Bachelor's Thesis

"Effects of different land uses on the hydrological response of two paired micro-catchments"

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Effects of different land uses on the hydrological response of two paired micro-catchments

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Preface

This research was written as a part of my bachelor study Civil Engineering at the University of Twente. I have spent about 3 months abroad in Indonesia to acquire experience in working in another culture. I would say this was a successful journey, as I have never been so far away from home, had to left so many lovely people behind, only to meet other wonderful people here and gain a ton of life experience. The friendships I made here, made the time I spent here a time to not forget. As this adventure comes to end, so does my time as a bachelor's student at the University of Twente. However, the next adventure of starting a master awaits.

I would not have been able to successfully finish this adventure without some help. Therefore, I would like to start with thanking Martijn Booij for helping me from the start. He put me in touch with Hero Marhaento, guided me during the setting up of my proposal and the actual writing of this thesis. The way he supported me and the feedback he gave helped me to stay focussed on improving this thesis. Of course, I would also like to thank Hero Marhaento, for giving me a warm welcome and showing me the friendliness of Indonesian people. He gave me the opportunity to get this experience abroad and guided me along the way, giving feedback, when I could not see the bigger picture.

Furthermore, I would like to thank Muhammad Chrisna Satriagasa and Ghalbi Mahendra Putra for helping me getting the data and with any question I had concerning the study areas. It was my pleasure joining the field trip to see Penanggungan and Tamansari in my first weekend, which gave me so much more context about this thesis. I would also like to thank Ellen van Oosterzee, who supported me with any obstacles concerning the visa application.

Terima Kasih!

Saskia van Brenk
10 July 2019
Yogyakarta, Java, Indonesia

Summary

For tropical catchments there is a wet and a dry season, the total amount of rainfall is commonly higher, the intensity of this rainfall is higher and the evaporation rates are higher than in temperate regions. The hydrological responses of tropical areas can be more extreme than in temperate areas. The Gadjah Mada University (UGM) is currently doing fieldwork in two micro-catchments, Tamansari (16.4 Ha) and Penanggungan (3.6 Ha), both are located in the Banjarnegara district, Central Java, Indonesia. Erosion is a big problem in the area and also downstream of these two catchments. Floods are a problem downstream. Agroforestry, which is the land use of Tamansari, is thought to solve both the erosion and flooding problem. However, the impact the different land uses have on the hydrology of the areas, is unknown.

As literature cannot simply answer this question, since a lot of variables play a role in hydrology, a paired catchment method will be used. Findings of this study would be beneficial for water managers, in this specific case for UGM in their ongoing corporation with the farmers to solve erosion and water quantity problems downstream of Tamansari and Penanggungan.

The aim of this study is to get insight in the hydrological response of a micro catchment mostly occupied with seasonal crops and a micro-catchment mostly occupied with combined trees and seasonal crops in form of agroforestry and learn the differences.

Based on drone mapping, the dominant land use of Tamansari catchment is agroforestry where trees are combined with seasonal crops like cabbage, potatoes and carrots on the same unit of land, whereas the dominant land use of Penanggungan is seasonal crops without any trees. For both catchments, meteorological data and discharge data are available from May 2017 to March 2018, so that made it possible to compare them to each other. Furthermore, after a data quality check, the hydrological responses of the two catchments were compared based on their water balance and the annual, seasonal, monthly and daily flow duration curves (FDC).

The results showed that both catchments had their lowest rainfall in August and their highest rainfall in February. Based on the annual FDCs, the sharp turns identifying the high, mean and low flows of the discharge in Penanggungan were located around 10 mm per day for the high flows and 0.5 mm per day for the low flows, with exceedance frequencies of 0.03 and 0.95 respectively. For Tamansari, the sharp turns were located around 7 mm per day for the high flows and 0.5 mm per day for the low flows, with exceedance frequencies of 0.04 and 0.93 respectively. The line in the mean flow regime was more horizontal for Tamansari, which meant that the mean flows in Tamansari were steadier and less variable than the mean flows of Penanggungan.

Based on the seasonal FDCs, for the dry season a low variation in the discharge and a similar shape can be observed for the two catchments. You can see a turn towards the higher flows and a small drop towards the lower flows. The discharges in the dry season are lower for Penanggungan than Tamansari, contrary to the wet season. For the wet season the high and low flows were more distinguishable than for the dry season. For Penanggungan, the sharp turns of discharge were located around 13 mm per day for the high flows and 1.1 mm per day for the low flows, with exceedance frequencies of 0.05 and 0.93 respectively. For Tamansari, the sharp turns were located around 6.3 mm per day for the high flows and 0.4 mm per day for the low flows, with the exceedance frequencies of 0.07 and 0.91 respectively.

Based on the monthly FDCs, in August, the month with the lowest rainfall, both catchments showed a similar FDC shape: a steady and almost horizontal mean and low flow and a slight turn into the higher flows, where Penanggungan had a slightly steeper change into the higher flows than Tamansari. While

in February, the month with the highest rainfall, the shape of the FDC of Penanggungan shows the high and low flow regime better than the FDC of Tamansari, as the flows are more extreme for Penanggungan. However, both shapes are not really horizontal and show some bumps, which makes it hard to locate sharp turns from the mean flows into the high and low flows. A notable difference is that the range of high flows is larger for Penanggungan than for Tamansari.

Based on the daily FDCs, for the driest day, both curves show a very low and a very small range of discharges. For Tamansari, the plot seems more horizontal. The curves do not clearly show high and low flows. For the wettest day, the FDCs show a different shape. Penanggungan shows a clear high flow starting around 0.025 mm and an exceedance frequency of 0.15. The high flow part is shown very steeply in the graph, the mean flows are displayed almost horizontally. Tamansari clearly shows two states and a small and steep transition state between the two almost horizontal lines. The high flows changes to transition area around 0.38 mm and 0.28 exceedance. The other sharp turn in the graph, from the transfer area to a steady mean or low flow, is around 0.01 mm 0.33 exceedance.

Finally, based on the observation, it can generally be concluded that a micro-catchment mostly occupied with seasonal crops like Penanggungan catchment responds more extreme to rainfall than a micro-catchment mostly occupied with combined trees and seasonal crops in form of agroforestry like in Tamansari catchment. The results of the FDCs supported this observation, by showing Tamansari generally had a steadier and less variable flow and the range of discharge values was smaller than Penanggungan, especially during the wettest month of February. In drier periods, the two catchments behave similarly, but in general, Tamansari produced more discharge than Penanggungan.

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1. Introduction

Water is one of the necessities of life. However, it can be a threat as a natural disaster as well, for instance floods, droughts or tsunamis. These disaster events can largely impact the land use of an area. But it also works the other way around: the type of land use has an impact on disaster events. Hydrology is a study field which looks into the hydrological cycle and the hydrological response of catchments (like discharge, precipitation and evaporation). A lot of factors influence the hydrology of an area, like the size, the slope or the vegetation present (Brown et al., 2005).

For tropical catchments there is a wet and a dry season, the total amount of rainfall is commonly higher than in temperate regions, the intensity of this rainfall is higher and the evaporation rates are higher than other areas (Roberts et al., 2005). The hydrological response of tropical areas can be more extreme than in temperate areas. Tropical regions have greater energy inputs and faster rates of change, including human-induced change. These human influences will profoundly influence tropical hydrology, but the understanding of the key hydrological interactions is limited (Wohl et al., 2012).

Lots of studies on (de)forestation in the tropics have been done and summarized by Brown et al. (2005). They found that most studies showed an increase in water yield, when the forest area was reduced. The opposite was also found to be true: increasing the forest cover causes a decrease in the water yield. However, Bruijnzeel (1988) stated that surface infiltration and evapotranspiration associated with the representative types of vegetation play a key role in determining what happens to the flow regime after forest conversion. This would not necessarily lead to the conclusions stated by Brown et al. (2005).

Bruijnzeel (1990) gives an example of a study in Mbeya, Tanzania (Edwards, in Bruijnzeel (1990)), which does not support the conclusion that reduction in forest area leads to an increase in water yield. He concludes that the circumstances in this area were atypical for the humid tropics. The potential for watershed management in the tropics through modification of the surface cover in conjunction with soil conservation measures is stressed, after which is stated that much is expected from agroforestry in this respect. Bruijnzeel (1990) concludes that most studies show a forest uses more water than most agricultural crops or grassland.

1.1. State of the art

To see the impact on the hydrology after changing the land use paired catchment studies have been carried out. Paired catchment studies involve the use of two catchments with similar characteristics in terms of slope, aspect, soils, area, climate and vegetation located adjacent or in close proximity to each other (Brown et al., 2005). Brown et al. (2005) have summarized what different papers stated on the changes in water yield due to permanent changes in vegetation. Multiple papers stated that the reduction of forests increased the water yield and the establishment of forests on thinly vegetated land decreased the water yield. Nobrega et al. (2015) add that the water balance change from deforestation is due to the reduced evapotranspiration and increasing discharge.

Reported permanent increases in the total water yield, after conversion from forest to grassland or cropping, are of 200 – 300 mm per year (Bruijnzeel, 1990). A study in Costa Rica (Imbach et al., in Bruijnzeel (1990)), found permanent gains in water yield after two areas were converted from forest to agroforestry.

In Indonesia, different studies on the water balance and different land uses were carried out. Marhaento et al. (2017a) found that land use change really has an influence on the water balance, by showing that the Soil & Water Assessment Tool model performed better when including land use change than without land use change over time from 1990 till 2013.

The main process responsible for changes in water yield as a result of alterations in vegetation at the mean annual scale is evapotranspiration (Brown et al., 2005). Furthermore, surface infiltration and evapotranspiration associated with the representative types of vegetation play a key role in determining what happens to the flow regime after forest conversion. Marhaento et al. (2017b) studied the difference between the influence of climate and land use on stream flow changes for a tropical catchment in Indonesia. They stated that land use change will affect the evapotranspiration and change the water balance. They even showed, for the Samin catchment, Java, Indonesia, that 72% of the changes in streamflow can be attributed to land use change and 28% to climate change.

Satriagasa et al. (2018a) and Satriagasa et al. (2018b) have focused on the spatial pattern of landslides and on land use change and landslides in the Karangkobar district, Central Java, Indonesia. It was concluded that agricultural land often is on steep slopes and that landslides appear most often in these areas. This can be explained by the vegetation type. The agricultural land does not have trees with deep roots, like agroforestry land. Crops have much smaller roots compared to trees. Deeper roots give structure and strength to the soil.

The magnitude of changes at annual and seasonal time steps is important, however many water resource management issues require to understand the impact of (changes in) permanent vegetation on a flow regime. This impact can be shown with a flow duration curve (FDC). The FDC for a catchment provides a graphical (and statistical) summary of the streamflow variability at a given location, with the shape being determined by the rainfall pattern, catchment size and the physiographic characteristics of the catchment. The shape of the flow duration curve is also influenced by water resources development (water abstractions, upstream reservoirs, etc.) and land-use type (Smakhtin, in Brown et al. (2005)).

As many studies have been done on the impact of land use change on the annual flows, the effects of vegetation change on seasonal, monthly and daily flows are less well understood. However, Brown et al., (2005) states this impact on smaller time scales can be as or maybe be even more important than the annual water yield.

1.2. Study area

The Gadjah Mada University, located in Yogyakarta, Indonesia, (UGM) is currently doing fieldwork in two micro-catchments, Tamansari and Penanggungan, with the land uses agroforestry and agriculture respectively. This fieldwork consists of gathering data on the hydrology, the sediment and erosion in these areas. UGM is informing farmers in the two micro-catchments on different farming practices, like agroforestry, and different crops, like coffee. Erosion is a big problem in the area and also downstream of these two catchments. Floods are also a problem downstream. Using different farming practices and using different crops, are aimed to decrease the erosion and water quantity problem. These solutions have deeper rooted vegetation than the current vegetation. However, the impact the potential land use change will have on the hydrology of the areas, is unknown.

As recommended by UGM, Tamansari catchment and Penanggungan catchment were selected for this study, since the catchments have a lot of similarities, which is a basis for a paired catchment study. They are located close to each other, so there is a similar climate. Besides, slope, elevation, soil type and size of the two catchments are similar, because both are considered micro-catchments. Another, practical, reason for choosing these two catchments was that data was already available.

Tamansari catchment and Penanggungan catchment are both located in central Java, see Figure 1-1. Tamansari catchment is located in Karangkobar district. The catchment has a surface area of 16.39 ha. The dominant land use of Tamansari is agroforestry. This means that there is active planting or managing of trees, combined with agriculture or cattle raising. Crops that can be found in Tamansari are maize, cabbage, tea and coffee.

Penanggungan catchment is located a few kilometres to the north-east of Tamansari catchment. Penanggungan has a surface area of 3.58 ha. The dominant land use of Penanggungan is agriculture. This means that the dominant activity is growing (different) crops. These crops include cabbage, potatoes and carrots.

Not only the land use is different, the social context is very different in both catchments as well. In Tamansari catchment, the owners of the land work on their land. The harvest is for own use. This results in the fact that the farmers live in old and poorly maintained houses. The fact that there is agroforestry in Tamansari is due to the investments from the farmers. They allowed trees to grow and would harvest them when their own harvest would disappoint.

In Penanggungan catchment it is workers that you see in the fields, but not the owners. The crops that are grown are meant for export. The workers are somewhat middle-class people, which have nice colourful houses and maybe even a car. The way the farming is done in this catchment is based on optimizing the harvest, so this means no room for trees.

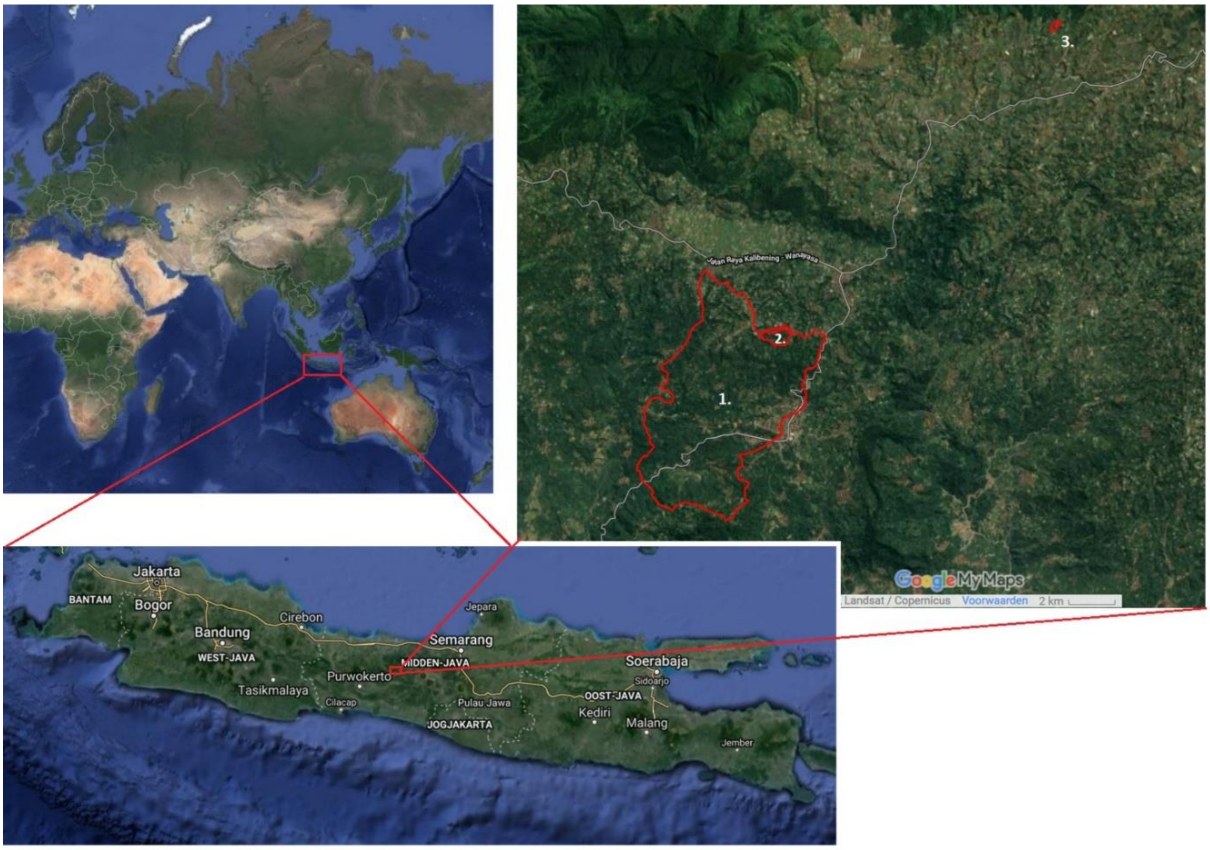

Figure 1-1. Study area (1. Karangkobar district, 2. Tamansari catchment, 3. Penanggungan catchment

1.3. Research gap, aim and questions

UGM is working together with the farmers on (partly) solving the erosion problems in Tamansari and Penanggungan catchment which will benefit the area downstream, which suffers from flooding. This will be done by changing the farming style from cropping to agroforestry. However, what is unknown to UGM yet, is the hydrological response of both catchments, or what will happen to the hydrological response when land use changes will be carried out. This study will focus on the different farming practices agroforestry and traditional farming. By pairing the two micro-catchments, this study aims to get insight in the hydrological response of a micro catchment mostly occupied with seasonal crops and a micro-catchment mostly occupied with combined trees and seasonal crops in form of agroforestry and learn the differences.

As literature cannot answer this question, since a lot of variables play a role in hydrology, a paired catchment method will be used. This aims to see the difference in response caused by the difference in land use. As suggested by literature, attention will be given to seasonal flows as well as annual flows. Findings of this study would be beneficial to water managers, in this specific case for UGM in their ongoing corporation with the farmers to solve erosion and water quantity problems downstream of Tamansari and Penanggungan.

To study the different hydrological responses of agroforestry and traditional farming, the following research questions will be answered:

1. What is the quality of the used hydrological and meteorological data and what information can be extracted to characterise the two catchments for comparison to other hydrological studies?
2. How do the hydrological responses of the Tamansari and Penanggungan catchment compare to each other?

1.4. Thesis structure

This thesis has the following structure. Chapter 2 will describe the methods used during the study. The results will be presented in chapter 3. Next, chapter 4 will be a discussion on the found results. Lastly, in chapter 5 conclusions for the research questions and research aim will be drawn and recommendations will be given for future research.

2. Methods

First, the data and measuring devices will be briefly described in paragraph 2.1, after which the methods for the different research questions will be explained. Paragraph 2.2 is about research question 1: "*What is the quality of the used hydrological and meteorological data and what information can be extracted to characterise the two catchments for comparison to other hydrological studies?*". Paragraph 2.3 is about research question 2: "*How do the hydrological responses of the Tamansari and Penanggungan catchment compare to each other?*".

2.1. Data availability and measuring devices

A number of variables are important for hydrological research. These are meteorological data (Table 2-1), like rainfall and temperature, to estimate the evapotranspiration; hydrological data (Table 2-2), like the discharge; and spatial data (Table 2-3), like elevation, slope, soil and land use type.

All the available data by UGM is shown, however not all this data will be needed. The data that is used, is checked in the tables with a '**V**'. Nevertheless, it is good to keep in mind what other data is available, since other factors might explain a hydrological response, besides the land use.

Table 2-1. Meteorological data availability in 5 minute-intervals (Location Tamansari: -7.25609, 109.73632, Location Penanggungan: -7.1959, 109.78965)

	Name	Tamansari Station	Penanggungan Station
V	**Rainfall (mm)**	available (May 2017 – April 2018)	available (April 2017 – March 2018)
V	**Temperature (°C)**	available (May 2017 – April 2018)	available (April 2017 – March 2018)
	Wind speed & direction	available (Jan 2019 – March 2019)	-
	Solar radiation	available (Jan 2019 – March 2019)	-

Table 2-2. Hydrological data availability in 5 minute-intervals (Location Tamansari: -7.25506, 109.73771, Location Penanggungan: -7.19676, 109.78866)

	Name	Tamansari Station	Penanggungan Station
V	**(Calibrated) Water Level**	available (May 2017 – April 2018)	available (April 2017 – March 2018)
	Sediment (concentration)	available (April 2017 – March 2019)	available (April 2017 – March 2019)

Table 2-3. Spatial data availability

	Name	Information
	Google Earth satellite imagery z19 – th 2015	Available
V	**Tamansari aerial photograph 2018**	Available
	Tamansari aerial photograph 2019	Ongoing stitching & finalization
V	**Penanggungan aerial photograph 2018**	Available
	Landsat 1989 - 2019	Available
V	**Soil map**	Available
	Geologic map scale 1:100.000	Available
V	**Topographic map scale 1:25.000**	Available

The locations of the measuring stations are shown in Figure 2-1 and Figure 2-2. The blue waves icon represents an Automatic Water Level Recorder (AWLR station), which gathers the water level data.

The orange cloud icon represents an Automatic Rainfall Recorder (ARR station), where the rainfall data is gathered. This is also the location where the temperature data is gathered.

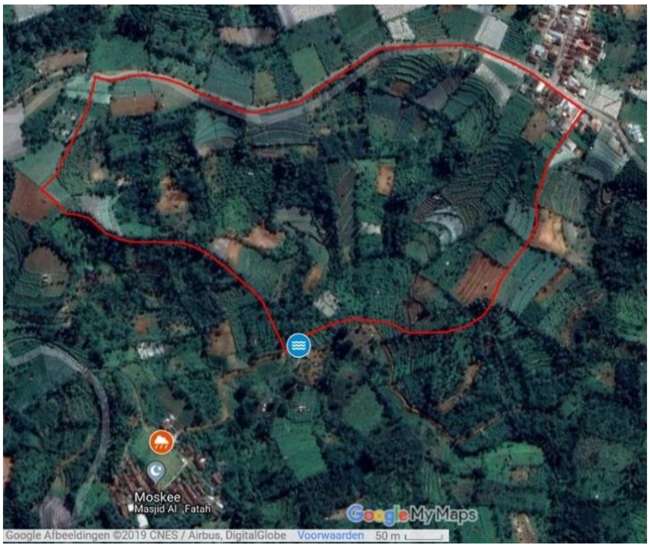

Figure 2-1. Measuring stations Tamansari

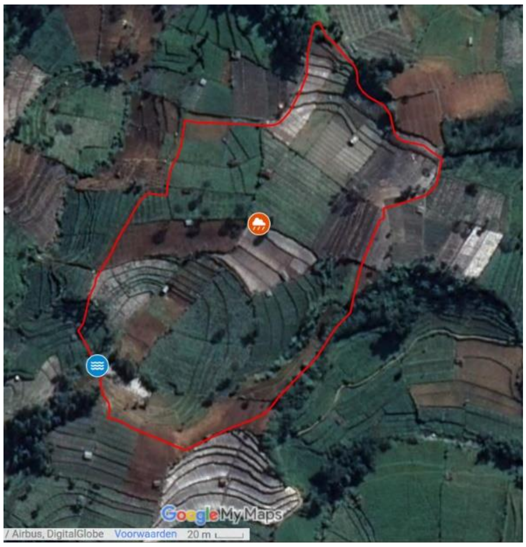

Figure 2-2. Measuring stations Penanggungan

The devices present at the measuring stations are a HOBO Rain Gauge (ARR) and a HOBO Water Level Logger (AWLR). The temperature gets measured between 0° and 50°C. The rainfall gets measured in tabs, where each tab represents 0.2 mm of rainfall, with a maximum of 4000 tabs per time interval. The AWLR measures the water pressure and air pressure, to come to a true water level. The difference in measured compared to true water level can be up to 0.1%.

The data is collected from the stations about once a month. The exact dates are unknown. The data is extracted by multiple persons, since a few students are responsible for collecting the data. This resulted in a varying time interval in the data, sometimes the interval was 5 minutes, other times 10 minutes. To work with a homogenous dataset, the dataset was adjusted to be a 10-minute interval dataset. The process is described in Appendix I.

The soil map and topographical map were not produced by UGM, but were produced by Badan Informasi Geospasial, the Geospatial Information Agency of Indonesia.

2.2. Data quality checking and data extraction

The hydrological data contained information on the water level and on the calibrated water level. The calibrated water level is the water level corrected by measuring the exact water level at the time of downloading the data. This manual measurement is compared to the last automatic measurement, to come up with a calibration value.

The quality of the data is checked in a number of steps. First, when the data is received, an inspection is done, to see if there are gaps and if the format is workable. Then a few statistics are calculated, to spot outliers. The statistics are minimum, maximum, mean, sum and number of values. Following, plots from the calibrated water level, discharge (explanation in paragraph 2.2.3), rainfall and temperature as a function of time are made, to check the trend of the data.

To improve the quality of the dataset, it is adjusted for unreasonable values and for gaps in the data. The exact alterations can be found in Appendix II and Appendix III. The statistics and plots before and after adjusting the data will be compared, to look at the data quality.

Besides the meteorological and discharge data, there were also aerial photographs and GIS data available of the study areas. The aerial photographs have a high resolution, since 1 pixel represents 10x10 centimetres (Satriagasa, Personal communication, 2019). As for the GIS data, an elevation map of Merawu watershed (a larger watershed, of which Tamansari and Penanggungan are a part of), a soil map of Merawu watershed and the borders of the areas of both catchments were available.

A general observation for Penanggungan's and Tamansari's hydrological and meteorological data was that not all timesteps were exactly 5 minutes. The received data showed a few 4- and 6-minute intervals when the interval was set to be 5 minutes, and a few 9-minute intervals were observed, when the interval was set to be 10 minutes. No adjustments for this 1-minute deviation was made, since it would make a little impact. Besides, it is unknown how these deviations were present in the dataset. So, in adjusting the data, these intervals were also set to 5 or 10 minutes.

2.2.1. Rainfall

The statistics (minimum, maximum and mean) and plots of rainfall against time can reveal outlier values. The total amount of rainfall is compared to climate-data.org (2019), to see if it falls into a reasonable amount. The maximum intensity is presented to an expert, to see if these values can happen as well (Marhaento, Personal communication, 2019).

To fill the large rainfall data gap (16 July 2017 till 10 October 2017) in the Tamansari data, Penanggungan rainfall data is used. To adjust for the 300 metre elevation difference between the two catchments a conversion is used. The conversion used is 153 mm more rainfall per year per 100 metre rise in elevation (Marhaento et al., 2017b).

2.2.2. Temperature and evapotranspiration

The statistics (minimum, maximum and mean) and plots of temperature against time can reveal outlier values. The minimum, maximum and mean temperature is compared to climate-data.org (2019), to see how the measured data compares to the values of Karangkobar catchment. For values that are not possible, adjustments are made. These adjustments are stated in Appendix II and Appendix III.

The biggest adjustment was filling the large temperature gap (16 July 2017 till 10 October 2017) in the temperature data of Tamansari. To fill the gap, Penanggungan temperature data was used with a conversion for the elevation difference. A conversion of 6,5 °C fall in temperature per kilometre rise was used (Rose, 2019).

The temperature is used to calculate the potential evapotranspiration (ET_0). The method that will be used for calculating the ET_0 is the method of Hargreaves (Hargreaves et al., 1982). Hargreaves is a widely accepted method, which uses only a few variables. Other methods used variables which were unknown for the study area. The equation is as follows:

$$ET_0 = 0.0023 * (T_m + 17.8)\left(\sqrt{T_{max} - T_{min}}\right) * R_a \qquad (1)$$

In which ET_0 is the potential evapotranspiration (mm), T_m is the daily mean air temperature (°C), T_{max} is the daily maximum air temperature (°C), T_{min} is the daily minimum air temperature (°C) and R_a is the extraterrestrial radiation (MJ/m^{2}day). The R_a will be determined using the calculations of Duffie & Beckman (2013). The values used, are the monthly values at -5° latitude, since this is the closest latitude for both catchments.

To estimate the actual evapotranspiration (ET) on an annual basis, a ratio for ET/ET_0 (1374/1644) is used. This ratio is based on the study Marhaento et al. (2017b) did in the Samin catchment in Indonesia. It is thought the climate and land use they found in 1994 is similar to the land use in Tamansari and

Penanggungan catchment. Therefore, the ratio of this study is used to estimate the ET based on the ET_0.

2.2.3. Water level and discharge

The discharge for Tamansari is calculated by using the discharge rating curve found by Karo Karo (2018) and the discharge for Penanggungan with the discharge rating curve of Putra (2018). The objective of the research of Karo Karo was to know the characteristics of the discharge hydrographs of Tamansari catchment. This resulted in the following rating curve, where *Q* is the discharge (m^3/sec) and *CWL* is the calibrated water level (metres):

$$Q = 3{,}085 * \ CWL^{1{,}674} \tag{2}$$

The purpose of the research of Putra was to determine the hydrograph characteristics peak discharge and direct runoff and to find out the characteristics of rainfall, which affect the peak discharge and direct runoff. He found the following rating curve, where *Q* is the discharge (m^3/sec) and *CWL* is the calibrated water level (metres):

$$Q = 2{,}2194 * \ CWL^{2{,}5} \tag{3}$$

The statistics (minimum, maximum and mean) and plots of CWL and discharge against time can reveal outlier values. The discharge cannot be compared to the discharge of another catchment, since all characteristics might be different. A water balance can reveal if the total discharge is realistic.

A water balance is calculated to verify if the measured data are in agreement with each other. The water balance is calculated over the time period of 1 year, so the assumption can be made that the change in the storage of the catchment will be relatively small compared to the other terms in Equation 4. The water balance uses the following variables:

$$\frac{dS}{dt} = P - Q - ET \tag{4}$$

With *dS/dt* is the storage change (mm), *P* is the precipitation measured (mm), *Q* is the discharge calculated (mm) and *ET* is the calculated actual evapotranspiration (mm).

The discharge for Tamansari and Penanggungan seemed unrealistic. The annual discharge was calculated using Q = P – ET, after Equation 4, with the assumption the water storage change over the year is relatively small. The Q calculated by the water balance is used to calculate a constant to correct the Q calculated with the rating curves. For Penanggungan this was 1/7 and 12/50 for Tamansari; for an explanation on these numbers, see Appendix II and Appendix III.

2.2.4. Land cover and land use

The aerial photos of both catchments were used to quantify the land cover in both catchments, since the aerial photos have a higher resolution than a Landsat image. Manually, the aerial photographs were classified into five classes: trees, crops, crops with tree border, mixed and built-up. Because the classification is done manually, the resolution is decreased slightly. ‘Crops with tree border’ and ‘mixed’ both represent the agroforestry land use. Farmland with trees at the border of the plot of land is classified as ‘crops with tree border’. When the aerial photo shows a mix of crops and trees, the area will be classified as ‘mixed’. When only crops are shown, the area is classified as ‘crops’. When there is an area with densely located trees, the area is classified as ‘trees’. And when there is a group of buildings or a large building, this area is classified as ‘built-up’. This means that a single small shed does not get classified as built up.

2.2.5. Elevation and slope

The elevation of the two micro-catchments is determined using the received elevations contour map and the spatial references of the two micro-catchments. This elevation map contains relief lines of the Merawu watershed, with each line representing a 2.5-meter interval.

This elevation map is also used for calculating the average slope. The micro-catchments are very small compared to Merawu, and so would lose their detail, when the whole Merawu watershed map would be used. This is why the sections of the map located in the catchments Tamansari and Penanggungan were used, and not the whole elevation map. This resulted in a more detailed calculation.

To calculate the average slope, several tools in ArcGIS were used. First, the elevation contour map was transferred into a slope map, using the 'topo to raster' tool in initial settings. The slope map contains the height of the slopes and was transferred into a slope map in degrees, using the 'slope' tool in initial settings. Using the tool 'zonal statistics', the mean slope for the two catchments was calculated, using the last slope map in degrees as input.

2.2.6. Soil

The soil map of Merawu watershed will be combined with the spatial areas of Penanggungan and Tamansari, to look at the soil present. Afterward, literature should be found to know about the properties of this soil.

2.3. Hydrological response

The hydrological response of the two paired micro-catchments is analysed using a water balance and several flow duration curves. A flow duration curve was used, since the flow duration curve plots the discharge as a function of its exceedance frequency. Since the rain events do not have to be similar in one year of data, it might be hard to compare the two catchments. This is why the flow duration curve was chosen.

Several flow duration curves are analysed: the annual curve, the seasonal curves, the monthly curves and the curves of the days with the most and the least rainfall. The range of flow duration curves will show the response of the catchments in general and to high and low rainfall.

2.3.1. Water balance

The annual total rainfall, ET and discharge are calculated. ET is determined as described in paragraph 2.2.2. The discharge will have to be converted from cubic meters per second to mm, so all variables are in the same unit and can be compared to each other. A graph for each of the catchments is made, showing the rainfall, evapotranspiration and discharge per month. This will give an overview of the variables in relation to each other.

2.3.2. Annual Flow Duration Curve

The annual FDC is based on daily discharges. All the discharges are ranked; the highest discharge gets a 1 and the lowest discharge gets the highest number (the number of the number of daily discharges; *N*). The exceedance frequency can be calculated by dividing the rank (*x*) by the total amount plus one. To put this into a formula:

$$Exceedance\ frequency = \frac{x}{N+1} \tag{5}$$

The exceedance frequency will be plotted on the x-axis and the discharge will be on the y-axis. This method is based on Searcy (1959). The y-axis of the graphs can be plotted on a normal scale on or a logarithmic scale, depending on which one shows the characteristics best. Often this means the logarithmic scale is chosen, since this gives a better view of the high and low flows. However, sometimes the range of discharges is not big, then a normal scale is used.

The shape of a flow duration curve is defined by the hydrologic and geologic characteristics of the catchment (Searcy, 1959). A steep slope in the curve represents a highly variable stream flow, which means the flow is largely from direct runoff. A flat slope in the curve represents the presence of water storage.

2.3.3. Seasonal Flow Duration Curve

The wet season is from November till March and the dry season is from May till September (World Weather & Climate Information, 2019). This makes April and October function as transition months from one season into the other and are not considered in the seasonal analysis. The seasonal FDCs are also based on daily discharges and made in the same way as the annual FDC, described in paragraph 2.3.2.

2.3.4. Monthly Flow Duration Curve

The monthly figures are also based on daily discharges. The FDCs are made the same way as the annual FDC, described in paragraph 2.3.2.

2.3.5. Daily Flow Duration Curve

The daily FDCs of the day with the most and the day with the least amount of rainfall were created. If the amount of rainfall is the same for two or more days, the day with the wettest (or respectively driest) days before is selected. For Penanggungan, this resulted in 27 August 2017 and 28 May 2017, as driest and wettest day respectively. For Tamansari, this resulted in 27 August 2017 and 24 February 2018, as driest and wettest day respectively. The daily FDCs were created in the same way as described for the annual curves in paragraph 2.3.2. However, the daily flow duration curves are based on the 10-minute interval discharges, to take a more detailed look into quick responses.

2.3.6. Relation rainfall and discharge

To get more insight into the relation between the rainfall and discharge, plots with these two variables are made. Time scales for these plots are a year, wet and dry season, all based on the daily values. Timing of the rainfall and discharge is varied, because the response time of the catchment is not known (lag). To elaborate, the rainfall on day ‘t’, was plotted against the discharge on day ‘t’, ‘t+1’, ‘t+2’ and ‘t+3’ to see if a clearer relation would show. To look at a quicker response a plot of the wettest day based on the 10-minute values is created as well. Here a lag of 1 and 2 hours is considered.

3. Results

This chapter will show the results. The results will be shown in the same order as the research questions. So, paragraph 3.1 is about research question 1: "*What is the quality of the used hydrological and meteorological data and what information can be extracted to characterise the two catchments for comparison to other hydrological studies?*". Paragraph 3.2 is about research question 2: "*How do the hydrological responses of the Tamansari and Penanggungan catchment compare to each other?*".

3.1. Data quality checking and data extraction

The following paragraphs explain the changes made in the dataset based on observations in the raw data. Furthermore, the statistics and plotted figures for checking the data are shown, before and after the adjustments. Appendix II shows the exact changes in the dataset for Penanggungan, Appendix III shows the adjustments for Tamansari.

3.1.1. Rainfall

As stated in paragraph 2.2, a 10-minute interval dataset was created. The rainfall measured at the 5-minute interval, cannot simply be deleted, since the total amount of rainfall measured, would then be wrong. Therefore, the rainfall measured at the 5-minute interval, was combined with the following 10-minute interval to keep the total amount of rainfall the same. For example, the rainfall measured at 00:05 was added to the rainfall measured at 00:10, so the total amount over the time would still be complete.

The rainfall data for Penanggungan looked reasonable, compared to climate-data.org (2019). However, from 21 March 2018 onwards, no 0 mm measurements were recorded. However, a lot of empty values were observed. So, the gaps observed in the data are thought to be the 0 measurements.

A big gap was found in the Tamansari rainfall data (16 July 2017 till 10 October 2017, see Figure 3-1) and filled using the rainfall data from Penanggungan. Since the first 2,5 month of the dataset was deleted (explained in paragraph 3.1.3), the total number of rainfall observations stayed almost the same after filling the data gap. Table 3-1 shows that the mean rainfall has become lower. This is due to the 0 values not being represented in the Tamansari before dataset. The rainfall data after adjustments can be seen in Figure 3-2.

Exact adjustments can be found in Appendix II and Appendix III. Figures for observing trends in the data for both catchments can be found in Appendix IV and Appendix V.

Table 3-1. Rainfall Statistics per 10-minute interval; sum over one year; since some data was deleted, the sum is from data between 17 July 2017 and 30 April 2018

	Penanggungan before	Penanggungan after	Tamansari before	Tamansari after
MIN (mm)	0.0	0.0	0.2	0.0
MAX (mm)	15.6	15.6	16.6	15.2
MEAN (mm)	0.1	0.1	1.0	0.1
SUM (mm)	3836.8	3836.8	2697.9	2699.9
TOTAL NUMBER OF DATAPOINTS	51,052	52,560	2637	41,393

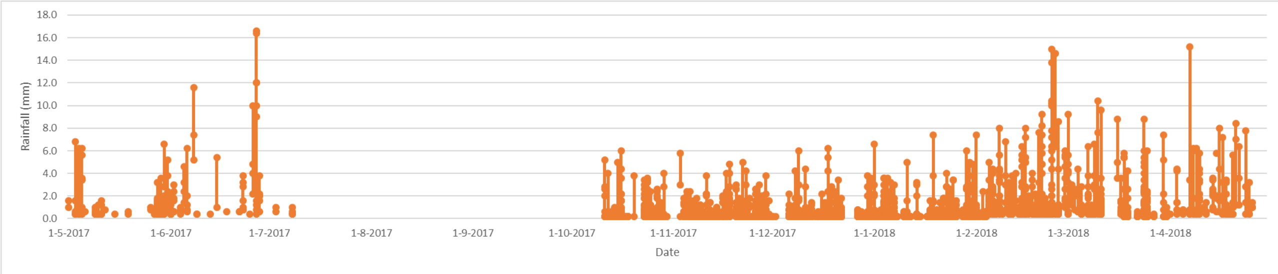

Figure 3-1. Rainfall Tamansari before adjustments

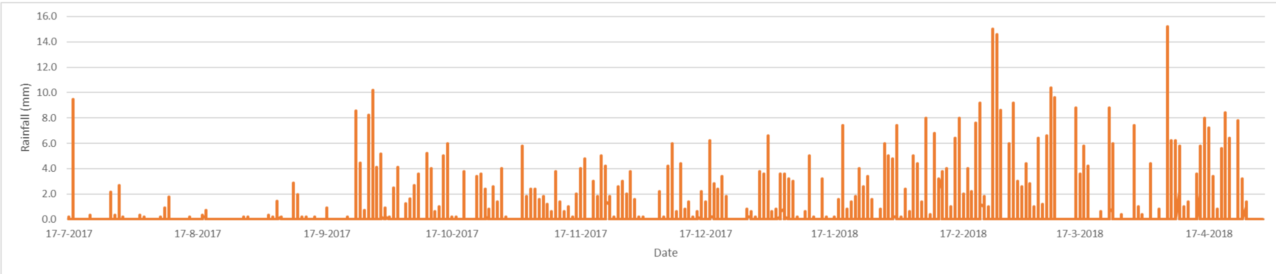

Figure 3-2. Rainfall Tamansari after adjustments (Be aware of the different time scale)

3.1.2. Temperature and evapotranspiration

The received Penanggungan temperature data showed many gaps. The dataset had 2387 gaps, of which the longest was 68 time steps (so 11 hours and 20 minutes). However, on average the gaps were 1 hour and 20 minutes. The gaps were interpolated linearly, since the data of the temperature shows random gaps and can have big gaps.

Besides the gaps, the temperature data of Penanggungan also showed some unreliable values, as seen through the minimum and maximum temperature in Table 3-2. The maximum temperature was 44 degrees Celsius, on 16 March 2019. This was a onetime extreme value, which is thought to be false. The temperatures 10 minutes before and after were 16 degrees Celsius. The extremely high value was deleted and treated the same as the other temperature gaps. There were also low values, of 9 degrees. However, this was not a onetime extreme value, but this value fitted in with the temperatures around this time. As a rule of thumb, the temperatures below 10 degrees were compared to the same time the day before. If the difference was more than 5 degrees, the low values were deleted (Marhaento, Personal communication, 2019). Again, these gaps were treated the same as the other gaps.

The mean, minimum and maximum temperature shown in Table 3-2 is lower compared to the temperature data on climate-data.org (2019). However, the temperature data was not thought to be impossible. The data on climate-data.org is an average for whole Karangkobar, and the altitude of Penanggungan is about 800 meters higher than the average altitude of Karangkobar stated on this website. As a result, no changes were made on the data based on these observations.

The Tamansari temperature data showed fewer gaps, 10 gaps in total. However, the biggest gap was 12391 data points, from 16 July 2017 till 10 October 2017. This gap was filled, using Penanggungan temperature data converted for altitude. The next biggest gap was 30 data points, so 5 hours. This gap and the smaller gaps were filled in the same way as the Penanggungan temperature data gaps.

The temperature data seemed reasonable, compared to climate-data.org (2019). Only two outliers, seen in Figure 3-3, were deleted and treated like a normal temperature gap to be linearly filled. The highest measurement was 32 °C, but the temperature measured 10-minutes before and after were 23 and 26 °C. A 6 to 9 °C difference in 10 minutes, seems unreasonable. The second highest value was 28

°C, but the temperature measured 10 minutes before and after were 23 degrees. A 5 °C difference in 10 minutes, seems unreasonable. The results of all the adjustments can be seen in Figure 3-4.

Detailed explanations of the adjustments made in both datasets, can be found in Appendix II and Appendix III. All figures of the temperature data before and after adjustments can be found in Appendix VI and Appendix VII.

Table 3-3 shows the potential evapotranspiration calculated with the Hargreaves method. The sum over the time period seems reasonable, since it is in the same range as the total amount of rainfall in the corresponding time periods. However, for both catchments, the maximum potential evapotranspiration drops significantly after the adjustments to the dataset. This is due to the adjustment of the high temperature outliers. The high temperatures resulted in a high value for the ET_0, based on the formula Hargreaves et al. (1982) uses.

Table 3-2. Temperature Statistics per 10-minute interval

	Penanggungan before	Penanggungan after	Tamansari before	Tamansari after
MIN (°C)	9.3	9.5	13.8	11.4
MAX (°C)	44.7	24.4	32.7	27.3
MEAN (°C)	17.9	18.0	19.9	19.7
TOTAL NUMBER OF DATAPOINTS	42,394	52,560	40,114	41,393

Table 3-3. Potential Evapotranspiration Statistics per day; sum over one year; for Tamansari the sum is from data between 17 July 2017 and 30 April 2018

	Penanggungan after	Tamansari after
MIN (mm)	1.3	2.0
MAX (mm)	10.2	10.9
MEAN (mm)	6.2	8.1
SUM (mm)	2247.9	2326.9
TOTAL NUMBER OF DATAPOINTS	365	288

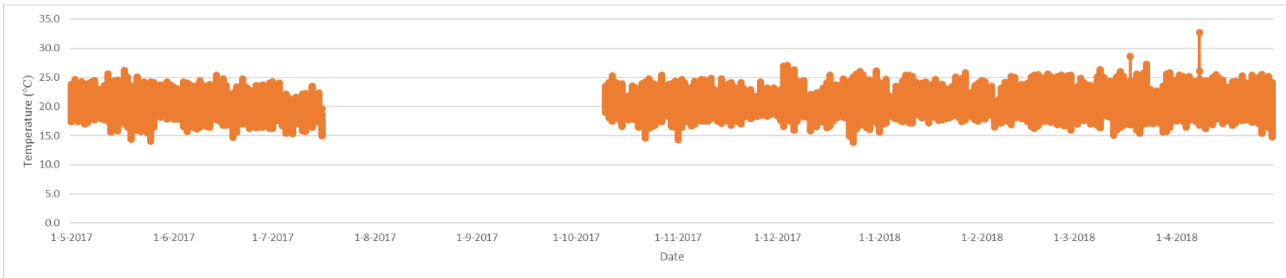

Figure 3-3. Temperature Tamansari before adjustments

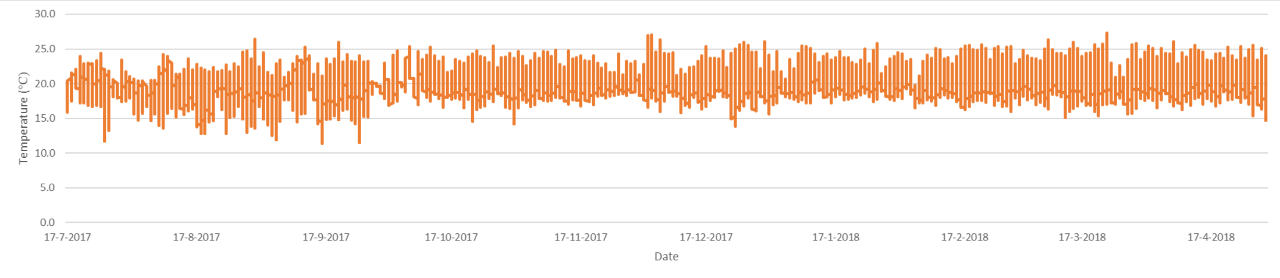

Figure 3-4. Temperature Tamansari after adjustments

3.1.3. Water level and discharge

For Penanggungan, not a lot of changes were made to the data of the calibrated water level. The biggest issue with the data was the disproportionally high discharge. The changes to get a more reasonable discharge cannot be seen in the calibrated water levels in Table 3-4, but can be seen in the discharge statistics before and after in Table 3-5. The discharge was scaled from almost 11,000 mm per year to 1561.37 mm per year. All adjustments to the dataset can be found in Appendix II. Figures from the plotted water level data and the discharges, helping with making the observations, can be found in Appendix VIII and Appendix X.

For Tamansari, the discharge was also too high and scaled from almost 5000 mm to 800.39 mm per year. However, this does not include all twelve months, since Figure 3-5 (a bigger sized version can be found in Appendix IX) shows a deviating behaviour at the beginning of May and no data from 20 May till 16 July 2017. This deviating and missing data led to deleting the first 2.5 months of the dataset, so the dataset starts on 17 July 2017 at 13:10. From 8 April 2018 at 10:20 onwards, calibrated water levels were also not available. This explains the lower amount of values than expected for a year in Table 3-4 and Table 3-5 for Tamansari.

Another issue the Tamansari data showed, was negative calibrated water levels. This could not be true, according to the persons gathering the data. The negative calibrated water levels were adjusted to 0 values, with a corresponding 0 m^3/sec discharge. All detailed adjustments to the Tamansari dataset can be found in Appendix III. All figures helping with the observations of the data can be found in Appendix IX and Appendix XI.

Table 3-4. Calibrated Water Level Statistics per 10-minute interval

	Penanggungan before	Penanggungan after	Tamansari before	Tamansari after
MIN (m)	0.000	0.000	-0.015	0.000
MAX (m)	0.872	0.872	0.438	0.363
MEAN (m)	0.102	0.102	0.058	0.050
TOTAL NUMBER OF DATAPOINTS	52,559	52,560	40,878	38,142

Table 3-5. Discharge Statistics per 10-minute interval; sum over one year; since some data was deleted, the sum is from data between 17 July 2017 and 8 April 2018

	Penanggungan before	Penanggungan after	Tamansari before	Tamansari after
MIN (mm)	0.00	0.00	0.00	0.00
MAX (mm)	26.41	3.77	2.84	0.50
MEAN (mm)	0.21	0.03	0.10	0.02
SUM (mm)	10,929.36	1561.37	4985.94	800.39
TOTAL NUMBER OF DATAPOINTS	52,559	52,560	52,332	38,142

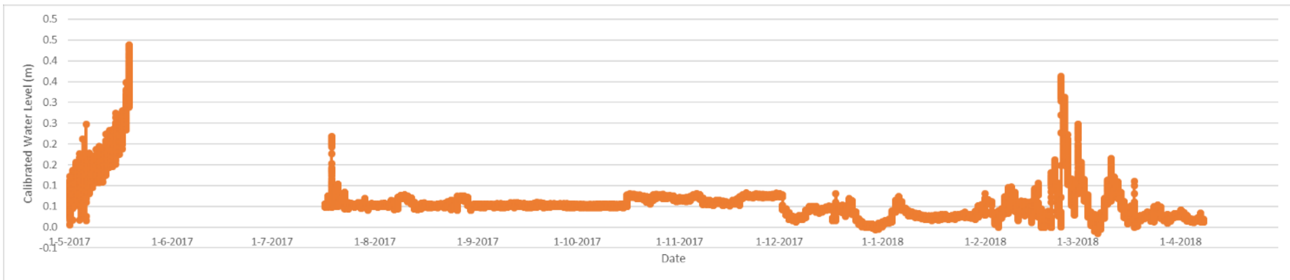

Figure 3-5. Calibrated Water Level Tamansari before adjustments

3.1.4. Land cover and land use

The introduction of this report, chapter 1, stated the dominant land uses for both micro-catchments. For Tamansari this is agroforestry and for Penanggungan this is agriculture. High-resolution aerial photographs were digitized by hand, to create land cover maps in ArcGIS, to check and quantify these land uses. Figure 3-6 and Figure 3-7 show the aerial photo and land cover map for Penanggungan catchment. Figure 3-8 and Figure 3-9 show the aerial photo and land cover map for Tamansari. Larger figures can be found in Appendix XII and Appendix XIII. The land cover of both catchments is quantified and shown in Table 3-6.

Figure 3-6. Penanggungan aerial photograph

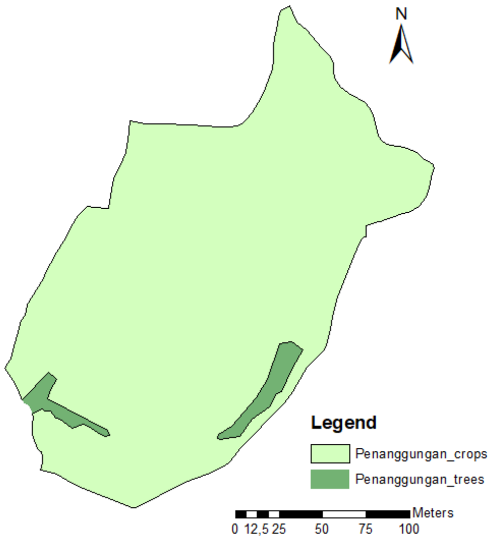

Figure 3-7. Penanggungan Land Cover Map

Figure 3-8. Tamansari aerial photograph

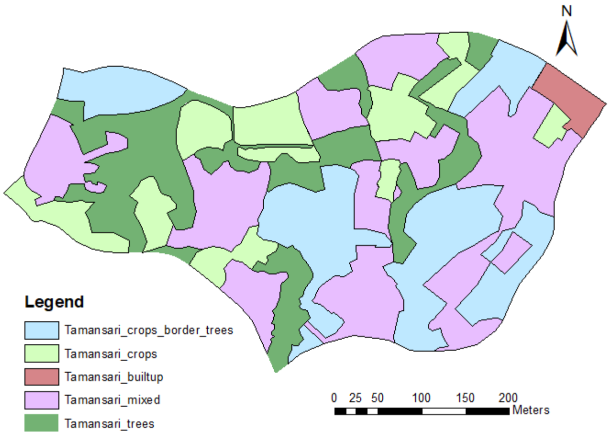

Figure 3-9. Tamansari Land Cover Map

Table 3-6. Land cover quantification

Land cover		Total area	Trees	Crops	Crops with tree border	Mixed	Built-up
Penanggungan	Ha	3.58	0.11	3.48	0	0	0
	%	100	3	97	0	0	0
Tamansari	Ha	16.39	3.58	2.64	4.11	5.75	0.32
	%	100	22	16	25	35	2

As Table 3-6 shows, Penanggungan and Tamansari have a completely different land cover. For Penanggungan it is shown that 97% of the land cover is crops and farming ground, so it can be stated that agriculture is the dominant land use of the area. A visit to the area has confirmed this, as shown in Figure 3-10. The image shows a lot of crops, and not many trees. This photograph shows only a part of the catchment; however, this image was general for the whole area. Image classification and a field visit both confirm that the dominant land use is agriculture.

Figure 3-10. Crops at Penanggungan catchment

The land cover for Tamansari is more diverse, as Table 3-6 shows the four main covers are trees, crops, a mix from those two and crops with trees at the borders. The last two are examples of agroforestry. A visit to this area can give more context about the mix of the land covers. Trees can be present at the border of farmland, as shown in Figure 3-11. This type of land cover is classified as 'crops with tree border'. The other way that trees are present, is inside of the crop fields, as shown in Figure 3-12. This is classified as 'mixed' cover. Image classification and a field visit, both show that trees are integrated into the farmland of the Tamansari catchment. Both methods confirm the dominant land use from catchment as agroforestry.

Figure 3-11. Trees as a border of the farmland

Figure 3-12. Trees in between the crops

3.1.5. Elevation and slope

The elevation profile of Penanggungan and Tamansari catchment are respectively shown in Figure 3-13 and Figure 3-14. The highest point in Penanggungan is 1512.5 meters above MSL and the lowest point is 1462.5 meters above MSL. This results in an average slope of 17.1 degrees. For Tamansari the highest point is 1225 meters above MSL, and the lowest point is 1150 meters above MSL. This results in an average slope of 18.2 degrees. The output from the calculation process can be found in Appendix XIV, Appendix XV and Appendix XVI.

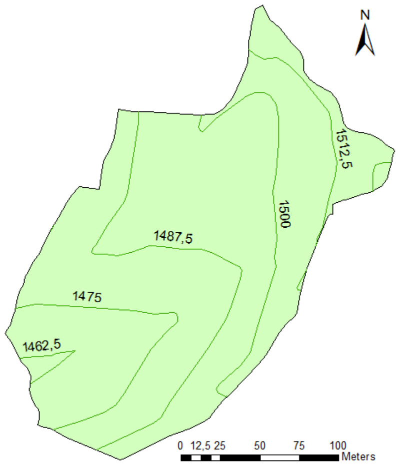

Figure 3-13. Penanggungan elevation map; numbers represent height above mean sea level in meters

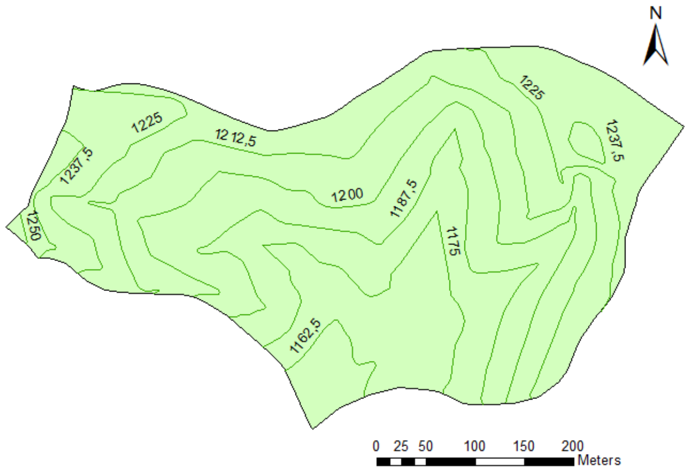

Figure 3-14. Tamansari elevation map; numbers represent height above mean sea level in meters

3.1.6. Soil

The dataset of Merawu watershed classifies Tamansari and Penanggungan as Dystropepts, Eutropepts, Tropudalfs. These subgroups fall in the Inceptisols order. (United States Department of Agriculture, Soil Conservation Service, n.d.) The soil in Penanggungan consists of basalt, andesite, breccia and fine-grained tephra. The soils in Tamansari consists of fine-grained tephra and coarse-grained tephra. So, both catchments have volcanic soils. However, the percentages of lithology are unknown.

3.2. Hydrological response

This paragraph will show the results of the hydrological response. First, the water balance will be shown. Next, the FDC will be shown, from large scale (years) to smaller scale (days). In this paragraph edits of the FDCs of Tamansari and Penanggungan will be shown together. Separate figures can be found from Appendix XVII through Appendix XXIII.

3.2.1. Water balance

The water balance has already come forward when checking the data in Appendix II and Appendix III. The total values for the rainfall, potential evapotranspiration, actual evapotranspiration and discharge can be found in Table 3-7. It shows the two catchments have similar potential and actual evapotranspiration, although for Tamansari this is based on 9.5 months and for Penanggungan this is 12 months. This means that the annual total Tamansari evapotranspiration will be even higher. This is probably due to the higher temperatures in Tamansari.

The discharge and rainfall values between the two catchments show a big difference. However, this can again be largely explained by the fact that the Penanggungan data is based on a full year and there was about 3 months data missing for Tamansari. Probably the total discharge of Tamansari will be lower than the discharge of Penanggungan, since the dry season is not fully included in the data. For Penanggungan the total discharge was 41% of the annual rainfall, for Tamansari this was 30%.

In Figure 3-15 and Figure 3-16 the rainfall, potential evapotranspiration and discharge are shown per month. Here it should be noted again, that for Tamansari April, May, June, July have partly or completely missing data. The discharge for Tamansari shows up steadier than for Penanggungan, which shows a high peak in February. Steadier means the discharge show less variation through the year and a less heavy reaction to the rain. Both catchments show their lowest rainfall in August and their highest rainfall in February. The discharge was 86% of the rainfall in February and 177% in August for Penanggungan. The discharge was 20% of the rainfall in February and 463% in August for

Tamansari. The closer the percentage is to 100%, the more the catchments response follows the rain pattern. Since February was the wettest month and August the driest, this shows the discharge of Penanggungan reacts heavier to the rainfall than Tamansari and that Tamansari has a steadier response. This might be due to the difference in land use, however it can also be due to the fact that Penanggungan is a smaller catchment and has less storage.

Table 3-7. Total rainfall, potential evapotranspiration, actual evapotranspiration and discharge for the year; for Penanggungan this is 1 April 2017 – 31 March 2018, for Tamansari this is 17 July 2017 – 31 April 2018, with missing discharge data from 8 April 2018 – 31 April 2018.

	P (mm)	ET_0 (mm)	ET (mm)	Q (mm)
Penanggungan	3837	2248	1979	1561
Tamansari	2700	2327	1945	800

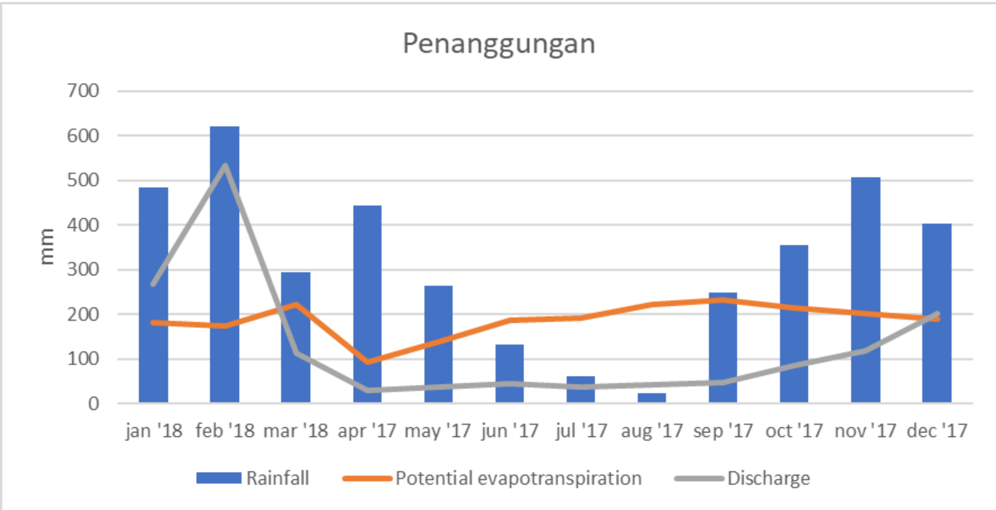

Figure 3-15. Penanggungan rainfall, potential evapotranspiration and discharge for the period April 2017 - March 2018

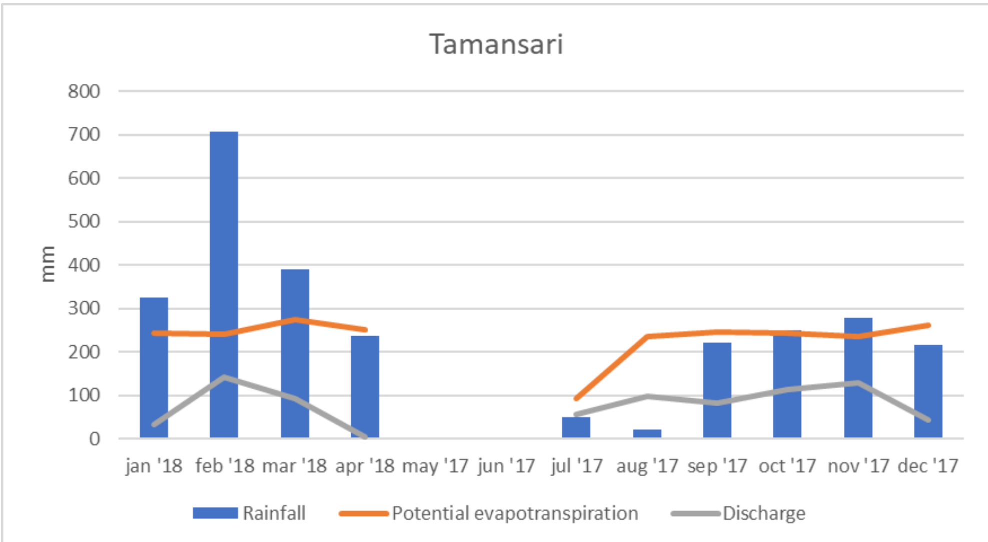

Figure 3-16. Tamansari rainfall, potential evapotranspiration and discharge for the period May 2017 - April 2018, including missing hydrological and meteorological data from 1 May 2017 - 17 July 2017 and missing discharge data from 8 April 2018 – 31 April 2018

3.2.2. Annual Flow Duration Curve

In Figure 3-17 the flow duration curves for Penanggungan and Tamansari are shown. The shapes of the curve look similar in first instance. You can clearly distinguish the high and low flows as they make a sharp turn from the almost horizontal mean flows. For Penanggungan these sharp turns are located around 10 mm per day for the high flows and 0.5 mm per day for the low flows, with the exceedance frequencies of 0.03 and 0.95 respectively. For Tamansari, these sharp turns are located around 7 mm per day for the high flows and 0.5 mm per day for the low flows, with the exceedance frequencies of 0.04 and 0.93 respectively. The mean flows in Tamansari are more horizontal than the mean flows of Penanggungan. This shows the flows of Tamansari have less variability than the flows of Penanggungan. Following Searcy (1959), this would suggest that Tamansari has more storage capacity than Penanggungan. Another observation that can be made is that the maximum discharge for Tamansari is significantly lower than Penanggungan.

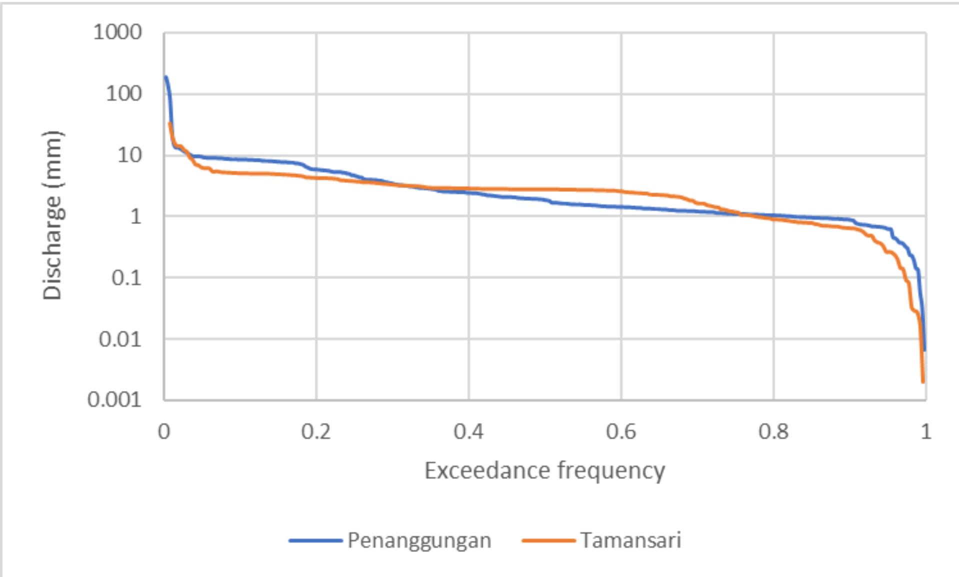

Figure 3-17. Annual Flow Duration Curve Penanggungan (April 2017 – March 2018) and Tamansari (17 July 2017 - 8 April 2018), based on daily discharges

3.2.3. Seasonal Flow Duration Curve

Two seasonal FDCs have been created for both catchments: one for the dry (May-September) and one for the wet (November-March) season. Figure 3-18 shows the FDCs for the dry season for both catchments. Both curves show a low variation in the discharge and a similar shape. You can see a turn towards the higher flows and a small drop towards the lower flows. The sharp drop for Tamansari is seen because of one low value of 1.25 mm. So, in general, the Tamansari curve is more horizontal, so steadier; less variability. The discharge is higher than the discharge of Penanggungan.

Figure 3-19 shows the FDCs for the wet season for both catchments. Again, the shapes of both graphs show a similar shape. High and low flows are distinguishable. However, the sharp turns are sharper in the Penanggungan graph. For Penanggungan these sharp turns are located around 13 mm per day for the high flows and 1.1 mm per day for the low flows, with the exceedance frequencies of 0.05 and 0.93 respectively. For Tamansari, these sharp turns are located around 6.3 mm per day for the high flows and 0.4 mm per day for the low flows, with the exceedance frequencies of 0.07 and 0.91 respectively. The discharges in the wet season are higher for Penanggungan than Tamansari, contrary to the dry season.

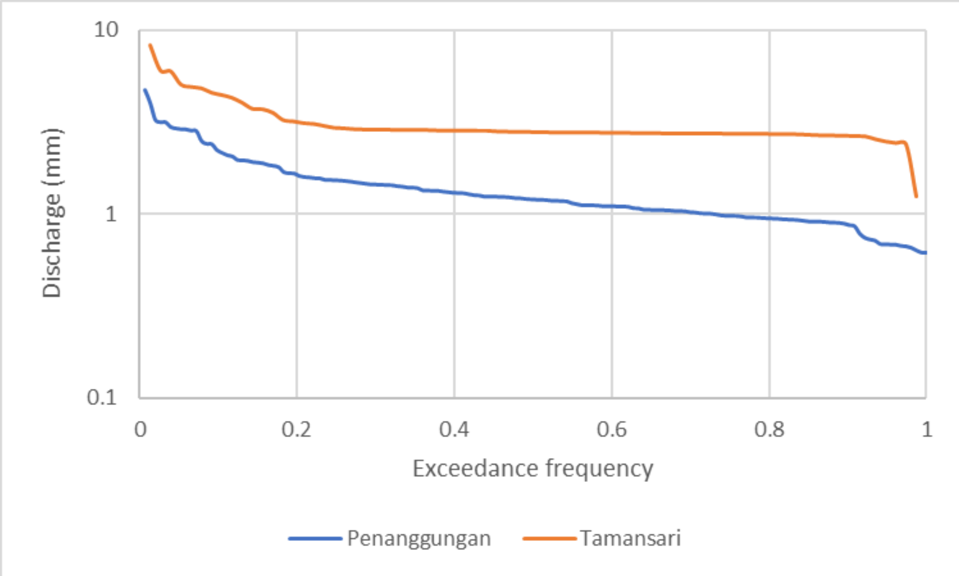

Figure 3-18. Dry season Flow Duration Curve Penanggungan (May 2017 - September 2017) and Tamansari (17 July 2017 - September 2017), based on daily discharges

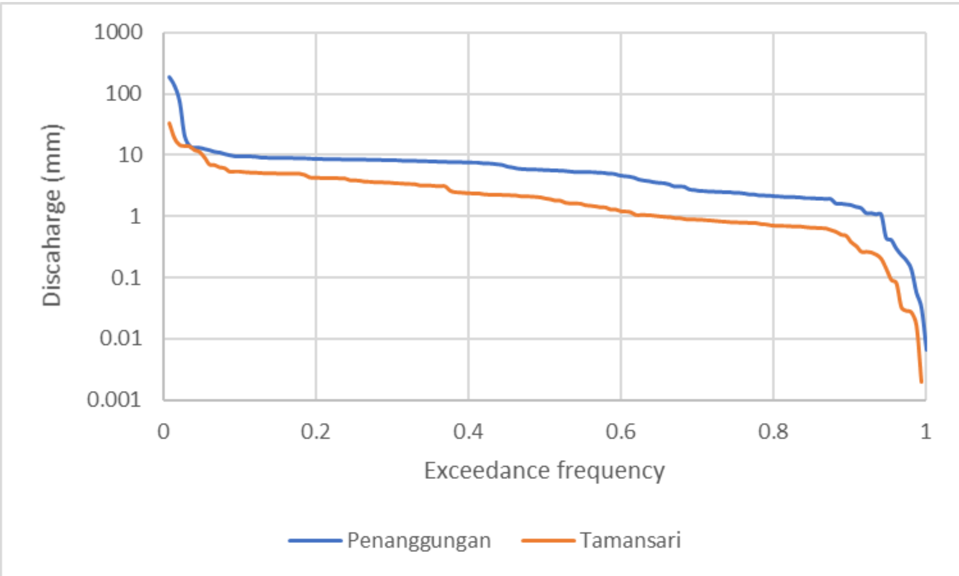

Figure 3-19. Wet season Flow Duration Curve Penanggungan (November 2017 – March 2018) and Tamansari (November 2017 – March 2018), based on daily discharges

3.2.4. Monthly Flow Duration Curve

For all available months, a daily based FDC was made. This means the FDCs for July and April of Tamansari are based on a few days and May and June are completely missing. This leaves mid July 2017 until March 2018 to compare. All monthly graphs can be found in Appendix XX and Appendix XXI. Since August and February are the months with the least and most rainfall for both catchments, they will be treated in more detail.

Figure 3-20 shows the FDCs of Penanggungan and Tamansari for August, the month with the lowest amount of rainfall. For Penanggungan this was 23.6 mm and for Tamansari this was 21.1 mm. Both figures show a similar shape; a less variable and almost horizontal mean and low flow and a slight turn into the higher flows. For Penanggungan, the graph shows a slightly steeper change towards the higher flows than Tamansari.

Figure 3-21 shows the FDCs of Penanggungan and Tamansari for February, the month with the highest amount of rainfall. For Penanggungan this was 532.9 mm and for Tamansari this was 708.0 mm. The shape of the FDC of Penanggungan shows the high and low flow regime better, as they are more extreme. However, both shapes are not completely horizontal and show some bumps, which makes it hard to locate sharp turns from the mean flows into the high and low flows. Another difference between the two graphs is the range for the discharge. For Tamansari the range is up until 35 mm, whereas for Penanggungan the biggest discharge was 187.1 mm. This is a high amount, even though on this day (27 February 2018) and the day before a total of 64.2 mm of rainfall was measured.

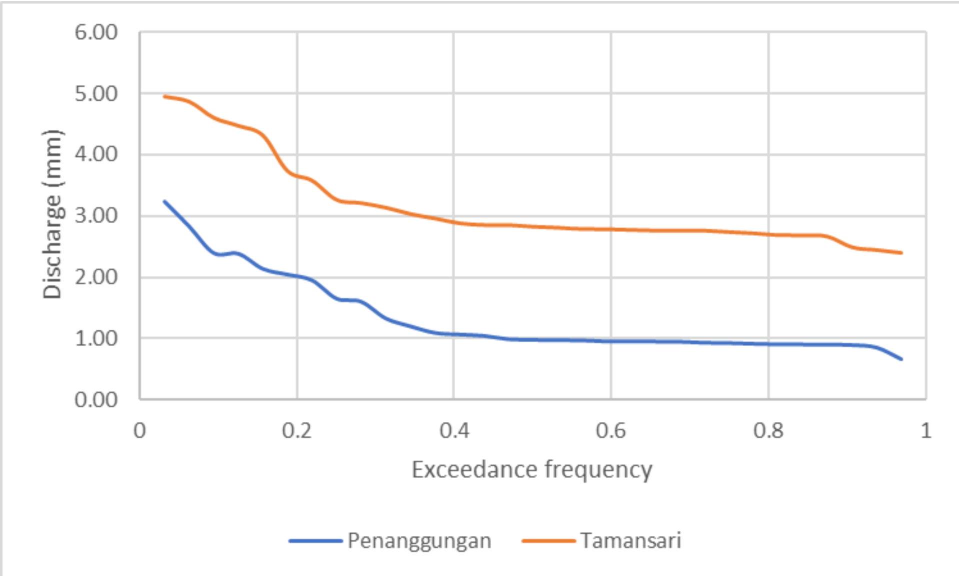

Figure 3-20. Driest month Flow Duration Curve Penanggungan (August 2017) and Tamansari (August 2017), based on daily discharges

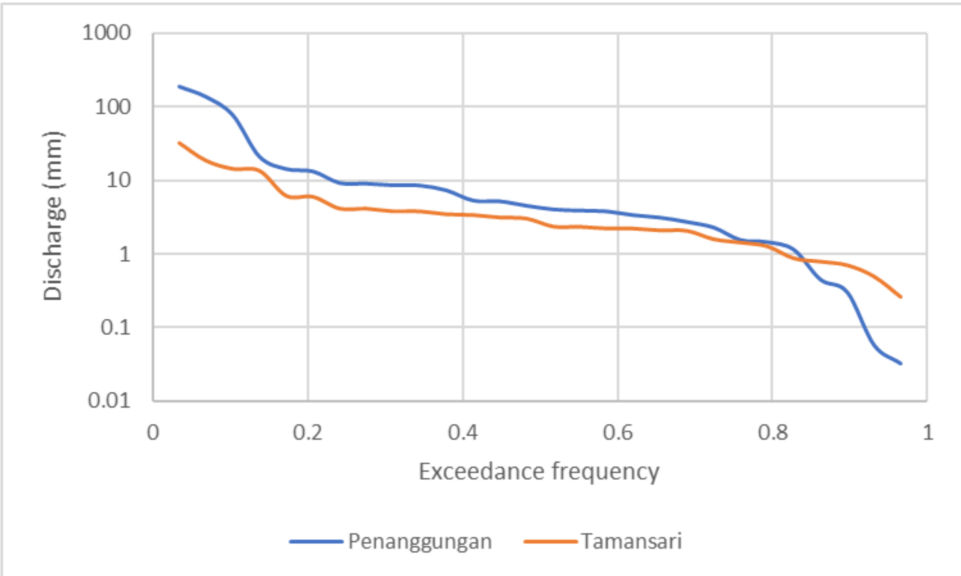

Figure 3-21. Wettest month Flow Duration Curve Penanggungan (February 2018) and Tamansari (February 2018), based on daily discharges

3.2.5. Daily Flow Duration Curve

Figure 3-22 shows the FDCs for the days with the smallest amount of rainfall. For Penanggungan and Tamansari this was day 8 of 0 mm rainfall on 27 August 2017. Both curves show a very low and a very small range of discharges. For Tamansari, the plot seems more horizontal, considering the scale. The graph does not clearly show high and low flows.

Figure 3-23 shows the FDCs for the days with the largest amount of rainfall. For Penanggungan this was 92.8 mm on 28 May 2017. For Tamansari this was 120.0 mm on 24 February 2018. The figures show a different shape. Penanggungan shows a clear high flow starting around 0.03 mm and an exceedance frequency of 0.10. The high flow part is shown a little steep in the graph, the mean flows are displayed almost horizontally. Tamansari clearly shows two states and a small and steep transition state between the two almost horizontal lines. The high flow changes to the steep transition area around 0.38 mm and an exceedance frequency of 0.28. The other sharp turn in the graph, from the transfer area to a steady mean or low flow, is around 0.01 mm and an exceedance frequency of 0.33. The graph might show that the soil is saturated and the high flows are direct runoff from the rainfall.

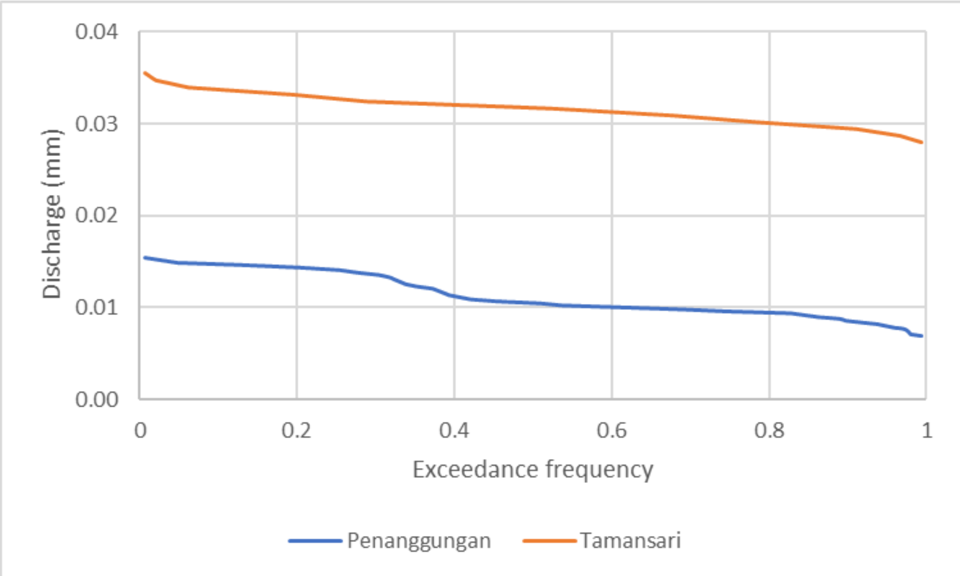

Figure 3-22. Driest day Flow Duration Curve Penanggungan (27 August 2017) and Tamansari (27 August 2017), based on 10-minute discharges

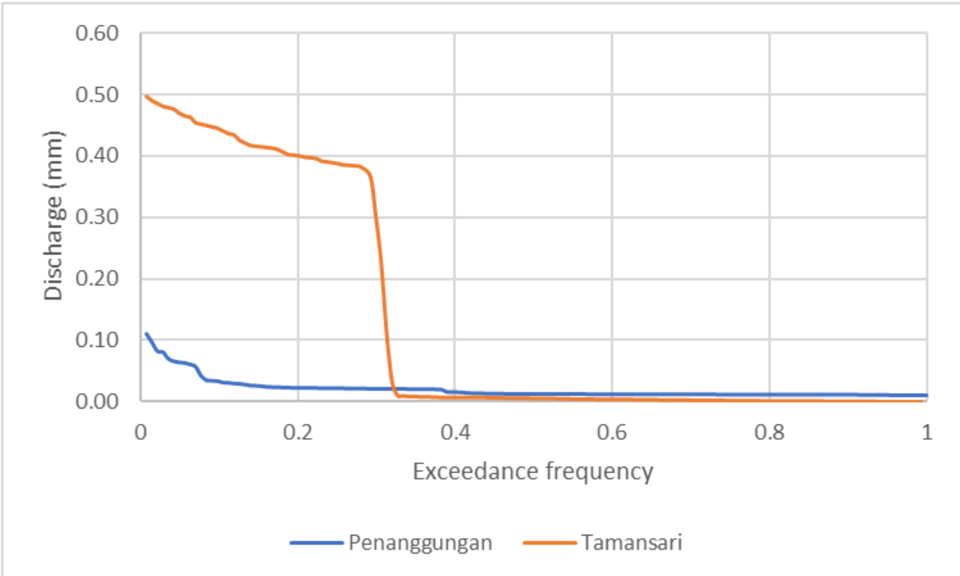

Figure 3-23. Wettest day Flow Duration Curve Penanggungan (28 May 2017) and Tamansari (24 February 2018), based on 10-minute discharges

3.2.6. Relation rainfall and discharge

Several plots were made to look at the rainfall and discharge relation. Varying the discharge between the rainfall on day ‘t’ and the discharge on day ‘t’, ‘t+1’, ‘t+2’ and ‘t+3’ did not give other results. This was done for the data of the complete year and the seasons, but all these figures did not show a clear relation other than random. The plots for the discharge on day ‘t’ per year, wet and dry season are shown in Appendix XXIV. This appendix also shows the figures for Penanggungan and Tamansari on a quicker response; the wettest day plots based on the 10-minute interval. Figure 3-24 shows the plot for Penanggungan on the wettest day. This was the only plot showing a clear trend; the more rainfall, the higher the discharge. For Tamansari, this trend was less visible, however, the majority of the higher discharges occurred with rainfall, almost all the lower discharges had 0 mm rainfall, see Figure 3-25. Both figures, for Penanggungan and Tamansari, have big values for the rainfall compared to the discharge. Looking at a lag of 1 and 2 hours in the discharge response on the wettest day also did not show clear results for Penanggungan and Tamansari.

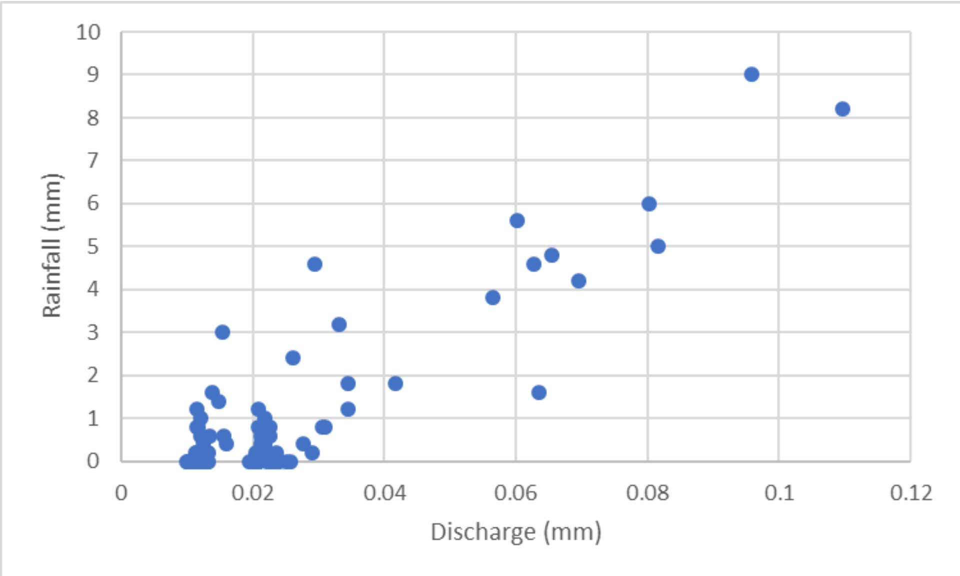

Figure 3-24. Rainfall-discharge plot Penanggungan, wettest day (28 May 2017) based on 10-minute interval

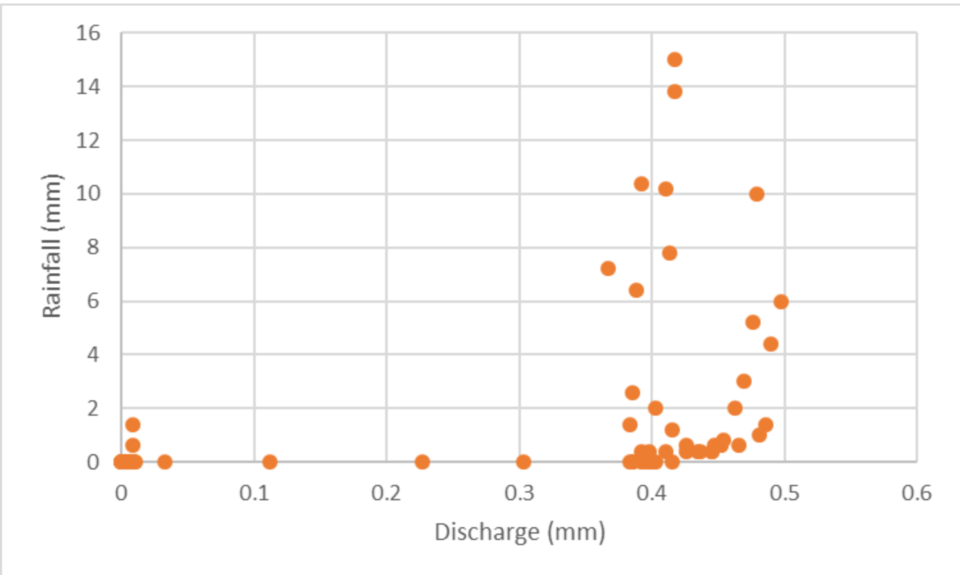

Figure 3-25. Rainfall-discharge plot Tamansari, wettest day (28 May 2017) based on 10-minute interval

4. Discussion

The results of this research will be put up for discussion in this chapter. Methods and choices in this research, have an impact on the outcome. A general choice often made during this study, was using a simple method. The reason for this choice was because of time considerations, since the whole study could take 10 weeks. Besides this, it was important to be flexible, since the data changed until halfway of the research.

Even though this was a small scale study, it shows the difference between traditional cropping and agroforestry. This way the study adds to the growing recognition of the potential of agroforestry, which Bruijnzeel et al. (1990) already stated. The insight this study provides can help water managers. Furthermore, because of the small scale of the catchments, this study can help to bridge and connect studies done in lab environments and studies done in bigger sized catchments.

4.1. Data quality checking and data extraction

The discharge is based on the measurements of the water level, the calibration of the water level and the discharge rating curves, found by two UGM students. Since the students did research on these rating curves for their thesis, the document available on the construction of the rating curves was in Indonesian. Only a small abstract was available in English. This did not give the option of checking what this curve was based on or optimised for. Using the calibrated water level and discharge rating curve, resulted in unbelievably high discharges for both Penanggungan and Tamansari.

These high discharges led to a lot of assumptions (on (1) the storage and (2) ET) to calculate a more reasonable discharge. Later it became clear for Penanggungan that a spring is used to irrigate the area. However, how big the contribution of the spring is to the total rainfall is not known at the moment. For Tamansari, there is no explanation yet, to why the discharge was so high. Another aspect not taken into account, because of the high discharges, is the fact that there can be human interventions as well, like water extraction for irrigation. All questions still unanswered, led to the choice to scale the discharge using assumptions and this will have impacted the result significantly.

(1) The storage change over the year is assumed to be very small compared to the rainfall, discharge and ET (Equation 4). However, the data starts at the beginning of the dry season, whereas this assumption would be better suited for the end of the dry season.

(2) The ET is calculated as a percentage of ET_0. ET is likely to be closer to ET_0 in the high season than in the cooler wet season. This has a big influence on the water balance, when not looking at the complete year, but for example, looking at one month. Besides this, the same percentage is used for Penanggungan and Tamansari. As the Samin catchment described by Marhaento et al. (2017b) is thought to resemble both farming land and agroforestry, for the goal of this study, this might not do justice. The ET will be different compared to ET_0 for both catchments, since they have different vegetation (Allen et al., 1998). Also the choice for the Hargreaves method for calculation ET_0 (and thus ET) leaves the different vegetation out of the direct calculation (Equation 1) and thus might show the difference between the two catchments less.

The things mentioned are thought to have the biggest influence on the results on the hydrological response. The data showed some gaps and outliers and all in all, the quality of the data is questionable and lacks the confidence to be completely trusted. This means the conclusions on the hydrological response should be handled with caution as well.

4.2. Hydrological response

Something to keep in mind interpreting the results and drawing conclusions is the fact that the Tamansari figures are not based on 12 complete months of data; half of the dry season is missing. Therefore, conclusions may not be valid for the whole year or dry season.

Because the FDCs are created using one year of data, they should be interpreted with caution. Not a lot of data points created the curves. This is especially true for the monthly figures, which consist of about 30 daily data points. This is why they are displayed as points rather than a curve. So, conclusions from the monthly curves should be handled with extreme caution. The conclusions based on the annual, seasonal and daily figures are more reliable, as they are made up of more than a hundred data points (which for hydrological studies is still not a lot).

A still unexplained phenomenon is the observation in the FDCs that the lowest daily discharges occur during the wet season. Whilst they almost go to zero, the daily discharges in the dry season are low, but not as low as discharges in the wet season. Looking into the relation between the rainfall and discharge for the wet and dry season, did not give an explanation for this observation.

The annual figures, wet season and wettest month all show similar results. The wettest day also shows a clear high flow regime, however not so big for Penanggungan and in another shape for Tamansari compared to the wet month and season. The dry season, driest month and driest day also show similar results. A slightly different flow regime will show up, the longer time period will be considered. This is not strange, as more time gets included. As the wet and dry figures have different conclusions, this does not mean a general conclusion on the annual data and the hydrological response cannot be given. However, since the annual figures are similar to the wet figures, it is a question how much the dry data influences the annual FDC. Especially with the phenomenon explained in the paragraph above; the fact that the lowest discharges occur in the wet season.

As for general conclusions, this study can only conclude based on one year of data, and thus conclusions should not be interpreted as a hard truth for every year and cannot be used to predict discharges in the future. However, this year of data can be compared to climate data of Karangkobar district (climate-data.org, 2019). This shows that Penanggungan had a normal amount of rainfall this year, with 3800 mm of rainfall compared to 3990 mm for Karangkobar. For Tamansari this is harder to compare, since 2,5 months of data are missing in the dry season. However, Tamansari had almost 2700 mm of rainfall. It is likely that Tamansari had a drier year compared to the climate-data.org (2019) data. As for the temperature, in Karangkobar the mean temperature is 21.0 degrees Celsius. For Penanggungan and Tamansari this was 18.0 °C and 19.7 °C respectively. So for both catchments this was a little colder than normal.

The paired catchment method is selected for comparing two similar catchments, with one difference; in this case the land use. Although elevation, slope, soil type, rainfall and temperature are quite similar, it cannot be concluded with 100% certainty the differences seen in the hydrological responses is due to the difference in land use. The size of the catchments could have an influence as well, as Tamansari is 4 to 5 times bigger. The bigger size could also explain the slower response of Tamansari. Still, both catchments are very small in the study field of hydrology. Besides the size, the amount of rainfall also showed some differences, whereas Tamansari had about 2700 mm rainfall and Penanggungan 3800 mm. This can influence the discharge as well. The height difference can also have an influence on the amount of rainfall and temperature difference between the two catchments, and thus influence this study.

5. Conclusions and Recommendations

This chapter will give the conclusions reached at the end of this study as well as recommendations for UGM and further research. The conclusions will be treated in the same order as the initial research questions, stated in paragraph 0. First, conclusions will be made on the quality of the data and information extraction. Then the hydrological response of both catchments will be addressed. After the conclusions, the recommendations will be given.

5.1. Conclusions

The calibrated water levels, in combination with the discharge rating curves and the temperature data, did not perform well in terms of good data quality. The rainfall data, aerial photographs and GIS data were thought to be of suitable quality. Since the hydrology of two catchments is studied in this research, the hydrological data is very important. So, to answer the first research question: '*What is the quality of the used hydrological and meteorological data and what information can be extracted to characterise the two catchments for comparison to other hydrological studies?*', the raw data is not always bad, however, the quality is not good enough and the quantity is very little for the aim of this study. With adjustments, the data quality can be improved. The data available for extracting other information needed to describe the catchments were sufficient to describe the land cover and land use, the elevation and slope and the soil of the two catchments. These factors sufficiently describe the important characteristics of the areas.

The water balance in Figure 3-15 and Figure 3-16, showed that Penanggungan reacts more extreme to rainfall than Tamansari, which showed a steadier flow throughout the months. Especially the month February, the month with the largest amount of rainfall, showed Tamansari responds less quickly to the rainfall than Penanggungan. Annual values showed that for Penanggungan the total discharge was 41% of the annual rainfall, for Tamansari this was 30%.

The flow duration curves support that Tamansari has a less variable flow than Penanggungan. The annual figures, wet season and wettest month all show similar results. The FDC of Tamansari show sharp turns into the high flow for lower exceedance frequencies and sharp turns into the lower flows for higher exceedance frequencies than Penanggungan. This seems logical, as the Tamansari catchment is covered with trees, whereas Penanggungan is mostly covered with just crops. The mean flows showed up in the FDCs more horizontal for Tamansari than for Penanggungan, which means that the mean flows in Tamansari are steadier and less variable than the mean flows of Penanggungan. The wettest day also shows a high flow regime, however not so big for Penanggungan and in another shape for Tamansari compared to the wet month and season. Overall, Penanggungan showed higher flows than Tamansari, especially shown in Figure 3-21, which shows the FDC of February, the month with the largest amount of rainfall.

The dry season, driest month and driest day also show similar results. The FDC show low variation in the discharge and a similar shape can be observed for both catchments. Low or high flow regimes are almost not present. Overall, Penanggungan showed lower flows than Tamansari.

Analysing the relation between rainfall and discharge did not show a clear correlation between the two variables. Only the wettest day for Penanggungan, Figure 3-24, showed a clear relation, where more rainfall meant a higher discharge.

Based on these observations an answer can be given on the second research question: '*How do the hydrological responses of the Tamansari and Penanggungan catchment compare to each other?*'. Tamansari showed lower discharges in the wet season and higher discharges in the dry season than Penanggungan. This, the water balance and FDCs show that a micro-catchment mostly occupied with seasonal crops like Penanggungan reacted more extreme to rainfall than a micro-catchment mostly occupied with combined trees and seasonal crops in form of agroforestry like Tamansari. Although not all figures analysing the relation between the rainfall and discharge support this conclusion, these conclusions are in line with (de)forestation studies from Brown et al. (2005) and Bruijnzeel (1990). It also agrees with the study from Mwangi et al. (2016), which states that agroforestry in the Mara River Basin would generally reduce surface runoff, reduce base flow and increase the ET. The combined result showed that the water yield would decrease, based on a SWAT model.

With these answers on the research questions, the aim '*to get insight in the hydrological response of a micro catchment mostly occupied with seasonal crops and a micro-catchment mostly occupied with combined trees and seasonal crops in form of agroforestry and learn the differences'* is achieved. The hydrological response of both catchments has been studied through FDCs and the differences have been stated; although not all observations could be explained, the bigger picture fits in with the known literature.

5.2. Recommendations

One of the biggest issues, also stated in chapter 4, this study has dealt with, is having little data and missing data within this small dataset. So, for giving more body to the conclusions based on 1 year of data more data should be gathered. This will give UGM the opportunity to look at the consequences of having a different farming practice with its corresponding land use. This might also help excluding other factors like a different amount of rainfall or a height difference influencing the results. What should also be looked into, is the other impact agroforestry might have on the hydrology of an area, as Gerjerts et al. (2017) states this type of land use has shown a positive effect on the hydrological conditions, for example the increasing the soil moisture and lowering the air temperature, after a drought period.

When gathering more data, it is recommended to check the quality of the data simultaneously. In this way, it will be easier to explain unusual values in the data and big gaps can be prevented. To improve the quality of the data, the unusual high discharges should be investigated. For Penanggungan it should be studied what the impact of the spring is to the total amount of water. For Tamansari, an explanation for the unusual high discharge is still needed. It is a waste of this high temporal resolution data if data has to be deleted from the dataset, because values seem unrealistic and cannot be explained.

An interesting observation from this study still unexplained is the fact that the lowest discharges occur during the wet season. This does not seem logical. Analysing the relation between the rainfall and discharge for the wet and dry season could not give an explanation to this observation. Therefore, it is recommended to look for an explanation of why the lowest discharges occur during the wet season, as this will help understanding the hydrology of the area.

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I. Appendix – From raw data to 10-minute interval dataset

The data of Penanggungan and Tamansari were received separately, in different files. The Penanggungan data was received as Excel file. It consisted of 4 tabs, respectively the water level of 2017 and 2018, the meteorological data of 2017 and 2018. The water level tabs were combined and the meteorological tabs were combined, to get a full dataset from April 1st 2017 till March 31st 2018. The columns of the water level were Number, Date and Time, Date, Time, AM/PM, Water Level (meters), Calibrated Water Level (meters) and Discharge (m^3/sec). The columns of the rainfall were: Date and Time, Time, Tab, Rainfall (mm) and Temperature (Celsius). In which the 'Tab' represents the amount of tabs the measuring device has made. One tab represents 0,2 mm of rainfall.

After combining the tabs, the files were inspected. Things like yellow marked cells or empty rows, were adjusted and deleted. Besides, some cells containing date and/or time, were adjusted, to fit the overall format. The format differed, since several people were collecting the data, so the measuring devices were not always programmed the same way. I was observed that the time intervals in all the data was not always the same. Sometimes it was a 5 minute interval, sometimes a 10 minute interval and this would differ between the meteorological and water level data. So, to help combining the water level and meteorological data, some columns were added. The columns Year, Month, Day, Hour and Minute were added to both tabs.

A Matlab script was used to combine the water level, rainfall and temperature data, based on the columns Year, Month, Day, Hour and Minute. The script checks if the date and time are exactly the same, and then combines the data in a new table, which can be exported. The export has the columns Year, Month, Day, Hour, Minute, Water Level (meters), Calibrated Water Level (meters), Discharge (m^3/sec), Rainfall (mm), Temperature (Celsius) based on a 10 minute interval. The 5 minute interval data, was not used, since averaging it into the 10 minute interval would influence the data very little. The time scale is already very small. However, the 5 minute rainfall data was not deleted, since this would influence the overall amount of rainfall very much. Instead, the 5 minute interval rainfall was added to the following 10 minute interval.

Extra columns are added to the exported table, to make the data more workable: Day Number (amount of days, so 1 to 365), Number (Number of datapoint), Date and Time, Date, Time, Extraterrestrial Radiation (MJ/m^2day). In addition, some columns were calculated: Interval and Discharge (mm). Some plots were made to make the discharge, rainfall and temperature data visual. More information about the calculations or Extraterrestrial Radiation can be found in chapter 2.2, more information on the plots will be given in chapter 3 Results. To be able to see outliers and get a better view on the data, for each column, some statistics were calculated: Minimum, Maximum, Mean, Sum and Amount, in which the amount shows how many data points there are. In some cases there are some gaps, which can be detected this way. Afterwards, based on the column Day Number and/or Month, a Pivot table can be accumulated to show the daily and monthly results.

A new tab is made, where computations to the data can be done. Examples of computations, to improve the quality of the data are, filling in gaps in the data or removing outliers. The reason for doing this in a new tab, is to see the difference in the plots and statistics before and after the 'touch ups'. These touch ups will be explained in Appendix II and Appendix III. A general touch up, so for applicable for discharge, temperature and rainfall, was the fact that there was no data on 3 March 2018 at 00:00. When looking at the original data, there were the date 2 March 2018 at 00:00 appeared twice, once on the place of the 3rd of March. It was assumed that this second 2 March 2018 00:00 contained the data of 3 March 2018 00:00. The data was in the right location and the values fitted the values 10 minutes before and after. So, the values of 2 March were manually put in the spot of 3 March 00:00.

II. Appendix – Penanggungan Dataset Adjustments

1 = General check, 2 = Statistics, 3 = Visual, 4 = Water Balance; The General check was done for the raw data, the other 3 methods were done for the sorted dataset with only the 10-minute interval data.

What?	Observation	Adjustment
1. Separate tabs	Separate tabs for 2017 and 2018 data.	Copied and pasted, so that the correct columns of 2018, continue under 2017.
1. Marked cells	Some (blocks) of cells were marked yellow or green. This meant nothing according to the person providing the data.	Unmark the marked cells
1. Empty rows	Some empty rows were present in the dataset. This meant nothing according to the person providing the data.	Delete empty rows
1. Water Level	From 3 February 2018, there are no more water level values.	Since the calibrated water level is used for this research, the water level column could be deleted.
1. Temperature	Gaps in the data	Fill the gaps linearly. Since the data gaps were random, the temperature was not based on the day before or after, since there could be gaps here as well.
1. Rainfall	From 6 February 2018 there are no values in the column 'Tabs', however, the 'Rainfall' column still had values.	Since the rainfall is used for this research, the tab column was deleted.
1. Rainfall	Gaps in the data, from 21 March 2018 onwards there are a few values, none of them are 0	It was assumed the empty values were actually 0 measurements, so the empty cells got the value 0 mm.
1. Date and Time	The columns 'Date and Time' and 'Date' can have several formats.	Change the formats, so they all have the same.
1. Interval	Not all intervals are 5 minutes, on 17 July 2017, the interval for the water level changes from 5 minutes to 10 minutes. On 3 February 2018 the interval changes back to a 5-minute interval. For the rainfall and temperature, something similar happens. 18 July 2017the interval witches from a 5- to a 10-minute interval and on 6 February 2018 it switches back from a 10- to a 5-minute interval.	A Matlab script was written, to combine the water level data with the rainfall and temperature data, based on the same time and day. Afterwards the 5-minute intervals were deleted, to create a homogenous timed 10 minute interval dataset. (Except for the rainfall data, this was not deleted, but the 5-minute values were added to the following time step).
2. Calculations	-	The time interval is calculated, by using the column 'Date and Time' and the discharge is calculated, using the calibrated water level

		and the rating curve 2,2194*CWL^{2,5}.
2. Interval	All intervals are 10 minutes, except for one 20-minute interval at 3 March 2018. In the original data, there was no temperature and rainfall data on 3 March 2018 00:00.	In the raw data, the date and time 2 March 2018 00:00 was found twice, one I the spot where 3 March 2018 would be expected. Since the values seemed reasonable with the values before and after, it was assumed there was a mistake in the date and the water level, rainfall and temperature data was manually put into the structured data.
2. Rainfall	The maximum intensity is 15,6 mm and the total amount of rainfall is 3000 mm.	This seems realistic compared to climate-data.org (2019). This could happen, so the data was not altered.
2. Temperature	The maximum temperature is 44 degrees (16 March 2018), this is way too high, especially since the temperature values before and after are 16 degrees Celsius.	The 44 degrees were removed and the gap was filled liked the other temperature gaps.
2. Temperature	The minimum temperature is 4 degrees, this is way too low. This value was interpolated at the last data point. Because there was no temperature measured afterwards, the last three values were interpolated between 18 and 0 degrees.	The last three values were set to the last measured value: 18,045 degrees Celsius.
2. Temperature	The (new) minimum temperature is 9 degrees. This seems low, however, 9 degrees is measured a lot of times.	Since climate-data.org (2019) states a minimum daily temperature of 15.4 degrees. As a rule of thumb, every value lower than 10 degrees, which had a difference larger than 5 degrees with the temperature at the same time the day before, was deleted. The gaps were treated like other temperature gaps.
3. Calibrated Water Level	Quite constant through the year, but high deviation in February and March. This cannot be directly explained looking at the rainfall.	Since these months are in the wet season, higher deviation is not strange. Another explanation, for the lower values can be an extraction of water for irrigation.
3. Rainfall	The pattern looks good, however there still is some rain in the other months, there seems to be more rainfall in the months from October – May.	The pattern looked good, so no changes were made based on this observation.
3. Temperature	There is a low variation of temperature in April/May, compared to the rest of the year.	There was nothing found to clarify this pattern, since the range was still realistic, no

		changes were made based on this observation.
4. Calculations	-	The ET_0 was calculated using the Hargreaves method (Hargreaves & Samani, 1982). This method calculates the ET_0 per day, so first a pivot table was made from the data, to structure the minimum, maximum and mean daily temperature.
4. Calculations	Not all variables for the water balance are in the same units.	Rainfall and ET_0 were respectively 3002 and 2249 mm in these 365 days. So, the discharge was also calculated to mm from m^3/sec. This led to a discharge of 10 930 mm
4. Water Balance	For dS/dt = 0 over 1 year; ET = P – Q gives ET = 3002 – 10,930 This doesn't seem right, and also knowing ET_0 is 2249 mm. Since the rainfall looks normal, and ET_0 is in the same range as the rainfall, which seems normal, the discharge must be wrong.	The discharge will be adjusted based on the annual outflow. First, the ET will be determined, using the same ratio for ET/ET_0 as Marhaento, Booij & Hoekstra (2017). It is thought the climate and land use of the Samin catchment of 1994 is comparable to the two micro-catchments. This results in the ratio ET/ET_0 of 1374/1644. Together with the rainfall in the time period, Q will be calculated by P – ET. This calculated discharge is compared to the discharge from the measurements and result in a ratio aswell: $Q_{calculated}$ / $Q_{measurements}$ is 10,000/70,000. This ratio is used to transfer all the 10-minute interval discharges.

III. Appendix – Tamansari Dataset Adjustments

1 = General check, 2 = Statistics, 3 = Visual, 4 = Water Balance; The General check was done for the raw data, the other 3 methods were done for the sorted dataset with only the 10-minute interval data.

What?	Observation	Adjustment
1. Separate tabs	Separate tabs for 2017 and 2018 data.	Copied and pasted, so that the correct columns of the months continue under May 2017.
1. Marked cells	Some (blocks) of cells were marked yellow or green. This meant nothing according to the person providing the data.	Unmark the marked cells
1. Water Level	From 20 May 2017 there are no more (calibrated) water level values till 17 July 2017.	The group collecting the data explained they didn't measure the water levels, because it was the dry season. The water level data cannot be interpolated or filled otherwise, so the total values of the discharge should have this in consideration.
1. Rainfall & Temperature	From 16 July 2017 till 10 October 2017 there are no measurements for rainfall and temperature.	The rainfall and temperature data of Penanggungan will be used, since the two catchments are only 10 km away from each other. For the rainfall, a correction for the height difference will be done, using the conversion of 153 mm more rainfall per year every 100 m rise (Marhaento et al., 2017a). For the temperature, the conversion of 6,5 degrees Celsius fall in temperature per kilometre rise. (Rose, 2019) Penanggungan is 300 meters higher than Tamansari.
1. Temperature	Gaps in the data	Fill the gaps linearly. Since the data gaps were random, the temperature was not based on the day before or after, since there could be gaps here aswell.
1. Rainfall	Gaps in the data, there are a few values, none of them are 0	It was assumed the empty values were actually 0 measurements, so the empty cells got the value 0 mm.
1. Calibrated Water Level	Gaps in data from 20 May 2017 till 17 July 2017	Since the gap is so big, this cannot simply be filled. When looking at annual values this should be kept in mind.

1. Interval	Not all intervals are 5 minutes, on 17 July 2017, the interval for the water level changes from 5 minutes to 10 minutes. On 4 February 2018 the interval changes back to a 5-minute interval. For the rainfall and temperature, something similar happens. 18 March 2018 the interval witches from a 5- to a 10-minute interval.	A Matlab script was written, to combine the water level data with the rainfall and temperature data, based on the same time and day. Afterwards the 5-minute intervals were deleted, to create a homogenous timed 10-minute interval dataset. (Except for the rainfall data, this was not deleted, but the 5-minute values were added to the following 10-minute time step).
2. Calculations	-	The time interval is calculated, by using the column 'Date and Time' and the discharge is calculated, using the calibrated water level and the rating curve $3.085*CWL^{1.674}$.
2. Calibrated Water Level	Negative values, which result in no discharges.	Based on the way the data is gathered and calibrated, all negative values were adjusted to 0 meter measurements.
2. Rainfall	Th maximum intensity is 16.6 mm per time interval of 10 minutes, and the total amount of rain is 2697.7 mm.	This seems realistic compared to climate-data.org (2019). This could happen, so the data was not altered (keeping in mind there is some rainfall data missing).
2. Temperature	The minimum temperature is 13 degrees and the maximum is 32 degrees, whilst the mean temperature is almost 20 degrees.	Except for the 32 degrees outlier, since the second highest temperature this day was 26 degrees, the temperature data looks realistic compared to climate-data.org (2019). The 32 degrees outlier is deleted and treated as a normal temperature gap.
3. Calibrated Water Level	Rising water level in May, without much rainfall	Together with the gap in the data from May 2017 till 17 July 2017, this data will be deleted and not taken into account. So, the dataset will consist of 17 July 2017 13:10 till 30 April 2018 23:50.[1]
3. Rainfall	Highest rainfall is in the dry season, in July	As stated in the row above, this data will not be taken into consideration.

[1] Although there is calibrated water level data missing from 8 April 10:20 onwards, rainfall and temperature data was available.

3. Temperature	Two outliers, of 32 and 28 degrees, which are higher than the temperatures around this time. This was checked in the data, and appeared on 8 April 2018 and 18 March 2018, respectively.	The two outlier values were deleted, and treated as a 'normal' temperature gap, so filled linearly.
4. Water Balance	The discharge is higher than the rainfall. The untreated data gives Q = 4985.9 mm, ET_0 = 2233.7 mm and P = 2697.9 mm. After talking to the people of the lab, who collected the data, it was assumed there is a systematic error in the data or in the discharge rating curve. The high discharge is too high to be explained by the fact it is a micro catchment and thus water might enter the catchment from outside of the catchment.	The discharge will be adjusted based on the annual outflow. First, the ET will be determined, using the same ratio for ET/ET_0 as Marhaento, Booij & Hoekstra (2017). It is thought the climate and land use of the Samin catchment of 1994 is comparable to the two micro-catchments. This results in the ratio ET/ET_0 of 1374/1644. Together with the rainfall in the time period, Q will be calculated by P – ET. This calculated discharge is compared to the discharge from the measurements and result in a ratio aswell: $Q_{calculated}$ / $Q_{measurements}$ is 1200/5000. This ratio is used to transfer all the 10 minute interval discharges.

IV. Appendix – Rainfall plots Penanggungan

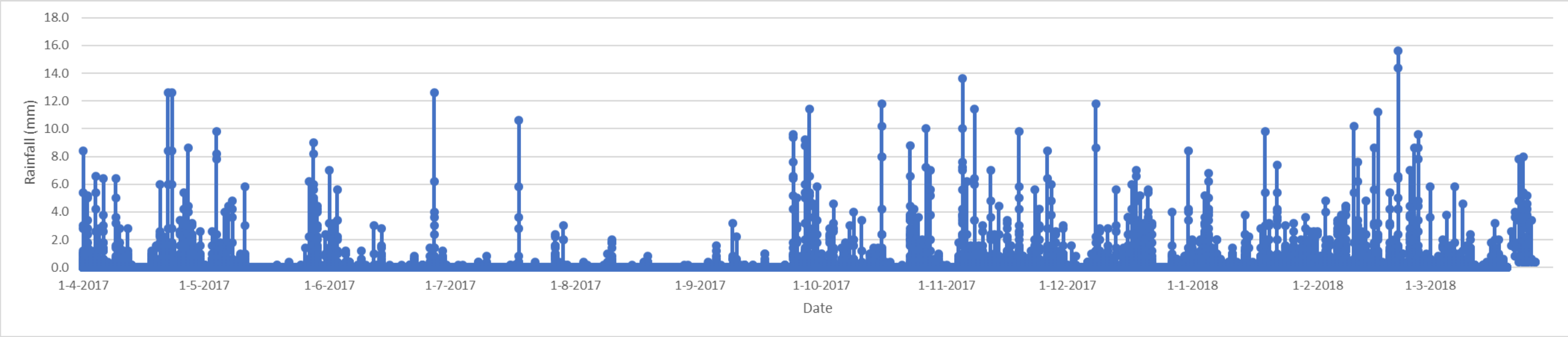

Figure IV-1. Rainfall Penanggungan before adjustments

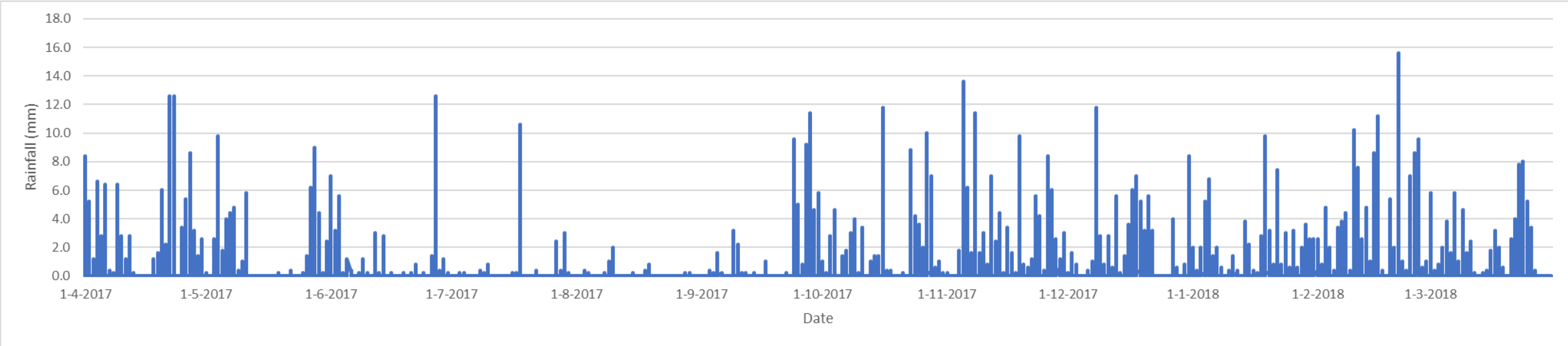

Figure IV-2. Rainfall Penanggungan after adjustments

V. Appendix – Rainfall plots Tamansari

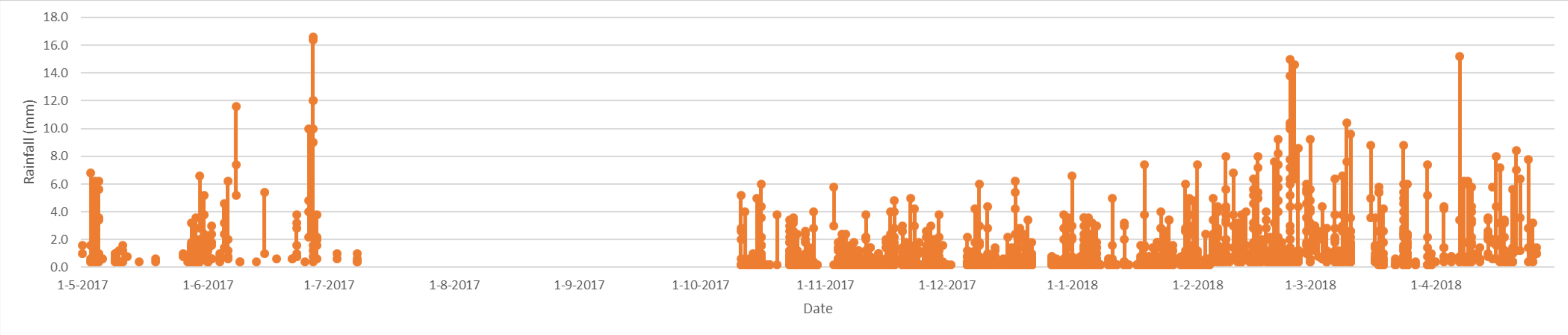

Figure V-1. Rainfall Tamansari before adjustments

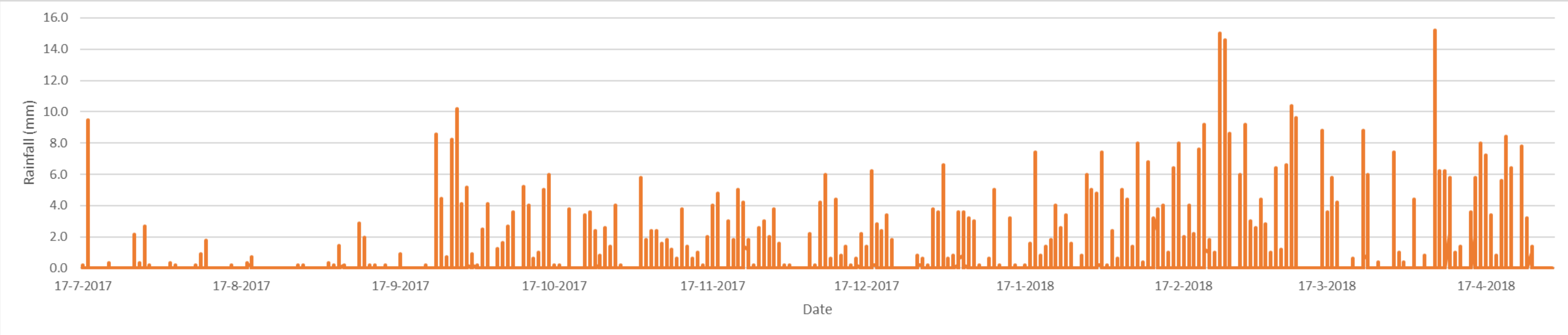

Figure V-2. Rainfall Tamansari after adjustments; be aware of the different timescale

VI. Appendix – Temperature plots Penanggungan

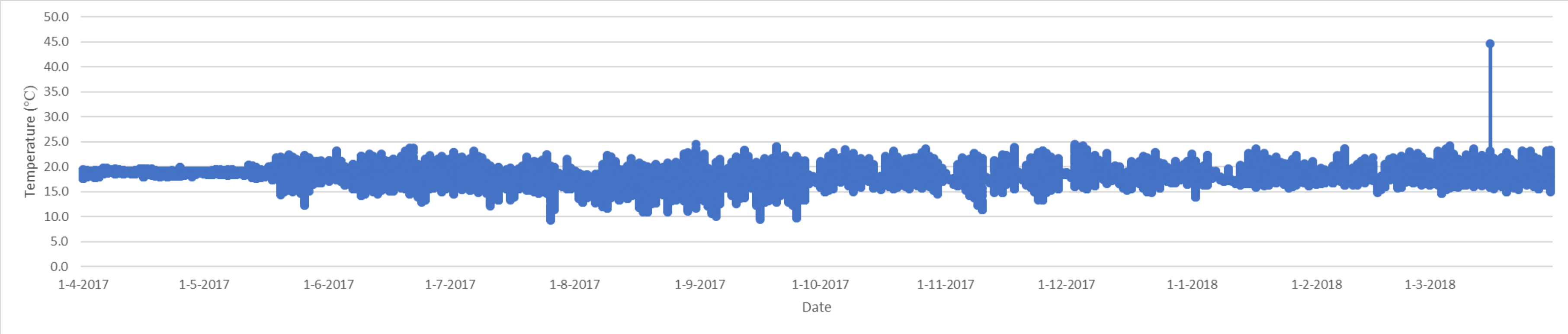

Figure VI-1. Temperature Penanggungan before adjustments

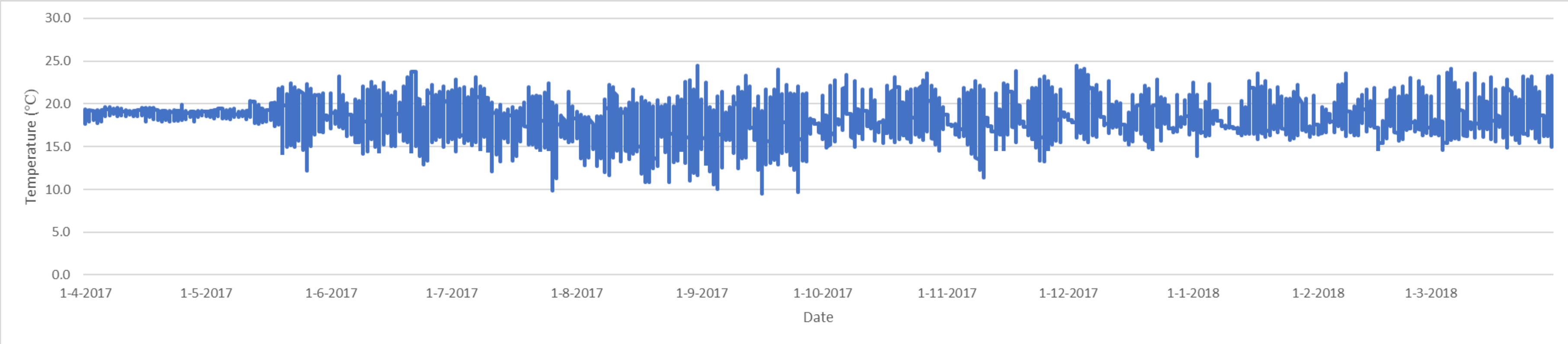

Figure VI-2. Temperature Penanggungan after adjustments

VII. Appendix – Temperature plots Tamansari

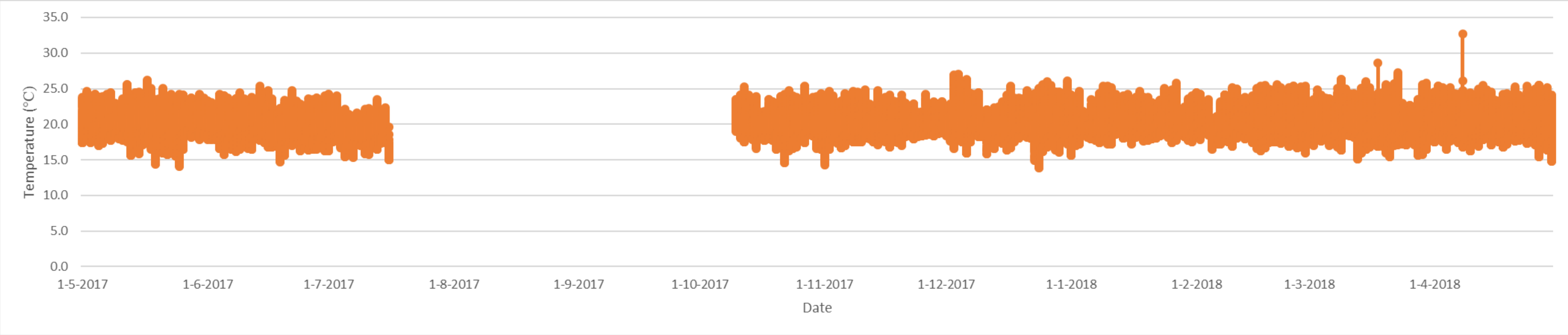

Figure VII-1. Temperature Tamansari before adjustments

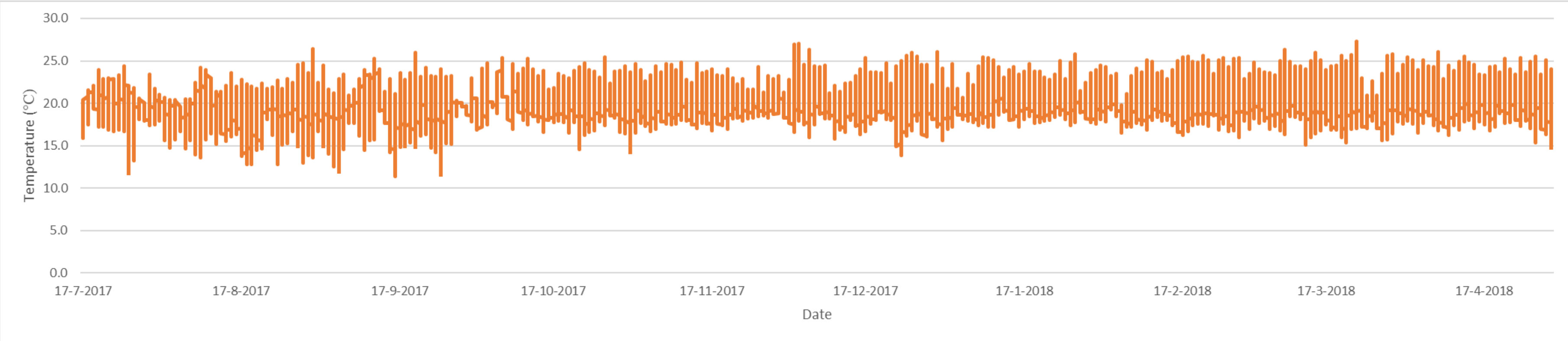

Figure VII-2. Temperature Tamansari after adjustments; be aware of the different timescale

VIII. Appendix – Calibrated Water Level plots Penanggungan

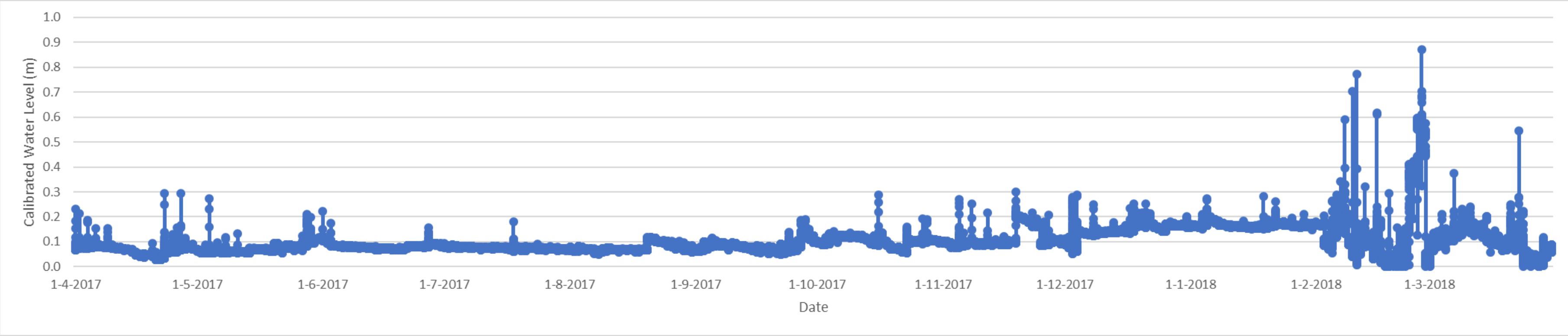

Figure VIII-1. Calibrated Water Level Penanggungan before adjustments

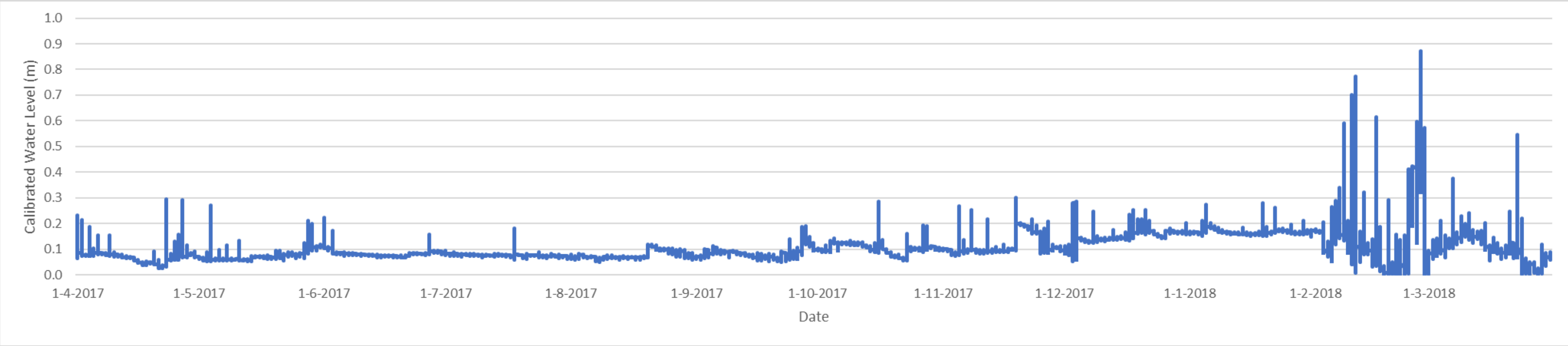

Figure VIII-2. Calibrated Water Level Penanggungan after adjustments

IX. Appendix – Calibrated Water Level plots Tamansari

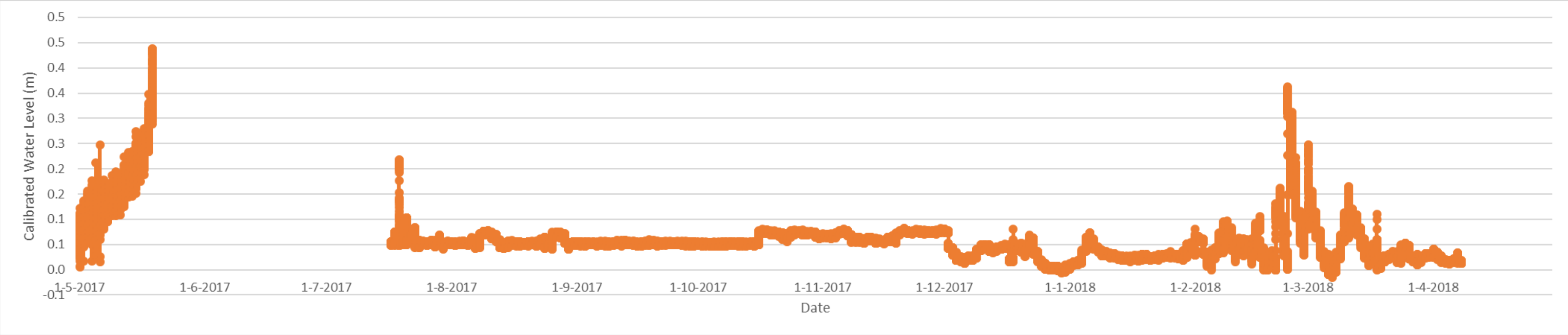

Figure IX-1. Calibrated Water Level Tamansari before adjustments

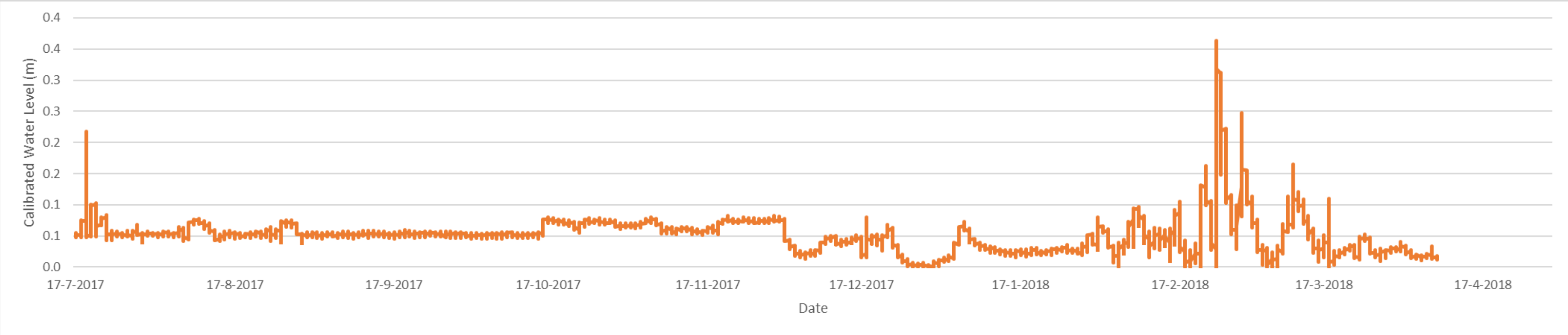

Figure IX-2. Calibrated Water Level Tamansari after adjustments; be aware of the different timescale

X. Appendix – Discharge plots Penanggungan

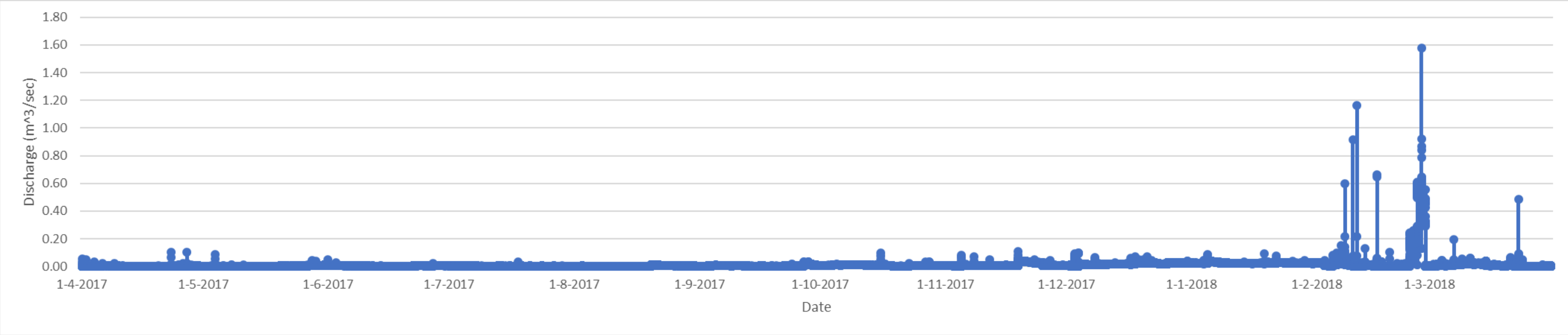

Figure X-1. Discharge Penanggungan before adjustments

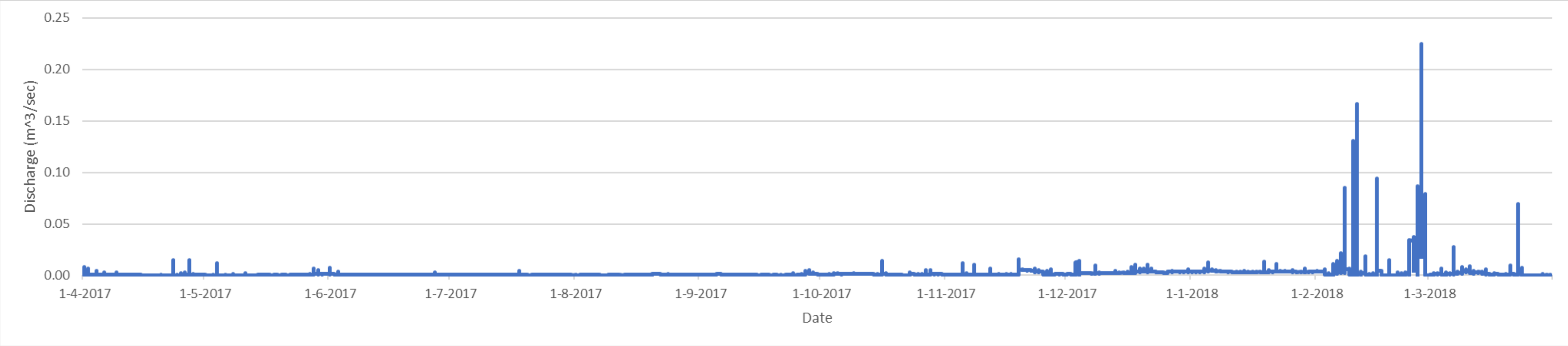

Figure X-2. Discharge Penanggungan after adjustments

XI. Appendix – Discharge plots Tamansari

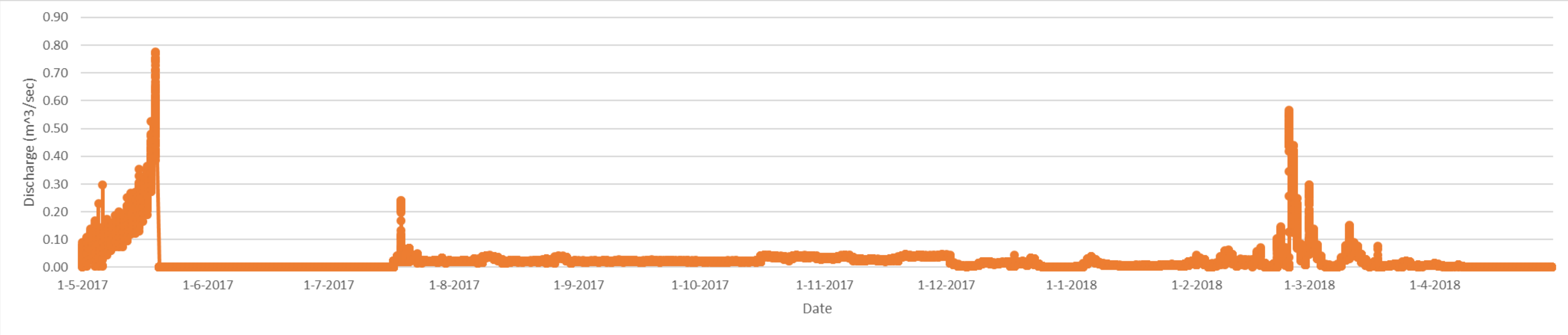

Figure XI-1. Discharge Tamansari before adjustments

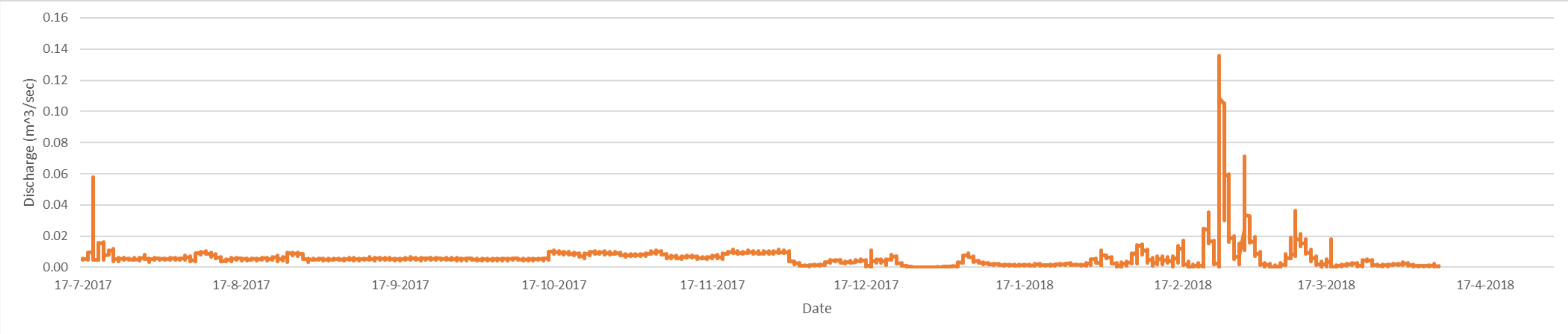

Figure XI-2. Discharge Tamansari after adjustments; be aware of the different timescale

XII. Appendix – Penanggungan aerial photo and land cover map

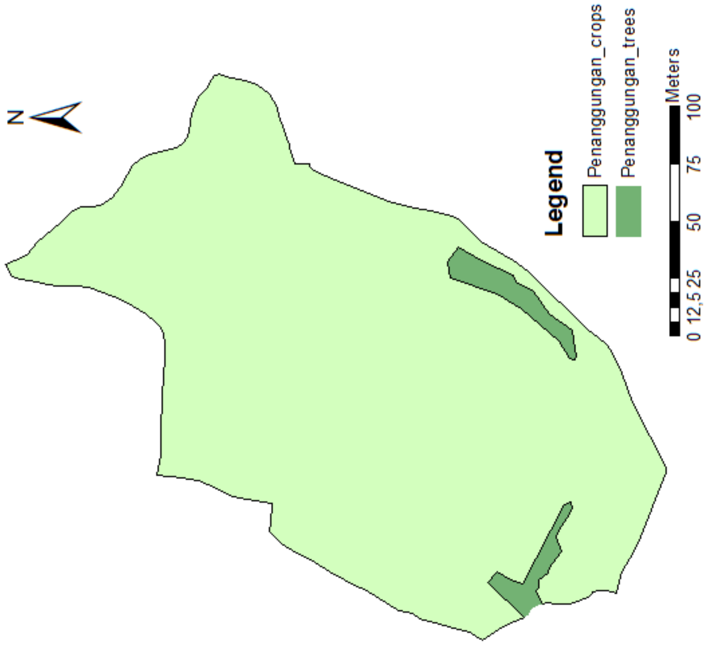

Figure XII-1. Penanggungan Land Cover Map

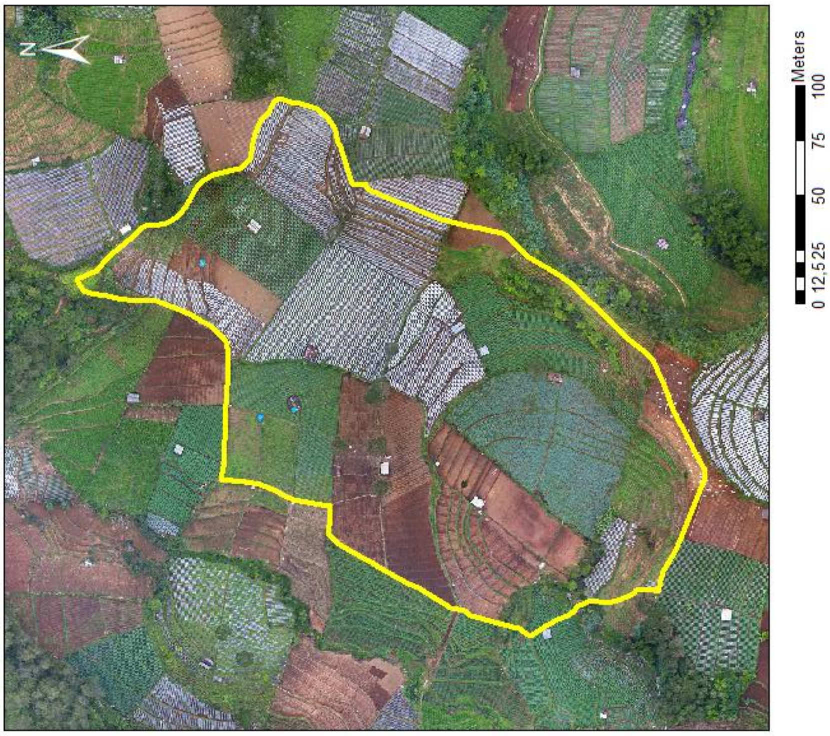

Figure XII-2. Penanggungan aerial photograph

XIII. Appendix – Tamansari aerial photo and land cover map

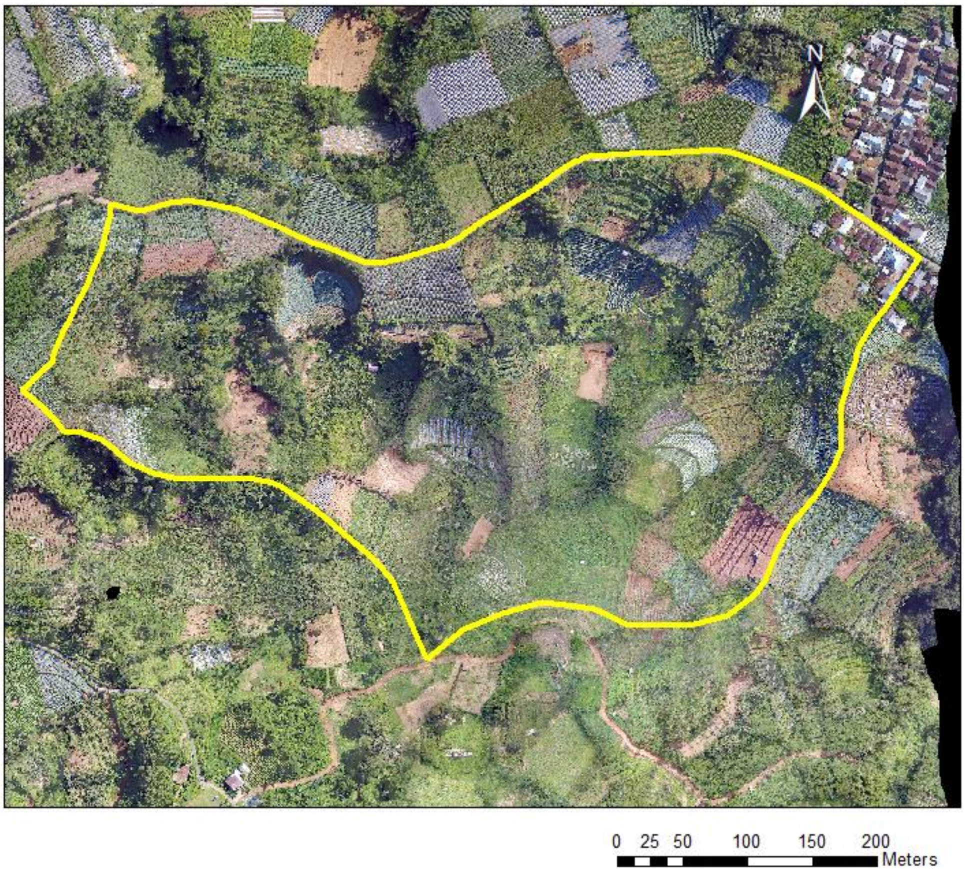

Figure XIII-1. Tamansari aerial photograph

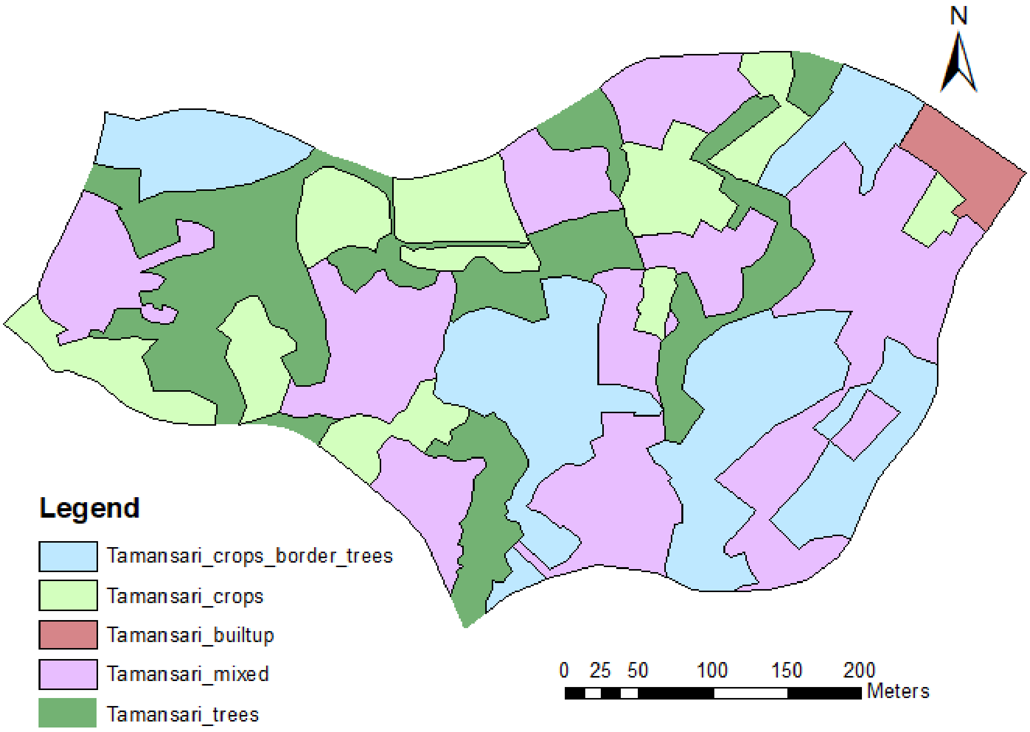

Figure XIII-2. Tamansari Land Cover Map

XIV. Appendix – Penanggungan and Tamansari elevation maps

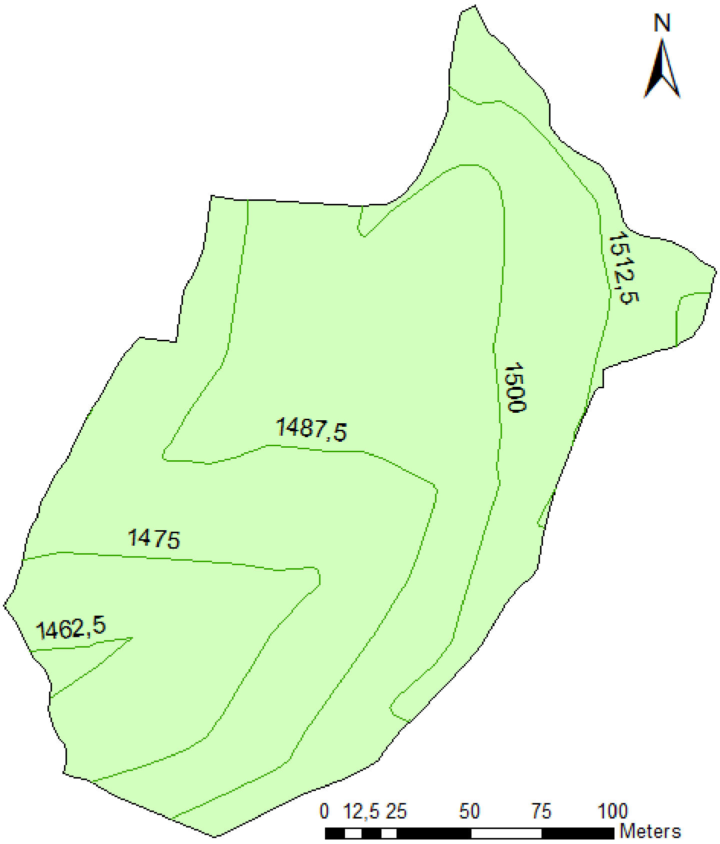

Figure XIV-1. Penanggungan Elevation Map (meters above MSL)

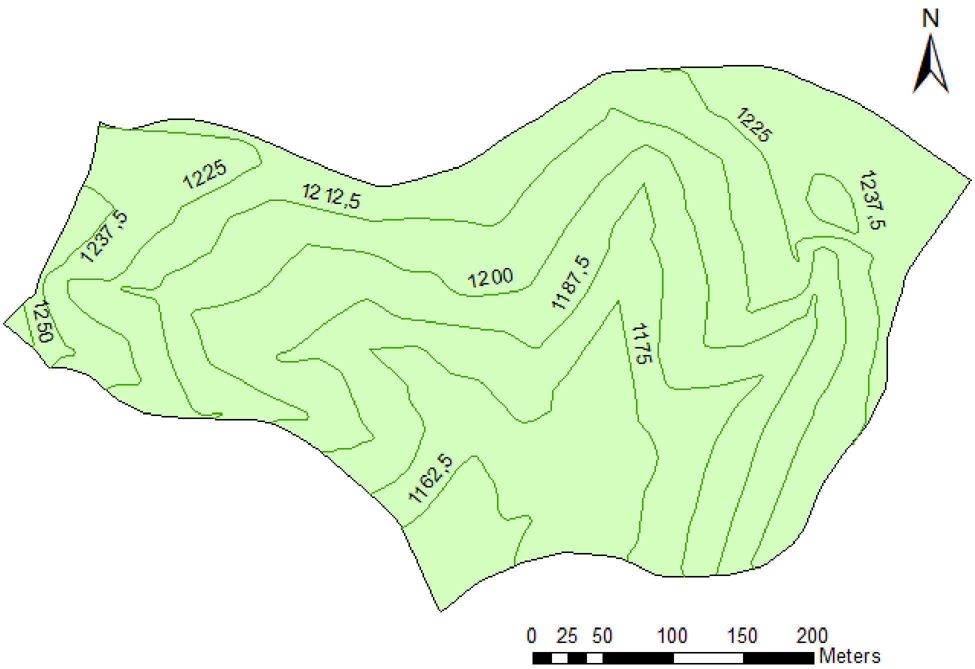

Figure XIV-2. Tamansari Elevation Map (meters above MSL)

XV. Appendix – Penanggungan slope calculations

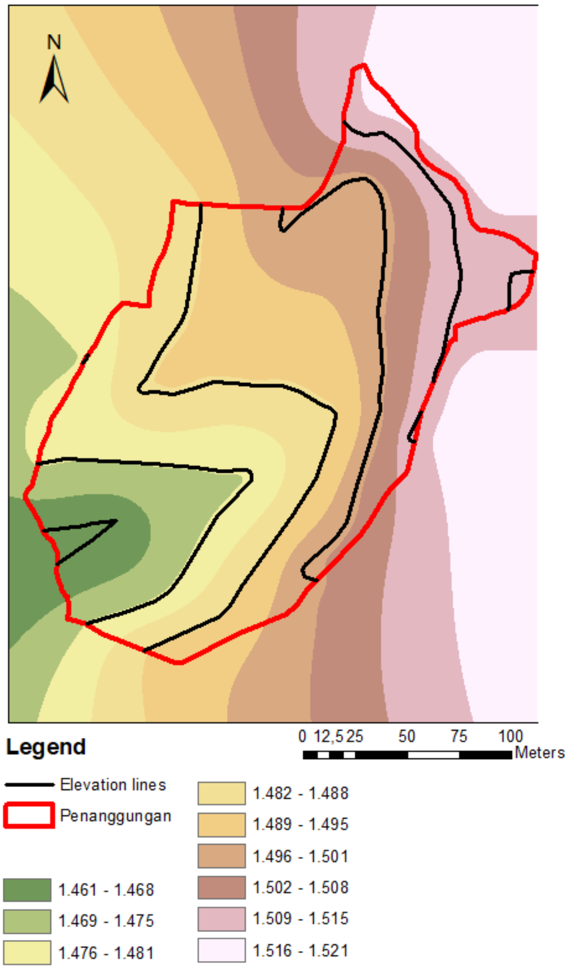

Figure XV-1. Penanggungan Elevation Raster Map (meters above MSL)

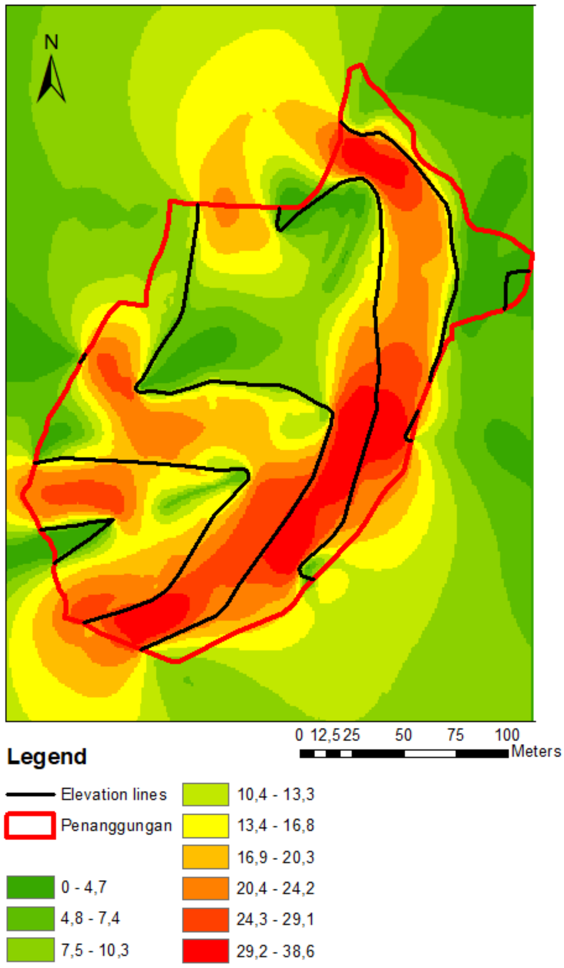

Figure XV-2. Penanggungan Slope Map (degrees)

XVI. Appendix – Tamansari slope calculations

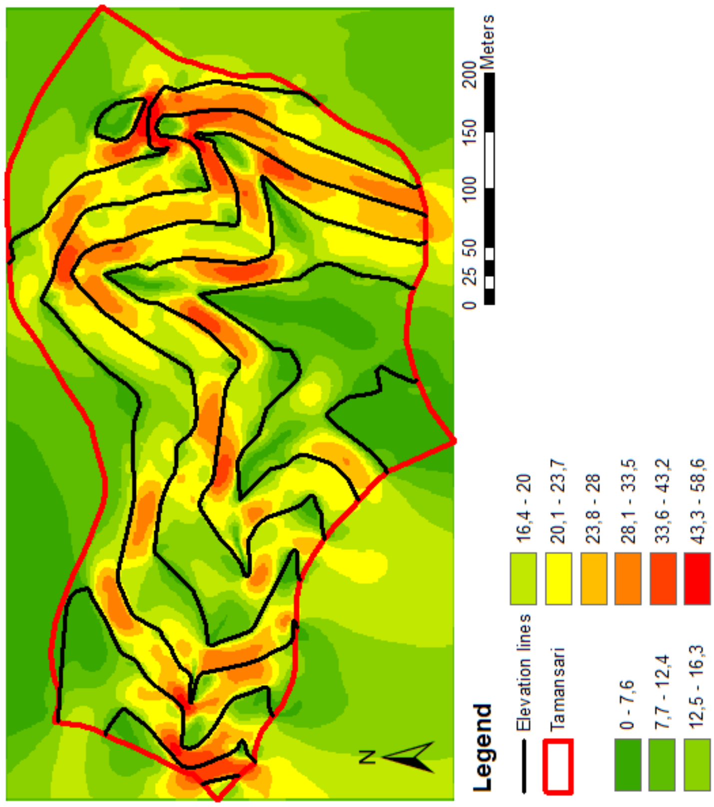

Figure XVI-1. Tamansari Slope Map (degrees)

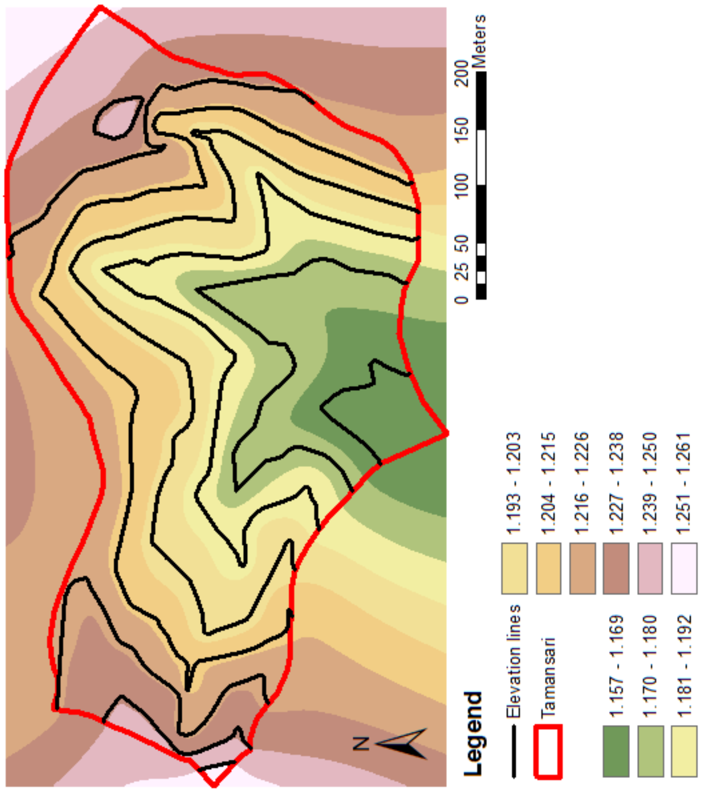

Figure XVI-2. Tamansari Elevation Raster Map (meters above MSL)

XVII. Appendix – Penanggungan and Tamansari one year FDC on daily discharge

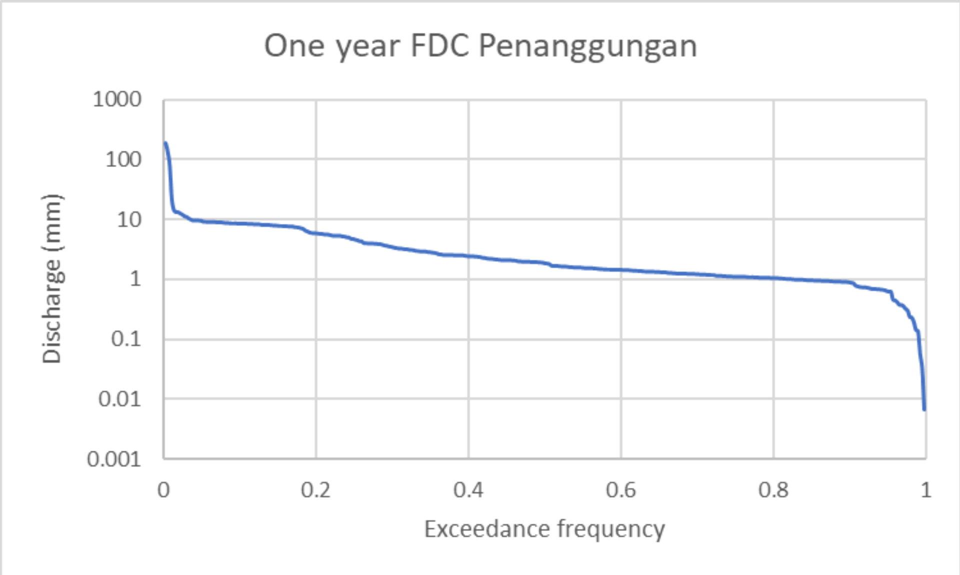

Figure XVII-1. Annual Flow Duration Curve Penanggungan (April 2017 - March 2018), based on daily discharges

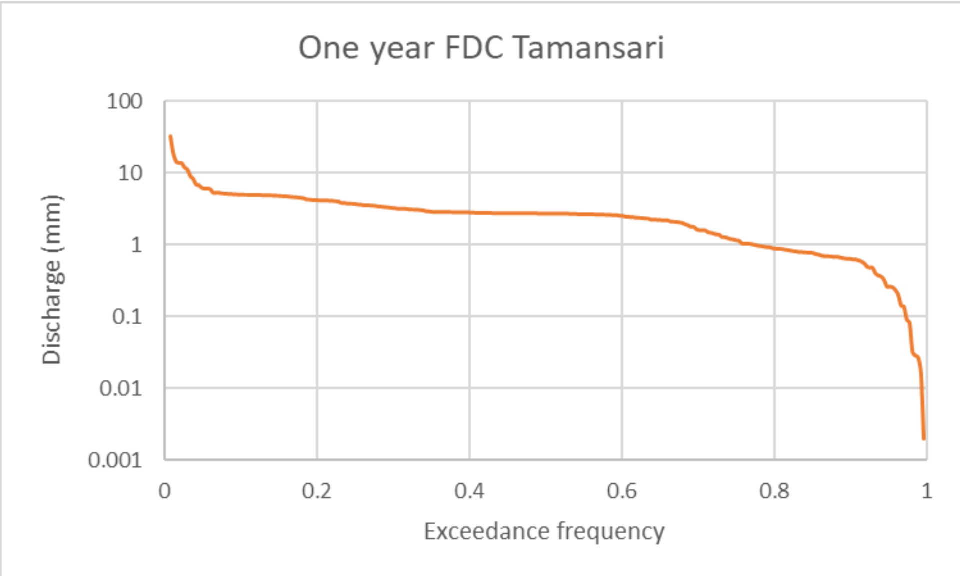

Figure XVII-2. Annual Flow Duration Curve Tamansari (17 July 2017 – 8 April 2018), based on daily discharges

XVIII. Appendix – Penanggungan Seasonal FDC on daily discharge

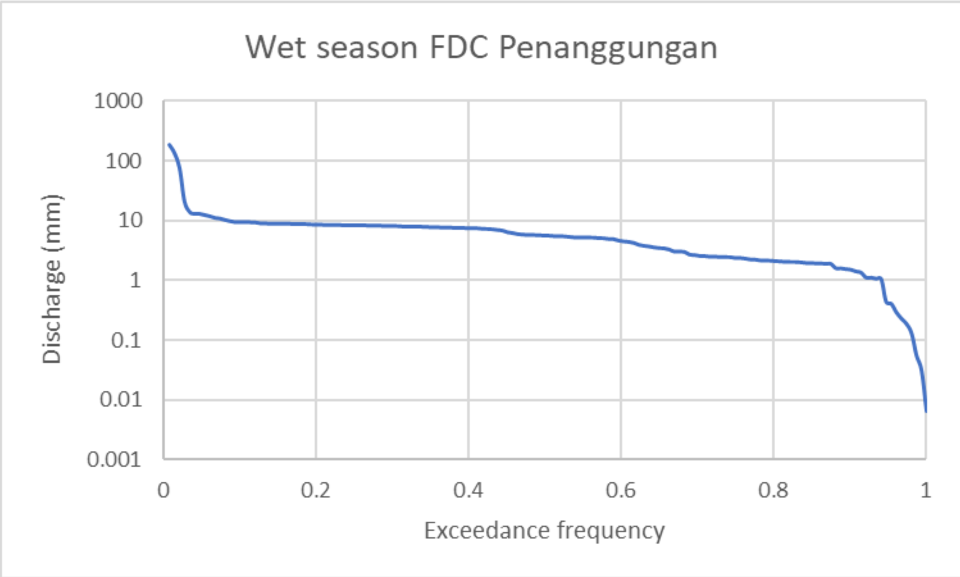

Figure XVIII-1. Wet season Flow Duration Curve Penanggungan (November 2017 - March 2018), based on daily discharges

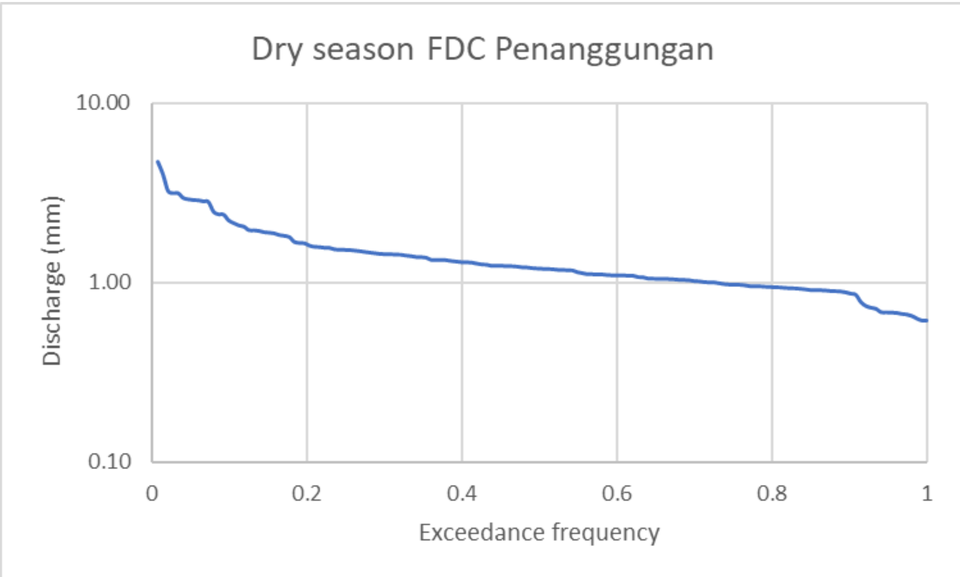

Figure XVIII-2. Dry season Flow Duration Curve Penanggungan (May 2017 – September 2017), based on daily discharges

XIX. Appendix – Tamansari Seasonal FDC on daily discharge

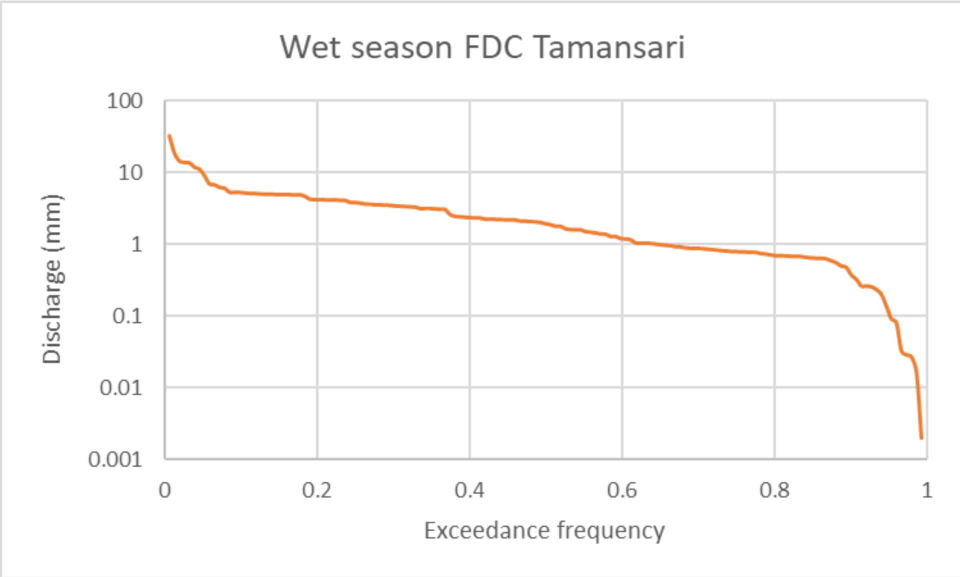

Figure XIX-1. Wet season Flow Duration Curve Tamansari (November 2017 - March 2018), based on daily discharges

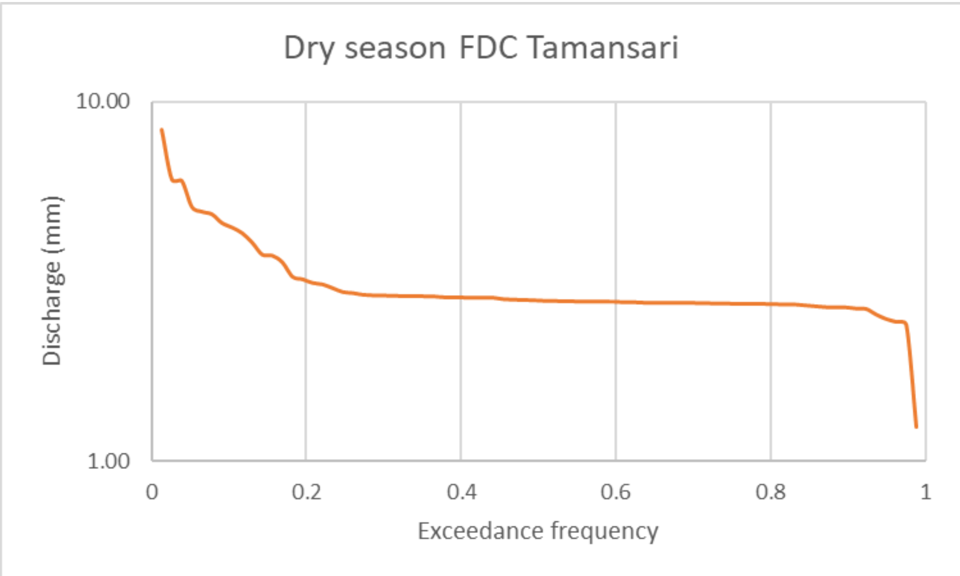

Figure XIX-2. Dry season Flow Duration Curve Tamansari (17 July 2017 – September 2017), based on daily discharges

XX. Appendix – Penanggungan Monthly FDC on daily discharge

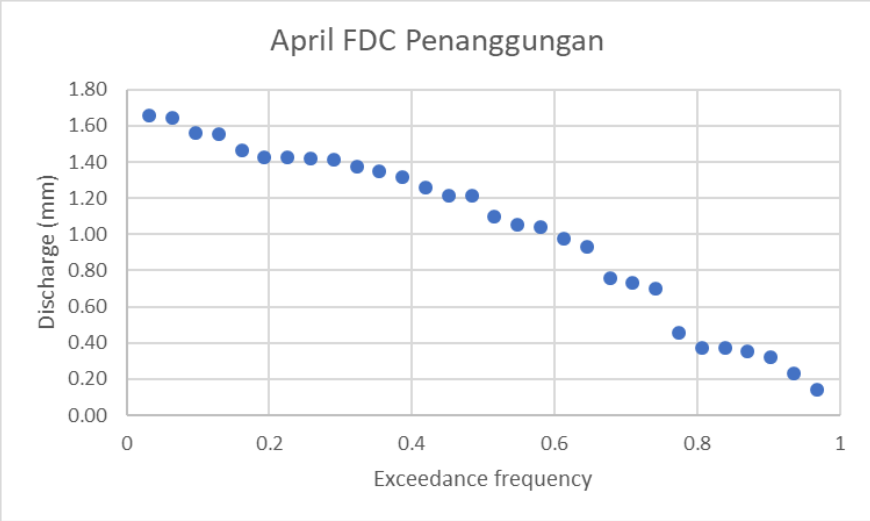

Figure XX-1. April 2017 Flow Duration Curve Penanggungan, based on daily discharges

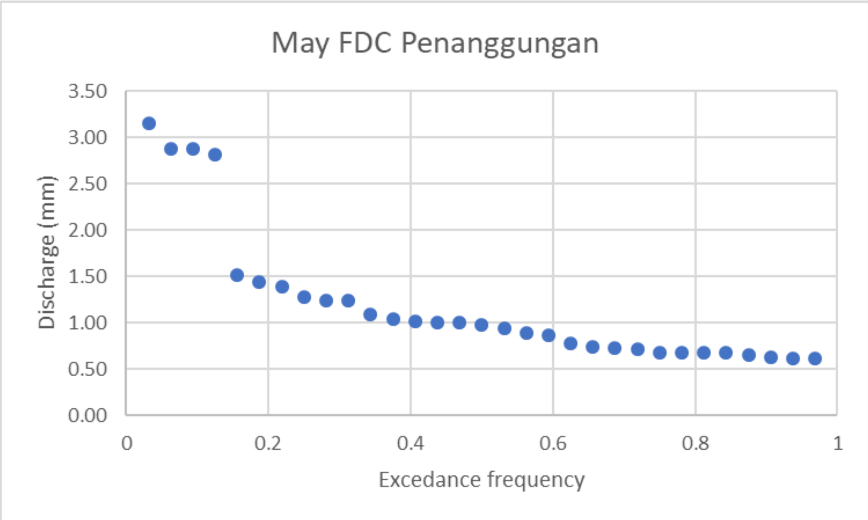

Figure XX-2. May 2017 Flow Duration Curve Penanggungan, based on daily discharges

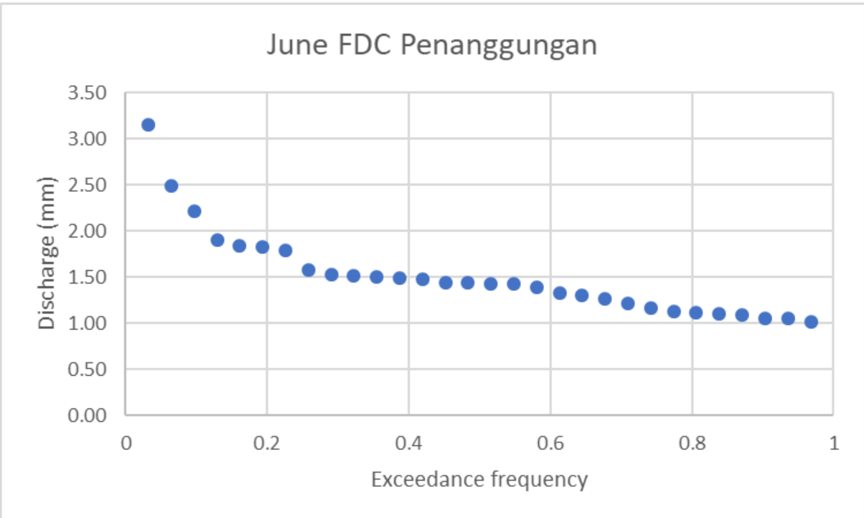

Figure XX-3. June 2017 Flow Duration Curve Penanggungan, based on daily discharges

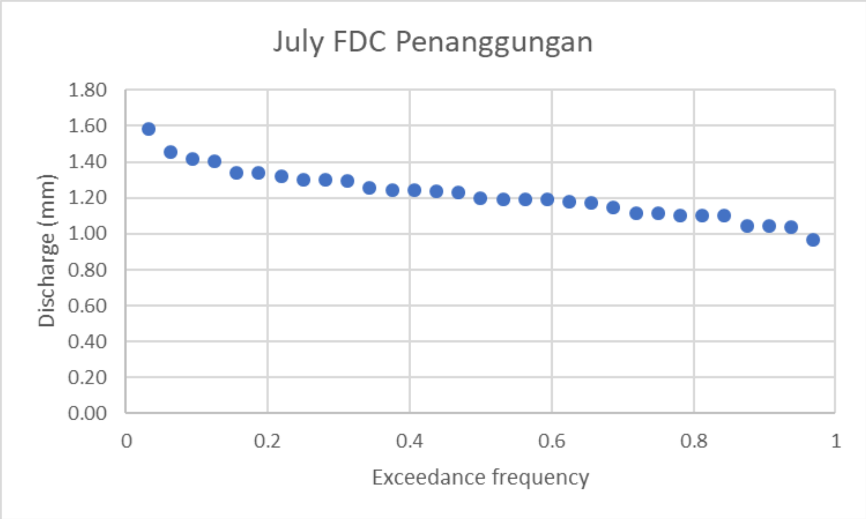

Figure XX-4. July 2017 Flow Duration Curve Penanggungan, based on daily discharges

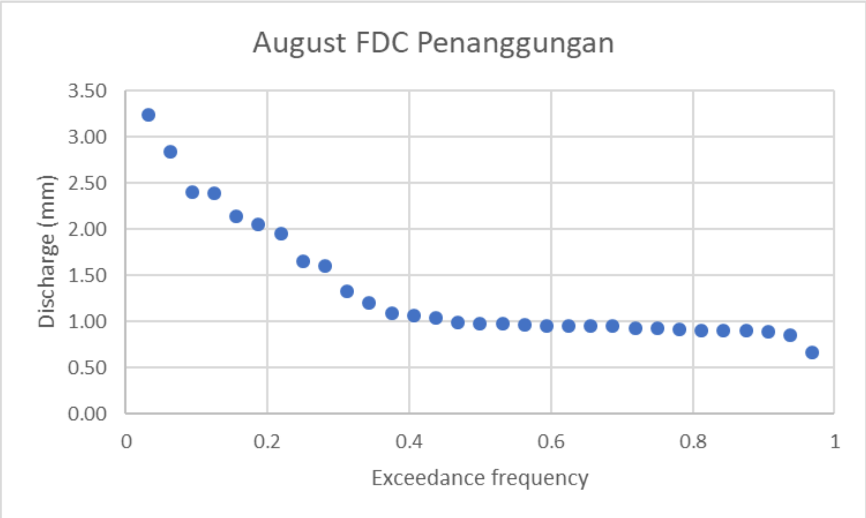

Figure XX-5. August 2017 Flow Duration Curve Penanggungan, based on daily discharges

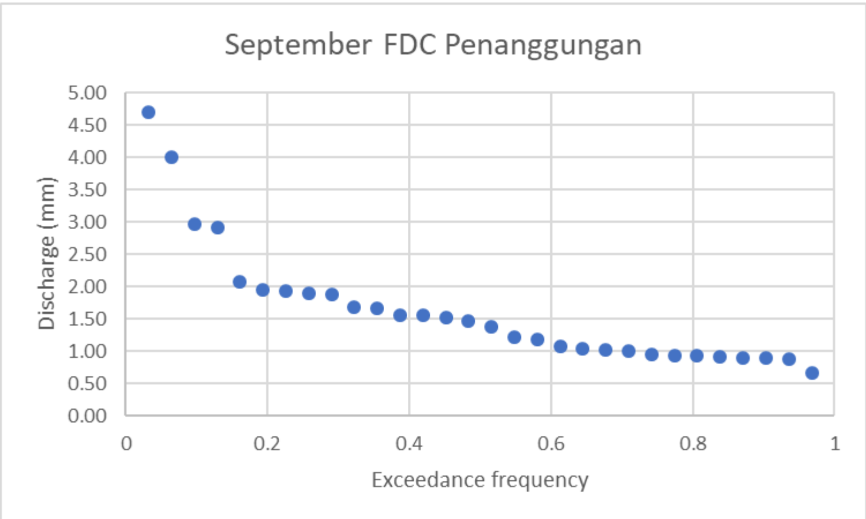

Figure XX-6. September 2017 Flow Duration Curve Penanggungan, based on daily discharges

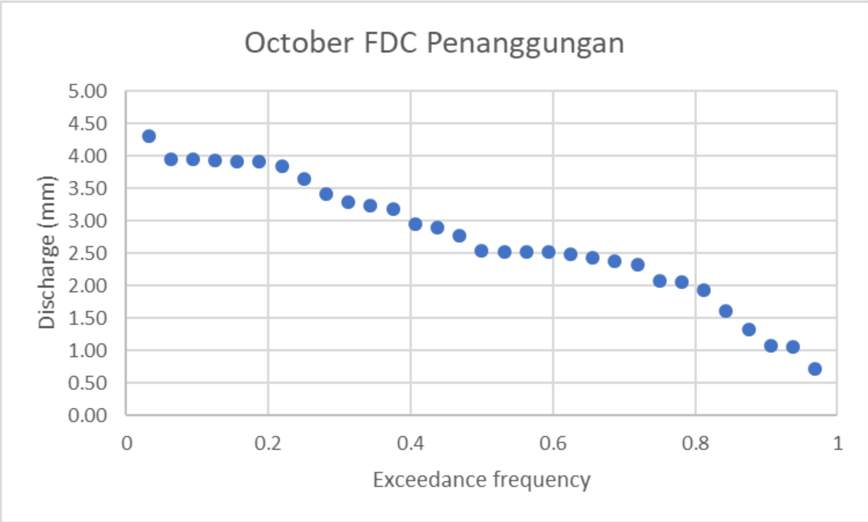

Figure XX-7. October 2017 Flow Duration Curve Penanggungan, based on daily discharges

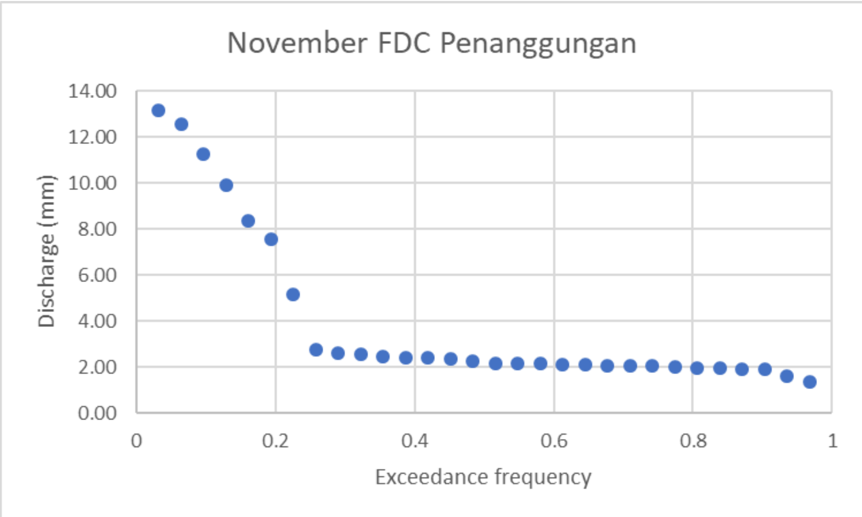

Figure XX-8. November 2017 Flow Duration Curve Penanggungan, based on daily discharges

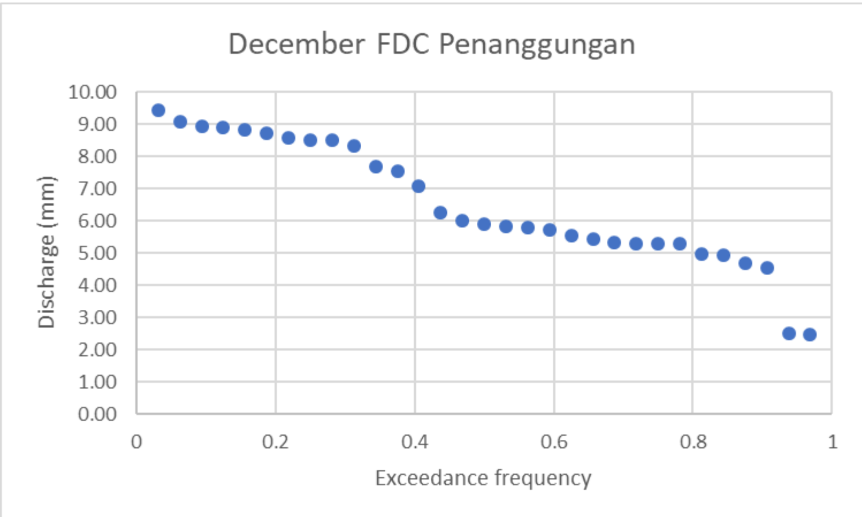

Figure XX-9. December 2017 Flow Duration Curve Penanggungan, based on daily discharges

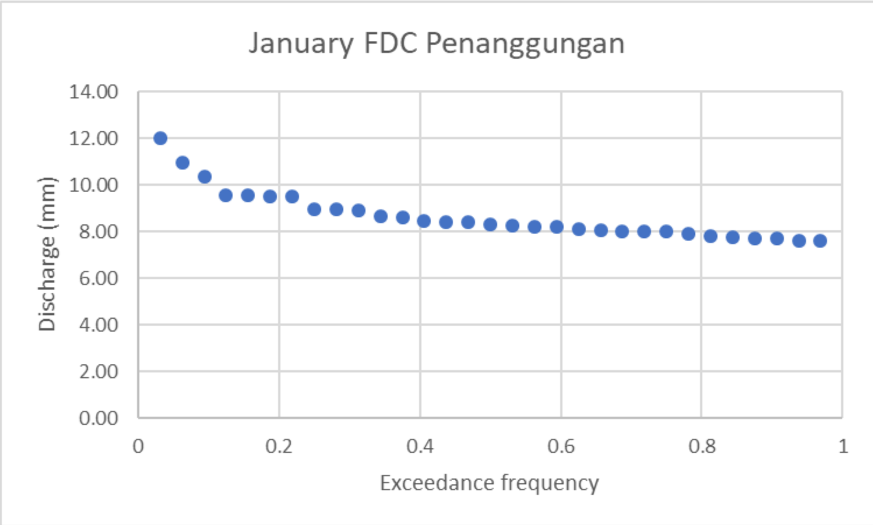

Figure XX-10. January 2018 Flow Duration Curve Penanggungan, based on daily discharges

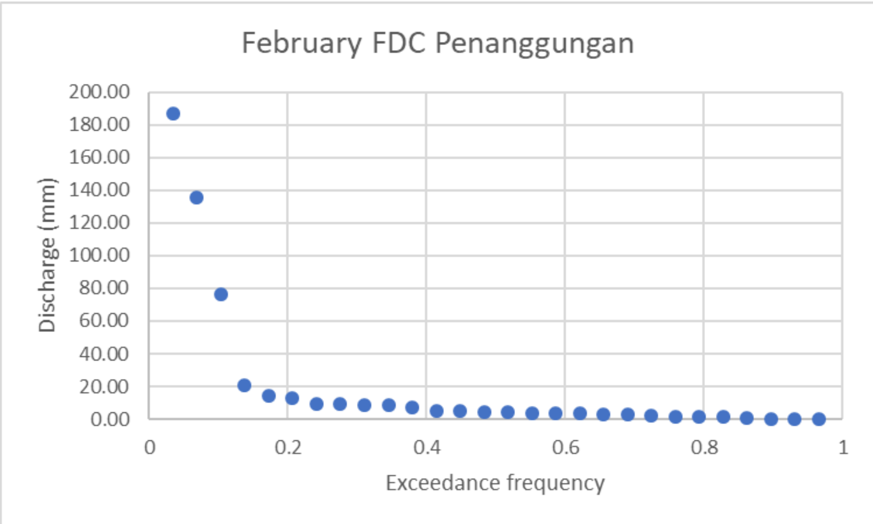

Figure XX-11. February 2018 Flow Duration Curve Penanggungan, based on daily discharges

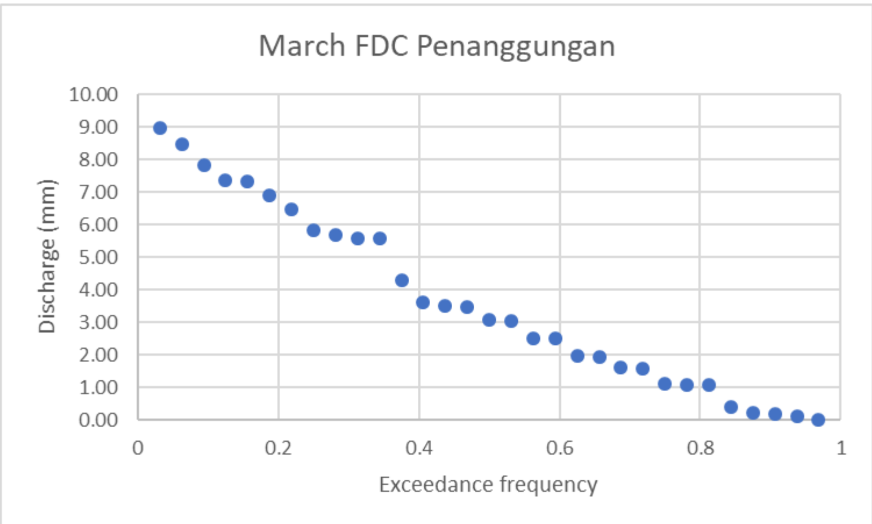

Figure XX-12. March 2018 Flow Duration Curve Penanggungan, based on daily discharges

XXI. Appendix – Tamansari Monthly FDC on daily discharge

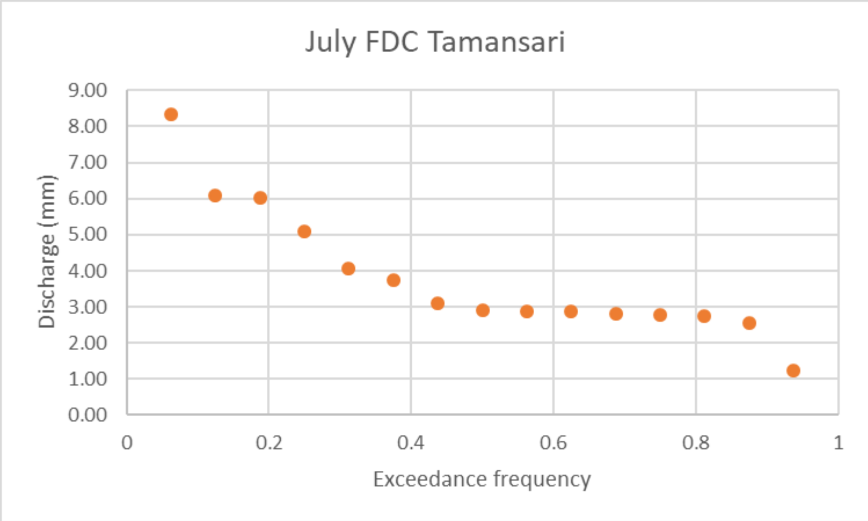

Figure XXI-1. July 2017 Flow Duration Curve Tamansari (17 July – 31 July), based on daily discharges

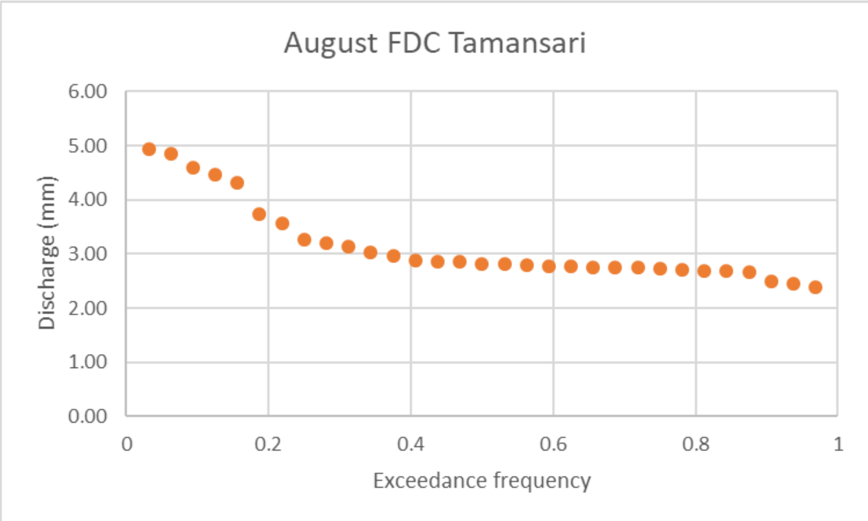

Figure XXI-2. August 2017 Flow Duration Curve Tamansari, based on daily discharges

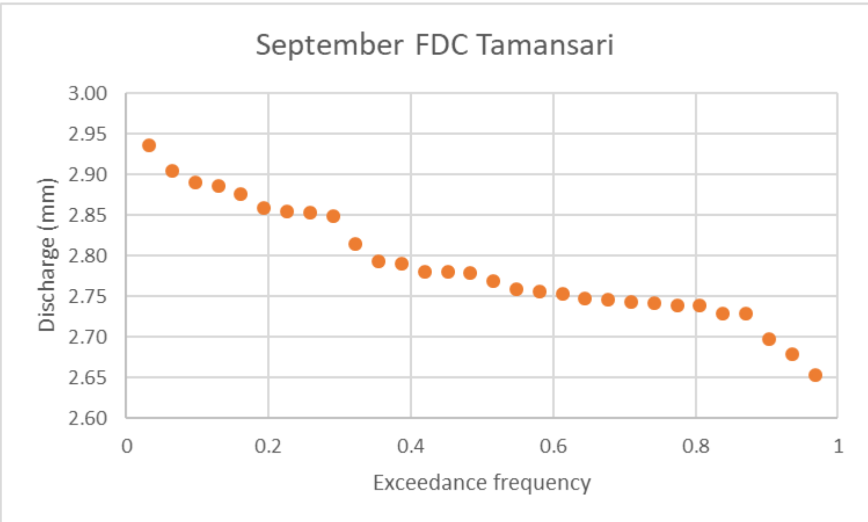

Figure XXI-3. September 2017 Flow Duration Curve Tamansari, based on daily discharges

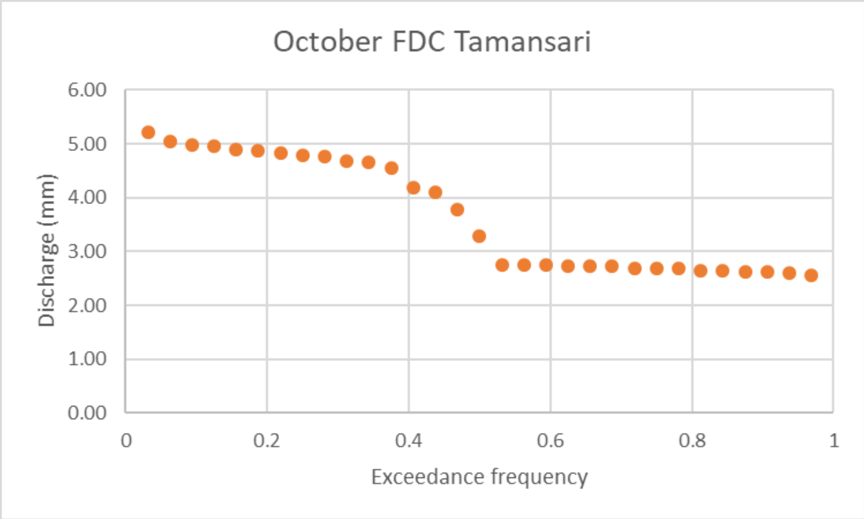

Figure XXI-4. October 2017 Flow Duration Curve Tamansari, based on daily discharges

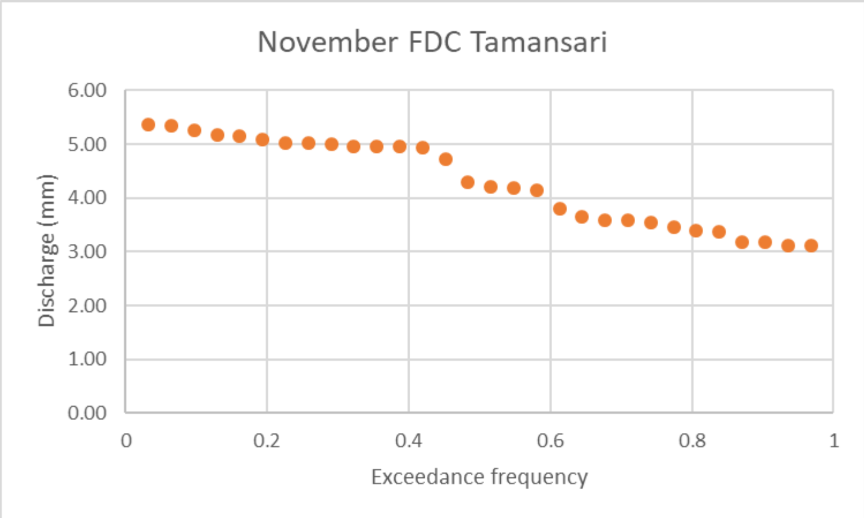

Figure XXI-5. November 2017 Flow Duration Curve Tamansari, based on daily discharges

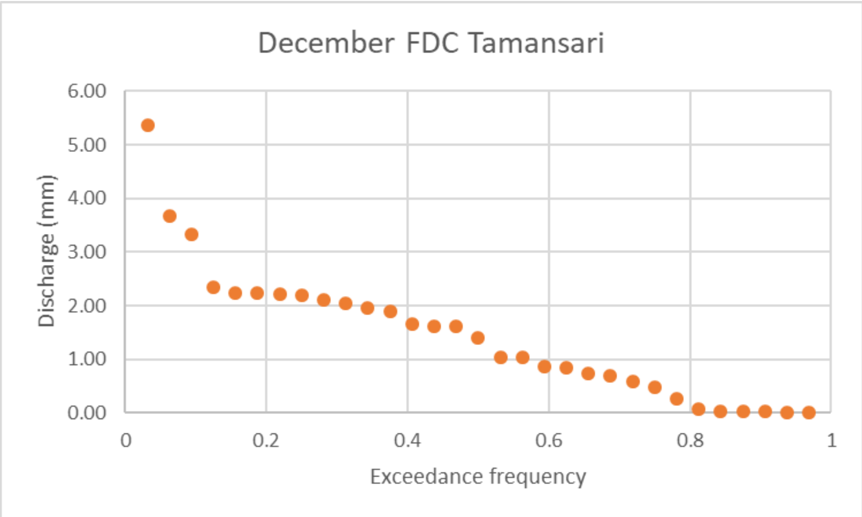

Figure XXI-6. December 2017 Flow Duration Curve Tamansari, based on daily discharges

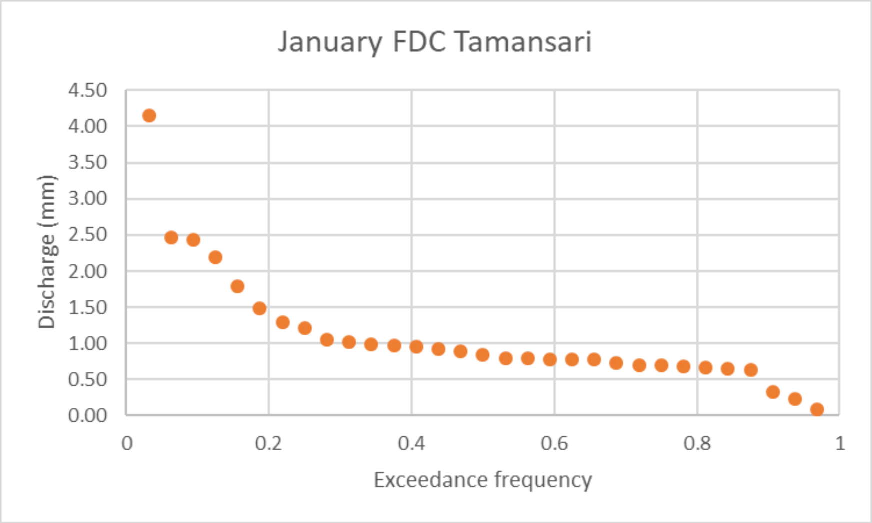

Figure XXI-7. January 2018 Flow Duration Curve Tamansari, based on daily discharges

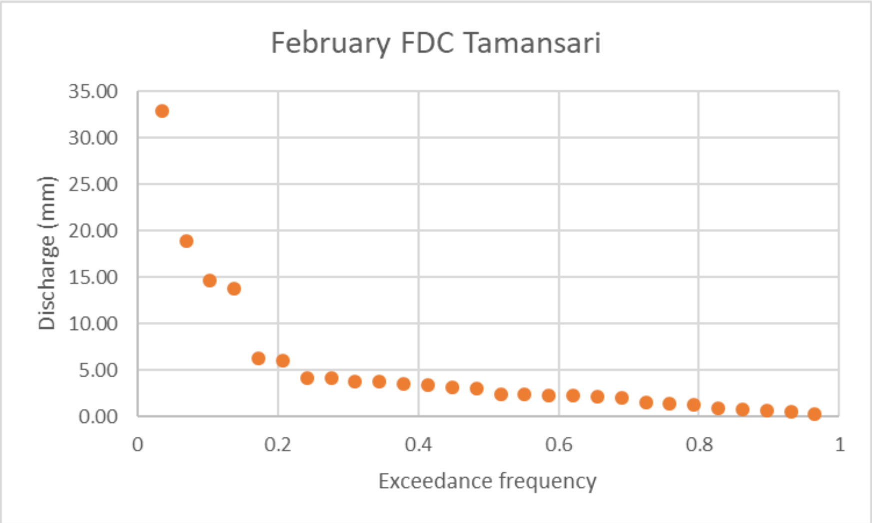

Figure XXI-8. February 2018 Flow Duration Curve Tamansari, based on daily discharges

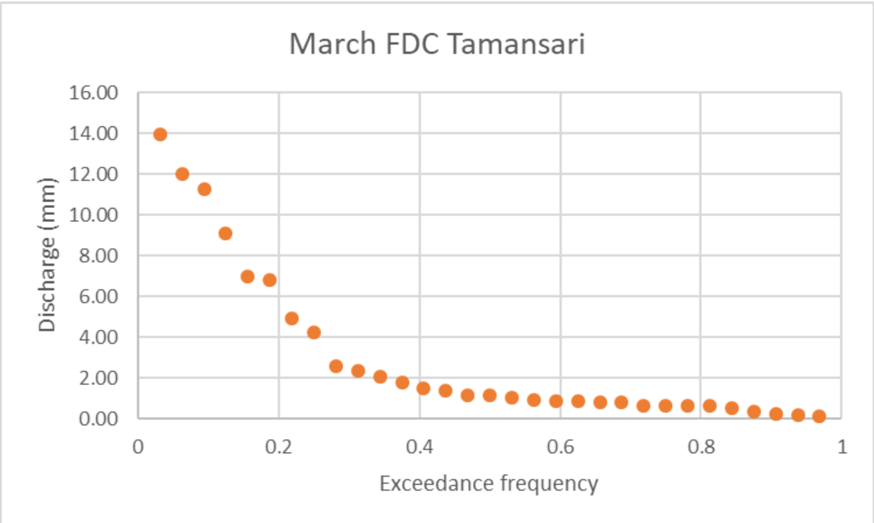

Figure XXI-9. March 2018 Flow Duration Curve Tamansari, based on daily discharges

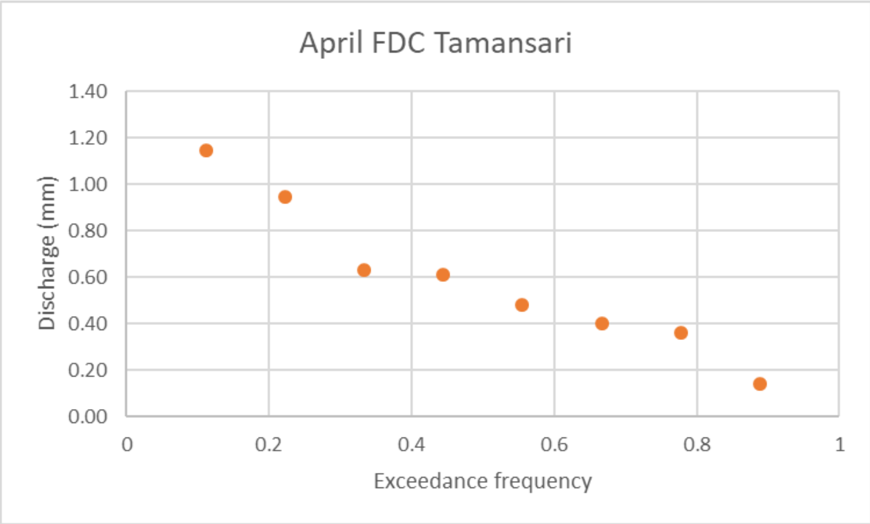

Figure XXI-10. April 2018 Flow Duration Curve Tamansari (1 April – 8 April), based on daily discharges

XXII. Appendix – Penanggungan min and max day FDC on 10-minute discharge

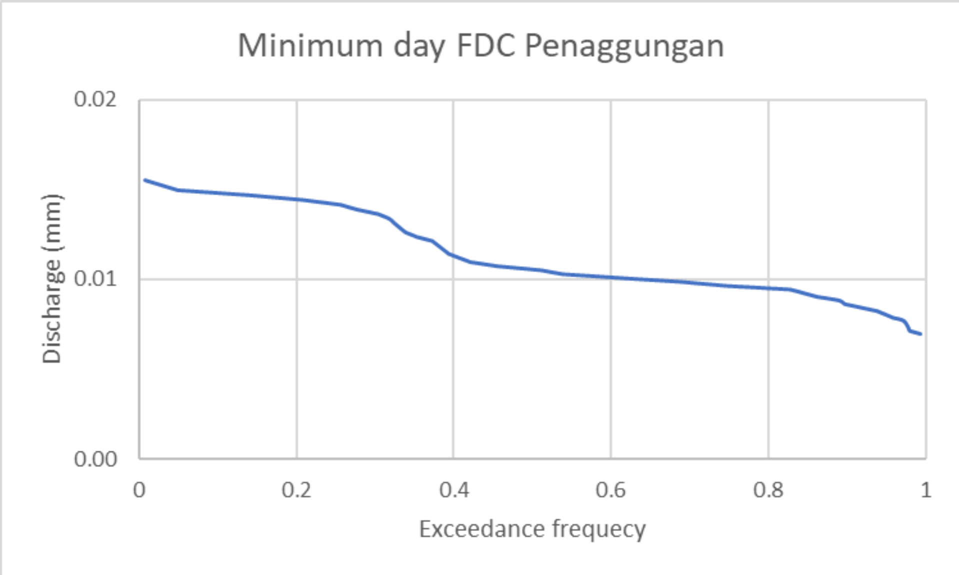

Figure XXII-1. Driest day Flow Duration Curve Penanggungan (27 August 2017), based on 10-minute discharges

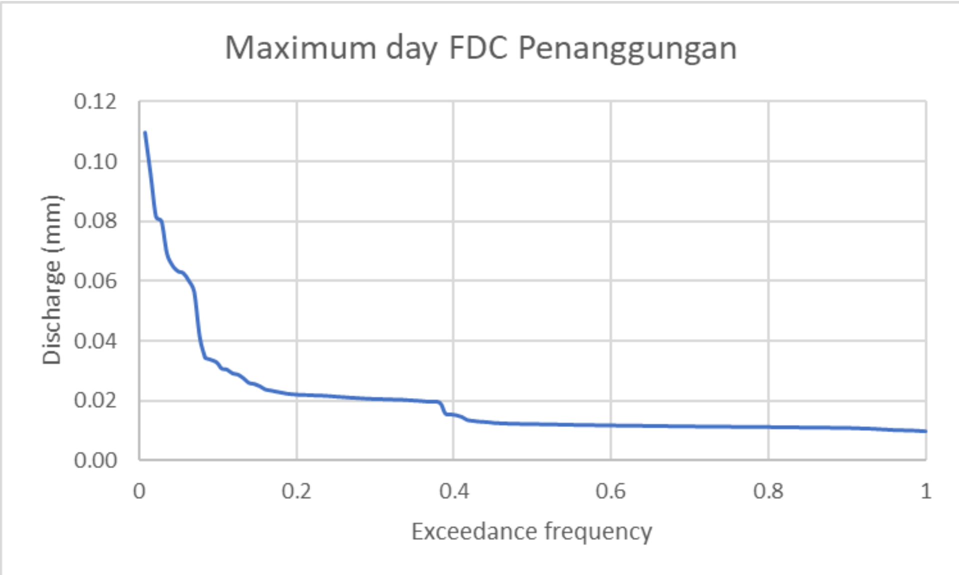

Figure XXII-2. Wettest day Flow Duration Curve Penanggungan (28 May 2017), based on 10-minute discharges

XXIII. Appendix – Tamansari min and max day FDC on 10-minute discharge

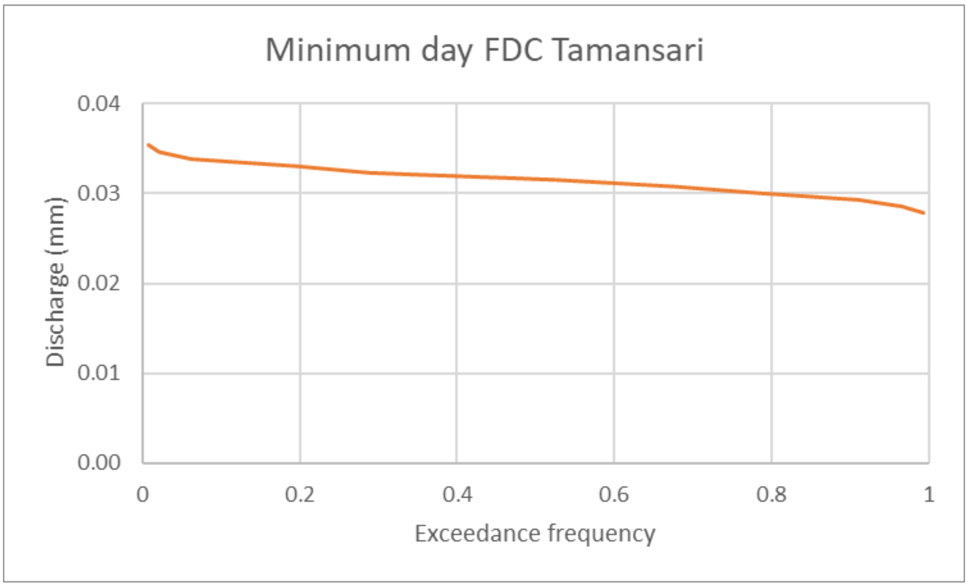

Figure XXIII-1. Driest day Flow Duration Curve Tamansari (27 August 2017), based on 10-minute discharges

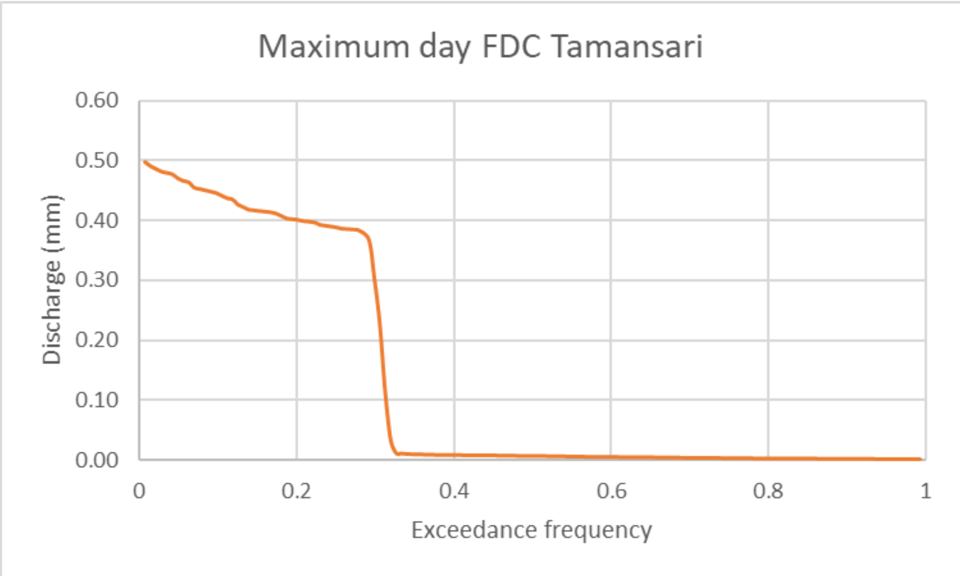

Figure XXIII-2. Wettest day Flow Duration Curve Tamansari (24 February 2018), based on 10-minute discharges

XXIV. Appendix – Penanggungan and Tamansari Rainfall-Discharge plots

The structure behind the graphs: year, wet season, dry season, wettest day; altering between Penanggungan and Tamansari. The scale of the year plots was altered. This means a few extreme values are not seen is these plots, to clearly show the majority of the points. In other words, a smaller piece of the picture is shown, which does not include a few extreme values.

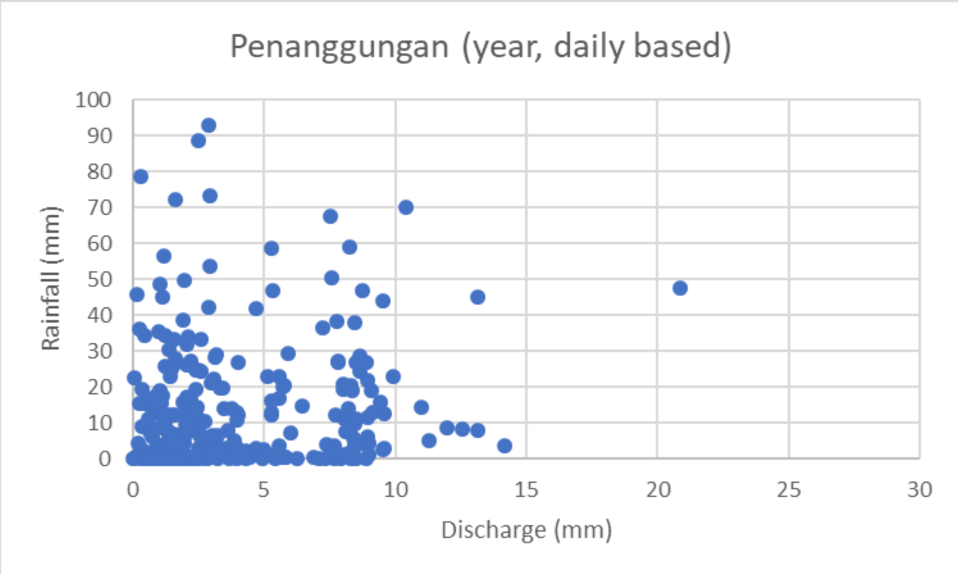

Figure XXIV-1. Annual rainfall-discharge plot Penanggungan (April 2017 - March 2018), based on daily discharges

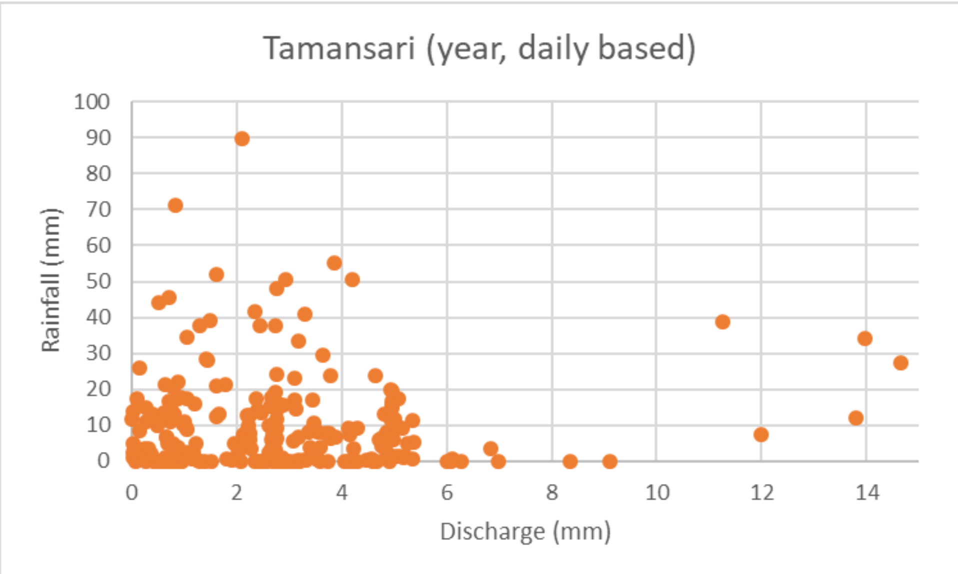

Figure XXIV-2. Annual rainfall-discharge plot Tamansari (17 July 2017 – 8 April 2018), based on daily discharges

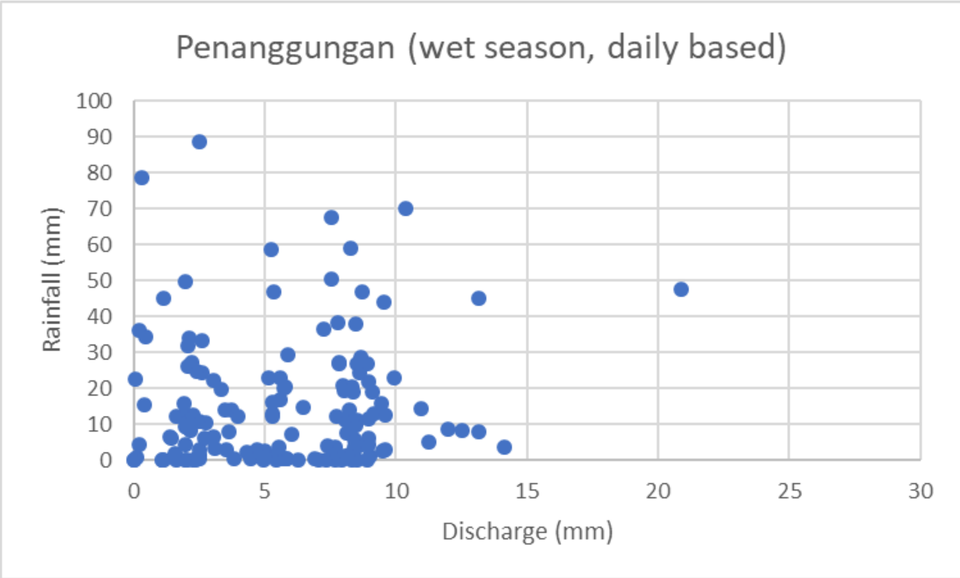

Figure XXIV-3. Wet season rainfall-discharge plot Penanggungan (November 2017 - March 2018), based on daily discharges

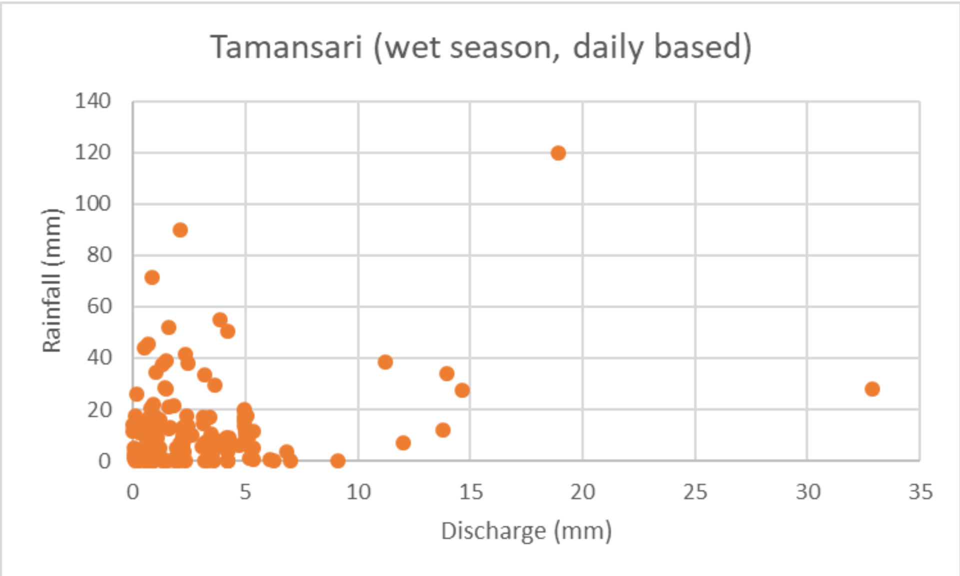

Figure XXIV-4. Wet season rainfall-discharge plot Tamansari (November 2017 - March 2018), based on daily discharges

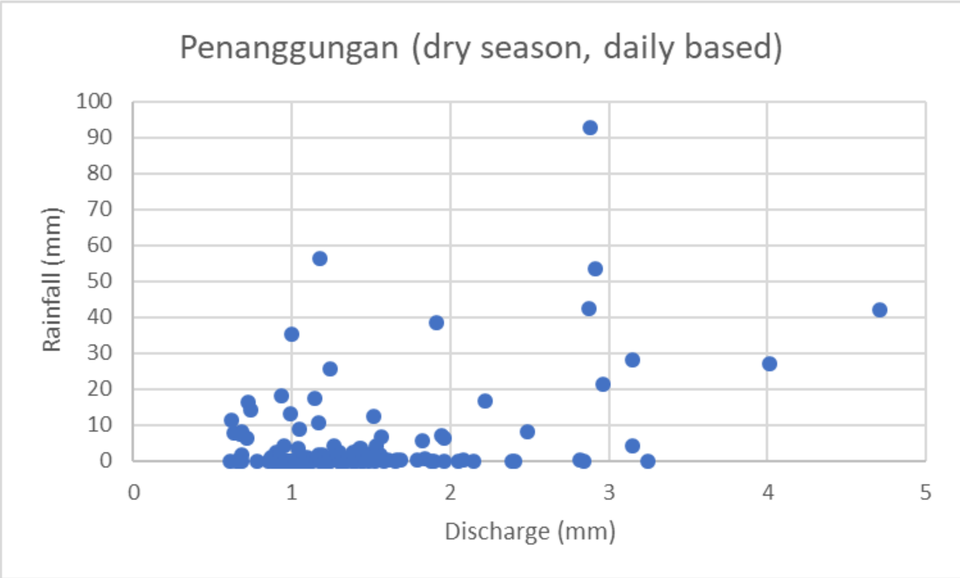

Figure XXIV-5. Dry season rainfall-discharge plot Penanggungan (May 2017 – September 2017), based on daily discharges

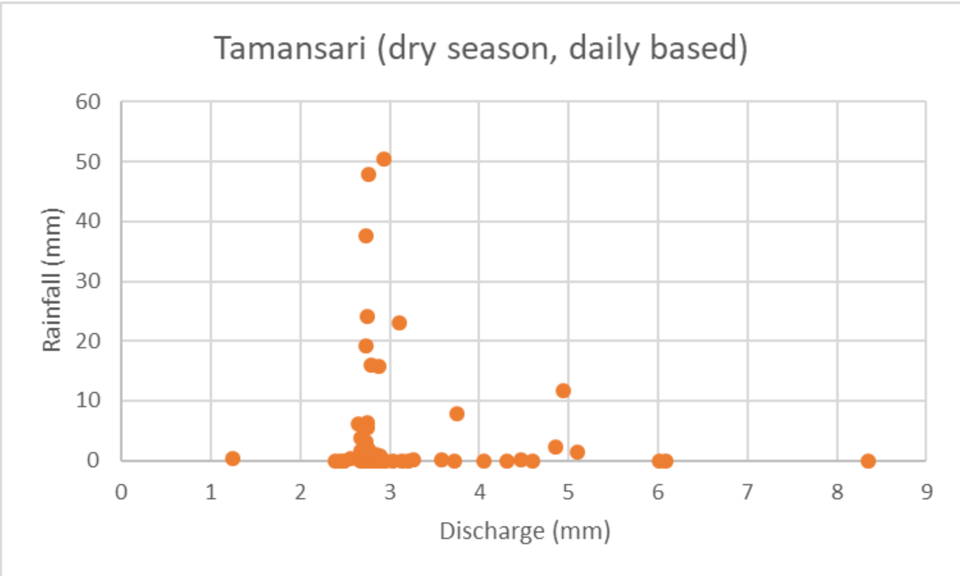

Figure XXIV-6. Dry season rainfall-discharge plot Penanggungan (17 July 2017 – September 2017), based on daily discharges

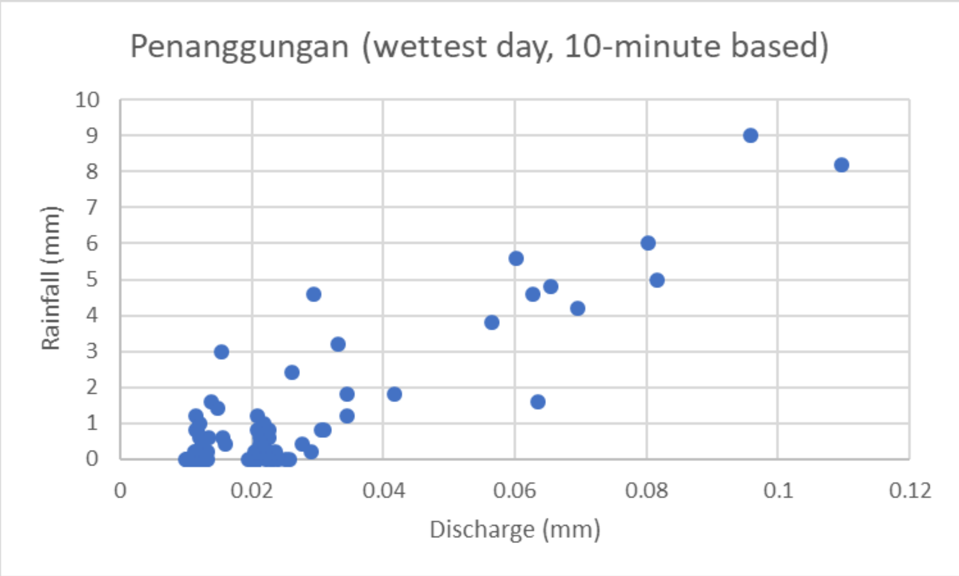

Figure XXIV-7. Wettest day rainfall-discharge plot Penanggungan (28 May 2017), based on daily discharges

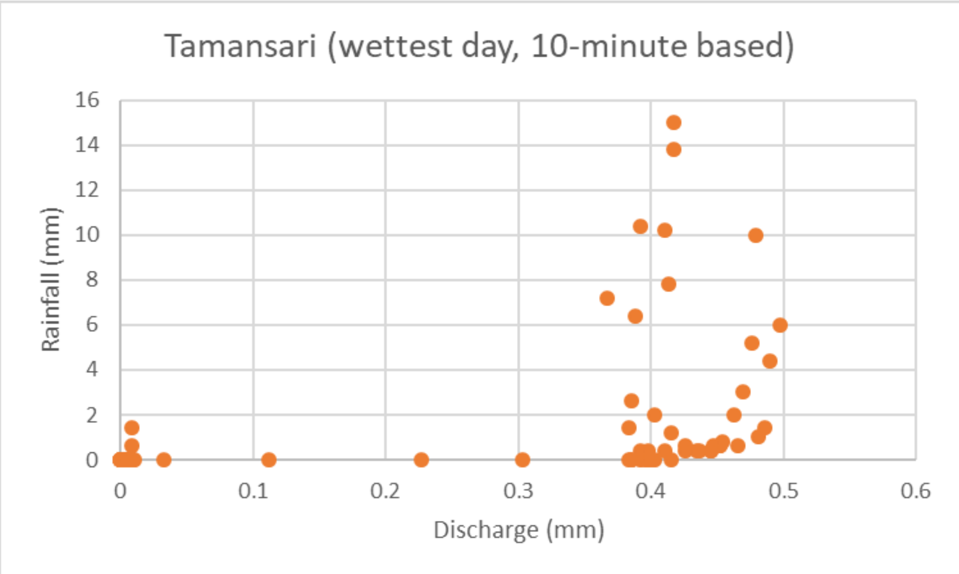

Figure XXIV-8. Wettest day rainfall-discharge plot Tamansari (24 February 2018), based on daily discharges