Spatial Data and Catchment Discretization for Assessment Coastal Urban Drainage Performance Using GIS and MIKE URBAN-SWMM

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Abstract. The urban drainage model requires spatial data and catchment discretization because of the complexity of system. Using integration of Geometric Information System (GIS) technology and urban storm water models, the performance of urban drainage system can be analysed.[1] Especially in coastal area, the main problem of urban drainage is overloaded capacity because of rapid urbanization and coastal floods caused by storm surges and wave action superimposed on high water levels generated during the cycle of tides. Land use change, watershed area as settlements area, clogged drainage pipe/channel, the changing of imperviousness of land cover also contributes to large volume of surface runoff. Moreover, the developments can change land cover in urban area and increasing rainfall runoff. One of the solutions for coastal urban drainage is by using polder system for flood control. The purpose of this paper is to illustrated how GIS can model the catchment discretization and MIKE URBAN-SWMM (Storm Water Management Model) can analyse water balance based on the rainfall return period of 25, 50 and 100 years. The research shows evaluation result of the polder performance including inundation depth and pump performance by linking GIS between storm water models. The case study is analysing the Pluit polder in Jakarta-Indonesia, which is connected to the Indonesia Central Bank compartment. Based on the model, this polder system can reduce flooding in Indonesia Central Bank Compartment up to 50%, however the inundation is still occurred.

Keywords: polder, pumps, GIS, MIKE URBAN-SWMM, coastal urban drainage

1. Introduction

The rapid growth of population and urbanization increased the pressure urban drainage system [1]. The main problems in Indonesia are caused by land use changing, watershed area as settlements area, clogged drainage pipe/channel, the changing of imperviousness of land cover also contributes to surface runoff occurrence. The developments that change land cover in urban area can cause increasing of rainfall runoff. The capacity of drainage pipes/channels is overloaded.
If inundation occurred, it can be concluded that there is drainage system problem. Inundation data is also important for drainage system design process in the future. Some study result estimation of urban storm inundation area based on calculation of Statistics Indonesia data [2].

One of the solving problem for coastal urban drainage is using polder system for flood control. A polder is a tract of lowland reclaimed from the sea, or other body of water, by dikes, etc. In the polder the runoff is controlled by pumping and the water table is independent of the water table in the adjacent.

In Jakarta, polder development is done for the development of new areas with the up-to-date technology and it is managed by appointed project developers. On the other hand, in the existing urbanized areas, the polder management is organized by the co-operation of Indonesia government and the local people of Jakarta. Nevertheless, the polder development in Jakarta area is often not carried out based on a well-balanced approach (principle of conversation) between utilization of natural resources and evaluation of ecological functions. As a consequence, urban drainage and flooding problems, salinity intrusion in the groundwater, and land subsidence's rates increase significantly. Based on available data in Jakarta area, a correlation between the pumping capacity and open storage area is designed. This correlation later can be used as guidance to evaluate the performance of such polders in Jakarta area for countering flood problems [3].

MIKE SWMM package as well-known SWMM (Storm Water Management Model) is one of the comprehensive model to perform hydrologic, hydraulic and water quality and quantity analysis of storm water and urban drainage system [5][6]. MIKE SWMM accounts for special variations by subdividing to overall catchment into sub-catchments, predicting runoff from the sub-catchments on the basis of their individual properties and combining their outflows using a flow routing scheme. SWMM can simulate individual rainfall event and continuous rainfall event. SWMM is one of the most important methods in urban storm disaster prevention researches, which can describe the rainfall-runoff processes of the rainstorm and provide a strong data support to the flood risk evaluation, loss assessment and disaster forecast research. In SWMM, the urban region is divided into smaller computational units which have own hydrological characteristics and independent rainfall-runoff processes, called sub-catchments [1].

The significant amount of spatially detailed information derived from remote sensing (e.g. digital maps, digital terrain model) or interpolation of point measure and handle within a geographic information system (GIS), offers new opportunity for hydrology modeling [6]. This technology is innovative tool in urban drainage system. GIS combines special data (maps, photographs, satellite images) with the other quantitative, qualitative and description information databases [7][10]. This technology offers an analytical framework for data synthesis that combine a system capable of data capture, storage, management, analysis and display.

2. Research Methodology

2.1. Study Area

The Bank Indonesia Museum compartment is in the territory of the Pluit’s polder system which was flooded in 2002. Based on the data from the Research Center for Water Resources, the height of the inundation was approximately 30 – 100 cm above the ground. The flood was cause by the runoff from the upstream, high rainfall, uncontrolled land use and the low topographic condition of North Jakarta (-0.5m - +1.2 m) due to the land subsidence, especially the beach area where the ground level is below sea level. Therefore a polder system is placed in North Jakarta that is suitable for low topographic condition which is prone to flooding. The polder system placed in North Jakarta can be seen in the Master plan of DKI Jakarta in Figure 1.
The polder system in Pluit, North Jakarta was built during the Dutch’s era in DKI Jakarta. However the performance of the polder system in Pluit have continuously decline. This is due to the lack of maintenance and management from the stakeholder to the flooding control and counter measure system in DKI Jakarta. Therefore, flood always happens during the rainy season with the increase amount of runoff. An evaluation or performance analysis of the Pluit polder system needed to be taken in order to repair the polder system and to make use of the system in the future hence minimizing the inundation due to flooding.

2.2. Catchment Modelling in GIS

To model the drainage system will use a high solution Digital Elevation Model (DEM) for the objective proposed. For this research, the solution of DEM is 1: 1000. The DEM choice and resolution was found to be critical for a realistic definition of watershed and sub watershed boundaries (Figure 2a) and topography map (Figure 2b), and consequently for simulated output is catchment discretization to model the drainage system. The DEM is very helpful in applying routing models including the physical velocities derived from geomorphological characteristic of catchment, such as ground slope, upstream areas and flow direction to determine the direction of flow. Some required characteristics data of the drainage system and sub-catchment, such as surface, average slope, length, width achieved by applying GIS.
2.3. Coastal Urban Drainage Model in MIKE URBAN – SWMM

The performance analysis of the polder system related with coastal urban drainage will use the MIKE URBAN and SWMM (Storm Water Management Model) to analyze the magnitude of the polder system effect to the Bank Indonesia Museum compartment. The SWMM (Storm Water Management Model) came up by U.S. Environmental Protection Agency is one of the comprehensive model which is the earliest proposed, it has a great influence and is widely used in water amount and quality simulation of urban drainage system. It can simulate individual rainfall event and continuous rainfall event. SWMM is one of the most important methods in urban storm disaster prevention researches, which can describe the rainfall-runoff processes of the rainstorm and provide a strong data support to the flood risk evaluation, lose assessment and disaster forecast research [1][8]. In SWMM, the urban region is divided into smaller computational units which have own hydrological characteristics and independent rainfall-runoff processes, called sub-catchments. The results receive are used to give suggestions on how to overcome the inundation in that area.

2.4. Data Collection Techniques

Data needed are obtained from Research Center for Water Resources which is categorized as two types of data, primary data and secondary data. The primary data is the elevation of the nearest benchmark point, which is Benchmark 5 (BM 5) in DKI Jakarta was done using leveling method as the reference point from the ground level and the water level of the Besar River located behind the Bank Indonesia Museum compartment. The coordinate of BM 5 can be seen in Table 1. The leveling was done to validate the data and the binding elevation of the ground level from the river’s cross section data available. Secondary data collection is needed to prepare data needed for modelling, and to identify and get detailed description of the area studied. The data needed in this research are as followed:

a. Rainfall station
   The nearest rainfall station to the studied area is located in Pantai Indah Kapuk, which the rainfall station 02026A (Kapuk).

b. Statistical analysis to calculate the design rainfall.
   The data needed are as followed:
   - Daily maximum rainfall data
   - Data distribution. Normal, Log-Normal, Log-Pearson Type III and Gumbel distribution are used to obtain the rain plan. While to analyse the compatibility of the data to the distribution, Chi-Square and Kolmogorov-Smirnov criteria is tested.
   - Rain distribution. The determination of rain distribution according to time is done based on the Guidelines for Flood Protection Dam.
c. Design rainfall distribution

d. Evapotranspiration data

e. Pump capacity data

The existing pump station is located in Pluit Dam with the total of 11 pumps.

f. Data of tides

The tides data is needed to find out the effect of the tides to the water elevation of the channel, and to show how the impact of the sea level to inundate the city of Jakarta. The data on sea level shows that the height of the maximum tides is +1.95 MPP and the normal sea level is +1.4 MPP. While the ground in North Jakarta is around -0.5 to +1.2 m.

g. Topography map

Topography map with the scale of 1:1000 from the Bakosurtanal is needed to obtain information of the elevation of the studied area which is part of the drainage system planning both macro and micro.

h. Benchmark (BM) data

The location of the benchmark (BM) point used for the Bank Indonesia Museum compartment can be seen in Table 1.

Table 1. Benchmark (BM) location

| Points Location                        | Coordinate x | Coordinate y | T. BM (m PP) | Field Measurement Result (m.dpl) |
|----------------------------------------|--------------|--------------|--------------|-------------------------------|
| Jln. Bank T-Junction (near the bridge) | 700533       | 9321339      | BM 5 DKI     | 2.096779                      |

i. Watershed modelling.

The watershed model for study area is depend of the river to figure out how much of the river parts around the studied area is affecting the drainage system and how big the watershed which is affecting the area studied.

2.5. Hydrology Modelling

For the hydrology modeling, input data is based on element from coastal urban drainage model using GIS. The parameter for hydrology modeling are infiltration, routing catchment, climatology, time series, rain gauges, inflow hydrograph.[9]

a. Infiltration

The equation used in the infiltration element is Green-Ampt equation with the following parameters:

- Soil capillary suction. The average absorption height of the capillary with the assumption around 10.16 – 30.48 mm, the value used was 20.32 mm.
- Hydcon. The hydraulic conductivity of saturated soil in mm/day with the assumption around 3.4 – 117.8 mm/day, the value used was 31.25 mm/day.
- SMDMAX or initial soil moisture. The initial moisture deficiency of the soil with the assumption of 0.31 – 0.34, the value used was 0.31. Generally the soil characteristic in the studied area is sand, silty sand, sandy silt and silt.

b. Routing catchment

This stage analysis the flow routing which is charged to the river in the modeling. The river intended will get charged from the service area in the form of surface flow discharge. The parameter needed for this element are width, ground slope, imperviousness, impervious manning, pervious manning, impervious depression storage, pervious depression storage, and percent impervious area without depression storage.[8][9]

c. Climatology

This element is used to calculate the weather factors which consist of temperature, evaporation, wind speed, snow melt, and areal depletion. However for this research only evaporation is chosen.
d. Time series
This element is used to calculate the weather factors which consist of temperature, evaporation, wind speed, snow melt, and areal depletion. However for this research only evaporation is chosen.

e. Rain-gauges
This element is used to determine the position of rain post and also to input the desired design rainfall.

f. Inflow hydrograph
This element is used to charge flooding discharge at a desired node in the river. The drainage system which is modelled will be charge with flooding discharge at 4 nodes, 3 nodes upstream as the main inflow and 1 node downstream as the lateral inflow.

2.6. The Final Model of Coastal Urban Drainage System

Before modeling the Pluit polder system in the program, the cross section of the river need to be validated. To validate the ground level elevation obtained from the cross section of the river, the ground level elevation need to be bind with the ground level elevation of the existing field. The nearest benchmark node is BM 5 which is used a benchmark to measure the ground level elevation in the field. The ground level elevation obtained is +1.497779 m above sea level.

Validating the cross section of the river is done be comparing the ground level elevation measured on the field with the ground level elevation from the cross section of the river. The final result of the main drainage system modeling, especially for node 46, 47 and 48 which is the node modeling in the program for Sungai Besar that is closest to the Bank Indonesia Museum compartment. The location of the nodes and BM 5 can be seen in Figure 3.

![Figure 3. The location of the nodes and BM 5](image)

The node chosen as a binding node in the program is node 48 with ground level elevation of +1.544 m above sea level. The conclusion from the binding result is that the cross section of the river used in valid because the ground level elevation at node 48 only has a difference of 0.046221 m or ± 5 cm from the ground level elevation from the field measurement. The binding result of the elevation can be seen in Table 2.
Table 2. Validation result of the river cross section

| Ground level elevation (m.dpl) |                |
|-------------------------------|----------------|
| River cross section           | 1.544          |
| Field measurement             | 1.497779       |
| Difference                    | 0.046221       |

After all parameter completed for the element model, the final modeling of the Pluit polder system can be seen in Figure 4.

![Figure 4. The final model of the coastal urban drainage system](image)

3. Result

3.1. Water balance

The water balance for the distribution of planned rain for 25 years both with and without pump operated after calibration and model simulation can be seen in Table 3.

Table 3. Water balance for design rainfall in 25 years

| Runoff Quantity                  | 1st Simulation 25 years without pump | 2nd Simulation 25 years with pump |
|----------------------------------|--------------------------------------|-----------------------------------|
|                                  | Volume | Depth | Volume | Depth |
| Total Precipitation              | 952.318 | 5593.334 | 952.318 | 5593.334 |
| Evaporation Loss                 | 0.878  | 5.158  | 0.878  | 5.158  |
| Infiltration Loss                | 14.308 | 84.036 | 14.308 | 84.036 |
| Surface Runoff                   | 940.062 | 5521.352 | 940.062 | 5521.352 |
| Final Surface Storage            | 0.054  | 0.318  | 0.054  | 0.318  |
| Continuity Error (%)             | -0.313 | -0.313 | -0.313 | -0.313 |
The negative percentage of continuity error in the water balance show how much volume of water that is went out of the Pluit polder system. The amount of water that is gone or went out of the polder system can be cause by surcharge or surface flooding, evaporation loss, and infiltration loss. The bigger the percentage hence more water is gone or going out.[2][12]

3.2. Flow velocity of Besar River

The velocity of Sungai Besar’s flow that is modeled need to be validated before operating the program. The value of the flow velocity of Sungai Besar obtained from the program can be seen in Table 4.

| Flow velocity (m/sec) | Normal flow | Back water |
|-----------------------|-------------|------------|
| Min.                  | 0.043       | 0.046*     |
| Max.                  | 1.327       | -1.259*    |

*The negative result obtained from the program indicates that there is back water.

3.3. The influence of the Pluit Polder System towards the Bank Indonesia Museum compartment

The Pluit polder system affected the height of inundation around the Bank Indonesia Museum compartment. The height of the inundation can be seen throughout Table 5.

| Rain for 25 years without pump | Rain for 25 years with pump |
|--------------------------------|-----------------------------|
|                                | Elevation                  | Height of inundation         | Elevation                  | Height of inundation         |
| Ground level (m)               | Max. Water level (m)       | (m)                          | Ground level (m)           | Max. Water level (m)       |
| 46                              | 1.48                       | 1.56                         | 46                          | 1.48                       |
| 47                              | 1.48                       | 1.56                         | 46                          | 1.48                       |
| 48                              | 1.54                       | 1.60                         | 48                          | 1.54                       |

4. Conclusion and Suggestion

The flow velocity in Sungai Besar meets the minimum requirement which is less than 3 m/sec (ranging from 0.043 – 1.327 m/sec). The pump can reduce the volume of surface runoff of the Pluit
polder system and the water volume of the Pluit reservoir by 50%. The time length of the pump operation is 28 – 33 hours. The performance of the Pluit polder system highly affects the area of Bank Indonesia Museum compartment, as there is still an inundation with depth is 38.1 cm from the ground level. Therefore a dike construction with the height of 40 cm is suggested surrounding the compartment area to reduce the inundation cause by the flood. These basins have combined effects including storm water runoff control effect and improvement of water environment and is an effective technique in a storm water control plan. This study indicated that the integration of MIKE SWMM and GIS with accurate hydrometric and precipitation data could improve the modelling.

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