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## Article

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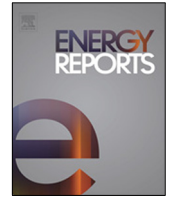
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## Research paper

# Potential hydropower estimation for the Mindanao River Basin in the Philippines based on watershed modelling using the soil and water assessment tool

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## ABSTRACT

This study aims to identify potential hydropower sites and calculate the theoretical potential hydropower capacity based on watershed modelling of the Mindanao River Basin (MRB) in the Philippines for the sustainable development of a previously unstudied region. The Soil and Water Assessment Tool (SWAT) was applied to delineate the watershed of the MRB and simulate the river discharges with inputs from observed precipitation and global gridded precipitation datasets. Observed weather data, such as temperature, humidity, and solar radiation, from four meteorological stations in the Philippines were also used as inputs for SWAT modelling. Simulated discharges were calibrated at three river gauges on the Nituan, Libungan and Pulangi Rivers. However, due to limited river discharge records, model validations were conducted in proxy basins: the calibrated model parameters in river A were used in the watershed modelling of proxy river B. Of the delineated 107 sub-basins in the MRB watershed, only 33 were identified as having potential sites for hydropower development. These potential sub-basins hosted a total of 154 potential sites with an estimated monthly average power capacity of 5,551.35 MW for all 33 sub-basins. The estimated theoretical power capacity of 15,266.22 MW for all sites in the MRB is approximately equivalent to the Philippines' total available power capacity in 2017 of 15,393 MW. These sites were classified into 16 mini-scale hydropower sites, 114 small-scale hydropower sites and 24 medium-scale hydropower sites based on the simulated river discharges and potential power capacities. Based on these results, hydropower development could be an alternative to strengthen the exploration of renewable energy resources and improve the energy situation in Mindanao; hydropower development could also have mitigation effects on frequent floods in flat, low-lying downstream areas.

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## 1. Introduction

Global greenhouse gas emissions from energy production accounted for 29% of all emissions in 2012 (Zarfi et al., 2014), whereas 1.4 billion people have no access to electricity and another 1 billion people have irregular access, according to the United Nations Development Programme (UNDP) (Carrasco et al., 2019). By 2030, the electricity demand will grow at an annual rate of 2.5%, according to the International Energy Agency (IEA) (Liu et al., 2013). In developed countries, it is primarily the motivation

to employ renewable energy that drives the sustainable energy industry, whereas in developing countries, sustainable energy is usually encouraged by the necessity to address energy shortages to boost development in rural areas (Brimmo et al., 2017). In some developing countries, rural communities not connected to the electricity grid are experiencing worsening electricity shortages due to economic and technical failures (Kaunda et al., 2014). Therefore, better access to renewable energy is an alternative means to balance economic growth and mitigate the impacts of climate change.

The ASEAN's major source of energy remains oil until 2030 (Ministry of the Economic, Trade and Industry, Japan, 2009). The capacity of energy sources in the ASEAN region is 22 billion barrels of oil, 227 trillion ft<sup>3</sup> of natural gas, 46 billion tons of coal, 20 GW of geothermal and 234 GW of hydropower (Bakhtyar et al., 2013). The hydropower capacity was 90% of the renewable energy

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and 16% of the total world electric energy in 2005, and there was 17.913 MW of installed hydropower capacity in the ASEAN region in the year 2000 (Darmawi et al., 2013). Hydropower prevents CO<sub>2</sub> emissions per year of approximately 3 GT (9% of global annual emissions) and manifested 78% of renewable electricity generation in 2015 (Berga, 2016). Accordingly, hydropower production in developing countries is expected to rise by 70% over the next few decades (Hecht et al., 2019).

The Philippines is one of many developing countries that face a continuously increasing demand for electricity, with an annual average increasing rate of 4.3%, despite the efforts of the power sector to improve services and sustain electricity supplies to consumers in recent years (Ayson et al., 2010). The Philippines increased its proportion of renewable energy from 39.8% in 2010 to 40.7% in 2011 within a total primary energy supply of 39.29–30.40 million tonnes of oil equivalent (Mtoe) over the same period (Brahim, 2014). From June 2016 to June 2017, the total installed and average available energy capacities in the country increased from 14,348 MW and 10,361 MW to 21,621 MW and 15,393 MW, respectively. In 2017, renewable energy contributed 32.55% (7038 MW) and 31% (4822 MW) to the total installed and average available capacities, respectively, among which hydropower contributed 16.83% (3683 MW) (Department of Energy, 2017a).

The island of Mindanao in the Philippines currently boasts a total gross power generation of 5,170,538 MWh, 7% of which is geothermal, 7% is oil-based, 38% is generated through hydropower, and 48% is from coal. The generation capacity reaches 1070 MW from coal, 788 MW from oil-based fuels, 108 MW from geothermal sources, 1080 MW from hydropower, 59 MW from solar networks, and 36 MW from biomass; hence, the total power capacity of renewable energy is 1,283 MW (40.80%) (Department of Energy, 2017a). Evidently, hydropower contributes considerably to the total indigenous energy supply, accounting for 9.9% of the 21.7% increase in the country's production. For example, the additional hydropower capacity of 91.0 MW provided in 2011 significantly increased the energy supply from 1.9 Mtoe in 2010 to 2.4 Mtoe in 2011 (Ayson et al., 2010).

Despite these power generation capacities, the continuously increasing demand (with an average rate of 3.8% over the past few decades) remains a concern (Bangsamoro Development Agency, 2014). In fact, the maximum peak demand of power in Mindanao reached approximately 1,696 MW in April 2017 (Department of Energy, 2017a). This consistently increasing demand constitutes a major challenge, particularly as the installed capacity of hydroelectric power (as of June 30, 2017) has increased by only 78.39 MW since 2010 (Department of Energy, 2017b). Therefore, as of June 2017, the power sector needs to add at least 13,088.31 MW of hydropower to meet the domestic power demand (Ayson et al., 2010).

On the basis of the above, the purpose of this study is to estimate the theoretical potential hydropower to support the implementation of the Renewable Energy Act of the Philippines to improve the electricity production rate of Mindanao by utilizing the abundance of water resources in the region. The paper is organized as follows. Section 2 presents literature reviews on hydropower, and Section 3 describes the materials used in this study. Section 4 shows the methods utilized for watershed modelling. The results and discussion are given in Sections 5 and 6, respectively, followed by the conclusions in Section 7.

## 2. Literature review of hydropower

The wooden waterwheel was the first tool for generating hydropower; consequently, a vast number of waterwheels were used for milling grain in Europe and Asia 2000 years ago. When

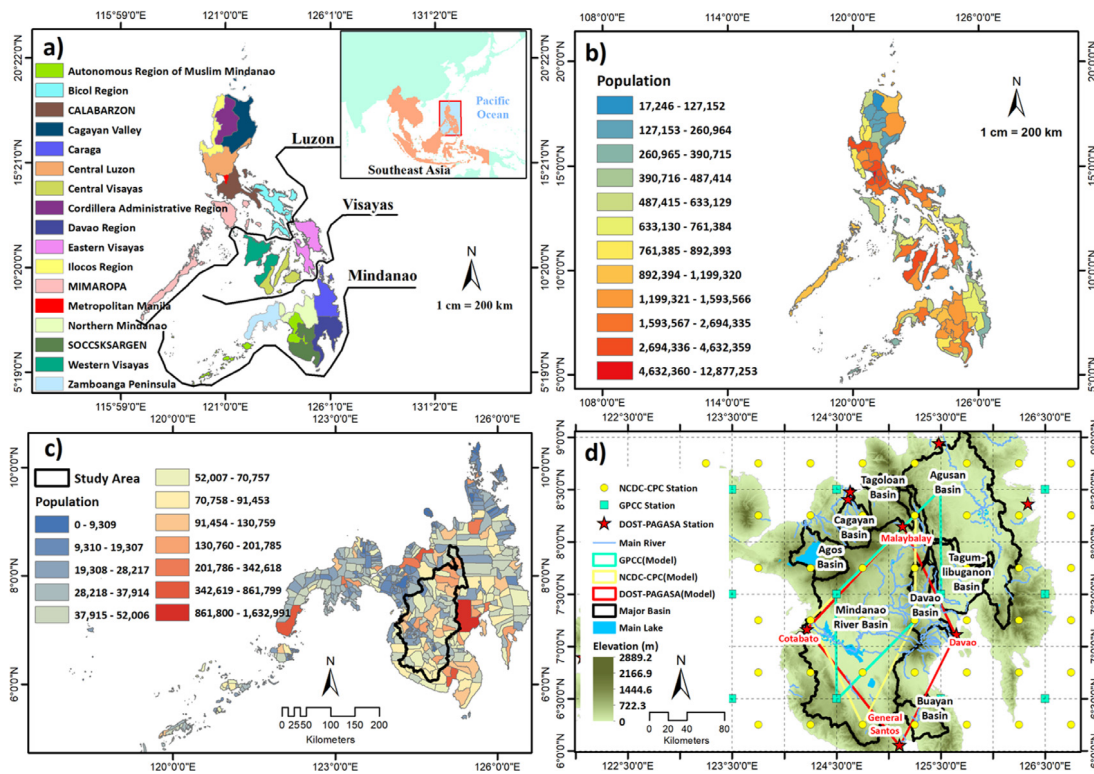
the industrial revolution initiated the development of waterwheel technology for hydropower in the 19th century, the modern turbine was further improved through engineering (Paish, 2002). Generating electricity from running water by a waterwheel began on the Fox River in Wisconsin in 1882 (Jawahar and Michael, 2017).

Energy is generated from flowing water at a given head difference (Kaunda et al., 2014). However, energy is theoretically determined by the flow rate and the height difference of falling water over a particular period. Therefore, assessments of theoretical hydropower are currently possible based on this principle by using a geospatial dataset and watershed modelling climate inputs in combination with a geographic information system (GIS). For example, the theoretical hydropower on the Asam River of India was calculated by using a watershed model and the Soil and Water Assessment Tool (SWAT) interfaced with GIS (Kusre et al., 2010). Similarly, in the Philippines, SWAT was used in some areas to estimate the theoretical potential hydropower in the Visayas (Jason et al., 2017), the Misamis Occidental (Tarife et al., 2017), and the Agusan River Basin (Cuasay et al., 2014). Recently, Guiamel and Lee (2020) reported watershed modelling results for the Mindanao River Basin (MRB) by using the SWAT to estimate river discharges, and discussed how to improve the modelling results through calibration and validation processes based on proxy basin principle to overcome the scarcity of observed data. Moreover, small-scale hydropower plants in the Sakarya Basin of Turkey were investigated using GIS to locate potential sites and to calculate the corresponding power capacity (Bayazit et al., 2017).

The impacts of climate change on hydropower safety have also been assessed using SWAT in Dak Nong, Vietnam (Bang et al., 2013). Similarly, hydrological modelling in the upper Mekong Basin has found a significant effect of climate change on the average seasonal river discharge since hydropower operations began (Räsänen et al., 2017). Hydrological modelling of the Hoa Binh Reservoir in Vietnam was conducted to optimize its flood control and hydropower generation applications, but the modelling revealed a significant reduction in the peak flood discharge downstream during the rainy season while maintaining the reservoir level during the dry season (Ngo et al., 2007).

Hydropower is a more sustainable source of renewable energy than other alternatives because it is clean, cheap, and environmentally friendly (Elbatran et al., 2015). Hydropower represents a significant source of energy compared with fossil and nuclear fuels. In fact, small-, mini-, and micro-scale hydropower all play important roles in rural electrification, and hydropower has a considerably higher capacity than other sources of renewable energy to replace fossil fuels (Okot, 2013). Most small-scale hydropower is designed for run-of-the-river use to maintain natural river flows and to avoid the construction of dams (Ferreira et al., 2016). However, hydropower is capable of supplementing the inherent intermittency of solar and wind energy because of the potential energy in reservoirs (Soito and Freitas, 2011). Other advantages of hydropower include its global availability, very efficient energy conversion, low operating cost, and relatively long life span. Furthermore, the fuel source (water) is not affected by fluctuating markets, providing a flexible source of electricity (Liu et al., 2013). In addition to providing electricity, hydropower development creates multiple socio-economic benefits and applications, such as a potable water supply, irrigation systems and flood control (Zhang et al., 2014).

On the other hand, hydropower also presents some drawbacks. Two disadvantages of hydropower are hydropeaking and disconnected water bodies. Hydropeaking refers to changes in river flow due to the storage of water for hydropower use, and disconnected water bodies are formed by the construction of hydropower dams and run-of-the-river facilities built within the river system



**Fig. 1.** (a) Seventeen regional administrative boundaries of the Philippines, (b) population at the provincial level, (c) population of Mindanao at the municipality/city level, and (d) major basins in Mindanao and the weather stations and gridded points for the precipitation data used in the SWAT simulations. The dashed lines in Fig. 1(d) connect the four points used for the estimation of precipitation patterns from the precipitation datasets.

(Mattmann et al., 2016). Moreover, hydropower development has many environmental impacts, for example, on fauna, flora, the landscape and archaeological remains (Botelho et al., 2017). A number of concerns, such as high capital requirements, rehabilitation, community resettlement, and disturbances to geography, are linked predominantly to the development of large-scale hydropower (Nautiyal et al., 2011). Therefore, to minimize the negative effects of hydropower, small-scale or micro-scale hydropower should be considered to achieve the most cost-effective energy technologies for rural electrification in developing countries (Manzano-Agugliaro et al., 2017). Micro-scale hydropower is also far more cost-effective than fossil fuels and does not require large areas to operate; thus, micro-scale hydropower should be considered for electricity generation on the order of less than 100 KW (Jawahar and Michael, 2017). Additionally, when hydropower sites are near demand centres, small-scale hydropower is economically more competitive and more sustainable than small-scale fossil fuel plants (Ohunakin et al., 2011).

In general, the use of hydropower is helpful for reducing pollution and carbon emissions when properly managed. However, hydropower also represents a potentially devastating risk to humans and can disturb natural environmental systems (Tahseen and Karney, 2017). Therefore, it would be beneficial to develop potential water resources in Mindanao for hydropower generation to improve the electricity generation rate under the proper management of local authorities.

### 3. Study area and datasets

#### 3.1. Study area

The Philippines, situated in Southeast Asia, is composed of 7107 archipelagic islands that are further grouped into three major zones, Luzon, the Visayas, and Mindanao, as shown in

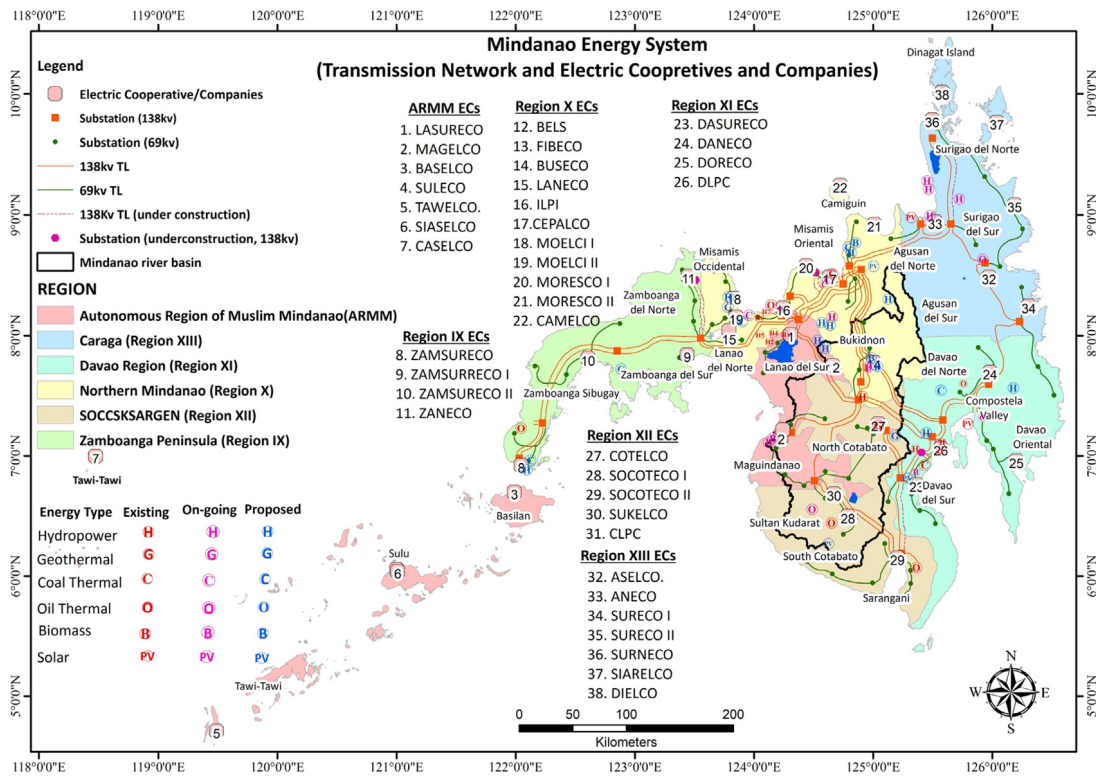
Fig. 1(a). The population of the Philippines was 100,981,437 in the 2015 census, as reflected in Fig. 1(b) (National Economic and Development Authority 2017). The land area of the entire country is 300,000 km<sup>2</sup>, with Luzon accounting for 142,000 km<sup>2</sup>, the Visayas comprising 57,000 km<sup>2</sup>, and Mindanao spanning 120,812 km<sup>2</sup> (Philippine Statistic Authority 2015).

Mindanao is the second-largest group of islands after Luzon, with a population of 24,135,775 in the 2015 census, as depicted in Fig. 1(c) (National Economic and Development Authority, 2017). Mindanao is separated into six administrative regions and further subdivided into 27 provinces, 35 cities, and 422 municipalities (Philippine Statistic Authority, 2015). In addition, it has 8 major river basins, as presented in Fig. 1(d).

The MRB is the second major river basin in the Philippines with an area of 21,503 km<sup>2</sup> (University of the Philippines, 2017). The MRB covers 72 municipalities and 1,732 villages in the 8 provinces of Maguindanao, Lanao del Sur, Sultan Kudarat, North Cotabato, South Cotabato, Bukidnon, Davao del Sur, and Davao del Norte (University of the Philippines, 2015). The MRB contains many major rivers, such as the Rio Grande de Mindanao, the Tamontaka River, the Pulangi Ambal-Simuay River, the Ala River and the Pulangi River (Bangsamoro Development Agency, 2014). The downstream region of the MRB is a perennial flood area, particularly in Maguindanao Province, because of the effects of the Rio Grande de Mindanao, the Simuay River, the Kabuntalan River, the Libungan-Alamada River, and the wetlands of the Ligawasan, Libungan and Ebpanan marshes (Bangsamoro Development Agency, 2015).

The country's power sector is composed of three major components: power transmission, power generation, and power distribution; national power and private operators coexist for the operations and management of energy resources and allocations. The Mindanao energy system consists of "on-grid" component and an "off-grid" component; there are 27 electric cooperatives in





**Fig. 2.** Mindanao energy system showing the locations of the power sources, including hydropower, geothermal, coal thermal, oil thermal, biomass, and solar. Also included are the grid connection types, transmission networks, and the locations of electric cooperatives working in the six regions of Mindanao.

the region that are connected to 138 kV and 69 kV transmission lines, as shown in Fig. 2 (National Grid Cooperation of the Philippines, 2016). Moreover, the Department of Energy (DOE) reports that the country’s economy has been linked to the considerable growth of the power sector; for instance, the total installed energy capacity increased from 16,226.9 MW in 2011 to 17,025.0 MW in 2012. Hydropower contributed 9.9% of the 21.7% increased production in the country (Ayson et al., 2010). Hydropower generation in Mindanao contributed 38% (or 1947 GWh) of the gross power generation in June 2017 (Department of Energy 2017a). Most of the hydropower plants in Mindanao are located in the northern part of the MRB, as shown in Fig. 2. Therefore, the areas in the southern part are investigated herein to discover potential resources with which to maximize the economic growth of the region.

### 3.2. Datasets

The datasets, that is, the precipitation data, digital elevation model (DEM), administrative boundaries, soil types, land use and land cover data, weather records and river discharges, used in the watershed modelling, the validation of the modelling results, and the hydropower estimates are described in the following and summarized in Table 1.

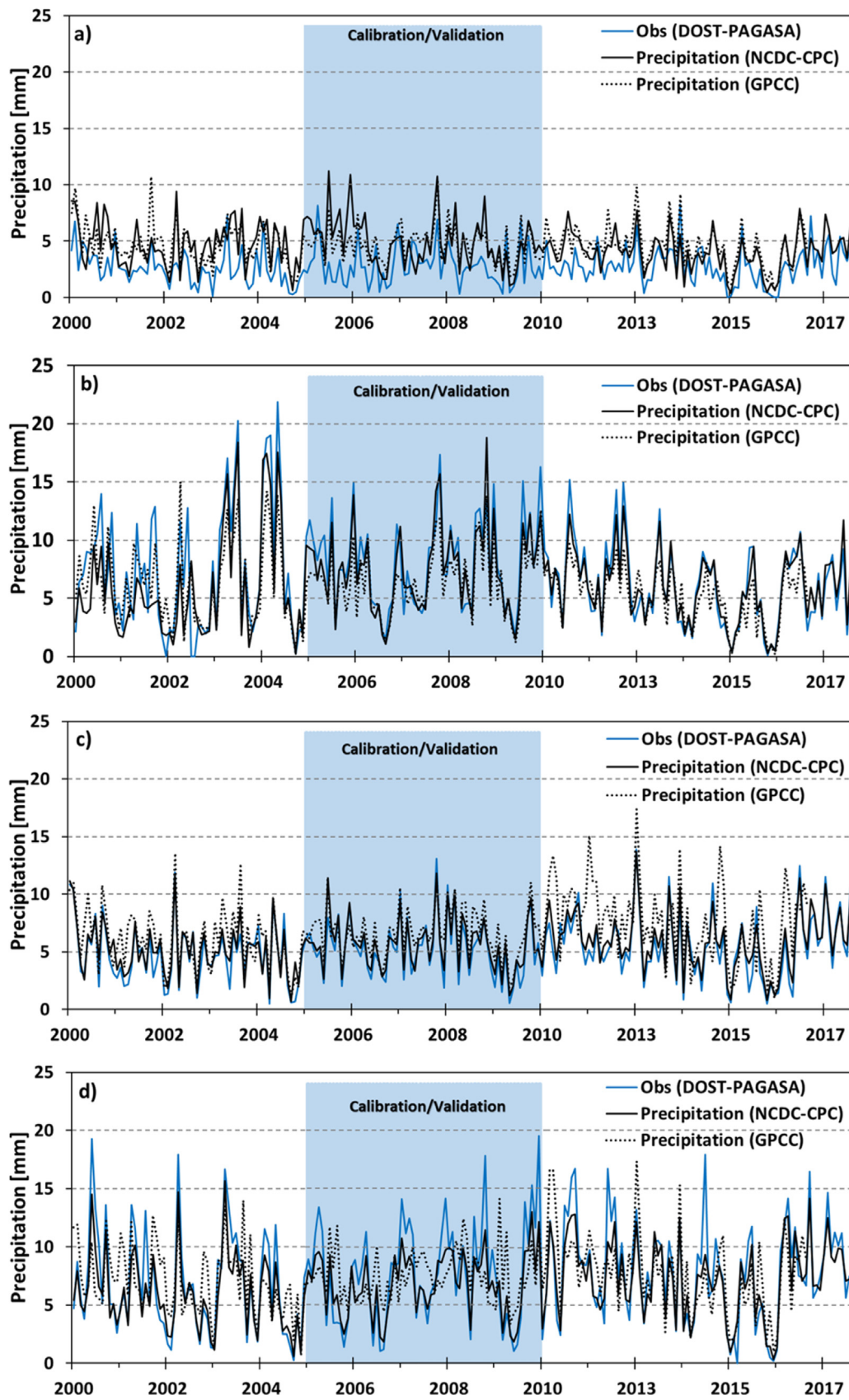
Precipitation is a sensitive input in SWAT and has a direct influence on the simulated streamflow (Eini et al., 2019; Tuo et al., 2016; Guiamel and Lee, 2020); the more accurate the precipitation records are within a study region, the more reliable the outcome that can be obtained from SWAT. However, only four weather stations are located in the large study area. Two of them, the Cotabato and Malaybalay stations, are located within the domain of the MRB, whereas the other two, the Davao and General Santos stations, are situated outside the MRB, as shown in Fig. 1(d). The precipitation data, which span 22 years from

1995 to 2017, were obtained from the Department of Science and Technology (DOST)-Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA). To investigate the quality of other available precipitation datasets within the MRB, two global gridded precipitation datasets were compared with the observed precipitation data at the four DOST-PAGASA stations (Fig. 3) (Cabrera and Lee, 2018, 2019, 2020). The two gridded datasets are the NOAA’s National Climatic Data Center (NCDC)–Climate Prediction Center (CPC) dataset (Chen et al., 2008) and the NOAA’s Global Precipitation Climatology Centre (GPCC) dataset, retrieved from the NOAA’s Earth System Research Laboratory (Schneider et al., 2015). The correlation coefficients at General Santos were 0.46 (NCDC–CPC) and 0.78 (GPCC), those at Cotabato were 0.90 (NCDC–CPC) and 0.83 (GPCC), those at Davao were 0.95 (NCDC–CPC) and 0.63 (GPCC), and those at Malaybalay were 0.92 (NCDC–CPC) and 0.52 (GPCC). The comparison results based on statistical indices are summarized in Table A1.

This study used a 10-m resolution synthetic aperture radar (SAR) DEM. The DEM was obtained from the University of the Philippines Training Center for Applied Geodesy and Photogrammetry (UP-TCAGP), and the data were projected using Universal Transverse Mercator (UTM) Zone 51 and the 1984 World Geodetic System (WGS84) as the horizontal datum (Cuasay et al., 2014; Jason et al., 2017; Tarife et al., 2017).

The administrative boundaries of the study area were obtained from a global administrative map and compared with another shapefile from the Philippines GIS Organization (PhilGIS). The downstream region of the MRB is centred on the coordinates of 124°47’35.71” longitude and 7°12’17.06” latitude. This shapefile was used to extract the locations and areas covered by the MRB.

The soil types were obtained from the Bureau of Soil and Water Management (BSWM) and PhilGIS as a secondary source. The soil types were locally classified and identified according to previous studies in the region (Cuasay et al., 2014; Jason et al.,



**Fig. 3.** Precipitation comparisons between the observations from DOST-PAGASA and the two gridded global precipitation datasets NCDC-CPC and GPCC at (a) General Santos, (b) Cotabato, (c) Davao, and (d) Malaybalay. Note that the Cotabato and Malaybalay stations are located within the MRB, whereas the other two stations, General Santos and Davao, are situated outside the MRB. The blue-shaded zones from 2005 to 2010 indicate the calibration and validation periods for the watershed modelling.

**Table 1**

Summary of the datasets used for the SWAT simulations, calibration, and validation of results in this study.

Data	Description	Year	Format	Source
Digital Elevation Model (DEM)	RADARSAT synthetic aperture radar (SAR) (10 m resolution)	2017	GeoTIFF	Department of Science and Technology and University of the Philippines-Project ( <a href="https://lipad.dream.upd.edu.ph/">https://lipad.dream.upd.edu.ph/</a> )
Administrative map	Regional and village boundaries	2015	Shapefile	Global Administrative Map ( <a href="https://gadm.org/index.html">https://gadm.org/index.html</a> )
Land use and land cover	Landsat 8 (30 m resolution)	2010–2015	Shapefile	National Mapping and Resource Information Authority ( <a href="http://www.namria.gov.ph/">http://www.namria.gov.ph/</a> )
Soil map	Soil type		Shapefile	Philippines GIS Organization ( <a href="http://philgis.org/">http://philgis.org/</a> )
Population	Population census	2015	Spreadsheet	Philippines Statistic Authority ( <a href="https://psa.gov.ph/">https://psa.gov.ph/</a> )
Weather records	Temperature, wind, humidity, and solar radiation	1995–2017	Spreadsheet	Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) ( <a href="http://www.pagasa.dost.gov.ph/">www.pagasa.dost.gov.ph/</a> )
Precipitation	DOST-PAGASA, observation stations	1995–2017	Spreadsheet	
	NCDC–CPC gridded global daily precipitation (0.5° lat & 0.5° lon)	1979–2017	NetCDF	National Climatic Data Center ( <a href="ftp://ftp.cdc.noaa.gov/Datasets/cpc_global_precip/">ftp://ftp.cdc.noaa.gov/Datasets/cpc_global_precip/</a> )
	GPCC gridded global daily land surface precipitation (1° lat & 1° lon)	1982–2016	NetCDF	Global Precipitation Climatology Centre ( <a href="ftp://ftp.dwd.de/pub/data/gpcc/html/fulldata-daily_v2018_doi_download.html">ftp://ftp.dwd.de/pub/data/gpcc/html/fulldata-daily_v2018_doi_download.html</a> )
River discharge	Nituan River	2005–2010	Spreadsheet	Department of Public Works and Highways, Bureau of Standards ( <a href="http://www.dpwh.gov.ph/dpwh/org-chart/bureau/BRS">http://www.dpwh.gov.ph/dpwh/org-chart/bureau/BRS</a> )
	Libungan River	2006–2008		
	Pulangi River	2009–2010		

2017; Tarife et al., 2017). This dataset also used the same projection as the DEM and administrative boundaries. The total area of the MRB watershed is 2,041,449.74 ha. The hydraulic response unit (HRU) in SWAT was employed to further reclassify the soil into 6 types: mountain soil (39.04%), clay (25.45%), sandy loam (15.87%), clay loam (16.21%), loam (2.39%) and silt loam (1.04%).

The land use and land cover dataset was obtained from the National Mapping and Resource Information Authority (NAMRIA). This 30-m resolution dataset was processed from Landsat 8 images beginning in 2010 and then validated on the ground in 2015. The land use and land cover types were reclassified according to the HRU of SWAT as follows: the total area of the watershed is 2,041,449.74 ha, containing agricultural area (52.65%), bushland (23.78%), open forest (7.84%), closed forest (5.71%), marshland (4.01%), grassland (4.37%), water bodies (1.12%), and built-up area (0.53%).

Then, the DEM, the administrative map, the land use and land cover data, and the soil map were interpolated over the same grid space with a 30 × 30 m grid resolution. The SAR-DEM data was registered and projected to the UTM zone 51 N as described. All data were integrated into the GIS environment.

Temperature, humidity, wind speed, solar radiation and precipitation are physical inputs in SWAT modelling (Gassman et al.,

2007; Neitsch et al., 2011). The three datasets of temperature, humidity and wind speed are available at the four stations for the period from 1995 to 2017. However, the solar radiation dataset is only available for the General Santos station from 2016–2017.

River discharge records were obtained from the Bureau of Standards of the Department of Public Works and Highways (DPWH). The number of gauges is limited and only 3 river gauges are available within the MRB, with a short record of datasets. For example, the river gauges from the Nituan, Libungan and Pulangi rivers were collected from 2005 to 2010, from 2006 to 2008 and from 2009 to 2010, respectively.

## 4. Methodology

### 4.1. SWAT

SWAT is a scientific tool used to evaluate the streamflow, agricultural chemical distributions and sediment yield in a large basin (Gassman et al., 2007; Neitsch et al., 2011). Accordingly, SWAT has been accepted as an effective tool for the assessment of water resources (Guiamel and Lee, 2020) and for evaluating non-point source pollution and the impacts of climate change



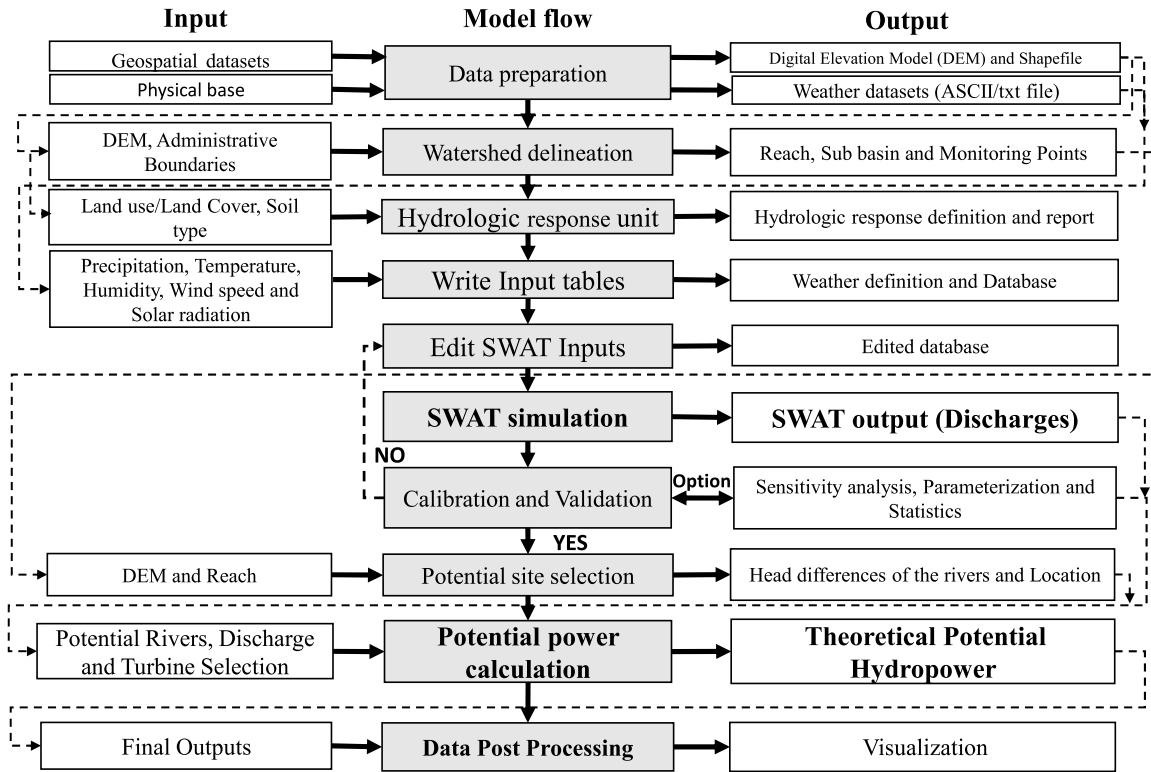


Fig. 4. Watershed modelling with SWAT and an analysis flowchart consisting of the inputs, model flow, and outputs at each procedure step in this study.

on water supplies in watersheds (Adu and Kumarasamy, 2018; Arnold and Fohrer, 2005). The hydrological cycle in a watershed model is considered via the water balance equation given in Eq. (1). This equation represents the driving physics of SWAT (Cuceloglu et al., 2017; Winchell et al., 2013):

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (1)$$

where  $SW_t$  is the final soil water content (mm H<sub>2</sub>O),  $SW_0$  is the initial soil water content (mm H<sub>2</sub>O),  $R_{day}$  is the amount of precipitation on day  $i$  (mm H<sub>2</sub>O),  $Q_{surf}$  is the amount of surface runoff on day  $i$  (mm H<sub>2</sub>O),  $E_a$  is the amount of evapotranspiration on  $i$  (mm H<sub>2</sub>O),  $W_{seep}$  is the amount of water entering the vadose zone from the soil profile on day  $i$  (mm H<sub>2</sub>O), and  $Q_{gw}$  is the amount of return flow on day  $i$  (mm H<sub>2</sub>O).

#### 4.2. Estimation of potential hydropower

Hydropower is generated from the transformation of the potential energy of water falling from an elevated reservoir into kinetic energy. This falling water drives turbines and produces mechanical energy, which then operate generators, which produce electrical energy (Kusre et al., 2010). Therefore, the theoretical power can be computed by Eq. (2) (Gaiuso, 2010; Jason et al., 2017; Tarife et al., 2017):

$$P = \rho \times n \times g \times Q \times h \quad (2)$$

where  $P$  is the theoretical potential power (W),  $\rho$  is the density of water [1000 kg/m<sup>3</sup>],  $n$  is the turbine efficiency [0.80],  $g$  is the acceleration due to gravity [9.81 m/s<sup>2</sup>],  $Q$  is the flow rate (discharge) [m<sup>3</sup>/s] and  $h$  is the head (elevation difference) [m].

The efficiency of a turbine depends on the size and type of the hydropower system. For example, the efficiency of a large-scale hydropower turbine is 90%, while that for a micro-scale

hydropower turbine ranges from 60% to 85%; in addition, Francis turbines are used for medium heads of approximately 10–50 m (Elbatran et al., 2015; Kaunda et al., 2014; Paish, 2002). This study assumed a turbine efficiency ( $n$ ) of 80% to calculate the theoretical potential power capacity. A useful alternative for maximizing power generation is a fully open gate valve of a hydraulic system (Jawahar and Michael, 2017).

Elevation is one of the most important components for selecting a site to assess the potential sustainable flow of water resources. The following criteria were implemented in the site selection:

- The vertical elevation difference exceeds 20 m (Jason et al., 2017);
- The horizontal distance between the intake reservoir and the powerhouse is more than 500 m (Tarife et al., 2017);
- The river and streambed have a minimum slope of 5% or 0.02 (Kusre et al., 2010).

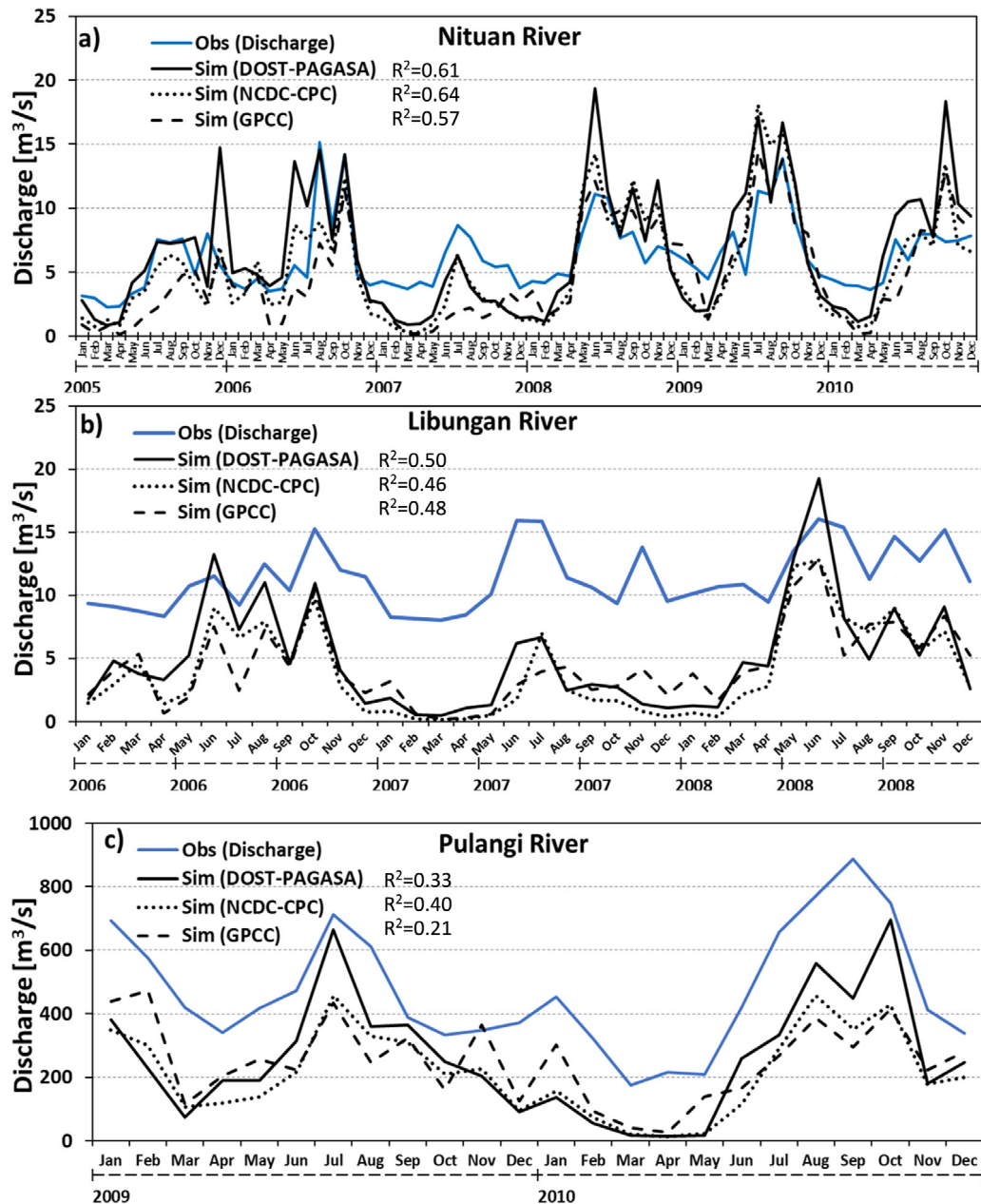
The streams of each sub-basin were divided into multiple segments. Each segment was assigned in hierarchical order from the upstream region as no. 1 to the final sub-basin in the downstream region. Segments from 1 to 4 in upstream were eliminated because of unsustainable stream flow. The succeeding segments from 5 to the last were considered to have sustainable flow in the potential site selection (Strahler, 1957).

#### 4.3. Analysis procedure

For reproducibility, the methodological procedure for this study is described in detail in the following (Fig. 4).

**Step 1.** Data preparation: Prepare the input weather dataset to match the required formats in SWAT. The geospatial datasets were processed by aligning the projection onto UTM Zone 51 with WGS84 as the horizontal datum. Then, the DEM and land use and land cover data were unmasked with the basin boundaries by ArcGIS.





**Fig. 5.** Comparisons among the calibration results of river discharges at the (a) Nituan River for 5 years from 2005 to 2010, (b) Libungan River for 3 years from 2006 to 2008, and (c) Pulangi River for 2 years from 2009 to 2010. The blue line indicates the observed discharges at the river gauges, and the black lines are the simulated discharges resulting from the three different precipitation inputs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Step 2.** Watershed delineation: The ArcSWAT interface was used to delineate the watershed using the processed inputs of the geospatial datasets.

**Step 3.** Defining the HRUs: The processed land use and land cover data were used to generate the HRUs by ArcSWAT.

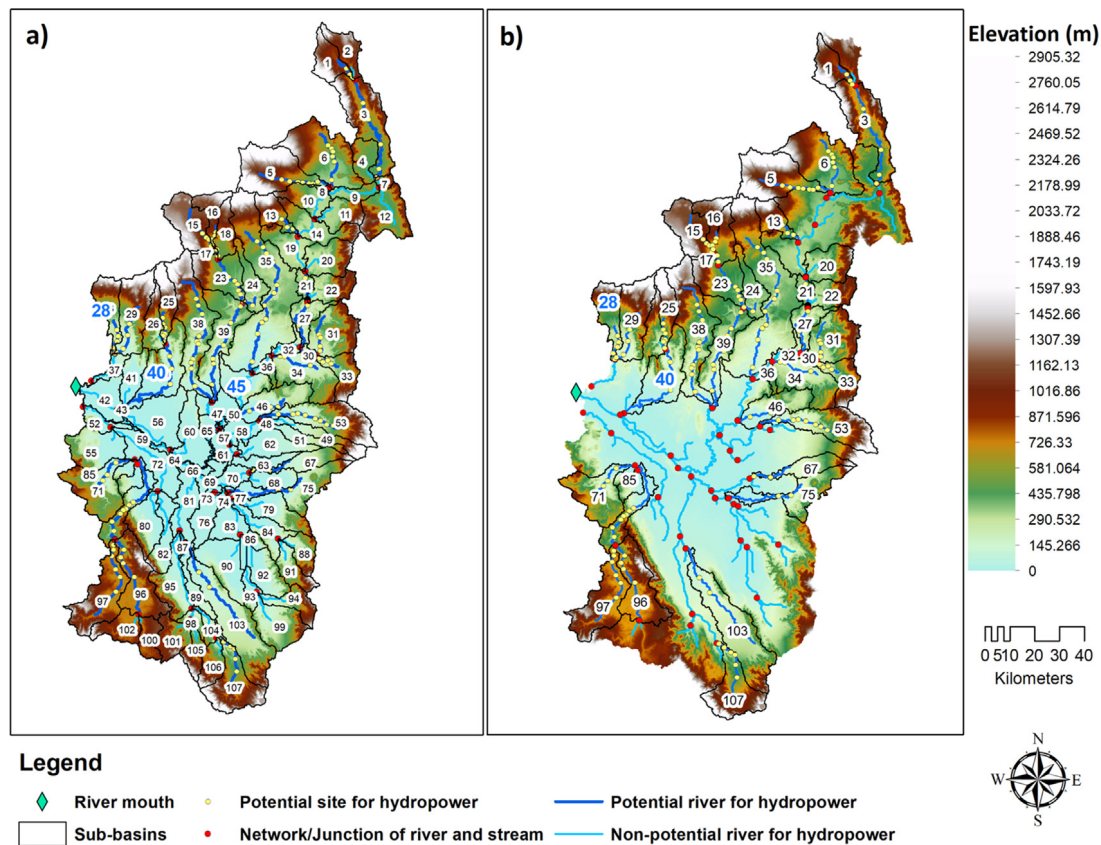
**Step 4.** Write input tables: The processed weather dataset was loaded into the database and used for the entire SWAT modelling process; this step played a vital role in using the identified weather stations in the study area.

**Step 5.** Edit SWAT inputs: This step was primarily for establishing the initial values of the physical parameters, which were then adjusted in the calibration process.

**Step 6.** SWAT simulation: SWAT simulations were conducted monthly for 17 years from 2000 to 2017 with a 2-year warm-up period from 2000 to 2002. Due to the available river discharge

records spanning 5 years from 2005 to 2010, the SWAT model was calibrated and validated for the same 5 years, as presented in Fig. 3. Additionally, the model outputs were determined and imported to the database, and the available outputs, such as the hydrological cycle, sediment, nitrogen cycle, phosphorus cycle, plant growth, landscape, nutrition losses, land use summary, instream processes, point sources, and reservoir, were quickly checked. The hydrological cycle was checked in every simulation of this study.

**Step 7.** Calibration: This step was conducted to calibrate the 11 parameters from ArcSWAT to improve the model performance by adjusting the parameters based on the sensitivity analysis from the SWAT Calibration and Uncertainty Programs (SWAT-CUP) outputs. The calibration process was independently performed from ArcSWAT using the text file. In this work, the model calibration was implemented by comparison with observed discharges



**Fig. 6.** Comparison among the delineated MRB watersheds: (a) results of the potential site selection for theoretical hydropower in 107 sub-basins and (b) results of the potential site selection in 33 sub-basins after removing the sub-basins without any potential sites. Potential sites are indicated by yellow dots. Rivers with potential hydropower sites are illustrated as dark blue lines, while those without any potential sites for hydropower are indicated by light blue lines. No potential sites are identified in the low-lying, flood-prone areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from 3 rivers, namely, the Nituan River from 2005 to 2010, the Libungan River from 2006 to 2008, and the Pulangi River from 2009 to 2010.

**Step 8. Validation:** Due to the limited number of river gauges and the insufficient discharge records in the study area, the validation was performed based on the proxy river basin principle (Klemeš, 1986; Guiamel and Lee, 2020). For example, the calibrated/fitted parameters of River A (the Nituan River) were applied to model the watershed of the proxy or neighbouring River B (Libungan River and Pulangi River) to simulate the river discharges therein. Then, the simulated discharges of River B were validated with the observed discharges. The validation results are summarized in Table A2 in terms of statistical indices.

**Step 9 Extraction of elevation:** After obtaining satisfactory results from the calibration and validation, the DEM was used as the input file to be unmasked in the delineated reach/river. GIS tools were used to undertake this step based on the abovementioned criteria for the selection of potential hydropower sites.

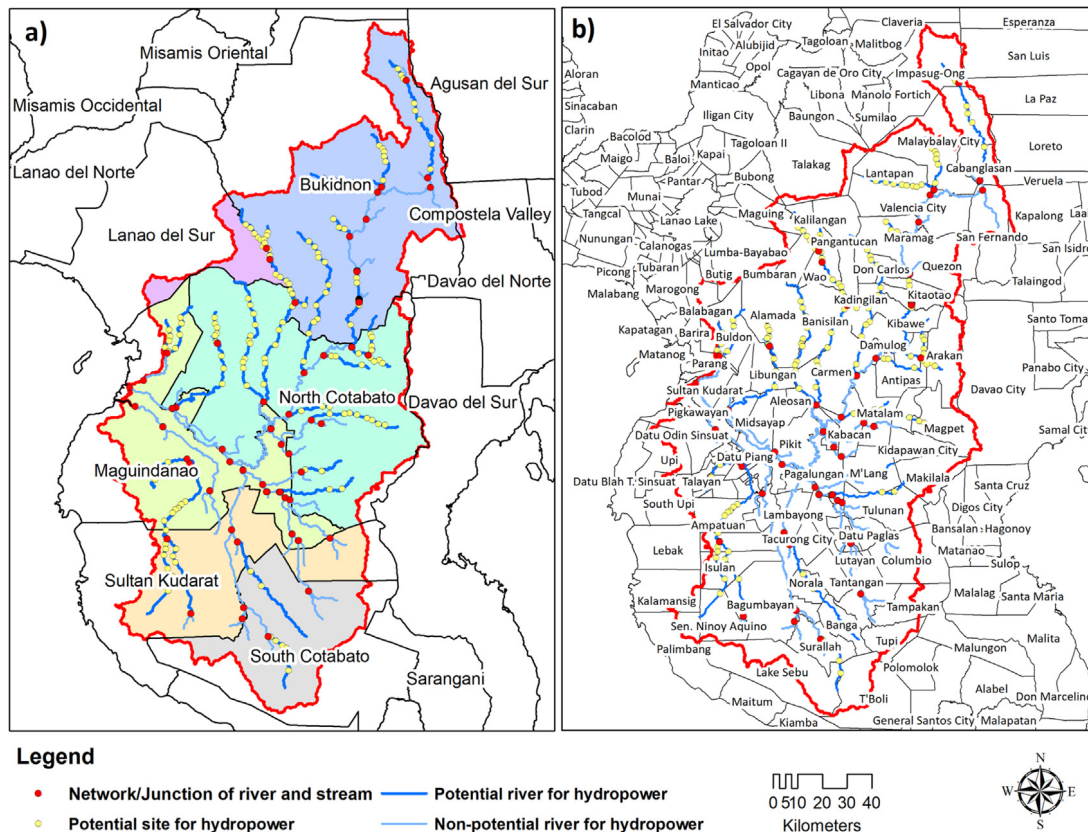
**Step 10: Calculation of the theoretical potential hydropower capacity:** The capacity was calculated using Eq. (2). The theoretical power calculation used the results from the validated discharge with the DOST-PAGASA precipitation dataset.

**Step 11: Classification of hydropower by capacity:** The calculated theoretical power capacity was classified into the following types based on the common criteria shown in Table A3: pico-, micro-, mini-, small-, medium- and large-scale hydropower.

## 5. Results

### 5.1. Calibration of watershed modelling

The SWAT simulations were run from 2000 to 2017 with a 3-year warm-up period from 2000 to 2002. Then, according to the available discharge records for each river, the calibration was carried out in three sub-basins, as shown in Fig. 5: sub-basin 28 for the Nituan River for 5 years from 2005 to 2010, sub-basin 40 for the Libungan River for 3 years from 2006 to 2008, and sub-basin 45 for the Pulangi River for 2 years from 2009 to 2010. The coefficients of determination ( $R^2$ ) for the DOST-PAGASA precipitation model were 0.61 at the Nituan River, 0.50 at the Libungan River and 0.42 at the Pulangi River. The NCDC-CPC precipitation model produced  $R^2$  values of 0.66 at the Nituan River, 0.49 at the Libungan River and 0.55 at the Pulangi River, while the  $R^2$  values of the GPCC precipitation model were 0.62 at the Nituan River, 0.51 at the Libungan River and 0.27 at the Pulangi River. An  $R^2$  value larger than 0.50 is acceptable according to the general criteria on watershed evaluation performance (Aqnoy et al., 2019; Moriasi et al., 2015). The calibration results indicate that the SWAT runs for the Nituan River were satisfactory with all precipitation data ( $R^2 > 0.6$ ), whereas the results for the Libungan River and Pulangi River showed  $R^2$  values lower than 0.5. In general, the results with the NCDC-CPC data are relatively good results compared with those with the DOST-PAGASA data. The underestimated simulated discharges at the Libungan and Pulangi Rivers were partly due to insufficient information on the management of dam-made reservoirs (Ligaray et al., 2017). The MRB is



**Fig. 7.** Locations of theoretical potential hydropower sites at (a) the provincial level and (b) the municipal level. The potential sites are situated in 6 out of 8 provinces and in 41 out of 72 municipalities in the MRB region.

a large area with a limited dataset on its dams; the presence of large areas of marshland and varying elevations ranging from 0 to 2,905.32 m, as shown in Fig. 6, further contributed to the low performance of the models. Wetland (marshland) is a challenging terrain because it typically absorbs surface and subsurface water at several points between an inlet and an outlet even though the inlet of the watershed is well defined (Rezaeianzadeh et al., 2018). In addition, the negative values of the Nash–Sutcliffe efficiency (NSE) in Table A2 also indicate an unsatisfactory model performance characterized by extreme values from a high precipitation intensity. This means that the average observed discharge is better than the simulated discharge (Moriassi et al., 2015).

## 5.2. Validation of watershed modelling in a proxy basin

After calibration, the models were validated by using the proxy basin principle due to the lack of river discharge records and the limited number of river gauges in the study area. This method is particularly useful if the available discharge records are not sufficient for a split-sample analysis and if only two validation results are acceptable and identical. In addition, this method has also been used for ungauged basins and at regional watershed scales (Rientjes et al., 2011).

The  $R^2$  values at the Nituan and Libungan Rivers were 0.61 and 0.50, respectively, for the DOST-PAGASA model, whereas the model performance at the Pulangi River decreased to 0.33 for DOST-PAGASA, 0.40 for the NCDC–CPC dataset, and 0.21 for the GPCC dataset. For the Nituan River, the performances with all data were acceptable ( $>0.5$ ). In contrast, for the Libungan River, the general performances were not satisfactory, particularly with the NCDC and GPCC data. Overall, the results with the NCDC–CPC precipitation data showed a slightly higher performance than

the other precipitation datasets. In addition, the p-factors and r-factors of all the models displayed no significant changes from calibration to validation, as shown in Table A2.

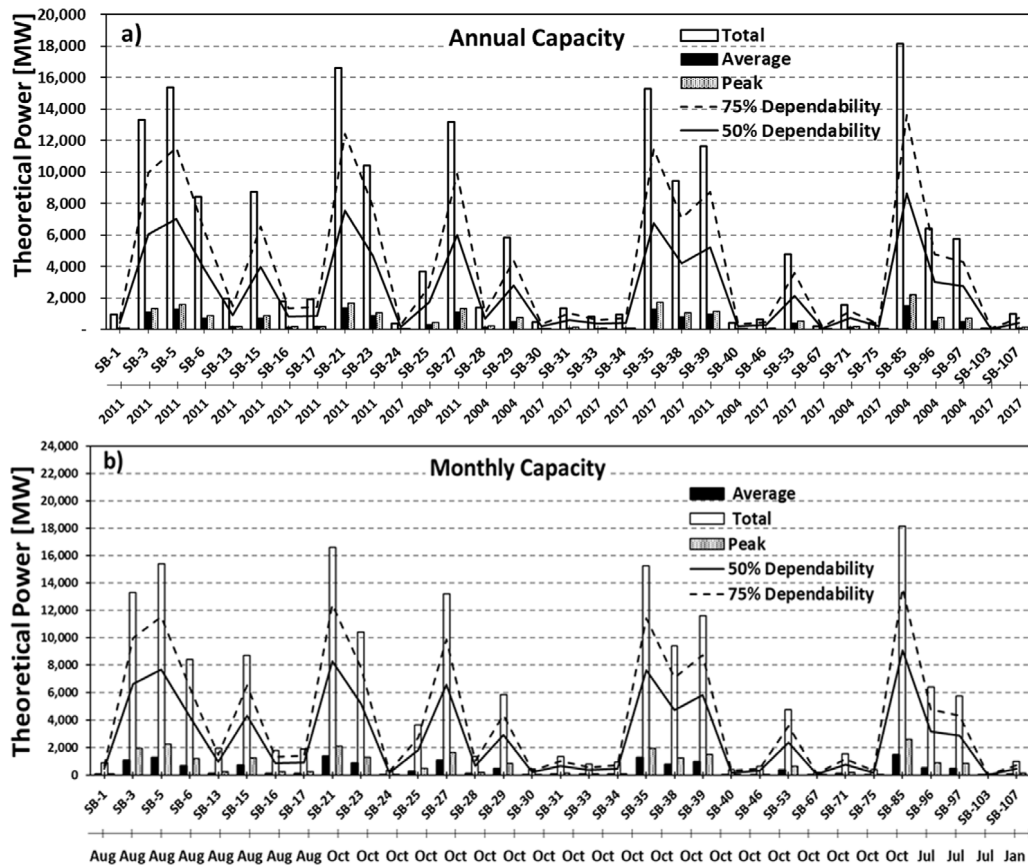
## 5.3. Theoretical potential hydropower

The theoretical potential hydropower sites were extracted from the 107 sub-basins in the MRB watershed, as depicted in Fig. 6(a). From this watershed, 33 potential sub-basins were identified for hydropower development (Fig. 6(b)). Then, 154 potential hydropower sites were identified among the 33 potential sub-basins based on the abovementioned criteria. The calculated monthly theoretical potential hydropower capacity at all 154 sites among these 33 sub-basins was 15,266.22 MW, and the average monthly power capacity was 5,551 MW. As shown in Fig. 6(b), all sites are located in the upstream and mid-stream areas. In the downstream marshland, which are frequently prone to flooding, no potential sites were identified due to the low relief and flat slope gradients. The potential sites cover 41 municipalities in 6 provinces within the MRB watershed (Fig. 7).

The estimated theoretical power capacity was calculated using the simulated discharge data from the DOST-PAGASA precipitation model. The calculated capacity was further classified using the criteria presented in Table A3. The theoretical hydropower potentials were classified into 16 potential sites for mini-scale hydropower, 114 sites for small-scale hydropower and 24 sites for medium-scale hydropower. Fig. A.1 shows the simulated discharges for each sub-basin and all 154 potential sites. Table A4 indicates the minimum and maximum elevations, calculated capacities, and classification of potential sites for each sub-basin.

The results were further analysed using a basin-wide approach and a temporal approach on an annual and monthly basis.





**Fig. 8.** (a) Annual theoretical power capacity and (b) monthly theoretical power capacity of each of the 33 potential sub-basins. The secondary axis of (a) indicates the year of the calculated peak theoretical power of each sub-basin from the 15-year simulation results from 2003 to 2017, whereas that of (b) indicates the month of the calculated peak power from the same simulation results. *Total* represents the sum of the theoretical power capacity of all sites in each sub-basin, whereas *Average* and *Peak* indicate the mean and peak values, respectively, of the theoretical power capacity of all sites in each sub-basin. The dashed line and thick line reflect the 50% and 75% dependability of the total theoretical power, respectively. For example, in sub-basin 21, the calculated annual peak theoretical power capacity is obtained for 2011. Similarly, the calculated monthly peak theoretical power capacity at sub-basin 21 is found for October.

**Table A1**

Comparison of the precipitation datasets between the observations and global gridded datasets at four stations within and near the MRB in terms of six statistical indices: the correlation coefficient (*R*), coefficient of determinant ( $R^2$ ), index of agreement (*d*), standard deviation ( $\sigma$ ), root mean square error (*RMSE*) and average (*mean*).

Statistics	Stations											
	General Santos			Cotabato			Davao			Malaybalay		
	DOST-PAGASA	NCDC-CPC	GPCC	DOST-PAGASA	NCDC-CPC	GPCC	DOST-PAGASA	NCDC-CPC	GPCC	DOST-PAGASA	NCDC-CPC	GPCC
<i>R</i>	N/A	0.46	0.78	N/A	0.90	0.83	N/A	0.95	0.63	N/A	0.92	0.52
$R^2$	N/A	0.21	0.60	N/A	0.81	0.69	N/A	0.91	0.63	N/A	0.85	0.27
<i>d</i>	N/A	0.47	0.63	N/A	0.95	0.83	N/A	0.97	0.67	N/A	0.92	0.65
<i>RMSE</i>	N/A	2.63	2.27	N/A	2.06	2.76	N/A	0.92	2.92	N/A	2.01	3.76
$\sigma$	1.62	2.05	1.76	4.41	3.83	3.07	2.60	2.40	2.86	4.30	3.10	2.97
<i>Mean</i>	2.71	4.51	4.68	7.07	6.37	5.97	5.10	5.53	6.83	7.39	6.64	7.45

In addition, the 50% and 75% dependability assumptions were included to visualize possible trends for planning applications. The power generation varied with the size of the hydropower plant, and the hydropower plant size was determined by either the hydropower capacity (Aun and Schei, 2009) or the elevation difference (Von Sperling, 2012).

## 6. Discussion

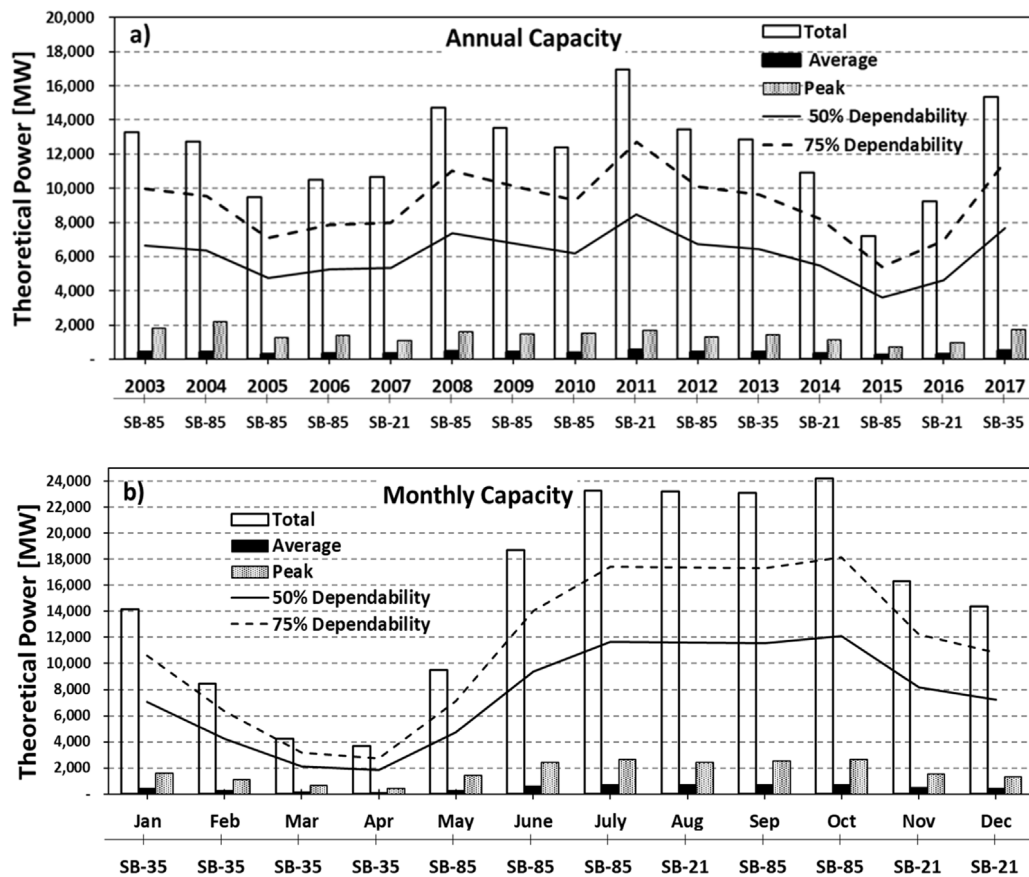
### 6.1. Basin-wide analysis of hydropower potential

The terrain of each potential site was investigated to assess the theoretical power induced by the kinetic energy flowing into the turbine. Fig. 8(a) depicts the theoretical potential capacity of each sub-basin. Among the 33 potential sub-basins, sub-basins

number 21, 35 and 85 were identified as having high hydropower potentials. *Total* in Fig. 8 indicate the sum of the theoretical power capacity of all sites in each sub-basin, while *Average* and *Peak* in Fig. 8 represent the mean and peak values, respectively, of the calculated theoretical power capacities of all sites in each sub-basin. The highest annual peak power capacities in sub-basins 21, 35 and 85 were 1,688.64 MW, 1,730.72 MW and 2,184.68 MW, respectively. The 50% and 75% dependability values signify 50% and 75% of the total value shown to ensure reliable power supply during the remaining 50% and 25% of the time, respectively. During the time of remaining dependability, alternate arrangements of energy resources for power generation must be considered in the MRB region.

Fig. 8(b) shows the monthly theoretical power capacity of each of the 33 potential sub-basins. The months of July, August





**Fig. 9.** (a) Annual theoretical power capacity for all sites of each year from 2003 to 2017 and (b) monthly theoretical power capacity for all sites of each month from 2003 to 2017. The secondary axis of (a) indicates the sub-basin with the calculated peak theoretical power of the corresponding year on the primary axis, whereas that of (b) indicates the sub-basin of the calculated peak power of the corresponding month on the primary axis. *Total* represents the sum of the theoretical power capacity of all sites in each year and month, whereas *Average* and *Peak* indicate the mean and peak values, respectively, of the theoretical power capacity of all sites in each year and month. The dashed line and thick line reflect the 50% and 75% dependability of the total theoretical power, respectively. For example, in 2011, the calculated annual peak theoretical power capacity was obtained in sub-basin 21. Similarly, the calculated monthly peak theoretical power capacity in October is found in sub-basin 85.

**Table A2**

Summary of the statistics of the validation results for the river discharges by the proxy basin principle using the fitted parameters from the calibration. Sub-basins 28, 40, and 45 represent the Nituan, Libungan, and Pulangi Rivers, respectively. KGE denotes the Kling–Gupta efficiency.

Statistics	DOST-PAGASA			NCDC-CPC			GPCC		
	Sub-basin	Sub-basin	Sub-basin	Sub-basin	Sub-basin	Sub-basin	Sub-basin	Sub-basin	Sub-basin
	28	40	45	28	40	45	28	40	45
$R^2$	0.61	0.50	0.33	0.64	0.46	0.40	0.57	0.48	0.21
PBIAS	5.6	57.8	70.4	25.4	60.2	71.4	30.9	39.7	58.9
KGE	0.33	0.14	0.09	0.45	0.17	0.05	0.60	0.29	0.05
NSE	-0.14	-7.33	-2.76	-0.10	-7.85	-2.80	-0.03	-3.51	-1.90
RSR	1.07	2.88	1.94	1.05	2.98	1.95	1.01	2.12	1.70
<i>p</i> -factor	0.51	0.06	0.08	0.60	0.11	0.00	0.60	0.11	0.08
<i>r</i> -factor	1.50	0.58	0.20	1.70	0.33	0.10	0.83	0.85	0.34

and October exhibited high potential for the generation of hydropower. Moreover, sub-basins 5, 21, 35 and 85 were identified as having high potentials with estimated monthly peak capacities of 2,257.27 MW, 2095.73 MW, 1,986.65 MW and 2,636.84 MW, respectively. These generated peak powers in sub-basins 5, 21, 35, and 85 were mainly because of the high discharges shown in Fig. 5 and the large number of identified potential sites (Fig. 6). For example, sub-basins 5, 35 and 85 were shown to host 8, 12, and 7 potential sites, respectively. In contrast, sub-basin 21 indicated only 2 potential sites with a high peak discharge of 595.4

m<sup>3</sup>/s. Moreover, the elevation difference of each site contributed to the variation in theoretical potential power capacity.

In sub-basins 5 and 35, small-scale hydropower was suitable at 4 sites and 10 sites, respectively. For sub-basin 85, the 7 potential sites could accommodate 2 small-scale hydropower and 5 medium-scale hydropower units based on the simulated discharges (Table A4). In general, the majority of potential sites in the MRB watershed are suitable for small-scale hydropower generation according to the generation capacity criteria ranging from 1 MW to 10 MW (Carrasco et al., 2019). In addition, during the seasons with low precipitation, sub-basins 21, 35, and 85 could sustain hydropower generation due to favourable geographical factors.

For steady and reliable energy that is sustained in successive years, a water supply from multiple sub-basins to one potential site is desirable in hydropower planning and development. For example, the potential sites in sub-basin 39 gather water from multiple upstream sub-basins, such as sub-basins 15, 16, 17, 23 and 24, for the steady and reliable generation of power, as shown in Fig. 6(b). Moreover, the potential sites located in relatively downstream sub-basins, such as sub-basins 3, 21, 27, 30, 32, 17, 23, and 85, are also supplied by water from multiple upstream sub-basins. Table A5 depicts the locations of the potential hydropower sites in the MRB according to the administrative divisions.

**Table A3**

Common criteria for the classification of theoretical hydropower by capacity.

Classification	Capacity (MW) (Cuasay et al., 2014)	Capacity (MW) (Aun and Schei, 2009)	Capacity (MW) (Tarife et al., 2017)	Capacity (MW) (Carrasco et al., 2019)
Pico	Less than 0.005	Less than 0.005	Less than 0.005	Less than 0.005
Micro	0.005 to 0.100	Less than 0.1	0.005 to 0.100	0.005 to 0.100
Mini	0.101 to 1	Less than 1	0.100 to 1	0.100 to 1
Small	1.001 to 3	1 to 100	1 to 25	1 to 10
Medium	3.001 to 10	Greater than 100	25 to 100	10 to 100
Large	Greater than 10	Greater than 500	Greater than 100	Greater than 100

**Table A4**

Summary of the calculated theoretical potential hydropower results for the 33 potential sub-basins in the MRB, including the length of the river and the minimum and maximum elevations of each sub-basin.

Sub-basin	Number of sites	Capacity			Classification			River length (m)	Min elevation (m)	Max elevation (m)
		Average	Monthly	Annual peak	Mini	Small	Medium			
1	3	77.61	137.45	93.75		3		13235.83	629.90	785.04
3	6	1108.16	1954.45	1339.12		3	3	56807.80	359.32	629.90
5	8	1282.31	2257.27	1575.80		4	4	35820.82	312.38	954.40
6	6	702.06	1220.71	865.40		5	1	32987.21	312.38	670.23
13	3	162.97	283.76	200.93		3		15021.99	271.00	546.53
15	6	726.51	1257.29	885.24		6		24626.12	519.16	1168.47
16	4	149.64	261.76	182.82		4		11212.74	519.16	868.14
17	2	160.07	277.99	195.09		2		5420.66	475.84	519.16
21	2	1383.18	2095.73	1688.64		2		13635.53	124.34	270.19
23	6	866.06	1335.64	1044.84		4	2	29032.85	202.84	480.03
24	2	31.80	46.99	41.96	1	1		9970.95	202.84	254.35
25	6	306.51	534.30	447.51		6		16144.41	131.25	507.00
27	2	1099.24	1669.54	1336.43			2	27608.17	49.69	124.34
28	5	115.09	219.34	205.56	1	4		17747.08	51.55	292.08
29	5	487.25	880.78	765.90		4	1	30242.17	51.55	727.99
30	1	37.46	59.49	48.44		1		9865.61	49.69	102.63
31	4	112.94	179.63	146.29		4		20817.64	102.63	242.59
33	4	67.49	106.71	86.90	2	2		14857.49	280.64	280.64
34	3	80.65	122.66	104.22		3		23435.88	29.10	156.90
35	12	1272.45	1986.65	1730.72		10	2	80420.19	20.41	585.60
38	11	785.77	1252.57	1042.66		11		71360.98	16.07	961.98
39	7	968.81	1498.15	1157.61		4	3	57044.32	16.07	202.84
40	3	35.32	69.43	65.83	3			53347.51	0.00	123.32
46	3	54.09	83.57	71.05		3		27390.73	9.52	123.32
53	8	397.77	645.35	526.51		8		44883.29	31.01	586.03
67	2	16.90	27.42	24.85	2			23260.89	13.95	90.09
71	3	129.94	227.87	191.67		3		26881.00	0.38	181.84
75	2	34.96	56.84	52.46	1	1		42939.37	6.15	130.54
85	7	1512.53	2636.84	2184.68		2	5	51982.21	0.24	330.82
96	4	532.31	919.87	740.86		3	1	39395.31	330.82	688.37
97	6	478.94	845.32	698.73		6		39387.74	330.82	713.51
103	2	6.10	12.76	8.00	2			58764.55	47.78	220.22
107	6	83.31	143.85	116.17	4	2		30663.24	192.98	573.37
Total	154	15266.22			16	114	24			

## 6.2. Temporal analysis of hydropower potential

Fig. 9 illustrates the annual and monthly trends of the potential hydropower in the MRB. Fig. 9(a) depicts the annual theoretical power capacity from all sites for each year from 2003 to 2017, and Fig. 9(b) shows the monthly theoretical power capacity from all sites for each month from 2003 to 2017. The highest hydropower generation in the MRB was obtained for 2011 with an estimated annual power capacity of 16,969.24 MW, followed by annual power capacities of 15,343.90 MW and 14,712.87 MW

in 2017 and 2008, respectively. The lowest power generation capacity was observed for 2015 with an estimated annual power of 7191.18 MW.

The monthly analysis of the power capacity (Fig. 9(b)) illustrates that the months from June to October represent the season with a high hydropower generation potential, providing an estimated theoretical power capacity ranging from 18,722.1 MW to 24,195 MW for all sites. In contrast, from February to April, the power generation decreases anywhere from 4218.11 MW to 3669.13 MW. These trends of the monthly theoretical potential

**Table A5**

Locations of the theoretical potential hydropower sites in the MRB according to the administrative divisions.

Province	Municipality	Barangay (Villages)	Number of sites	Min elevation (m)	Max elevation (m)	Sub-basin
Bukidnon	Impasug-Ong	Bulonay	3	629.90	785.04	1
		Busdi	3	359.32	629.90	3
	Malaybalay City	Casisang	2	312.38	670.23	6
		San Jose	1	312.38	670.23	
		Laguaitas	1	312.38	670.23	
		Violeta	1	312.38	670.23	
		Simaya	1	312.38	670.23	
	Cabanglasan	Iba	1	359.32	629.90	3
		Paradise	1	359.32	629.90	
		Jasaan	1	359.32	629.90	
	Valencia City	Lilingayon	3	312.38	954.40	5
		Bagontaas	1	312.38	954.40	
		Lurogan	2	312.38	954.40	
	Lantapan	Bantuanon	2	312.38	954.40	
	Kitaotao	San Lorenzo	2	124.34	270.19	21
	Kadingilan	Matampay	1	202.84	249.39	24
		Kibalagon	1	202.84	249.39	
	Maramag	Kuya	1	20.41	585.60	35
		Danggawan	1	20.41	585.60	
		Panalsalan	1	271.00	546.53	13
		San Roque	1	271.00	546.53	
		Bayabason	1	271.00	546.53	
	Kalilangan	San Vicente Ferrer	1	519.16	1,168.47	15
Malinao		5	519.16	1,168.47		
Baborawon		2	519.16	868.14	16	
Canituan		2	519.16	868.14		
Canituan		1	480.03	519.16	17	
Pamotolon		1	480.03	519.16		
Lampanusan		2	202.84	480.03	23	
Husayan		1	20.41	585.60	35	
Balaoro		1	20.41	585.60		
Balaoro		1	20.41	585.60		
Lampanusan	1	202.84	480.03	23		
Pangantucan	Malipayon	1	202.84	480.03	480.03	
	Kimanait	1	202.84	480.03		
Dangcagan	Dolorosa	1	49.69	124.34	27	
	Sanipon	1	49.69	124.34		
Kibawe	Romagooc	1	20.41	585.60	35	
	New Kidapawan	1	20.41	585.60		
Don Carlos	Old Nongnongan	2	20.41	585.60	585.60	
	Calaocalao	1	20.41	585.60		
Damulog	Omonay	1	20.41	585.60		
Barira	Lipawan	1	51.55	292.08	28	
	Rominimbang	2	51.55	292.08		
Buldon	Kulimpang	2	51.55	727.99	29	
	Eddor	1	51.55	727.99		
	Ampuan	1	51.55	727.99	28	
	Cabayuan	1	51.55	292.08		
	Aratuc	1	51.55	727.99		
Parang	Orandang	1	51.55	292.08	28	
Guindulungan	Tambunan II	1	0.38	181.84	71	
Talayan	Lanting	1	0.38	181.84	181.84	
	Fukol	1	0.38	181.84		
Ampatuan	Saniag	1	0.24	330.82	85	
	Saniag	1	0.24	330.82		
	Saniag	1	0.24	330.82		
	Tubak	3	0.24	330.82		

(continued on next page)

Table A5 (continued).

Province	Municipality	Barangay (Villages)	Number of sites	Min elevation (m)	Max elevation (m)	Sub-basin		
North Cotabato	Banisan	Capayangan	1	202.84	480.03	23		
	Alamada	Lower Dado	2	131.25	507.00	25		
		Pigcawaran	4	131.25	507.00			
	President Roxas	Kitacubong		1	-	131.25	40	
			Lamalama	1	49.69	102.63	30	
		Datu Indang	2	102.63	242.59	31		
		Kimaruhing	1	102.63	242.59			
		Bato-Bato		2	102.63	242.59	33	
	Bato-Bato		1	102.63	280.64			
	Arakan	Doroluman	1	102.63	280.64	34		
		Santo Niño	1	102.63	280.64			
	Antipas	Malatab	2	29.10	156.90	34		
		Camutan	1	29.10	156.90			
	Alamada	Guling	1	16.07	961.98	38		
		Bao	2	16.07	961.98			
		Malitubog	2	16.07	961.98			
	Banisan	Malagap	1	16.07	961.98	39		
		Wadya	2	16.07	961.98			
		Banisan Poblacio	1	16.07	961.98			
		Pinamulaan	1	16.07	202.84			
	Carmen	Busaon	1	16.07	202.84	39		
		Liliongan	1	20.41	585.60			
		Bentangan		1	16.07		961.98	38
			Tonganon	1	16.07		961.98	
		Macabenban		1	16.07		202.84	39
			Malapag	1	16.07		202.84	
	Bentangan		2	16.07	202.84			
	Palanggalan		1	16.07	202.84	40		
		Kapayawi	1	-	131.25			
	Libungan	Barongis	1	-	131.25	46		
		Pedtad	1	9.52	123.32			
	Kabacan	Minamaing	1	9.52	123.32	46		
		New Alimodian	1	9.52	123.32			
Lampayan		1	31.01	586.03				
Magpet	Binay	1	31.01	586.03	53			
	Doles	1	31.01	586.03				
	Ilian	2	31.01	586.03				
M'Lang	Dungo-An	1	13.95	90.09	67			
	Magallon	1	13.95	90.09				
	New Kalibo	1	13.95	90.09				
	La Fortuna	1	6.15	130.54				
President Roxas	Idaoman	2	31.01	586.03	53			
Tulunan	Bituan	1	6.15	130.54	75			
Bagumbayan	Kabulanan	1	330.82	688.37	96			
	Lagandang	2	330.82	688.37				
Isulan	Laguilayan	1	330.82	688.37	97			
	Laguilayan	2	330.82	713.51				
	Bual	2	330.82	713.51				
Esperanza	Margues	1	330.82	713.51	85			
	Pamantingan	1	0.24	330.82				
Sen. Ninoy Aquino	Bugso	1	330.82	713.51				
Noralá	Dumaguil	1	47.78	220.22	103			
	Benigno Aquino, Jr.	1	47.78	220.22	103			
South Cotabato	Surallah	Colongulo	1	192.98	573.37	107		
		Centrala	1	192.98	573.37			
		Tubiala	1	192.98	573.37			
		Lamsugod	1	192.98	573.37			
		Tubiala	1	192.98	573.37			
Lake Sebu	Halilan	1	192.98	573.37				

power generation are important information to balance seasonal demands in the region as well as to design possible power storage devices to reduce monthly peak demands. For example, in April,

the calculated monthly theoretical power capacity of all sites was 3,669.13 MW, which is sufficient to supply the observed highest peak demand of 1,696 MW in April 2017 (Department



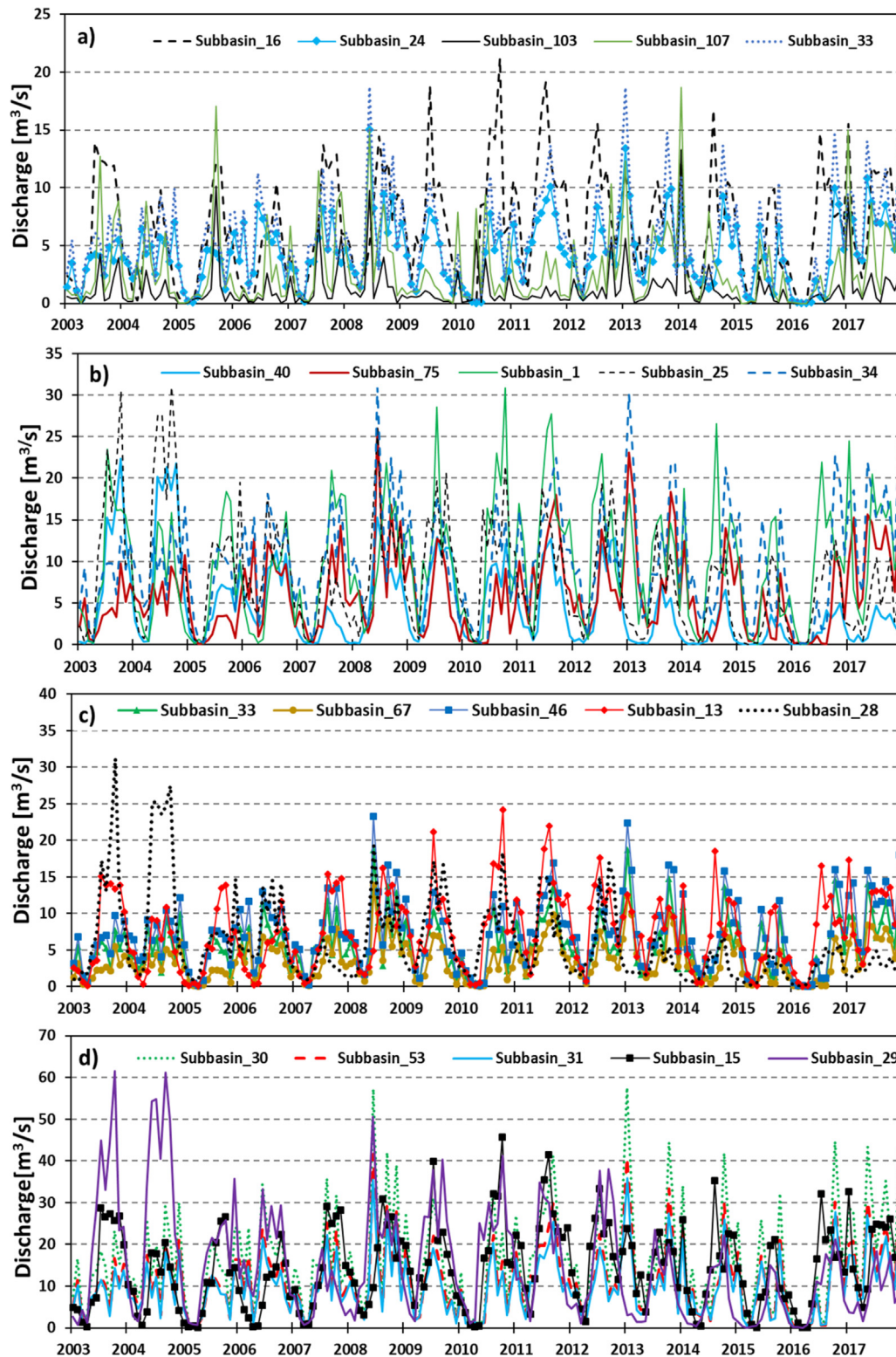


Fig. A.1. Sub-basin-wise simulated flow rates of the 33 potential sub-basins used for the calculation of the theoretical power capacity in the MRB.

of Energy 2017a). This finding will be beneficial for managing the development of hydropower generation by season and, for example, for increasing the storage capacity during rainy seasons to reinforce possible shortages during dry seasons.

In addition, all of the calculated annual and monthly peak theoretical power capacities were obtained from sub-basins 21, 35, and 85 based on the river discharges. The 50% and 75%

dependability levels also presented clear seasonal variations. The months from June to October constitute the high-capacity season for hydropower generation, especially in these three sub-basins.

## 7. Conclusions

Watershed modelling with SWAT was conducted to estimate river discharges in the MRB. First, the physical parameters of

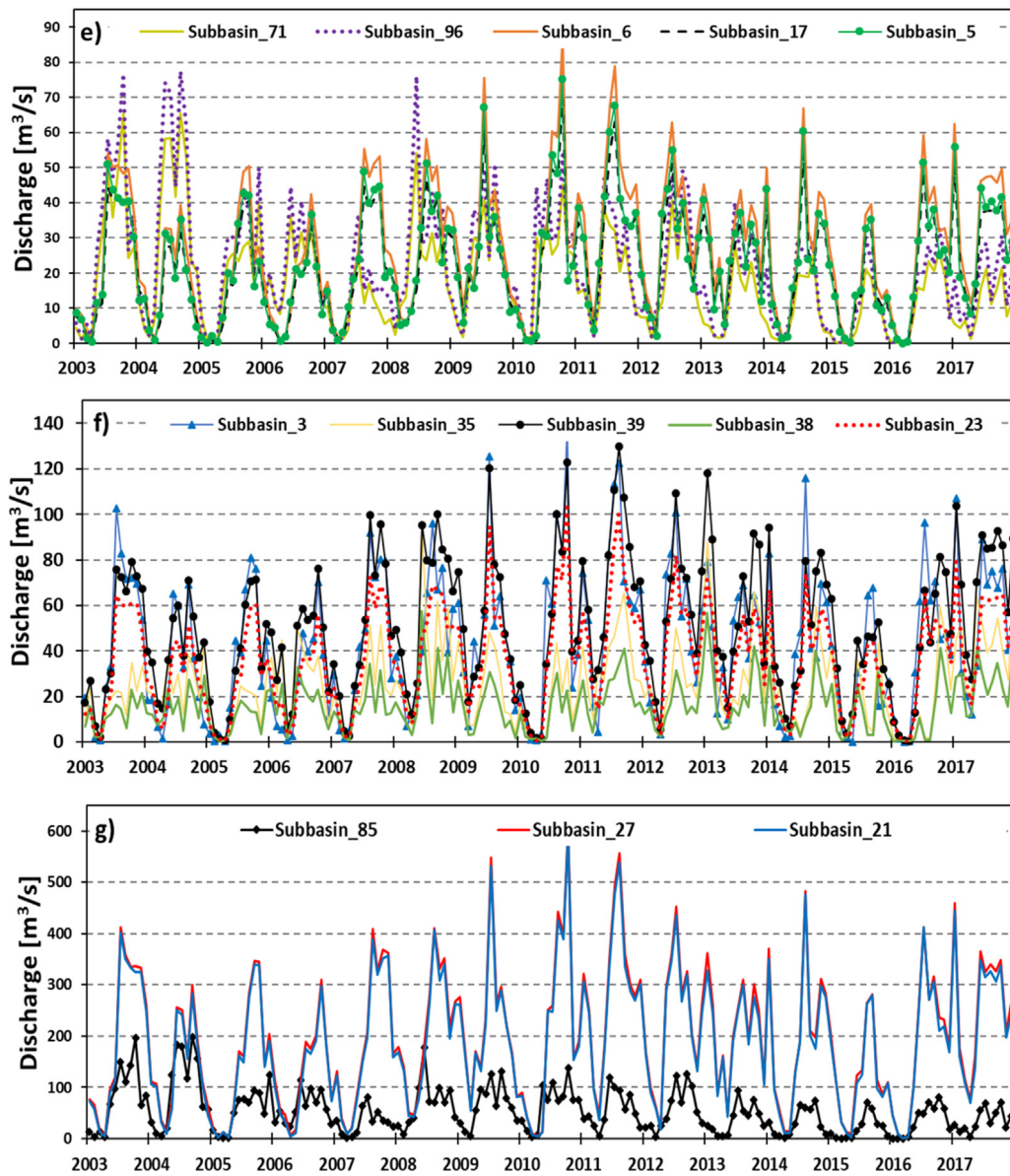


Fig. A.1. (continued).

SWAT were calibrated using SWAT-CUP (SUF12). The calibrated modelling results were validated by comparing the simulated river discharges with the observed discharges in a proxy basin due to insufficient river discharge records. Then, the river discharges validated using the DOST-PAGASA precipitation dataset for input were used to calculate the theoretical hydropower capacity. The MRB was delineated into 107 sub-basins, 33 of which were identified as potential sites for the development of theoretical hydropower with an estimated monthly average capacity of 5551.35 MW for all sites from the 33 sub-basins.

The monthly trend of the theoretical hydropower capacity shows that the months from June to October constitute the season with a high potential for the generation of hydropower basically because of the influence of precipitation: the rainy season demonstrated a high potential for hydropower generation. Moreover, the seasonal trend showed a variation in hydropower generation that will be useful for improving the storage capacity of hydropower systems and mitigate the possible effects of heavy rainfall downstream of the MRB during rainy seasons. The 50% and 75% dependability assumptions illustrate the seasonal power availability for the MRB. For the remaining 50% and 25% of power,

alternative energy sources for power generation will need to be considered to supplement the necessary energy demand in dry seasons and peak demand seasons in the region.

A basin-wide analysis illustrated the potential capacities of each sub-basin for generating power within the MRB watershed. For example, among the 33 potential sub-basins in the MRB, sub-basins 21, 25 and 85 were found to have high hydropower potential. According to the general hydropower classification, small-scale hydropower (with a capacity between 1 MW and 10 MW) is suitable for the MRB. The calculated monthly theoretical power capacity from all 154 sites of 33 sub-basins in the MRB was 15,266.22 MW, which is almost equivalent to the available power capacity of 15,393 MW in 2017 for the Philippines. Furthermore, the calculated average monthly theoretical power capacity in the MRB of 5,551.35 MW can supply the peak electricity demand in Mindanao of 1696 MW (Department of Energy 2017a).

The identified sites and calculated theoretical potential power capacities in the MRB were assessed only based on the theoretical technical side of hydropower development with the available weather and river discharge datasets via SWAT watershed modelling. Nevertheless, the findings of this study contribute



to the identification of potential sites for planning hydropower development in the region.

Finally, the implementation of hydropower development is a desirable alternative to reduce the dependency of the Philippines on fossil fuels, particularly coal, oil, and natural gas (Hoq et al., 2011). Consequently, this study might be helpful to the authorities to develop potential water resources in Mindanao for hydropower generation in support of the implementation of Republic Act No. 9513, otherwise known as the “Renewable Energy Act of 2008”, to improve the electricity generation rate in Mindanao.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### CRedit authorship contribution statement

**Ismail Adal Guiamel:** Investigation, Visualization, Data curation, Software, Methodology, Conceptualization, Writing - original draft. **Han Soo Lee:** Writing - original draft, Writing - review & editing, Supervision, Methodology, Software, Data curation, Conceptualization.

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### Appendix

See Tables A1–A5 and Fig. A.1.

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