual evapotranspiration amount is explained in the next subsection.

3.2.2 Estimation of Potential and Actual Evapotranspiration Amounts

To estimate the amount of the actual evapotranspiration, the potential evapotranspiration amount was first calculated using the Thornthwaite method in this research (Thornthwaite, 1948). The Thornthwaite method employs empirical equations using temperature and possible sunshine duration as the variables. The Thornthwaite method is easier to apply than other estimation methods such as the Penman-Monteith equation and the Jensen equation (Jensen and Haise, 1963; Steele et al., 1997) for the estimation of the potential evapotranspiration amount in vast areas or data-scarce areas because it technically requires only the temperature data. It is suitable for this research because the target area covers five countries in Southeast Asia. This research first estimated the monthly potential evapotranspiration amount using Equations (2)-(4) using the average monthly temperature as the input variable:

$$E_{pi} = 0.533 \times D_i \times \left(\frac{10t_i}{J}\right)^{a} \times 30 \tag{2}$$

$$a = 0.000000675J^3 - 0.0000771J^2 + 0.01792J + 0.49293 \tag{3}$$

$$J = \sum_{i=1}^{12} (\frac{t_i}{5})^{1.514} \tag{4}$$

Where E_{pi} denotes the potential evapotranspiration amount (mm/month) in month i, D_i is the possible sunshine duration index (12 hours/day is considered as 1) in month i, and t_i is the average monthly temperature (℃) in month i.

In this research, the average monthly temperature (t_i) in 2013 was calculated for each basin based on the temperature data of the NCEP-CFSR. Equation (2), which was used to estimate the monthly potential evapotranspiration amount, includes the possible sunshine duration index (D_i) variable. The Thornthwaite method uses the index (D_i) that considers 12 sunshine hours as 1. Therefore, the possible sunshine duration index (D_i) is calculated by dividing the possible sunshine duration by 12. The calculation of the possible sunshine duration index (D_i) is further explained by the following equations (Kousaka, 2013).

$$D_i = K_i = \sum_{i=1}^{12} I_i \tag{5}$$

$$I = \frac{N}{12} \tag{6}$$

$$N = \frac{24}{\pi} \times \omega_s \tag{7}$$

$$\omega_s = \arccos(-\tan\Phi\tan\delta) \tag{8}$$

$$\delta = 0.4093 \times \sin\left(\frac{2\pi}{365} \times Ju - 1.405\right) \tag{9}$$

Where D_i is the possible sunshine duration index (/month) in month i, K_i is the sum of the possible sunshine duration (I) in month i, I is the possible sunshine duration index (/day), N is the daily possible sunshine duration (/day), ω_s is the sunset time angle (rad), Φ is latitude, δ is the declination of the sun, and Ju is the Julian day.

After estimating the potential evapotranspiration amount using Equations (2)-(9), the amount of actual evapotranspiration was calculated using Equation (10) which was developed and validated by Kousaka (2013):

$$E_{Ai} = 0.014 \times E_{pi} + 0.68 \times TN_i + 31.61 \times PN_i + 35.39 \tag{10}$$

Where E_{Ai} is the amount of monthly actual evapotranspiration (mm) in month i, E_{pi} is the amount of potential evapotranspiration (mm/month) in month i, TN_i is the standardized average monthly temperature in month i, and PN_i is the standardized average monthly rainfall in month i.

3.3 Estimation of Basin-scale Water Use Amount

3.3.1 Estimation of Basin Population

To estimate the amount of water used for each basin, this research first calculated the basin population using the Zonal statistics on ArcMap 10.8 based on the LandScan Global 2013 data and the GDBD boundary information. The Zonal statistics function is provided via the spatial analyst tool. The population distribution information stored in the LandScan Global 2013 data was masked by the basin boundary information of the GDBD. The gridded population distribution information was then summed for each basin in the target area.

3.3.2 Estimation of Water Use Amount

The amount of water use was estimated by multiplying the calculated basin population by the unit water withdrawal (m^3/capita) by sector i.e., agricultural, domestic, and industrial water withdrawal. The water withdrawal data for each sector was based on the AQUASTAT database provided by the Food and Agriculture Organization of the United Nations (Black, 2016). In this research, the amount of water used by each basin was estimated using Equation (11) (Okabayashi et al., 2020):

$$Wu = (Au + Du + Iu) \times Bp \tag{11}$$

Where Wu is the amount of water use (m^3/year), Au, Du, and Iu respectively denote the unit water withdrawal (m^3/capita/year) of agricultural, domestic, and industrial sectors, and Bp is the basin population.

The dataset for the units of water withdrawal is shown in Table 3. The amount of water withdrawal varies for each country. For example, the total unit water withdrawal in Vietnam and the Philippines is almost double that of Malaysia. In four countries in the target area, Indonesia, Thailand, the Philippines, and Vietnam, agricultural water withdrawal is dominant among the three water sectors.

Table 3. The Units of Water Withdrawn by Three Sectors (Agriculture, Domestic, and Industry) in Indonesia, Thailand, the Philippines, Vietnam, and Malaysia (Black, 2016)

	Indonesia	Thailand	Philippines	Vietnam	Malaysia
Total	526	867	843	948	418
Agriculture	431	784	694	898	93
Domestic	61	41	64	14	146
Industry	34	42	85	36	179

(m^3 per capita)

3.4 Assessment of Water Stress

In this research, water stress was used as an indicator to assess the sustainability of the balance between the amount of water resources and the water use of the basins. Water stress was calculated using Equation (12) based on the estimated amount of water resources and water use at each basin.

$$Ws = \frac{Wu}{Wr} \tag{12}$$

Where Ws is water stress, Wu is the amount of water use (m^3/year), and Wr is the amount of water resources (m^3/year).

By referring to the previous studies (Wada et al., 2011; Munia et al., 2016; Okabayashi et al., 2020), this research set the criteria that the basin shows low water stress if Ws is less than 0.1, low-moderate water stress if Ws is between 0.1 and 0.2, moderate water stress if Ws is between 0.2 and 0.3, high-moderate water stress if Ws is between 0.3 and 0.4, and high water stress if Ws is more than 0.4. Further analyses were done based on the ratio of the number of basins and the water stress criterion for each country. The ratio of the population affected by each water stress criterion was also calculated for each country based on the LandScan Global 2013 data.

4. Results and Discussions

4.1 Extraction of Basin Information

The basin information in the target area of the selected five countries was extracted from the GDBD using the national border data obtained from the GADM as a mask. As a result of geoprocessing using the ArcMap 10.8 software, 943 basins in Indonesia, 313 basins in Thailand, 105 basins in the Philippines, 190 basins in Vietnam, and 218 basins in Malaysia were extracted as shown in Figure 2. This research estimated the amount of water resources and water use for all 1,769 basins to assess basin-scale water stress.

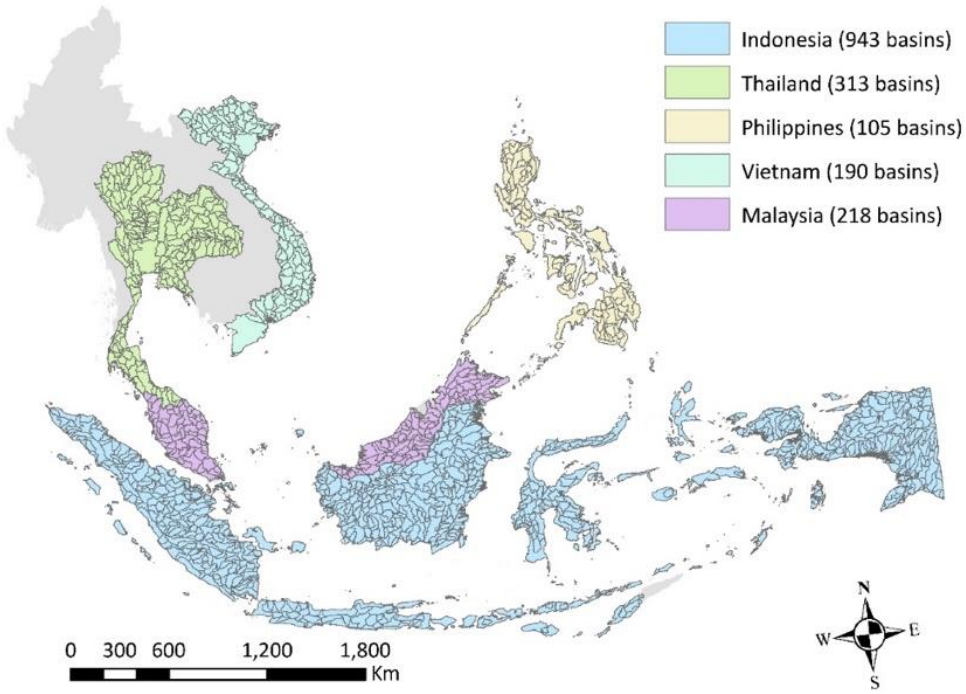

Figure 2. Extracted Basins in the Target Areas (Indonesia, Thailand, the Philippines, Vietnam, and Malaysia)

Source: Authors' Analysis

The basin population was then calculated using the Zonal statistics as shown in Figure 3. A high basin population was confirmed for the basins mainly where the capital cities are located. In Indonesia, for example, most of the basins on the island of Java, where Jakarta is located, showed a high population. In the same manner, the population was concentrated in the basins around Bangkok in Thailand, Metro Manila in the Philippines, Hanoi and Ho Chi Minh City in Vietnam, and Kuala Lumpur in Malaysia. This situation of the concentrated population in the capital areas affects the concentration of water usage and might cause high water stress in the capital areas.

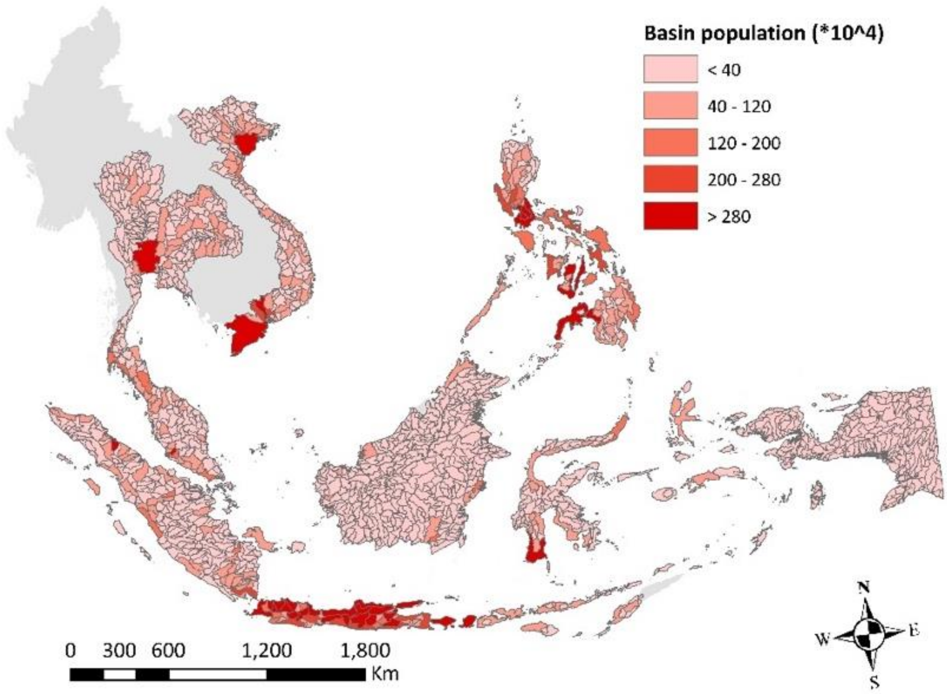

Figure 3. Basin Population in the Target Areas (Indonesia, Thailand, the Philippines, Vietnam, and Malaysia)

Source: Authors' Analysis

4.2 Estimation of the Water Resources Amount

The water resources amount was estimated based on the amount of rainfall and actual evapotranspiration. This research obtained the necessary weather data, specifically rainfall, and temperature, from the NCEP-CFSR and allocated a corresponding weather grid based on the nearest distance to the centroid of each basin. Figure 4 shows the spatial distribution of the total rainfall (mm/year) for the year 2013 in the target area. The annual rainfall amount in 2013 was relatively high near the equator in the target area. Some existing climatic conditions and weather systems, such as northeasterly winds (Chang et al., 2005), the Borneo Vortex (Tangang et al., 2008), and the easterly winds influenced by the Madden-Julien Oscillation around Java (Salahuddin and Curtis, 2011) affect the monsoonal rainfall in this area (Chen et al., 2013; Yazawa, 2017; Yazawa and Shimizu, 2020). In addition, the amount of total rainfall was high in the Philippines and Vietnam since there were some typhoons in the Pacific Ocean and South China Sea in 2013 as well. It should be noted here that the NCEP-CFSR tends to overestimate rainfall in some regions, for example, in Bolivia (Blacutt et al., 2015) and China (Zhu et al., 2016). Thus, the amount of rainfall and eventual water resources estimated in this research might be overestimated in the target area.

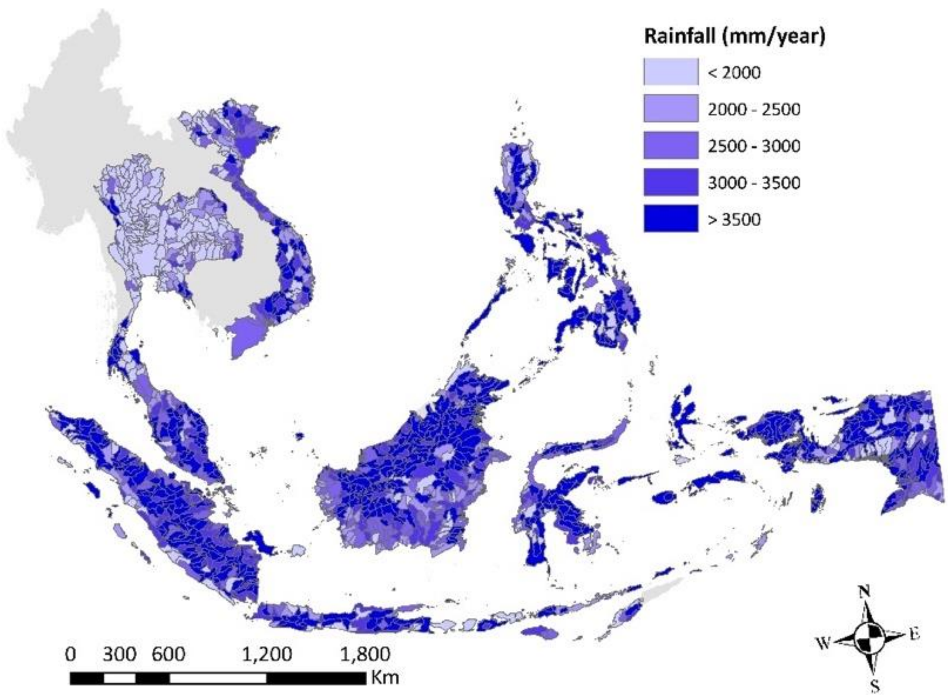

Figure 4. Annual Rainfall (mm/year) of the Year 2013 at Each Basin in the Target Area (Indonesia, Thailand, the Philippines, Vietnam, and Malaysia)

Source: Authors' Analysis

The spatial distribution of the amount of annual actual evapotranspiration is shown in Figure 5. More than 50% of the basins in Indonesia and Malaysia exceeded 1,000 mm/year of annual actual evapotranspiration. Based on Equations (2)-(9), the low-latitude areas had a longer possible sunshine duration and thus showed a higher amount of actual evapotranspiration. The results of the estimated actual evapotranspiration amounts in Indonesia and Malaysia showed relatively higher values than the other countries. In the northern middle of Thailand, i.e., around the Chao Phraya River Basin, the estimated actual evapotranspiration amount in the year 2013 was the highest in the target area because of the high average temperature.

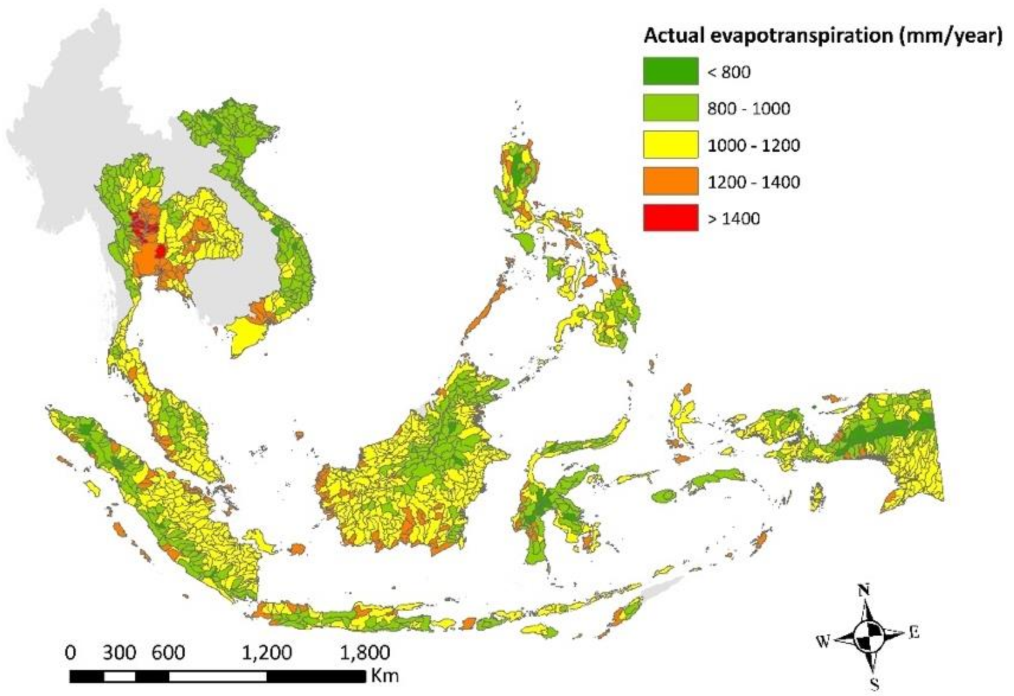

Figure 5. Annual Actual Evapotranspiration Amount (mm/year) for Each Basin in the Target Area (Indonesia, Thailand, the Philippines, Vietnam, and Malaysia)

Source: Authors' Analysis

Figure 6 shows the distribution of the water resources amount (m^3/year) in the target area. Although basins with relatively high amounts of actual evapotranspiration were dominant in Indonesia and Malaysia, a high amount of water resources was estimated because of the large rainfall amount as shown in Figure 4. The amount of water resources in northern Thailand was lower than in the southern area of the country. This is because of the low annual rainfall and high actual evapotranspiration in northern Thailand according to the results shown in Figures 4 and 5. Because of the high rainfall amount that might be caused by the typhoons in Southeast Asia in 2013, a high amount of water resources was estimated, particularly in the Philippines. In this research, the assumption of the water resources amount estimated by Equation (1) included the amount of water that could not be actually used because of the water discharged as floods caused by heavy rain and typhoons. As a limitation and in relation to the future work following this research, the water discharged by storm events should be separated to accurately estimate the available water resources.

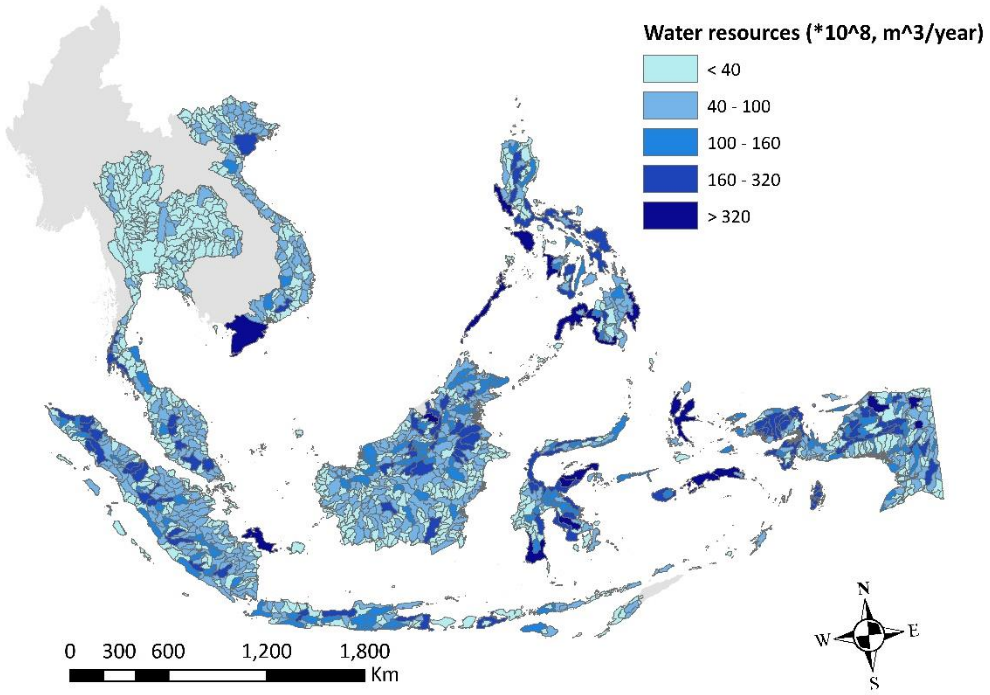

Figure 6. Water Resource Amount (m^3/year) Estimated For Each Basin in the Target Area (Indonesia, Thailand, the Philippines, Vietnam, and Malaysia)

Source: Authors' Analysis

4.3 Estimation of the Water Use Amount

The distribution of the estimated water use amount (m^3/year) in the target area is shown in Figure 7. Since the amount of water use was proportional to the basin population based on the assumption of Equation (11), the high amount of water use was estimated for the basins where the capital cities are located. The unit water withdrawal shown in Table 3 was comparatively high in Thailand, the Philippines, and Vietnam. There were high-population basins with high water use amount in these three countries. These countries had a high agricultural water use compared to Indonesia and Malaysia. This could be the result of the high consumption of water for rice cultivation and production (Tabbal et al., 2002; Gheewala et al., 2014). The total unit water withdrawal in Thailand was the second largest among the target five countries (Table 3). The population in Thailand was concentrated in the northern middle basins, i.e., around Bangkok. Therefore, the basins around Bangkok, such as the Chao Phraya River Basin, showed a high amount of water use as shown in Figure 7.

The amount of water use assumed using Equation (11) in this research, depending on the basin population only to simplify the estimation. However, in the countries in the target area, the water used for agriculture, e.g., crop production, has been dominant in terms of water consumption (Tabbal et al., 2002; Gheewala et al., 2014). Thus, the assumption of the estimation of water use amount could be the other limitation of this research. This needs to be updated since the estimation did not consider different land use situations.

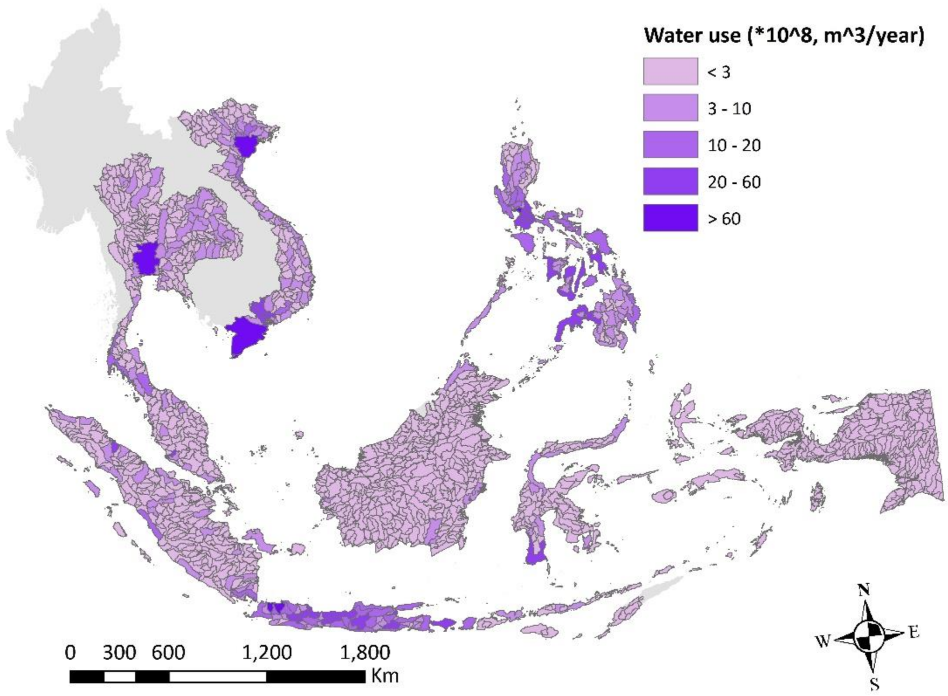

Figure 7. Water Use Amount (m^3/year) Estimated For Each Basin in the target Area (Indonesia, Thailand, the Philippines, Vietnam, and Malaysia)

Source: Authors' Analysis

4.4 Assessment of Water Stress

4.4.1 Spatial Distribution of Basin-scale Water Stress in Each Country

Water stress was assessed for all basins in the target area. Figures 8 to 12 show the results of the spatial distribution of water stress regarding basins in Indonesia, Thailand, the Philippines, Vietnam, and Malaysia. Figure (b) shows the water stress of the basins around the existing/expected megacities, i.e., Jakarta in Indonesia, Bangkok in Thailand, Metro Manila in the Philippines, Ho Chi Minh City in Vietnam, and Kuala Lumpur in Malaysia.

In Indonesia, the basins with high-moderate and high water stress were mainly concentrated on the island of Java where the capital of Jakarta is located, as shown in Figure 8. Since the amount of rainfall was high in Indonesia, the high water stress in Java was caused by the high amount of actual evapotranspiration, which was affected by latitude. The amount of water use was proportional to the basin population. Since Jakarta has become a megacity, water-related issues including groundwater depletion and water quality degradation have been raised through the rapid population increase (Douglass, 2010). Thus, the high water stress concentrated in the capital region, i.e., the results shown in Figure 8(b), has to be taken into consideration as part of the sustainable water management of Indonesia.

The basins in Thailand showed high water stress, particularly in the northern middle area of the country (Figure 9). Most of the basins with high water stress belong to the Chao Phraya River Basin. In said area, the low amount of water resources caused by the low annual rainfall and high actual evapotranspiration was confirmed in Figures 4, 5, and 6. Moreover, the population was concentrated on the basins around Bangkok as shown in Figure 3 since there is not only the capital area but also an industrial park. This caused a high amount of water use (Figure 7). Thus, high water stress was confirmed around Bangkok as shown in Figure 9(b). According to the previous study (Haddeland et al., 2006), the northwestern area of Thailand, i.e., basins belonging to the Mekong River Basin, showed the high irrigation water requirements and an incremental increase in evapotranspiration. Therefore, there is a possibility that the actual water stress around this area might be higher than the results of this research. Furthermore, a long-term assessment is needed since this research used data from only one year.

High water stress was confirmed in some of the basins on the islands of Luzon and Mindanao in the Philippines (Figure 10). Although the Philippines suffered from typhoons in 2013, the basins with high water stress showed a low amount of rainfall, a high amount of evapotranspiration, and eventually a low amount of water resources. On the other hand, the amount of water use was relatively high because of the large basin population. As shown in Figure 10(b), Metro Manila was at the center of the high water stress, while the surrounding regions showed moderate water stress. There is the possibility that the basins with moderate water stress will become high-water stress areas if the economy keeps developing and the urban area expands. There have been some discussions on the necessity of new water resources for Metro Manila from the surrounding regions with the response being to construct water infrastructures (Catindig-Reyes, 2019; Yazawa and Honda, 2021). This result also suggests preparing for additional water resources to neutralize the high water stress in the capital area.

The distribution of water stress in Vietnam (Figure 11) showed clear results for there being high basin water stress around the two large cities, Hanoi in the north and Ho Chi Minh City in the south. The amount of water resources in the basins around these cities was higher than in the other areas in Vietnam, as shown in Figure 6. However, the amount of estimated water use was also high because of the dense population. The basins around Hanoi are a part of the Red River Basin where both a city and an agricultural area are located. The current high water stress might deteriorate if the population increases or the economy develops without a management strategy in place. Ho Chi Minh City, as previously mentioned, has been expected to become a megacity with an increase in population. The basins around the city already show high water stress as shown in Figure 11(b). Thus, the water stress would be worsened if proper water resource management is not conducted.

The distribution of water stress in Malaysia is shown in Figure 12. The basins in the west of the Malay Peninsula, where Kuala Lumpur is located, show the only high water stress in the country. In Malaysia, the urban population accounts for more than 70% of the total population of the country, according to the 2010 Census (Department of Statistics Malaysia, 2011). The situation of having an urban dense population has caused a high amount of water use, thus the high water stress in the capital area [Figure 12(b)]. For the capital region of Malaysia, the inter-basin and interstate water transfer project, e.g., the Pahang-Selangor raw water transfer project, has been conducted to deal with the water shortage issue (Yazawa, 2017). This could be an example of good practice for urban basins with a high water stress in other countries.

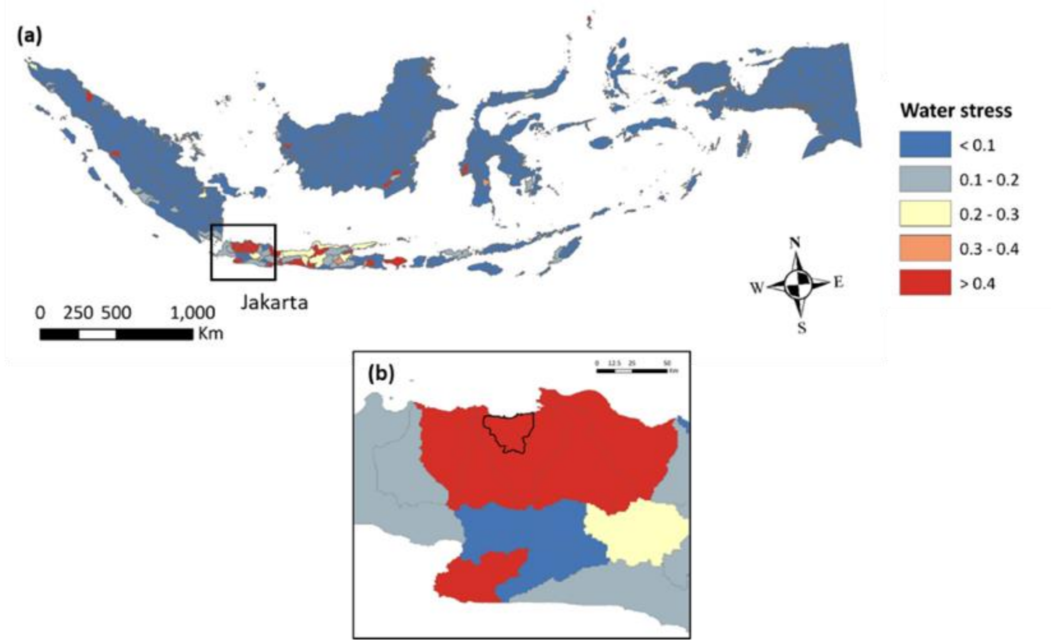

Figure 8. Water Stress (a) of Each Basin in Indonesia and (b) of the Basins Around Jakarta

Source: Authors' Analysis

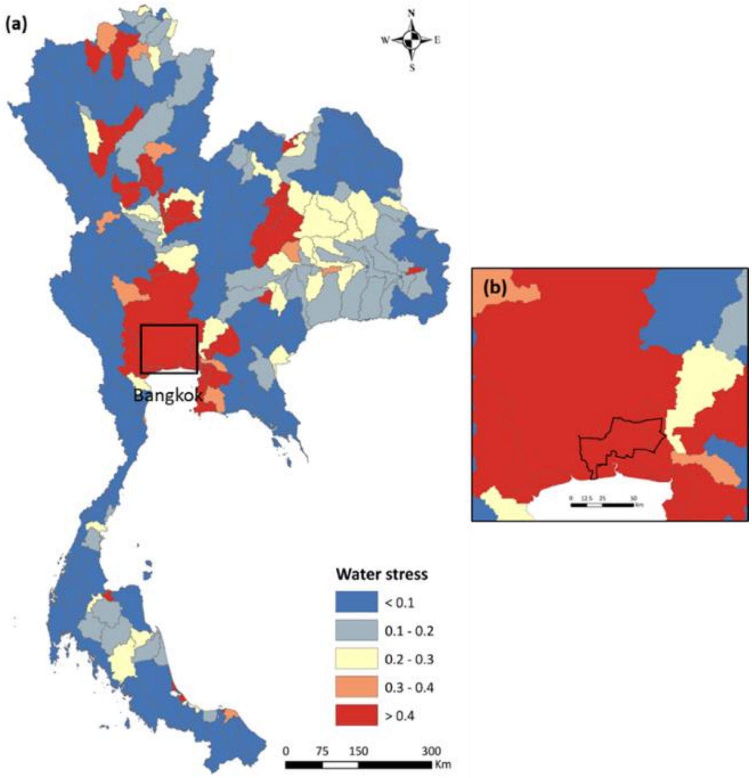

Figure 9. Water Stress (a) of Each Basin in Thailand and (b) of the Basins Around Bangkok

Source: Authors' Analysis

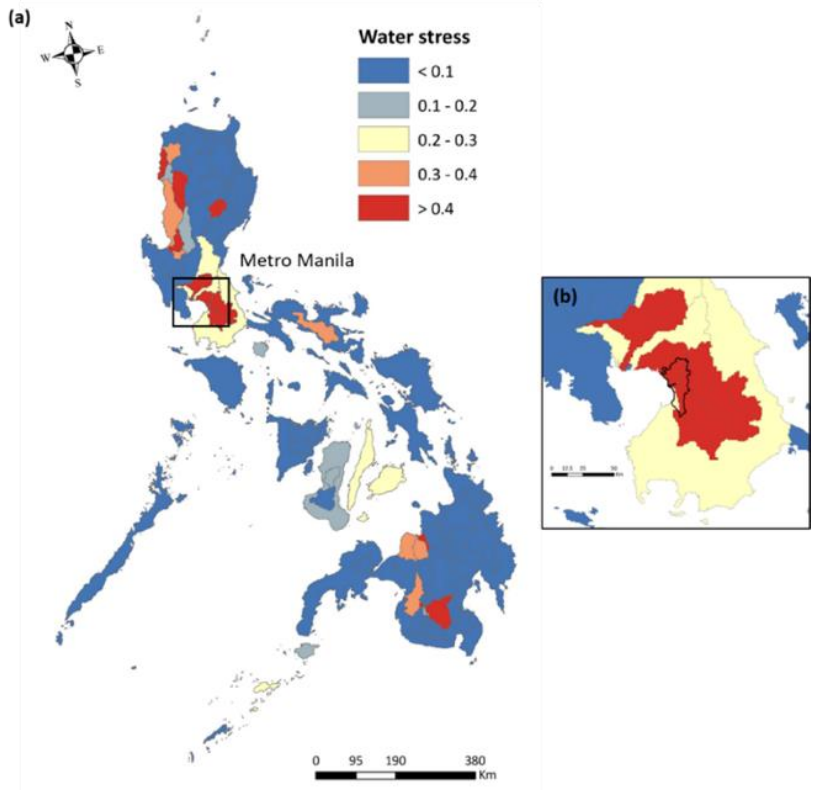

Figure 10. Water Stress (a) of Each Basin in the Philippines and (b) of the Basins Around Metro Manila

Source: Authors' Analysis

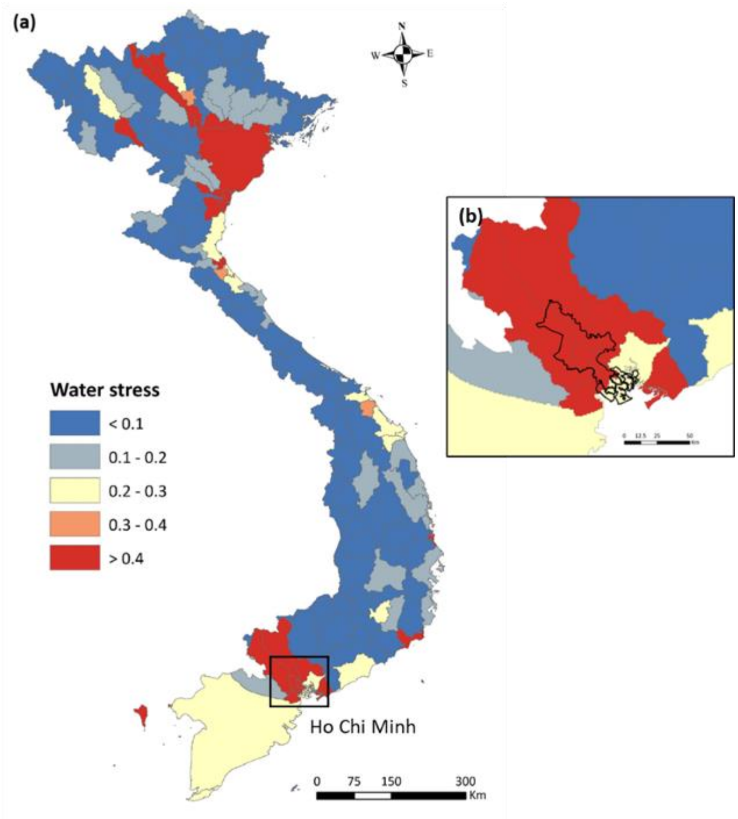

Figure 11. Water Stress (a) of Each Basin in Vietnam and (b) of the Basins Around Ho Chi Minh City

Source: Authors' Analysis

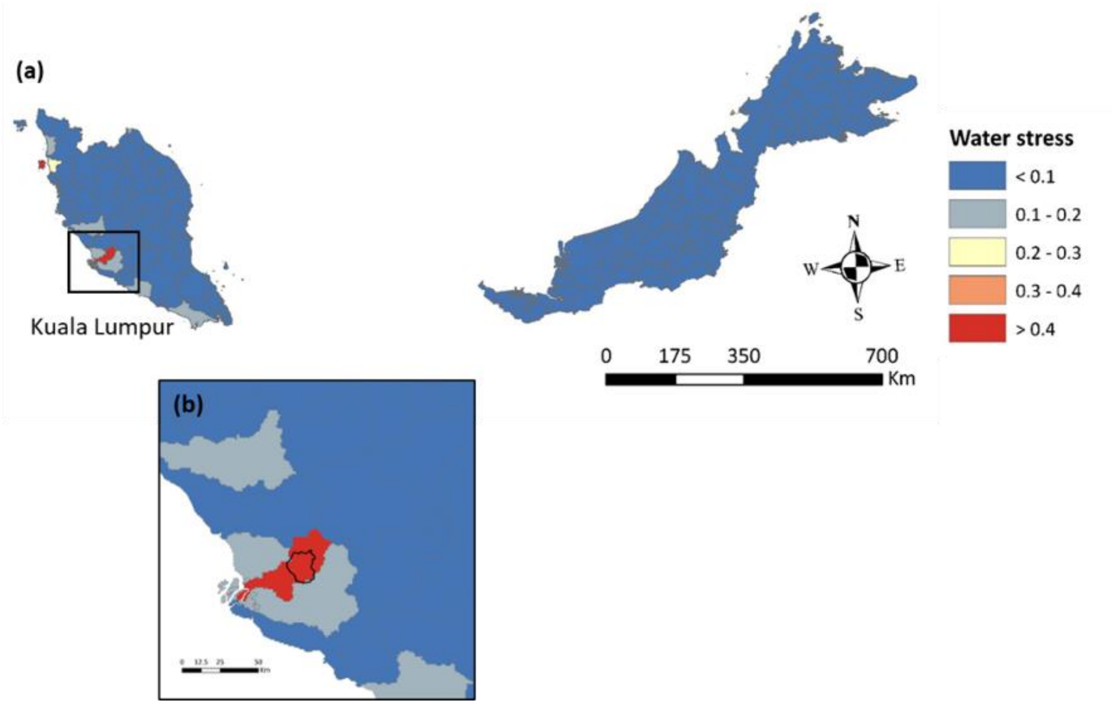

Figure 12. Water Stress (a) of Each Basin in Malaysia and (b) of the Basins Around Kuala Lumpur

Source: Authors' Analysis

4.4.2 Ratios of Basins and Populations under Water Stress

Figure 13 shows the ratio of the basins and populations under each water stress criterion. Based on the ratio of the basins, 96.9% of basins were under less than moderate water stress (i.e., Ws < 0.3) in Indonesia. The remaining 3.1% of basins in Indonesia showed high-moderate and high water stress (i.e., $Ws \geqq$ 0.3). The ratio of the population in Indonesia under high-moderate and high water stress was 29.3%. In the same manner, the ratios of the basins under high-moderate and high water stress were 15.3% in Thailand, 19.0% in the Philippines, 15.3% in Vietnam, and 1.4% in Malaysia. The ratios of the population under high-moderate and high water stress were 41.8% in Thailand, 31.9% in the Philippines, 43.3% in Vietnam, and 19.9% in Malaysia. In all countries in the target area, the ratio of the population under high-moderate and high water stress became higher than the ratio based on the number of basins. These results indicate that a dense population causes a higher level of water stress because of the high amount of water use and concentration of the population around the high water stress basins, which are usually around a capital area. This implies that the high population depends on limited or specific water resources.

The basins with moderate water stress, particularly around the capitals, have the potential to be highly water stressed areas with a more affected population if the urban areas expand as part of economic development. In the target area, monsoonal rainfall brought with it high amounts of rainfall and thus high water resources in most of the basins. On the other hand, the amount of water use, which was mostly determined by basin population in this research, was also high in the basins around the cities. This caused high water stress in the basins around the capital areas of each country. To neutralize the water stress in the capital basins through the consideration of the population concentration in the capital areas and the impacts of climate change, water resources management plans, including infrastructure construction (e.g., water transfer, the addition of water resources, etc.) to increase the amount of water recourses available and technology development and education (e.g. water conservation, etc.) to change the water withdrawal, are needed.

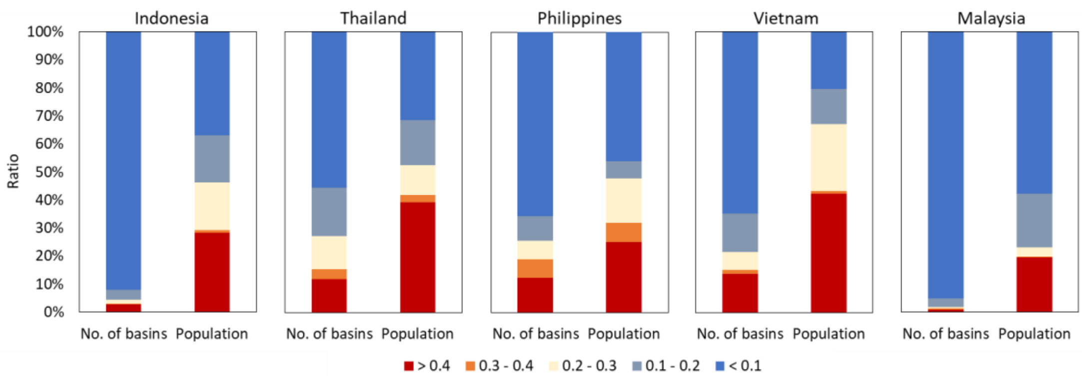

Figure 13. Ratio of Basins and Populations under Each Water Stress Criterion in Indonesia, Thailand, the Philippines, Vietnam, and Malaysia

Source: Authors' Analysis

Conclusions

This research assessed basin-scale water stress by estimating the amount of water resources and water use for all 1,769 basins in Indonesia, Thailand, the Philippines, Vietnam, and Malaysia. In all five countries, the basins around the capital areas showed high water stress as the amount of water use amount exceeded 40% of the amount of water resources available. The comparison between the ratios of the basins and the populations under high-moderate and high water stress revealed that the high population depends on limited or specific water resources. Proper water resources management plans are needed to neutralize the water stress while considering the developing economy and changing climate in the capital basins. Overall, water balance analyses using basin-scale water stress enable water resource planning on a larger scale, considering multiple basins in a country.

This research used the Thornthwaite method to estimate the potential evapotranspiration amount and the empirical method to calculate the actual evapotranspiration amount without the consideration of land cover differences. Therefore, the validation of the estimated evapotranspiration amounts is needed in future work. In addition, the detailed water utilization/demand, such as virtual water, should be taken into consideration for use in a more accurate calculation since the estimation of the amount of water use depends on the basin population and the determined unit water withdrawal in this research. Finally, the assessment of the basin-scale water stress conducted in this research used only one year's worth of data. Further scenarios using long-term multiple data sets are important to investigate the uncertainties of the water stress assessment. Thus, the main data sets, such as the basin boundary, weather, and population information, must be updated in future analyses.

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