Modelling Peak Flow at 10-minutes Resolution in the Upper Ciliwung Catchment, Indonesia

Exploring the possibilities of high frequency rainfall-runoff measurements for an accurate prediction of peak discharges using a fully distributed model and its applications in a fast responding tropical catchment

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MSc Thesis

Chairgroup Hydrology and Quantitive Water Management (HWM)

Wageningen, February 2019

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Cover picture: Impression of the Ciliwung river about 5 kilometres north of the Katulampa weir in the city of Bogor, Indonesia. Photo was taken by the author in January 2011.

Abstract

The Indonesian capital city of Jakarta is a typical delta city suffering from regular riverine flooding in the wet season. One of the causes is the ongoing structural increase of the peak discharge intensity of the rivers crossing the city, due to land use change in the upstream parts of the catchments, the steep mountainous areas in the south of Java island. The Ciliwung is the largest of these rivers and the upstream part of the catchment, the Upper Ciliwung (±160 km^2) was used as study area. Many modelling studies already have shown the negative effect of land use change, especially deforestation, which led to increased peak discharges at the outlet of the Upper Ciliwung, the Katulampa weir, approximately 30 km south of the border of the city of Jakarta. So far modelling studies in the upper Ciliwung were only done at low temporal resolution, much coarser than the timescale of observed rainfall-runoff processes in the study area (<2h). The objectives of this study were to explore the possibilities of high frequency rainfall-runoff measurements for two applications: more accurate event based peak flow modelling and simulation of land use change effects on peak discharges. The fully distributed wflow_sbm model was used for the discharge simulations. Based on adjusted NSE values (NSE_{adj}>0.6) and visual comparisons of the hydrographs of the simulated discharge (Q_{sim}) with the observed discharge (Q_{obs}), wflow_sbm showed promising results of the prediction of peak discharge at average rainfall amounts, but only for dry initial catchment conditions. This model is in its current state unsuitable for flood risk prediction because it was not possible to model continuous high base flow at wet initial conditions, even after extreme rainfall input (>100 mm/h). Furthermore, it was shown that extrapolation of rainfall data from the only available observation point measuring rainfall at 10-minutes interval in the west part of the catchment was insufficient to give an accurate indication of the exact amount of water entering the Upper Ciliwung catchment. This caused for most events unrealistic simulated runoff patterns, either mistimed or wrong in magnitude with respect to Q_{obs}, causing difficulties in evaluating the exact model performance at this high temporal resolution. Given the fact that the dynamics of the discharge signal are well simulated for dry initial conditions and assumed that Q_{sim} resembles reality to a certain extent, the scenario analysis revealed that peak discharges could already decrease by up to 18% for a small reforestation project in the west of the catchment. The theoretical increase of the total peak discharge volume caused by a unit area of added built up space could be compensated by twice the unit area of added forest. The conclusions and recommendations coming forward in this study should be taken with care as not the full catchment dynamics were explored due to data scarcity and model limitations.

Preface

The phenomenon is always fantastic: a tropical rain shower in the wet season seen from a high-rise in or around Jakarta, Indonesia. My fascination for these kinds of natural spectacles was one of the main reasons I wanted to do my MSc thesis about a subject related to such an event in this region. There must have been something in which I could contribute to the knowledge about the impact of such huge rainfall events.

It took me a very long time to actually find a topic, as the very infamous Ciliwung river, for its poor water quality and yearly flood risk, was already thoroughly studied in the past decades. One of the words of my first supervisor, Roel, when we talked sometimes about the flooding problems in Jakarta were: "There is just no storage..." and always kept me thinking about what I could do for this amazing region, where I was born, were my family and girlfriend live. It must have been possible to apply my knowledge gathered from all those years of lectures and study hours in Wageningen to a subject related to the Ciliwung catchment for the big inevitable MSc thesis. One day, I was finally lucky: I discovered a lot of rainfall-runoff data to work with, based on which I could formulate a novel research question about peak discharge prediction in the Ciliwung catchment. After a lot of brainstorm meetings with my supervisors Roel and Lieke and positive feedback after my research proposal presentation, I was gain lucky, to get the opportunity to explore the possibilities of the 'wflow model' for the Upper Ciliwung. This lead to a new problem. My second supervisor, Lieke, already told me: "You should not be afraid to learn how to model." I was actually, but I also realized that I had to accept that fact and try, as I always had to do in my student career, try to master a lot of new research techniques. I have to admit, it became a hell of a job, to don't know anything and to have to ask a lot of questions. After error after error in wflow and confusion all about, there was no light at the end of the tunnel for a very long time and I couldn't even imagine seeing myself with workable results to make a good scientific story about my long wanted own research subject.

Like my mother always says: "everything comes at its time," and so it was with this thesis. Thanks to the unconditional support, cozy meetings and effective suggestions of my supervisors and additional help from the experts from Deltares, piece for piece I managed to complete the big puzzle, consisting of so much data, figures and wflow model output, and was finally able to write my very own hydrological report about the Ciliwung river.

In the first place I want to thank them, Roel and Lieke, for all their support and time spent for me during my research and the setup. Thanks to their dedication to always try to help their students as much as they can and pointing me in the right direction, I could manage to successfully complete all parts of my thesis work.

Then I have to thank Arnejan van Loenen (Deltares) for his tremendous effort of creating a wflow model of the Upper Ciliwung Catchment for me and his openness to help me from a distance. The same counts for Albrecht Weerts (Deltares), who brought me into contact with Arnejan and many other colleagues. He was always open for questions and a helping hand in troubleshooting even though he wasn't a formal supervisor, so many thanks to him as well.

Small thanks as well for Mark van der Laan who tried to help me with his 'water' network in my data hunting phase. Via Mark I came into contact with Victor Coenen (Witteveen and Bos) and thanks to him I reached Jan-Jaap Brinkman (Deltares), who provided me very quickly with lots of information about past research around the Ciliwung. Herewith I also want to thank them.

Furthermore, I want to thank my sayang Azka who tried to do the same, contacting many water boards and communities in and around Jakarta, by translating my research ideas in proper Bahasa, the Indonesian language, which unfortunately did not lead to any replies or research partners. She kept on trying to help and eventually found some background information of the Ciliwung in the library of the University of Indonesia.

At last but not least, I have to thank my family in Amsterdam, for their patience, unconditional trust and silent support during my whole thesis period, which gave me the mental power to finish this thesis report.

Terima kasih banyak semuanya.

Rizky

Amsterdam, 8 February 2019

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1 Introduction

1.1 Problem statement

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 frequently suffers 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 ground water extraction (Abidin et al., 2001) threatens neighbourhoods in northern parts of the city close to the coastline every day.

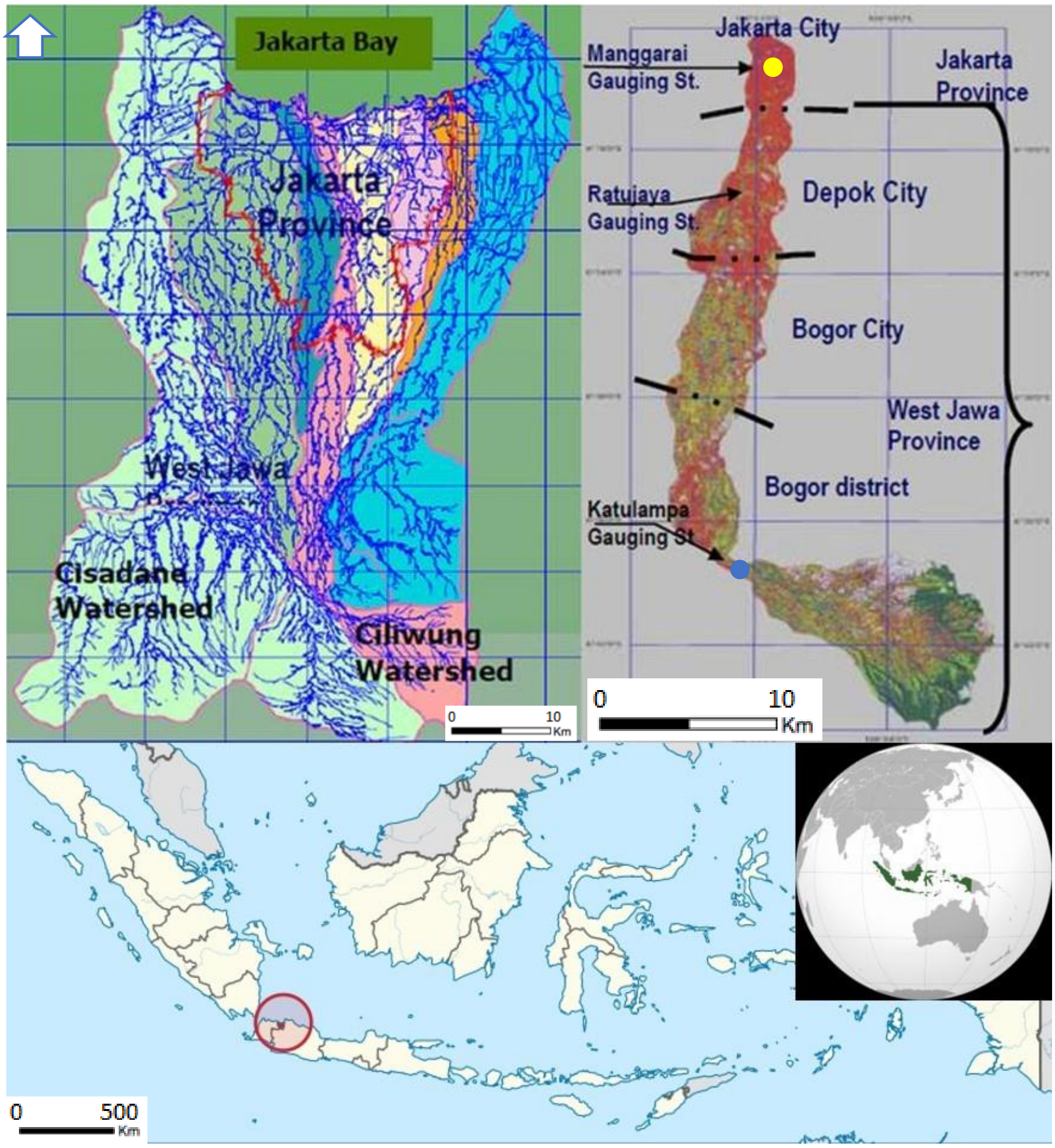


Figure 1-1. Location of the study area around the capital city of Jakarta, Indonesia (bottom of the figure). In the upper left, the Ciliwung catchment is shown in pink between the other watersheds crossing the city of Jakarta. The catchment shape is shown on the upper right of the figure. The yellow dot corresponds to the downstream gauging station Manggarai in the city of Jakarta and the blue dot to the gauging station Katulampa, the outlet of the Upper Ciliwung catchment. The colours correspond to the colours of the example hydrographs from these locations in Figure 1-2. (Adapted from Hendrayanto, 2008)

In the last decades riverine flooding became an almost yearly phenomenon in Jakarta (Doan et al., 2012). Usually at the peak of the wet season, from November to January (Siswanto et al., 2015), high intensity tropical rain showers cause peak discharges in a short time period via the numerous rivers crossing Jakarta (Figure 1-1), originating from mountainous upstream areas (Van Loenen et al., 2014). Several devastating flood events resulted in high economic losses and casualties (Hurford et al., 2010, Ward et al., 2014). In

2007, 80 people were killed during a major flooding event in which 40% of the city of Jakarta was inundated. This was the worst flood in almost 300 years with an estimated damage of 900 million USD (Brinkman and Hartman, 2008). Another major flooding event in 2014 left 26 people death and caused losses of almost 400 million USD due to, among others, damaged buildings and infrastructure (Siswanto et al., 2015).

Already since the 1920s, when the Dutch colonial rulers set up tea plantations in the upstream part of these river catchments, it was identified that ongoing deforestation and change of land use caused a change in runoff patterns in the greater Jakarta area (Jabodetabek, Murniningsih and Anggraheni, 2016). The amount of direct runoff increased after heavy rainfall events (Agustina, 2013, Ward et al., 2014) and the attenuation of peak discharges decreased due to a decrease of storage capacity, thereby increasing the risk of floods in the densely populated downstream parts of the Ciliwung catchment, including the city of Jakarta. (Conservation International Indonesia, 2010)

Several studies have already investigated the impact of land use change on discharge in the Ciliwung catchment (e.g. Agustina, 2013, Poerbandono et al., 2014, Emam et al., 2016, Remondi et al., 2016). It was shown that the discharge volume and peak discharge intensities of the Ciliwung have increased over the last decades due to land use change and will even further increase based on several scenarios in which the forested areas even more decrease, 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 didn't find any proof of a climate change induced rising trend of the average discharge either (Diermanse, 2007). 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, 2010).

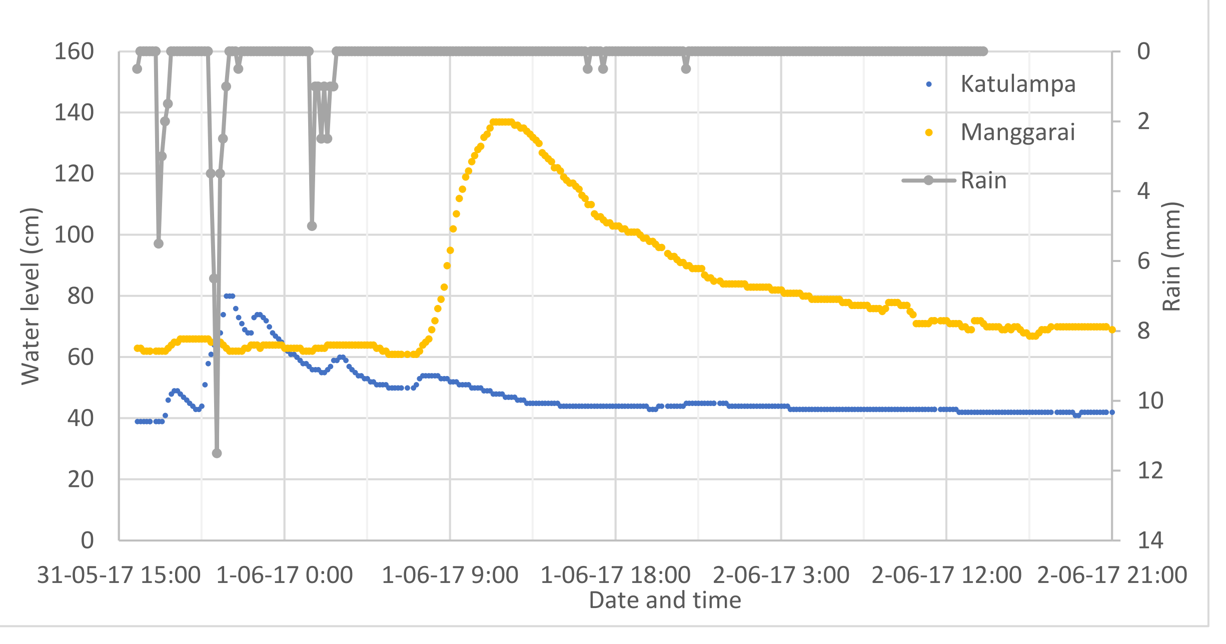


Figure 1-2. Example of a rainfall event and measured water levels at 10-minutes time interval at the outlet of the Upper Ciliwung (Katulampa, blue) and at the city centre gauging station (Manggarai, yellow) in the Upper Ciliwung (For the exact locations, see catchment overview map in Figure 1-1).

1.2 Previous modelling studies in the Ciliwung catchment

Analysis and simulations of the (peak) discharge in relation to land use change in Indonesia has so far only been done using models at hourly to monthly time step (e.g. Conservation International Indonesia, 2010, Poerbandono et al., 2014, Emam et al., 2016). The recently implemented Flood Management Information System, based on a combined SOBEK and Delft3D model for the forecasting of floods in the Jabodetabek, monitors the water levels and weather conditions at an hourly time interval (Van Loenen et al., 2014). However, the timescale of processes, such as the response time of water levels after peak rainfall, especially in tropical catchments, is much faster. To illustrate: a tropical rainfall event usually lasts for about two hours in which most rain falls within one hour (Diermanse, 2007). In Figure 1-2 one can observe such fast developing peak water levels after a rainfall event in the upstream part of the Ciliwung catchment and the corresponding response of water levels in the city centre of Jakarta. Within one hour the maximum water level upstream could have been reached and the recession could already have started.

The average response time of the Ciliwung at Katulampa, the outlet of the Upper Ciliwung (Figure 1-1) after a rainfall event upstream can be as low as 50 minutes (Agustina, 2013). Here after, the average response time of the peak discharge in the city centre of Jakarta 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 for a possible flood disaster in the earliest possible stage of an upcoming storm event, it is important to know under which circumstances an extreme 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 discharge response of the Ciliwung can be predicted more accurate after certain rainfall events.

In the past many models have been used to simulate the discharge in the Ciliwung catchment. Most of them used discharge data measured at a daily interval or longer to calibrate the model. Yustika et al. (2016) 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 modelling of the discharge in the neighbouring 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 relatively coarse compared to the fast development of a discharge peak in the Ciliwung catchment. Melsen et al. (2011) already discussed that the calibration and validation time interval should be at least equal, or smaller than the timescale of the relevant hydrological process for the end user. If water agencies and local governments want to predict more accurately the peak discharges after a rainfall event in a relatively small and urbanized tropical catchment like the Ciliwung (Diermanse, 2007), rainfall-runoff modelling at higher temporal resolution is needed.

In most studies the effect of a future landscape or land use scenarios, some of them based on some kind of policy, was analysed (e.g. Agustina, 2013, Poerbandono et al., 2014, Emam et al., 2016). A modelling study and scenario analysis based on recent high frequency rainfall-runoff measurements in this area is still missing in the literature. If the accuracy of the discharge and corresponding water level predictions can improve on the minute by improving a monitoring scheme and the modelling resolution, this will help water boards to a better time an early flood warning for millions of people living in this kind of river catchments. Furthermore, a well-designed presentation of any positive effect of certain scenarios, such as peak discharge reduction after reforestation, could encourage policy makers in redesigning the catchment landscape to decrease future flood risk.

1.3 Research questions

This thesis research will focus on the impact of the use of high frequency rainfall-runoff measurements for the modelling of peak discharges in the Upper Ciliwung catchment. Furthermore the change of runoff patterns related to land use change will be analysed. The following research question was posed at the start of the research:

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 accurately model peak discharges for the current situation and future scenarios?

This question is split into three sub-questions:

- *What are the rainfall characteristics in terms of duration, intensity and total amount 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 at very high temporal resolution?*
- *How will changes in land use in the Upper Ciliwung influence the peak discharge for a certain rainfall event?*

1.4 Report outline

In the following chapter the study area is briefly introduced. In chapter 3 the data, including sources and the fully distributed wflow_sbm model will be presented, as well as the main settings to run the base model for the Upper Ciliwung. Hereafter the model performance measure (NSE) is described. In the last part of chapter 3, the different land use change maps are presented, which serves as input for the scenario analysis. In chapter 4, first some basic rainfall-runoff statistics in the Ciliwung catchment are shown. Thereafter, the model performance for calibration and validation are described and visualized. Furthermore a simple water balance calculation of one the rainfall events used for validation is given. In the final part of this chapter, the quantification of the land use change effect on the peak discharge is presented. In chapter 5, a list of general (model) limitations and assumptions is given before answering the research questions. Each sub-question was answered by critically evaluating the results from the corresponding sections in chapter 4. The key results are also compared with results from relevant previous studies in the area and put in broader perspective for further research and society. In chapter 6 the answer to the main research questions is given as well as the conclusions and recommendations which came forward in this study.

2 Study area

2.1 Geography

The Ciliwung catchment is situated in the Indonesian province of West Java (Figure 1-1). The Ciliwung river, with a length of 117 km, is the largest of a dozen of main rivers crossing the city of Jakarta in south-north direction towards the Jakarta Bay. More than 4 million people live close to this river, which has a catchment area of approximately 375 km^2, of which 25% is situated in the Jakarta province (Doan et al., 2012).

The study area is the Upper Ciliwung catchment (also called Bogor Watershed or Ciliwung Hulu in the literature, see Figure 2-1) which has a catchment area of approximately 160 km^2. The sources of the main river and its tributaries are on the slopes of the mountains, with peaks of around 2900m above sea level (+MSL), in the south-east of the catchment. The drainage system is in west-north-west direction and after 26km the main river reaches the Katulampa weir (Figure 2-1), the outlet of the Upper Ciliwung catchment at approximately 300m +MSL (Indonesia Conservation International, 2010). This weir, located in the outskirts of the city of Bogor, is the first monitoring point of alarming water levels (Figure 2-2) which could imply an upcoming flooding in downstream cities (Agustina, 2013, Van Loenen et al., 2014).

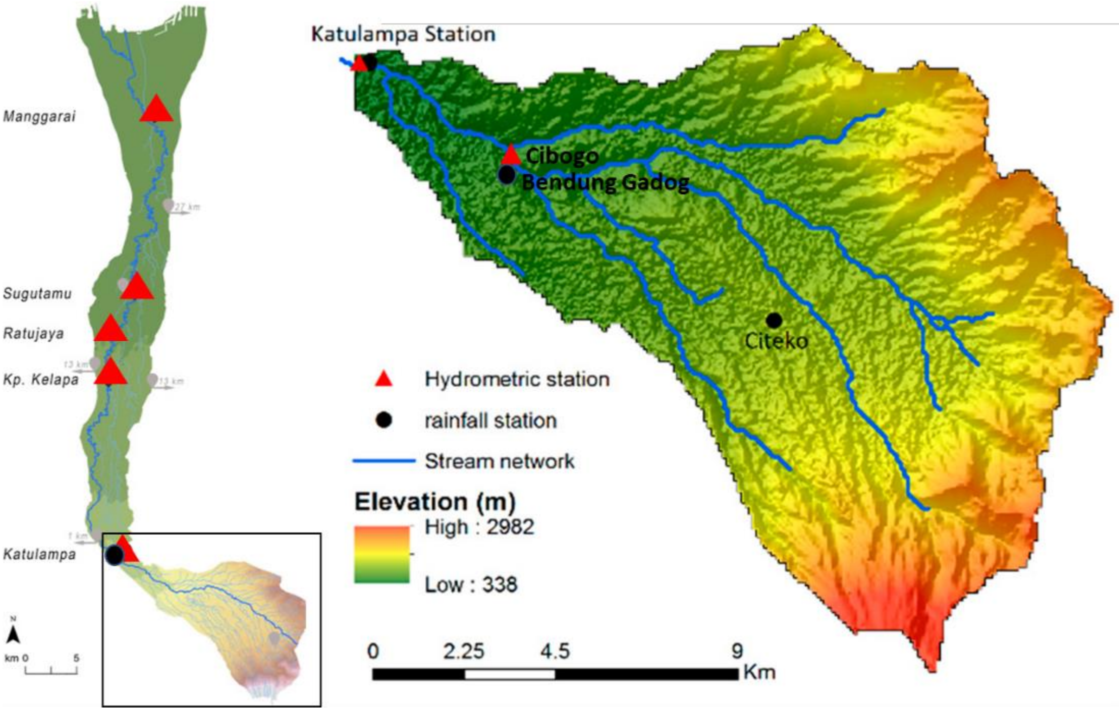


Figure 2-1. The location of the Upper Ciliwung catchment (black rectangle) is shown on the left hand side of the Figure, and on the right hand side, the main streams, rainfall and hydrometric stations in the Upper Ciliwung are shown. (Adapted from Remondi et al., 2015 and Emam et al., 2016)

2.2 Climate

The mountainous area surrounding the Upper Ciliwung has a year-round tropical climate with an average temperature of 24 degrees Celsius and an average annual rainfall between 3000-6000 mm, with the lowest rainfall rates in the low land area near Bogor and the highest average rainfall higher upstream in the mountains (Harto et al., 1998). There are two distinct seasons in this region, a 'wet season' from November to April and a 'dry season' from approximately May to October. The wet season is triggered by a north-west monsoon, giving a constant supply of relatively warm air from above the Java and South Chinese sea, causing the many rainfall events on Java Island (Harto et al., 1998, Siswanto et al., 2015, Diermanse, 2007). Although differences in rainfall are noticed between the peak of the dry season and wet season in the Upper Ciliwung (Figure 2-3), compared to the lower lying parts of the Ciliwung catchment, these differences are less distinct, due to the orography induced rainfall patterns in the mountains, which also occurs in the dry season (Diermanse, 2007).

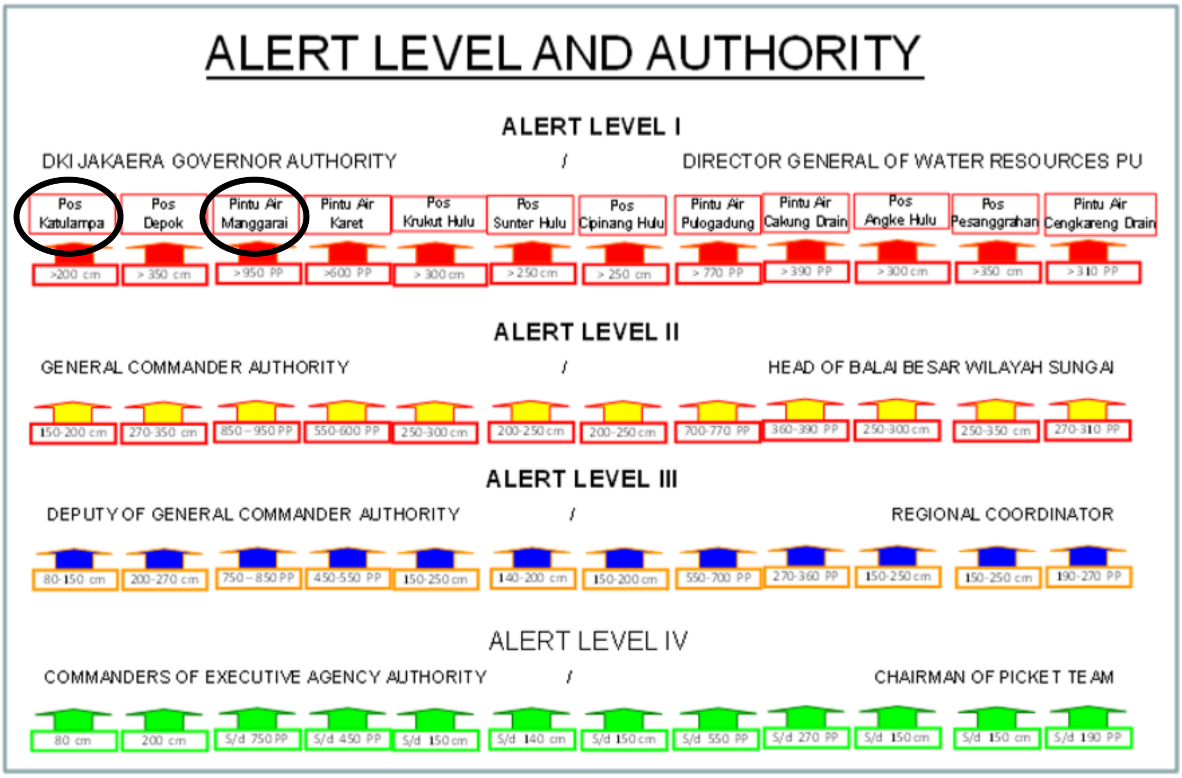


Figure 2-2. Flood warning levels (highest is level I) based on certain water level ranges for different monitoring points along the Ciliwung river and the responsible authorities for each warning level. (Van Loenen et al., 2014) Encircled are the relevant locations in this study: (Pos) Katulampa, upstream, and (Pintu Air) Manggarai, downstream in Jakarta.

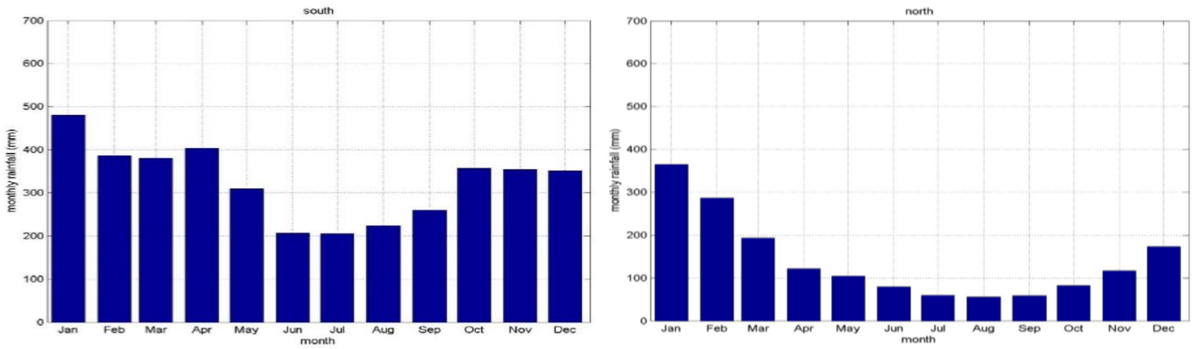


Figure 2-3. Monthly average rainfall totals in the south of the Ciliwung Catchment (left), including the Upper Ciliwung, and north of the Ciliwung Catchment (right), including the city of Jakarta. (Diermanse, 2007)

2.3 Land use

The main land use types in the Upper Ciliwung catchment are: urban area, agriculture and forests. There is a clear trend in land use change since the 1980's. Paddies and forests have constantly been replaced in favour of housing and other kinds of agriculture. (Agustina, 2013, Harto et al., 1998) The exact area of the various land use types present differs in the literature (see Table 2-1). In general, built-up areas contribute to ±15% of the catchment, while the other 85% is a mix of original/secondary forest (up to 30%) and cultivated land, among others tea plantations and paddy fields (up to 60%).

Table 2-1. Different land use distributions used in models of previous studies in the Upper Ciliwung.

	2002 *Farid et al. (2010)*	**2009** *Emam et al. (2016)*	**2010** *Yustika et al. (2016)*	**2010** *Agustina (2013)*
Urban	13%	16%	7%	14%
Agriculture	63%	26%	71%	63%
Forest	24%	58%	22%	23%

2.4 Hydrogeology

The hydrological base in the Ciliwung catchment is formed by basalt from the Miocene and most other deposits are Quaternary sediments. An alluvial fan, the Bogor fan, has formed around the slopes of the southern mountains, consisting of fine tuff left from recent volcanic activity (see Figure 2-4, Delinom, 2010).

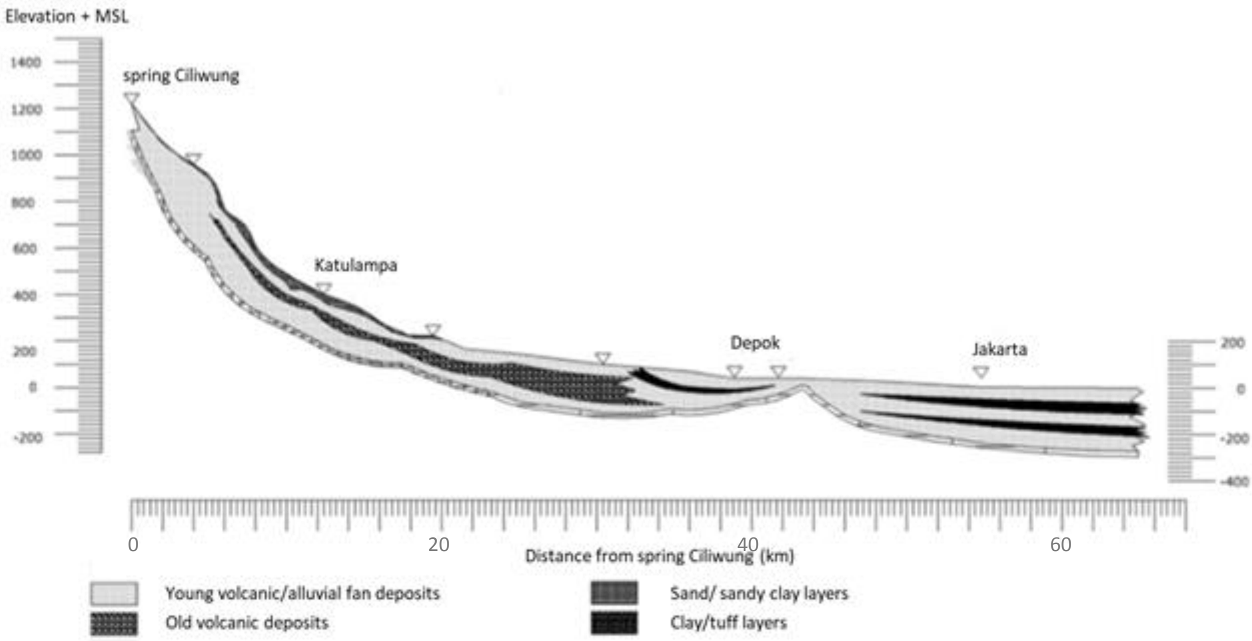


Figure 2-4. Hydrogeological cross-section of the Ciliwung catchment (south-north), from the spring of the Ciliwung in the mountains to the shoreline in Jakarta. Adapted from Irawan (2012)

In general there are two aquifer systems on top of each other in the Upper Ciliwung catchment and beyond (Figure 2-4). The main unconfined aquifer was composed of young volcanic deposits, which consists of tuffacueous pumice, breccia and andesite mixed with sand and sandstones. The hydraulic conductivity ranges from 0.8-36 m/day. The confined aquifer, covered by the unconfined aquifer, consists of old volcanic material: andesite pumice, tuff and conglomerate, and is less permeable with an hydraulic conductivity range of 0.001-10 m/day. The depth of the aquifers ranges from 10 – 60 m below surface. (Irawan, 2012)

3 Material and methods

3.1 Available data

An online database with hydrometeorological data from a large number of meteorological stations in Indonesia was available from Tech4Water (2018). The rainfall measurement data can be viewed per five minutes time interval up to one year. For this study, the online collected data came from the Automatic Rainfall Recorder (ARR) at the Bendung Gadog gauging station (Figure 2-1), which was assumed representative for rainfall in the Upper Ciliwung catchment. Water level data at several locations in the Jabodetabek are measured and stored every ten minutes on the website of Posko Banjir. Water levels measured at the outlet of the Upper Ciliwung catchment, Katulampa ($h_{Katulampa}$, see Figure 1-2 and Figure 2-1 for the location) were used in this study. These were also converted to discharges in m^3/s, using the stage-discharge (Q-h) relationships derived from weir equations as described in Odink (2007), for use in the modelling part of this study. The water levels at Manggarai in the city of Jakarta ($h_{Manggarai}$, see Figure 1-2 and Figure 2-1 for the location*)* corresponding to the response of the upstream precipitation events were also extracted. Only the peak water levels in the city which are assumed to be solely caused by rainfall in the Upper Ciliwung were analysed. An overview of the data used in this study can be found in Table 3-1.

Table 3-1. Overview of the available data, measurement frequencies and sources used in this study.

	Data source	**Measurement frequency**	**Relevant locations**
Water Levels	Posko Banjir	10 minutes	Katulampa (Upper Ciliwung) and Manggarai (Jakarta)
Rainfall	Tech4Water	5 minutes-1 year	Bendung Gadog (Upper Ciliwung)

A table of basic statistics was made from the total amount and duration of a precipitation event and the response time at the Katulampa and Manggarai weir. For this purpose, rainfall data, only available from the period 2013-2017, from the Bendung Gadog ARR measured at 5 minutes interval and water level data at Katulampa and downstream at Manggarai, measured at 10 minutes interval were used. This provided a quick overview of current rainfall-runoff and signal delay characteristics in the Ciliwung catchment and if these were within expectations with respect to findings in the literature.

3.2 Modelling the Upper Ciliwung

In this study, a recently developed fully distributed hydrological model by Deltares, wflow_sbm (Schellekens, 2018), was used. The model concept is part of the distributed hydrological model platform developed for the Deltares Openstreams project. The Openstreams project aims to facilitate the integration of different modelling concepts, among others HBV, TOPMODEL and sbm (Schellekens, 2018). Wflow models are also able to simulate the discharge at very small time steps.

3.2.1 Wflow_sbm theory

The previous version of wflow_sbm, topog_sbm is a combination of the earlier developed spatially explicit hydro-ecological Topog_IRM model (e.g. Hatton et al., 1992, Vertessy et al., 1996) and elements of TOPMODEL (Beven and Kirkby, 1979). The model was designed for the simulation of runoff in fast responding small catchments (< 10km²) with steep slopes and relatively thin soils (Vertessy & Elsenbeer, 1999, Schellekens, 2018). The fully distributed topog_sbm model consists of a simple bucket module for soil water flow, with a 1D kinematic wave overland and subsurface flow scheme and a topography based surface and subsurface flow routing. The wflow_sbm model was therefore assumed to be the best suitable model concept for peak discharge simulations in the Upper Ciliwung catchment. An overview of the main stores and fluxes involved in the wflow_sbm model can be found in Figure 3-1.

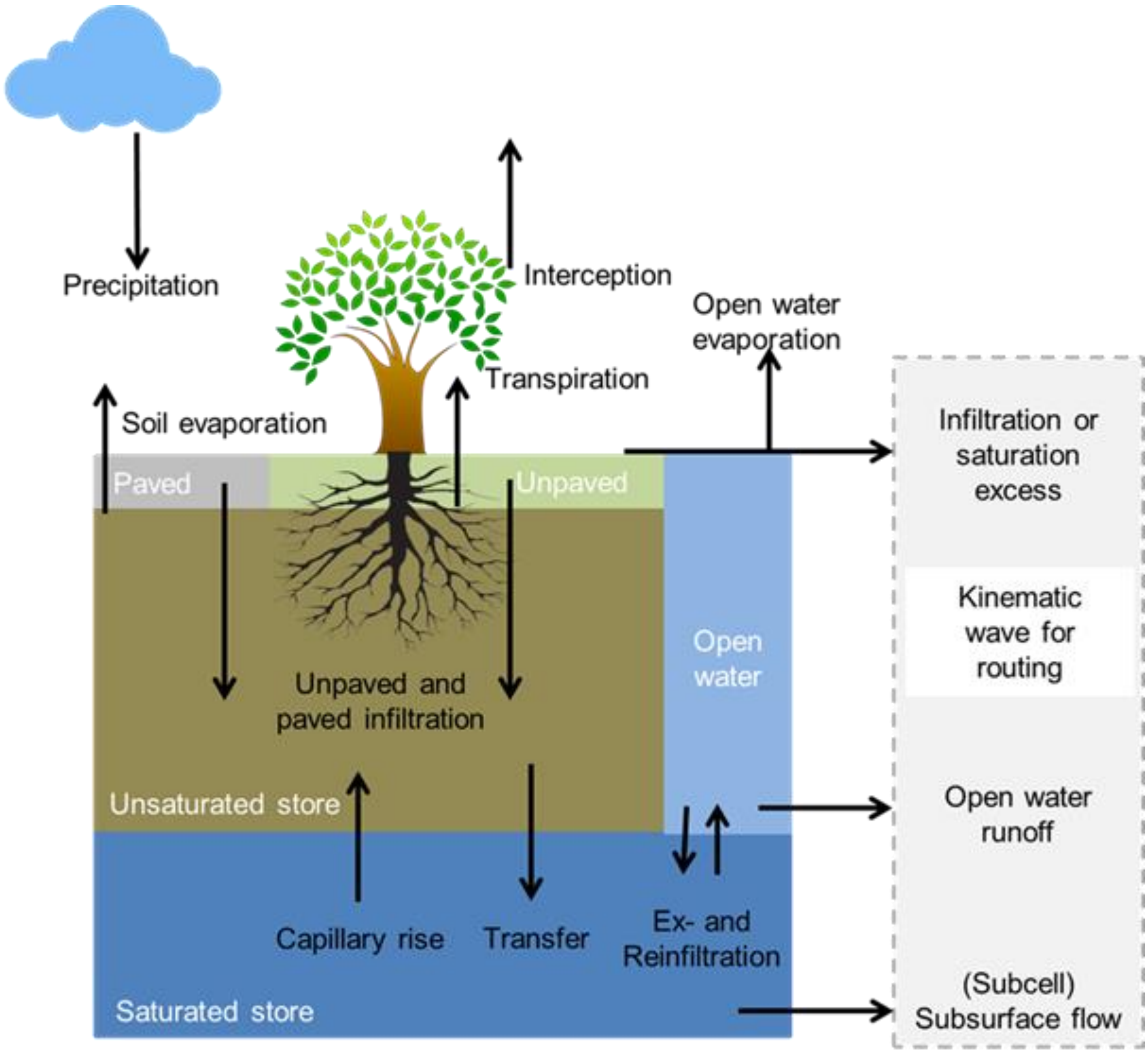


Figure 3-1. Overview of the stores and fluxes taken into account in the wflow_sbm model (Schellekens, 2018).

In the following, a description of the model representation of the main relevant processes for the study area are given, unless stated otherwise, according to Schellekens (2018).

Precipitation, Potential Evapotranspiration and Temperature.

The model needs total precipitation and, if available, potential evaporation in mm per time step as input. Temperature input is only needed if snowfall is expected in a catchment situated in a colder climate or at a certain altitude. In the tropical climate of the Upper Ciliwung catchment there is never snowfall and therefore temperature is not needed as model input.

At the time of research, the interpolation of point data was not working in wflow. One can only assign the forcing data per 'sub-catchment'. The sub-catchments used in this study will be further introduced in section 3.2.2.

Soil Evaporation and Interception

On sub-daily time steps the interception evaporation is calculated using the simplified Rutter model (Rutter et al., 1971). The model calculates the water balance of a canopy based on losses of throughfall and stemflow and evaporation of intercepted rainfall by leaves and trunks (Gash and Morton, 1978). A brief overview of Rutter's modified interception model can be found in Gash and Morton (1978).

The simplified version of Rutter's interception model is implemented in wflow_sbm as follows:

$$\text{(1)}\quad Actual\ Wet\ Canopy\ Evaporation\ (Net\ Interception,\ mm) = Precipitation\ (P) - Throughfall\ (TF) - Stemflow\ (SF)$$

With:

(2) $Stemflow\ (mm)\ =\ P\ *\ p\ *\ 0.1$

(3) $p\ =\ canopy\ gap\ fraction\ =\ -\ e^{k_{ext}\ *\ LAI}$

LAI = Leaf Area Index (-)

K_{ext} = extinction coefficient (-)

P in (mm)

(4) $Throughfall\ (mm) =\ P\ *\ p\ -\ C_{max}$

With:

(5) $C_{max}\ \left(Canopy\ Capacity\ (mm)\right) = C_{max}(leaves)\ +\ C_{max}(wood)\ =\ Specific\ leaf\ storage\ (SI) * LAI\ +\ C_{max}(wood)$

The values of C_{max}(wood), K_{ext} and SI differ according to land use and can be found in Appendix A.

The soil evaporation is defined as:

(6) $ET_{soil}\ =\ ET_{pot}\ *\ \frac{S_d}{CSW}$

With: CSW = Soil water capacity

Storage and Subsurface flow

The soil module of the model is considered as a simple bucket with an unsaturated and saturated soil layer.

The storage of the unsaturated zone U (m) exists of a saturated part U_s and a deficit part U_d which are related as follows:

(7) $U_s\ =\ U - U_d$

(8) $U_d\ =\ (\theta_s - \theta_r)\ *\ z_t - U$

In which z_t is depth (m) of the pseudo-water table at the top of S, θ_s is the saturated volumetric water content and θ_r the residual water content, both dimensionless.

The storage S (m) of the saturated soil layer is defined as:

(9) $S\ =\ (z_t - z_i)\ *\ (\theta_s - \theta_r)$

With:

z_i = depth of the soil profile (m).

The saturation deficit (S_d) for the whole soil profile is:

(10) $S_d\ =\ (\theta_s - \theta_r) * z_t - S$

All rainfall is assumed to fall in the U store first (Vertessy and Elsenbeer, 1999). The flow (m^2/d) between the saturated and unsaturated stores (st) is then defined as:

(11) $st\ =\ K_{sat}\ *\ \frac{U_s}{S_d}$

K_{sat} = saturated conductivity (m/s) at depth z_i calculated by:

(12) $K_{sat}\ =\ K_0\ *\ e^{(-zf)}$

With:

K_0 = saturated conductivity at soil surface

f = model parameter (-) calculated by:

(13) $f\ =\ \frac{\theta_s - \theta_r}{M}$

M = governing parameter of the decay of K_0 with depth.

The rate of the flow increases with decreasing saturated store deficit.

The lateral subsurface flow (m^2/s) through the saturated layers is calculated as:

(14) $sf = K_0 * tan(\beta) * e^{\left(-\frac{S_d}{M}\right)}$

With:

β = element slope angle.

Overland flow & Runoff

The flux of overland flow is calculated according to (Vertessy and Elsenbeer, 1999):

(15) $q = v\, A\, \Delta t$

With:

A = area of an element

Δt = time step

in which the flow velocity v is calculated using the Manning-equation:

(16) $v = \frac{h^{2/3}\sqrt{tan(\beta)}}{n}$

with:

n = Manning coefficient (-)

h = flow depth (m)

The one-dimensional kinematic wave flow routing is governed by the continuity equation:

(17) $\frac{dh}{dt} + \frac{dq}{dx} = v_0$

With:

q = net flux overland flow flux (m^2/s)

x = distance downslope (m)

v_0 = rate of water lost or added (m/s)

Overland flow will be generated in the model in a number of situations:

- The rainfall rate exceeds K_0
- The rainfall depth exceeds U_d and saturation excess is generated
- Rain falls on a saturated element
- Exfiltrating water, as a consequence of subsurface flow from upstream, entering a saturated element

If a neighbouring downstream element is not saturated the overland flow can reinfiltrate in that cell.

The runoff generation in each cell is calculated from the water balance:

$$Q = P - ET - \Delta S$$

The effective rainfall amount: precipitation (P) - evapotranspiration (ET), which could end up as runoff depends on the prementioned processes in each cell. The amount which is stored at each time step in either the U or the S store, ΔS, is calculated as infiltration minus exfiltration. The total amount of runoff is calculated as the sum of saturation and infiltration excess, overland flow and lateral saturated subsurface flow. (Vertessy and Elsenbeer, 1999). Water is routed through the catchment via the local drainage direction (Arnal, 2014).

3.2.2 Base model

The wflow_sbm model of the Upper Ciliwung catchment was generated using the wflow-modelbuilder based on a selection of global data sets (Schellekens, 2018). The catchment model representation is shown in Figure 3-2.

The model consist of grid cells with cell size of 0.0005° x 0.0005° (lat lon, approximately 0.053 x 0.055 km) and computation is done using a PCRaster python script and static maps (Arnal, 2014). These static input maps are raster files (in .map format) of the following: a Digital Elevation Model (DEM, SRTM V4, 30m resolution), land use (Global Land Cover Climatology map by the USGS Land Cover Institute (LCI)), soil texture derived from FAO's Harmonized World Soil Database (0.25km^2 resolution) and map files of catchment delineation (HydroBASINS subcatchments), the local drainage direction (ldd), rivers and tributaries based on streams and stream-orders calculated from the DEM. The generated Upper Ciliwung catchment raster is situated along the following coordinates (in lat lon): [107.008272, -6.76269], [107.008272, -6.627204], [106.839351, -6.627204], [106.839351, -6.76269], [107.008272, -6.76269]. In two maps (wflow_outlet.map and wflow_gauges.map) the outlet of the Upper Ciliwung at the Katulampa weir is represented, at which point the discharges were calculated (Figure 3-2. The model representation of the Upper Ciliwung in wflow_sbm is shown in the left figure and includes the location of rivers, tributaries and the Katulampa outlet (red triangle). In the red area in the right figure (Sub-catchment 2) the rainfall measured at Bendung Gadog ARR was uniformly distributed.Figure 3-2). The current land use as implemented in the wflow_sbm model is shown in Figure 3-3.

The input of forcing data should be distributed over the catchment based on areas defined as different 'sub-catchments' in the wflow_subcatch.map. Each sub-catchment should cover an area where it can be assumed that, for example, the observed rainfall is uniformly distributed, regardless of whether or not these sub-catchments also have a hydrological meaning in reality. In theory, one could also choose to use the whole catchment as one 'sub-catchment' if it is justified to apply the same (point) rainfall observations at each cell within a sub-catchment. For this research, due to a lack of catchment wide rainfall data at high measurement frequency, the point observations from the Bendung Gadog ARR were assigned to a small area in the west of the catchment, 'Sub-catchment 2' (Figure 3-2). This choice was made for two reasons: In the first place, a test run revealed that if one would assign this point observation over the whole catchment, the simulated discharge at Katulampa would be severely overestimated by up to 10 times compared to the observed discharge. This implied that the extent of the total rainfall measured at each time step at the Bendung Gadog ARR must have been considerably smaller. The second reason, was the assumption that the orography was the only factor inducing a rainfall event in the Upper Ciliwung. It was assumed that at the altitude of the rainfall station, approximately 10km upstream from the catchment outlet in south-east direction, the rainfall would start.

To the other parts of the catchment, defined as 'Sub-catchment 1', no rainfall was assigned for all simulations. The two sub-catchments are shown in Figure 3-2.

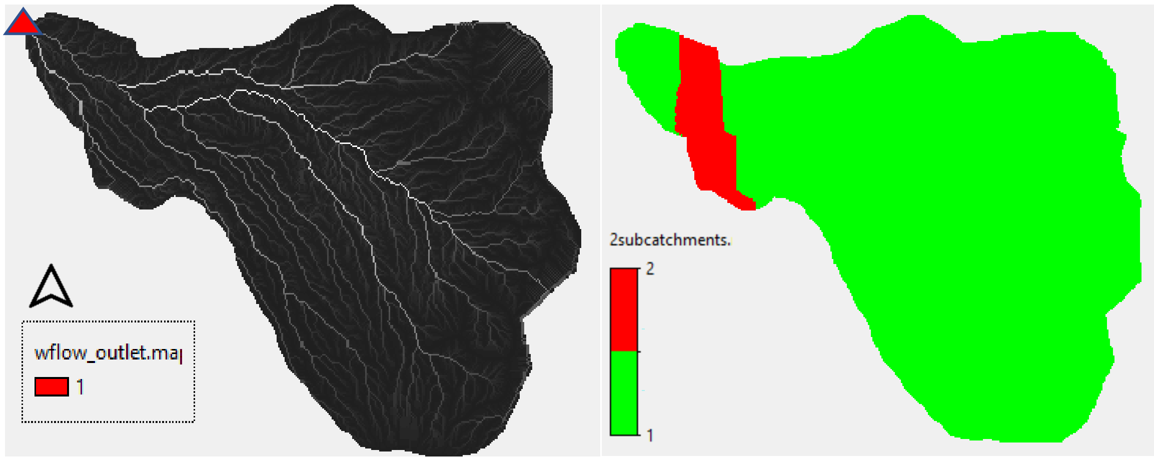


Figure 3-2. The model representation of the Upper Ciliwung in wflow_sbm is shown in the left figure and includes the location of rivers, tributaries and the Katulampa outlet (red triangle). In the red area in the right figure (Sub-catchment 2) the rainfall measured at Bendung Gadog ARR was uniformly distributed. There was no rainfall assigned to the green area (Sub-catchment 1) for all simulations.

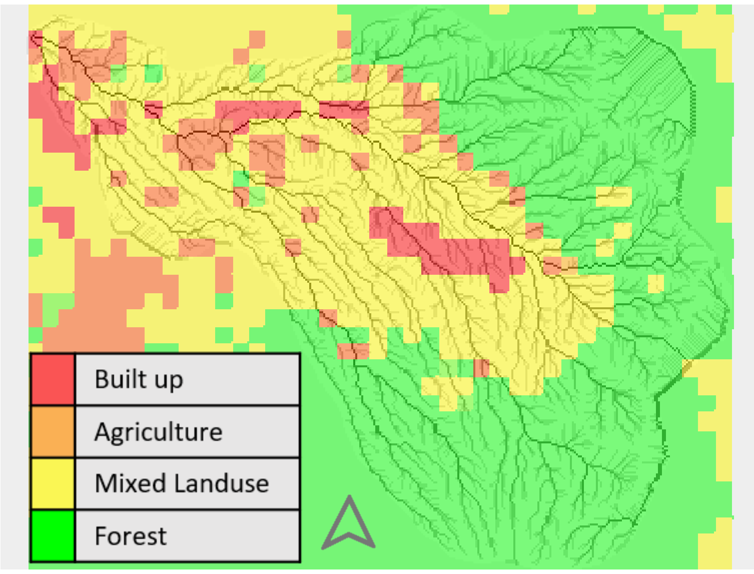


Figure 3-3. Map of the current land use as implemented in the wflow_sbm model. Small square ~ 238 ha.

There are two different types of parameter input files, map files and table files (.tbl format). Parameter values stored in .map format directly covers the spatial distribution of a parameter in the catchment and can be adapted per grid cell. Parameters stored in .tbl format are converted into a .map file after a value is assigned based on soil texture and/or land cover in each grid cell and can also be sub-catchment dependent (Schellekens, 2018). All parameters can be assigned using either a .tbl file or .map file.

The default model output per time step, discharge (m^3/s) and water levels (m), at the catchment outlet is given in both .tss and .csv-format.

3.2.2.1 Forcing data

The rainfall data measured at a frequency of 5 minutes from the Bendung Gadog ARR (P_{obs}) were first recalculated to 10-minutes rainfall totals, in line with the measurement frequency of the water levels (section 3.1), for the use as model input. As discussed in the previous section, the rainfall observations were uniformly distributed in area Sub-catchment 2. The final input of a rainfall event was stored in .tss format. The potential evapotranspiration (ET_{pot}) was set to 0 mm for each time step in this study, assumed that there is no evapotranspiration during a (storm) rainfall event and that the actual amount of evapotranspiration would otherwise be negligible compared to the magnitude of the total discharge and rainfall during this short timescale rainfall-runoff process. As explained in the previous section, temperature was not needed as model input.

To investigate the magnitude of P_{obs} in area Sub-catchment 2 relative to a catchment wide covering rainfall input like a satellite observation cell from the Tropical Rainfall Measurement Mission (TRMM, 2018, 0.25° x 0.25° resolution), a simplified water balance for one of the studied rainfall events was calculated.

$$Q_{obs,total} = P_{obs} - ET_{act,(sim)}$$

The observed river discharge (Q_{obs}) at the Katulampa weir was calculated from the every 10-minutes measured water level records ($h_{Katulampa}$, see also section 3.1) using the stage-discharge relationship described in Odink (2007):

$$For: 0.33 < h_{Katulampa} < 1.05;\ Q_{obs} = 95.34 * (h_{Katulampa} - 0.33)^{2.310} \tag{18}$$

$$For: 1.05 < h_{Katulampa} < 3.50;\ Q_{obs} = 76.76 * (h_{Katulampa} - 0.27)^{2.145}$$

With: Q_{obs} in (m^3/s) and $h_{Katulampa}$ in (m)

Errors in the calculated total volume discharged during the studied event at Katulampa ($Q_{obs,total}$) were calculated from the uncertainty bounds constructed for Q_{obs}. These bounds were based on the average error in Q-h relations found in previous studies (McMillan and Westerberg, 2015). For low flow conditions ($h_{Katulampa}$ < 0.99 m) an uncertainty of ±25% was estimated, while for peak flow conditions ($h_{Katulampa}$ > 1.0 m) an uncertainty of ±13% was taken into account.

The uncertainty in P_{obs} for both observation sources was approximated at ±10% to account for random measurement errors. The actual evapotranspiration (ET_{act}) was estimated based on a 2 months test simulation of the wflow_sbm model in the Upper Ciliwung between January and March for which a constant potential evaporation value of 4 mm/3hours was recalculated to ET_{act}. An uncertainty of ±15% in the ET_{act} model calculation was taken into account.

In this way it was examined to what extent the usage of the rainfall input in Sub-catchment 2 could be justified, assumed that Q_{obs} is approximately the 'true' discharge at Katulampa.

3.2.2.2 Model parameters

The original topog_sbm had six input parameters: soil depth, saturated hydraulic conductivity at soil surface (K_0), decay constant of K_0 with depth (M), Mannings coefficient (N) and both the saturated and minimum residual soil water content (θ_s and θ_r, respectively). Vertessy and Elsenbeer (1999) used this model to simulate storm runoff in a very small, < 1 ha Amazonian catchment, for time steps of 5 minutes. They managed to predict the peak runoff and lag time to a certain extent for a large number of different rainfall events. In wflow_sbm there is a larger number of partly land cover and soil type dependent input parameters. The most important parameters and units can be found in Table 3-2 and example maps can be found in Appendix B. All final parameters values and variables used before and after calibration can be found in Appendix B.

Table 3-2. Most important/sensitive parameters of the wflow_sbm model.

Parameter	Units	Filename and Format
Vertical Saturated Conductivity (K_0)	mm/d	KsatVer.map
Decay governing parameter of K_0 with depth (M)	-	M.map
Saturated water content (θ_s)	mm/mm	ThetaS.map
Minimum Soil Depth (z_{min})	mm	SoilMinThickness.map
Manning's roughness parameter (N)	-	N.tbl
N for river cells (N_{river})	-	N_river.tbl

3.2.2.3 Sensitivity Analysis

Before calibration, a sensitivity analysis was carried out to investigate the impact of 50% change in key parameters values on the simulated discharge at the Katulampa outlet. Standard Values for Java Island (Van Loenen, 2018, personal statement, see Appendix B) were used as base values and 2 rainfall events with total P_{obs} of 12.5 and 28.5 mm were used as model forcing. Next to the most important parameters (Table 3-2), also the effect of changes in θ_r (theta R) and values of the infiltration capacity of the soil (Infilt) were investigated, as it was expected that these would also influence the amount of water stored or released and eventually the shape of the hydrograph. Based on the outcome, the most sensitive parameters were chosen for optimization of the base model.

3.2.2.4 Calibration and validation

The manual calibration of the model was done based on two peak flow events, one in a relatively dry catchment, with at least 3 days of no rainfall and one in a relatively wet catchment (see Table 3-3). The hydrograph of the calibration events for dry and wet initial conditions can be found in Figure 3-4 and Figure 3-5 respectively. Before any simulation in wet initial catchment conditions, the initial model states (i.e. amount of water in storage) were obtained after a model initialization run using 2 months of 3-hourly precipitation data (TRMM, 2018) and a constant evapotranspiration rate of 4 mm/d between January and March 2017 (Table 3-3).

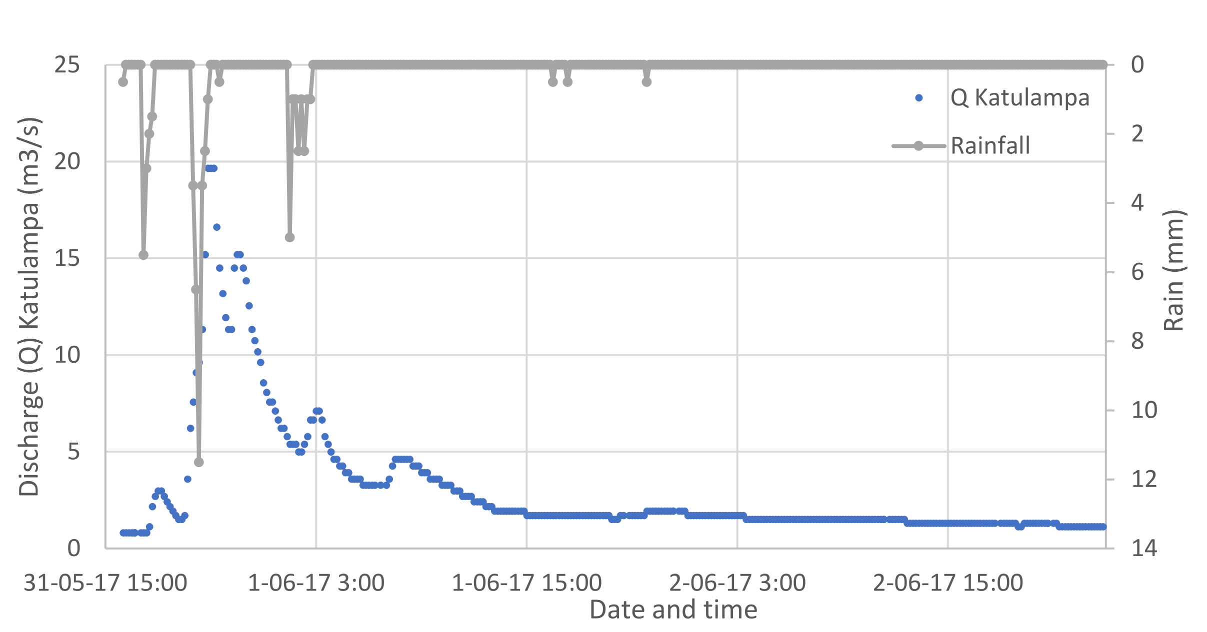


Figure 3-4. Hydrograph of an event in dry initial catchment conditions used for calibration.

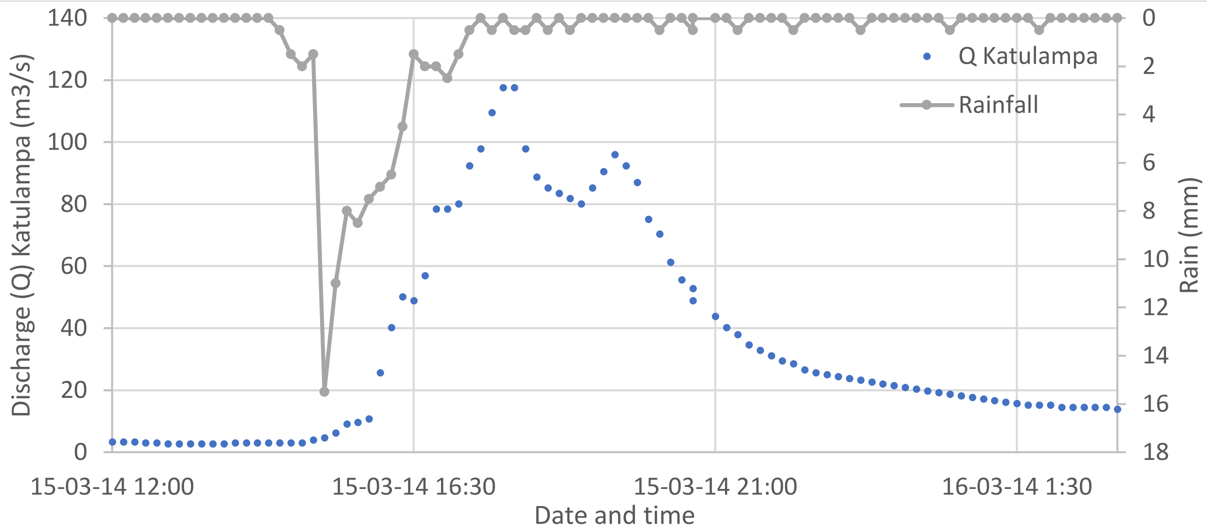


Figure 3-5. Hydrograph of an event in wet initial catchment conditions used for calibration.

As a goodness of fit measure, the Nash-Sutcliffe efficiency (NSE) was used (Nash and Sutcliffe, 1970):

$$(19)\ NSE = 1 - \frac{\sum_{k=1}^{n} \left(Q_{k,sim} - Q_{k,obs}\right)^2}{\sum_{k=1}^{n} \left(Q_{k,obs} - \overline{Q}_{obs}\right)^2}$$

As it is widely used, the model performance can easily be compared with the model performance results from previous studies in the same area. Furthermore, a more suitable modification of the NSE (NSE_{adj}) was also used for the model evaluation. The NSE_{adj} is more sensitive for systematic under or overestimation of Q_{obs} under peak flow conditions (Krause et al., 2005).

$$(20)\ NSE_{adj} = 1 - \frac{\sum_{k=1}^{n} \left(Q_{k,sim} - Q_{k,obs}\right)^4}{\sum_{k=1}^{n} \left(Q_{k,obs} - \overline{Q}_{obs}\right)^4}$$

As this study aims to simulate peak discharges as accurate as possible, the model performance based on NSE_{adj} was decisive for the evaluation of each parameter set during the calibration procedure.

The first 20 time steps of each simulation were used as warm-up steps to allow for sufficient time for the attenuation of possible unrealistic initial base flow conditions or recession rates, especially for wet initial condition simulations after the initialization run (section 3.2.2.4), which could influence the total model performance. For this reason, the simulation results of the first 20 time steps were not taken into the calculation of the NSE and NSE_{adj} for all model runs.

After calibrating the model for two different conditions, two rainfall events were chosen for validation of both model settings (Table 3-3): an event in a relatively dry catchment condition and an event which caused a severe flooding in Jakarta in the period of 10 to 20 January 2014 (Siswanto et al., 2015).

Table 3-3. Calibration and validation periods.

	Dry (3 days without rain before the event)	**Wet (At least 1 rainfall event in three days before the event**)**
Calibration:	31-05-17 16:00 – 03-06-17 0:00	15-03-14 12:00 – 16-03-14 09:00⁺
Validation:	21-01-17 12:00 - 22-01-17 18:00*	22-01-14 13:00 – 23-01-14 22:00
	*Also used for validation using 1 hour time step.	⁺Also used for calibration using 1 hour time step.
	** Model states obtained using initialization run using TRMM data and constant ETpot of 4.0 mm/day between 05-01-17 15:00 – 06-03-17 12:00	

Based on the best values of NSE_{adj} for calibration and validation and an extra visual inspection of the ability of the model to simulate the timing, shape and magnitude of the discharge peak in both dry and wet conditions, the best suitable model settings were chosen for the use as base model for the scenario analysis.

One of the limitations of wflow_sbm is that results for different time steps may differ completely due to the simple numerical solution used by the model (Schellekens, 2018). Furthermore, for any model, the computation of results at smaller time steps will be more time consuming, because more computer power is needed. Therefore it was investigated if there was any gain in model performance using 10-minute time steps compared to hourly time steps. In this way it was determined if the computational effort is worth considering. Due to time constrains, this was only done using the wet calibration and the dry validation event (Table 3-3).

3.2.3 Scenario Analysis

This study will investigate the impact of land use change scenarios for a typical rainfall event, in terms of duration and total amount, relative to the base model and compare the outcome with results from previous studies. This gives insight in the added value of using small modelling time steps for the calculation of the impact of land use change on the peak discharge at Katulampa.

Only small areas in the west of the catchment were changed:

(1) ±8 km² increase of built up area at the cost of forest and agriculture (Larger villages, Figure 3-6).

(2) ±1 km² decrease of built up areas for a small reforestation project (Reforestation, Figure 3-7).

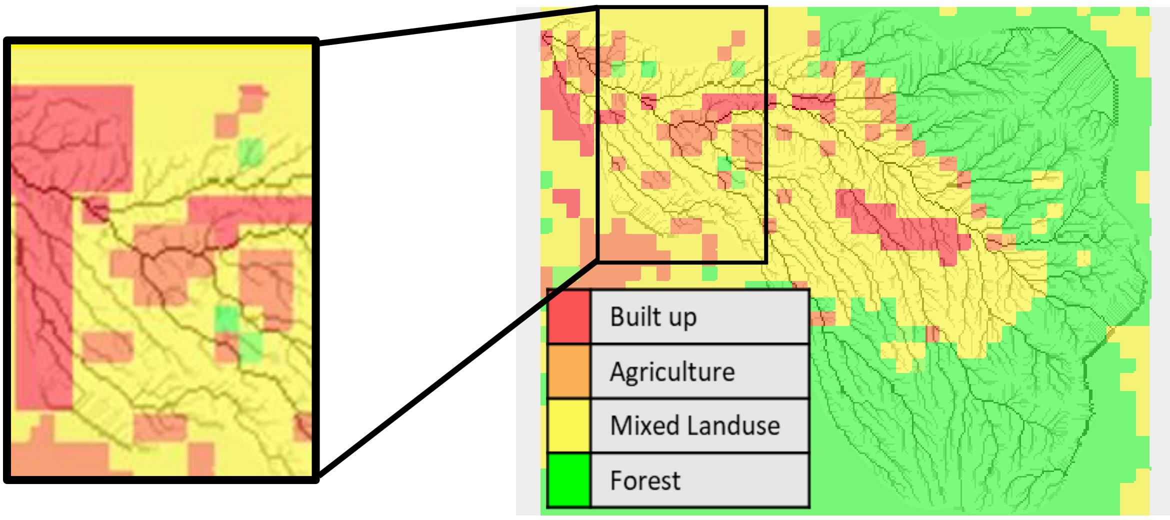


Figure 3-6. Land use map of the west of the catchment showing scenario 1: Larger villages (left), compared to the (area of the) current land use map (right). Smallest square ~ 238 ha.

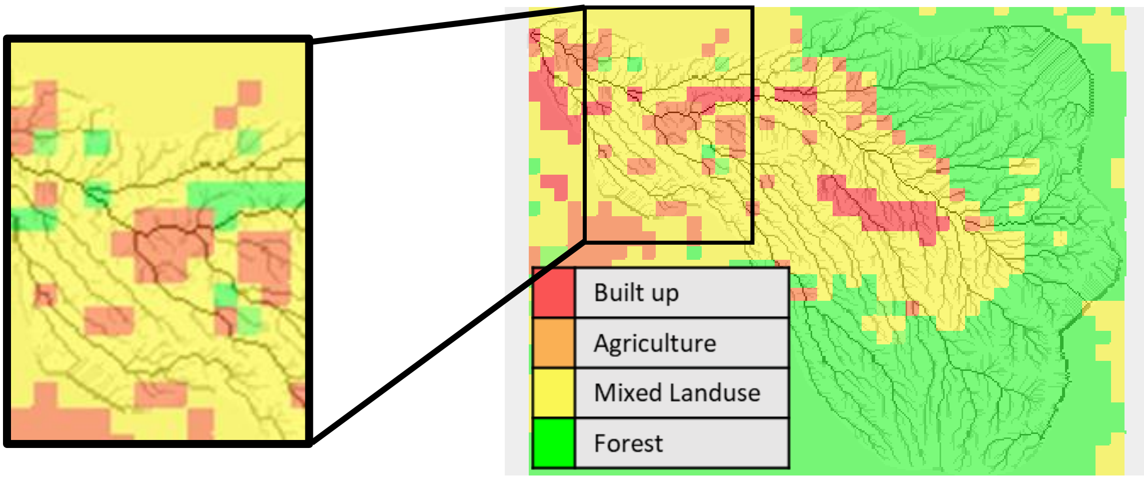


Figure 3-7. Land use map of the west of the catchment showing scenario 2: Reforestation (left), compared to the (area of the) current land use map (right). Smallest square ~ 238 ha.

The main reason that changes were only made in this part of the catchment, was that the model was calibrated based on rainfall input in Sub-catchment 2, in the west of the catchment (section 3.2.2). It was assumed that the impact of land use change on the resulting discharge simulations close to the densely populated catchment outlet would be more distinct, than if changes in the whole catchment were made. In this way, it was expected that the effect of every mm of rain falling on the changed landscape could be studied in more detail and better quantified. Furthermore, the impact of small changes in the more upstream parts of the catchment could theoretically be attenuated by the catchment itself due to (re)infiltration to deeper parts of the confined aquifer or interception (canopy storage). The described small changes are also realistic to occur or to implement in the next decade, in contrast to land use change scenarios analysed in previous studies (e.g. Poerbandono et al., 2014, Emam et al., 2016).

The changed area per land use type in each scenario can be found in Table 3-4. The parameters adapted for the realization of each scenario compared to the base model can be found in Appendix C. The rainfall event used for the simulations of each scenario, was the same as the rainfall event of the validation event in a relatively dry catchment, occurred between the 21st of January and 22nd of January (Table 3-3). Only changes in Q_{sim} before and after the peak discharge directly caused by the rainfall event were evaluated with respect to the base model.

The outcome of the comparison between these two scenarios will provide insight in the effect of land use change on short timescale runoff processes, possibly interesting in view of flood risk mitigation possibilities in the upstream part of the Ciliwung catchment.

Table 3-4. Land use (LU) distribution in the base model and for the different scenarios.

	Current LU (km^2)	**Scenario 1: Larger Villages (km^2)**	**ΔLU (km^2)**	**Scenario 2: Reforestation (km^2)**	**ΔLU (km^2)**
Built up	8.72	17.06	+8.34	7.60	-1.12
Forest	80.60	80.39	-0.21	81.72	+1.12
Agriculture	8.75	7.74	-1.01	8.75	0
Mix Agriculture/ Original Vegetation	51.48	43.36	-7.12	51.46	0
Grassland	9.88	9.88	0	9.88	0
Total	159,43	159,43		159,43	

4 Results

4.1 Current rainfall-runoff characteristics

An overview of the calculated basic statistics of rainfall-runoff characteristics between 2013 and 2017 can be found in Table 4-1. The event based rainfall data from the Bendung Gadog ARR showed that typical rainfall events in the Upper Ciliwung lasts on average between 77-100 minutes. This is as expected from findings in the literature (<2 hours, see section 1.2). The longer rainfall events occur usually in the wet season (November-April), but not necessarily causing a higher amount of precipitation (see Table 4-1).

The delay between the measured discharge peak at the Katulampa weir after the peak of a rainfall event upstream is on average 84 minutes. The mean travel time of the discharge peak between Katulampa and Manggarai, in the city centre of Jakarta, is approximately 848 minutes (±14hours, see Figure 4-1).

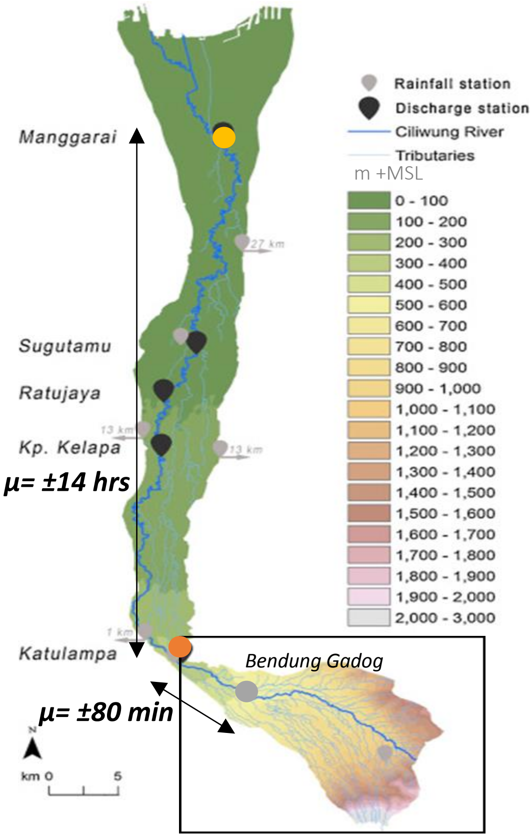


Figure 4-1. Overview of the average (μ) peak discharge response times at 2 locations in the Ciliwung catchment, Katulampa (orange circle) and Manggarai (yellow circle) after a rainfall event in the Upper Ciliwung measured at Bendung Gadog (grey circle). The rectangle shows the location of the Upper Ciliwung catchment. Catchment map and legend were adapted from Remondi et al. (2015).

Table 4-1. Event based statistics of rainfall-runoff characteristics in the period 2013-2017.

n=Rainfall Event	Mean± Standard Deviaton
Duration rainfall wet season	100±37 minutes (n=11)
Duration rainfall dry season	77±31 minutes (n=8)
Total Precipitation wet season	30±16 mm (n=11)
Total Precipitation dry season	31±20 mm (n=8)
Response time peak water level at Katulampa after rainfall peak	84±39 minutes (n=19)
Response time peak water level Manggarai relative to Katulampa	848±177 minutes (n=19)

The maximum water levels at the Katulampa outlet $h_{max,Katulampa}$ are weakly correlated with the maximum water level records at Manggarai ($h_{max,Manggarai}$, R^2 = 0.47). There is statistically significant predictive power of $h_{max,Katulampa}$ for downstream $h_{max,Manggarai}$ (at α=0.05, sign F =0.001):

$$h_{max,Manggarai} = 583 + 1{,}21 * h_{max,Katulampa} \quad (21)$$

If one would substitute the alarming water levels at Katulampa as stated in Figure 2-2 in eq. 21, approximately the corresponding alarming water levels at Manggarai are found, showing that the observed water levels are in the correct order of magnitude.

4.2 Model performance

4.2.1 Sensitivity Analysis Base model

The variation of the discharge signal caused by changing values of an individual parameter in the sbm_wflow model can be observed in Figure 4-2 and Figure 4-3. There are a few parameters causing a distinct change in the simulated discharge (Q_{sim}) compared to the uncalibrated base model, by increasing or decreasing their magnitude by 50%, keeping all other parameter values unchanged. Θ_s (theta S), soil minimum thickness and k_{sat} (ksat) are among the most sensitive for both low and high discharges, causing a distinct change of Q_{sim} of up to 100% or even more compared to the base model.

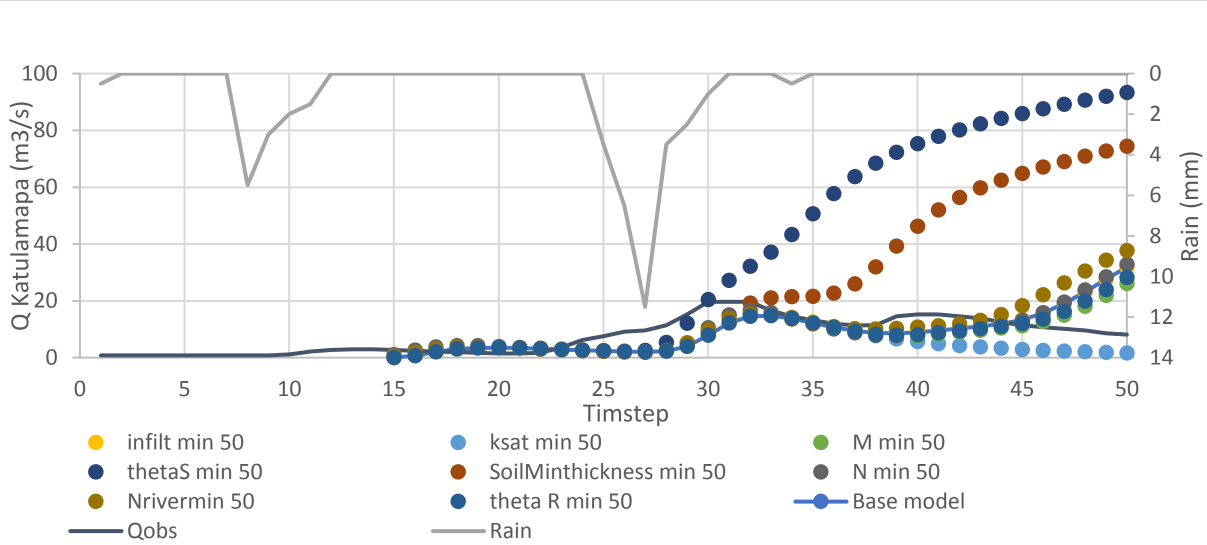


Figure 4-2. Impact of a 50% reduction of some model parameter values on the simulated discharge.

Smaller differences in Q_{sim} were observed after changing the value of the decay governing parameter of k_{sat} with depth (M) and the Manning coefficient for river cells (Nriver) by 50%.

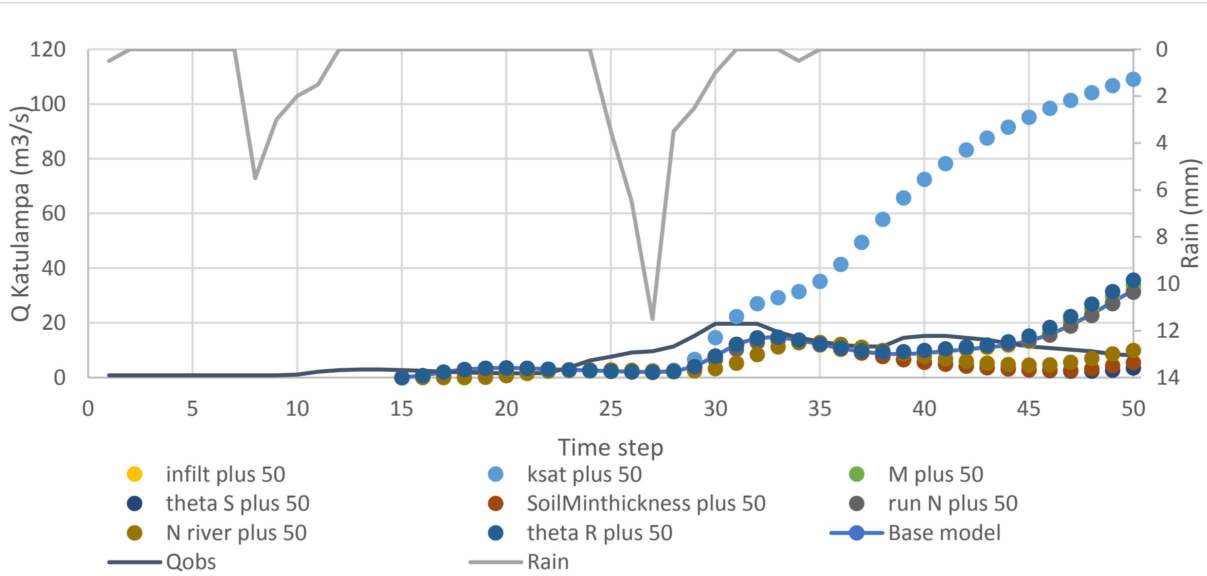


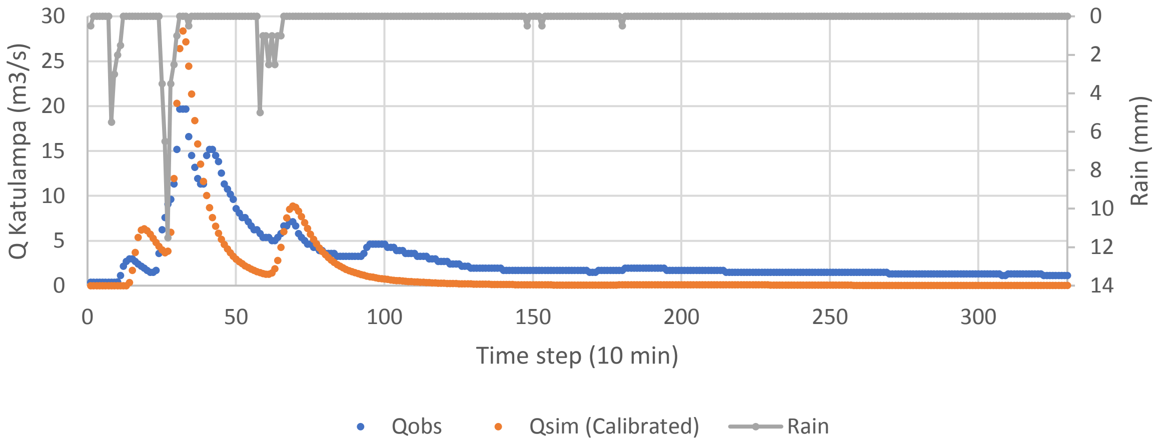
Figure 4-3. Impact of a 50% increase of some model parameter values on the simulated discharge.

4.2.2 Calibration and validation

The hydrographs of Q_{sim} compared to Q_{obs} at Katulampa after manual calibration are shown in Figure 4-4. The adapted parameter values used for calibration and validation can be found in appendix C. The model performances after calibration and validation are shown in Table 4-2. The best performance was obtained from the calibration on a event in dry initial catchment conditions (NSE = 0.41, NSE_{adj} =0.87). Based on the assumption that rain only falls on area Sub-catchment 2 (Figure 3-2), one can observe in Figure 4-4 that the model can reasonably simulate the discharge for dry initial conditions, but certainly not in the case of wet catchment conditions. This is also expressed in the calculated NSE values for calibration and validation (Table 4-2).

Table 4-2. Model performances after calibration of the base model for different initial catchment conditions ('Dry' or 'Wet') and validation using either the calibrated model based on 'dry' or 'wet' conditions for different time steps.

Calibration event	**Performance 10 min time step**		**Performance 1hr time step**
15-03-14 12:00 16-03-14 09:00 (Wet)	NSE=-0.51 NSE_{adj}=-1.53		NSE=-0.06 NSE_{adj} =-0.19
31-05-17 16:00 03-06-17 00:00 (Dry)	NSE=0.41 NSE_{adj} =0.87		
Validation event	**Performance Dry (10 min)**	**Performance Wet (10 min)**	**Performance Wet (1hr)**
21-01-17 12:00 22-01-17 18:00 (Dry)	NSE=0.31 NSE_{adj} =0.61	NSE=0.35 NSE_{adj} =0.67	NSE=0.20 NSE_{adj} =0.31
22-01-14 13:00 23-01-14 22:00 (Wet)	NSE=-13.0 NSE_{adj} =-161	NSE=-12.7 NSE_{adj} =-157	



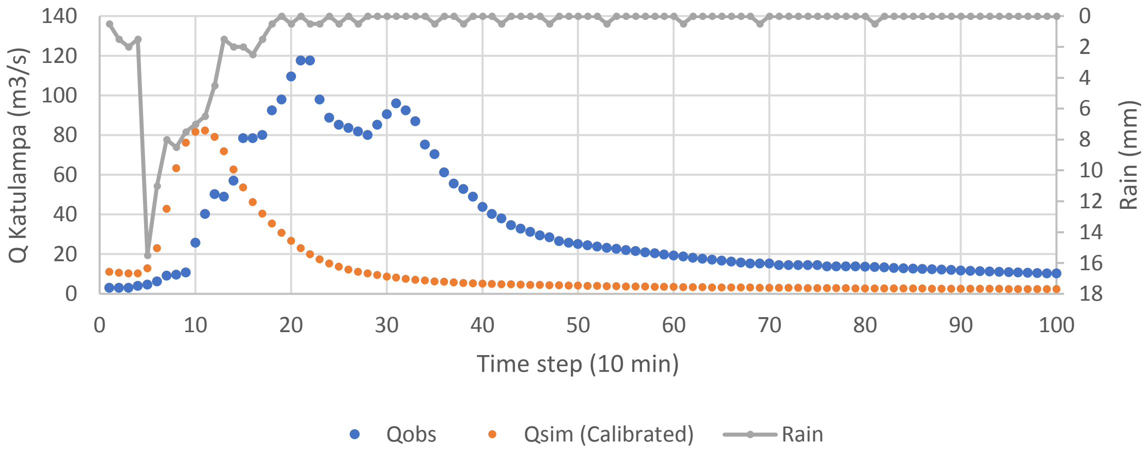


Figure 4-4. Results of the model calibration on dry initial catchment conditions (upper figure) and on wet initial conditions (lower figure).

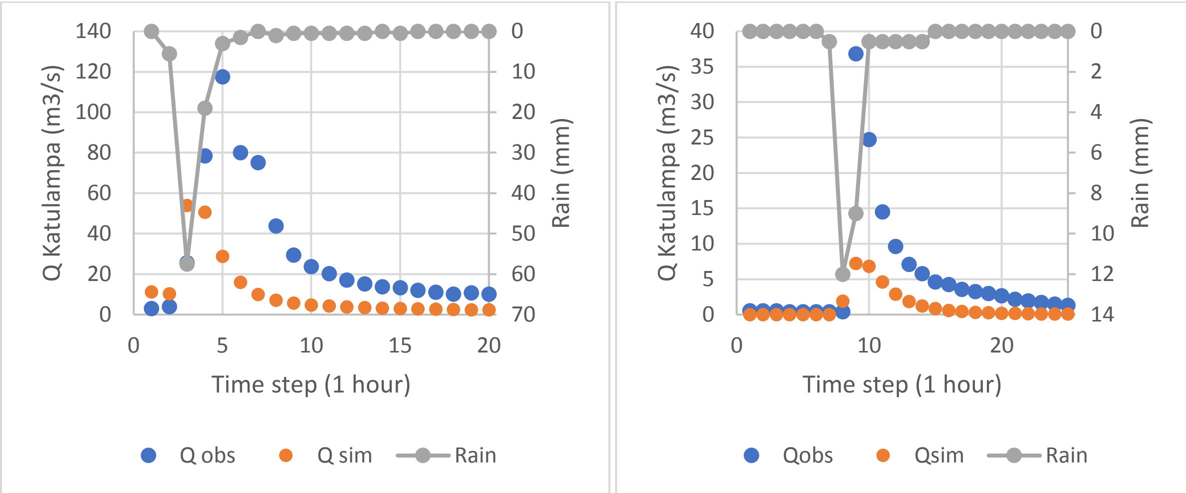
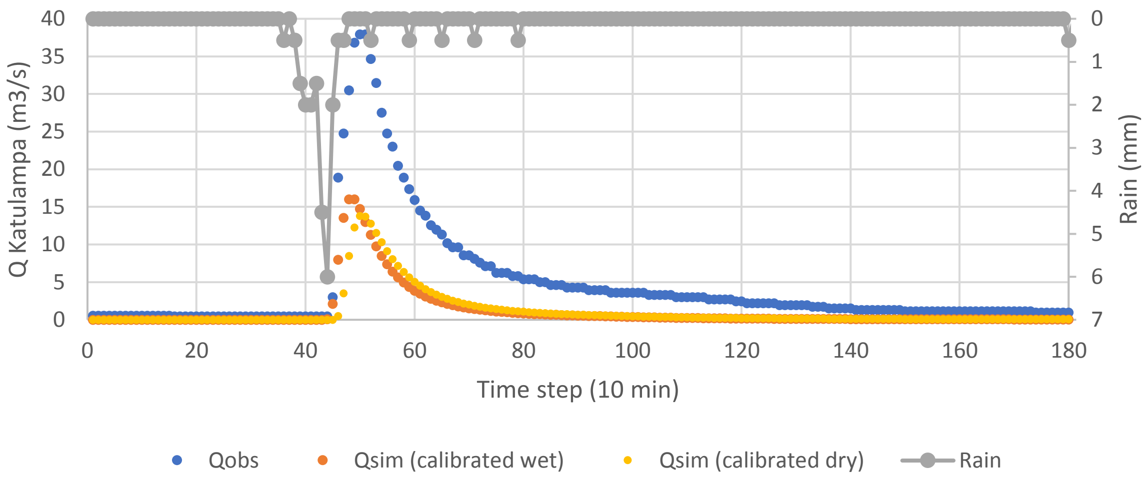


Figure 4-5. Calibration result at a larger time step for the a 'wet' event (left) and for a 'dry' validation event (right).

Some of the dynamics of the discharge peak are reasonably simulated, such as the timing of peak flow and the shape of the discharge signal in terms of rise and recession (see Figure 4-4 (upper) and Figure 4-6 (lower)). However, the model underestimated the observed peak discharge by 20 m^3/s for the validation event at dry initial conditions (Figure 4-6 (upper)). From Figure 4-4 (lower) and Figure 4-6 (lower) it can clearly be observed that both timing and magnitude of the Q_{sim} completely misfits the observed peak flow in a wetter catchment from the very start of the rainfall event. This counts for both calibration and validation events. For the calibration event, the first peak of Q_{sim} is 2 hours ahead of Q_{obs}, while the peak discharge is underestimated by at least 20 m^3/s. The second peak is not simulated at all. The peak discharge, part of the flood event of 2014 ('wet' validation event), is overestimated by approximately 70 m^3/s and the mistiming ranges from 800-1000 minutes (up to 16.5 hours).

The same calibration procedure of an event in wet initial conditions at hourly time steps resulted in a slightly better overall model performance compared to the calibration of the same event at 10-minutes time steps (Table 3-3). The performance is still worse compared to using the average of Q_{obs} for predicting Q_{obs} (NSE and NSE_{adj} < 0). Furthermore it should be noted that one of the discharge peaks of Q_{obs} (100 m^3/s, see Figure 4-4 and Figure 4-5) are missing due to the lower measurement frequency. The peak discharge of the validation event is even more underestimated, about 10 m^3/s more compared to the simulation result at smaller time steps. The better overall performance using small time steps can also be seen from the calculated NSE_{adj} values for the different time steps used (0.31 vs. 0.67, see Table 4-2).



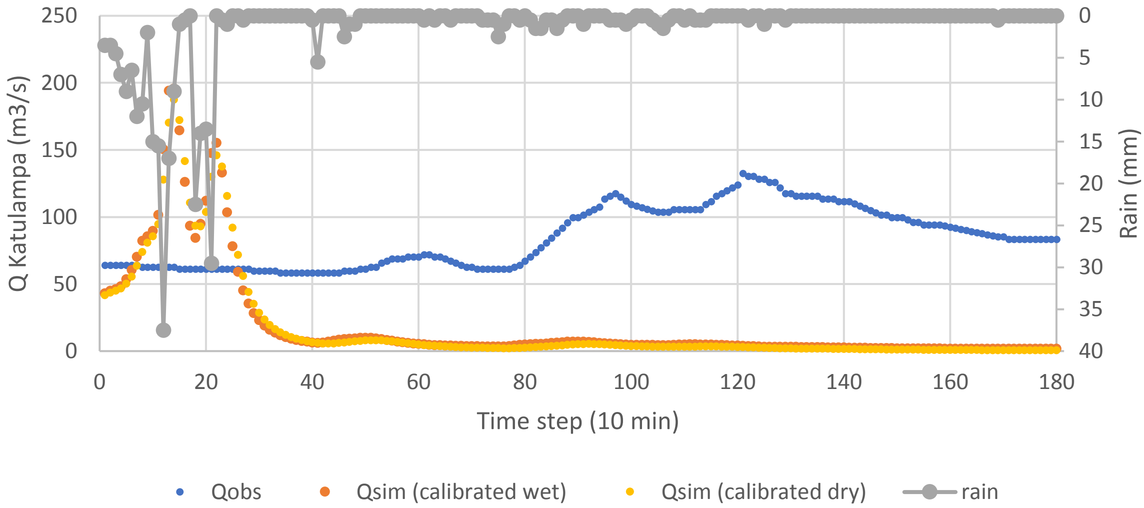


Figure 4-6. Result of the model validation for the 'dry' event (upper) and 'wet' event (lower) using the model calibrated on two different conditions.

4.2.3 Water Balance

The simple water balance calculation was made for the wet validation event (occurred between the 21st of January 2017, 12:00, and the 22nd of January 2017, 18:00). Table 4-3 shows the total amount of water per component including an uncertainty range (section 3.2.2.1). When the storage changes are not taken into account, the total amount of rain in area Sub-catchment 2 is between 100-200 mm too short to cover the amount of water needed to reach Q_{obs}. On catchment average, this amount equals to 3-4 mm. Substituting the P_{obs} of the Bendung Gadog ARR by a catchment covering rainfall observation from a TRMM cell (P_{obs} TRMM) at 3-hours measurement resolution, lead to a calculated rainfall surplus of around 11 mm (Table 4-4). These findings imply that neither the extrapolated point observations nor the TRMM satellite data can sufficiently account for the high spatial variation of the rainfall patterns in this catchment.

Table 4-3. Water balance of the event between 21 and 22 january 2014 using 10-minute interval data for Q_{obs}, ET_{act} from a sbm_wflow test simulation (sim) and Bendung Gadog observations in Sub-catchment 2 for P_{obs}.

	Total per component (m^3)	**ΔP in mm over Sub-catchment 2 (8.34 km^2)**	**ΔP in mm over Upper Ciliwung catchment (159.43 km^2)**
Q_{obs}	$5.0 \pm 1.2*10^5$		
P_{obs} B.Gadog	$2.0 \pm 0.2*10^5$		
ET_{act} (sim)	$2.3 \pm 0.3*10^5$		
Balance	$\mathbf{5.3 \pm 1.3*10^5}$	**150 ± 50 mm**	**3.3 ± 1.1 mm**

Table 4-4. Water balance of the event between 21 and 22 January 2014 using 10-minute interval data for Q_{obs}, ET_{act} from a sbm_wflow test simulation (sim) and TRMM 3-hourly measurement data for P_{obs}.

	Total per component (m^3)	**ΔP in mm over Upper Ciliwung catchment (159.43 km^2)**
Q_{obs}	5.0 ± 1.2*10^5	
P_{obs} *TRMM*	24.3 ± 2.4*10^5	
ET_{act} *(sim)*	2.3 ± 0.3*10^5	
Balance	**-17.0 ± 2.1*10^5**	**-10.7 ± 2.5 mm**

4.3 Scenario Analysis

Based on the validation results (Table 4-2), the base model calibrated on wet initial conditions was used for the scenario analysis. The parameters values adapted for each scenario can be found in Appendix C.

The impact of the two land use change scenarios can be observed in Figure 4-7. From this figure it can be observed that for both scenarios timing, rise and recession of the discharge peak did not significantly changed and only the quantity of water discharged at Katulampa changed. The average change in Q_{sim} corresponding to the new land use change distribution is stated in Table 4-5 and Table 4-6 and is further discussed in the next sections.

4.3.1 Larger Villages scenario

In this scenario, a slight increase of built up space (Table 3-4) has been simulated for different initial conditions. At dry initial catchment conditions, the peak discharge increased with 0.9 m^3/s (5%) compared to the base model, based on the same rainfall input as observed during the dry validation event (21.5 mm/2hrs). At wet initial conditions, the peak discharge increased by 3.2 m^3/s (15%) compared to the base model (Figure 4-7).

The total discharge volume raised by 5% for dry initial conditions and a total volume increase of 16% for wet initial conditions (Table 4-5), calculated from the start of the discharge response after a rainfall event.

These results show that there is a consistency in increasing peak discharge and total discharge volume for different initial conditions for the Larger Villages scenario compared to the base model.

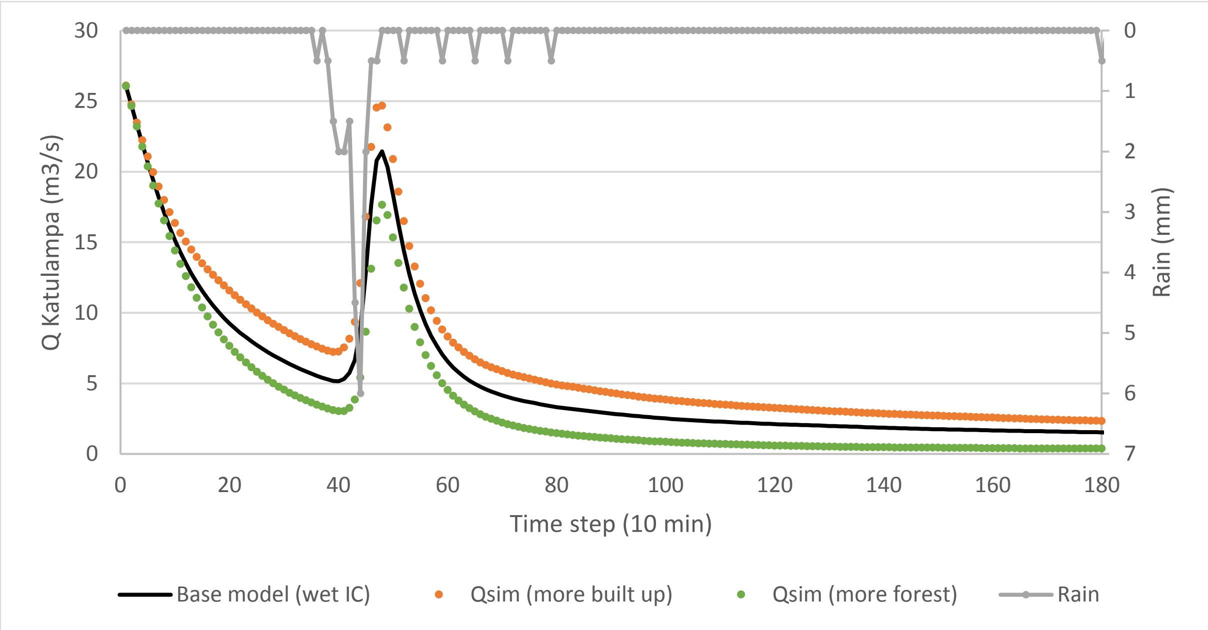


Figure 4-7. Impact of the larger villages (orange dots) and reforestation (green dots) scenario on Q_{sim} relative to the base model (black line) for wet initial conditions.

4.3.2 Reforestation scenario

In this scenario, the total forested area was changed at the cost of built up space (Table 3-4). Again the same rainfall event part of the dry validation event was used as model input. Compared to the base model, the peak discharge decreased by 2.0 m^3/s (12.5%) for dry initial conditions and by 3.8 m^3/s (18%) for wet initial conditions (Figure 4-7).

Calculated over the whole discharge signal, the total discharge volume decreased by 12.5% for dry initial conditions and by 23% for wet initial conditions, compared to the base model (Figure 4-7).

These results show the opposite of the Larger Villages scenario: there is a consistency in decreasing peak discharge and total discharge volume for different initial conditions for the reforestation scenario compared to the base model.

4.3.3 Comparison of simulations

In Figure 4-7 the impact of the different land use change scenarios were already clearly visible. Reforestation causes a reduction of the simulated peak flow compared to the base model. An average reduction of 18% was calculated for wet initial catchment conditions and 12.5% for dry initial conditions. On the other hand, the increased built up space caused an average increase of simulated discharge peak between 5-16%. (see also Table 4-5 and Table 4-6)

Zooming in to the exact changes of the total discharge volume caused by a rainfall event, based on the changed land use (Table 3-4) and the average duration and standard deviation of a precipitation event (section 3.1), a water increment rate per unit added built up area and a water reduction rate per unit area reforested was calculated for dry and wet initial catchment conditions for different seasons.

For an average precipitation event, lasting 100 minutes in the wet season and 77 minutes in the dry season (Table 4-1), the estimated water increment rate ranged between 0.26 and 1.5 $m^3/s/ha$ built up in the wet season and between 0.20 and 1.1 $m^3/s/ha$ built up in the dry season (see Table 4-5).

In the same way, the reduction rate was calculated, which ranged from approximately 0.57 to 1.7 $m^3/s/ha$ forest in the wet season and from 0.44 to 1.3 $m^3/s/ha$ forest in the dry season (see Table 4-6).

Table 4-5. The changes in peak discharge (ΔQ_{sim} peak) and average discharge volume (average $\Delta Q_{sim,total}$), based on the rainfall event as appeared in the 'wet' validation period and calculated water increment rates for different seasons and initial conditions (IC) of the Larger Villages scenario relative to the base model.

	Scenario 1: (Larger Villages)	
Average $\Delta Q_{sim,total}$	1.1-3.2 m^3/s (5-16%)	
ΔQ_{sim} peak	0.9-3.2 m^3/s (5-15%)	
	Wet season	Dry Season
Water increment rate wet IC	$1.5 \pm 0.55 * 10^{-2}$ (m^3/ha built up/event)	$1.1 \pm 0.46 * 10^{-2}$ (m^3/ha built up/event)
Water increment rate dry IC	$0.26 \pm 0.09 * 10^{-2}$ (m^3/ha built up/event)	$0.20 \pm 0.08 * 10^{-2}$ (m^3/ha built up/event)

Table 4-6. The changes in peak discharge (ΔQ_{sim} peak) and average discharge volume (average $\Delta Q_{sim,total}$), based on the rainfall event as appeared in the 'wet' validation period and calculated water reduction rates for different seasons and initial conditions (IC) of the Reforestation scenario relative to the base model.

	Scenario 2: (Reforestation)	
Average $\Delta Q_{sim\ total}$	- 0.5-2.8 m3/s (- 12.5-23%)	
ΔQ_{sim} peak	- 2.0-3.8 m3/s (- 12.5-18%)	
	Wet season	Dry Season
Water reduction rate wet IC	$1.7 \pm 0.63 * 10^{-2}$ (m^3/ha forest/event)	$1.3 \pm 0.53 * 10^{-2}$ (m^3/ha forest/event)
Water reduction rate dry IC	$0.57 \pm 0.21 * 10^{-2}$ (m^3/ha forest/event)	$0.44 \pm 0.18 * 10^{-2}$ (m^3/ha forest/event)

When comparing the reduction rates for every unit of added forest with the increment rates for every unit added built up space, one could calculate the compensation needed for a theoretical increase of the total discharge volume. Taking all possible ranges into account for different initial conditions and rainfall durations, as shown in Table 4-5 and Table 4-6, it can be calculated that approximately 2 ha of forest should be sufficient to compensate the increased discharge volume caused by 1 ha of added built up space for an average rainfall event.

5 Discussion

In this study, the added value of a fully distributed model for event based modelling at high temporal resolution were explored in the Upper Ciliwung catchment, Indonesia, with the goal to more accurately simulate peak discharge at the Katulampa outlet. The results showed that the wflow_sbm model in its current state and given limited spatial information on rainfall input, could only simulate certain aspects of the observed discharge, such as the shape and timing of the discharge peak at Katulampa. The results were influenced by a number of (model) assumptions and limitations which are summarized in the next section.

5.1 General assumptions and limitations

Point data of precipitation

High frequency measurements of precipitation (P_{obs}) were only available as point source at the Bendung Gadog ARR. A first modelling attempt, using a uniform rainfall distribution for the whole Ciliwung catchment, based on a rainfall event measured at Bendung Gadog ARR, revealed that the discharge would be severely overestimated by up to a factor 10. This implies that the observations from the Bendung Gadog ARR are not representative for the whole catchment. Local orography, with elevations ranging from 300 to 2900 m, in combination with dominant wind directions, especially during the northwest monsoon (Siswanto et al., 2015), seems to cause large differences in total rainfall amounts in space and time. To tackle a part of this problem, a more local rainfall area was created: Sub-catchment 2 (section 3.2.2). This area is only a small portion of the total catchment, but was assumed to cover the start of an orography induced rainfall event. In this area the P_{obs} from the Bendung Gadog ARR were uniformly distributed. As a consequence, the response of the catchment as whole was not fully explored. Figure 4-4 (upper) and Figure 4-6 (upper) showed that for certain events, after forcing the model with the P_{obs} distributed in Sub-catchment 2, this already lead to a reasonable model fit with respect to Q_{obs} or even an overestimation. For the events for which Q_{obs} was severely underestimated and mistimed it became clear from a simple water balance calculation (section 4.2.3) that it is very important to know the rainfall distribution in space and time very accurately as model input. In this way, it would be possible to get to a better discharge prediction at high temporal resolution.

No evaporation

The actual evapotranspiration (ET_{act}) in each grid cell was not modelled, as 0 mm/d potential evaporation (ET_{pot}) was given as model input. This has caused a structural overestimation of Q_{sim}. However, the model did account for interception, as a land use dependent canopy storage was calculated independent of ET_{pot} (section 3.2.1, eq. 1-5). Given the short timescale of the rainfall events and the relatively short simulation period, the magnitude of ET_{act} was assumed negligible compared to P_{obs} and Q_{sim}.

Base flow and initial conditions

The model initialization run of 2 months, using TRMM precipitation data measured at a time step of 3 hours, was used to store a certain amount of water in the cells, as a rough estimation of wet initial conditions of the catchment. For discharge simulations of situations in which there was hardly any base flow (Figure 4-4 upper and Figure 4-6 upper) prior to a rainfall event, the initial conditions were set to zero (all cells empty storage) as this gave the best simulation results. Generally, one would expect that this approach leads to an underestimation of Q_{sim} if correct rainfall data in space and time were available as model input. Based on the results, it was assumed that any over- or underestimation of the simulated peak discharge events is solely caused by the lack of representative P_{obs} input data and the ignorance of ET_{act} in all simulations.

All the discharge simulations showed that the model is too rapidly routing the river water towards the outlet of the catchment and that storage was released very quickly as well (see for example Figure 4-7). As a consequence, almost no base flow remains, even after very extreme rainfall events (Figure 4-6 (lower)). This is far from realistic and is probably caused by a too simplistic bucket representation of the soil routine (Schellekens, 2018) compared to reality. Also the very steep slopes (up to 40%, Farid et al., 2014) and a too dense drainage network representation of the catchment probably catalyses the fast runoff simulations. The conceptualization of the processes in wflow_sbm are probably not appropriate for such steep catchments. Another explanation for the rapid decrease in base flow is given by Arnal (2014): The exfiltration flux from the saturated zone to the kinematic wave could be a too dynamic model feature causing a lowering of the storage capacity. Furthermore, the amount of water which drains into the kinematic wave store itself could have been overestimated by the model, thereby contributing to accelerated runoff in the catchment. The model results of the scenario analysis (Figure 4-7, Table 4-3 and

Table 4-4) showed that Q_{sim} is very sensitive to differences in initial conditions but depending on the start of the simulation period of a rainfall event, most of any initially stored water was already drained. Although one could set up (average) initial conditions very detailed per grid cell, it became clear from the results of this study that, especially for (future) simulations at high temporal resolution using wflow_sbm over longer periods, the actual impact of initial conditions at the start of a rainfall event on the magnitude of peak flow is difficult to evaluate in the Upper Ciliwung. This makes the wflow_sbm model in its current state unsuitable for accurate flood forecasting. Also Vertessy and Elsenbeer (1999) showed that modelling at very short time steps using a previous version of wflow_sbm, topog_sbm, is in any case very challenging as initial soil moisture conditions has the largest impact on the resulting overland flow and discharge at the catchment outlet.

Parameter sensitivity

The impact of changes in the parameter values on the discharge was only investigated for the base values ±50%. The distribution of the parameter values, given their uncertainty, was not taken into account in the sensitivity analysis. This can imply that unrealistic parameter values were tested. Also the exact contribution of each parameter to the total discharge variation was not calculated, due to a lack of knowledge about the scale of variation for the different parameters involved. For future research when wflow_sbm or any other model will be manually calibrated at this resolution, a more formal approach of sensitivity analysis is recommended, for example using Sobol sensitivity indices (Sobol, 2001). In this way, a better range of possible parameter values can be obtained for the use in a calibration process.

For this study, only the optimal values obtained after calibration for the parameters k_{sat}, governing parameter of the decay of k_{sat} (M), and the Manning coefficients (N and N_{river}) were compared with realistic ranges found in the literature (e.g. Irawan, 2012 for k_{sat}, Farid et al., 2010 for N_{river} and Schellekens, 2018 for N and M). All other best parameter values found (e.g. Θ_s, minimum soil thickness) were not validated, since ranges of values are unknown in the study area.

5.2 Answers to the research questions

Based on the results from chapter 3, the three sub-research questions can be answered. This includes a critical reflection with respect to methods used and results from previous studies. Furthermore, the results of this study will be put in broader perspective for possible follow up studies and society.

- *What are the rainfall characteristics in terms of duration, intensity and total amount and how does the water level at different locations in the Ciliwung catchment react on this rainfall?*

The statistics of the small number of rainfall-runoff events (Table 4-1) revealed that the rainfall-runoff data measured at 10 minutes-interval are of reasonable quality (section 4.1).

The average duration of the rainfall (77-100 minutes) is still in line with values found in literature (Diermanse, 2007). This also means that when monitoring at hourly time steps, or larger intervals, for example using TRMM (3-hours interval) or its successor Global Precipitation Measurement (GPM, 4-hours interval) satellite imagery, one could miss the exact amount of (peak) rainfall, causing an initial delay in discharge forecasting possibilities, especially for the shorter rainfall events. As stated in Table 4-1, the corresponding discharge peak after a rainfall event in the Upper Ciliwung could arrive at Katulampa in less than one hour. The variation in response times of peak water levels at Katulampa is within the range of values found by Agustina (2013). Depending on the current monitoring schedule and interval this could cause a serious delay in terms of early warning of alarming flood water levels at Katulampa and eventually for the city of Jakarta.

The travel time of a discharge peak from Katulampa to the Manggarai gauging station in the city centre of Jakarta was calculated and the average (14±2hrs) is in line with common values found in the literature (e.g. Agustina, 2013, Brinkman and Hartman, 2008). The correlation between the maximum water levels upstream at Katulampa and downstream at Manggarai was statistically significant. If the extreme water level thresholds for certain warning levels (Figure 2-2) are substituted in the regression equation (eq. 23), for example 200 cm, the result shows approximately the lower bound for the threshold of warning level II at Manggarai, 850 cm.

The calculated total precipitation amounts do not differ significantly between seasons. This is not in line with the findings in the literature (Figure 2-3), in which total average rainfall in the wet season differ considerably from dry season averages (Diermanse, 2007, Liu et al., 2015). However, the data set did not contain the most extreme events usually occurring between November and February (section 2.2), due to a lack of data of such events at the Water4Tech website.

To conclude, the pre-mentioned findings gave a good first impression of the quality of the data and that $h_{Katulampa}$ and at least the timing and duration of the P_{obs} data used for this study are in general in the right order of magnitude with respect to findings in the literature. Furthermore, these results, demonstrating short response rates and short intense rain showers, confirm the need to investigate high-frequency modelling.

- *How accurate can the current and future response of the catchment on rainfall be simulated at very high temporal resolution?*

Based on the first visual inspection of the modelling results using wflow_sbm and the individual NSE values (Table 4-2), it could be concluded that this model cannot simulate the peak discharges very accurate with respect to Q_{obs} at 10-minutes resolution. Compared to the modelling results at a lower temporal resolution, some aspects of Q_{obs} are better simulated. The wflow_sbm model calibrated at hourly time steps underestimated Q_{obs} up to 20 m^3/s more compared to the model calibrated at 10-minutes time step. Furthermore, the shape of the discharge peak was not well represented compared to the model calibrated at higher temporal resolution. From (Table 4-2) it can be seen that the NSE values do not really confirm a gain in performance of this event based modelling for smaller time-steps compared to the use of hourly time steps (Figure 4-5), indicating that the time step is probably not the main problem in the model.

In previous sbm-model research in other catchments, the model performance was relatively low due to structural underestimation of peak flow or even overestimation of the base flow (Vertessy and Elsenbeer, 1999 and Arnal, 2014). Also for other modelling studies at lower temporal resolution up to a month, an underestimation of the observed peak flow induced by above average precipitation amounts in the Upper Ciliwung was observed (Conservation International Indonesia, 2010). However, purely based on the NSE, in several model studies in the Upper Ciliwung at different temporal resolutions, peak discharges are simulated much better compared to this study (NSE > 0.55, e.g. Farid et al., 2010, Emam et al., 2016, Yustika et al., 2016). The question remains, however, how the model performance at this high temporal resolution would be if the discussed rainfall input as well as the modelling of the storage release, was correct.

The high NSE_{adj} values for the model performance in dry catchment conditions showed the potential of the model for accurate peak flow simulation for below-average precipitation events (<30 mm, Figure 4-4 (upper) and Figure 4-6 (upper)). The visual inspection of the Q_{sim} simulated at 10-minutes time steps made also clear that for some events the dynamics of the response to rainfall are well simulated, such as the sharp rising limb and the less sharp recession (Figure 4-6 (upper)). It should still be stressed that either timing, magnitude or both are simulated wrong in 3 out of 4 simulated events. The different validation results showed that timing and magnitude of the discharge peak barely changes for different parameter sets (Figure 4-6), which suggests that the parameterization is of minor importance for accurate peak discharge simulation in this catchment. A water balance check of the dry validation event (Table 4-3 and Table 4-4) showed that there was a catchment wide shortage of about 2-5 mm, when using only area Sub-catchment 2 as location for rainfall input. This is the most logical explanation for the variation in errors of Q_{sim}. The Q_{sim} / Q_{obs} ratio with respect to the P_{obs} input seems to be correctly modelled to a certain extent, as well as the dynamics of the peak discharge development.

Given the above insights, the event based modelling at high temporal resolution could work out fine, under two conditions: The P_{obs} input is given in better detail in space and time and if one would use wflow_sbm in these kinds of steep tropical catchments, the modelling of base flow and storage release will be improved.

A possible solution for improving the rainfall measurements is adding 1 or 2 extra observation points in the catchment and implementing a proper interpolation method in any distributed model like wflow_sbm. An interpolation method with limited point data could be regression kriging, as easiest way to distribute the by orography induced increasing rainfall rates (Liu et al., 2015). A possible solution for the too quick storage release and base flow decline could be to add one or more correction or delay factors in the way the kinematic wave or exfiltration fluxes are calculated to improve the realism of modelling in these kinds of catchments. Such a delay factor for ground water flow fluxes is already possible in the SWAT model and leads to satisfactory model performances (NSE up to 0.74) for discharge modelling in the Upper Ciliwung (Yustika et al., 2016).

It became not clear from the modelling results whether the discharge during extreme weather conditions in combination with a constant high base flow in the catchment (e.g. Figure 4-6 (lower)) could also be modelled accurately at this temporal resolution.

- *How will changes in land use in the Upper Ciliwung influence the peak discharge for a typical rainfall event?*

Assumed that the simulated discharge Q_{sim} resembles reality to some extent and that a rainfall event of up to 30mm/2hours is indeed a typical rainfall event in the Upper Ciliwung, it was estimated that peak discharges at Katulampa can considerably reduce after small reforestation projects (Figure 3-7) in the west of the catchment. It was calculated that already 2 km^2 of added forest could theoretically reduce the peak discharge up to 18% (Table 4-6) depending on the initial conditions of the catchment. The impact of reforestation in other studies ranged from approximately 6% reduction of peak discharges for average wet season rainfall events up to 40% for extremer rainfall events (Conservation International Indonesia, 2010, Farid et al., 2014) and from 0.1% to 20% estimated discharge reduction on a monthly average (Poerbandono et al., 2014). The change in reforested areas used in these studies ranged from 5 to 40 km^2. Based on these findings, it can be noted that the peak discharge reduction found in this study falls within the range found in the literature. However, given the very broad range in the exact area of land use changed and found discharge reductions, the challenge remains to give the exact quantification of the impact of a unit change of land use on the peak discharge for a certain rainfall event, which could resemble possible impacts in reality. This was also demonstrated within this study by showing that there could be a broad range of water reduction and increment rates for one single rainfall event in a season and also in between wet and dry seasons (Table 4-5 and Table 4-6).

When zooming in and comparing the water reduction (yield) rates per unit area of added forest per average rainfall event to an earlier study, the differences found were relatively high (up to 10 times). In this study 0.44-1.7*10^{-2} m^3/ha/event was calculated for an average rainfall duration of 100 minutes while Conservation International Indonesia (2010) found a range of 0.15-0.20*10^{-2} m^3/ha/event, for an average rainfall duration of 180 minutes. This discrepancy can be explained in several ways. At first the lower rate from the previous study was based solely on peak discharge reduction at hourly time step. In this study, the exact saving per event was calculated in more detail and from minute-to-minute from the start to the end of the discharge response after the rainfall peak. Another explanation could be the small cell size of the wflow_sbm model, contributing to a local larger total water reduction amount, which cannot be accounted for using a model at lower spatial resolution. However, it should be stressed that the land use map used in this study compared to previous studies in the area is relatively coarse given the catchment area, as it is based on global land use maps (section 3.2.2) with a 0.5 km^2 resolution. For an even better estimation of the reduction of peak discharge per unit reforestation, a higher resolution land use map could be used in follow up studies, as used by e.g. Agustina (2013) and Emam et al. (2016).

The built up scenario showed as expected a simulated increase of the average discharge volume and peak flow for the studied rainfall event (5-16%, Table 4-5). These percentages lie in the very broad ranges found in the literature (3-60%, e.g. Farid et al., 2014, Poerbandono et al., 2014, Emam et al., 2016), for comparable changes in built up areas (~ 10 km^2). The largest possible change in peak discharge (15%) was simulated for wet initial conditions. Keeping in mind that one of the highest alarming water levels is reached at $h_{Katulampa}$ of >1.5 m or >120 m^3/s (see eq. 18 and Figure 2-2), from the peak discharges observed in Figure 3-5 it can be calculated that this alarming threshold would be exceeded for this built up area scenario. This is valuable information for policy makers dealing with decisions concerning rapid development, as well as environmental impacts in the Upper Ciliwung and beyond. The results from the studied scenario should be taken with care as part of the assigned built up areas are crossing canyons and rivers in reality. However this extreme implementation could compensate for the fact that just part of the catchment is studied compared to previous studies.

From Table 4-5 and Table 4-6 it can be calculated that an increased discharge volume per average rainfall event per ha added built up space could be compensated by less than 2 ha of reforested areas, taking the possible ranges of increment/reduction rates into account. This result should also be evaluated with caution. The reduction rate is based on the rigorous scenario that all planted forest came at the cost of built up areas, meaning that villages would partly disappear. In reality it will take a much longer time until a reforestation project will be complete compared to the ever ongoing delivery of new built up and paved areas, apart from the question, which land cover types could actually be sacrificed for a ha of forest. On the other hand, these results demonstrate how rigorous measures has to be, to compensate the extra discharge peak, as a consequence of expanding villages and further concretization of the Upper Ciliwung catchment.

The average (peak) flow differences were based on one rainfall event only and it was assumed that for both rates these differences would also apply for all rainfall events. In reality, this will differ depending on the rainfall intensity, initial conditions and the definition of the duration of an rainfall event, which is also shown in previous modelling studies (see e.g. Conservation International Indonesia, 2010, Emam et al., 2016). In this study, only the uncertainty with respect to initial conditions was taken into account, as these have the largest influence on the modelled peak flow (Vertessy and Elsenbeer, 1999).

Even though there is a large uncertainty on the exact impact of land use change, it was shown that for both scenarios the impact of small changes in the landscape can be estimated on a minute-to-minute-base after a rainfall event. But as mentioned before, using wflow_sbm, any discharge simulations in the Upper Ciliwung catchment will only resemble reality for the simulation of dry initial conditions (~ 0 m^3/s base flow). For this reason it is impossible to conclude that the impact of land use changes at specific locations at this high temporal resolution will have the same impact on peak discharge during wet initial conditions in combination with extreme rainfall events, which could potentially cause flooding in the city of Jakarta.

5.3 Perspective

This study shows that there are some challenges remaining for the accurate modelling of peak discharges at Katulampa in the Upper Ciliwung catchment at 10-minutes resolution due to insufficient rainfall input in space and time and a lack of proper storage release and base flow modelling. This also means that wflow_sbm is in its current state not the best tool for rainfall-runoff modelling in this steep mountainous catchment. It is still believed that a fully distributed model was the best choice for rainfall-runoff modelling in this study area. This in the first place because the Ciliwung river and tributaries originate from steep mountainous terrain and the local (steep) slopes from which the drainage pattern of the rivers are derived can only by accounted for at high spatial resolution using a distributed model. The second reason is the fact that an exact distribution of different land use types is possible in a fully distributed model. In contrast to a lumped model, the impact of small changes in land use at specific locations in the catchment can be investigated very detailed using a model like wflow_sbm as described in the previous sections. Especially the calculated impact of small land use changes on peak discharges can have implications for policy makers in the area, as such small changes, like the expansions of villages, hotels and agricultural land or small reforestation efforts, are not unlikely to occur in the next decade. The hard numbers of estimated river discharge increase as presented in this study and compensation needed for every unit of added built up area to prevent further flood risk frequencies could be a first step to convince stakeholders in the Upper Ciliwung to more carefully consider the design of any new large real estate projects as part of city expansion or ever increasing tourist services in the popular Puncak area, situated in the heart of this catchment. Recent reforestation projects showed that it can take up to 10 years for a new forest of about 25 ha to grow to a mature state, much slower than the time needed to build new villa complexes of the same size.

The ultimate goal of research in this area at high temporal and spatial resolution, if all mentioned model challenges are resolved, would be flood risk mitigation in the whole Ciliwung catchment. Flood impact mitigation can be approached in two different ways: making a very precise minute-to-minute forecast of upcoming critical discharge/water levels at the Katulampa outlet, to save time for evacuation of downstream cities. The other possibility is to determine the exact number and locations of possible areas for reforestation needed upstream to reduce the risk of threatening high water levels in the whole Greater Jakarta area for certain extreme peak rainfall events in the wet season.

In order to reach this goal, the first step will be to collect real-time data of the rainfall distribution in space and time more accurately to enable high temporal resolution modelling, especially in the wet season. As mentioned in the previous section, this could be achieved by increasing the network of rain gauges in the Upper Ciliwung catchment and more frequently monitoring at all existing rainfall stations.

6 Conclusions and Recommendations

The main research question will be answered by summarizing the answers of the sub-research questions.

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 accurately model peak discharges for the current situation and future scenarios?

The available rainfall-runoff data measured at 10-minutes interval in the Upper Ciliwung are of reasonable quality in terms of timing and magnitude compared to literature values.

Using these data, the wflow_sbm model was calibrated, which yielded promising results for peak discharge simulation (NSE_{adj} >0.6), as well as bad model fits, especially for wet initial conditions (NSE and NSE_{adj} << 0). The main challenge to improve the model performance is to accurately obtain the rainfall distribution in space and time as model input to increase the accuracy of event based modelling in the Upper Ciliwung using a fully distributed model like wflow_sbm. The results showed that event-based modelling at high temporal resolution (10 min) was more accurate than modelling at hourly time steps. Based on the poor validation results at extreme rainfall events (>100 mm) in combination with high base flow conditions, it remained unclear if high temporal resolution modelling could be of added value for flood risk prediction. The model performance should therefore be re-evaluated after all model challenges which came forward in this study are resolved.

The high spatial resolution of a distributed model like wflow_sbm is ideal to simulate the minute-to-minute impact of small changes in land use on the discharge at the outlet of the Upper Ciliwung. The peak flow reduction could decrease up to 18% after a small reforestation project for an average rainfall event in the wet season. It was shown that the increase of the peak discharge caused by 1 ha of extra built up area, could be compensated by approximately 2 ha of extra forest. It is not clear if the calculated impact of a small land use change scenario on the peak discharge at the Katulampa outlet also holds during more extreme rainfall events (>> 30mm/2h).

Based on the answer of the main research question, the following can be concluded:

- Wflow_sbm showed promising results for modelling at high temporal resolution (NSE_{adj} >0.6), given dry initial conditions.
- The added value of modelling at 10-minutes resolution for long term extreme discharge prediction is still unknown, due a lack of accurate input data and modelling challenges.
- The impact of land use change on the discharge can be modelled in detail for average rainfall events at 10 minutes resolution.
- A small reforestation project can theoretically reduce the discharge peak up to 18%.
- For every ha of added built up area in the Upper Ciliwung, almost double the area of forest is needed to compensate the increased amount of peak discharge.
- The impact of similar land use change scenarios on peak discharge at more extreme rainfall events at 10-minutes resolution remains unknown.

The following is recommended for the improvement of similar modelling studies:

- To improve wflow_sbm for peak discharge modelling at wet initial conditions in the Upper Ciliwung: a delay factor should be added for certain (ground water) fluxes contributing to quick storage and catchment runoff.
- The interpolation of point data should become possible in wflow, including regression kriging to use for example in mountainous regions prone to orography induced rainfall.
- Add an extra gauging station in the north of the Upper Ciliwung catchment
- Increase the monitoring interval at all new and existing rainfall stations in and around the Upper Ciliwung catchment to at least 10 minutes, especially during the wet season.
- Continuously prepare the rainfall data at high resolution in space and time in the Upper Ciliwung, for the accurate prediction of the magnitude and timing of peak discharges at Katulampa.
- When all modelling challenges are overcome, evaluate the impact of small realistic changes in land use in the Upper Ciliwung for extreme events at this high temporal resolution.

Given the millions of people at risk living and working near the Ciliwung river, every investment contributing to flood risk mitigation should be considered. The outcome of future research to high temporal resolution modelling could also be valuable for cities situated in similar catchments all over the world.

7 Literature

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8 Appendices

Appendix A: Land use dependent parameters for the calculation of the total Canopy Capacity

Table 8-1. Land use dependent values of k_{ext}, SI and C_{max}(wood) for the calculation of total Canopy Capacity (eq. 1-5, section 2.2.2.3).

Land use	Extinction Coefficient (kext)	Specific leaf storage (SI)	Canopy Capacity Branches and Trunks (Cmax wood)
Evergreen Needle leaf Forest	0.8	0.045	0.5
Evergreen Broadleaf Forest	0.8	0.036	0.5
Deciduous Needle leaf Forest	0.8	0.045	0.5
Deciduous Broadleaf Forest	0.8	0.036	0.5
Mixed Forests	0.8	0.03926	0.5
Closed Shrublands	0.6	0.07	0.2
Open Shrublands	0.6	0.07	0.1
Woody Savannas	0.6	0.07	0.2
Savannas	0.6	0.09	0.01
Grasslands	0.6	0.1272	0.0
Permanent Wetland	0.6	0.1272	0.01
Croplands	0.6	0.1272	0.0
Urban and Built-Up	0.6	0.04	0.01
Cropland/Natural Vegetation Mosaic	0.6	0.1272	0.01
Snow and Ice	0.6	0.0	0.0
Barren or Sparsely Vegetated	0.6	0.04	0.04

Appendix B: Parameters of the sbm_wflow model relevant in this area and example maps

Table 8-2. Input parameters used in wflow_sbm for the Upper Ciliwung based on Standard Values for Java Island (Van Loenen, 2018, personal statement).

Parameter	Description	Value
Alpha (-)*	River width estimation factor	35
Annual Q (m^3/s)*	Yearly discharge estimation	2290
Cap Scale (mm/d)	Scaling factor for Capillary rise calculation	100
E over R (mm/d / mm/d)	Ratio average ET(wet canopy) and average P	Built up: 0.3 Forest: 0.3 Grassland/Mixed agriculture/vegetation: 0.2
Infiltration capacity soil (mm/d)	Infiltration rate of the non-compacted area of a cell	Loam: 32 Sandy clay loam: 82
Infiltration capacity paved (mm/d)	Infiltration rate of the compacted area of a cell	10
M (-)	Governing parameter of the decrease of k_{sat} with depth	Loam: 436 Sandy clay loam: 5123
N (-)	Manning's roughness coefficient	Built up: 0.17 Forest: 0.15 Agriculture: 0.17 Grassland 0.6
Nriver	N for river cells	0.036
Paved fraction (-)	Fraction of the compacted area in a cell	Built up >0.7 Forest: <0.01 Agriculture 0.1-0.3
Rooting Depth (mm)	Rooting depth of vegetation	Forest: 5000 Builtup: 300 Agriculture: 500 Grassland/Mixed agriculture/vegetation: 500
k_{sat} (mm/d)	Vertical Hydraulic conductivity	Built up: 50 Forest: 931 Agriculture and Grassland: 308 Mixed agriculture/vegetation: 860.5
Soil minimum thickness (mm)	Minimum soil depth (z_{min})	1920
Soil maximum thickness (mm)	Maximum soil depth (z_{max})	2880
Theta R (mm/mm)	Residual water content	Loam: 0.055 Sandy clay loam: 0.027
Theta S (mm/mm)	Water content at saturation	Forest: 0.51 All other LU types: 0.46

* To be set in the initialization file: wflow_sbm.ini. More details about the .ini file can be found in Schellekens (2018).

Figure 8-1. Example .map file showing the dominant soil texture in the Upper Ciliwung catchment and beyond.

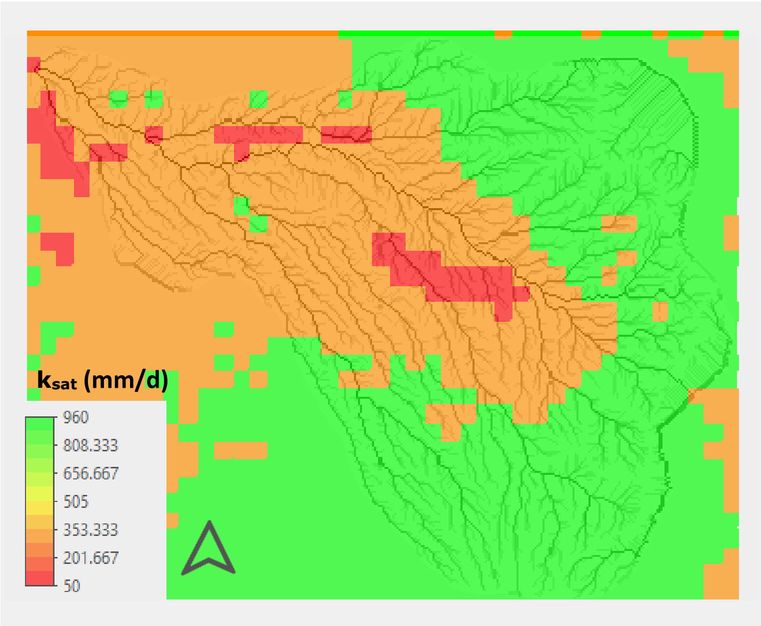

Figure 8-2. Example .map file showing the land use dependent distribution of the vertical hydraulic conductivity in the Upper Ciliwung catchment and beyond.

Appendix C: Parameter values changed after calibration and for each land use change scenario.

Simulation	**Parameters Changed**
Calibration dry	**k_{sat} (mm/day):** *Built up:* 45 *Forest:* 838 *Agriculture/Grassland:* 277 *Forest/agriculture and mixed vegetation:* 774.5 **M (-) :** *Loam:* 305.5 *Sandy clay loam:* 3586 **Nriver (-)** : 0.054
Calibration wet	**k_{sat} (mm/day):** *Forest:* 1862 *Values other LU unchanged* **Theta S (-):** *Forest:* 0.31 *values other LU:* 0.09
Calibration wet (hourly time step)	**k_{sat} (mm/day):** *Forest:* 1862 *values other LU unchanged* **Theta S (-):** *Forest:* 0.31 *values other LU unchanged*
Scenario 1: More built up	**k_{sat} (mm/day):** *Forest:* 1862 *Built up:* 0 *values other LU unchanged* **Theta S (-):** *Forest:* 0.10 *values other LU:* 0.09 **Infiltration capacity paved (mm/d):** 1 **Paved fraction(-):** *Built up:* 1 *values other LU unchanged*
Scenario 2: More forest	**Soil minimum thickness (mm):** 3840 **Soil maximum thickness (mm):** 5760 **Paved fraction (-):** *Forest:* 0 *values other LU unchanged* **Infiltration capacity soil (mm/d):** *Loam:* 48.5 *Sandy clay loam:* 124 **Infiltration capacity paved (mm/d):** 1000