Chapter 43

Quantifying future water environment using numerical simulations: a scenario-based approach for sustainable groundwater management plan in Medan, Indonesia

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43.1 Introduction

Water is a basic necessity for sustainable and inclusive development of human society. Yet, access to clean and safe drinking water is a major challenge (Heinemann et al., 2002; FAO, 2016), which is well recognized under the global sustainable development goals (SDGs). To put things in perspective, more than 1.1 billion people do not have adequate access to clean drinking water and it is feared that nearly two-thirds of the nations will be under water stress by 2025 (Pink, 2016; Kumar, 2019). Researchers argue that water insecurity as a major hindrance for socioeconomic growth in the developing world. This is especially the case in Asia and Africa, where increasing demand for water and contamination of key water sources complicate the scenario further (Huizinga et al., 2017; Mukate et al., 2017). While it is estimated that about 3 billion people will reside in Asian cities by year 2050 (United Nations, Department of Economic and Social Affairs, Population Division (UN DESA), 2015), countries such as India, Pakistan, and Afghanistan have already reached the water stress level in 2015, and several other countries such as Nepal and Bangladesh are underway (Gareth et al., 2014). Thus ensuring sustainable water supply and meeting the SDGs in growing Asian cities remains a critical challenge. Although the concepts of water security vary within the academia (Hoekstra et al., 2018), most researchers now agree that the water crisis in the 21st century is much more a management issue rather than the actual scarcity of water (Tundisi, 2008).

Of the various issues that impound water scarcity, frequent extreme weather conditions, deteriorating water quality, and lack of water governance are main factors in most of the developing countries, which broadened the debates on water security over the last two decades (Mukherjee et al., 2020). Key functions such as water availability and runoff alter the flood regimes of rivers due to changes in climatic patterns. According to the Intergovernmental Panel on Climate Change (IPCC) (2014) report, a greater number of regions are likely to experience extreme weather events, including heavy precipitation and floods in the future. Consequently, the SDGs have put focus simultaneously on water quantity and quality, an approach that was largely missing in the Millennium Development Goals, which only provided quantity related targets (Angelo et al., 2018). Nonetheless, a multitude of other factors, including population growth, rapid urbanization, and climate change, are also expected to pose significant challenges in achieving water security in the future (Huizinga et al., 2017; Mukate et al., 2017).

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Together with wastewater infrastructure improvement, sewerage network improvement, and building dams, nature-based solution, along with adaptive governance of water resources, has been identified as an important tool for achieving water security (UN, 2018; Kalantari et al., 2018; Wild et al., 2017). However, managing urban water environment still remains a significant challenge (UN Water, 2017; Ferguson et al., 2018); and the concept of urban water security is fundamentally different from the concept of water security (Hoekstra et al., 2018). A number of allied factors, such as high population density, concentrated demand of fresh water, distribution system, and wastewater recycling and taxing are particularly important for an urban context. To meet the challenges posed by such complexity, tapping reliable, all-weather sources remain an important first step for urban water planners.

Unfortunately, water resource planning in cities has been done largely in a piecemeal manner, without taking into account of larger socioeconomic factors, and this is the case especially in the developing countries (Downing, 2012). While planners in developing countries are often obsessed with meeting the basic water demands through adequate supply, a critical step to achieve future urban water security is to integrate both hydrological as well as socioeconomic factors. It is highly imperative to understand urban water security through a system perspective, including natural (i.e., source), social, economic, and infrastructural components.

Several holistic approaches have been conceptualized in the field of water resource management since the 1980s, of which the integrated water resource management (IWRM) model has received the highest attention (Hoekstra et al., 2018). Different components of water resource governance are targeted by the IWRM model (e.g., socioeconomic status, hydrometeorological factors, agriculture, industries, and wastewater), to aid science-led decision-making (Frija et al., 2015; Blanco-Gutiérrez et al., 2013). Several numerical IWRM models such as RIBASIM (River Basin Simulation Model), HEC-HMS, Flo-2D, MIKE, WEAP (Water Evaluation and Planning), and WBalMo (Water Balance Model) have been developed and widely used to address water security issues (Ingol-Blanco and McKinney, 2013; Slaughter et al., 2014; Kumar et al., 2018). Some of these models such as WEAP and HEC-HMS are widely used in water resource modeling for water resource planners in developing countries, because they are not data intensive and the software package comes free of cost.

Unplanned rapid urban expansion, in combination with high economic growth, results in unhealthy water environment around water bodies in most of the developing countries. Despite its importance, their current status and their management strategies for the near future is poorly documented. This study strives to apply integrated analysis to assess the current situation and the simulated future status of water quality and quantity (flooding) in the Deli River watershed crossing Medan city, Indonesia, with the ultimate goal to help to formulate plans for sustainable water resource management in the area. The research procedure applies systems analysis and includes studies of technical models and future scenarios that are affecting water infrastructure in a city. The study highlights practical recommendations that are based on the results and are important for successful implementation of sustainable water management strategies and improving decision-making process in water-related sector in Indonesia.

43.2 Study area

Medan is the capital city of North Sumatra province. It is located between3°35′N latitude and 98°40′E longitude (Fig. 43.1). Medan city is divided into 21 districts. The total population of Medan is 2,191,140 (Statistics Indonesia, 2014), and its total area is 265 km^2. The climate is classified as equatorial, characterized by heavy and frequent rainfall. The annual rainfall is about 2263 mm and the temperature ranges from 24°C to 32°C. Medan city is characterized by three watersheds: Belawan watershed, Deli watershed, and Percut watershed.

43.3 Methodology

Systems approach can be a meaningful solution to solve issues in urban water management that requires understanding complexity associated with water resource management. Integrated systems approaches capture interdisciplinarity, associated with diverse natural, technical, and institutional dimensions that are associated with complex city infrastructure (Urban, 2015). Properly understanding and solution of these issues requires researchers and professionals from different professional disciplines, including academia, to exchange ideas, and learn from each other to explore new, robust solutions. In this work an integrated approach is used to assess the current situation as well as predict future situation of water environment and likely adaptation measures for urban water management as shown in Fig. 43.2.

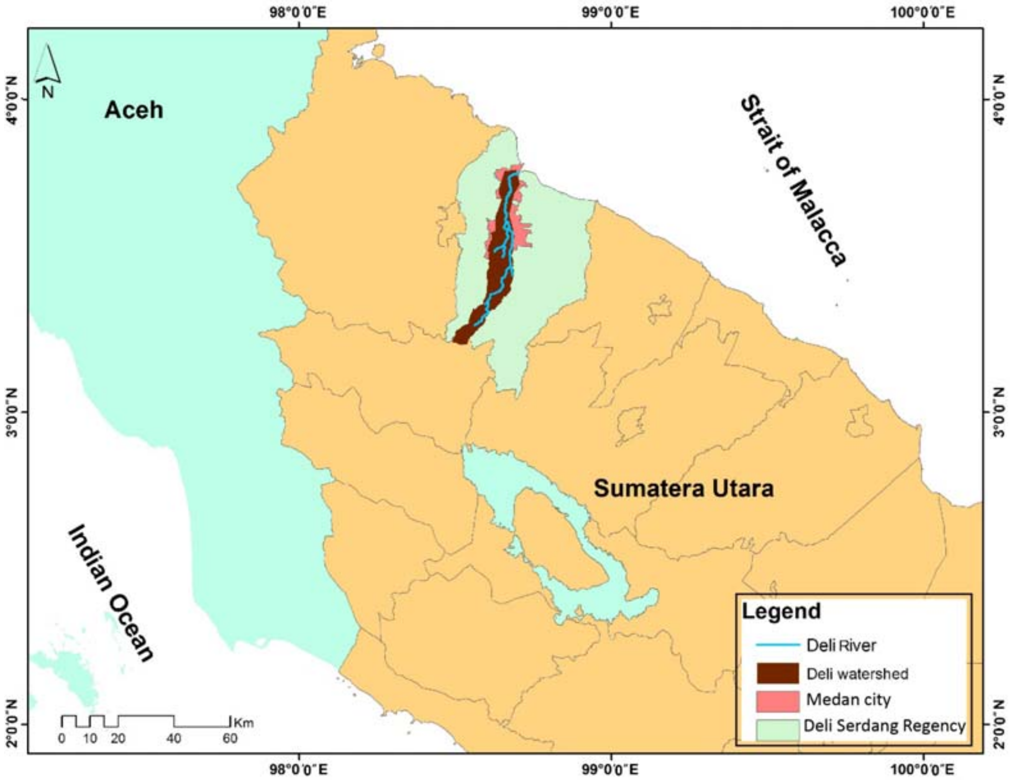

FIGURE 43.1 Deli watershed location.

43.3.1 Different drivers

43.3.1.1 Precipitation change

In this study, precipitation is a relevant indicator to determine the effect of climate change on flood and water quality. For analysis of food systems, study of precipitation change was carried out with emphasis on daily maximum rainfall and mean monthly rainfall. There are three rain-gauge stations: Tutungan in the upstream, Sampali in the center, and Belawan in the downstream of the watershed. Precipitation change assessment was started with screening of daily rainfall data of Sampali station. Selection of Sampali station was made considering its location and availability of long record (1980−2015) of rainfall data. Rainfall data of 1980−2004 were considered for the precipitation change assessment. Changes in daily maximum rainfall for different return periods and mean monthly rainfall were used for comparing flood inundation and river pollution conditions. Daily rainfall outputs of three GCMs: MRI-CGCM3, MIROC5, and HadGEM2-ES were extracted for assessing future climate conditions. Out of these three GCMs, MRI-CGCM3 precipitation outputs were found to be suitable considering rainfall characteristics of observation data. Future climate was characterized by MRI-CGCM3 rainfall data of 2020−44 period. Quantile mapping technique was applied for correcting biases in the GCM output. Finally, empirical frequency analysis was applied for estimating daily maximum rainfall (Figs. 43.3−43.5).

In order to evaluate the effects of climate change on water quality, the change in monthly average precipitation was evaluated. The GCM output is downscaled at the local level to aid reliable impact assessment (Sunyer et al., 2015). Statistical downscaling was followed by trend analysis to get climate variables at monthly scale. Trend analysis is a less computation demanding technique, which enables reduction of biases in the precipitation frequency and intensity (Elshamy et al., 2009). Regarding future simulation to assess the climate change impact, MRI-CGCM3 and MIROC5 precipitation output was used because of its wide use and high temporal resolution compared to other climate models. Our study is based on the RCP4.5 and RCP8.5 emission scenario, which assumes that global annual GHG emissions (measured in CO_2 equivalents) will peak around 2040 and then will decline (Intergovernmental Panel on Climate Change (IPCC), 2014). In this study the GCM data are from the 1985 to 2004 and 2020 to 2039 periods (each with a 20-year length) and represent the current and future (2030) climates, respectively. The result is shown in

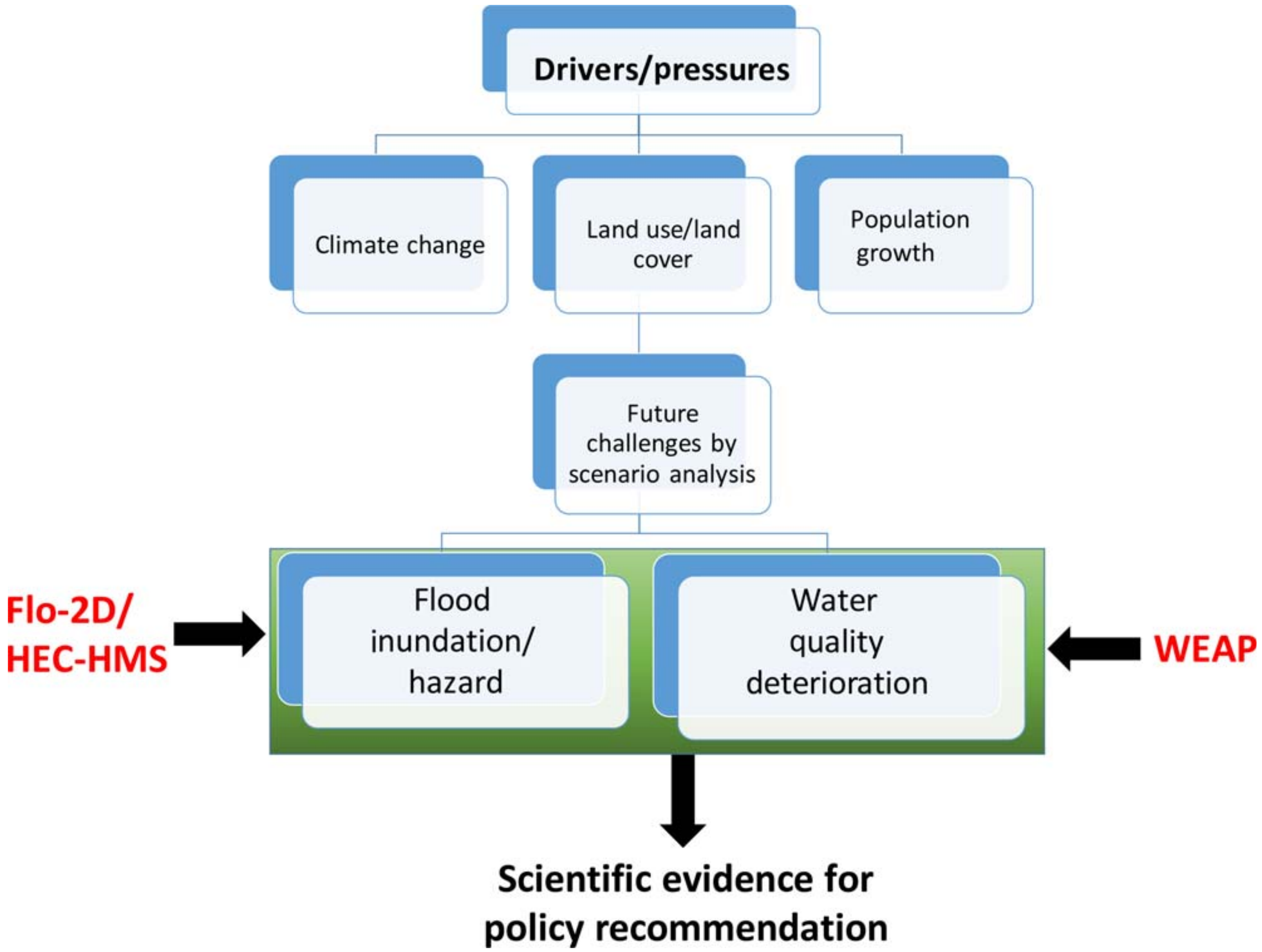

FIGURE 43.2 Research framework under this work.

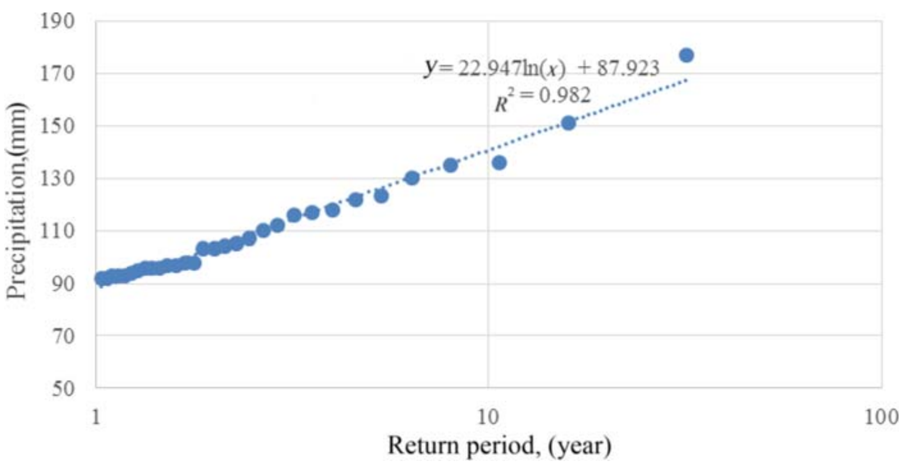

FIGURE 43.3 Empirical rainfall frequency analysis for current climate.

Fig. 43.6, which indicates that annual precipitation in the simulated GCM output is not much different than that of current observed one. The values for total annual precipitation in the case of observed_2015, Sim_2030_MRICGCM3_45, Sim_2030_MIROC5_45, Sim_2030_MRICGCM3_85, and Sim_2030_MIROC5_85 are 2061.6, 2139.1, 2187.1, 2114.7, and 2156.9 mm, respectively. We have fixed other parameters as constant like population growth for estimating the

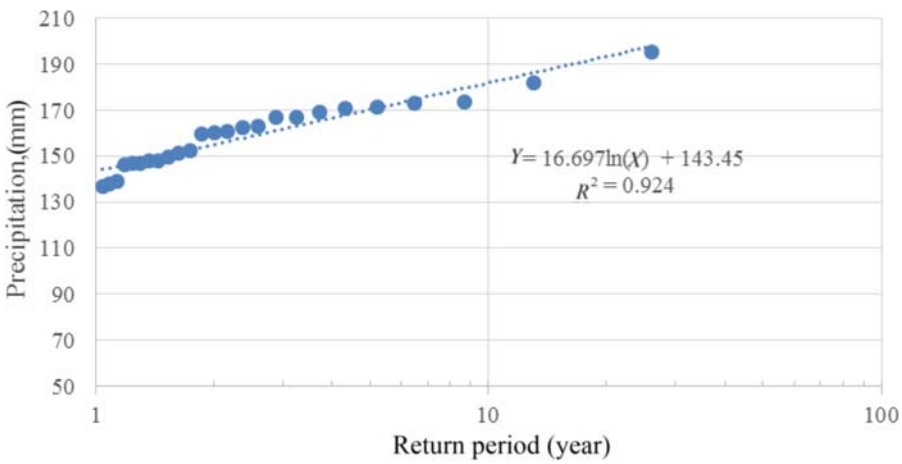

FIGURE 43.4 Empirical rainfall frequency analysis for future climate (MRI-CGCM3 RCP4.5).

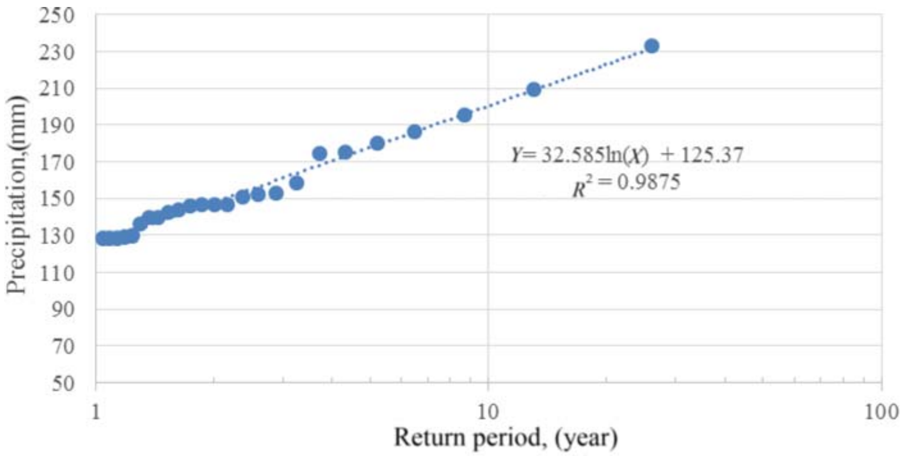

FIGURE 43.5 Empirical rainfall frequency analysis for future climate (MRI-CGCM3 RCP8.5).

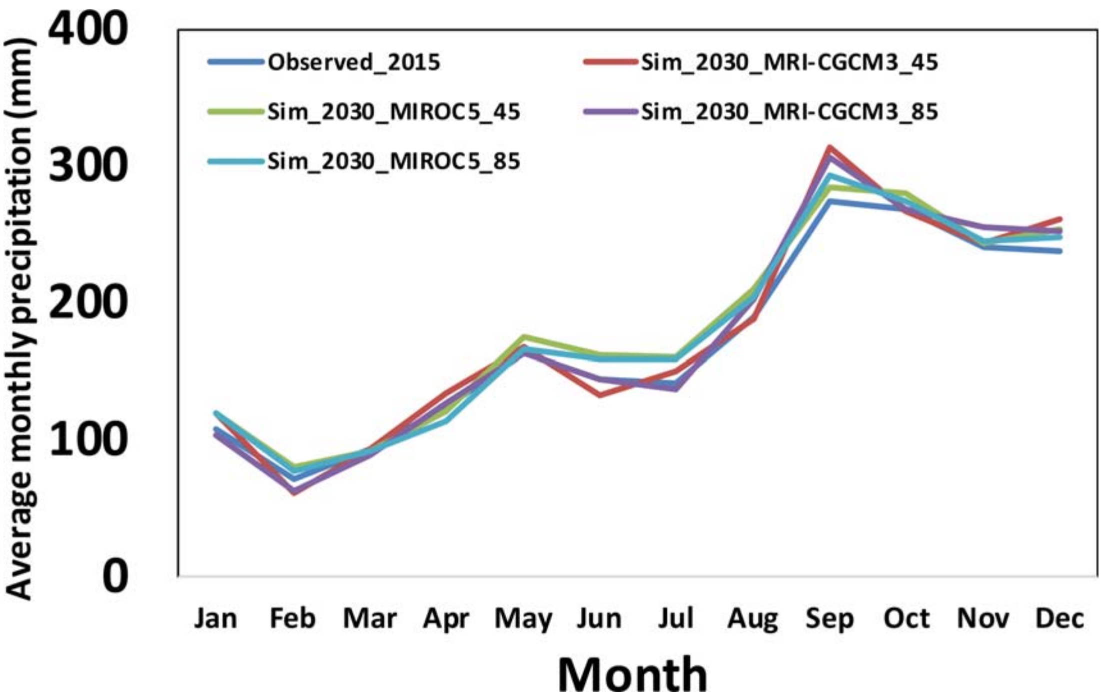

FIGURE 43.6 Graph showing a comparative study for current and future monthly rainfall.

effect of precipitation only on water quality. Once all other factors are kept constant, we have given simulated value of precipitation as an input on the water quality simulation for future, starting from year 2016, that is, right after year 2015. Finally, for water quality simulation, we have used MRI-CGCM3 with RCP_8.5.

43.3.1.2 Land use change

Two past land use maps are established and used for the analysis regarding prediction of future land use/land cover map of 2030. In order to prepare the land use maps for Deli watershed, four satellite images Landsat are applied (Table 43.1). It was observed that the watershed covers two different scenes located in various paths/rows. For this reason, appropriate processing is required before image analysis and classification. First two Landsat images were merged in a single raster image using Mosaic Dataset of ArcGIS. Then, band composites, clipping, and supervised classification were done to get the land use map of the watershed. Land Change Modeler for ArcGIS was used to predict the land use pattern based on the previous change trend. Through image classification, only four classes are identified.

43.3.1.3 Population growth

The whole study area has been divided into different demand sites for estimating the effect of population growth (one of our two major key drivers), on water quality status. These demand sites mainly represent the population of different cities on both sides of Deli River within the study area, and who have direct impact on river environment through discharging domestic sewerages into the river. Future population is estimated from ratio method using data for United Nations, Department of Economic and Social Affairs, Population Division (UN DESA) (2015) projection rate. The total population of 2,200,001 was considered at base year, that is, 2010 in our study area. For the future population projection, the annual growth rate was considered 0.96, 1.58, 2.25, and 2.04 during the period of 2011−15, 2016−20, 2021−25, and 2025−30, respectively. Henceforth, population considered for current year (2015) and target year (2030) was 2,307,648 and 3,085,883, respectively.

43.3.2 Urban flood

Of the three watersheds of Medan city, the Deli River has a big potential for causing flood inundation. Due to the small river flow capacity for the Deli, flood had occurred frequently in Deli River watershed, which flows through the central part of the city. The flood events were reported increasing due to urbanization of the city and its surrounding areas, enhanced by changing climate. This study aims to contribute to the reduction of flood damage, stabilization and enhancement of people's livelihoods, and promotion of local economy with improved city flood risk management plan. Medan floodway was constructed at Titi Kuning at Deli River to Percut River with current of design discharge 70 m^3/s, planned to be increased to 120 m^3/s and further.

Flood modeling consists of two parts: the hydrologic modeling estimates the peak discharge while hydraulic modeling flood inundation simulation. Total catchment area of Deli River basin is about 400 km^2. Out of this, upper catchment area (u/s of floodway) is about 160 km^2. HEC-HMS was run for peak discharge simulation in upper region with outlet at floodway diversion point. Flo-2D model was run in the lower watershed boundary. Topography data were extracted from SRTM with 30 m resolution (Fig. 43.7).

TABLE 43.1 Satellite images applied.

No.	Path/row	Data set	Acquisition data	Land cloud cover (%)
1	129/057	Landsat 7 ETM C1 Level 1	May 19, 2003	1
2	129/058	Landsat 7 ETM C1 Level 1	May 19, 2003	0
3	129/057	Landsat 8 OLI/TIRS C1 Level 1	February 21, 2015	12.87
4	129/058	Landsat 8 OLI/TIRS C1 Level 1	February 21, 2015	2.54

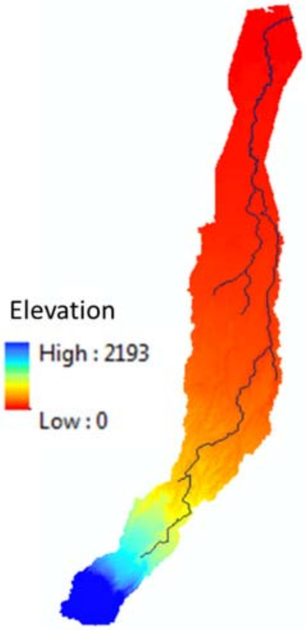

FIGURE 43.7 Deli River basin, Medan.

43.3.3 Water quality

43.3.3.1 Basic information regarding the model and data requirement

WEAP model was used to simulate future water quality variables in the year 2030 to assess alternative management policies in the Deli River basin. A wide range of input data such as point and nonpoint pollution sources, their locations and concentrations, past spatiotemporal water quality, wastewater treatment plant (WWTP) population, historical rainfall, evaporation, temperatures, drainage networks, river flow−stage−width relationships, river length, groundwater, surface water inflows, and land use/land cover is used for water quality modeling.

WEAP model was developed for the Deli River basin for four command areas with interbasin transfers. Hydrologic modeling requires the entire study area to be split into smaller catchments with consideration of the confluence points and physiographic and climatic characteristics (Fig. 43.8). The hydrology module within the WEAP tool enables modeling of the catchment runoff and pollutant transport processes into the river. Pollutant transport from a catchment accompanied by rainfall−runoff is enabled by ticking the water quality modeling option. Pollutants that accumulate on catchment surfaces during nonrainy days reach water bodies through surface runoff. The WEAP hydrology module computes catchment surface pollutants generated over time by multiplying the runoff volume and concentration or intensity for different types of land use. During simulation the land use information was broadly categorized into three categories: agricultural, forest, and built-up areas. The soil data parameters were identified using previous secondary data and the literature. Daily rainfall has been collected at Sampali meteorological station, for the period from 1990 to 2010. Daily average stream flow data from 2005 to 2014 were measured at five stations, Mangonsidi, Raden Saleh, Unibis, Simpang Kantor, and Medan Labuhan of the Deli River, and were utilized to calibrate and validate the WEAP hydrology module simulation. Data for the water quality indicators (biochemical oxygen demand (BOD) and *Escherichia coli*) were also collected at four of the abovementioned five stations and used for water quality modeling.

43.3.3.2 Model setup

The entire problem domain and its different components are divided into four catchments considering influent locations of major tributaries (Fig. 43.8). Other major considerations are the five demand sites and one WWTP to represent the problem domain. Here, demand sites are meant to identify domestic (population) defined with their attributes explaining water consumption and wastewater pollution loads per capita, water supply source, and wastewater return flow. Dynamic attributes are described as functions of time and include population and industries. WWTPs are pollution handling facilities with design specifications that include total capacity and removal rates of pollutants. The flow of wastewater into the Deli River and its tributaries mainly feeds through domestic, industrial, and stormwater runoff routes. In the absence of any precise information about the type of WWTP operational at current stage, UASB-SBR type of

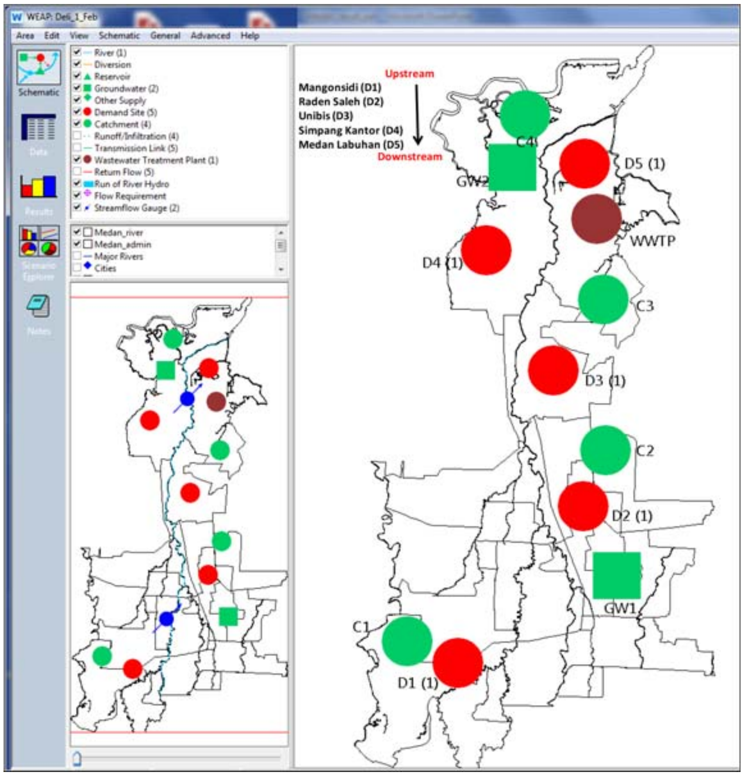

FIGURE 43.8 Schematic diagram showing the problem domain for water quality modeling in Medan using WEAP interface. *WEAP*, Water Evaluation and Planning.

TABLE 43.2 Comparison of daily maximum rainfall for 50- and 100-year return period.

Return period (year)	Current climate	MRI-CGCM3	
		RCP4.5	RCP8.5
50	177.7	208.8	252.9
100	193.6	220.4	275.4

WWTP is considered in the modeling and its treatment efficiency is assumed as 97% for BOD, 77% for total nitrogen, and 99.69% for fecal coliform (Khan et al., 2013). No precise data are available regarding the total volume of wastewater production from domestic sources. In the absence of detailed information, the daily volume of domestic wastewater generation is estimated 130 L of average daily consumption per capita based on literature review (WWAP, 2017). Future projection was made to observe the water quality of Deli River in 2030 considering the effect of climate change and population growth and current existing WWTPs of capacity of 18 MLD.

43.4 Results and discussion

43.4.1 Precipitation change

Using bias-corrected rainfall, daily maximum rainfall for different return periods was estimated. Table 43.2 provides comparison of daily rainfall for 50- and 100-year return period. However, in this study, 50-year daily maximum rainfall was employed for assessing flood inundation simulation. An increase of 17.5% and 43% was found for RCP4.5 and RCP8.5 emission scenarios, respectively, with respect to baseline period. This significant increase in daily maximum points out that climate change consideration should be incorporated into Medan future flood risk management plan for its sustainable urban water environment.

An assessment of the climate change impacts on precipitation over the Deli River Basin was conducted by using bias-corrected GCM data for the 1985−2004 and 2020−39 periods. The quantile-based bias corrections were used to identify the bias pattern in the GCM precipitation data. This bias pattern was identified by comparing the observations with the corresponding GCM data. A comparison of the daily precipitation values indicated that peaks in the GCM values were significantly smaller than the peaks in the observation values. The GCM precipitation data showed significantly larger wet days than those of the observed precipitation data. The performance of the quantile-based correction technique was evaluated by comparing the monthly average rainy days and daily precipitation amounts. Plots of the monthly average rainy days and daily rainfall magnitudes indicated a similar number of rainy days and extreme rainfall magnitudes, thereby demonstrating the effectiveness of the quantile-based bias correction technique.

Rainfall intensity duration frequency (IDF) curves can be used to estimate rainfall intensities for different durations and return periods. Frequency analysis using Gumbel extreme value method enabled the generation of rainfall IDF curves and extreme precipitation change assessment for the present and future climate scenarios over the Deli River watershed. In this study the 1-day maximum precipitation for the 50- and 100-year return period was determined for the current and future precipitation data sets. These values clearly indicate that extreme precipitation events for all return periods and all durations will be more frequent and intense in the future Table 43.3.

43.4.2 Land use change

The comparison between current and predicted land use maps show an increase of urban growth (Fig. 43.9). Our results indicate an expansion of built-up areas to about 20%, which may lead to a rise in runoff while reducing infiltration. Consequently, flood risk can be more significant in the future. The results indicate that a suitable land use plan is required to avoid increasing the vulnerability of people and buildings.

TABLE 43.3 Comparison of 1-day maximum rainfall for current and future climate conditions.

Return period (year)	One-day maximum rainfall (mm)		
	Current	Future average of three GCMs	Future extreme among three GCMs
50	207	227	330
100	228	249	365

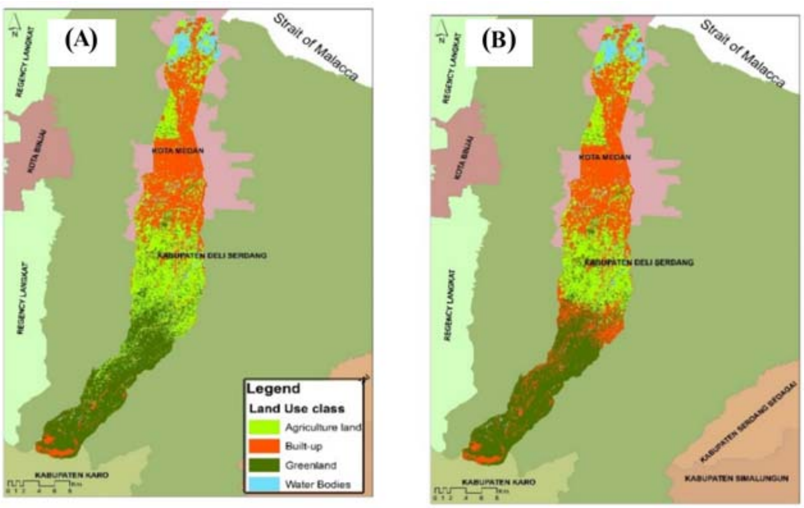

FIGURE 43.9 Land use change map: (A) land use 2015 and (B) land use 2030.

43.4.3 Urban flood

Although river improvement and drainage projects, including floodway connecting Deli River to Percut River, had been undertaken with utilization, flooding is still remain a considerable hazard in the Medan city. The HEC-HMS was calibrated for the flood event of November 2001 flood event. During this flood event a peak discharge of 290 m^3/s was reported (source: Mitsubishi UFJ Research and Consulting Co., Ltd. Report). On the other hand, simulated flood discharge was 314 m^3/s, which can be considered acceptably well. After diverting flood discharge of 70 m^3/s via floodway, inundation simulation task was proceeded for the current climate condition. Fig. 43.10 provides a spatial comparison of flood inundation simulation in lower region for current and future conditions. Table 43.4 indicates there will significant increase of flood inundation despite increased flood diversion. It is expected that the flood inundation will increase in 2030, especially marked by an estimated inundation of 3−4.5 m depth in the central and northern part of Medan, and in the south along the Deli River. Therefore flood risk master plan of Medan requires more attention to address the problem increased flooding.

43.4.4 Water quality

Future simulation of water quality was conducted using selected parameters (BOD and *E. coli*) under business as usual (BAU) scenario while including effect of population growth and climate change. The simulation considered the capacity of currently existing WWTP (capacity of 18 MLD and mere coverage of 16% of total population in the study area) and

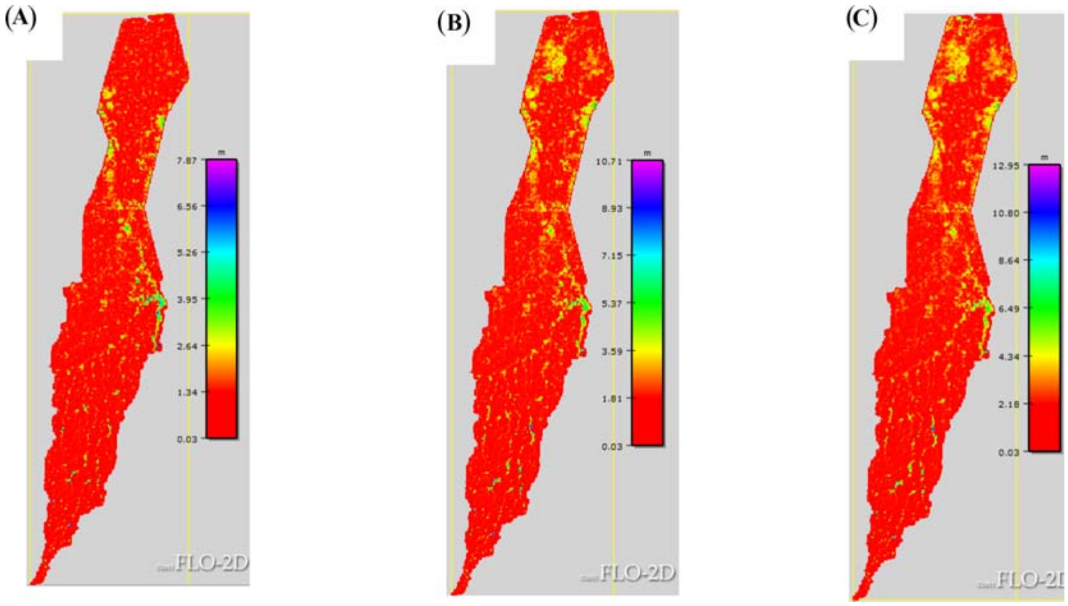

FIGURE 43.10 (A) Maximum flow depth for current climate (2015) for 50-year return period; (B) maximum flow depth (m) for 2030 for MRI RCP45 for 50-year return period; and (C) maximum flow depth (m) for 2030 for MRI RCP85 for 50-year return period.

TABLE 43.4 Comparison of flood inundation under current and future climate conditions.

Inundation depth (m)	Inundation area (km^2)	
	Current	Future
0.2−0.5	17.4	23.8
0.5−1.5	21.3	32.6
>1.5	8.2	16.6

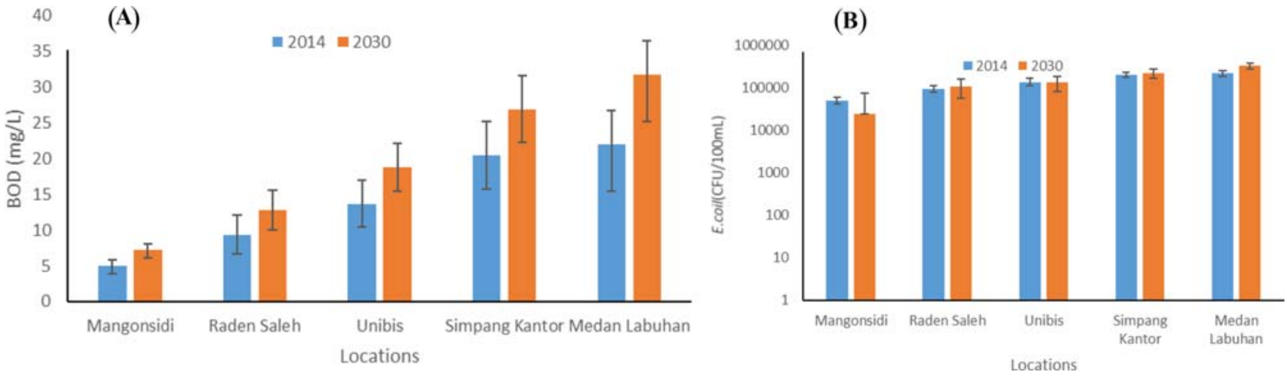

FIGURE 43.11 The simulation result of the annual average values of (A) BOD and (B) *Escherichia coli* for five different locations in 2014 and 2030 under different scenarios (current situation and business as usual).

that this capacity will continue by year 2030. The result for water quality is shown in Fig. 43.11. It can be observed that current status of water quality throughout the river is very poor as compared with local guideline for class 2 (BOD < 5 mg/L; *E. coli* < 1000 CFU/100 mL). And it is even worse in the case of downstream locations of the river because of the cumulative effect of waste disposal and injection of untreated wastewater coming from the upstream areas. Our results show that in the case of BAU scenario, effect of both climate change and population changes are prominent in water quality status. It is expected to deteriorate further in 2030 when compared to current situation. Due to climate change and population changes, the water quality parameters BOD and *E. coli* will be further deteriorating by 54.2% and 12.4%, respectively, on average in 2030 compared to the current situation. Furthermore, the individual contribution from population and climate change on BOD and *E. coli* was 86% and 14% and 92% and 8%, respectively. A high concentration of nitrate in water indicates the influence of untreated sewerage input. The value for BOD varies from 5.2 to 22.6 mg/L, which indicates that most of the water samples are moderately to extremely polluted, and not safe for a healthy aquatic system. The *E. coli* value, a commonly used biological indicator of water quality status, also shows that no significant improvement in future course of time, although this might be because of unavailability of data like rate of chlorination.

43.5 Conclusion and recommendation

Although river improvement and drainage projects, including floodway connecting Deli River to Percut River, had been undertaken, these projects have not been able to reduce flooding in the Medan city. In the present study the HEC-HMS model was used to provide spatial comparison of flood inundation simulation in lower reaches of the Medan river basin for current and future scenarios. Result shows that there will be significant increase of flood inundation despite increased flood diversion projects. Furthermore, the flood inundation is expected to increase in 2030. The extent of inundation can be 3−4.5 m in depth in the central and northern part of Medan, and in the south along the Deli River. Regarding the water quality component, it was observed that current status of water quality throughout the river is very poor as compared to local guideline for class 2 (BOD < 5 mg/L; *E. coli* < 1000 CFU/100 mL). In addition, the water quality status is even worse in the case of downstream locations of the river. From the result of BAU scenario, effects of both climate change and population change are prominent in water quality status. Water quality is expected to deteriorate further in 2030 when compared to current situation. Due to climate change and population changes, the two water quality parameters BOD and *E. coli* will be further deteriorating to 54.2% and 12.4%, respectively, on average by 2030 when compared to the current situation. The previous results suggest that current management policies and water resource management plans in near future are not enough to check the pollution level within the desirable limit and reduce the frequency of flooding in the study area and hence calls for transdisciplinary research in more holistic way for doing it sustainably.

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