Flood Risk in the Ciliwung Catchment

Exploration of the possibilities of recent high frequency rainfall-runoff measurements for a flood risk assessment for the city of Jakarta

Research Proposal MSc Thesis

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Introduction

People living in delta cities always have to be prepared for certain threats directly or indirectly caused by the forces or use of water (Makaske et al., 2017). The Indonesian capital, Jakarta, is an example of a mega delta city which is frequently suffering from typical disasters in a river delta, such as coastal flooding and riverine flooding (Van Loenen et al., 2014). Sea level rise in combination with an increasing subsidence rate, due to extensive groundwater extraction (Abidin et al., 2001) threatens neighborhoods close to the coastline every day.

Riverine flooding is a yearly threat for the city in the wet season (Doan et al., 2012) as high intensity tropical rain showers can result in peak discharges in a short time period via the numerous rivers crossing Jakarta, originating from mountainous upstream areas (Loenen et al., 2014). Recent devastating riverine floods, resulting in big economic damage and casualties, occurred in 2002, 2007, 2013, 2014 and 2015 (Brinkman and Hartman, 2008, Hurford et al., 2010, Ward et al., 2014, Siswanto et al., 2015). Due to ongoing deforestation and change of land use in the upstream part of the catchments of these rivers the storage capacity is decreasing. As a consequence, the amount of direct runoff increases after a heavy rainfall event (Agustina, 2013, Ward et al., 2014) and the attenuation of peak discharge is decreasing, thereby increasing the risk of floods in the densely populated downstream parts of the catchment. (Conservation International Indonesia, 2010)

Problem Analysis

The Ciliwung river is the largest of a dozen of main rivers crossing the city of Jakarta (Figure 1) and has a length of 117 km (Doan et al., 2012). Several studies have already investigated the effect of land use change on discharge in the upstream part of the Ciliwung catchment. (e.g. Agustina, 2013, Poerbandono et al., 2014, Emam et al., 2016, Remondi et al., 2016). It is shown that the discharge of this river has increased over the last decades due to land use change and will even further increase based on several scenarios in which the forested area decreases, while plantation and built up areas increase. Moreover, Poerbandono et al. (2014) showed that land use change has a larger impact on increasing discharge than increasing rainfall intensity due to climate change. The Jakarta Flood Project Team (Diermanse, 2007) also didn't find any proof of a climate change induced rising trend of the average discharge.

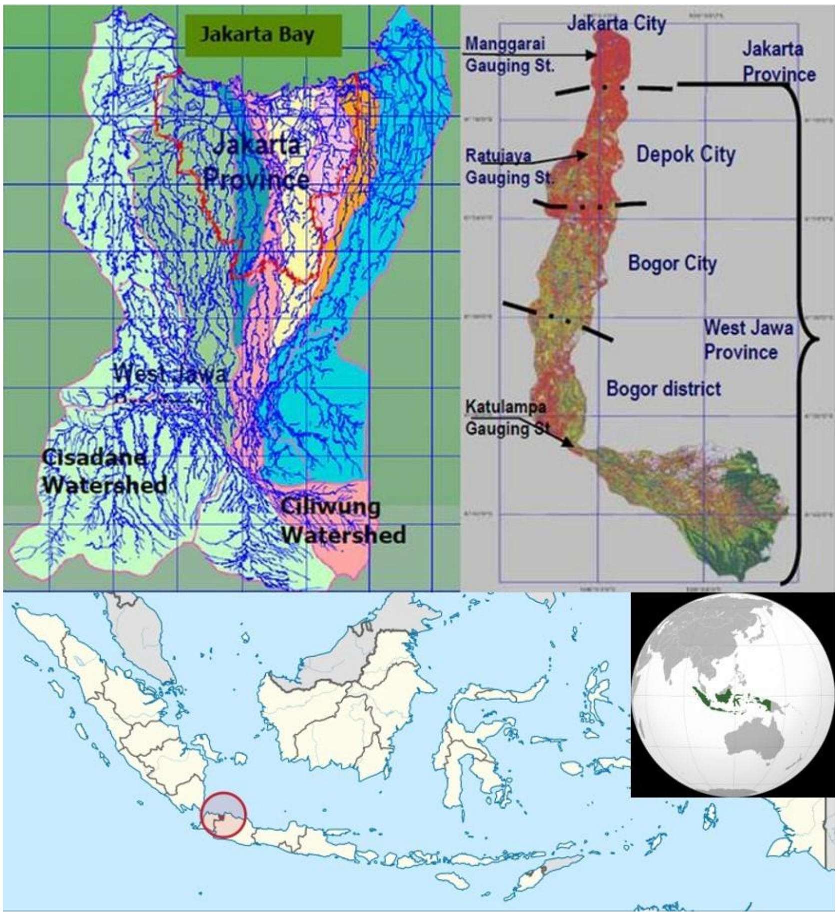

Figure 1. Location of the Ciliwung Watershed. (Adapted from Hendrayanto, 2012)

Analysis and simulations of the (peak) discharge in relation to land use change has so far only been done based on hourly or daily discharge observations (e.g. Conservation International Indonesia, 2009, Emam et al., 2016). Poerbandono et al. (2014) analyzed trends and predicted the effect of land use on discharge for a monthly time step. The recently implemented Flood Management Information System, based on a combined SOBEK and Delft3D model for the forecasting of floods for the greater Jakarta area, monitors the water levels and weather conditions at an hourly time interval (Van Loenen et al., 2014). The timescale of a flooding event is much faster. A tropical rainfall storm event usually last for about two hours with the most rain falling in one hour (Diermanse, 2007). The average response time of the Ciliwung in the city center of Jakarta after a rainfall event upstream of Bogor is 13 to 14 hours (Brinkman and Hartman, 2008, Van Heeringen and Van Loenen, 2011). To be able to prepare the citizens living near the Ciliwung of a possible flood disaster in the earliest possible stage of an upcoming event, it is important to know under which circumstances a discharge peak will develop and how it propagates to the downstream part of the catchment. Continuous rainfall and discharge measurements should be used in a flood forecasting system as rainfall continuously varies in space and time (Yulianto, 2006). In this way the response of the discharge of the Ciliwung can be analyzed in detail after certain storm events. A better understanding of the water level response during and after high intensity rain storms in different seasons is needed in order to accurately forecast floods. This will help water agencies in their decision making weather or not a warning should be issued for people living near the rivers in the low lying areas of Jakarta.

In order to structurally reduce the risk of flooding, a number of measures could be taken, among others, reforestation in the upstream part of the catchment (Conservation International Indonesia, 2009). In most studies the effect of a future landscape scenarios, based on some kind of policy, is analyzed (e.g. Agustina, 2013, Emam et al., 2016, Poerbandono et al., 2014). However, the minimum change of land use needed for which certain rainfall intensities, like the storm event causing flooding in 2014 (Ward et al., 2014), would not cause any risk in downstream areas, has so far not been calculated. A modeling study and scenario analysis based on recent short time interval measurements of rainfall and river stage and or discharge is also still missing in the literature.

In a few studies, relatively low values for certain performance criteria used are found. For example, Emam et al. (2016) used hourly rainfall-runoff measurements of two storm events in the Ciliwung catchment for calibration and validation of the HEC-HMS model, resulting in Nash-Sutcliffe efficiencies of respectively 0.64 and 0.58. Melsen et al., (2011) already discussed that the calibration and validation time interval should be at least equal, or smaller than the relevant hydrological process for the end user. If water agencies and local governments want to predict accurately the onset of a peak discharges after a rainfall (storm) event, which is a very fast process in the tropics, especially in a relatively small and urbanized catchment like the Ciliwung (Diermanse, 2007), rainfall-runoff data measured at short time intervals is needed as model input. In this way a model simulation performance will increase which in turn could lead to a better prediction of future critical conditions of the Ciliwung river.

Research goals and questions

This thesis research will focus on the impact of the use of high frequency measurements for the analysis of the propagation of a discharge peak, modeling and prediction of runoff response related to land use change in the upstream part of the Ciliwung catchment in two different seasons. The objectives of this research are:

- To describe the recent rainfall characteristics in the wet and dry season in the upstream part of the Ciliwung catchment.
- To analyze the response of the discharge/water levels at different locations of the Ciliwung catchment for different rainfall events.
- To model the current discharge in the upstream part of the Ciliwung catchment using recent 10-minutes interval measurements for model calibration and validation.
- To simulate the response of the water levels for future land use scenarios and predict at which combination of land use certain past rainfall events would not have caused a risk for downstream areas.

Based on the research objectives, the main research questions has been formulated:

How can high frequency measurements of rainfall and water levels in combination with information on landscape characteristics in the upstream part of the Ciliwung catchment contribute to a flood risk assessment for downstream parts, including the city of Jakarta, for the current situation and future scenarios.

This question is split into three sub-questions:

- *What are the rainfall characteristics in terms of amount, frequency and intensity and how does the water level at different locations in the Ciliwung catchment react on this rainfall?*
- *How accurate can the current and future response of the catchment on rainfall be simulated?*
- *How will changes in land use influence the risk of critical water levels for certain rainfall patterns?*

Methods

Data

An online database with rainfall data from a number of meteorological stations in the whole Greater Jakarta area (Jabodetabek) is available from WaterTech (http://www.tech4water.com). The rainfall-measurements can be viewed per five minutes time interval up to one month. Continuous water level data are measured and stored every ten minutes on the website of Posko Banjir (www.serverjakarta.com/dataTinggiAir.aspx). The rainfall data used for this study will be taken from Bendung Gadog gauging station (figure 2) which is assumed representative for rainfall in the upstream part of the Ciliwung Catchment. There are two river gauging stations chosen for discharge analysis upstream: Cibogo, close to the rainfall station, and Katulampa as outlet of the upstream part of the catchment (figure 2). For the latter station, stage-discharge curves are available (Odink, 2007) to calculate discharges from the recorded water level for the modeling part of this research. For the analysis of the effect of upstream rainfall on the (peak) discharge in the city of Jakarta, the water level records collected next to the Manggarai weir gates (figure 2) will be used.

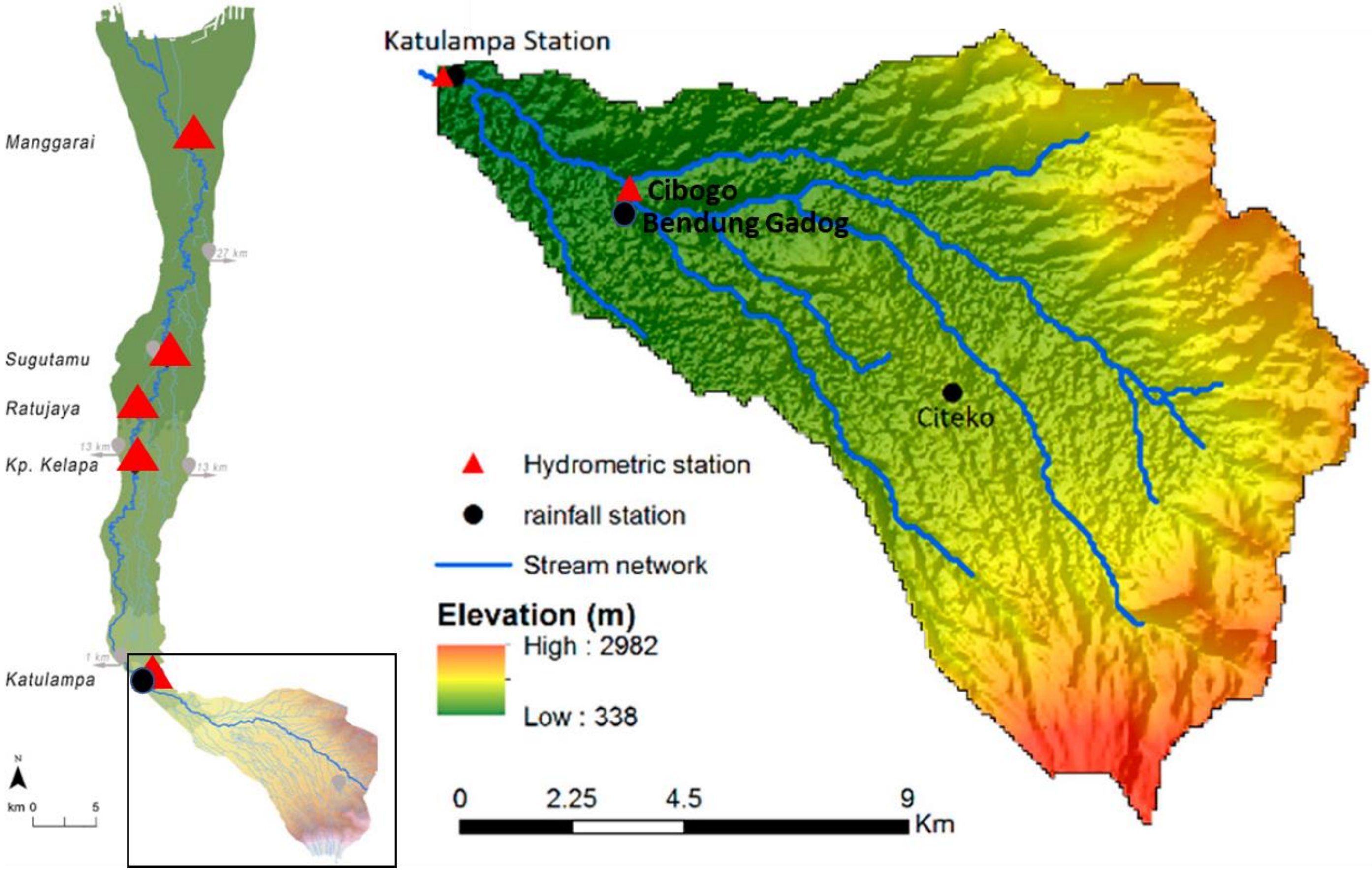

Figure 2. Location of the Upper Ciliwung Catchment and main rainfall and hydrometric stations. Adapted from Remondi et al., 2015 and Emam et al., 2016)

Significant positive trends of Ciliwung discharge due to land use change are found in the last 15 years (Poerbandono et al., 2014). This also counts for the annual 1-2 day precipitation maxima in the wet season (Siswanto et al., 2015). However, the most complete and useful data of rainfall events are only available for the years 2013, 2014, 2016 and 2017. For this reason rainfall and river response from only these specific years will be analyzed. Complete and representative data for a dry season (May-September) are found over the whole season, mostly in May, while data for the wet or monsoon season (October-April) are taken from the peak of the wet season, between December and February (Siswanto et al., 2015), when usually most of the year's precipitation falls, which could cause flooding in Jakarta.

Ten rainfall events per chosen year per season will be studied in detail. A comparison between the rainfall-runoff characteristics between the seasons will be made to investigate the effect of relative drier initial conditions of the catchment on the river response. The whole period of a rainfall event and discharge response should not coincide with a rainfall event in the downstream part of the catchment. In this way, only the influence of upstream rainfall can be analyzed. The start and end of a period for the analysis of a rainfall event is marked when the water levels of before and after the corresponding rainfall event are more or less similar and remain constant. Figure 3 shows an example of the start and end of period around rainfall event including water levels of the two stations in the upper Ciliwung catchment.

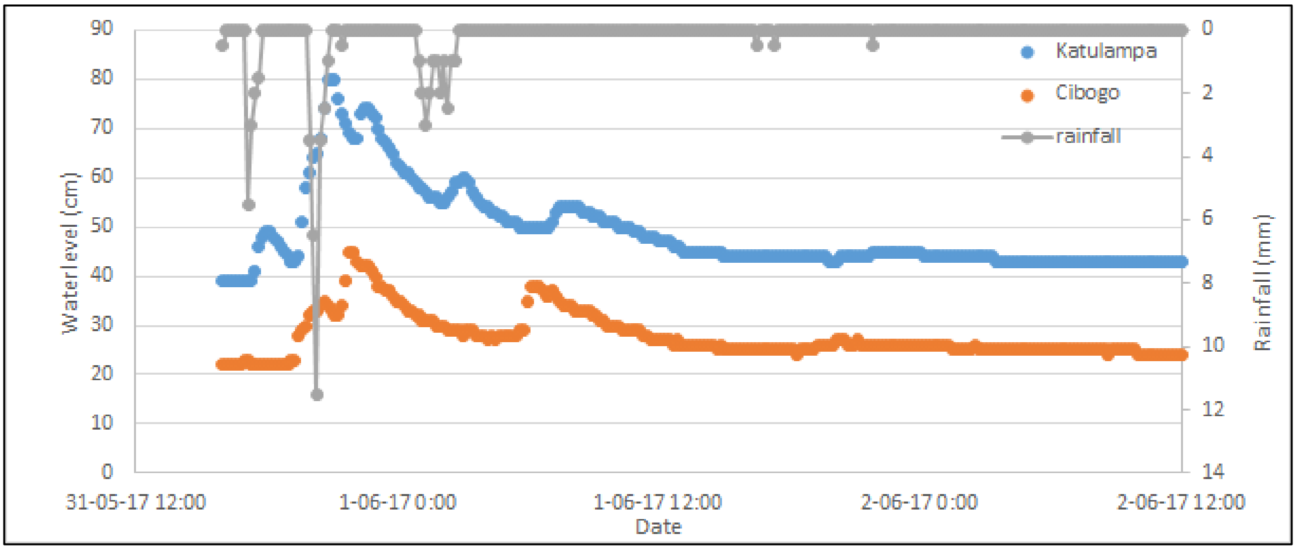

Figure 3. Example of a period before and after a rainfall event for analysis.

To be able to answer the first sub-question, the following analysis for each rainfall event will be carried out, most of them using a spreadsheet in Microsoft Excel:

- Calculation of the amount of rain and duration of each event and the long term averages.
- Lag-time between peak of rainfall event and discharge peak for different locations.
- Description of the growth, propagation and attenuation of the discharge peak and the behavior for different types of rainfall for each season.
- Correlation analysis between duration, intensity and amount of the rainfall and water level response at different locations.
- Calculation of the exact travel time of a discharge peak from upstream to the city center of Jakarta and the 'time saving' compared to the use of data with hourly time interval.

Modeling

In the past many models have been used to simulate the discharge in the Ciliwung catchment. Most of them used discharge data with a daily time interval or longer to calibrate the model. Yustika et al. (2012) used the SWAT model to simulate the effect of 'best management practices' on the discharge in the upper Ciliwung catchment. Also Ridwansyah et al. (2014) showed the possibilities and user-friendliness of the SWAT model for the modeling of the discharge in the neighboring Cisadane catchment. Emam et al., (2016) used the HEC-HMS model to simulate discharges for future land use scenarios. This model has also been used in other tropical catchments with satisfactory simulation results (Du et al., 2012, Sampath et al., 2015). However these studies mention that the minimum output time interval for these models is one hour, which is too coarse to accurately analyze the development of a discharge peak. Based on a literature research and availabilities of licenses on the Wageningen Campus, a suitable model for a fast responding tropical catchment with relatively low storage, will be chosen for this study. The chosen model should be able to calculate results for a short interval timestep.

To answer the second sub-question a model will be set up to simulate discharges on a short time interval. In this study 10-minutes interval data of two rainfall events will be used for calibration, one in a relatively dry situation with at least 3 days of no antecedent rainfall and one in a wet situation. Two similar rainfall events will be chosen for the validation of the model. The model will be checked on the ability to simulate certain characteristics of the growth of a discharge peak for the current land use and rainfall events in both dry and wet situations. One of the rainfall-runoff events which will be used for the calibration of the model, will be a flooding event of 2014, which occurred in the period of 10 to 20 January 2014 (Siswanto et al., 2015). To include all the aspects of the flooding event during the calibration of the model, including the onset, rising limb and recession of the discharge peak after the storm event, the period 7 to 23 January will be used for the calibration. Validation will be done using data of a peak discharge event in February 2013, which caused a major flooding as well (Van Loenen et al., 2014), using the time series of an equal number of days around the event as for the calibration period.

The model performance will be compared with the model calibrated and validated with hourly measured data. For any model, the computation of results for a small time step will be more time consuming, because more computer power is needed. For this reason a comparison will be made with the use of hourly data for calibration and validation to check if the simulation accuracy significantly increases and the computational effort is worth considering.

Rainfall data from the Bendung Gadog rain gauge station will be used as model input. The river response data will come from the Katulampa weir for which the discharge have to be calculated from the water level records using the stage-discharge relationship described in Diermanse (2007). The delineation of the upper Ciliwung catchment and the average slope classes in each grid cell can be calculated from a DEM. Aster-GDEMs for any region around the globe can be downloaded for free (https://gdex.cr.usgs.gov/gdex). An R-script and user manual is available to preprocess the DEM for any catchment from the tutorial of the course Catchment Hydrology (HWM-32806). Land use data can be retrieved from Landsat 7 satellite images for every year (Agustina, 2013). The soil map of the upper Ciliwung catchment can be found in Emam et al. (2016).

A sensitivity analysis will be carried out to investigate the impact of small deviations of the used parameter values on the model results, in this case the simulated discharge at the Katulampa weir. The relative contribution of each parameter to the variation in model results will also be reported. An R-script is available from the tutorial of the course Numerical Techniques in Water and Air Flow (SLM-33806) to carry out the sensitivity analysis. In this way one can find out which parameters should be known or measured most precisely in order to predict the discharge and possible flooding conditions as accurately as possible.

The final step is to calculate a minimum rainfall amount needed to reach a critical discharge and water level for the Katulampa weir, corresponding to the highest alert level for the governments of the city of Jakarta (Agustina, 2013, Van Loenen et al., 2014). In combination with the answers to the first sub-question, a minute-to-minute forecast of an upcoming riverine flood event can be constructed from the early stages until a peak discharge reaches downtown Jakarta.

Scenario Analysis

The previous steps of this research were related to the rainfall-runoff response for the current land use. To make a prediction of (peak) discharges for a future scenario related to land use change, some parameters values directly connected to the new land cover have to be changed. Examples of future land use maps for the upper Ciliwung catchment can be found in the literature (e.g. Emam et al., 2016, see figure 4).

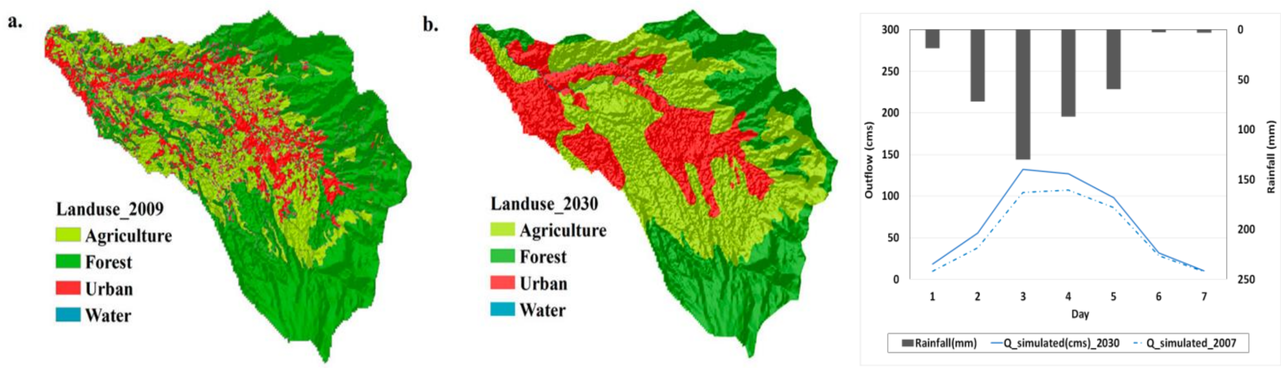

Figure 4. Example of current and future land use maps used in a previous study and simulated discharges (Emam et al. 2016).

First the land use change scenarios proposed by Emam et al. 2016 (figure 4) will be simulated to see if results are different after using the 10-minutes interval measurements for calibration and validation. Hereafter, peak discharge simulation under extreme scenarios will be evaluated: 100% increase of built up at the cost of forest and plantation compared to the current situation. Secondly, an 100% increase of forest at the cost of plantation, keeping urban space constant. For the last scenario the exact location of the reforestation area will be simulated for two different options; a stratified random and for a prescribed reforestation area. The reason behind this is that Indonesia Conservation International (2009) suggested a zone best suitable for reforestation and recommended to further investigate the effect on the discharge based on this reforestation zone. The outcome of the comparison between these last two scenarios in this research will provide insight in the effect of river discharge on different reforestation possibilities.

Just like in previous studies the change in stream flow at the Katulampa outlet will be calculated and compared to the current situation (e.g. Poerbandono et al., 2014, Emam et al., 2016, see figure 4). A similar result will be expected as in figure 4, but for a number of different rainfall events and for a shorter time interval. Based on sensitivity analysis, a range of possible discharge values will be calculated for a given land use scenario and rainfall pattern. In addition, this research will also analyze if the dynamics of the response of the river discharge will change due to land use change. Furthermore, a combination of land cover for which the rainfall storm of February 2014 would not have caused critical water levels at the Katulampa gauging station will also be calculated, based on trial and error.

In the end not only a realistic but also an understandable land use map of the upstream catchment should be constructed, supplemented with a table, clearly stating the effect of the discharge and flood risk for certain rainfall events and the uncertainties in the results. In this way the local governments can change or design policy based on the results of this research. This will also provide the answer to the third sub-question, after which the main research question can be answered.

Planning and Feasibility

The planning of this thesis project is based on 36 European Credit Transfer System (ECTS), which is equal to 24 weeks, based on a working week of 40 hours. The thesis period will start from 5th of April until 5th of November. Due to limited facilities at campus during public holiday, the summer holiday and some other already planned holidays and courses at which no thesis work can be performed (approximately one month), the 24 work weeks of this thesis will be divided over a 7 calendar months. The global planning for the whole thesis, including the public and personal holidays, can be found in the appendix.

In the first weeks some data has to be rearranged. The raw rainfall and water level measurements has to checked, data gaps have to be interpolated and all data have to be put into a practical spreadsheet. Two weeks will be reserved for getting to know the chosen model, including underlying theory and the most important parameters. Three weeks will be used to prepare the necessary input data and scripts for a base model.

There is a low risk of delay, due to the fact that the catchment itself doesn't have to be visited to carry out all research steps and data are available online free of charge. The license and user manuals of the model to be used should already be available at the campus. The scripts for the preprocessing steps of some input data are available via tutorials of several courses as described in the methods section. Furthermore, one week for each research part (i.e. Statistics, Modelling, Scenario and Sensitivity Analysis) is reserved for troubleshooting of all kind of unforeseen errors and troubles, which can be a model malfunctioning or the check and improvement of a piece of script for which the help (and waiting time for) the supervisors is needed. The last 6 weeks are reserved for the writing and correcting of the report, the preparation of a presentation and the finishing touch.

In the first month the main supervisor, Roel Dijksma, will be available every week to discuss any problem and the thesis progress. In case of absence of Roel, the second supervisor, Lieke Melsen, will be contacted. She can also be contacted for questions during the modelling phase.

In general, during the rest of the thesis period about every 2 weeks one of the supervisors can be consulted to discuss any problem or the progress of the thesis. More or less consultation hours will be scheduled based on the overall progress of the research.

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Appendix 1: Global Thesis Planning first half (week 1-12)

	Week # (40 hours)											
Main activity	5-11 April	12-23 April	24 April-2 May	3-14 May	15-22 May	23-30 May	31 May-6 June	7-19 June	20-26 June	27 June- 3 July	4-10 July	11-13 July
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
Data management and statistics												
Literature study models												
Getting to know the model												
Built the base model												
Current scenario modelling												
Scenario analysis												
Sensitivity analysis												
Report writing												
Presentation												
Notes:		16-18 April off	27 April: Kingsday	8-13 May off	21 May: Pentecost			11-14 June off				2 days less
			30 April off									Will be
												compensated

Appendix 2: Global Thesis Planning second half (week 13-24)

	Week # (40 hours)											
Main activity	6-10 Aug	13-17 Aug	20-24 Aug	27-31 Aug	3-7 Sep	10-14 Sep	17-21 Sep	24-28 Sep	1-5 Oct	8-12 Oct	15-19 Oct	22-5 November
	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22	Week 23	Week 24
Data management and statistics												
Literature study models												
Getting to know the model												
Built the base model												
Current scenario modelling												
Scenario analysis	■	■										
Sensitivity analysis		■	■	■	■	■						
Report writing							■	■	■	■		
Presentation										■	■	■
Notes:					From 3-28 September:							6 days compensation;
					1 day per week reserved for MOS-Module course							4 course days and
												2 days less in July
												Final Presentation
												and Examination day
												(5 November)