Integrated Flood Management for Transboundary River Basin: Case Study in Bengawan Solo River Basin - Indonesia

Purwanti Sri Pudyastuti

089051382

Supervisors

Prof. C.G. Kilsby

Dr. James Bathurst

Submitted for

PhD Degree at School of Civil Engineering and Geosciences

Faculty of Sciences, Agriculture and Engineering

Newcastle University

June 2024

DECLARATION

This report is submitted as part of the requirements for the Degree of Doctor of Philosophy at Newcastle University. I hereby certify that it is my own work, except where otherwise acknowledged, and that it has not been submitted for any other degree at this, or any other University.

Purwanti Sri Pudyastuti
June 2024

ACKNOWLEDGEMENTS

I thank Almighty God for all blessings in my life.

I would like to express my sincere gratitude to my supervisory team, Prof. C.G. Kilsby and Dr. James Bathurst, for their time, patience, guidance, correction and useful advice during the process of this research project. I also would like to thank to Dr. Stephen J. Birkinshaw for his invaluable contribution, advice, correction and help during the implementation of SHETRAN simulation in this research project, and also for providing the TRMM data. The advice and correction from the examiners, Dr. Mark Mulligan and Dr. Geoff Parkin, are also gratefully acknowledged. I would like to thank as well to all staffs, lecturers, and roommates at School of Civil Engineering and Geosciences for their knowledge and support.

I am greatly indebted to my working institution Universitas Muhammadiyah Surakarta and Directorate General Higher Education, Ministry of Education and Culture, Republic of Indonesia for the opportunity and scholarship. I also would like to thank to staff at Balai Sungai (River Research Center) in Surakarta for providing the data used in this research.

I would like to express my special thanks to my parents, my parents in law and all family members for their endless prayers and support.

Last but not least, I would like to thank to my beloved husband Nurmuntaha Agung Nugraha and my beloved children Fatiha, Azzam and Nisa for the unconditional love, care and endless support.

ABSTRACT

Bengawan Solo River flows from Upper Bengawan Solo Sub-catchment located in Wonogiri-Central Java Province to Java Ocean through some regions in Central Java and East Java Provinces, Indonesia. The length of the river is about 600 km, and the total area of Bengawan Solo River Basin is about 19,778 km^2. The average annual rainfall in the upper catchment of the river basin is approximately 1935 mm. In the end of December 2007, some regions in Central Java and East Java Provinces (Indonesia) located in Bengawan Solo River Basin were flooded due to high rainfall intensity which caused the overflow of River Bengawan Solo and release of excessive water from Wonogiri Dam in the upstream catchment. Some regions in the affected areas were inundated for several weeks. This flood phenomenon was the biggest flood in the river basin during the last 40 years. The flood continues to occur annually since then.

This research aims to improve the understanding of the flood generating mechanisms and the nature of flooding in Indonesia, particularly in the Bengawan Solo River Basin, and to use this understanding to inform robust methods of flood risk management taking into account present and future climate as well as possible land use management strategies.

The quality of the rainfall data in Bengawan Solo river basin is unsatisfactory with the average of cross-correlation 0.31. However, this research used the data because it is the only in situ data available in the river basin by selecting the most complete data from the available gauging stations. The Pettit test was applied in this research to detect the abrupt change of extreme rainfall in selected gauging stations. Moreover, the Mann-Kendall test was applied to investigate the trend of extreme rainfall. The annual maximum daily rainfall and monthly maximum daily rainfall during rainy season (October – March) were used in Pettit and Mann-Kendall test. The SHETRAN simulation was implemented in this research to investigate the impact of land use change to peak discharge using three different land use scenarios. Besides using in situ data, the SHETRAN simulation also used 3-hourly TRMM rainfall data. According to the results of the SHETRAN simulation, the peak discharge rises considerably with expanding urbanization; consequently, planned control over land use change and development is required to prevent future issues. Improved hydrometry data availability is also necessary for more accurate flood modelling.

The big flood event in December 2007 could be triggered by high precipitation (which was recorded as the highest maximum precipitation). The flood continues

to occur recently, although the maximum rainfall is not as high as the one occurred in December 2007. Considering the result from SHETRAN simulation and the fact that the number of buildings is increasing in Bengawan Solo River Basin, it can be understood that flooding will continue to occur although there is no upward trend of extreme rainfall.

Since flooding is likely to occur, attempts must be done to minimize the risk and reduce the severe impact of flooding. Learnt from this research with the limitation of reliable data, it is suggested that the agencies and authorities responsible in flood management in Bengawan Solo River Basin should improve the gauging networks and data base related to flood management, including hydrological and hydraulic data. Furthermore, the attempts have been done by Mekong River Commission and approach introduced by Cap-Net might be adopted by some modification appropriate to Bengawan Solo River Basin condition. Providing early good flood forecasting and warning system, conducting capacity building for all related stakeholders, enhance coordination and cooperation among related agencies and authorities, and development flood measure both structural and non-structural could be implemented to reduce the flood risk and minimize severe impact of flooding in Bengawan Solo River Basin.

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

1.1. Background

The Bengawan Solo River flows from the Upper Bengawan Solo River Basin located in Wonogiri-Central Java Province to the Java Sea through a number of regions in Central Java and East Java Provinces. The length of the river is some 600 km, and the area of the Bengawan Solo River Basin is around 20,000 km^2. The Bengawan Solo river basin lies between the longitudes 110^{o}18' E – 112^{o}45' E and latitudes 6^{o}49' S – 8^{o}08' S.

There are many trans-boundary river basins in Indonesia, and the Bengawan Solo River Basin is one of the largest, which administratively belongs to Central Java and East Java provinces. Trans-boundary river basin in this context means one which belongs to several districts and provinces in one nation or country. Moreover, the Bengawan Solo River Basin is the largest on Java Island with a population of approximately 16 million in 2005 (Hidayat et.al, 2009). The basin covers 18 districts in 2 provinces i.e. Boyolali, Klaten, Surakarta, Sukoharjo, Wonogiri, Karanganyar, Sragen, Blora, Rembang (Central Java Province) and Ponorogo, Madiun, Magetan, Ngawi, Bojonegoro, Tuban, Lamongan, Gresik, Pacitan (East Java Province).

In the Bengawan Solo River Basin, there is a large multi-purpose dam located upstream, called the Wonogiri Dam. There is a serious sedimentation problem due to the high erosion rate caused by unsustainable land use management in the upstream area. A study conducted by JICA team (Hidayat and Valiant, 2007) reported that the volume of sediment flowing from the watershed to the dam was approximately 3.2 million m^3 / year during 1993 – 2004 (Hidayat and Valiant, 2007). This situation has led to significant reduction of the Wonogiri Dam capacity. The dam was completed in 1980 with a 100 year design life, but is predicted to be full of sediment in 2020 if no preventative measures are implemented in the dam or its catchment area (Hidayat and Valiant, 2007).

Figure 1.1 shows the administrative map of the Bengawan Solo River Basin and its river systems and catchment boundaries.

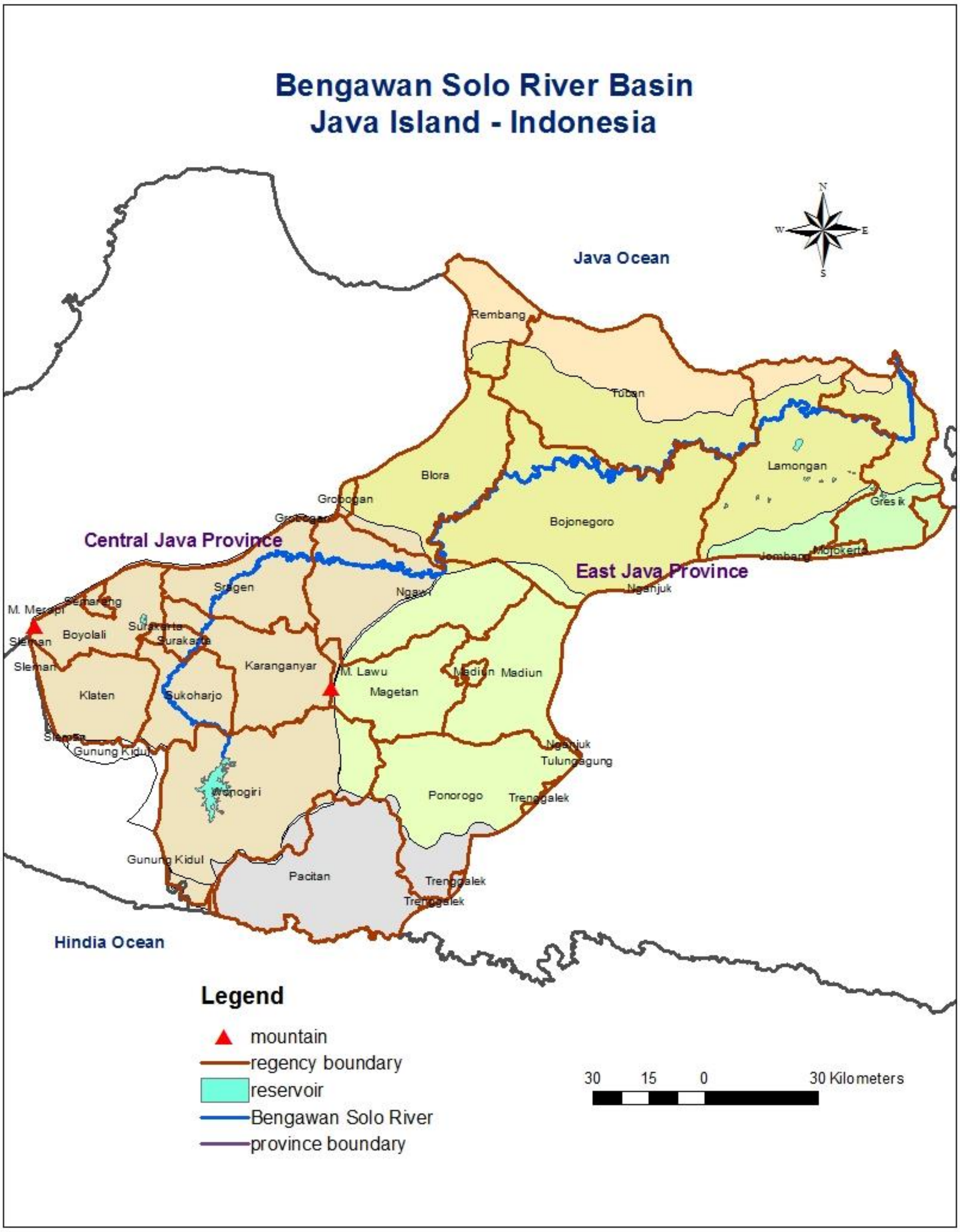


Figure 1. 1. Administrative map of the Bengawan Solo River Basin (source: processed from data from River Research Center)

The population in upper areas of Bengawan Solo River Basin during 2000 – 2011 increased as can be seen in the chart below. The increase in population causes an increase in the need for housing and other infrastructures. As a result, land use will change, and the impermeable layer will expand, increasing runoff. The growth of the population will increase exposure because more people will be affected. Furthermore, increasing runoff will increase the hazard. Flood risk increases as exposure and hazard levels rise.

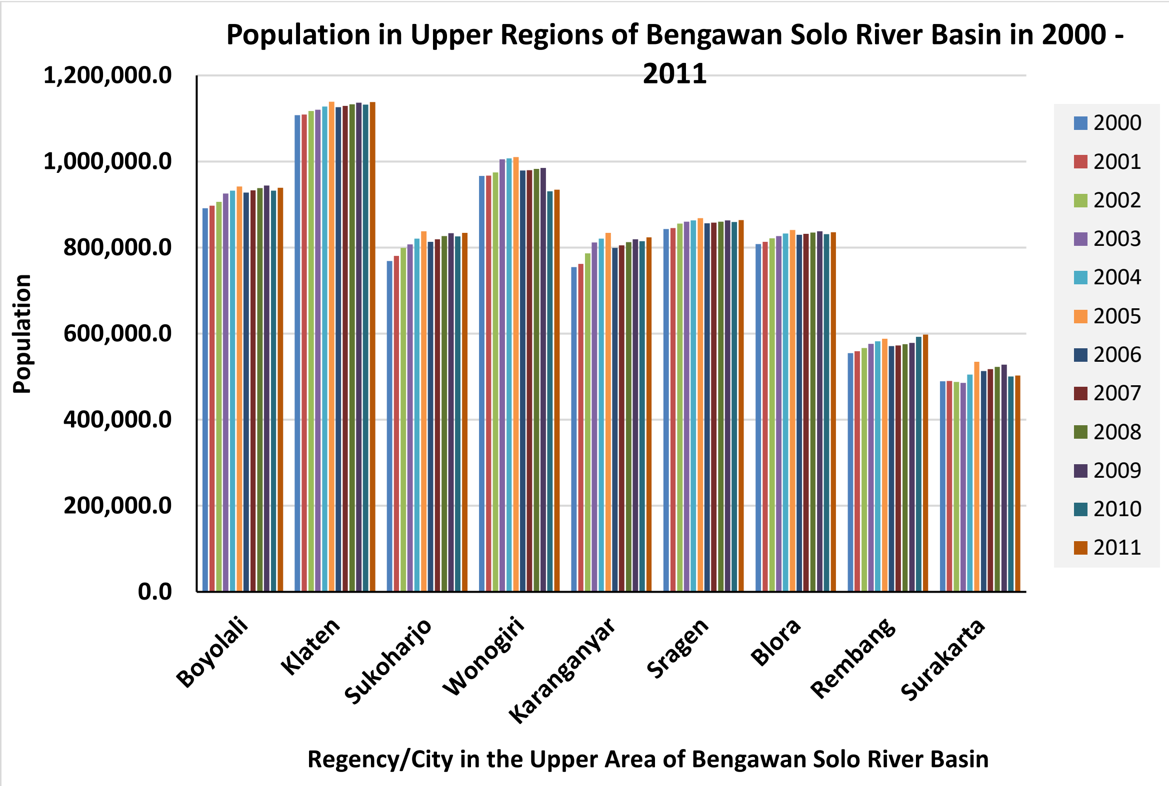


Figure 1. 2. The Population in Upper Areas of Bengawan Solo River Basin in 2000 - 2011

At the end of December 2007, some regions in Central Java and East Java Provinces (Indonesia) located in the Bengawan Solo River Basin were flooded due to overflow of River Bengawan Solo and release of excess water from the Wonogiri Dam in the upstream catchment. The flood inundated cities in Central Java Province, i.e. Surakarta City which has area of 44.04 km^2 and inhabited by 545,653 population (Dinas Kependudukan dan Pencatatan Sipil, 2012), and Sragen region which has area of 941.55 km^2 and inhabited by 877,402 population (Kabupaten Sragen, 2012). The districts of Ngawi, Bojonegoro, Lamongan and Tuban (East Java Province) located in the lower area of Bengawan Solo River Basin were also flooded and were inundated for a week. This flood is the largest recorded during the last 40 years. The flood not only damaged infrastructure and paddy fields in those regions, but also caused serious impacts in many other sectors. According to Kompas newspaper (8 January 2008 edition), the flood was not only caused by high rainfall intensity but also triggered by unsustainable land and water management in the upstream area of river basin. The flood mostly damaged the downstream area of the Bengawan Solo River Basin, especially regions located in East Java Province. In the beginning of March 2008, some areas in Central Java and East Java located in the Bengawan Solo River Basin were flooded again due to the overflow of River Bengawan Solo.

Moreover, rainfall intensity increases as a result of climate change, that raises the possibility of flooding. Aside from the quantity and intensity of the rainfall, other variables come into play, such as land use, infrastructure, and soil moisture. In addition, the problem regarding water resources management including flood management in Indonesia becomes more complex after the implementation of decentralization of government, especially in this trans-boundary river basin. It is clear that upstream conditions cause problems downstream, hence there should be upstream-downstream coordination and solidarity to manage the river basin (Pudyastuti, 2008), even though the upstream is not located in the same administrative region as the downstream. In addition, interaction between humans and the water cycle is complex (O'Connell, 2002), therefore integrated flood management involving all stakeholders and using a multidisciplinary approach is required to reduce the flood risk in the basin.

1.2. History of Flooding in the Bengawan Solo River Basin

1.2.1. *Flooding in 1966*

Solo (also widely known as Surakarta) is a municipality located in Upper Bengawan Solo River Basin, and the largest city in the basin. The city is famous for its Javanese culture. According to media reporting and stories from the older generation of people in Solo city, a major flood occurred on 16 – 18 March 1966 which inundated the whole area of Solo city. This is currently the flood of record. Figure 1.3 below shows the inundated Solo city during the 1966 flooding.

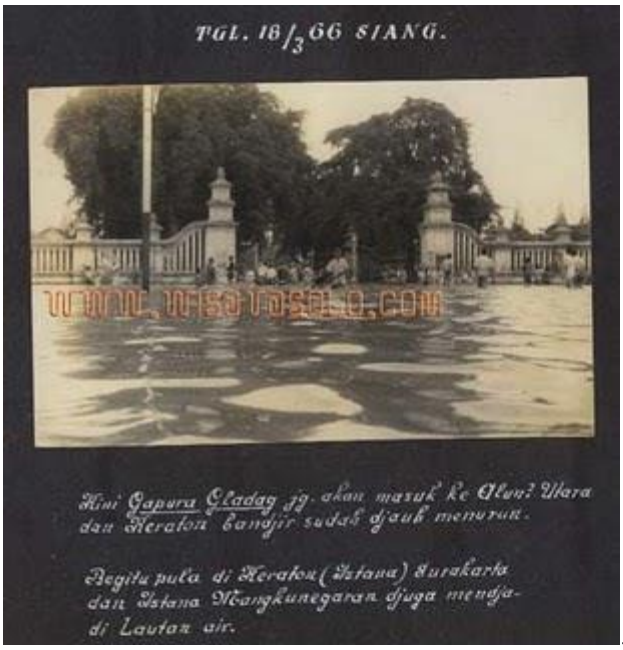


Figure 1. 3. Picture of Solo City during the flood on 18 March 1966 (source : http://dawudabd.blogspot.com/2008/01/banjir-solo-1966-2007.html)

Since the 1966 disaster, the government implemented several flood control projects including river straightening project, large dam construction in the upstream area (Wonogiri District), and embankments along several river reaches. The Wonogiri Dam constructed from 1976 to 1981 is designed to reduce the flood risk, particularly in the upstream area. However, river straightening measures implemented along the naturally meandering river are believed to contribute to higher flood risk in downstream areas as well as disturbing the river ecosystem.

1.2.2. *Flooding during period of 1993 - 2010*

Table 1.1 below shows the summary of flood events in the Bengawan Solo River Basin during period of 1993 – 2010, which was compiled based on mass media reports.

Date	Areas affected by flood	Cause of flood
1993	Sragen and Cepu (Central Java Province), Ngawi and Bojonegoro (East Java Province).	Overflow of Bengawan Solo River.
22 February 1999	Pasar Kliwon, Serengan, and Jebres of Solo city (Upper Bengawan Solo River Basin) were inundated. At that time, 2598 houses were inundated and more than 1400 people were displaced.	Embankment along Kaliwingko which was located between Solo and Sukoharjo was broken.
5 – 6 March 2003	Areas of Jagalan and Gandekan (Solo city) were inundated by 1 m depth of water. Wonogiri district (upstream catchment area) was inundated as well.	High rainfall intensity.
10 February 2007	Wonogiri district (upstream catchment area)	High rainfall intensity.
15 February 2007	Several areas of Solo city	High rainfall intensity.
19 April 2007	Sereal areas of Solo city, Sragen and Sukoharjo districts	High rainfall intensity.
26 April 2007	Wonogiri district. The flood damaged 58 hectares of agricultural field.	High rainfall intensity.
28 April 2007	Wonogiri district.	Overflow of Bengawan Solo River.
26 December 2007	Almost whole Bengawan Solo River Basin was flooded and inundated for several days. The flood was the largest since 1966.	High rainfall intensity, river overflow, embankment failure, and water released from the Wonogiri dam.
March 2008	Some part of Solo city and regions in downstream area were flooded.	High rainfall intensity.
2009	Some part of Solo city and regions in downstream area were flooded.	High rainfall intensity.
February - April 2010	Some part of Solo city and regions in downstream area were flooded.	High rainfall intensity.

Table 1. 1. Summary of recorded-flood events in the Bengawan Solo River Basin

Figure 1.4, Figure 1.5, and Figure 1.6 show flooding in several areas of the Bengawan Solo River Basin from in 2007.

Figure 1. 4. Water level of the Bengawan Solo River at Jurug gauging station during flood on December 2007 (photo contributed by Suwasono Adi)

Figure 1. 5. Houses in Kampung Sewu – Solo City were inundated during flooding on December 2007 (photo contributed by Suwasono Adi)

Figure 1. 6. Flooding in a part of Solo City (Surakarta) on the end of December 2007 (photo contributed by Suwasono Adi)

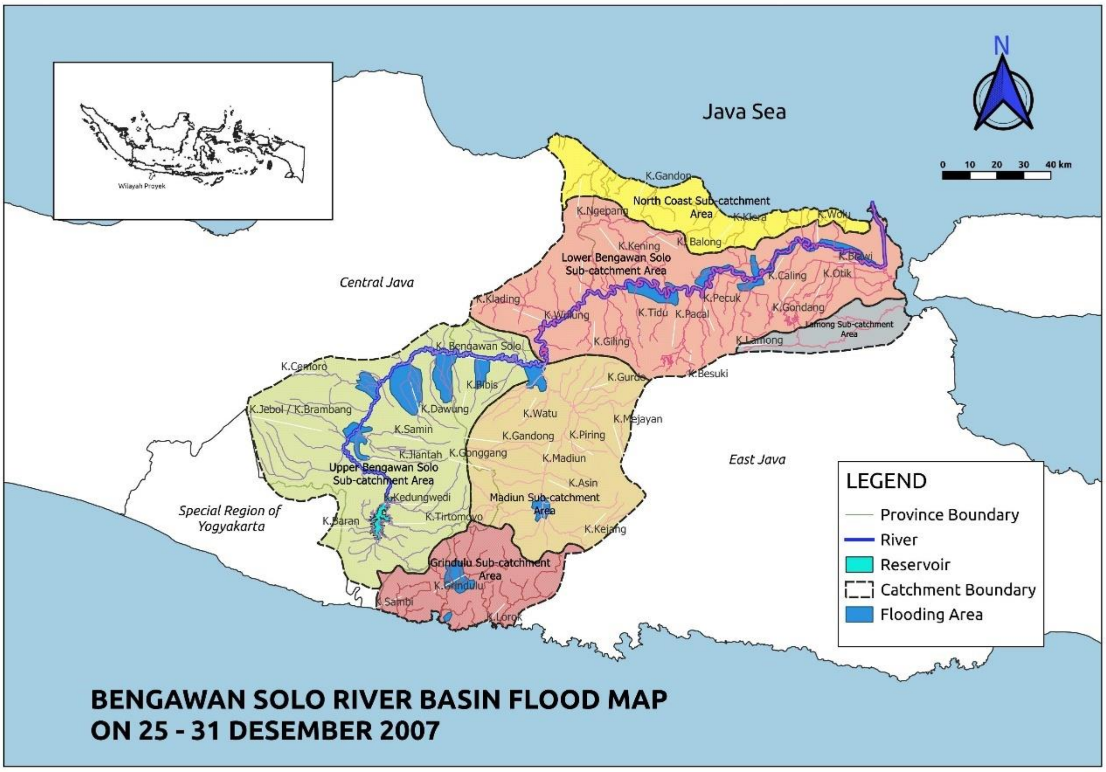


Figure 1. 7. Map of inundated area during flooding in the Bengawan Solo river basin on 25 – 31 December 2007 (source: redrawn from Gregersdotter, 2009)

The polygons with blue colour in Figure 1.7 shows the inundated area during flooding in some regions in Bengawan Solo river basin on 25 – 31 December 2007 (Gregersdotter, 2009). The regions got inundated at that time were situated in Surakarta, Sukoharjo, and Sragen regencies in Central Java Province (in Upper Bengawan Solo catchment); and Ngawi, Pacitan, Madiun, Bojonegoro, Lamongan and Gresik regencies in East Java Province (in Lower Bengawan Solo catchment).

1.3. Aim of Research

This research project aims to improve the understanding of the flood generating mechanisms and the nature of flooding in Indonesia, particularly in the Bengawan Solo River Basin, and to use this understanding to inform robust methods of flood risk management taking into account present climate as well as possible land use management strategies.

1.4. Research Objectives

The research objectives to achieve the aim of this research are as follows:

1. To collate findings regarding flood events in the Bengawan Solo River Basin from reports collected from local newspaper, journals, and previous related project reports.
2. To collect and analyse related available data including land use, climatology, environmental, socio-cultural, hydrological, and hydraulic data.
3. To analyse the existing condition and problems that trigger floods in the Bengawan Solo River Basin including land use management, as well as their environmental impact.
4. To analyse the observed record of flooding in the basin for change or trends.
5. To set up and apply a hydrological model to investigate the flood regime and the roles of extreme rainfall and land use management.

6. To use the results of the modelling programme to critically review existing and proposed methods for reducing flood risk in the basin under changing land use.

1.5. The Importance of This Research

Flooding is a common disaster in Indonesia recently, and even Jakarta, the capital city, is flooded on an annual basis. The Bengawan Solo River Basin, which is administratively located in provinces of Central Java and East Java, is one of the important river basins in Indonesia. The river basin has a significant role in agriculture as well as tourism. The soil in the watershed is fertile and suitable for rice paddy plantation which is the staple food for most of the Indonesian population. Recent frequent flood events have had severe impacts in many sectors.

Several efforts have been made to reduce the flood risk in the basin, including constructing large dam in upper catchment and embankment along selected river reaches. However, flood risk cannot be reduced to zero and creating flood-free areas in the basin is impossible. Therefore, the important effort is how to manage the flood risk in order to minimize the hazardous impact of the flood.

This research is trying to analyse the matters regarding flood risk in the basin comprehensively, and finding robust method of integrated flood management in the basin. Traditionally, flood problem in Indonesia has been solved mostly using engineering-centred approach by giving less consideration on other aspects such as social, environmental, and climate change. This research result will contribute significant improvement in solving flood problem in Indonesia, particularly in Bengawan Solo River Basin. Furthermore, the research result will be disseminated widely for stakeholder related to flood in order to broaden their perspective on integrated flood management.

1.6. Structure of Thesis

This thesis consists of 8 chapters as follows:

Chapter 1 Introduction, as described in this chapter.

Chapter 2 Literature Review which describes the review of literature related to the topic of this research.

Chapter 3 Data and Methodology. This chapter explains the data available and used in this research, including the availability of rainfall and discharge data. Moreover, the methodology applied in this research such as change point analysis, L-moments approach and SHETRAN model is described briefly in this chapter.

Chapter 4 Maximum Rainfall and Discharge Analysis, which describes the analysis of maximum daily rainfall and discharge at selected gauging stations, including the application of Mann-Kendall test, Pettit test, and generalized extreme value (GEV) distribution in the analysis of extreme (maximum) values.

Chapter 5 SHETRAN Simulation, which describes the initial application of SHETRAN model for simulating the flow in selected catchment, including special calibration for rice paddy field and simulation using single rainfall input from selected rain gauging stations.

Chapter 6 Improving Rainfall Input for SHETRAN Simulation. This chapter explains the combination of multiple rainfall input for SHETRAN simulation and choose the best combination using longest complete data series available at rain gauging networks in selected catchment. Furthermore, the application of 3-hourly TRMM precipitation data from 3B42 data product is also described in this chapter.

Chapter 7 Land Cover Change Sensitivity, which describes the SHETRAN simulation using different hypothetical land cover in selected catchment and how the response of the model.

Chapter 8 Discussion and Conclusion, which discusses the results and findings in previous chapters and draws conclusions as well as making recommendations for improved flood risk management in the Bengawan Solo river basin, Indonesia.

Chapter 2. Literature Review

This chapter presents a review of previous studies and reports related to the research topic. The issues being reviewed here include previous studies regarding the Bengawan Solo river basin, water resources management regulation in Indonesia, land use and climate change impact on flooding, the SHETRAN modelling system, integrated flood risk management and recent flood management in Indonesia.

2.1. Previous Studies and Reports regarding Bengawan Solo River Basin

The Bengawan Solo River has been famous in Indonesia for centuries and is often mentioned in folk story and traditional literature. A large number of researchers have studied the Bengawan Solo River and its basin in different aspects including hydrological, socio and cultural aspects.

Java Island, where the Bengawan Solo river basin is situated, typically has two seasons like other regions in Indonesia, *i.e.* rainy and dry season. The rainy season commonly occurs during October to April, and the dry season during the remainder of the year. The River Bengawan Solo has a monsoonal character with the highest discharge recognized during the four to five months of the rainy season (Hoekstra, 1989). During December to March, humid air brought to Java Island by W-NW monsoon dominates, producing abundant rainfall on the island (Hoekstra, 1988). In addition, river flow in the upper catchment of Bengawan Solo river basin has been found to be increasing significantly, whereas in the middle and lower catchment a moderate diminution has occurred (Pawitan and Haryani, 2012).

A historical study regarding big flood event in Bengawan Solo River Basin in 1966 (case study in Surakarta city), was carried out by Taqobalallah (2009). The study investigated the impact of Bengawan Solo flood in 1966 in Surakarta city and community's respond to the flood by interviewing old people witnessing the flood.

The study revealed that in 1966, Bengawan Solo River had problem with sedimentation and siltation. Moreover, the embankment constructed by Dutch colonial along the river was mostly damaged. Based on the information gathered from the old witnesses, the government and community at that time worked together to evacuate the flood victim, provide public kitchen for supplying food to the flood victim, and rebuild the damaged embankment after the flood water get shrink.

Other research regarding the Bengawan Solo River has concerned the method to choose suitable rainfall gauging stations for predicting flood discharge (Sobriyah *et al*, 2001). This research showed that the data at rainfall gauging stations at Jurug, Kajangan, Ketonggo, Babat, and Bojonegoro was suitable to be used for predicting flood discharge on Bengawan Solo River. In addition, Sobriyah (2005) also conducted research to estimate flood discharge in Bengawan Solo River Basin using rainfall data of years 1985, 1990, 1991, 1996 and 1997 at Jurug, Kajangan, Ketonggo, Babat and Bojonegoro raingauge stations. The flood estimation was carried out using a grid-based Rational Method with O'Donnell and Muskingum – Cunge routing (Sobriyah, 2005). This research was restricted to the current climate.

At the end of 2007 and beginning of 2008, parts of the Bengawan Solo river basin were affected by flooding with many casualties and cost about 852.89 billion Rupiahs (Indonesian currency, source: Indonesia Ministry of Public Work, 2008). The flood event was reported by mass media, both paper-based and online (BBWS Bengawan Solo, 2008; Kompas, 3 March 2008 edition). Based on these reports, the flood was caused by several factors as follows:

a) High rainfall intensity (about 80 – 135 mm) which was distributed uniformly across most regions in the basin;
b) The capacity of the Bengawan Solo River was exceeded: this is the second largest recorded event, after the 1966 flood;
c) The flood which struck regions of Madiun and Ngawi (located in the middle of Bengawan Solo River Basin) was the largest since 1963;
d) Around the Lower Bengawan Solo River Basin (regions of Bojonegoro, Babat, Lamongan and Gresik), the stream water level was the highest since 1963 (15.97 m);

e) Poor solid waste management in the flood affected areas: the uneducated community commonly throw the garbage into the river which diminishes the river function for discharging water and sediment.
f) Broken embankment along the flood prone areas.

According to a book written by journalists and scientists joining a group called Kompas Expedition Team (Kompas, 2008), the Bengawan Solo river basin has been degraded from the upstream area to downstream. It is explained in the book that the basin degradation is caused by several factors, such as reduction of forest area, reduced vegetation cover to prevent erosion in upstream area, conversion of landuse and uncontrolled waste disposal. In addition, the local community cultivates seasonal plants such as peanut, corn, and cassava along the river bank which causes erosion flowing into the stream during the wet season. This condition triggers sedimentation along the river, from upper catchment areas (Wonogiri, Sukoharjo, Solo, Sragen, Ngawi) to the lower one (Blora, Bojonegoro, Lamongan and Gresik). Furthermore, sedimentation becomes a serious problem in Wonogiri Dam which is situated in the upstream area of Bengawan Solo river basin. This sedimentation problem also affects the performance of hydropower system utilized in the dam.

Beside the sedimentation problem, the river basin also faces a catastrophic water pollution problem, because the Bengawan Solo River now has become a giant waste reservoir, either for domestic waste or industrial waste. Animal carcasses and waste from animal husbandry are disposed of in the river. The river damage is also now aggravated by sand mining activities practiced by local poor communities along the river.

Another scientific report concerning the Bengawan Solo River was written by Hidayat (2009). Based on several sources, the report concluded that climate change has impacted the flood risk in Java Island including the Bengawan Solo River Basin (Hidayat, 2009). However, the report did not discuss in detail how climate change might influence flood events in the basin.

UN-Habitat (2009) also conducted a study reporting on damage to the Upper Bengawan River Basin which was struck by flooding since the last 3 years, and in particular the city of Surakarta (Solo). The report claims that climate change has caused a changing extreme rainfall pattern affecting the city. This has triggered flooding which covered about 45 % of Solo city and gave severe impact mostly in slum settlements along the river banks (UN-Habitat, 2009).

In conclusion, research regarding flooding and related subjects in the Bengawan Solo River Basin by scholars is very limited. However, mass media has actively informed the occurrence of flood.

2.2. Regulation of Water Resources Management in Indonesia

Regulation and institutional aspects have an important role in water resources management, including management of flood risk. According to Saleth (2004), institutions are entities defined by a formation of legal, policy, and organizational rules, conventions, and practices that are structurally linked and operationally embedded within a well-specified environment (Azdan, 2011). From a very broad perspective, institutions can be decomposed by distinguishing the institutional structure (or, governance structure) from its institutional environment (or, governance framework) as summarized by Saleth (2004, p.3). While the institutional environment is characterized by the overall physical, cultural, historic, socio-economic, and political milieu of a country or region, the institutional structure is defined by the interactive effects of the legal, policy, and organizational or administrative components and their constituent aspects. Furthermore, Saleth (2004, p. 9) reported that water law assumes a central place in the functioning of water institutions as it gives full legal backing to water policy as well as providing the operational framework and enforcing power for water administration including its regulatory arrangement. Figure 2.1 below shows the connection between the institution and legal system in water environment and development.

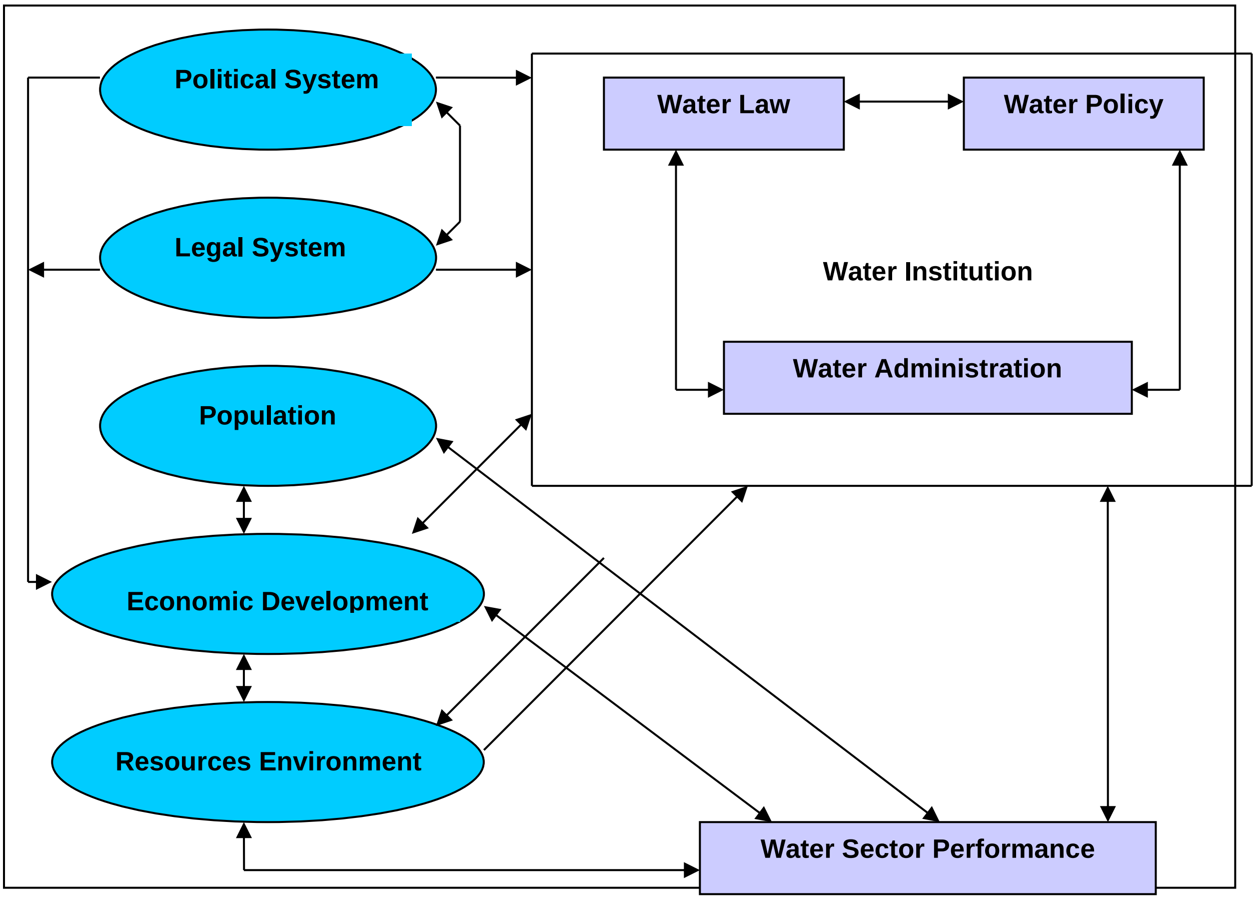


Figure 2. 1. Connections between institution and legal system in water environment and development. (source: Saleth, 2004)

Regarding water resources management, the Indonesian government has set up a regulation, entitled “Indonesian Water Resources Regulation” (Regulation No.7/2004). This regulation describes briefly the management of water resources in Indonesia which are distinguished into three aspects, namely water resources preservation and conservation, water resources utilization and development, and management of water-related disaster. This regulation also points out that the trans-boundary river basin (river basin belongs to many regencies / municipalities or provinces) should be managed together by local and the higher level of government and related institutions. Figure 2.2 below shows the aspects of water resources management in Indonesia as described in Regulation No. 7/2004.

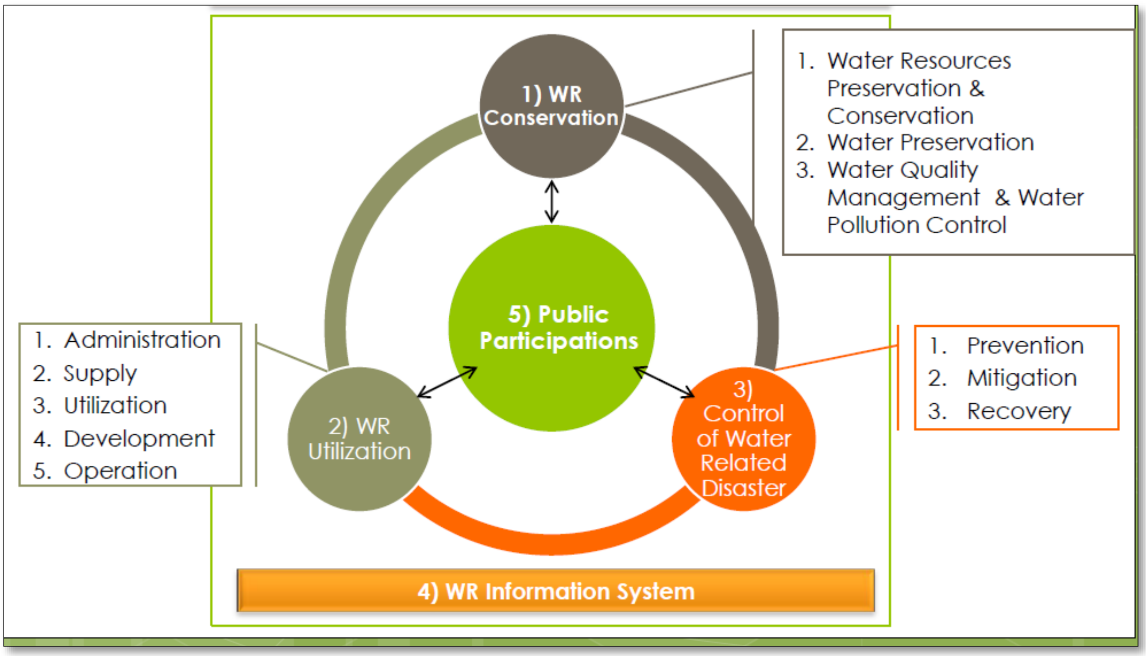


Figure 2. 2. The aspects in Regulation No 7/2004 about water resources in Indonesia. (source : Directorate of Water Resources and Irrigation, 2013)

Moreover, it is mentioned in the regulation that river shared by more than one province (trans-boundary) is managed by a national level department. In the implementation, the river basin is usually managed by a river basin organisation under Department of Public Work. After the implementation of decentralisation in Indonesia since 2004, there are problems in the management of natural resources including water resources, particularly in trans-boundary river basin. The problems include lack of coordination among related stakeholders, low law enforcement, lack of data base, and unimplemented regulation.

There is another government regulation, regarding river management in Indonesia, i.e. government regulation PP No. 38 / 2011. In this regulation, it is described that construct housing or building on the flood plain along the river is forbidden. Furthermore, where embankment is constructed along flood prone area, according to this regulation, it is forbidden either to construct building or to grow agricultural commodity along the embankment. However, in fact, there are some housing and slum area along the flood plain, and the embankment has changed into seasonal agricultural field.

2.3. Land Use, Hydrological Processes and Flooding

In water resources management, including management of flood, the water cycle or hydrologic cycle is the key phenomenon which must be understood by all related stakeholders. The processes in the hydrologic cycle include evaporation, rainfall, interception, surface runoff, infiltration, and percolation as shown in the picture below.

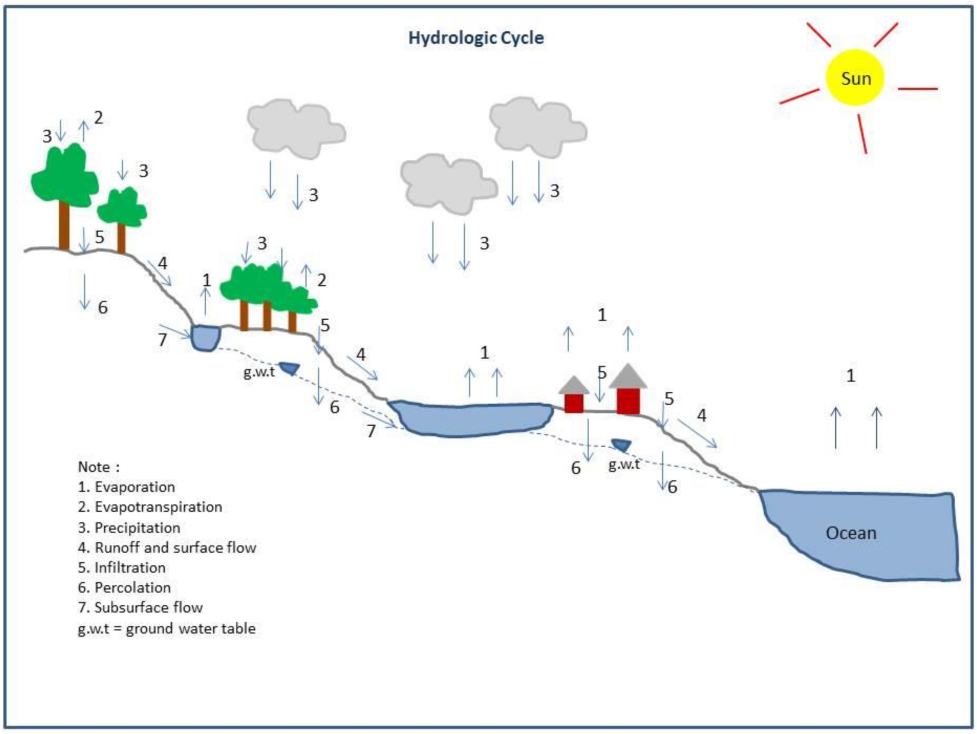


Figure 2. 3. Simple Schematic of Hydrological Cycle

Land use will affect the processes in the hydrological cycle, particularly the process of evapotranspiration, interception, infiltration, and percolation. Evaporation conditions in a dense area of building will be different from those in a vegetative-covered area. Area covered by a certain kind of vegetation will have different evapotranspiration conditions compared with an area covered by different type of vegetation, because each type has different characteristics due to different root depths and canopy. Infiltration processes are also greatly influenced by the character of the land. The roots of the plant and soil pores are very influential on infiltration and percolation processes. It is generally known that land which has been turned into impervious area would reduce the ability of land to absorb water into the ground.

There has been significant number of scholars conducted research regarding land use changes and its impact on floods around the world. One of the studies was conducted by De Roo *et al* (2001) in Oder river basin (The Czech Republic, Poland, and Germany) and Meuse river basin (France, Belgium, Germany and Netherlands). The study applied simulation using LISFLOOD model. The study showed that in Oder catchment between 1975 and 1992, there was no change in land use and therefore no change in flood hydrology was found. Whereas in the Meuse catchment, land use was changed from 1975 to 1992 which resulted in a slight increase of flood risk (De Roo, *et al*, 2001). Furthermore, several research results summarized by De Roo *et al* (2001) stated that the foremost changes in land use which influence hydrological processes are afforestation and deforestation, intensified agriculture, wetland drainage, road construction, and urbanization. Thomas *et al* (2011) summarized several reports regarding the effect of land use on evapotranspiration in the mid-latitude region. It was reported that evapotranspiration is largely dependent on land use. According to Thomas *et al* (2011), land use types can be ranked from low to high evapotranspiration as follows: bare soil, cropland, grassland, deciduous forest, and coniferous forest.

Another study was carried out in the Kishwaukee river basin (mid-western USA) using the Hydrological Simulation Program-Fortran (HSPF) and various land use scenarios generated either by urban growth model (LEAMluc) or hypothetically. It was indicated from the study that the land use scenarios generated by LEAMluc resulted in little changes in total runoff but some obvious changes in surface flow (Woonsup Choi, 2008). Moreover, Benito *et al* (2010) reported that between 1830 and 1900, the historical flood record in the Guadalentin catchment (southeast Spain) provides information about an anomalous increase in the frequency of large magnitude floods which can be attributed to climatic variability accentuated by rigorous deforestation and land use practices during the beginning of the nineteenth century.

Brath *et al* (2006) conducted a study assessing the impact of land use change to flood flow in Samoggia River Basin which is situated in the Apennines Mountains (Italy). The research conducted by simulating the Samoggia river flood discharge for different land use scenarios. The result showed that the flood regime sensitivity to land use change diminishes for increasing return period of the simulated peak discharge, and the impact of human activity appeared to be significant for peak flows with return period ranging from 10 – 200 years (Brath, 2006). In addition, research conducted by Cabello *et al* (2011) in six European test-bed basins (Llobregat, Guadalhorce, Gardon d'Anduze, Linth, Verzasca, and Sambuco) found that future changes in the rural land-use will generally affect the hazard levels. Specifically, the exposure factor of the risk equation could be considerably increased by alterations in urban land-use (Cabello *et al*, 2011).

Furthermore, a study of the impact of land use change on runoff was conducted by Descroix *et al* (2012) in the Niger River. The results showed that the sharp increase of runoff occurred in the Niger River's right bank which is still happening. This condition triggered a modification of the Niger River's regime from a single hydrograph to a two-flood hydrograph, and the local flood occurring during the wet season becoming the more prominent. This modification is likely caused by the enlarged are of bare soils and crusted soil areas as a result of human pressure. Moreover, land clearing and extension of crops due to demographic pressure which lead to soil clearing, fallow shortening and soil crusting allegedly has changed the hydrological functioning in the Sahelian area (Descroix *et al*, 2012).

A study carried out by Jinkang *et al* (2012) simulated the various urbanisation scenarios and related them to annual runoff, daily peak flow, and flood volume using HEC-HMS model (Jinkang, et al, 2012). The result showed that urban expansion during the study period (1988 – 2009) increased the annual runoff, daily peak flow, and flood volume. Furthermore, it was predicted that this will continue to increase since urban areas increase in the future. Jinkang *et al* (2012) also reported that when impermeable ratios change from 3% (1988) to 31% (2018), the average annual runoff would rise slightly and the annual runoff in the dry year would increase proportionately more than that in the wet year. In addition, the daily peak discharge of eight chosen floods in the study area would increase by between 2.3% to 13.9% (Jinkang Du, 2012).

Furthermore, a study regarding land use change was conducted by Jothityangkoon *et al* (2013) in northern Thailand. The research which was conducted in Upper Ping River catchment (northern Thailand) found that deforestation of 10%, 20%, and 30% resulted in increases in Probable Maximum Flood of 3.1%, 6.2% and 9.2% respectively (Jothityangkoon *et al*, 2013).

Bathurst *et al* (2011) conducted research in four different Latin American environment representing tropical and moderate rain forests and floods resulting from hurricanes, El Nino events, mid-latitude depressions and snowmelt. The results from small watersheds with different forest cover in Ecuador and a small watershed exposed to forest logging in Chile suggested that as discharge increases, the effect of forest cover on flood peak is decreasing either relatively or absolutely (Bathurst *et al*, 2011).

Adnan and Atkinson (2010) conducted research regarding the impact of climate change and land use change on stream flow trend in monsoon catchment, a case study in Kelantan catchment (Malaysia). The research which applied Mann – Kendall test to detect hydrological time series trend suggested that the increased in all seasons in the upper catchment, whereas in lower catchment, the stream flow increased in rainy season and decreased in dry season (Adnan and Atkinson, 2010). Moreover, the research also discovered the upward trend of rainfall during rainy season and downward trend during dry season. The research suggested that land use change (conversion from forest to rubber and oil palm plantation) in the upper catchment might give significant contribution in increasing stream flow in Kelantan catchment (Adnan and Atkinson, 2010).

In addition, according to Wheater (2009), the land on which we live has been changed intensely by anthropogenic activities. As a result, it has affected the hydrology that determines flood hazard, water resources and pollutant transport and dilution. Defra (2004, cited by Wheater, 2009) reported that the inseparable linkage of land and water management is increasingly recognised.

2.4. SHETRAN Modelling System

SHETRAN is a physically-based spatially-distributed (PBSD) modelling system for surface and subsurface water flow as well as sediment and solute transport in river basin (Ewen *et al*, 2000). The SHETRAN model was developed by the Water Resources System Research Laboratory, School of Civil Engineering and Geosciences, University of Newcastle upon Tyne, United Kingdom and can be freely downloaded from www.ceg.ncl.ac.uk/shetran/. The model includes components for vegetation interception and transpiration, snowmelt, overland flow, variably saturated subsurface flow, river/aquifer interaction and sediment yield. A three-dimensional grid is used with finite difference methods to solve the governing, physics-based, partial differential equations of mass and momentum (Ewen *et al*, 2000).

According to the SHETRAN V 4 User Guide and Data Input Manual, there are two versions of SHETRAN, *i.e* SHETRAN Windows and SHETRAN Standard, which both use standard SHETRAN text files for running the model. However, the Windows version cannot run the sediment and solute transport. Figure 2.4 shows the example of SHETRAN Windows v2.001 appearance.

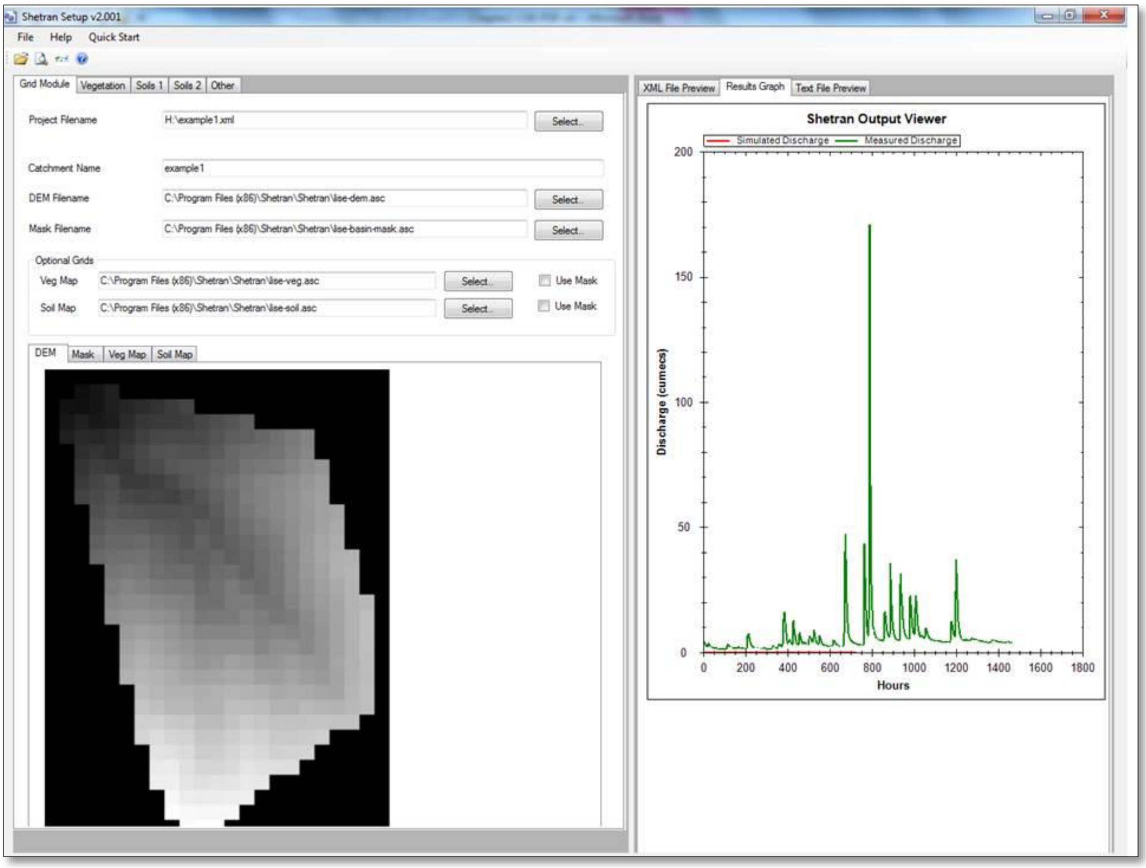


Figure 2. 4. The example of SHETRAN Windows v2.001 appearance.

In Figure 2.4, the system allows viewing of spatial maps of model parameters (left) and time series of model inputs and output variables (right)

SHETRAN consists of 8 main modules, namely FR (frame module), ET (evapotranspiration module), OC (overland / channel module), VS (variably saturated subsurface module), BK (bank module), SM (snowmelt module), SY (sediment erosion and transport module), and CM (contaminant transport module). The last four modules are optional.

The frame module data set (FR) contains the catchment geometry and basic simulation control parameters. Parameter data are read from the appropriate data file for each component or module selected. Moreover, the frame and the basic flow components (i.e. evaporation [ET], overland flow / channel [OC], and variably saturated subsurface [VS]) are all mutually inter-dependent and automatically used in every simulation. For every simulation, the visualisation_plan.txt file is used. It specifies the items to be recorded and for which locations in the catchment. Meteorological data are read throughout the simulation, controlled by a logical flag in the ET data file. Rainfall (PRD file) and potential evapotranspiration (EPD file) are also read in regular intervals, while time-varying boundary conditions can be set up for the VS and OC components.

The outputs of SHETRAN are saved in an HDF5 file (Hierarchical Data Format 5) called *shegraph.h5* and four (4) ASCII data files consisting of daily discharge at the outlet, daily mass balance data averaged over the catchment, phreatic surface levels and head data for each finite difference cell at the end of the simulation, and discharge at the outlet in every time step.

The SHETRAN model has been applied by several researchers to simulate flow as well as sediment yield. Lukey *et al* (2000) applied SHETRAN for a catchment in France. According to Lukey *et al* (2000), SHETRAN was able to reproduce the observed difference in runoff / rainfall ratio and the two orders of magnitude difference in sediment yield in the simulated catchment as a function of different vegetation covers and rainfall. Parkin *et al* (2007) applied the SHETRAN model to estimate the impact of groundwater abstractions on river flows in the Lambourne catchment. Moreover, Bathurst *et al* (2004) presented the result of blind validation of SHETRAN which considers internal catchment conditions and outlet discharge. The annual catchment water balance as well as important features of the event-scale response was well represented.

2.5. Climate Change Impact on Rainfall and Flooding

There have many studies of the climate change impact on different aspects, including food security, public health, and hydrological processes. All components of the climate system comprise water, therefore climate change affects the hydrological cycle through several mechanisms (Bates *et al*, 2008; Bao *et al*, 2012). In addition, Bates *et al* (2008) reported that heavy rainfall is likely to increase which gives impact to agricultural, water resources, public health, industries, and society.

Moreover, according to Bao *et al* (2012), the hydrological cycle changes could be driven by climate variability and human activities. In the last several decades, stream flow and rainfall in the Haihe River Basin have decreased, whereas the mean temperature was increasing (Bao, 2012). Bao *et al* (2012) in their research concluded that climate variability was the major driving factor for the stream flow decrease in the Taolinkou catchment. On the other hand, anthropogenic activities were the main driving factor for the streamflow decrease in the Zhangjiafen and Guantai catchment.

There is limited study regarding climate change in Indonesian archipelago. One of the studies was conducted by Suroso *et al* (2013) which investigated flood risk and adaptation assessment in South Sumatra Province, Indonesia. The study reported that there was an increased trend of temperature during the last 25 years in South Sumatra Province, and in the period of 2020 – 2030 the risk of extreme rainfall will increase in the province.

Moreover, there are several studies regarding rainfall trend under climate change in the South-East Asia region. One of the studies was conducted by Wu *et al* (2013), which investigated the rainfall trend in Mekong River Basin in relation with climate change. The study indicated that the annual and seasonal rainfall in the basin had a common variation trend with rainfall variability increasing in the central catchment and decreasing in the North and South catchment. Moreover, the northern mountainous region in the river basin was more sensitive to climate change. The study indicated upward trend of annual rainfall in northern region, and downward trend in southern region (Wu *et al*, 2013). In addition, Thompson *et al* (2013) investigated the uncertainty in river flow projections for the Mekong River using multiple GCMs and hydrological models. The research indicated that for some GCMs (CCCMA and NCAR), average discharge increases along the catchment, whereas for others (CSIRO and IPSL), the discharge declines at all gauging stations.

A study conducted by Xu *et al* (2013) in Qiantang River Basin (East China) produced interesting result which suggested that annual river runoff will likely to decrease under almost all emission scenarios and time stages of the future period. At Jinhua Station, decreasing annual river runoff can be noticed clearly which indicates less water resource possibly available for the region in the future. Moreover, monthly simulation indicated that the largest decrease will likely occur during winter while during summer, it is likely to increase. This denotes that more water-related disasters in the region is likely to occur (Xu *et al*, 2013).

Furthermore, Wang *et al* (2013) who applied projection by HRM2-HADCM3 climate model in Apalachicola river basin, Florida, reported that there was no significant change in rainfall intensity at the upstream and middle stream stations, but higher intensity at the downstream station. They also reported that the potential temporal change of extreme rainfall events coupled with overall increased intensities may intensify flood magnitudes and lead to increased sediment and nutrient loadings to the estuary, particularly in light of sea level change. Research conducted by Indrani and Al-Tabbaa (2009) in Kerala (India) found that during the spring season, the amount, intensity and frequency of extreme rainfall showed negative significant trend. Moreover, increasing trend of rainfall occurred during autumn. Huilan *et al* (2010) discovered the characteristics of climate change and abrupt change in rainfall and temperature during different time scales in Ili River Basin (Xinjiang, China). The rainfall in the research location increased from the mid-1980s to 2000 particularly during summer and winter, and has continued to increase at a smaller magnitude since 2000.

Significant numbers of studies regarding abrupt change in maximum rainfall have been conducted around the world to detect whether the climate change is occurred (Croitoru *et al*, 2013; Huilan *et al*, 2010; Indrani and Al-Tabbaa , 2009; Narisma *et al*, 2007; and Zhang *et al*, 2009).

Merz *et al* (2012) wrote an influential paper criticising current practice in flood trend studies. They highlighted that the question whether the magnitude and frequency of floods have changed due to climate change or other drivers of change is great interest, but that the current state of flood trend attribution is poor because it is mostly based on qualitative reasoning or even speculation. As reported by Merz *et al* (2012), changes in flood magnitude and frequency could be driven by several aspects related to the variables in atmosphere, catchments, and rivers. The drivers of change could be natural climate variability, anthropogenic climate change, urbanization, deforestation, agricultural management practices, reduction in river length, construction of dykes, and river training (Merz *et al*, 2012). To conclude, they urged that more scientific rigour in flood detection and attribution studies is required (Merz et al, 2012).

2.6. Integrated Flood Risk Management

In Indonesia, floods are the most common natural disaster. Floods are classified as fluvial (riverine) flooding, pluvial flooding, coastal flooding, flash flood, or groundwater flooding based on their origin and characteristics (The World Meteorological Organization and The Global Water Partnership, 2007). Fluvial or riverine floods occur when water exceeds the normal confines of a river or other body of water. When the river discharge exceeds the capacity of the main river channel, overflowing occurs. Pluvial or rainfall floods happen when excessive rainfall causes a flood event that is not caused by an overflowing water body. Pluvial flooding can occur in urban areas when the local drainage system is unable to collect and transport surface runoff.

Fluvial and pluvial floods are caused by overland flow from rainfall, which can be generated by several mechanisms in the tropical landscape. According to Tarboton (2003), each mechanism involved in runoff generation responds to rainfall differently in terms of the quantity of runoff produced, the maximum discharge rate, and the timing of contributions to flow of water in the channel.

Climate, geology, topography, vegetation, characteristics of soil, and land use all influence the relative importance of each process, and the dominant process in large and small storms may differ (Tarboton, 2003). In the hydrological cycle, there is a maximum limiting rate at which a soil in a given condition can absorb surface water input in the infiltration process. This was referred to as the infiltration capacity of the soil by Robert E. Horton, one of the founding fathers of quantitative hydrology, and thus this mechanism is also known as Horton overland flow (Tarboton, 2003). According to Xie *et al.* (2003), the overland flow from rainfall is primarily caused by two mechanisms, i.e. infiltration excess (Hortonian mechanism) and saturation excess (Dunnian mechanism). According to Hortonian mechanism, the runoff occurs when rainfall intensity exceeds the soil's water infiltration rate. Whereas the Dunnian mechanism, also known as saturation overland flow, is caused by topsoil saturation. Overland flow can occur when surface water enters already saturated areas. This is referred to as saturation excess overland flow. Saturation excess overland flow occurs when infiltrating water completely saturates the soil profile, leaving no space for additional water to infiltrate. Saturation from below occurs when a soil profile is fully saturated, causing the water table to rise to the surface. Once a location is saturated from below, any additional surface water input becomes overland flow (Tarboton, 2003). Moreover, overland flow can be supplemented by return flow, which is subsurface water that rises to the surface (Tarboton, 2003).

Coastal flooding occurs when seawater inundates normally dry low-lying land. Coastal flooding is primarily caused by storm surges (wind-induced) or a combination of storm surges, high tide, and elevated river discharge levels, which cause backwater effects in river delta areas. Tsunamis as a cause of coastal flooding are a less common occurrence. However, as tragically demonstrated by the December 2004 Indian Ocean tsunami they can have far-reaching consequences. Coastal floods are distinguished by the combination of damages caused by contact with flood waters and wind damage to structures.

Flash floods are short-term floods with a relatively high peak discharge. Flash floods can occur within minutes or hours of excessive rainfall, severe thunderstorms, and heavy rain from hurricanes and tropical storms in areas with steep gradients. A dam or levee failure can also cause flash floods. Because of their high flow velocities, flash floods frequently include mud and debris flow floods, which are sometimes exacerbated by concurrent landslides. In Indonesia, the flash floods generally carry soil material (in the form of mud), stones and wood (Adi, 2013). According to Adi (2013), the warning signs before a flash flood occurs, particularly in Java Island, include heavy rainfall, fallen trees, wood is carried into residential areas, higher water discharge, cloudy water, decreased river water level, and loud roaring noise. Based on the signs, it is possible that the heavy rainfall increased the river water discharge, the landslide process caused the wood to be carried away, and the river water became cloudy, causing the river flow to become blocked. The process of blocking river channels causes the water level to fall (Adi, 2013).

Groundwater flooding occurs when water rises from underlying rocks or flows from unusual springs. It is frequently characterized by long-lasting flooding that can cause significant disruption and damage. Groundwater flooding is more likely after extended periods of heavy rain. Increased rainfall causes more water to seep into the ground, raising the water table above normal levels. Flooding from groundwater is most likely in low-lying areas underlain by permeable rocks or aquifers (The World Meteorological Organization and The Global Water Partnership, 2007).

Flooding in Indonesia is usually caused by heavy rainfall, a land surface that is lower than sea level, a basin surrounded by hills dominated by impermeable area, the construction of buildings along riverbanks, a river flow that is not smooth due to debris, poor drainage system, and a lack of vegetation cover in the river's upstream areas. Usually, floods event is a result of excessive rainfall which flow as runoff and inundate an area. Runoff is the most important component of flood prediction, and catchment area conditions will impact the proportion of rainfall that becomes runoff.

According to Posthumus *et al* (2008), flood risk is defined by the probability of flooding and the damage caused by the flood event. As summarised by Posthumus *et al* (2008), flood risk management aims to manage the risk from flooding in an integrated and holistic approach to reduce the danger to human life and property while furthering sustainable development. In the implementation of flood risk management, both structural and non-structural measures should be applied. Structural measures include the construction of flood defence such as embankment and reservoir as well as the application of river engineering. Whereas non-structural measures could be the provision of flood warning system, land use regulation, and flood event management response (Posthumus *et al*, 2008).

Abbas *et al* (2012) reported that the implementation of integrated approach requires sustainable arrangements for financing, maintenance of the implemented measures, preventing their failure, and evaluating their utility. In addition, integrated flood risk management requires coordination between national governments, city governments, public sector companies, non-government organisations (NGOs), educational institutions, and private sectors.

According to a study facilitated by World Bank and Global Facility for Disaster Reduction and Recovery (GFDRR), there are 12 guiding principles for integrated flood risk management, reported by Abhas *et al* (2012) as follows :

1) There is no flood management blueprint; every flood risk scenario is unique.
2) Flood control designs need to be flexible enough to adapt to an uncertain and changing future.
3) Flood risk management must be incorporated into routine urban planning and governance due to rapid urbanization.
4) Using both structural and non-structural measurements, as well as appropriate criteria for "getting the balance right," is necessary for an integrated plan.
5) Structures with intricate engineering can transfer risk both upstream and downstream.
6) It is impossible to completely eliminate the risk from flooding. Hard-engineered measures are planned to protect to a pre-determined level.
7) Many flood management strategies have multiple co-benefits over and above their flood management role.
8) It is critical to take into account the broader social and ecological effects of flood control funding.

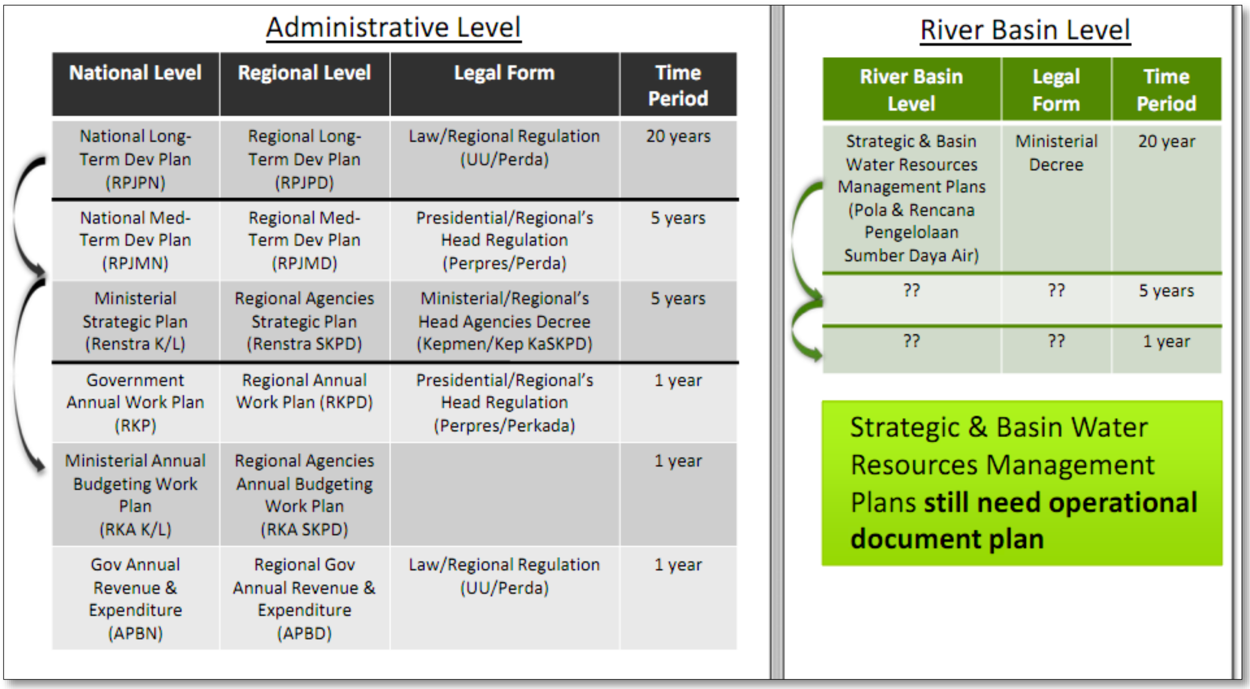
9) It is crucial to establish clear lines of accountability for creating and managing flood risk programs.
10) Collaboration across multiple stakeholders is necessary to implement flood risk management strategies.
11) Continuous communication to increase awareness and reinforce preparedness is essential.
12) Plan to recover fast after flooding and use the recovery to build capacity.

Although the guiding principles above have much to recommend them, flexibility is essential as different river basins will face different challenges in implementing such principles.

2.7. Existing Flood Management in Indonesia

According to Directorate Water Resources and Irrigation of National Development Planning Agency of Republic Indonesia (2013), in 2008 and 2011 there were 40,688 and 41,005 flood events around Indonesia respectively. The flood events were allegedly triggered by high rainfall intensity, environmental degradation due to land use change, and land subsidence along low lands area. In Indonesia, the management of flood risk involves many actors, such as governors, river basin organisations, NGOs, universities, and national governments including Ministry of Public Work, Ministry of Agriculture, Ministry of Forestry, Ministry of Environment, and Ministry of Housing. The most critical problem regarding these actors is the lack of coordination among them.

The plan for flood management is set up based on administrative level and river basin level as shown in Figure 2.5 below, according to the Directorate Water Resources and Irrigation of National Development Planning Agency of Republic Indonesia (2013).



Administrative Level

National Level	Regional Level	Legal Form	Time Period
National Long-Term Dev Plan (RPJPN)	Regional Long-Term Dev Plan (RPJPD)	Law/Regional Regulation (UU/Perda)	20 years
National Med-Term Dev Plan (RPJMN)	Regional Med-Term Dev Plan (RPJMD)	Presidential/Regional's Head Regulation (Perpres/Perda)	5 years
Ministerial Strategic Plan (Renstra K/L)	Regional Agencies Strategic Plan (Renstra SKPD)	Ministerial/Regional's Head Agencies Decree (Kepmen/Kep KaSKPD)	5 years
Government Annual Work Plan (RKP)	Regional Annual Work Plan (RKPD)	Presidential/Regional's Head Regulation (Perpres/Perkada)	1 year
Ministerial Annual Budgeting Work Plan (RKA K/L)	Regional Agencies Annual Budgeting Work Plan (RKA SKPD)		1 year
Gov Annual Revenue & Expenditure (APBN)	Regional Gov Annual Revenue & Expenditure (APBD)	Law/Regional Regulation (UU/Perda)	1 year

River Basin Level

River Basin Level	Legal Form	Time Period
Strategic & Basin Water Resources Management Plans (Pola & Rencana Pengelolaan Sumber Daya Air)	Ministerial Decree	20 year
??	??	5 years
??	??	1 year

Strategic & Basin Water Resources Management Plans **still need operational document plan**

Figure 2. 5. The administrative and river basin levels of flood management plan in Indonesia (source: Directorate of Water Resources and Irrigation, 2013).

Traditionally, the flood problem in Indonesia has been addressed using structural interventions such as by constructing dams, retention basins, barrages and dykes. In some large river basins such as the Citarum, Brantas and Bengawan Solo river basins, flood management projects have been implemented over the last few decades, particularly by constructing flood control structures. Recently, non-structural intervention such as reforestation and rehabilitation of critical land has also been implemented, but not yet with satisfactory results. Other attempts such as raising flood awareness and educating people to preserve the environment must be carried out to reduce the negative impact of flooding.

2.8. Summary

There have been few previous studies related to Bengawan Solo river basin. However, the topics related to flood including flood frequency and magnitude, impact of climate and land use change, are very limited. Studies with flood-related topics can be easily found in other parts of the world such as in European countries.

Moreover, some studies related to flooding need to use software and modelling which require some data including hydrological, hydraulic, land use and meteorological data. The focus of the studies varies in different perspective or point of view. Some researcher conducted study to investigate the frequency and magnitude of flooding, while the other researcher investigated the impact of abrupt change and land use change. The flood-related studies have been conducted around the world, and the result of the studies could be important in solving the flood problem. However, flood problem could be site-specific, therefore the approach applicable in a region is not necessarily applicable for other region. The aspects discussed in this literature review such as maximum rainfall, SHETRAN modelling, and integrated flood management approach were taken into account in this research.

Chapter 3. Data and Methodology

This chapter describes the data available and applied in this research. A brief explanation of the research methodology is also presented. In brief, daily rainfall and discharge from selected gauging stations over extended periods, TRMM satellite 3-hourly rainfall data for 1998 – 2000 and land use data have been applied in this research. In addition, some hydrological aspects related to the flood problem in the Bengawan Solo river basin are also discussed in this chapter.

3.1. Data Available

3.1.1. Rainfall data

The Indonesia Ministry of Public Work operates 107 rain gauging stations in the Bengawan Solo river basin. Of the available rain gauging data, 21 stations are located in the upper catchment, 58 in the middle, and 29 stations in the lower catchment. AWLRs (automatic water level recorders) have been placed along the main river as well. The operation and maintenance of the gauging networks are carried out by regional public work board (a board under Ministry of Public Work in lower level of region, province or regency / municipality). However, not all of the stations have satisfactory records, and there are gaps in the data record for both the rain gauging and AWLR networks. The unsatisfactory data record could be caused by human error, damaged gauges, or electricity cut-off which commonly occurs in Indonesia.

The data available are recorded on a daily basis. There are no hourly-based data available in the river basin. The figure below shows the location of rain gauging and AWLR stations in the Bengawan Solo river basin.

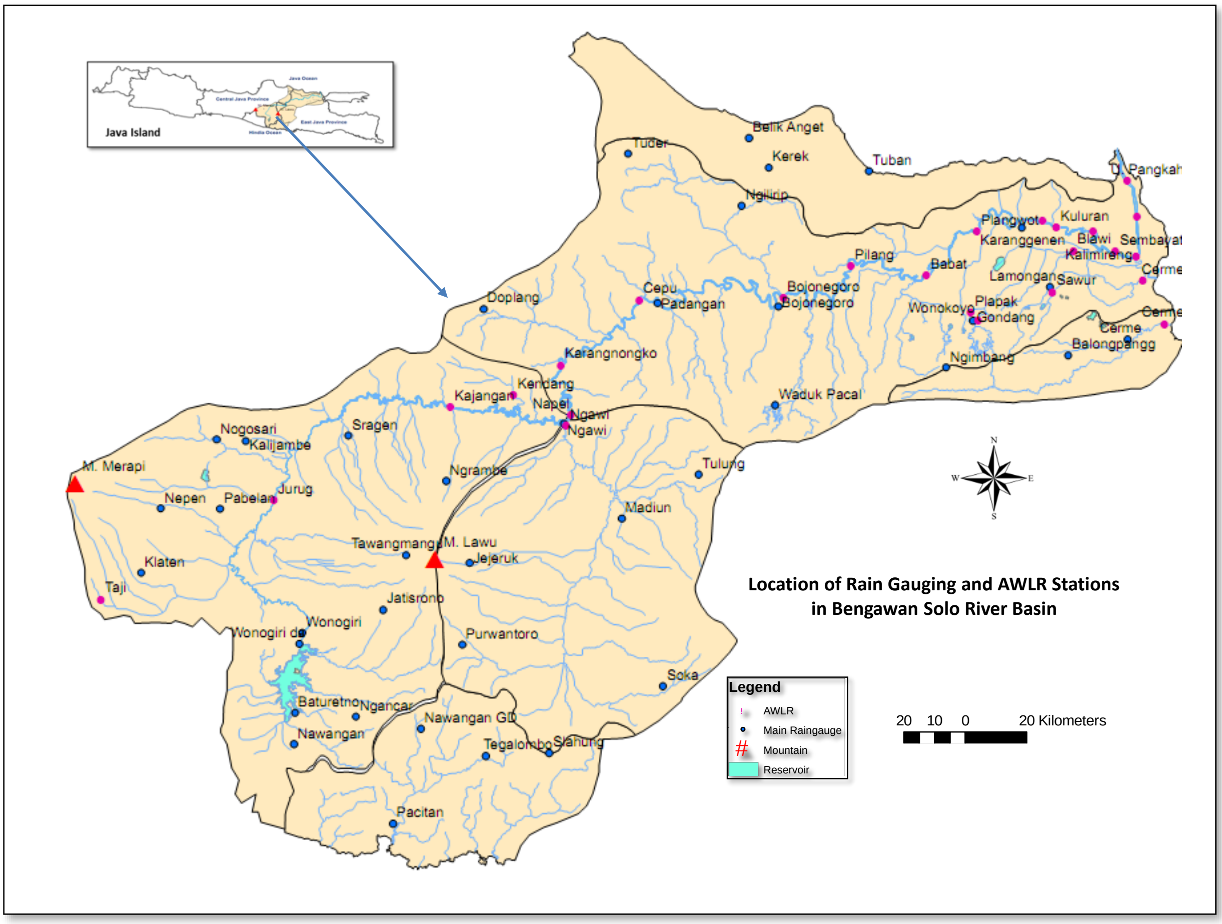


Figure 3. 1. Location of rain gauging and AWLR stations at Bengawan Solo River Basin (source: processed based on data from Indonesia River Research Center)

The rainfall data in this research were obtained from the River Laboratory and Research Centre based in Surakarta city, Central Java. The data were originally collected by regional public work board responsible for the catchment of gauging network and the Department of Hydrology of Bengawan Solo River Basin Organisation, also based in Surakarta city. Table 3.1 – Table 3.5 below show the summary of rainfall data availability, percentages of missing data, distance between gauging stations, cross correlation of daily rainfall between gauging stations, and annual rainfall in the upper catchment of Bengawan Solo river basin.

No	Station's Name	Data availability	Notes
1.	Baturetno	1979 – 2009	Missing data in January 1982, 1990, 1998. Missing data in 1986. Missing data in March 1998. Missing data in November 1987, 1989, and 1997. Missing data in December 1987 – 1989.
2.	Bendung Colo	1982 - 1987, 1998 - 2003, 2005 – 2009	Missing data in few months of 1998 and 2009
3.	Jatisrono	1975 – 2000	-
4.	Kalijambe	1975 – 2009	-
5.	Kalikenuk	1978 – 1987	-
6.	Klaten	1975 – 2009	-
7.	Nawangan	1975 – 2009	-
8.	Nepen	1975 – 2009	-
9.	Ngancar	1975 – 2003	Missing data in January - March 2002
10.	Pabelan	1975 – 2009	-
11.	Parangjoho	1978 - 2000, 2007 – 2009	Missing data in January - March 2007 and June - December 2009
12.	Purwantoro	1975 - 1978, 1981 – 2009	Missing data in June - December 2009
13.	Song Putri	1977 - 2000, 2008	-
14.	Sragen	1975 – 1999	-
15.	Tawangmangu	1975 – 2009	-
16.	Wonogiri Dam	1975 – 2000	-
17.	Wonogiri	1975 - 2003, 2008	In 2008, data is only few months available.

Table 3. 1. Summary of rainfall data availability in Upper Bengawan Solo catchment

No	Station's Name	% missing data
1	Baturetno	7.95
2	Bendung Colo	45.45
3	Jatisrono	0.00
4	Kalijambe	0.00
5	Kalikenuk	68.18
6	Klaten	0.00
7	Nawangan	0.00
8	Nepen	0.00
9	Ngancar	0.00
10	Pabelan	0.00
11	Parangjoho	13.64
12	Purwantoro	4.55
13	Song Putri	0.00
14	Sragen	4.55
15	Tawangmangu	0.00
16	Wonogiri Dam	0.00
17	Wonogiri	0.00

Table 3. 2. Percentage of missing data at gauging stations in Upper Bengawan Solo

	Distance between stations (km)																
Stations	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Baturetno(1)																	
Colo(2)	25																
Jatisrono(3)	29	21															
Kalijambe(4)	61	36	47														
Kalinekuk(5)	7	28	28	64													
Klaten(6)	47	34	55	39	54												
Nawangan(7)	7	32	36	68	10	51											
Nepen(8)	54	34	53	24	60	16	60										
Ngancar(9)	12	30	25	65	6	58	15	63									
Pabelan(10)	57	33	47	8	61	31	64	16	63								
Parangjoho(11)	13	26	38	59	19	38	13	48	25	54							
Purwantoro(12)	38	40	20	65	34	74	43	73	28	66	50						
SongPutri(13)	11	28	39	62	17	42	10	52	23	58	4	50					
Sragen(14)	60	37	36	25	61	57	67	46	60	31	64	49	66				
Tawangmangu(15)	40	27	12	43	39	59	47	54	36	45	48	23	49	26			
WonogiriDam(16)	15	10	20	46	18	39	22	43	20	43	19	36	21	46	29		
Wonogiri(17)	17	8	18	44	20	39	25	41	22	41	21	35	23	43	27	3	

Table 3. 3. Distance between rain gauging stations in Upper Bengawan Solo catchment

Stations	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
Baturetno(1)																	
Colo(2)	0.34																
Jatisrono(3)	0.39	0.36															
Kalijambe(4)	0.18	0.17	0.27														
Kalinekuk(5)	0.64	0.32	0.46	0.21													
Klaten(6)	0.33	0.28	0.35	0.28	0.37												
Nawangan(7)	0.56	0.30	0.35	0.19	0.50	0.34											
Nepen(8)	0.26	0.25	0.29	0.33	0.32	0.39	0.22										
Ngancar(9)	0.57	0.30	0.45	0.20	0.68	0.35	0.46	0.32									
Pabelan(10)	0.24	0.25	0.37	0.40	0.29	0.40	0.23	0.49	0.27								
Parangjoho(11)	0.52	0.23	0.37	0.17	0.57	0.37	0.44	0.25	0.46	0.22							
Purwantoro(12)	0.29	0.29	0.33	0.20	0.32	0.27	0.29	0.24	0.27	0.25	0.28						
SongPutri(13)	0.52	0.25	0.39	0.20	0.58	0.34	0.48	0.31	0.48	0.23	0.71	0.28					
Sragen(14)	0.19	0.23	0.32	0.49	0.21	0.26	0.17	0.28	0.20	0.36	0.21	0.24	0.21				
Tawangmangu(15)	0.33	0.27	0.38	0.25	0.36	0.31	0.31	0.27	0.35	0.30	0.33	0.27	0.35	0.29			
WonogiriDam(16)	0.31	0.21	0.23	0.13	0.23	0.15	0.32	0.15	0.25	0.15	0.17	0.14	0.21	0.13	0.21		
Wonogiri(17)	0.33	0.24	0.29	0.17	0.34	0.32	0.31	0.25	0.29	0.25	0.28	0.20	0.32	0.18	0.24	0.46	

Table 3. 4. Correlation between rain gauging stations in Upper Bengawan Solo catchment

Note : the number in the bracket at the top row indicates the station number referred in Table 3.1.

The correlation of rainfall data between rain gauging stations above was calculated using the equation below:

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\left(\sqrt{\sum_i [x_i - \bar{x}]^2}\right)\left(\sqrt{\sum_i [y_i - \bar{y}]^2}\right)} \qquad \textbf{(3.1)}$$

where:

x_i = the time series of x (the first rainfall time series data)

$\bar{x}$ = the mean of time series x

y_i = the time series of y (the second rainfall time series data)

$\bar{y}$ = the mean of time series y

Year	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
1975			3113	2781		1325	2525	2663	3147	2872			2731		2690	4550	2806
1976			1554	1671		826	1385	1376	1982	1261			1602		1595	2448	1713
1977			1588	2050		1643	1428	2128	2314	1817	591		1525	1650	1628	1789	1449
1978			2537	3191	2173	2453	1920	2724	2362	3050	2280		2240	2512	2529	3257	1836
1979	2154		1913	2279	2747	2103	1704	2374	2669	2573	2359			2435	2153	3410	2179
1980	1601		1744	2419	1788	1623	1626	2203	2202	2398	2108			1599	1780	2433	1966
1981	2005	1795	2504	2798	1728	2073	1967	2766	2195	2545	2179		2053	2889	2229	3157	1479
1982	973	1537	1636	2305	1390	1711	1253	2580	1472	2407	1209		1140	1595	1685	2494	862
1983	1514	1841	2567	2029	2083	1553	1506	3088	2025	2295	2360		2357	3074	1982	3251	1419
1984	1780	1692	2776	2582	2633	2200	2028	2704	2509	2422	2600	1914	2725	3776	2456	3486	2551
1985	1457	1739	2382	2314	2119	2020	1406	2610	2065	2333	2317	1217	2104	2872	2391	3322	2218
1986		2150	2312	2252	2155	2085	1401	2764	2314	2444	2218		2462	2814	2026	3403	1886
1987	1398	740	1715	2331	945	1683	1611	2074	1577	1924	1934		1628	1776	2204	2926	1824
1988	1612		2243	2633		1790	1893	2494	2371	2398	2072	1732	1766	2587	2289	3386	2169
1989	1425		2126	1967		1528	1553	2562	1996	2035	2001	1653	2097	1774	1627	3180	1508
1990	961		1525	2345		1281	1615	1765	1653	1774	1143	1451	1476	2134	1957	2930	1512
1991	1611		1948	2242		1232	1417	1443	1621	1977	1587	1249	1571	1832	1818	2902	1053
1992	2175		2458	3094		2065	1924	2309	2155	2132	2167	252	2284	2269	2266	3781	2190
1993	1930		2150	1947		1602	1648	2000	1984	2415	2021	485	1357	2602	1900	2657	2041
1994	1581		1627	2459		1504	1492	2483	1607	2641	1601	962	1742	1852	1806	2345	1799
1995	2518		2300	3279		1718	2888	3678	2487	2576	1286	396	1992	1590	2334	3778	2484
1996	1605		2011	2387		1715	1531	2585	1641	2247	1673		1655	1653	1867	2909	1896
1997	1114		1441	1917		1207	826	1157	1202	1292	780	166	1043	626	1647	2374	1346
1998	1808	526	2814	2629		2219	2590	2499	2399	2954	2529	1030	2032	2179	2619	3378	2724
1999	1807	836	2219	4032		1943	1874	3156	1789	1835	1443		1796	1424	2183	4007	2324
2000	1353	1379	2216	5159		1408	1265	2151	1753	1528	1249		1877	1381		3576	1725
2001	1399	1558		3018		1357	1293	1508	1430	1912		1303	1255			3355	1533
2002	1650	1790		2508		1334	1605	1563	704	1015		986	866			2646	731
2003	1563	2404		1867		1205	1049	1605	1771	1353		884	648			2316	522
2004	1320			2718		1676	1330	2276		2523			1467			2960	
2005	1437	2189		2202		1183	1551	2118		2084			1479			2690	
2006	1497	1896		2209		1602	1565	2158		2239			1460			2542	
2007	1539	1689		1997		1938	1512	1334		2108	1021		1848			2970	
2008	1805	1785		1819		1908	1402	2078		2426	1845		1496	1891		2240	
2009	1249			2457		1601	1141	2044		2045						3103	

Table 3. 5. Annual rainfall at gauging stations in Upper Bengawan Solo catchment

Note : The number in the top row indicates the number of station as referred at Table 3.1.

The mean and standard deviation of annual rainfall at all gauging stations in Upper Bengawan Solo catchment is shown in Table 3.6 below.

No	Station	Mean (mm)	Standard Deviation (mm)
1	Baturetno	1595	342
2	Colo	1620	507
3	Jatisrono	2131	447
4	Kalijambe	2511	665
5	Kalinekuk	1976	541
6	Klaten	1666	361
7	Nawangan	1621	419
8	Nepen	2258	560
9	Ngancar	1979	492
10	Pabelan	2167	479
11	Parangjoho	1791	555
12	Pracimantoro	1045	539
13	Purwantoro	1743	495
14	Song Putri	2111	677
15	Sragen	2066	331
16	Tawangmangu	3027	569
17	Wonogiri	1784	564

Table 3. 6. Mean and standard deviation of annual rainfall at gauging stations in Upper Bengawan Solo catchment

The charts below show the annual rainfall at preferred gauging stations which have more complete data if compared to the other gauging stations in the Upper Bengawan Solo catchment.

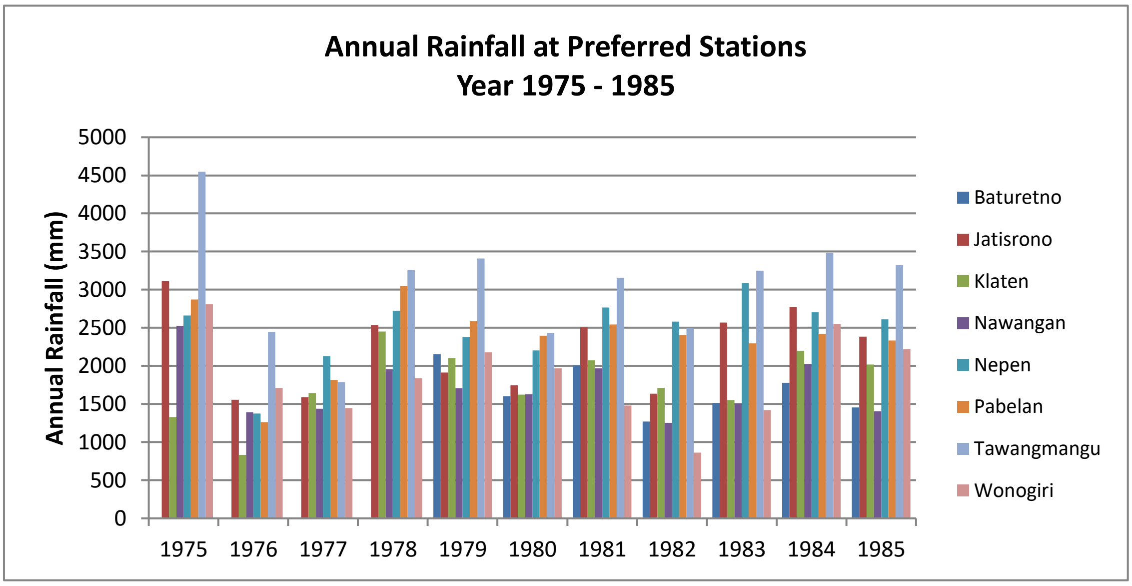


Figure 3. 2. Chart of annual rainfall at preferred stations in 1975 – 1985

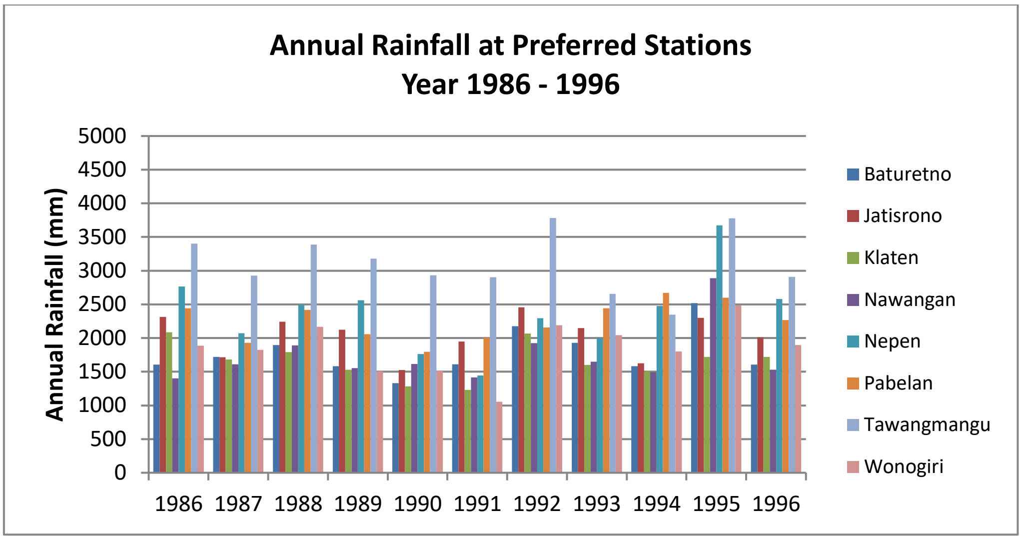


Figure 3. 3. Chart of annual rainfall at preferred stations in 1986 - 1996

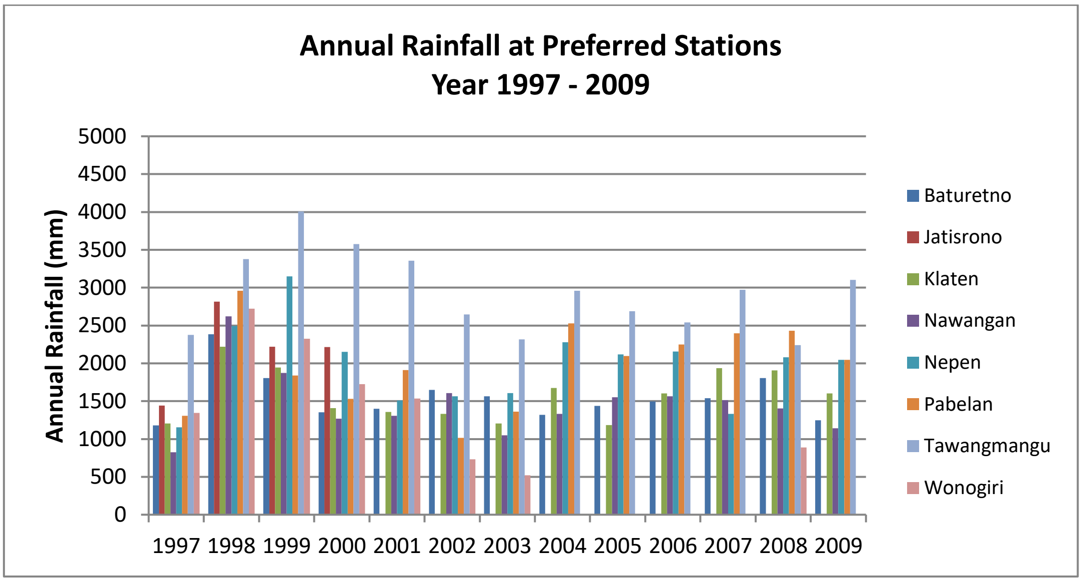


Figure 3. 4. Chart of annual rainfall at preferred stations in 1997 - 2009

According to the cross correlations shown in Table 3.4, it can be said that only a few rainfall gauging stations are well-correlated, taking account of the distance between stations. Considering the cross correlation of rainfall data between gauging stations and the completeness of data, this research uses only the data from stations which has more complete record. However, a few of these stations still have incomplete rainfall data because of missing data in a few months. Therefore, it is required to infill the missing rainfall data for further analysis. In this research, missing data was filled using Normal Ratio Method showed in the equation below.

$$\mathbf{P_A} = \frac{\sum_{i=1}^{n} \frac{NR_A}{NR_i} \times P_i}{n} \quad \textbf{(3. 2)}$$

where :

P_A = rainfall amount at station A

P_i = rainfall amount at station i

NR_A = normal rainfall at station A

NR_i = normal rainfall at station i

N = number of stations used for calculation

The missing rainfall data filled in is summarized on the table below.

No	Station's Name	Month of Missing Data
1.	Baturetno	January 1982. September 1984. November 1987. November 1989. January 1990. November 1997. January 1998. March 1998.

Table 3. 7. Summary of filled missing rainfall data at preferred gauging station

The tables below present the summary of rainfall data availability and annual rainfall in Middle and Lower Bengawan Solo catchment respectively.

No	Station's Name	Data availability	Notes
1.	Arjosari	1976 - 1991	16 years
2.	Bandar	1976 - 1991	16 years
3.	Bollu	1983 – 1988, 2006 - 2007	8 years
4.	Donorojo	1975 - 1991	17 years
5.	Dungus	1984 - 1988	5 years
6.	Giringan	1975 – 1978, 1984 – 1991, 1993 - 1995	15 years
7.	Glandangan	1984 - 2008	25 years
8.	Jejeruk	1975 – 1978, 1984 - 2008	29 years
9.	Jiwan	1976 - 2008	33 years
10.	Kalijambe	1984 - 1987	4 years
11.	Madiun	1983 - 1988	6 years
12.	Karangjati	1975 - 1982	8 years
13.	Karangmojo	1975 – 1978, 1984 - 1996	17 years
14.	Kasugihan	1983 – 1988, 2006 - 2007	8 years
15.	Kebonagung	1975 - 1991	17 years
16.	Kedungbanteng	1975 - 1982	8 years
17.	Kertobayon	1975 – 1978, 1984 - 1996	17 years
18.	Kp.Galar	1985 – 1991,1993	8 years
19.	Nawangan GD	1975 - 2008	34 years
20.	Ngadirojo	1975 - 1991	17 years
21.	Ngawi	1975 - 2008	34 years
22.	Ngebel	1975 – 1978, 1983 – 1993, 1995 - 2008	29 years
23.	Ngiloilo	1983 – 1984, 1986 – 1988, 2006 - 2007	7 years
24.	Ngrambe	1975 - 2004	30 years
25.	Nitikan	1975 – 1978, 1984 - 1996	17 years
26.	Pacitan	1975 - 2008	34 years
27.	Pringkuku	1975 - 1991	17 years
28.	Pudak	1975 – 1994, 2006 - 2007	22 years
29.	Pulung	1975 – 1994, 2006 - 2007	22 years
30.	Punung	1975 – 1991	17 years
31.	Sawo	1975 – 1994, 2006	21 years
32.	Slahung	1975 - 2008	34 years
33.	Sooko	1975 - 2008	34 years
34.	Sudimoro	1975 - 1991	17 years
35.	Tegalombo	1975 - 1998	24 years
36.	Tulakan	1975 - 1991	17 years
37.	Tulung	1975 - 2008	34 years
38.	Wates	1975 – 1978, 1984 - 1996	17 years
39.	Wijil	1984 - 1998	15 years

Table 3. 8. Summary of rainfall data availability in the middle catchment of Bengawan Solo river basin

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1975				2239		2791		7214				3287	1760		2042	5368	2339		3385	3374
1976	1030	1406		1950		1382		3330	1314			1478	608		883	1912	1439		1225	2093
1977	1621	2149		3613		1609		2153	1285			1477	1225		1359	1178	1630		1151	1871
1978	2338	2899		4910		2581		2580	1990			2432	2338		2223	3792	2183		2685	3053
1979	1561	2046		4337					2113			2033			2484	2821			2770	2311
1980	1614	1790		1894					1618			1878			2006	3779			1814	1913
1981	2562	2273		2261					1957			1577			2143	2757			2862	3128
1982	1682	1567		1277					1466			1679			1899	1199			919	1353
1983	2347	2911	1902	2410					2006		1829			1982		3070			2611	2836
1984	2268	2946	2561	2268	2739	2053	3250	2447	2145	2542	2000		1121	2772		3629	2389		3057	2423
1985	1857	2599	2137	1595	2467	2544	1447	2339	1958	2040	2121		1831	2088		3273	1946	2746	1755	2055
1986	1695	4182	1838	1403	2462	2467	2388	2388	1798	2140	1841		1662	1924		4246	1857	1985	2649	1507
1987	1553	991	1434	1413	1928	2053	1678	1796	1352	1876	1342		2374	1620		1127	1388	2306	2114	1635
1988	1727	3696	1123	1519	2974	1851	2722	1703	1813		2030		1790	2142		1988	1851	1644	2060	1963
1989	1991	4723		1872		714	2182	2285	2200				4156			2945	1913	807	2809	1786
1990	2126	3503		1273		1336	1613	1834	1492				2208			2105	1417	1720	1789	1486
1991	2285	4076		1321		2259	2025	1808	1501				1655			2025	1558	1863	1887	1614
1992							2348	2735	2521				1947				1961		2691	
1993						1874	1965	1915	2034				2263				1313	1218	1926	
1994						1873	1415	2179	1924				1270				1770		1740	
1995						1602	3098	2649	1903				1174				1613		2052	
1996							1863	1746	1510				914				1206		2582	
1997							1151	1431	914										1500	
1998							2141	2959	2762										3489	
1999							2232	2031	1639										2513	
2000							3125	1815	1895										2378	
2001							3870	2488	1976										2679	
2002							1822	1915	1683										1989	
2003							2314	2251	1468										1669	
2004							2735	2033	1597										2072	
2005							1526	2299	1732										2069	
2006			1760				1443	2248	1362					2238					1563	
2007			2366				1633	2603	1988					3302					2234	
2008							1749	1924	2117										2074	

Table 3. 9. Annual rainfall at gauging stations no 1 – 20 in the middle catchment of Bengawan Solo River Basin

Note : The number in the top row of Table 3.9 indicates the number of station referred at Table 3.8.

Year	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
1975	2598	3915		3604	4050	3222	3502	1742	2773	3035	1672	2469	1691	3536	3466	3439	2669	2648	
1976	1511	2000		2538	1998	1256	2240	1004	1530	1347	1179	1460	1652	1719	1380	1624	1190	1388	
1977	2040	2152		2627	1995	1630	1330	702	1678	2610	1598	1984	1500	1433	2252	2248	1265	1327	
1978	2531	3202		3261	2623	3151	3253	2109	2606	3222	2319	1770	2982	3409	2690	3262	1877	2240	
1979	1825			3310		2205	2039	1351	2376	2365	1820	1646	2238	2867	2095	2137	1561		
1980	1245			2613		1969	1587	1584	1841	1693	1095	856	1794	2296	1612	940	1518		
1981	1610			2392		2994	3008	3126	2586	2392	1982	1883	3385	2857	2162	2326	1544		
1982	1763			1923		1755	1283	1615	1589	2587	886	1373	1396	1456	1791	1448	1135		
1983	1981	2860	1738	2135		2235	2125	3319	2182	2217	1998	2114	3022	2604	2894	2092	1506		
1984	2062	3100	1143	2243	2115	2493	2264	3190	2647	2016	1609	2346	2415	2244	2738	2240	1900	1927	3239
1985	2108	2139		2747	1719	2777	2982	3149	2004	1749	1332	1852	1785	2168	1744	1866	1501	1410	3034
1986	1969	2436	1611	2164	2547	3222	1649	3301	2478	1852	1273	1899	2590	1685	2276	1988	1966	1407	2916
1987	1714	1759	1419	2611	1923	1153	1636	2851	1551	1122	910	1539	1928	1709	1031	1999	1700	1534	611
1988	1865	955	1418	2224	1858	2457	1282	2437	1605	1562	672	1574	2437	1856	1473	2030	1072	1414	1147
1989	2416	3107		2507	2503	1947	2321	2742	619	2477	730	1769	2618	2299	2073	2294	2089	1709	2318
1990	2351	2473		2726	1771	2142	1972	2352	1660	2031	1022	1548	2121	1677	1881	2233	1504	1450	1701
1991	1802	2314		2153	2339	2112	1950	2224	1648	1897	1252	782	1663	2126	1733	2157	1576	1185	3225
1992	2453	3634		2342	3349	3390		3809	2612		1316	1303	3188		2360		2188	1901	3119
1993	2116	2902		2705	2015	2110		2130	2392		1131	1124	2712		1780		1819	1355	2155
1994	1563			1787	2554	1495		2117	1468		706	1140	1789		1375		1609	1237	1724
1995	2336	2935		2263	2865	2485						2124	2544		1903		1832	1478	2410
1996	2238	2553		1594	2230	1812						1153	2183		1690		1316	1049	2327
1997	1622	1598		780		1097						550	1150		1142		1090		1255
1998	3192	4034		1638		3034						1701	3516		2625		3157		3128
1999	2016	3270		1754		1645						1054	2361				1755		
2000	1873	2788		1867		3146						1840	2061				1818		
2001	2574	2688		1975		2994						2424	1828				3918		
2002	1959	2217		998		1942						2084	2078				1445		
2003	1957	1910		3181		1877						2179	1820				1920		
2004	2361	2432		2579		2089						2859	1508				1945		
2005	2285	2323				2340						2339	2076				1577		
2006	1817	2654	1527			1720		2261	1827		1778	2213	2143				1456		
2007	2224	3473	1414			2379		3178	3301			2486	2630				1938		
2008	1763	2591				1772						1426	2079				1994		

Table 3. 10. Annual rainfall at gauging stations no 21 – 39 in the middle catchment of Bengawan Solo River Basin

Note : The number in the top row of Table 3.10 indicates the number of station referred at Table 3.9.

No	Station's Name	Data availability	Notes
1.	Bojonegoro	1975 - 2007	33 years
2.	Doplang	1975 - 2008	34 years
3.	Gondang	1975 - 2006	32 years
4.	Karangbinangun	1980 - 2008	29 years
5.	Karanggeneng	1975 - 1999	25 years
6.	Lamongan	1975 - 2008	34 years
7.	Mundu	1985 – 2008	24 years
8.	Nglirip	1975 - 2008	34 years
9.	Ngliron	1984 – 1990, 1992 - 2008	24 years
10.	Pacal	1975 - 2002	28 years
11.	Padangan	1975 - 2005	31 years
12.	Sembung	1989 - 2008	20 years
13.	Tuder	1975 - 2008	34 years

Table 3. 11. Summary of rainfall data availability in the lower catchment of Bengawan Solo River Basin

Year	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1975	847	2119	1714		1454	2059		2886		2424	2901		1609
1976	959	1366	1028		1026	1068		1161		1182	930		628
1977	1017	1249	1303		1282	1379		1413		2712	1110		1326
1978	1040	2148	2180		1349	2142		1314		3166	1910		1756
1979	1089	1840	1170		1059	2208		1038		1949	1245		1432
1980	1236	1604	1098	1395	1040	1694		1899		2191	2163		2346
1981	1260	2972	1478	1897	1487	1284		1622		1512	1727		1254
1982	1326	3084	1208	963	841	737		1496		2057	1401		814
1983	1328	2318	974	1771	1392	1400		1700		2656	1957		2715
1984	1376	1982	1286	1979	1429	1503		2013	675	2234	1699		3407
1985	1381	1761	1226	1358	1188	1506	899	1466	1566	1795	1746		1014
1986	1425	1948	1894	1688	1551	1655	1765	2074	2056	2602	2175		910
1987	1494	2012	1940	1646	1267	1317	1039	1371	1562	1522	1678		883
1988	1498	1546	1305	1654	1116	1310	722	3618	1155	1937	1951		1138
1989	1541	1463	1685	2072	1294	1582	925	1662	1109	3067	1641	2405	1501
1990	1546	991	1595	1225	1032	1353	688	1652	351	2411	1240	1952	1433
1991	1599	1357	958	1229	891	1333	479	1214		2158	1450	1665	1071
1992	1601	1924	2001	1625	1213	1248	914	1074	859	2668	2451	2984	1243
1993	1616	1662	1600	1134	951	1061	686	1155	1002	2118	1312	2123	1237
1994	1623	1412	1712	1324	1267	1313	768	1160	1031	1961	1159	2049	1050
1995	1667	1876	1912	2221	2314	1828	1011	1510	971	2488	1652	2204	1420
1996	1687	2394	2136	1510	1440	1737	1499	1308	1317	2150	1257	1256	1195
1997	1725	1107	1234	1386	1283	1645	948	903	630	1367	898	1276	1278
1998	1730	1959	2183	2110	2450	1936	3085	1814	1031	3847	1761	2394	1863
1999	1778	1888	2061	1519	1928	1863	2585	1462	795	2307	2133	2022	1908
2000	1917	1466	2288	1716		1622	1290	1209	1265	1710	2062	2075	1369
2001	1944	1742	1686	1628		1913	1500	1087	731	2061	1898	1899	1536
2002	1967	1198	1354	1267		1149	1470	768	537	836	1519	1621	1234
2003	2077	1127	1481	986		1241	1195	767	503		1757	1536	1179
2004	2161	1198	1776	1269		1328	1276	699	518		1079	1515	1780
2005	2447	1121	1926	1655		1576	1611	952	689		1511	1723	1711
2006	2491	757	1166	1095		1165	1527	681	436			1348	1237
2007	2540	1152		587		1010	1031	969	815			957	808
2008		1166		995		706	1784	1045	847			1152	1276

Table 3. 12. Annual rainfall at gauging stations in the lower catchment of Bengawan Solo River Basin

Note : The number in the top row of Table 3.12 indicates the number of station as referred at Table 3.11.

Since there are significant gaps in some rain gauging stations, hereinafter this research only considers the rain gauging stations with complete data. This research applies SHETRAN to simulate and compare the discharge in the research location. The precipitation data used in SHETRAN simulation for this research are *in situ* data available at preferred stations in the Upper Bengawan Solo catchment with complete record. The first SHETRAN simulation will use rainfall data from 17 rain gauging stations in Upper Bengawan Solo catchment during the period 1983 – 1986.

3.1.2. Recorded water level and discharge data

Along the Bengawan Solo River, there are 25 AWLRs (automatic water level recorders) set up by the government. However, the data recorded is not satisfactory, as only a few stations have complete data. Table 3.12 below shows the summary of AWLR stations with recorded data along the river.

No	Station's Name	Data availability	Notes
1.	Jarum	1978 – 1986, 1989 – 1993, 1995 - 1999	Many months gaps.
2.	Jurug	1976 – 1987, 1990 - 2009	Gaps from June 1987 to December 1989.
3.	Kajangan	1976 - 1998	
4.	Napel	1975 - 2008	
5.	Ngrembang	1975 – 1999, 2006 – 2007, 2008	In 2008 only up to May.
6.	Peren	1983 – 1990, 1994 – 1997, 2007	
7.	Serenan	1989 – 1997, 1999 - 2008	Many months gaps.
8.	Arjo Winangun	1976 – 1984, 1987 – 1999, 2007 – May 2009	
9.	Bendo	1985 – 1990, 2007, Jan – May 2009	
10.	Ketonggo	July 1981 – March 1987, 1988 – April 2009	
11.	Sekayu	1975 – April 2009	
12.	Babat	1975 - 2006	
13.	Blawi	1992 - 2007	Many months gaps.
14.	BobohLamong	1988 – 1999, 2007	Many months gaps.
15.	Bojonegoro	1976 - 2008	
16.	Brangkal	1982 - 2008	Many months gaps.
17.	Cepu Dengok	1976 - 2008	
18.	Karangnongko	1975 - 2008	
20.	Kuluran	1992 - 2008	
21.	Napel	1975 - 2008	

Table 3. 13. Summary of data availability at AWLR stations in Bengawan Solo River Basin

The figures below show the average recorded water level at Jurug station in 4 periods, which are 1980 – 1984, 1985 – 1989, 1990 – 1994, and 1995 - 2000. The catchment area of Jurug gauging station is about 3850 km^2. These periods are those in which the observed discharge data will be compared to simulated discharge resulted from SHETRAN simulation (described further in the next chapter). The periods have been chosen with regard to the completeness of rainfall data in the research location as described previously.

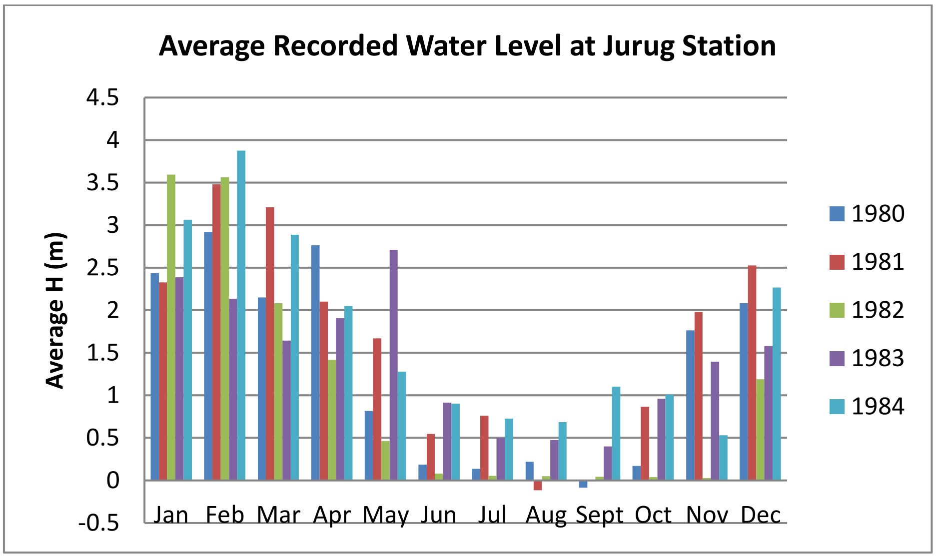


Figure 3. 5. Average recorded water level at Jurug Station 1980 – 1984

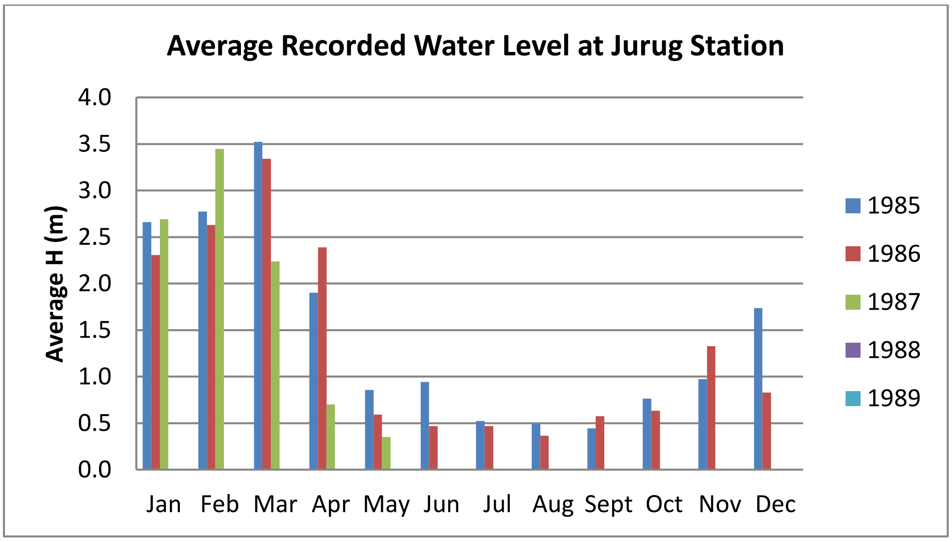


Figure 3. 6. Average recorded water level at Jurug Station 1985 – 1989

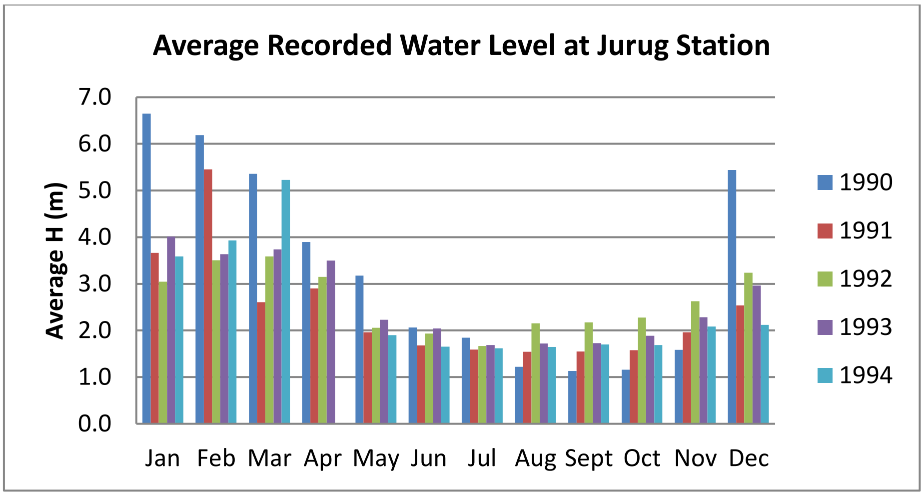


Figure 3. 7. Average recorded water level at Jurug Station 1990 – 1994

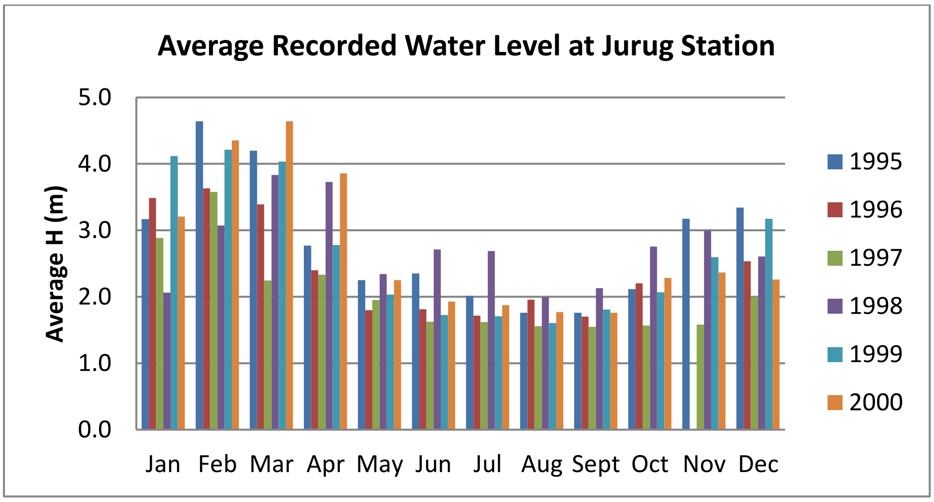


Figure 3. 8. Average recorded water level at Jurug Station 1995 – 2000

Figure 3.9 below shows the observed annual discharge at Jurug Station in 1976 – 2009.

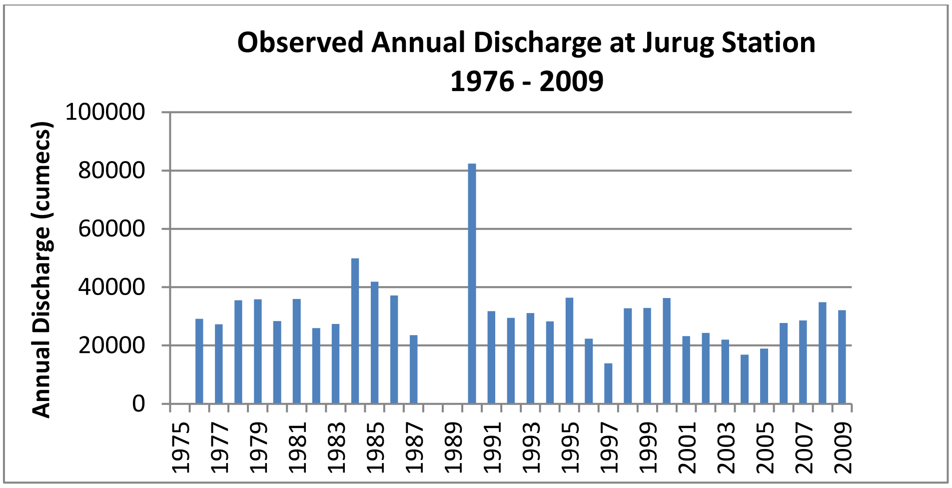


Figure 3. 9. Chart of observed annual discharge at Jurug Station

As can be seen in Figure 3.9, there are missing discharge data in 1988 and 1989, whereas the annual discharge recorded in 1990 is higher than the other years (almost double). In 1987, the water level data was recorded up to May 1987 only, and there was no water level data recorded in the remaining months in the year. During 1988 – 1989, there is no water level data recorded, therefore the discharge cannot be derived. The unavailability of water level data in 1988 – 1989 might be caused by damaged gauge. Moreover, the higher annual discharge in 1990 might be caused by rising river bed due to siltation or there was a problem with the gauge. This needs to be checked in the future for further research.

The discharge in the gauging stations was obtained by calculation using rating curve available for each station. However the rating curve is only available for the limited period. The rating curves used to derive the discharge at Jurug station are presented in the table below.

Year	Rating Curve Equation
1979 - 1983	$Q = 16.588 * (h + 0.552)^{1.9241}$
1984 – May 1987	$Q = 41.03156 * (h + 0.27655)^{1.54075}$
1990 - 1991	For $h \leq 2.4$, $Q = (6.067h – 6.432)^2$ For $h \geq 2.4$, $Q = (4.076 – 1.103)^2$
1992 - 2000	For $h < 2.4$, $Q = 27.89 * (h – 1.078)^2$ For $h > 2.4$, $Q = (4.116h – 2.362)^2$

Table 3. 14. Summary of rating curve used at Jurug Station

The mean and standard deviation of recorded water level at Jurug station for period of 1980 – 2000 can be seen in Table 3.15 below. In 1987, the record of water level at Jurug station was only up to May 1987. During period of 1988 – 1989, there was no water level recorded at Jurug gauging station.

Year	Mean (m)	Standard Deviation (m)
1980	1.29	1.31
1981	1.60	1.36
1982	1.04	1.49
1983	1.41	1.01
1984	1.69	1.31
1985	1.46	1.25
1986	1.32	1.18
1987	-	-
1988	-	-
1989	-	-
1990	3.30	2.20
1991	2.40	1.21
1992	2.62	0.94
1993	2.61	1.10
1994	2.46	1.29
1995	2.78	1.15
1996	2.42	0.86
1997	2.03	0.76
1998	2.74	0.91
1999	2.65	1.16
2000	2.71	1.29

Table 3. 15. Mean and standard deviation of recorded water level at Jurug Station 1980 – 2000

The chart and table below respectively show the annual discharge and statistics of flow data at Kajangan station which is situated downstream of Jurug station. The water level data in Kajangan station is available from year 1980 – 1989.

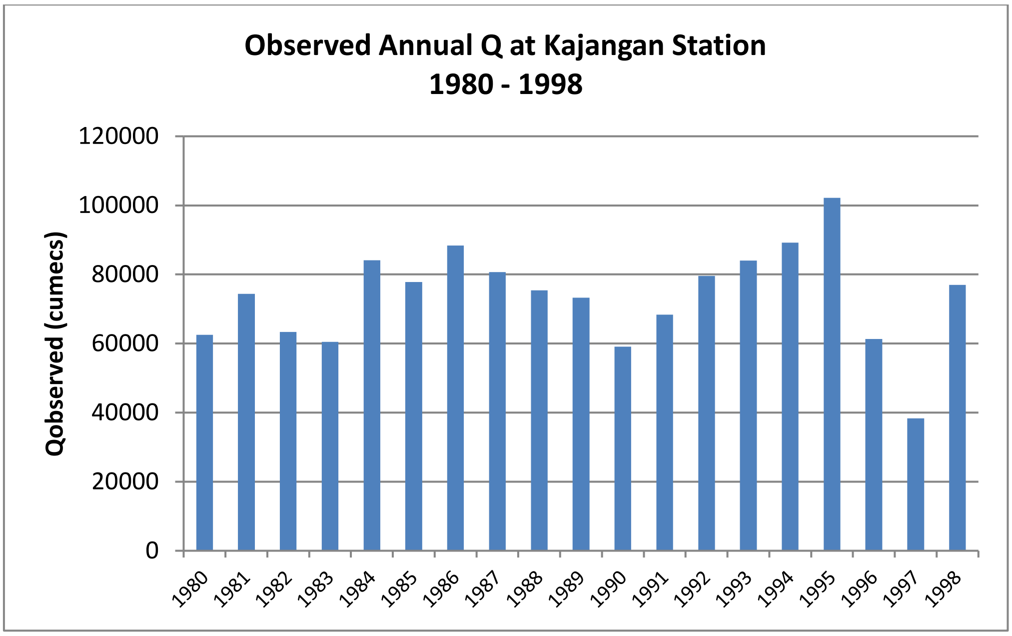


Figure 3. 10. Annual discharge at Kajangan Station in 1980 – 1998

Year	Mean (m)	Standard Deviation (m)
1980	1.96	1.27
1981	2.21	1.26
1982	1.82	1.51
1983	2.06	1.02
1984	2.33	1.36
1985	2.24	1.33
1986	2.21	1.34
1987	1.99	1.50
1988	2.05	1.23
1989	2.08	1.14
1990	1.89	1.16
1991	1.91	1.30
1992	2.20	1.16
1993	2.23	1.23
1994	2.15	1.48
1995	2.46	1.33
1996	2.16	1.01
1997	1.57	1.07
1998	2.49	1.00

Table 3. 16. Mean and standard deviation of recorded water level at Kajangan Station

The discharge data at Kajangan station will be used to correct the discharge data at Jurug station which seems to be wrongly derived.

3.1.3. Land use data

The land use in Bengawan Solo River Basin consists of rice paddy field, human settlement (both in rural and urban area), grass and bushes, forest, and critical land (bare ground). The land use map was obtained from Directorate or Water Resources, Ministry of Public Work. The year of the data is 2006.

The land use pattern in the river basin can be seen in Figure 3.11.

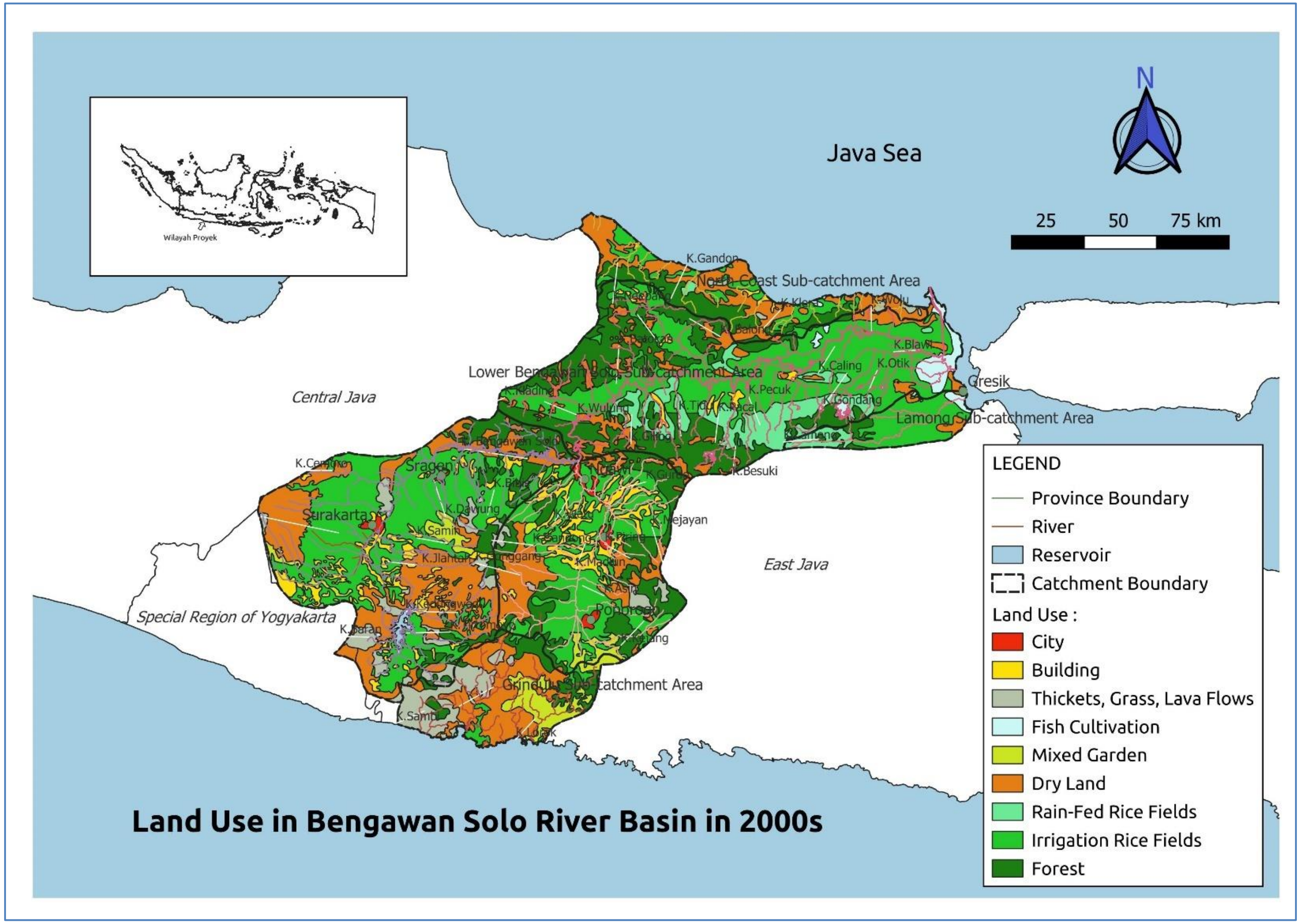


Figure 3. 11. Land use map of Bengawan Solo River Basin (source: redrawn from Directorate of Water Resources, Ministry of Public Work, Indonesia Government, 2006)

For the SHETRAN simulations, the catchment of Jurug station in Upper Bengawan Solo catchment was chosen as the area for simulation: this decision was based on the completeness of the in situ data in the catchment. Details of the SHETRAN simulation methodology in this research will be explained further in Chapter 5 and Chapter 6.

3.1.4. TRMM data

A joint space mission between NASA and Japan's National Space Development Agency called the *Tropical Rainfall Measuring Mission* (TRMM) is intended to observe and study tropical and subtropical rainfall and the associated release of energy. Instruments used by TRMM are precipitation radar (PR), TRMM microwave imager (TMI), visible and infrared scanner (VIRS), cloud and earth radiant energy sensor (CERES), and lightning imaging sensor (LIS).

According to NASA, the spatial and temporal variation of tropical rainfall around the globe is one of the critical unsolved problems of meteorology. The tropics and subtropics regions contribute about two thirds of the total rainfall on earth and are responsible for driving the weather and climate system (NASA, 1997). TRMM provides frequency distributions of rainfall intensity and areal coverage, the partitioning of rainfall, the vertical distribution of hydrometeors, variation of heaviest rainfall's timing, and diurnal intensification of orographically and sea-breeze forced systems over land. TRMM also enables the mapping of larger time and space variations of rainfall. In addition, the critical onset of large annual circulation systems such as the Asian Monsoon can be more comprehensively studied.

The free downloadable data products from TRMM can be distinguished into orbital products and gridded products, as summarized in Table 3.16 below.

Orbital Products	Gridded Products
1B01 Visible and Infrared Radiance	3A11 Monthly 5° x 5° Oceanic Rainfall
1B11 Microwave Brightness Temperature (TMI)	3A12 Monthly 0.5° x 0.5° mean 2A12, profile, and surface rainfall
1B21 Precipitaion Radar (PR) Power	3A25 Monthly 5° x 5° and .5° x .5° Spaceborne Radar Rainfall
1C21 Precipitation Radar (PR) Reflectivity	
2A12 TMI Hydrometeor Profile	3A26 Monthly 5° x 5° Surface Rain Total
2A21 Precipitation Radar (PR) Surface Cross-Section	3B31 Monthly 5° x 5° Combined Rainfall
	3A46 Monthly 1° x 1° SSM/I Rain
2A23 Precipitation Radar (PR) Rain Characteristics	3B42 3-hour 0.25° x 0.25° TRMM and Other-GPI Calibration Rainfall
2A25 Precipitation Radar (PR) Rainfall Rate and Profile	3B43 Monthly 0.25° x 0.25° TRMM and Other Sources Rainfall
2B31 Combined Rainfall Profile (PR, TMI)	CSH Monthly 0.5° x 0.5° Convective & Stratiform Heating

Table 3. 17. Data products from TRMM (source : NASA)

Since the cross correlation between rain gauging stations in this research location is not good enough as described previously, this research will also use TRMM 3-hourly precipitation data (3B42) to compare with in situ rainfall data, and will be described further in Chapter 6.

3.2. Existing Conditions in Bengawan Solo River Basin

3.2.1. Environmental conditions

According to Kompas (2008), Bengawan Solo river basin has been degraded from the upstream area to downstream. The basin degradation is caused by several factors, such as reduction of forest area, low vegetation cover to prevent erosion in upstream area, conversion of land use, and uncontrolled waste disposal.

Figure 3.12 shows the garbage which was blocked the sluice-gate in a weir located at upper Bengawan Solo catchment.

Figure 3. 12. Solid waste blocking the weir in the upper reach of Bengawan Solo River (source : Surakarta Public Work Agency)

Moreover, the slope in upper Bengawan Solo river basin is considerably steep. Unfortunately, the forest area is diminishing significantly, and has changed to either bare ground, agricultural field (for cassava plantation etc.), or human settlement. This condition leads to increase land erosion and sedimentation in the river which influence the river capacity to run the water during the rainy season. To reduce the rate of land erosion, the local government actually has implemented reforestation in upper area of Bengawan Solo River Basin after big flood event in 2007. Unfortunately, the reforestation program has not been successful because the trees are being ignored, therefore the trees do not grow well. The local community who are mostly poor prefer to take care of their own seasonal vegetable to support their daily life rather than maintaining the trees planted for reforestation.

Figure 3.13 below presents the slope condition in upper catchment.

Figure 3. 13. Slope condition in upper catchment of Bengawan Solo River Basin (source : Directorate Water Resources and Irrigation, National Development Planning Agency of Republic Indonesia, 2013)

3.2.2. Social conditions

According to the *Indonesian Central Bureau of Statistics*, the Bengawan Solo river basin had a population of some 16.4 M in 2012, with population density about 1,028 people / km^2. High population growth impacts on social and economic aspects, for example leads to urbanisation, industrialisation, and increases demand on housing, foods as well as water supplies. This situation has radically altered the land and water resources situation in the Bengawan Solo river basin.

Recently, it has become common that rice paddy fields in some regions have been re-developed into built areas such as housing, shopping mall or industrial area. Furthermore, in the upstream area, the forest area has been diminished and converted into agricultural area or housing. In response, the government of Indonesia has published regulations regarding natural resources management including land and water resources. For example, Regulation No.7/2004 about water resources management, government regulation PP No. 38/2011 about river management, Regulation No.18/2008 about waste management, and Regulation No.2/2012 about land use management. However, these regulations have not been effectively implemented and the situation is further aggravated by inadequate law enforcement.

3.3. Research Methodology

In the following chapters, this research applies statistical methods to characterise and investigate the properties of the extreme rainfall and discharge events in the basin. The L-moments approach is applied to assess the extreme rainfall event distribution and magnitude and maximum discharge at preferred gauging stations in a selected period. Changes in observed extreme or average precipitation could be caused by climate change, so change point analysis will be used to identify and diagnose any abrupt changes. Simulation using the SHETRAN model is also implemented to analyse the flood regime for different land use patterns in the selected sub-catchment. The research methodology is briefly explained in this chapter. Further details of the application and results of the applied methodology is described in the following chapters.

3.3.1. Assessment of annual maximum daily rainfall and discharge

Statistical modelling using Generalized Extreme Value (GEV) distribution has been widely applied for research in hydrology e.g. Villarini, (2011), who applied the GEV distribution to analyse the annual maximum daily rainfall and discharge at preferred gauging stations in certain periods.

If we consider the random variable X is the annual maximum daily rainfall for stations without statistically significant change points in mean and variance, the cumulative distribution function of GEV can be written as :

$$\mathrm{F}(\mathrm{x}|\mu,\sigma,\xi) = exp\left\{-\left[1+\ \xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} \qquad \textbf{(3.3)}$$

Where μ is the location parameter, σ is the scale parameter, and ξ is the shape parameter. The location parameter (μ) is related to the magnitude of the record. The scale parameter (σ) is related to the record variability and the shape parameter (ξ) provides information about the heaviness of the tail of the distribution. The larger value of ξ, the heavier of the tail, therefore the more likely extreme events are to occur (Malamud, 2004; Resnick 2006).

The parameters of GEV distribution are estimated here using the L-moments approach as pioneered by Hosking (1995).

According to Hosking (1995), L-moments are a modification of probability weighted moments. If the data values X_1, X_2, X_3,..., X_n are arranged in increasing order, then sample probability weighted moments are given by :

$$b_0 = n^{-1} \sum_{j=1}^{n} X_j \quad \textbf{(3.4)}$$

$$b_r = n^{-1} \sum_{j=r+1}^{n} \frac{(j-1)(j-2)\ldots(j-r)}{(n-1)(n-2)\ldots(n-r)} X_j \quad \textbf{(3.5)}$$

Hosking (1995) also explained that *L*-moments are linear combinations of probability weighted moments that have simple interpretations as measures of the location, dispersion and shape of the data sample. The first few *L*-moments according to Hosking (1995) are defined by :

$$l_1 = b_0 \quad \textbf{(3.6)}$$

$$l_2 = 2b_1 - b_0 \quad \textbf{(3.7)}$$

$$l_3 = 6b_2 - 6b_1 + b_0 \quad \textbf{(3.8)}$$

$$l_4 = 20b_3 - 30b_2 + 12b_1 - b_0 \quad \textbf{(3.9)}$$

The first *L*-moment, l_1 , is the sample mean which is a measure of location. The second one, l_2 , is Gini's mean difference statistic which is a measure of the dispersion of the data values about their mean.

The *L*-moments ratio can be obtained by dividing the higher order *L*-moments by the dispersion measure l_2 as formulated as follows:

$$t_r = \frac{l_r}{l_2} \quad \textbf{(3.10)}$$

A measure of skewness is t_3, and kurtosis is t_4 which are respectively described as *L*-skewness and *L*-kurtosis. Furthermore, the L-moment that is similar to the coefficient of variation is defined as L-CV which is formulated as :

$$t = \frac{l_2}{l_1} \quad \textbf{(3.11)}$$

Probability weighted moments for probability distribution with cumulative distribution function F(x) are defined by :

$$\beta_r = \int x \{F(x)\}^r \, dF(x), \qquad r = 0, 1, 2, \ldots \quad \textbf{(3.12)}$$

L-moments for probability distribution are described as follows :

$$\lambda_1 = \beta_0 \quad \textbf{(3.13)}$$

$$\lambda_2 = 2\beta_1 - \beta_0 \quad \textbf{(3.14)}$$

$$\lambda_3 = 6\beta_2 - 6\beta_1 + \beta_0 \quad \textbf{(3.15)}$$

$$\lambda_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0 \quad \textbf{(3.16)}$$

In addition, the *L*-moments ratio is calculated using the equation below :

$$\tau_r = \frac{\lambda_r}{\lambda_2} \quad \textbf{(3.17)}$$

3.3.2. Change point analysis

This research also carries out change point analysis to assess the maximum rainfall and discharge. According to Villarini *et al* (2011), change point analysis provides a tool to check the presence of abrupt changes in the distribution of the variable under study. Several previous studies summarized by Villarini *et al* (2011) indicated that climate change as well as anthropogenic effects such as changes in measuring procedure or gauge relocation could trigger the abrupt changes. This research applies the Pettitt test to check the presence of change points in the mean of the data. The Pettitt test has been successfully used in previous studies as summarized by Villarini *et al* (2011). Pettit test detects change points in mean at an unknown point in time. Villarini *et al* (2011) reported that the main benefits of this test are that it is less sensitive to outliers and skewed distributions, and the test significance can be calculated.

Further explanation of the application of change points analysis in this research will be described more detail in the next chapter.

3.3.3. SHETRAN simulation

SHETRAN is a finite-difference 3D coupled surface/subsurface physically based spatially distributed (PBSD) model for coupled water flow, multifractional sediment transport, and multiple, reactive solute transport in river basins (Ewen et al., 2000). SHETRAN has been developed within Water Resources Systems Research Laboratory, School of Civil Engineering and Geosciences, University of Newcastle upon Tyne, United Kingdom. Ewen et al. (2000) explained that SHETRAN is built around three main components: water flow, sediment transport, and solute transport. Because flow is assumed to be unaffected by transport and sediment transport is assumed to be unaffected by solute transport, the three components are arranged in a natural hierarchy.

SHETRAN represents water movement through a river basin as an integrated surface and subsurface representation, involving the main components of the land phase of the hydrological cycle such as interception, evapotranspiration, snowmelt, overland and channel flow, unsaturated and saturated zone flow. Each hydrological process is represented by a finite difference formulation of partial differential equations of mass and energy conservation, or by an empirical equation obtained from independent empirical studies. The horizontal spatial distribution of catchment parameters, rainfall input, and hydrological reaction is achieved by representing the catchment with an orthogonal grid network, and the vertical spatial distribution is obtained by a column of horizontal layers at each grid square (Mellor et al., 2000). Figure 3.14 presents the illustration of processes in SHETRAN model.

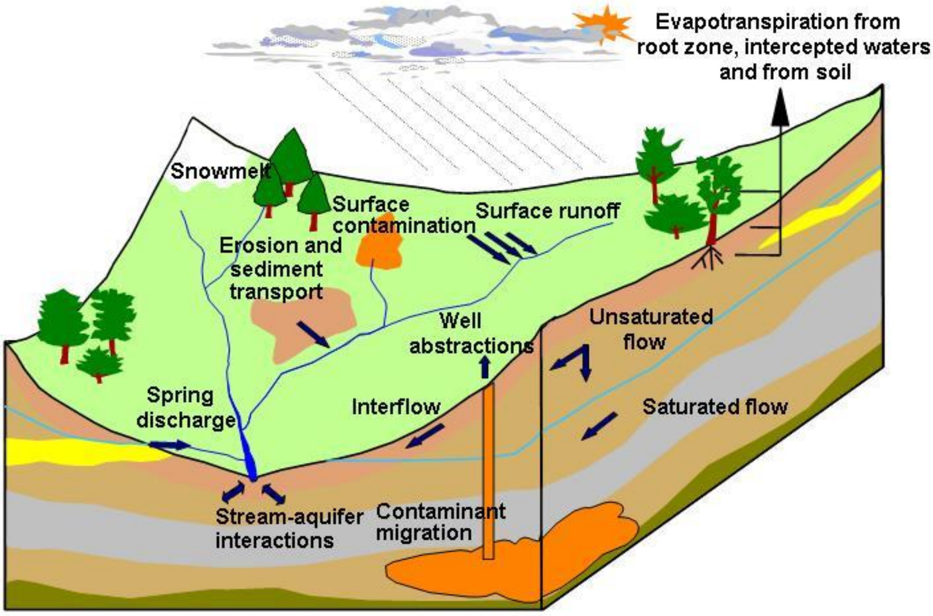


Figure 3. 14. SHETRAN Processes (source: https://research.ncl.ac.uk/shetran/index.htm)

The following are the data to be considered to apply SHETRAN model in the simulation of water flow (Ewen et al., 2000):

a) Each station's rainfall and meteorological data.
b) Each column and river link's station number.
c) Dimensions and placement of columns, river links, and finite-difference cells.
d) Each column's soil/rock types and depths;
e) Each column's land-use/vegetation
f) Channel flow diversions and discharges controlled by humans
g) Borehole pumping rates, artificial recharge rates, flow diversions, and so on
h) Subsurface initial hydraulic potentials
i) Overland and channel flow depths at the start
j) The initial thicknesses and temperatures of the snowpack
k) Limit hydraulic potentials (or flow rates)
l) Limit stream inflow rates
m) Parameters for canopy drainage and storage capacity.
n) fractions of ground cover
o) Resistances to canopy and aerodynamics (for PME)

p) The distribution of root density in vegetation over depth
q) Soil/rock porosity and specific storage
r) Soil/rock matric potential functions
s) Soil/rock unsaturated hydraulic conductivity functions
t) Soil/rock saturated hydraulic conductivity
u) Snow density, zero-plane displacement, and roughness height are all variables to consider.

This research implements the SHETRAN model to simulate the water flow/discharge in chosen catchment area. In applying SHETRAN simulation, the parameter data required are land use data, soil data, and DEM. Moreover, the simulation also needs input data including rainfall and potential evaporation (PET).

The catchment upstream of the Jurug gauging station is chosen as simulation area for SHETRAN in this research. Figure 3.15 below shows the percentage of land use type in Jurug station catchment area.

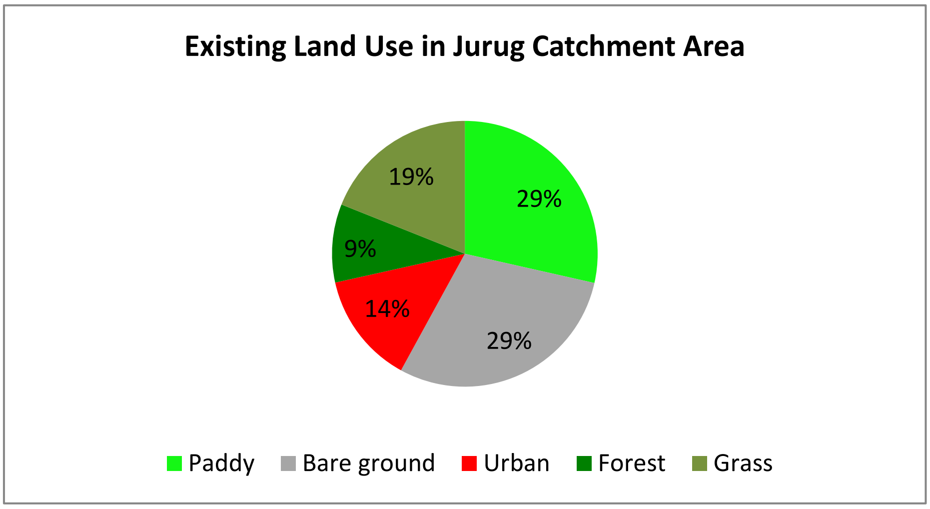


Figure 3. 15. The percentage of existing land use at Jurug Catchment

Figure 3.16 shows the Jurug gauging station catchment area and its existing land use pattern based on data from 2009. For the SHETRAN simulation, the codes for rice paddy, bare ground, urban, forest and grass are 1, 2, 3, 4, and 5 respectively, which is illustrated with colours light green, grey, red, green, and olive green as shown in figure below.

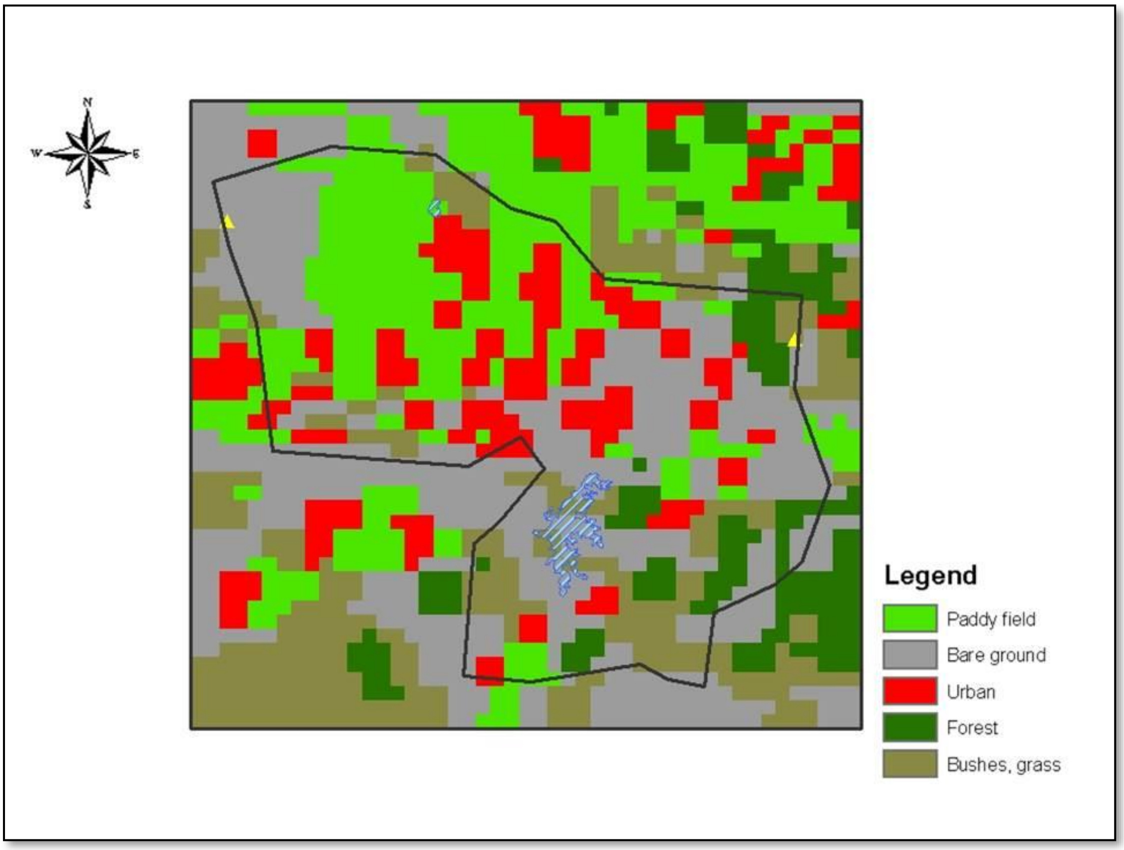


Figure 3. 16. Pattern of land use at Jurug catchment for SHETRAN simulation

Furthermore, different hypothetical land use scenarios are applied in the SHETRAN simulation to investigate the impact of land use change on peak discharge. The hypothetical land use scenarios are applied because there is no future land use plan available in Bengawan Solo river basin.

3.4. Summary

This research requires some data such as rainfall, water level, land use data as well as social and environmental data. The data required in this research is available, however there are some weaknesses, such as long data gaps in rainfall data; limited land use data; unsatisfactory cross correlation between gauging stations; and limited water level data and its rating curve equation.

Change point analysis of extreme (maximum) rainfall using Pettit test and trend analysis using Mann-Kendall test are applied in this research. Moreover, GEV and Gumbel distributions are used to estimate the frequency of maximum rainfall and discharge in selected return period, i.e. 2, 5, 10, 25, and 50 years return period. The detail of maximum rainfall analysis is described in Chapter 4.

SHETRAN simulation is applied to investigate the impact of land use change on discharge. The rainfall inputs for SHETRAN simulation in this research are in situ rainfall data and 3-hourly TRMM data in selected period (1998 – 2000). Different hypothetical land use scenarios are applied in the SHETRAN simulation to investigate the impact of land use change on discharge. Further detail explanation about the application of SHETRAN simulation in this research will be described in Chapter 5, Chapter 6, and Chapter 7.

Chapter 4. Maximum Rainfall and Discharge Analysis

Rainfall is widely recognised to be one of the climate variables subject to the Croitoru *et al* (2013) In the context of flood risk management, the analysis of extreme events is crucial (e.g. Segond, 2006) and as Begueria *et al* (2005) reported, high magnitude rainfall represents the primary natural hazard in many parts of the world. Croitoru *et al* (2013) summarized some results showing that changes in extreme climatic events are likely to have greater impact on society, the economy, and the environment than changes in mean values. Moreover, extreme rainfall usually generates extreme hydrological events such as flood and drought, and affects human and natural systems (Bartholy *et al*, 2007; Croitoru *et al*, 2013). Furthermore, Adnan and Atkinson (2010) reported that flooding is likely to increase in Kelantan, Malaysia (in a similar climatic regime to that studied here), due to changes in rainfall and land use.

This chapter describes the analysis of maximum daily rainfall in selected gauging stations to investigate the abrupt change in the Upper Bengawan Solo catchment.

The summary of data availability in the river basin has been described previously in Chapter 3. Taking into account the completeness of the data, the rain gauging stations used as reference stations in the analysis of extreme rainfall in this research are 6 stations located in the Upper Bengawan Solo catchment, namely Baturetno, Klaten, Pabelan, Nawangan, Nepen, and Tawangmangu. Figure 4.1 below shows the location of the rain gauging stations in the Upper Bengawan Solo catchment.

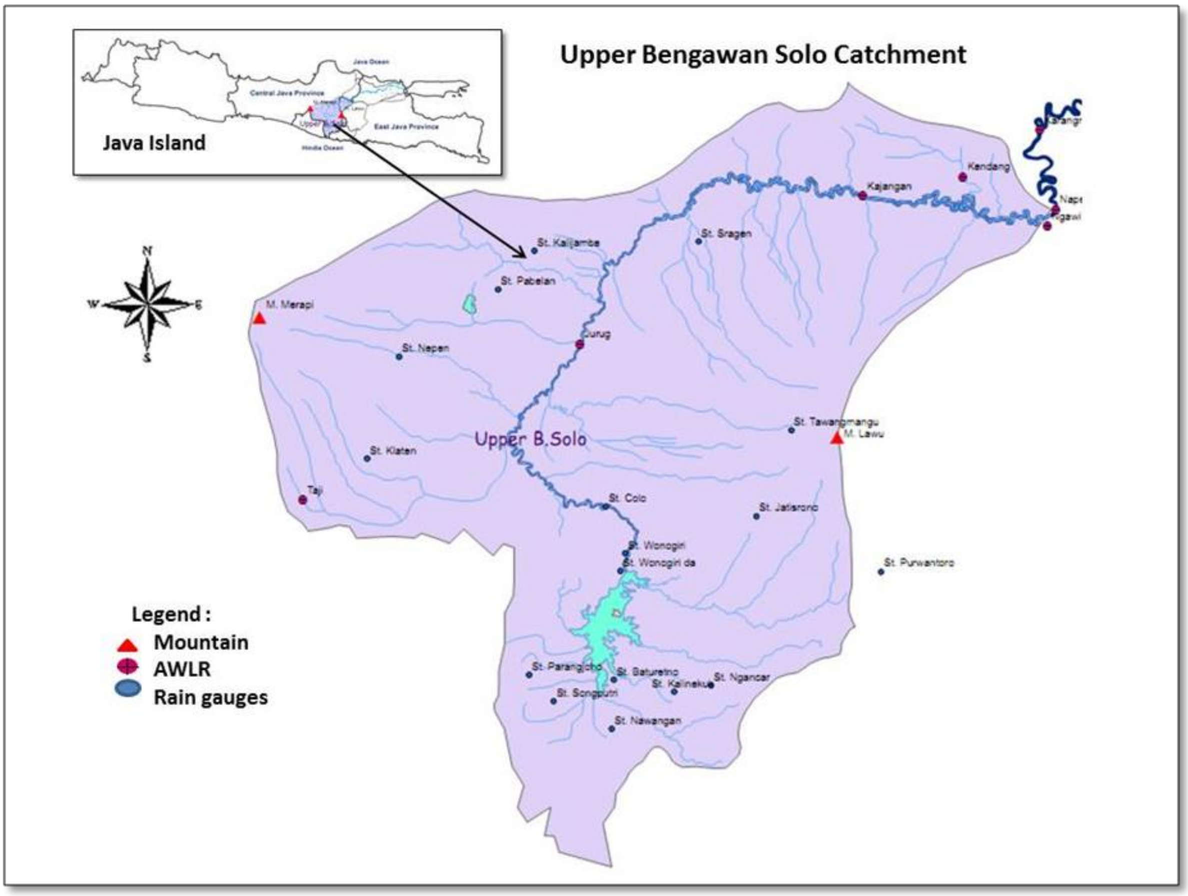


Figure 4. 1. Location of rain gauging and AWLR stations in the Upper Bengawan Solo Catchment (source: processed using the data from River Research Center)

4.1. Maximum Daily Rainfall of Selected Gauging Stations in Upper Bengawan Solo Catchment

Based on the explanation in Chapter 3 that there are some data gaps in some stations, the rainfall data used in this analysis is the maximum daily rainfall in 6 selected rain gauging stations with complete record in years 1979 – 2009.

Figure 4.2 – 4.8 below show the series of monthly maximum daily rainfall at the selected stations in the Upper Bengawan Solo Catchment. Table 4.1 and Table 4.2 show the annual maximum daily rainfall at the selected stations and the date of the highest maximum daily rainfall occurred at the selected gauging stations in the study area.

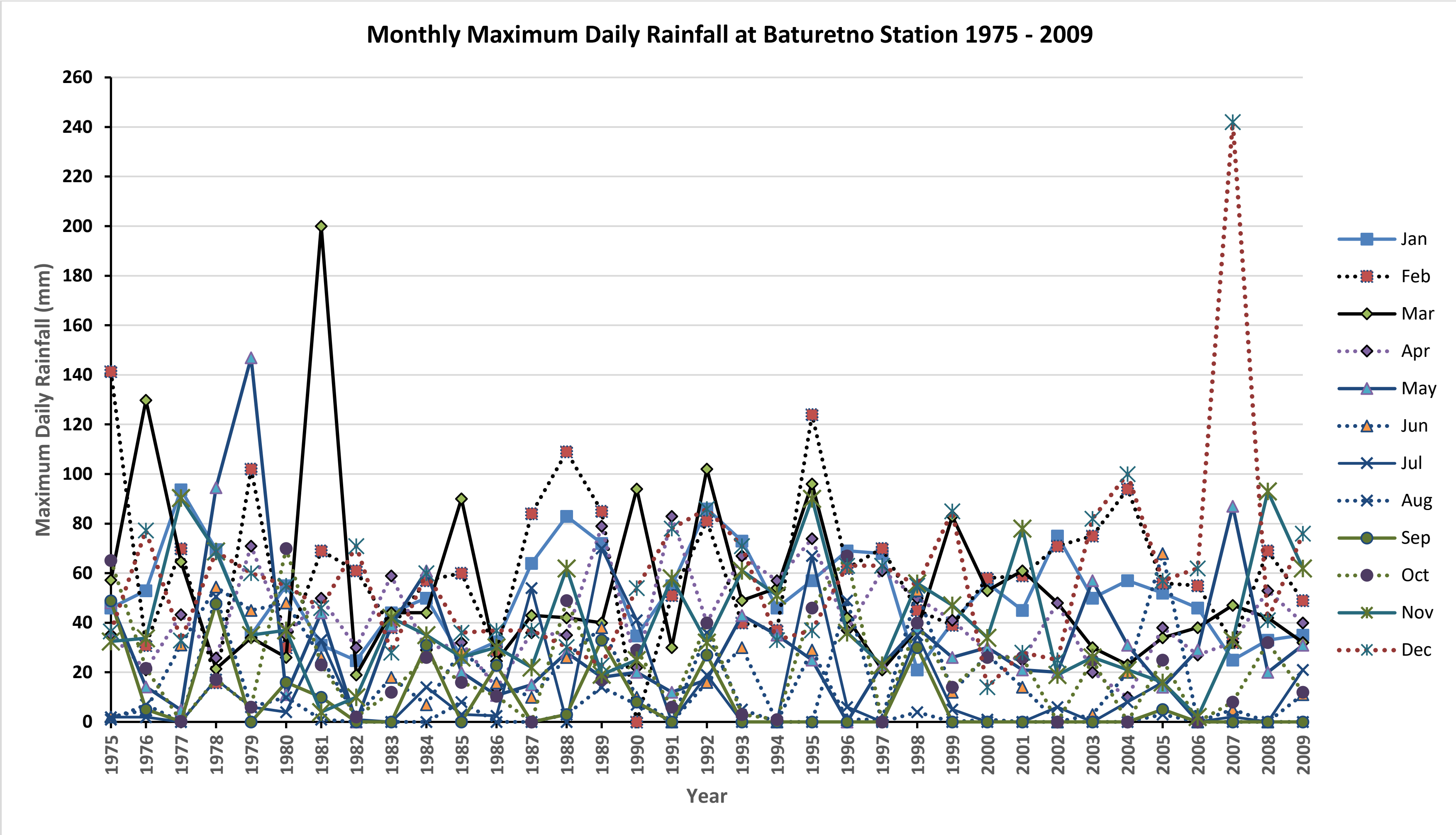


Figure 4. 2. Monthly Maximum Daily Rainfall at Baturetno Station in 1975 - 2009

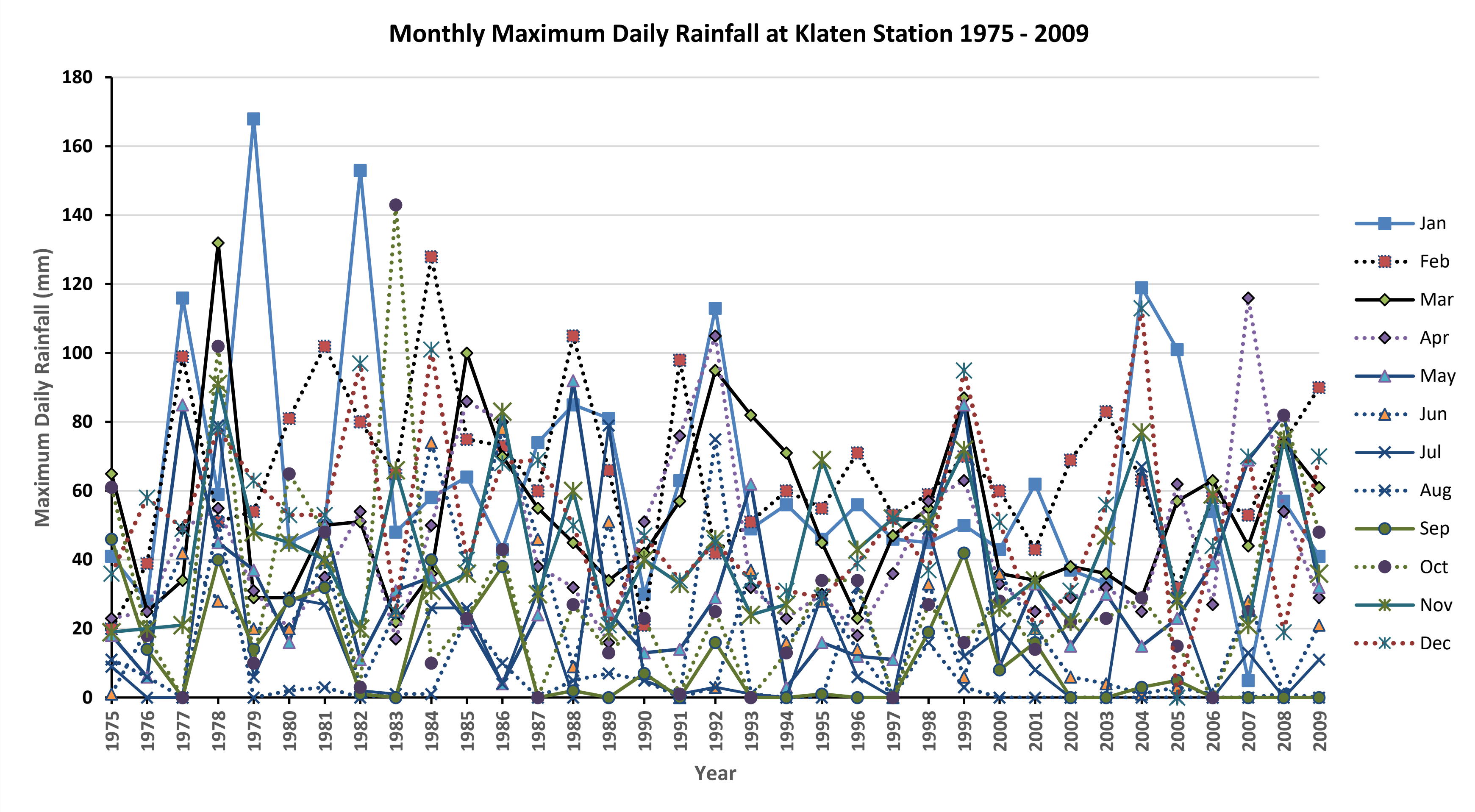


Figure 4. 3. Monthly Maximum Daily Rainfall at Klaten Station in 1975 - 2009

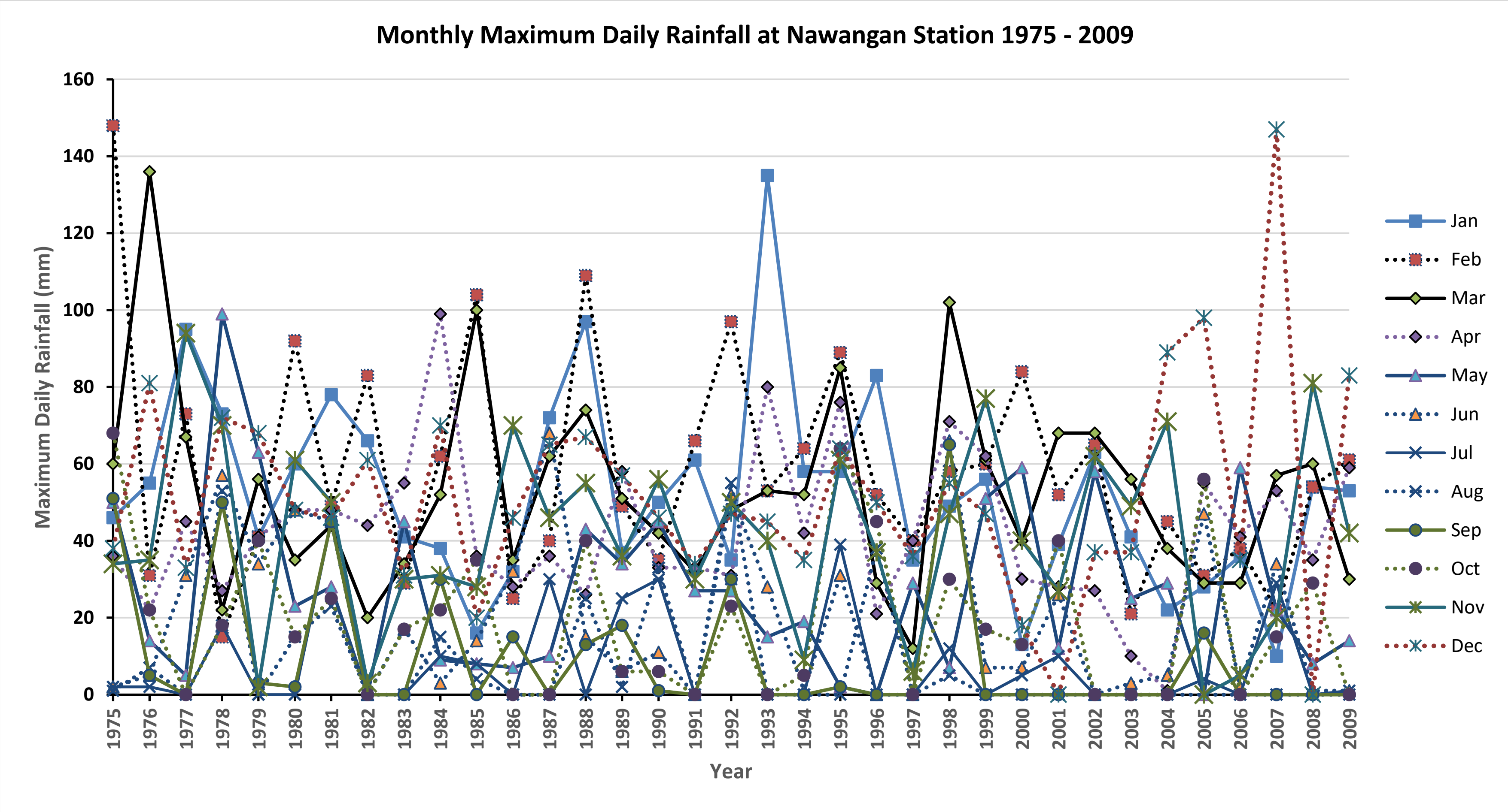


Figure 4. 4. Monthly Maximum Daily Rainfall at Nawangan Station in 1975 - 2009

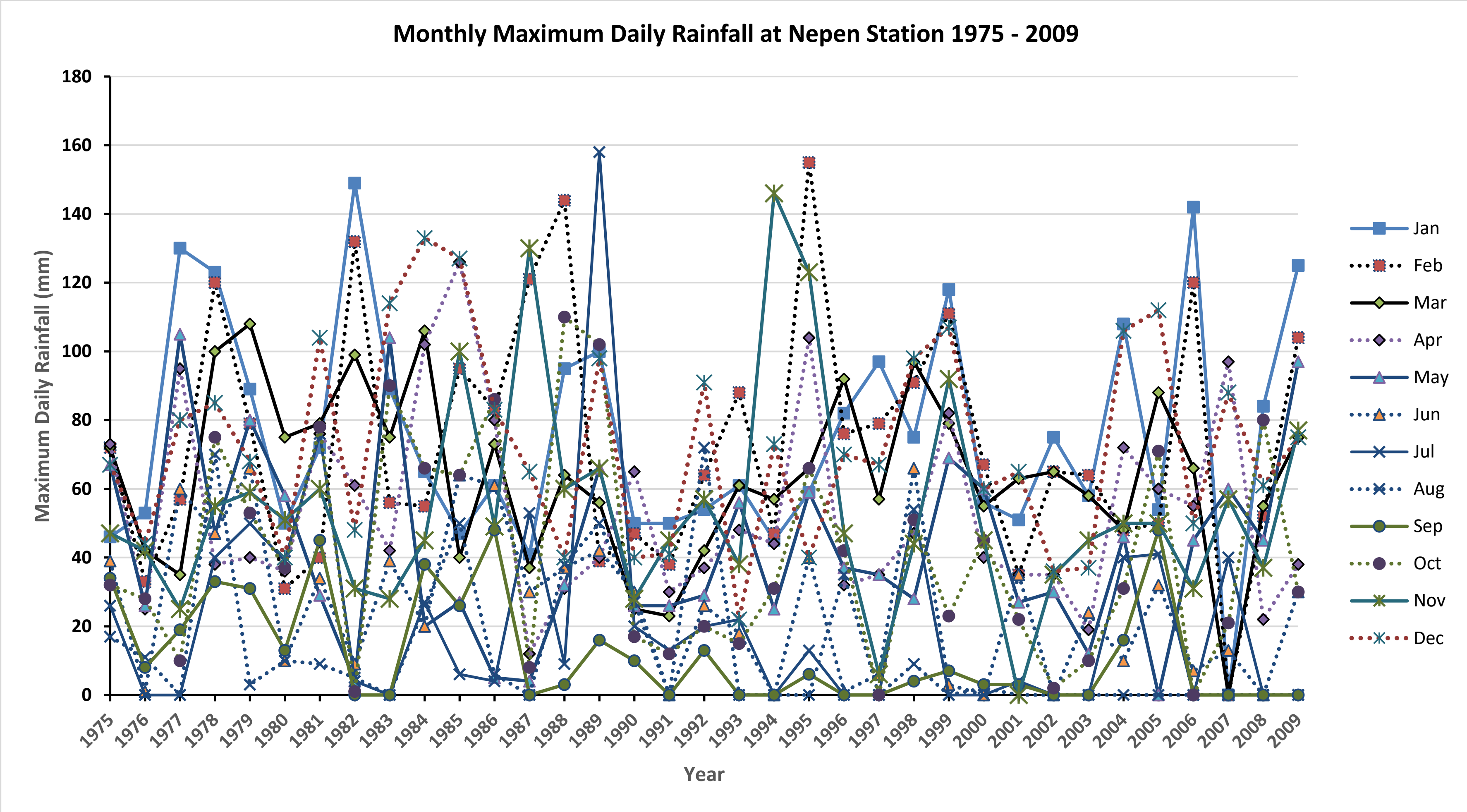


Figure 4. 5. Monthly Maximum Daily Rainfall at Nepen Station in 1975 - 2009

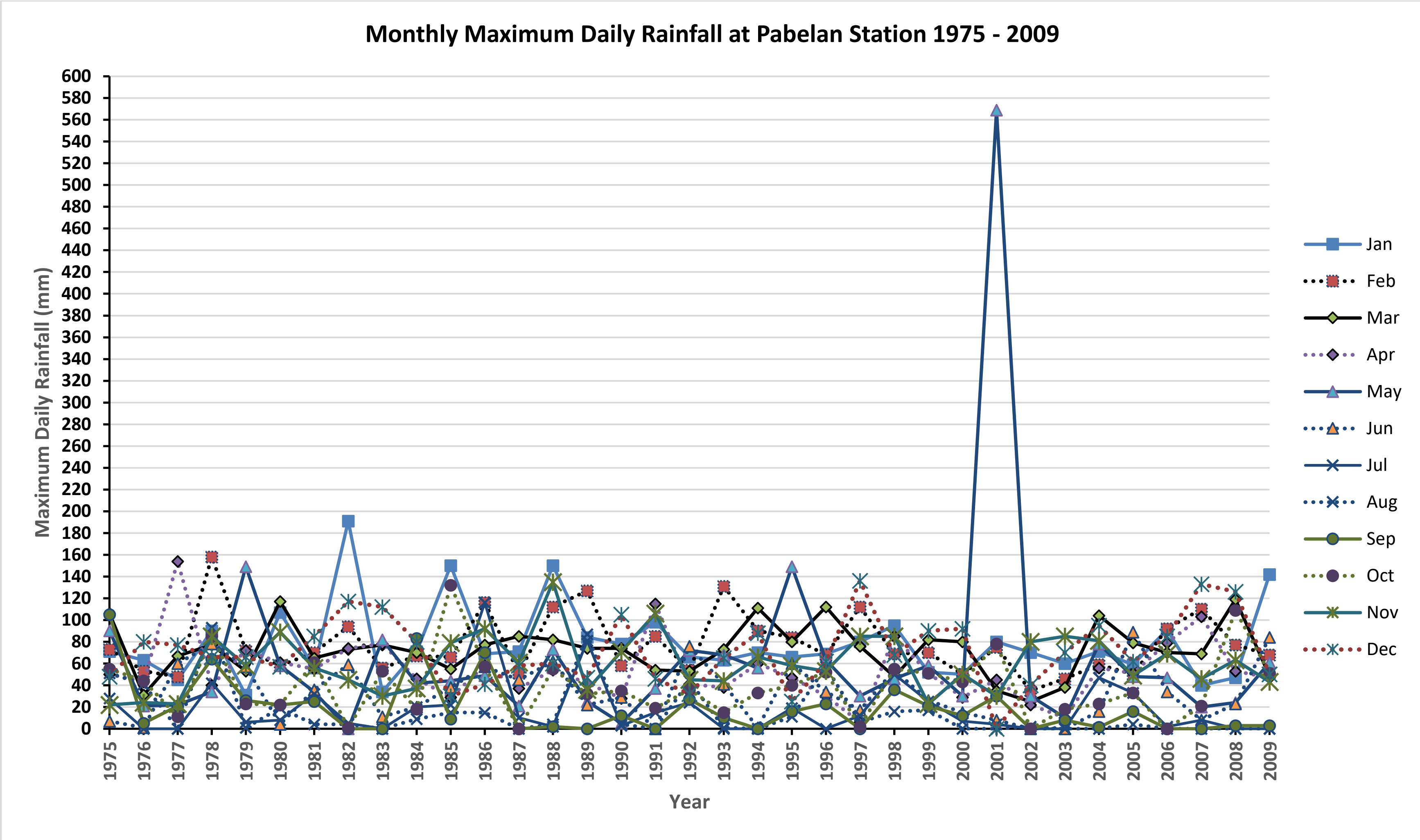


Figure 4. 6. Monthly Maximum Daily Rainfall at Pabelan Station in 1975 - 2009

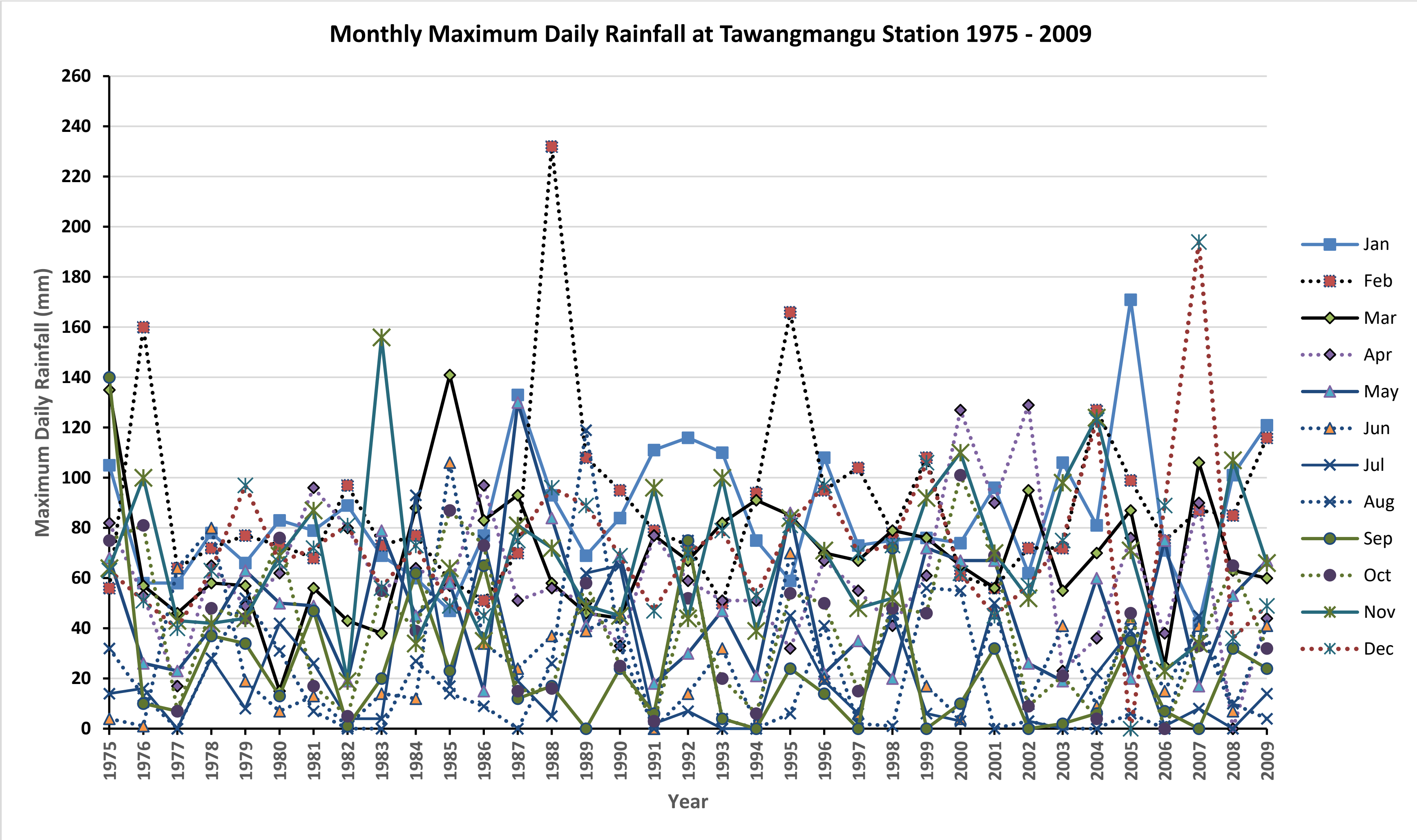


Figure 4. 7. Monthly Maximum Daily Rainfall at Tawangmangu Station in 1975 - 2009

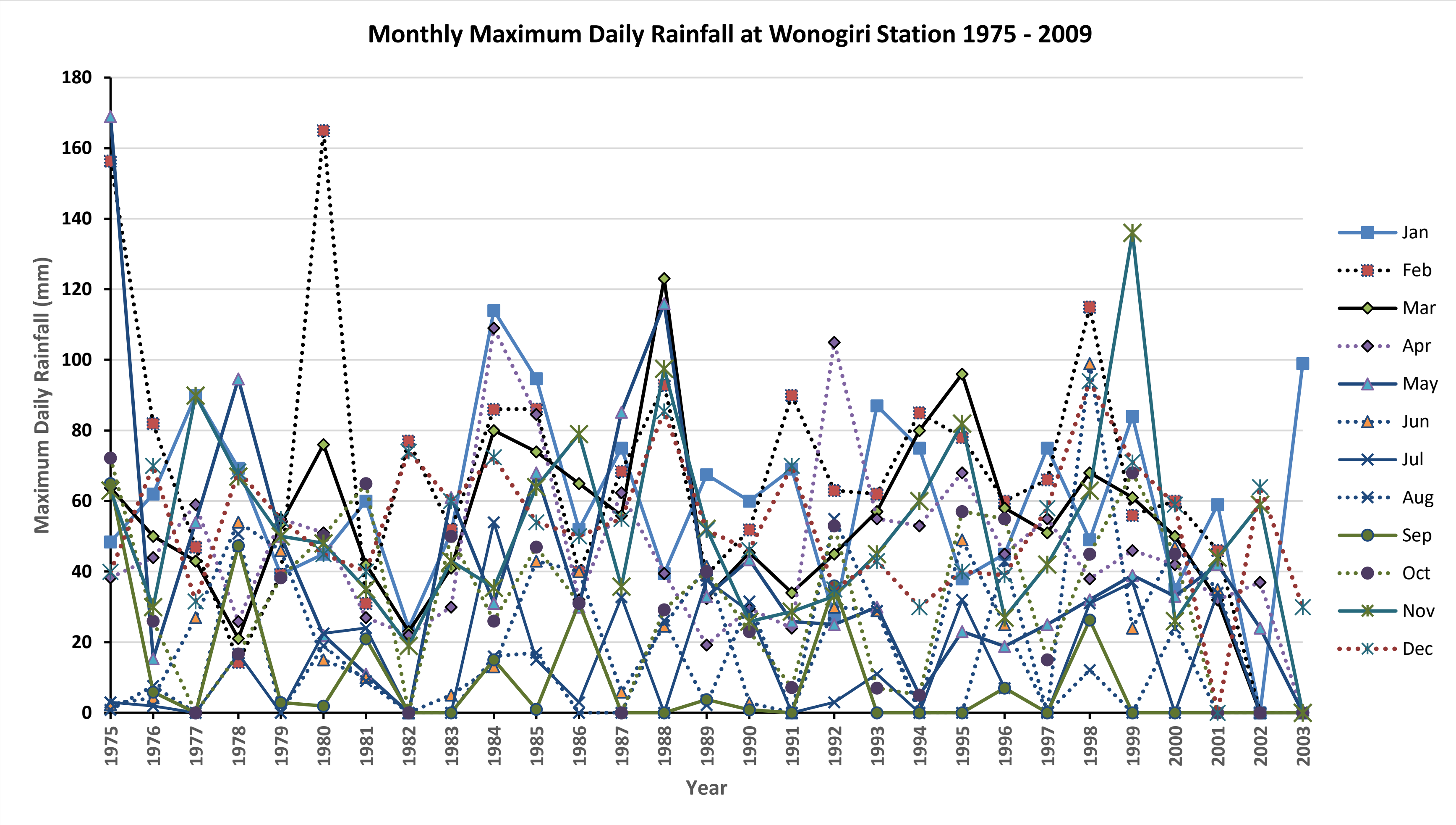


Figure 4. 8. Monthly Maximum Daily Rainfall at Wonogiri Station in 1975 - 2009

Year	Baturetno	Klaten	Nawangan	Nepen	Pabelan	Tawangmangu
1979	147	168	68	108	149	97
1980	70	81	92	75	117	83
1981	200	102	78	104	85	96
1982	71	153	83	149	191	97
1983	59	143	55	114	112	156
1984	61	128	99	133	83	93
1985	90	100	104	127	150	141
1986	37	83	70	86	116	97
1987	84	74	72	130	85	133
1988	109	105	109	144	150	232
1989	85	81	58	158	127	119
1990	94	51	56	65	105	95
1991	83	98	66	50	115	111
1992	102	113	97	91	76	116
1993	73	82	135	88	131	110
1994	57	71	64	146	111	94
1995	124	69	89	155	149	166
1996	69	71	83	92	112	108
1997	70	53	40	97	136	104
1998	56	59	102	98	95	79
1999	85	95	77	118	90	108
2000	58	60	84	67	92	127
2001	78	62	68	65	80	96
2002	75	69	68	75	80	129
2003	82	83	56	64	85	106
2004	100	119	89	108	104	127
2005	68	101	98	112	89	171
2006	62	63	59	142	92	89
2007	242	116	147	97	133	194
2008	93	82	81	84	126	107
2009	76	90	83	125	142	121

Table 4. 1. Annual Maximum daily rainfall (in mm) at 6 selected rain gauging stations in the Upper Bengawan Solo catchment

Station	**Highest Maximum Rainfall (mm)**	**Date**
Baturetno	242	26 December 2007
Klaten	168	19 January 1979
Nawangan	147	26 December 2007
Nepen	158	7 July 1989
Pabelan	191	24 January 1982
Tawangmangu	232	5 February 1988

Table 4. 2. The highest maximum daily rainfall events at 6 selected rain gauging stations in the Upper Bengawan Solo catchment

Figure 4.9 uses a box plot to show the frequency of annual maximum daily rainfall in stations considered in this research. The line and small square inside the box respectively indicate the median and the mean of data. The whiskers denote the 5th and 95th percentiles, while the limits of the box represent the 25th and 75th percentiles. It can be seen from the box plot that the highest maximum daily rainfall mostly occurred at the Pabelan and Tawangmangu stations.

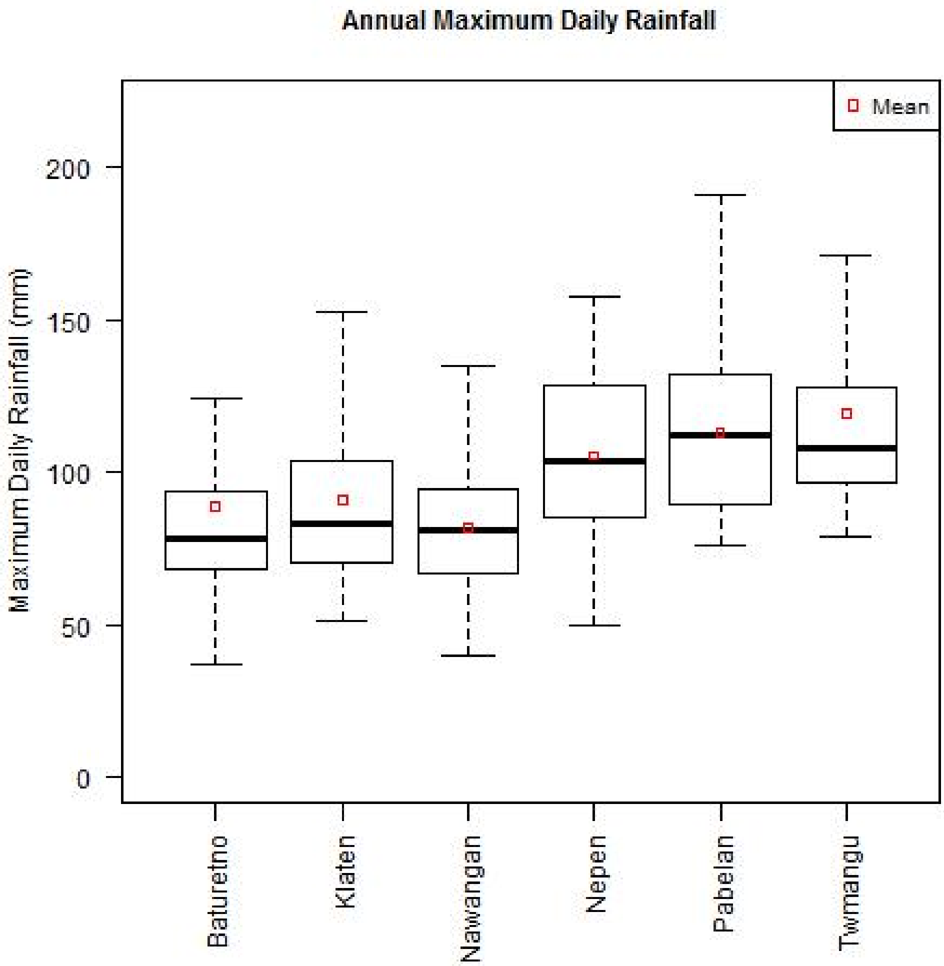


Figure 4. 9. Box plot of annual maximum daily rainfall at selected gauging stations

In addition, regarding the big flooding event in December 2007, the maximum daily rainfall at selected gauging stations in December 2007 is shown in Table below.

Station	Date	Maximum Rainfall (mm)
Baturetno	26-Dec-07	242
Klaten	28-Dec-07	70
Nawangan	26-Dec-07	147
Nepen	10-Dec-07	88
Pabelan	26-Dec-07	133
Tawangmangu	26-Dec-07	194

Table 4. 3. Maximum daily rainfall in December 2007

4.2. Change Point and Trend Analysis of Maximum Rainfall

According to Villarini *et al* (2011), change point analysis provides a tool to check for the occurrence of abrupt changes in the distribution of the variable under study such as rainfall and discharge, which may invalidate, or at least complicate, further analysis such as extreme value analysis which assume stationarity in time. Some researchers, as summarized by Villarini *et al* (2011), reported that these abrupt changes could be due to climatic changes as well as other anthropogenic effects (*e.g.* gauge repositioning, changes in the measuring procedure). The first and second moments of the distribution of the variable of interest are central in the procedure of change point testing.

As summarized by Villarini *et al* (2011), several approaches have been proposed to check for the presence of change points in the mean of the data. This research uses the Pettitt test which was used in previous studies as reviewed by Villarini *et al* (2011). The Pettitt test is a non-parametric test based on a version of the Mann-Whitney statistic which allows testing whether two samples come from the same population. The test detects change points in the mean at an unknown point in time. The main benefits of this test are that it is less sensitive to outliers and a skewed distribution, and the test significance can be computed.

In this study, it is assumed that there is no more than one change-point. According to Perreault *et al.* (2000), most applications of change point tests have been designed to detect abrupt changes in the mean of the distribution, and only a few can detect changes in the variance. The statistic used for the Pettitt test has also been explained by several researchers as summarized by Zarenistanak *et al* (2013). According to Zarenistanak *et al* (2013), the method in applying Pettitt test is described below.

First step is to calculate U_k statistic using formula as follows:

$$U_k = 2\sum_{i=0}^{n} m_i - k(n+1) \quad \textbf{(4.1)}$$

With m_i is the rank of the i_{th} observation with the values of x_1, x_2, …, x_n in the series are arranged in ascending order and k takes values from 1, 2, …, n. The next step is to define the statistical change point test as follows:

$$K = \max_{1 \le k \le n} |U_k| \quad \textbf{(4.2)}$$

If U_k reaches the maximum value of K in a series, a change point will occur in the series. The critical value is calculated as follows:

$$K_\alpha = [-\ln \alpha \, (n^3 + n^2)/6]^{1/2} \quad \textbf{(4.3)}$$

where n is number of observations and α is level of significance that determines the critical value.

Table 4.3 and Table 4.4 below show the result of the Pettit test with significance level 0.05 to investigate change point in annual maximum daily rainfall and monthly maximum daily rainfall during the wet season (October – March). It can be seen in Table 4.1 that the annual maximum daily rainfall at Klaten changes in 1988 with p-value 0.033. On the other hand, the p-values of Pettit test in other stations are bigger than 0.05, which mean statistically insignificant.

Moreover, during the wet season, there is significant abrupt change detected at Nepen station in March with p-value 0.047. In other stations, the p-values of Pettit test in wet season are bigger than 0.05, therefore statistically insignificant.

Station	Change in	p-value
Baturetno	1992	0.590
Klaten	1988	0.033
Nawangan	2003	0.697
Nepen	1989	0.121
Pabelan	1997	0.178
Tawangmangu	1984	0.374

Table 4. 4. The result of Pettit test for annual maximum daily rainfall

Month	Pettit Test	Baturetno	Klaten	Nawangan	Nepen	Pabelan	Tawangmangu
October	p-value	0.484	0.542	0.531	0.063	0.566	0.439
	change	2001	2006	2001	1989	2001	2001
November	p-value	0.374	0.578	0.531	0.252	0.674	0.495
	change	1990	1994	1985	1995	1984, 1998	1990
December	p-value	0.142	0.178	0.472	0.334	0.324	0.650
	change	2002	1988	2003	1986	1996	2007
January	p-value	0.107	0.160	0.090	0.395	0.334	0.296
	change	1986	1992	1996	1995	1991	1986
February	p-value	0.720	0.055	0.154	0.554	0.324	0.131
	change	2004	1989	2002	2000	1997	1987
March	p-value	0.324	0.236	0.590	0.047	0.484	0.107
	change	2002	1984	1983, 2003	1984	2000	1983

Table 4. 5. The result of Pettit test for monthly maximum daily rainfall

This study also applied the Mann-Kendall test to detect monotonic trends in annual maximum daily rainfall and monthly maximum daily rainfall at the selected gauging stations. The test is a non-parametric test widely used to detect significant trends in hydrological time series.

The Mann-Kendall test uses only the relative values of all terms in the series X_i. The first step is to replace the X_i values with the ranks k_i, with each value is assigned a number ranging from 1 to N. The second step is to calculate the statistic P, by comparing the rank (k_1) of the first value with those of the later values from the second to the N_{th} value. The number of later values whose rank exceeds k_i is counted, and denoted by n_1. Then compare the rank of second value (k_2) with those of the later values, and count the number of later values that exceed k_2 and denoted by n_2. This procedure is carried out for each value until k_{N-1} and its corresponding number n_{N-1}. P is calculated as follows:

$$P = \sum_{i=1}^{N-1} n_i \quad \textbf{(4.4)}$$

The statistic of τ in Mann Kendall test is calculated by:

$$\tau = \frac{4P}{N(N-1)} - 1 \quad \textbf{(4.5)}$$

The Mann Kendall τ can be used as the basis of significance test by comparing with:

$$\tau_t = 0 \pm t_g \sqrt{\frac{4N+10}{9N(N-1)}} \quad \textbf{(4.6)}$$

Where t_g is the desired probability point of Gaussian normal distribution. In this study, t_g at 0.05 point is used. The results using this test were tested at 95% confidence level (significance level 0.05). If the p-value of Mann-Kendall test is less then the significance level, null hypotheses is rejected. Rejecting null hypotheses indicates that there is a trend in the time series, while accepting null hypotheses indicates no trend is detected. So, if the null hypothesis is rejected, it means that the result is statistically significant.

Table 4.6 below shows the Mann-Kendall test result for monthly maximum daily rainfall during rainy season (October – March). Based on the Mann-Kendall test, there is no trend detected in maximum daily rainfall during the rainy season at the selected gauging stations.

Month	MK Stat	Baturetno	Klaten	Nawangan	Nepen	Pabelan	Tawangmangu
October	Tau	-0.083	0.044	-0.092	-0.164	-0.015	-0.083
	p-value	0.528	0.746	0.497	0.202	0.919	0.566
	trend	No	No	No	No	No	No
November	Tau	0.067	0.028	0.071	-0.096	-0.054	0.167
	p-value	0.610	0.838	0.586	0.464	0.683	0.242
	trend	No	No	No	No	No	No
December	Tau	0.158	-0.136	-0.061	-0.063	0.101	-0.024
	p-value	0.220	0.292	0.646	0.634	0.434	0.865
	trend	No	No	No	No	No	No
January	Tau	0.020	-0.229	-0.203	0.082	-0.124	0.105
	p-value	0.892	0.074	0.114	0.529	0.341	0.467
	trend	No	No	No	No	No	No
February	Tau	-0.022	-0.179	-0.142	-0.022	-0.074	0.196
	p-value	0.878	0.163	0.269	0.878	0.575	0.171
	trend	No	No	No	No	No	No
March	Tau	-0.058	0.115	0.004	-0.165	-0.043	0.091
	p-value	0.658	0.376	0.986	0.202	0.746	0.486
	trend	No	No	No	No	No	No

Table 4. 6. Mann Kendall test result for monthly maximum daily rainfall during the rainy season (October – March)

The result of MK test for annual maximum daily rainfall is presented in Table 4.7 below. The result indicates no trend was detected.

Station	Tau	p-value	Trend
Baturetno	-0.0323	0.81187	No
Klaten	-0.2465	0.05461	No
Nawangan	0.02386	0.86486	No
Nepen	-0.0972	0.45429	No
Pabelan	-0.1584	0.22047	No
Tawangmangu	0.12771	0.32377	No

Table 4. 7. Mann-Kendall test result for annual maximum daily rainfall

Comparing the result of Mann-Kendall test and Pettit test of annual and monthly maximum daily rainfall, it can be seen that the tests produced different results. The Pettit test produced different result for annual maximum daily rainfall and monthly maximum daily rainfall during wet season. For the annual maximum daily rainfall, abrupt change is detected at Klaten station, whereas in monthly-basis, there is no abrupt change detected in Klaten station. On the other hand, the Pettit test applied for maximum daily rainfall during rainy months (October – March) detected abrupt change at Nepen station which occurred in March.

Furthermore, based on the Mann – Kendall test, there is no trend detected both for monthly and annual maximum daily rainfall during rainy season at the selected gauging stations.

4.3. Return Period of Maximum Rainfall and Maximum Discharge

This research applied Generalized Extreme Value (GEV) and Gumbel distributions which have been widely used to estimate extreme values of given data series in hydrological application. According to Millington *et al* (2011), the GEV distribution is a family of continuous probability distribution which combines the Gumbel (EV1), Frechet and Weibull distributions. In the GEV distribution, there are 3 parameters used, location (ξ), scale (α), and shape (κ). The location parameter describes the shift of a distribution in a given direction on the horizontal axis. The scale parameter shows how spread out the distribution is, and defines where the bulk of the distribution lies. The shape parameter, which is derived from skewness, affects the shape of the distribution and governs the tail of each distribution. The Gumbel distribution (EV1) has shape parameter $\kappa=0$, while Frechet (EV2) and Weibull (EV3) have shape parameter $\kappa > 0$ and $\kappa < 0$ respectively.

As summarized by Millington et al (2011), EV1 (Gumbel) is effective for small sample sizes, whereas GEV shows better performance for sample sizes greater than 50. The cumulative density function (CDF) and probability density function (PDF) for GEV distribution are defined in (Hosking, 1990; Shaw, 1983, p.525-526) as:

$$F(x)=\exp\left\{-\left(1-\frac{\kappa(x-\xi)}{\alpha}\right)\right\}^{1/k} \quad \textbf{(4.7)}$$

$$f(x)=\alpha^{-1}\exp[-(1-\kappa)y-\exp(-y)] \quad \textbf{(4.8)}$$

where :

$$y=-\kappa^{-1}log\left[1-\frac{\kappa(x-\xi)}{\alpha}\right]\text{, when k} \neq 0 \quad \textbf{(4.9)}$$

Where ξ is the location parameter, α is the scale parameter, and κ is the shape parameter. These parameters are calculated as follows:

$$\xi = \lambda_1 - \alpha\{1 - \Gamma(1+\kappa)\}/\kappa \quad \textbf{(4.10)}$$

$$\alpha = \frac{\lambda_2\, \kappa}{(1-2^{-\kappa})\Gamma(1+\kappa)} \quad \textbf{(4.11)}$$

$$\kappa = 7.8590c + 2.9554c^2 \quad \textbf{(4.12)}$$

where Γ is Gamma function, and c is calculated using formula as follows:

$$c = \frac{2}{3+\tau_3} - \frac{\ln 2}{\ln 3} \quad \textbf{(4.13)}$$

The T-year return rainfall (Q_t) can be calculated using formula below after all parameters have been estimated.

$$Q_t = \xi + \left(\frac{\alpha}{\kappa}\right)\left\{1 - \left(-\log\left(\frac{T-1}{T}\right)\right)^{\kappa}\right\} \quad \textbf{(4.14)}$$

T is the return period in years.

The Gumbel (EV1) distribution uses 2 parameters, i.e. location (ξ) and scale (α). Gumbel distribution has been widely applied for rainfall frequency analysis in Indonesia. The CDF and PDF of Gumbel distribution is defined by Hosking (1990) as:

$$F(x) = exp\left[-exp\left(-\frac{x-\xi}{\alpha}\right)\right] \quad \textbf{(4.15)}$$

$$f(x) = \alpha^{-1}\exp\left(-\frac{x-\xi}{\alpha}\right)\exp\left[-\exp\left(-\frac{x-\xi}{\alpha}\right)\right] \quad \textbf{(4.16)}$$

The parameters of location (ξ) and scale (α) in Gumbel distribution can be calculated as follows:

$$\alpha = \frac{\lambda_2}{\log 2} \quad \textbf{(4.17)}$$

$$\xi = \lambda_1 - (\alpha\gamma) \quad \textbf{(4.18)}$$

where γ is Euler's constant 0.5772.

The T-year return rainfall using Gumbel distribution is estimated using formula as follows:

$$Q_t = \xi + \alpha y_t \qquad \textbf{(4.19)}$$

$$y_t = -ln\left[-ln\left(1 - \left(\frac{1}{T}\right)\right)\right] \qquad \textbf{(4.20)}$$

The L-moment ratio diagram which plots L-skewness (τ_3) versus L-kurtosis (τ_4) can be used to measure the goodness of fit. This technique has been widely used in regional flood frequency analysis, which applies the average values of L-skewness and L-kurtosis from several stations in a catchment area (Millington, 2011). This research does not investigate regional flood frequency, therefore the L-moment ratio diagram was applied for selected rain gauging stations. The L-moment parameters are calculated using formulas as described in Chapter 3.

According to Sankarasubramanian and Srinivasan (1999), L-moments approach is preferable for data with higher skewness for all sample size. Moreover, Gubareva and Gartsman (2010) summarized the advantages of L-moments approache compared to conventional moments, i.e L-moments always exist where the mean value exists for the probability distribution; the sample estimates of L-moments are unbiased, more effective and less sensitive to random outliers; and the calculation to obtain parameters in L-moments approach is relatively simple.

Table 4.8 below shows the values of L-skewness (τ_3) and L-kurtosis (τ_4) of maximum daily rainfall at the gauging stations. According to Hosking (1990), the values of L-skewness and L-kurtosis for Gumbel distribution are 0.1699 and 0.1504 respectively. Figure 4.10 shows the L-moment diagram for each rain gauging stations and distributions applied in this research, i.e. GEV and Gumbel distributions.

Stations	L-skewness (τ_3)	L-kurtosis (τ_4)
Baturetno	0.4032	0.3591
Klaten	0.2034	0.1397
Nawangan	0.1505	0.1717
Nepen	0.0281	0.0391
Pabelan	0.5170	0.4624
Tawangmangu	0.3468	0.2272
Gumbel	0.1699	0.1504

Table 4. 8. L-skewness (τ_3) and L-kurtosis (τ_4) of maximum daily rainfall at selected gauging stations

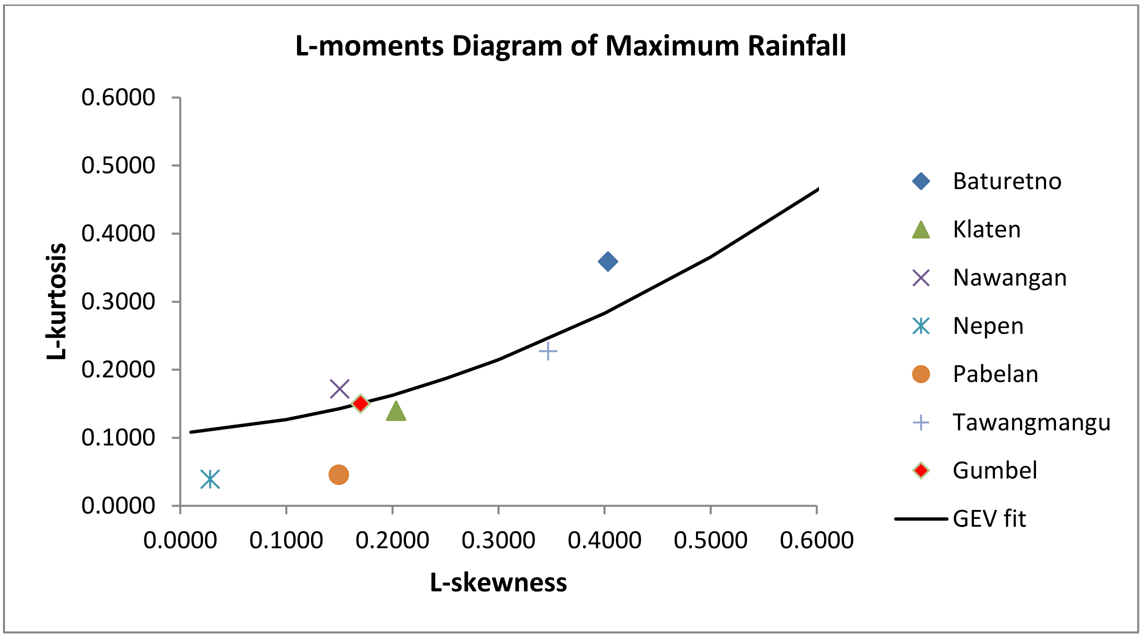


Figure 4. 10. L-moments diagram of maximum daily rainfall at selected gauging stations compared to GEV and Gumbel distribution

From the plot above, it can be seen that only the data series at Klaten and Nawangan stations fit the Gumbel distribution closely. On the other hand, all the stations lie satisfactorily close to the line of fit of the GEV distribution.

Figure 4.11 – 4.16 below show the growth curve of annual maximum daily rainfall in 6 selected rain gauging stations predicted using GEV and Gumbel distributions.

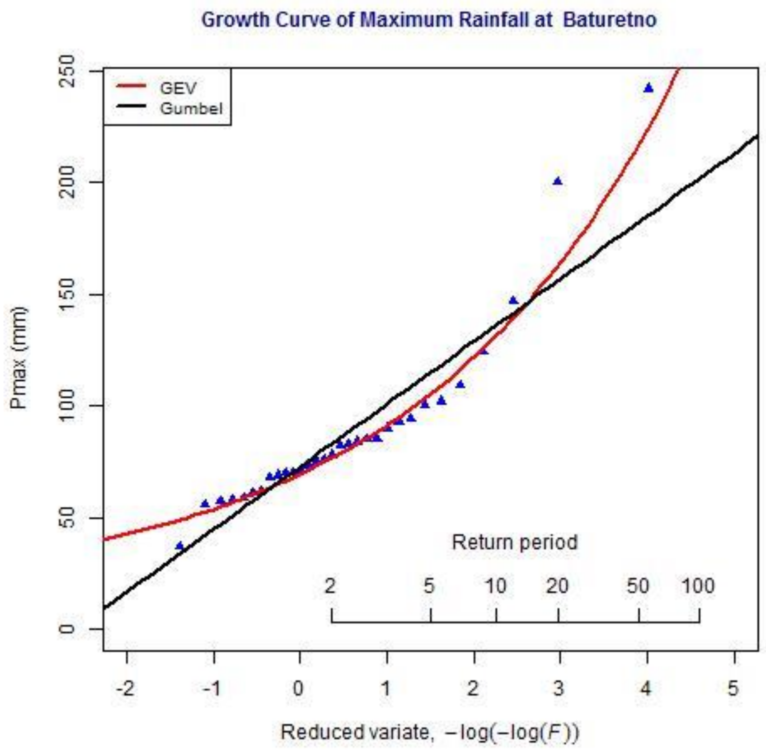


Figure 4. 11. Growth curve of maximum daily rainfall at Baturetno station

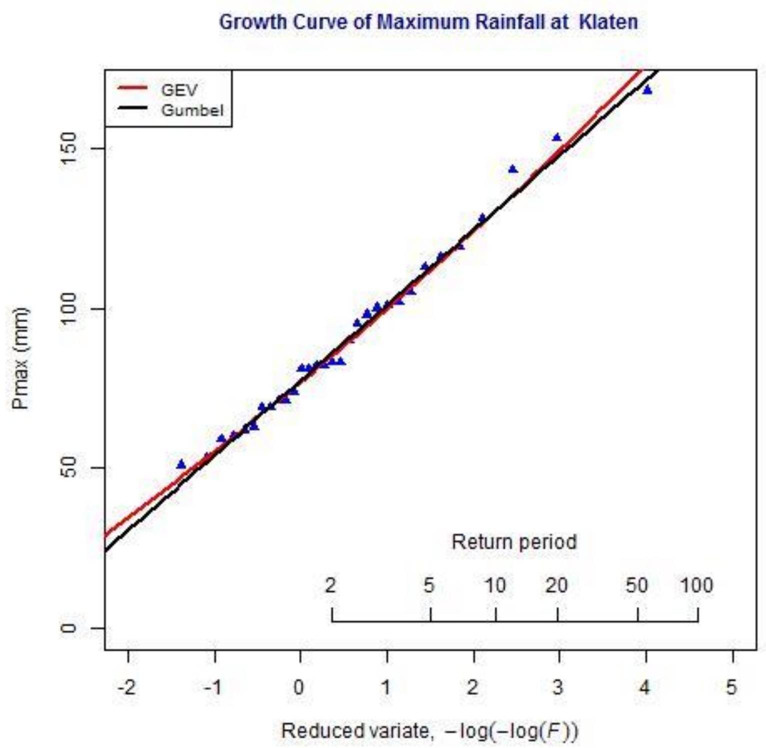


Figure 4. 12. Growth curve of maximum daily rainfall at Klaten station

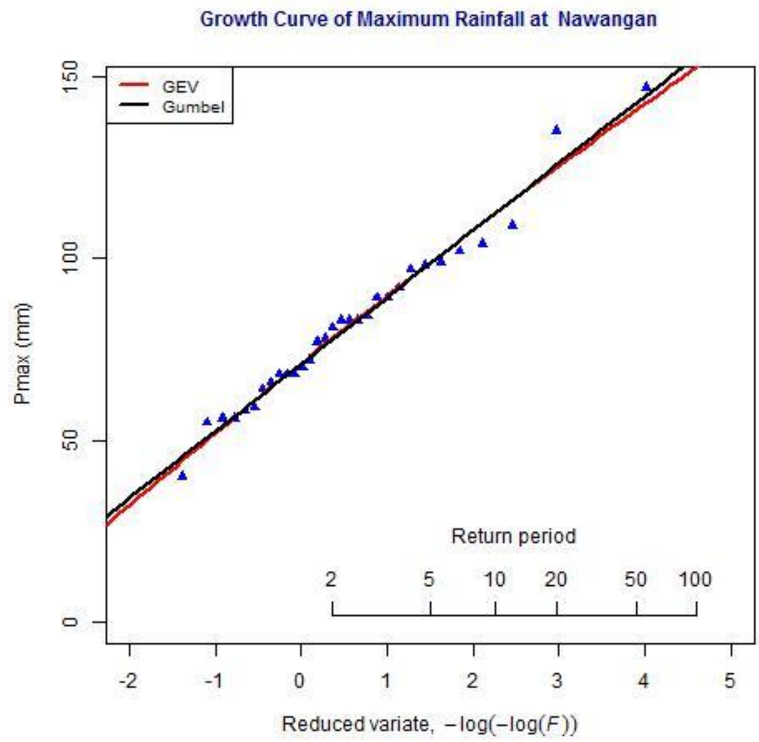


Figure 4. 13. Growth curve of maximum daily rainfall at Nawangan station

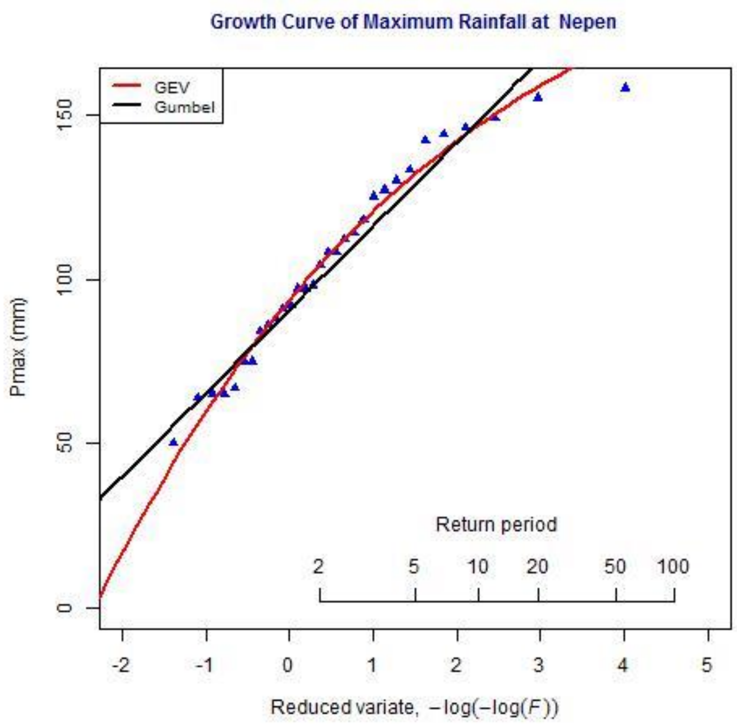


Figure 4. 14. Growth curve of maximum daily rainfall at Nepen station

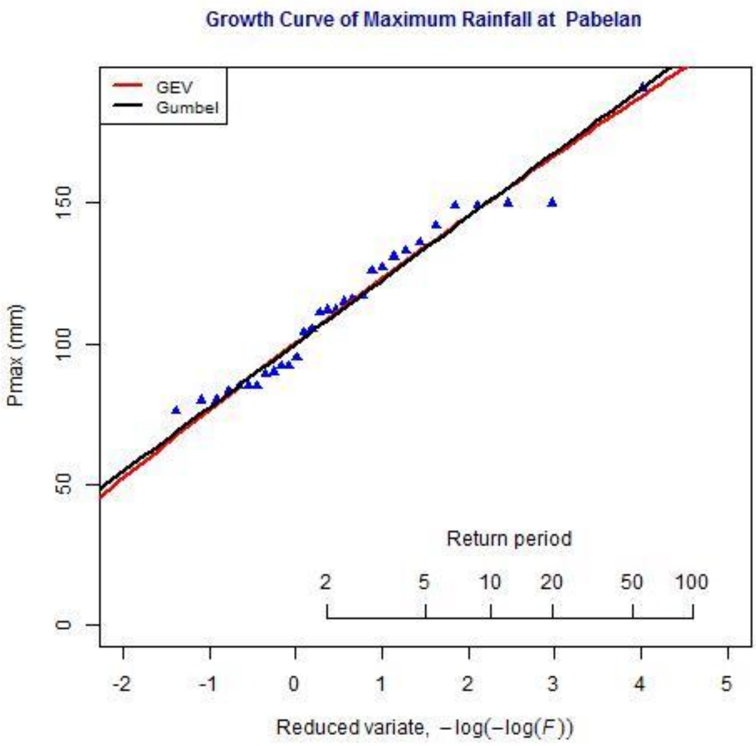


Figure 4. 15. Growth curve of maximum daily rainfall at Pabelan station

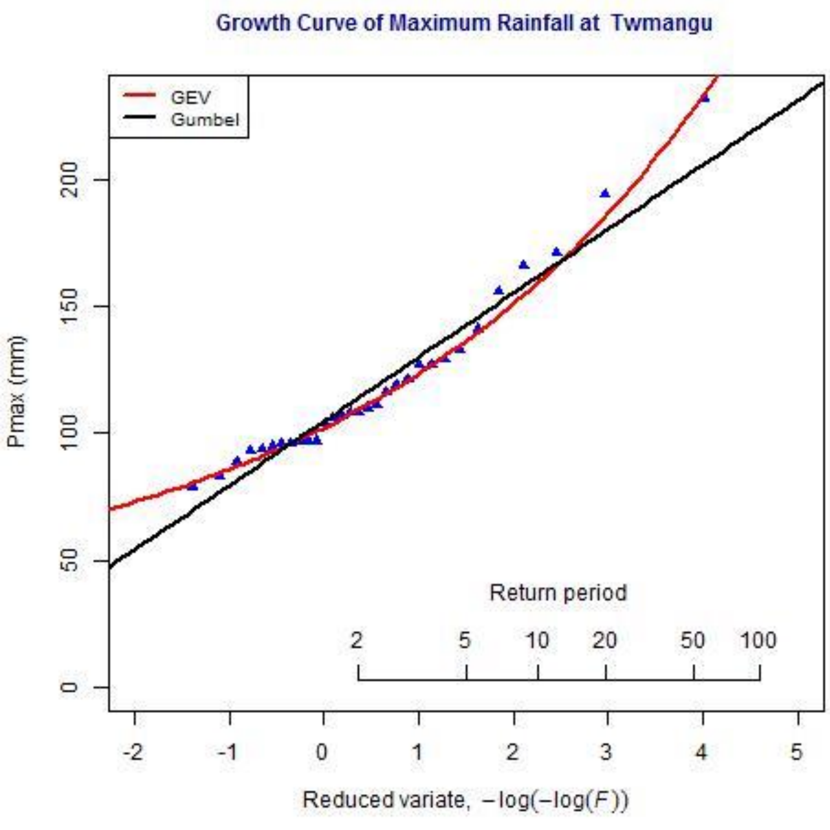


Figure 4. 16. Growth curve of maximum daily rainfall at Tawangmangu station

From the charts above, it can be seen that the data series at Klaten, Nawangan, Pabelan and Tawangmangu stations fit the GEV and Gumbel distribution well. However, estimates for return periods higher than 20 years are uncertain due to the short record lengths.

Figure 4.17 – 4.19 and Table 4.9 below show the charts and values of return level of annual maximum daily rainfall for return period 2, 5, 10, 25, and 50 years estimated using GEV and Gumbel distributions.

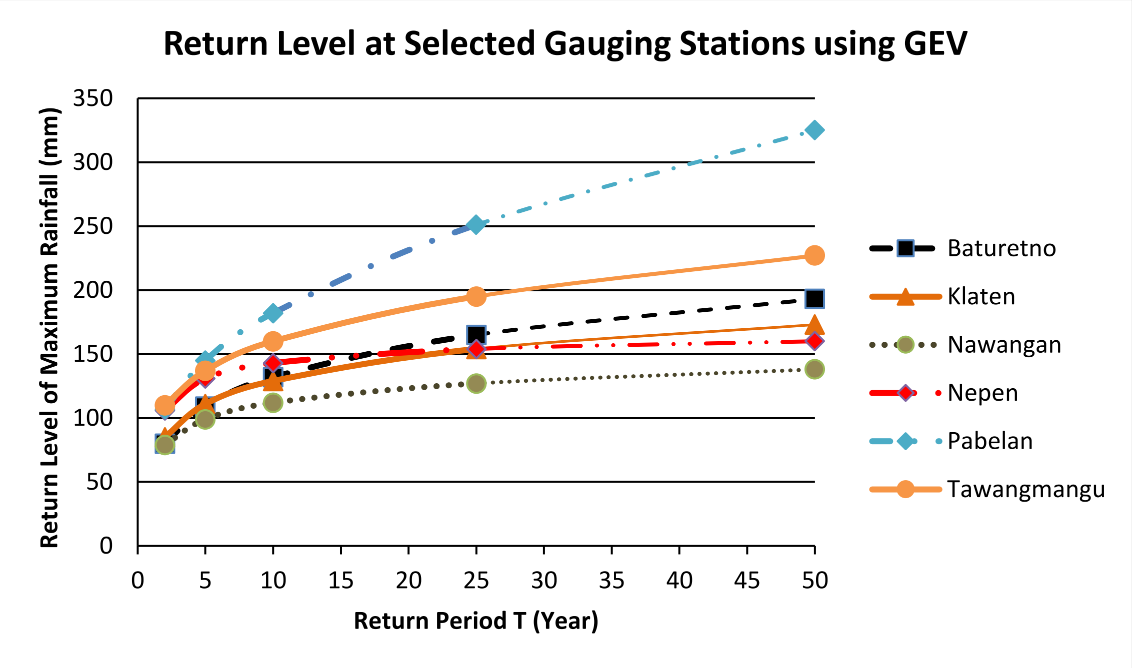


Figure 4. 17. Return level of maximum daily rainfall estimated using GEV distribution (estimates over 25-year return period are subject to large uncertainty due to data limitation).

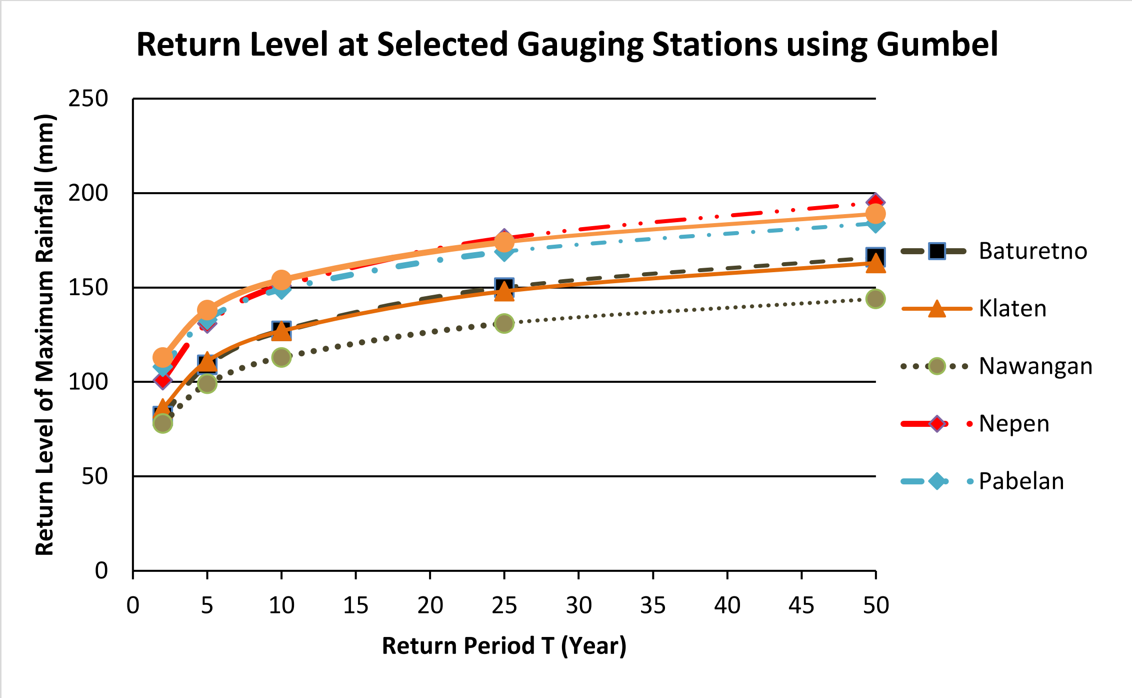


Figure 4. 18. Return level of maximum daily rainfall estimated using Gumbel distribution (estimates over 25-year return period are subject to large uncertainty due to data limitation).

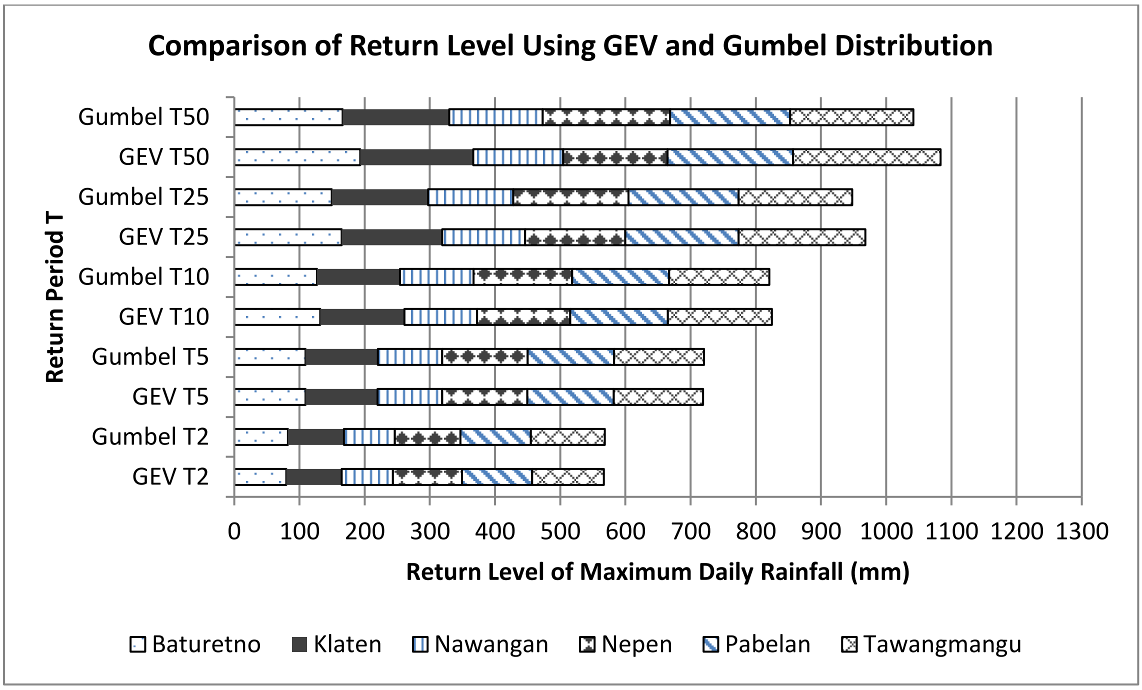


Figure 4. 19. Comparison of maximum daily rainfall return level estimated using GEV and Gumbel distribution

Station	Return Level of Maximum Rainfall at Return Period (mm)									
	2		5		10		25		50	
	GEV	Gumbel	GEV	Gumbel	GEV	Gumbel	GEV	Gumbel	GEV	Gumbel
Baturetno	80	82	109	109	132	127	165	150	193	166
Klaten	85	86	111	111	129	127	154	148	173	163
Nawangan	79	78	99	99	112	113	127	131	138	144
Nepen	106	101	131	131	143	151	154	176	160	195
Pabelan	107	108	145	133	182	149	251	169	325	184
Tawangmangu	110	113	137	138	160	154	195	174	227	189

Table 4. 9. The values of return level of maximum daily rainfall estimated using GEV and Gumbel distributions

The information about return level of maximum rainfall or maximum discharge is important in flood management. It has been widely applied for designing infrastructure related to flood control, such as in designing dam and drainage channel.

Regarding the discharge data, the maximum daily discharge at Sekayu, Napel and Karangnongko stations were used in the analysis of frequency. The data can be seen on Table 4.10 and Figure 4.20 below.

Year	Sekayu	Napel	Karangnongko
1975	468.44	1689.30	1920.49
1976	233.29	1792.32	1411.39
1977	226.76	1341.40	1146.31
1978	396.88	1998.30	1567.50
1979	323.47	2686.30	1835.32
1980	246.62	1838.97	1509.47
1981	290.31	1732.24	1341.73
1982	351.93	1944.41	1583.15
1983	342.31	1866.18	1204.07
1984	234.77	1811.25	1437.49
1985	316.70	1824.97	1444.99
1986	337.58	1849.08	1587.08
1987	298.35	1804.41	1448.74
1988	374.29	1653.53	1389.21
1989	448.01	2010.94	1497.99
1990	351.72	1637.12	1334.50
1991	289.65	1883.76	1448.74
1992	446.39	1562.58	1263.19
1993	338.67	2543.80	2025.14
1994	629.79	2390.93	1881.93
1995	465.75	1804.41	1347.01
1996	330.03	1719.88	1378.20
1997	103.87	1660.11	1190.37
1998	424.51	1780.56	1400.76
1999	251.40	1551.90	1477.27
2000	294.02	1424.24	1373.21
2001	179.99	1977.62	1517.60
2002	279.44	1745.61	1538.63
2003	212.11	1541.26	1355.83
2004	339.98	1507.41	1175.34
2005	130.12	1403.77	985.45
2006	372.47	1398.67	1073.90
2007	679.04	3249.27	2129.92
2008	250.49	2097.75	1503.23

Table 4. 10. Maximum daily discharge (in $m^3 s^{-1}$) at Sekayu, Napel and Karangnongko stations

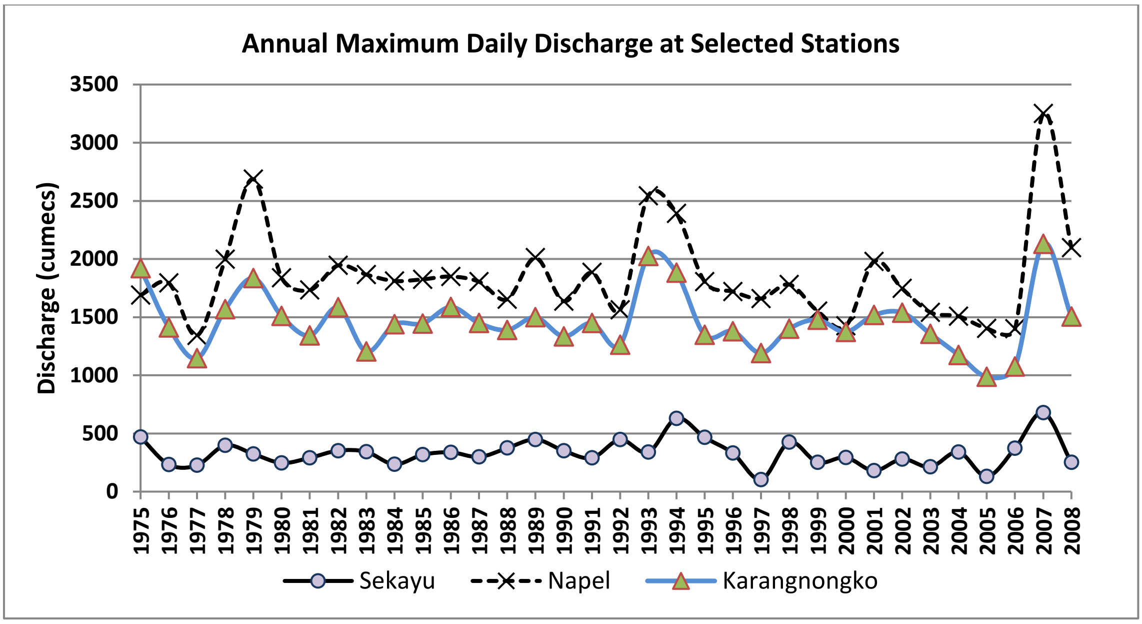


Figure 4. 20. Maximum daily discharge at Sekayu, Napel and Karangnongko stations

The return level of maximum daily discharge was estimated using GEV and Gumbel distribution as applied for the maximum daily rainfall. L-moments values and diagram of maximum daily discharge at the selected stations are presented on Table 4.11 and Figure 4.21 below.

Stations	L-skewness (τ_3)	L-kurtosis (τ_4)
Sekayu	0.1287	0.2336
Napel	0.2759	0.3022
Karangnongko	0.1463	0.2512
Gumbel	0.1699	0.1504

Table 4. 11. L-skewness (τ_3) and L-kurtosis (τ_4) of maximum daily rainfall at selected gauging stations

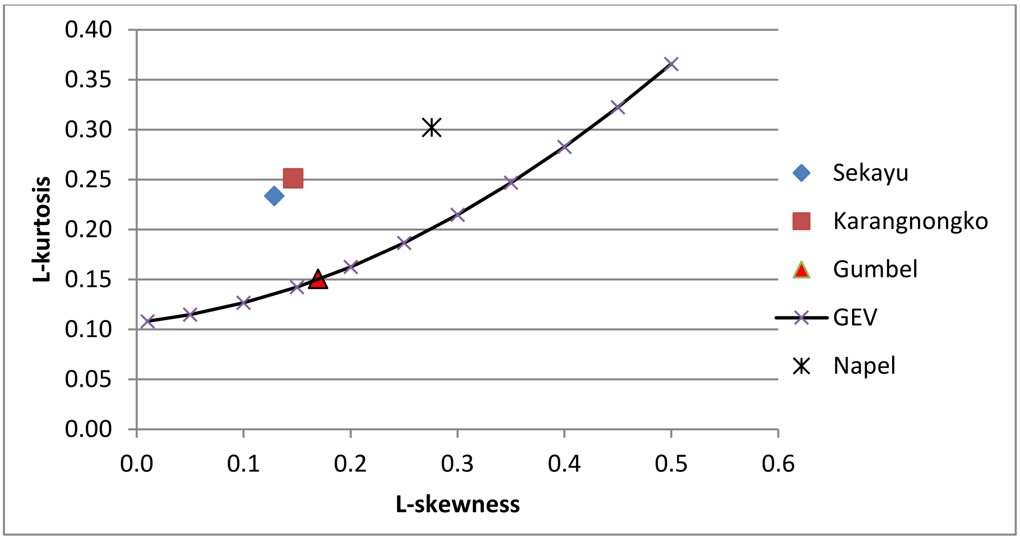


Figure 4. 21. L-moments diagram of maximum daily discharge at selected stations compared to GEV and Gumbel fits

The growth curve of maximum daily discharge at Jurug and Kajangan station can be seen on Figure 4.22 and 4.23 below.

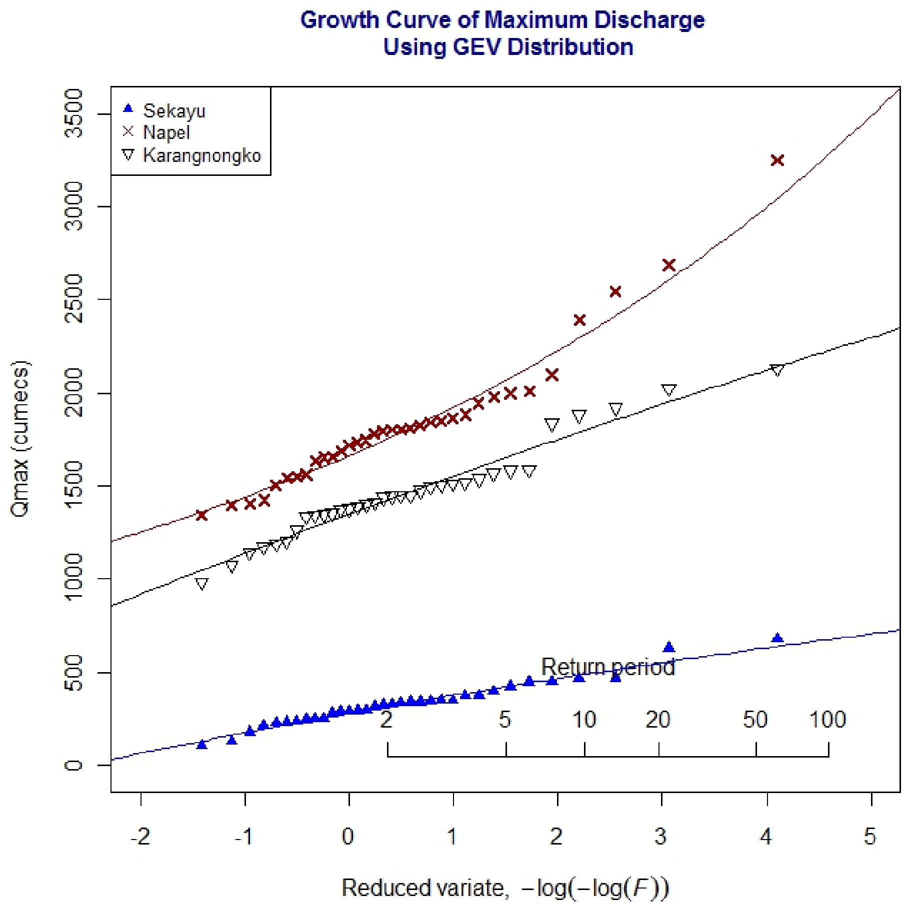


Figure 4. 22. Growth curve of maximum daily discharge estimated using GEV distribution at selected stations

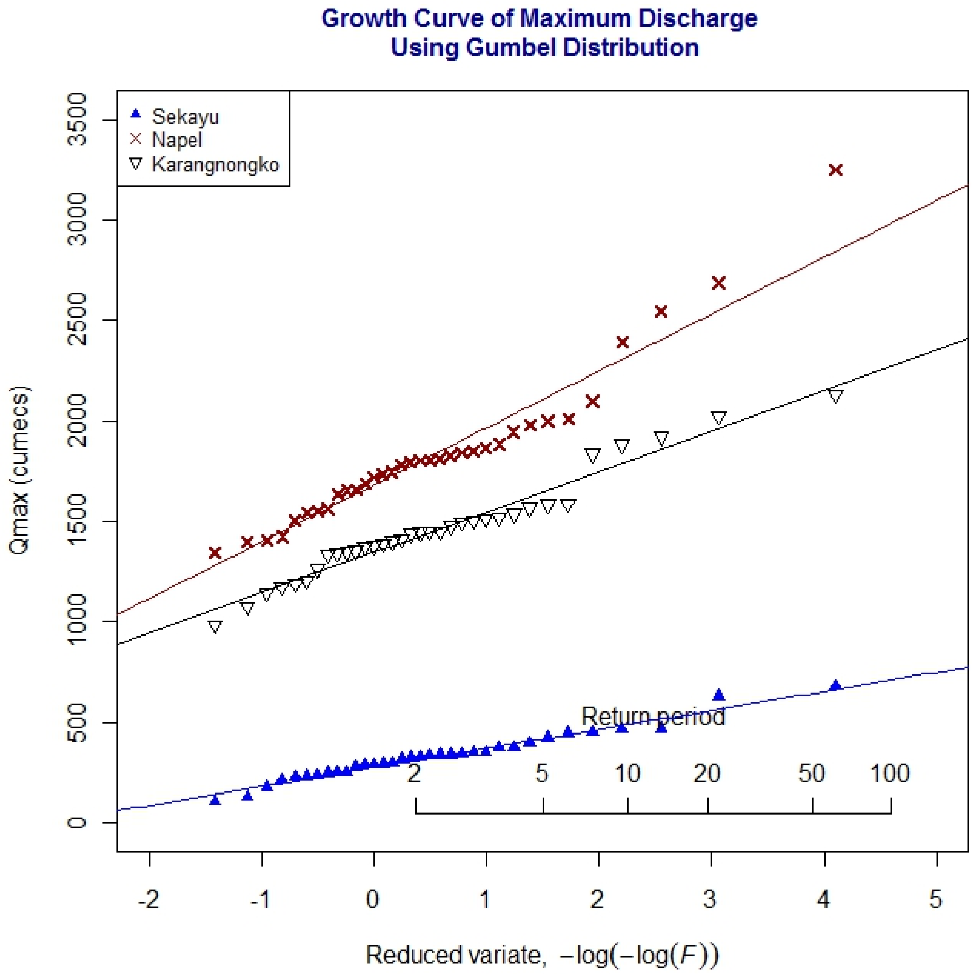


Figure 4. 23. Growth curve of maximum daily discharge estimated using Gumbel distribution at selected stations

From the figures above, it can be seen that the data series at Sekayu and Karangnongko stations fit the GEV and Gumbel distributions well.

Further discussion about the result in this chapter is described in Chapter 8.

4.4. Summary

The highest maximum rainfall was recorded at Baturetno station (which is situated in the Upper Bengawan Solo catchment) with rainfall depth 242 mm, occurred in 26 December 2007. Following the extreme rainfall, big flood struck many regions in the river basin and continue to occur annually since 2007.

According to the Pettit test applied in this research, the abrupt change of annual maximum daily rainfall was detected only at Klaten station (situated in Upper Bengawan Solo catchment) in 1988 with p-value 0.033. While in wet season, the abrupt change was detected only at Nepen station in March with p-value 0.047. To find whether the change caused by climate change or not, further research using more complete and reliable data is suggested. Furthermore, based on Mann-Kendall test, there was no trend detected in the maximum rainfall.

The maximum rainfall and discharge data in the selected gauging stations fit the GEV and Gumbel distribution well. However, to estimate the frequency of maximum rainfall and discharge for the return period more than 30 years is uncertain because the length of time series is limited (only 30 years length).

Chapter 5. SHETRAN Simulation

This study using SHETRAN to simulate water flow using related data from the study area. This chapter describes the initial stages in the SHETRAN simulation, including setting up the model and calibration for rice paddy field land use. In this study, the first simulation was simplified and used only a single rainfall input at a time from the 17 rain gauging stations in Upper Bengawan Solo catchment. This was done in order to identify the most useful rainfall records as well as to assist in identifying robust model parameters. The period of rainfall data is 1983 – 1986. After using single rainfall input, the next simulation was conducted by using multiple rainfall input from different combinations of selected rain gauging stations in 1983 – 1986. The period of 1983 – 1986 was selected for the first simulation because all the rain gauging stations during this period have complete daily records. The SHETRAN model for this research was set up by Dr. Stephen J.Birkinshaw.

5.1. Set Up SHETRAN Model

5.1.1. Jurug gauging station catchment area

In applying SHETRAN in this research, the Jurug gauging station has been chosen to define the simulated area. Figure 5.1 below shows the map of Jurug catchment with the existing land use. The Jurug catchment has an area of about 3850 km^2 and is situated in the Upper Bengawan Solo basin. The rainfall and discharge data in Jurug catchment is more complete than other stations in the whole Bengawan Solo river basin. However, there are some data in certain periods which had to be rechecked or corrected because the pattern is different compared to the data in other period. Annual potential evaporation (PET) Annual potential evaporation (PET) in Jurug catchment area is approximately 2244 mm. The annual average rainfall in the catchment is about 2048 mm.

In Jurug catchment, the percentage of forest area is only 9% of total area. The land use is dominated by rice paddy field and bare ground (locally referred to as “critical land”).

The DEM (digital elevation model) and the river links maps of Jurug catchment are shown in Figure 5.1 and Figure 5.2 below. The river links are shown in blue superimposed on a Digital Elevation Model. The size of the grid squares is 2 x 2 km^2 which is a coarse grid. Because there is a trade-off between simulation speed and accuracy, the coarse grid is used. Since the input data on rainfall will be the primary source of accuracy, a uniform Jurug land use pattern will negate the benefit of a higher resolution. Reducing the overland flow resistance can make up for the absence of channels in the coarse grid squares.

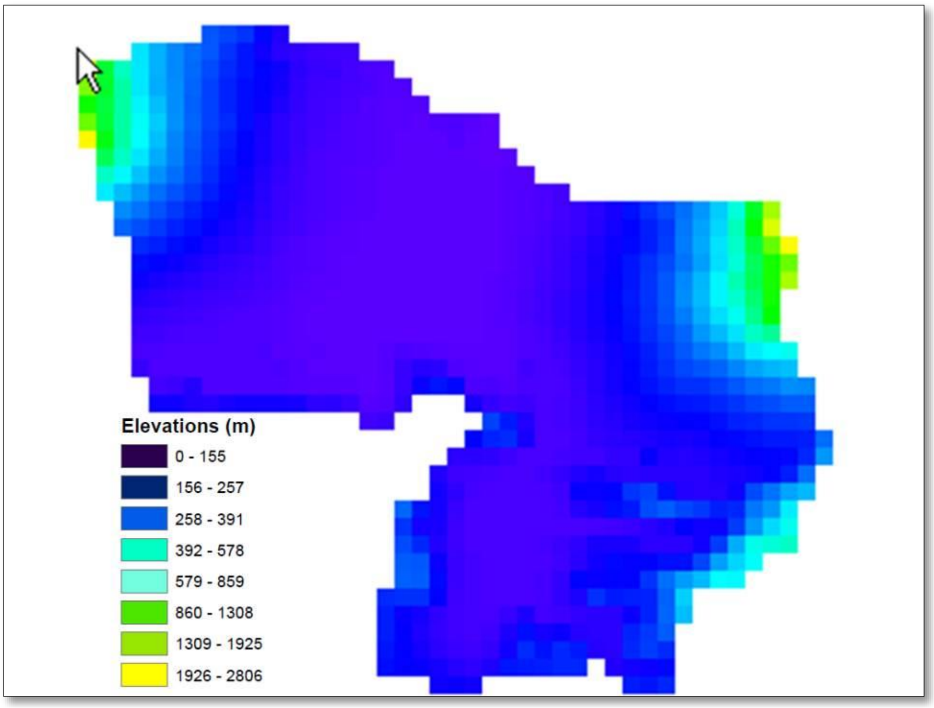


Figure 5. 1. The map of Digital Elevation Model (DEM) of Jurug catchment

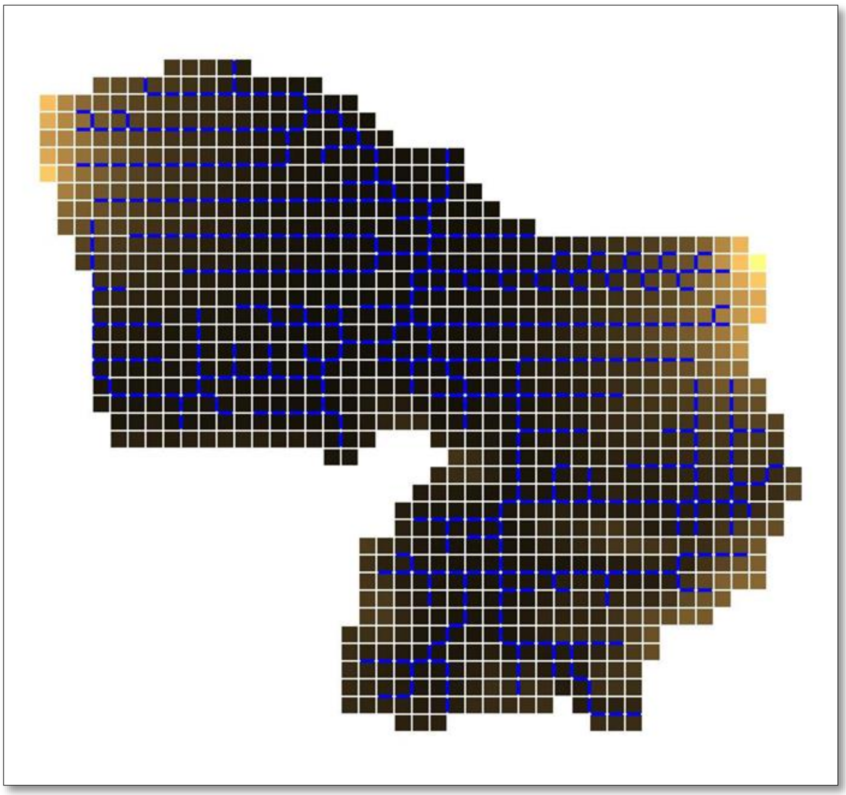


Figure 5. 2. Map of SHETRAN representation of river links for the Jurug catchment model.

5.1.2. Input data

This research applies the standard version of SHETRAN to simulate the flow in the catchment. There are some input data required in applying SHETRAN simulation, including potential evaporation (PET), DEM (Digital Elevation Model), rainfall gauging station location, soil type, land use type, and rainfall. The SHETRAN mesh for Jurug catchment uses 2000 x 2000 meter grid squares. The grid elevations can be seen in Figure 5.3.

The input data is written in text file format, and categorized in several types of files including *etd*, *frd*, *ocd*, *epd*, and *vsd*. The rainfall data is also written in text file format. The table below shows the parameter set up in the text files.

File type	Parameter in the file
Etd	Parameter for vegetation
Frd	Frame of meteorology station, rain gauging station, land use, grid in X and Y direction, ground surface elevation,
Ocd	Land use in X and Y direction, channel link data
epd	Monthly potential evaporation (PET)
Vsd	Parameter for soils

Table 5. 1. The parameters used in input data for SHETRAN simulation

For this research, the soil texture was obtained from Harmonized World Soil Database (HWSD), available at http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/. For each grid square, the top soil depth is 30 cm, and the 30 cm – 1 m soil texture. Moreover, the parameters for the porosity, the residual moisture content, the saturated conductivities, and the Van Genuchten parameters were selected from Appendix A of SHETRAN Version 4 Data Requirements, Data Processing and Paramater values (available in http://research.ncl.ac.uk/shetran/SHETRAN%20V4%20Data%20Requirements.pdf). The saturated conductivities were calibrated for this research. Table 5.2 below show the soil parameters for each soil type.

Soil Type	Saturated Water Content	Residual Water Content	Saturated Conductivity (m/day)	Van Genuchte n-alpha (/cm)	Van Genuchte n-n
Clay (20% sand, 60% clay)	0.544	0.326	0.014	4.580E-03	1.443
Silty Clay (10% sand, 40% clay)	0.529	0.212	0.019	6.540E-03	1.531
Silty Clay Loam (10% sand, 27% clay)	0.507	0.144	0.036	7.240E-03	1.608
Silt Loam (10% sand, 10% clay)	0.452	0.093	0.163	5.150E-03	1.681
Clay Loam (35% sand, 27% clay)	0.489	0.153	0.055	9.230E-03	1.657
Sandy Silt Loam (35% sand, 10% clay)	0.434	0.086	0.317	8.380E-03	1.587
Sandy Clay (52% sand, 40% clay)	0.499	0.233	0.029	1.069E-02	1.879
Sandy Clay Loam (65% sand, 24% clay)	0.461	0.167	0.103	1.236E-02	2.071

Sandy Loam (65% sand, 10% clay)	0.412	0.098	0.622	1.441E-02	1.736
Loamy Sand (85% sand, 6% clay)	0.370	0.075	1.467	1.986E-02	1.793
Sand (92% sand, 5% clay)	0.352	0.066	5.040	2.296E-02	1.847
Peat	0.910	0.319	0.464	1.200E-02	1.536

Table 5. 2. The parameter of soil types (source : Appendix A of SHETRAN Version 4 Data Requirements, Data Processing and Paramater values)

Daily in situ rainfall data is available, with various time series at each gauging station as described previously in Chapter 3.

The land use type is divided into 5 types, i.e. rice paddy field, bare ground, urban, forest and grass with code number 1, 2, 3, 4, and 5 respectively. The parameters for vegetation covers were set up based on Appendix B of SHETRAN Version 4 Data Requirements, Data Processing and Paramater values as can be seen on Table 5.3 below (available in http://research.ncl.ac.uk/shetran/SHETRAN%20V4%20Data%20Requirements.pdf).

Vegetation	Canopy Drainage		Canopy Storage	Vegetation cover indices	
	CK (mm s^{-1})	Cb (mm^{-1})	CSTCAP (mm)	PLAI	CLAI
Arable	1.40E-05	5.1	1.5	1.0	6.0
Bare ground	0	0	0	0	1.0
Grass	1.40E-05	5.1	1.5	1.0	6.0
Deciduous forest	1.40E-05	5.1	5.0	1.0	6.0
Evergreen forest	1.40E-05	5.1	5.0	1.0	6.0
Shrub	1.40E-05	5.1	1.5	1.0	3.0
Urban	1.40E-05	5.1	0.3	0.3	1.0

Table 5. 3. The parameters of vegetation covers (source: Appendix B of SHETRAN Version 4 Data Requirements, Data Processing and Paramater values

Note : Cb = Rutter b parameter; CK = Rutter k parameter; CLAI = canopy leaf area index; CSTCAP = canopy storage capacity; PLAI = plant area index

The monthly potential evaporation (PET) for each type of land use used in this simulation is presented in Table 5.4 below.

Month	PE for Land Use Type (mm)				
	1	2	3	4	5
1	190.4	190.4	190.4	247.52	190.4
2	187.6	187.6	187.6	243.88	187.6
3	184.8	184.8	184.8	240.24	184.8
4	180.6	180.6	180.6	234.78	180.6
5	169.4	169.4	169.4	220.22	169.4
6	161	161	161	209.3	161
7	170.8	170.8	170.8	222.04	170.8
8	191.8	191.8	191.8	249.34	191.8
9	204.4	204.4	204.4	265.72	204.4
10	221.2	221.2	221.2	287.56	221.2
11	200.2	200.2	200.2	260.26	200.2
12	193.2	193.2	193.2	251.16	193.2
13	190.4	190.4	190.4	247.52	190.4
	1 = rice paddy field 2 = bare ground 3 = urban 4 = forest 5 = grass				

Table 5. 4. Monthly potential evaporation (PET) of land use types (source : http://csi.cgiar.org/Aridity/)

Due to the higher vegetation and hence lower aerodynamic resistance the PET for forest (which is evergreen in Indonesia) is higher than other vegetation types (source: SHETRAN Version 4 Data Requirements, Data Processing and Paramater values).

5.1.3. Calibration for seasonal rice paddy field

Based on the available land use data, the rice paddy fields cover a significant area in Jurug catchment, about 29% of total area. Rice paddy cultivation usually starts during the rainy season because the soil needs plenty of water during land preparation. The rice paddy plant also requires a huge amount of water during its early process of growing. In some areas in Indonesia where the rainfall amount is sufficient and the irrigation system is well managed, the farmer grows rice paddy twice a year.

The volume of water required in rice paddy plantation depends on factors such as land preparation, consumptive use, percolation, water replacement and effective rainfall.

During the land preparation process, the water requirement for rice paddy fields depends on factors such as soil characteristic, duration of land preparation, energy and labour resources, and the mechanisation applied during the process.

According to Irrigation Design Criteria KP 01 applied in Indonesia, water requirement during land preparation for rice paddy is empirically set up as 250 mm per day. In condition where the field is dry for long period, the water amount required is 300 mm per day. This amount includes water required during plant seeding.

Consumptive use for rice paddy can be measured using evapotranspiration (ET). According to Son Hong Vu *et al* (2005), ET can be calculated using formula as follows:

$$ET = k_c * ET_o \quad \textbf{(5.1)}$$

where :

ET : crop evapotranspiration (mm/day)

ET_o : reference crop evapotranspiration (mm/day)

k_c : crop coefficient

ETo in Indonesia is calculated using formula :

$$ET_o = E_{pan} * k_{pan} \quad \textbf{(5.2)}$$

where :

ET_o = reference crop evapotranspiration (mm/day)

E_{pan} = pan evaporation

k_{pan} = pan coefficient

The crop coefficient value used in Indonesia according to FAO is shown in Table 5.5 below.

15 days period	Common Variety	Best variety
1	1.10	1.10
2	1.10	1.10
3	1.10	1.05
4	1.10	1.05
5	1.10	1.05
6	1.05	0.95
7	0.95	0.00
8	0.00	-

Table 5. 5. Crop coefficient (k_c) for rice paddy

The Strickler overland flow parameter controls the speed of water on the ground surface. A high value means the water can flow fast whereas a low value means the water flows slowly. Table 5.6 below shows Strickler coefficient for rice paddy field used in the simulation. The Stickler overland roughness coefficient was calibrated for this research.

This is time varying in order to account for the water stored in the paddy fields. In the wet season (January – May) when the rice is being grown, a low value is used as the paddy field stores a considerable amount. In the dry season (June – December) a high value is used as all the ditches are left open and the fields are dry.

Month	Strickler Coefficient
1	0.10
2	0.01
3	0.01
4	0.04
5	0.10
6	0.30
7	0.50
8	0.50
9	0.50
10	0.50
11	0.30
12	0.20

Table 5. 6. Time-varying Strickler coefficient for rice paddy field

In this SHETRAN simulation, the canopy storage for the rice paddies is time varying. In the wet season a value of 5 mm is used whereas in the dry season it is assumed the land is bare so a value of zero is used.

In order to account for the difference in transpiration between the paddy field in the wet season and the dry ground found in the dry season a time varying actual / potential evaporation ratio was used in Shetran. For the rice paddy this varied from 1.0 in the wet season to zero in the dry season. This ensures that in the dry season there is no transpiration as there is no vegetation. There may be no vegetation transpiration, however there can still be evaporation from the bare soil.

5.2. Initial SHETRAN Simulations

5.2.1. Simulation using single rainfall input

The first SHETRAN simulations were carried out in an exploratory phase aimed at identifying the most robust set of rain gauges as data quality and spatial heterogeneity of rainfall are both expected to be a problem. These simulations used rainfall input from single rain gauging stations in Jurug catchment. In situ rainfall data from 17 gauging stations available in the catchment in 1983 – 1986 were used as rainfall input. The rainfall data in year 1983 – 1986 was used in the first simulation by considering that most of the stations at this period have complete data. In this first simulation, the parameter for vegetation cover in *etd* input file can be seen in the table below.

Vegetation type	Leaf area index	Canopy storage capacity (mm)	AE/PE ratio
Rice paddy	4.0	0.0 – 5.0	– 1.0
Bare ground	0.8	3.0	0.0
Urban	0.8	1.0	0.6
Forest (evergreen)	6.0	5.0	1.0
Grass / Shrub	6.0	2.5	1.0

Table 5. 7. Parameter of vegetation cover used for SHETRAN simulation in the Jurug catchment

As described in SHETRAN V4 data requirement guideline, leaf area index is the ratio of total leaf area to the area of ground covered by vegetation. The canopy storage capacity is the maximum amount of water that can be held on the aerial portion of vegetation, expressed as an average depth for the vegetation in term of liquid water equivalent. The AE/PE ratio is the ratio of the actual evaporation to the potential evaporation.

The output of SHETRAN simulations is saved in several files. The output files contain results such as spatially averaged totals over the simulation (mass balance) including cumulative rainfall, cumulative canopy evaporation, cumulative soil evaporation, cumulative discharge, surface storage, and channel storage. In addition, the output files also contain the values of daily discharge and discharge in every time step. The simulation output is also available in the HDF file. The output in an HDF file can be seen on the Figure below.

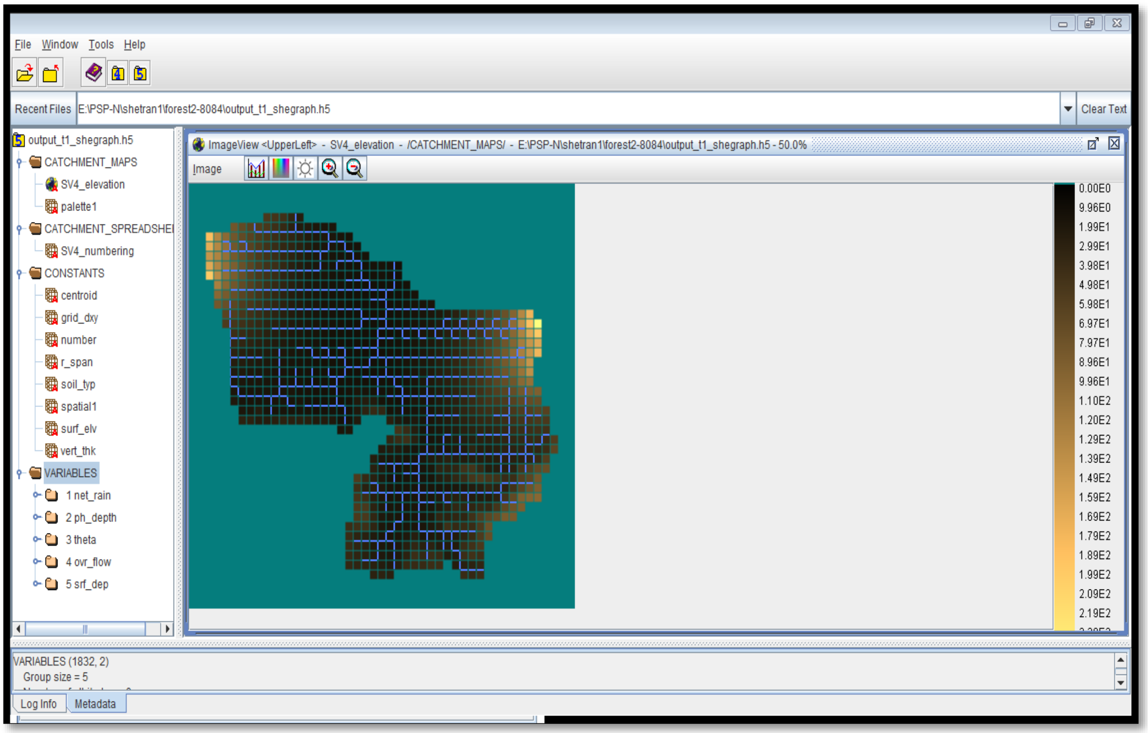


Figure 5. 3. SHETRAN simulation output in HDF file

The output in the HDF file contains catchment map and spread sheet, constant and variables.

The comparison between daily observed and simulated discharge for single rainfall input using rainfall data in 1983 – 1986 from every rain gauging station in the research location are presented in the following charts. There are 17 results for single rainfall input, and only a few diagrams are presented in this chapter. The remaining outputs can be seen in the Appendices.

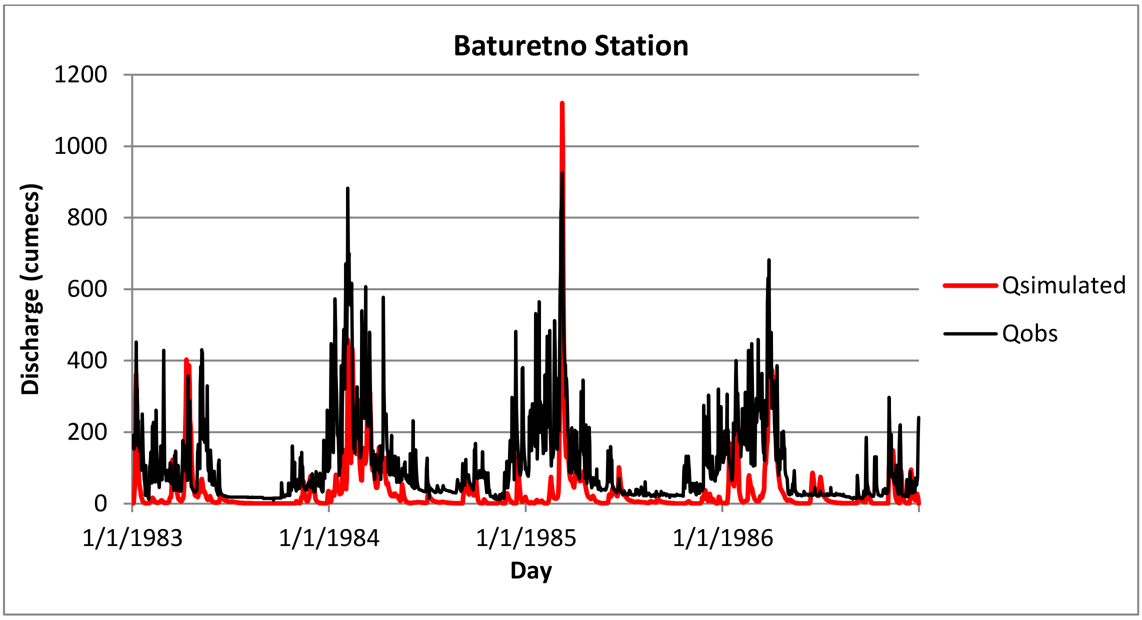


Figure 5. 4. Simulated and observed discharge with rainfall input from Baturetno station 1983 – 1986

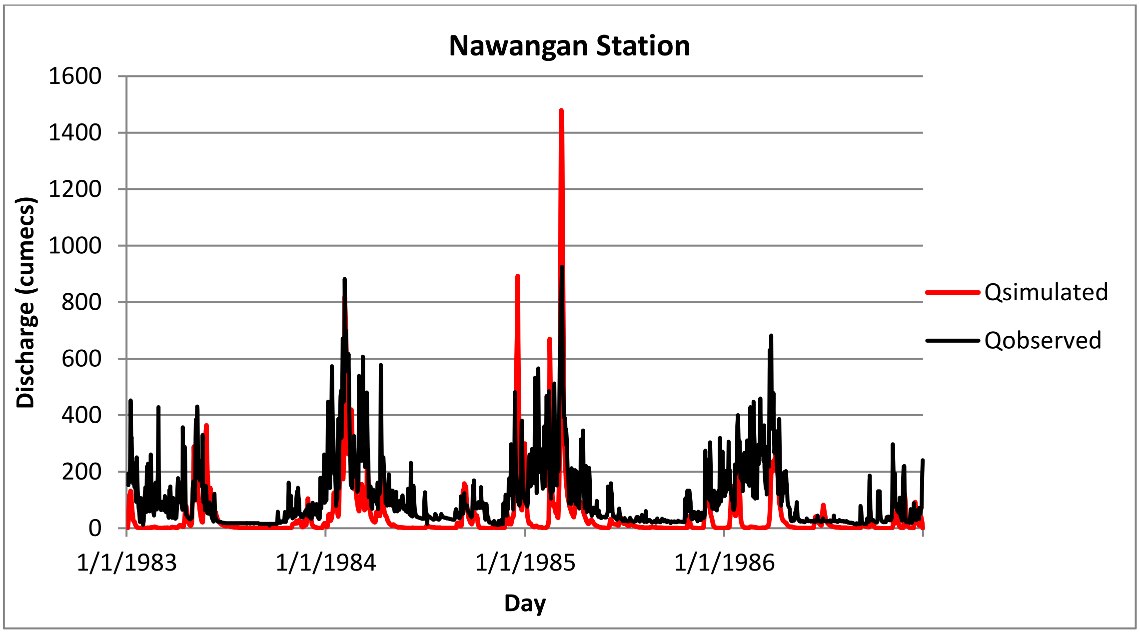


Figure 5. 5. Simulated and observed discharge with rainfall input from Nawangan station 1983 – 1986

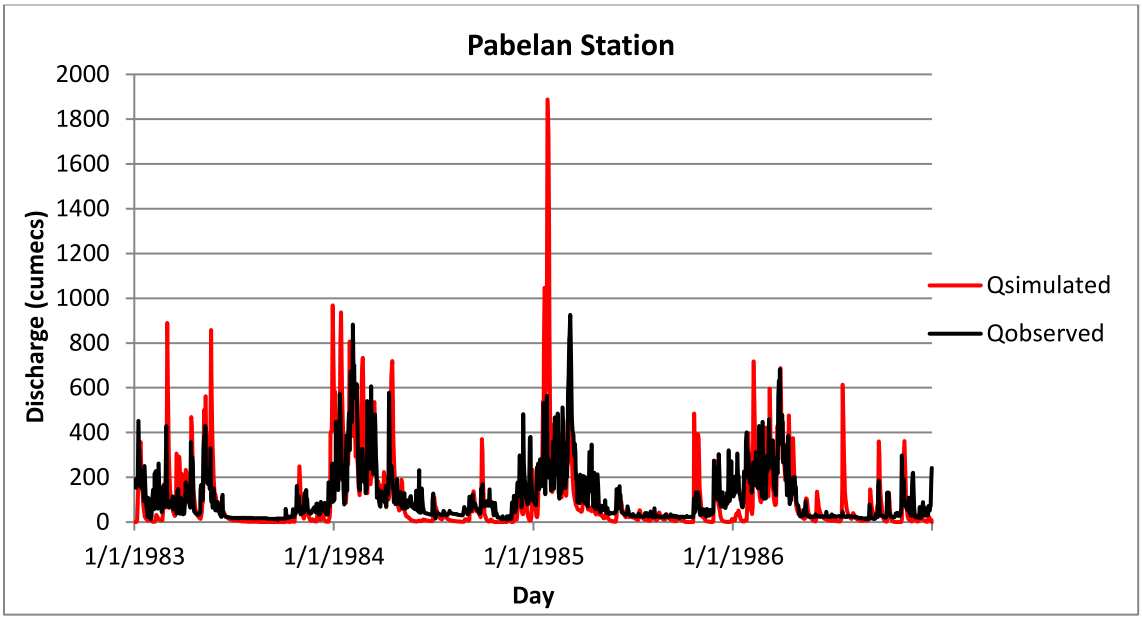


Figure 5. 6. Simulated and observed discharge with rainfall input from Pabelan station 1983 – 1986

Figure 5.6 shows that the simulated peak discharge in 1985 at Pabelan station is much higher than other years. It can be caused by the high daily maximum rainfall at that time in Pabelan station, i.e., 150 mm, that was the highest value when compared to the other years.

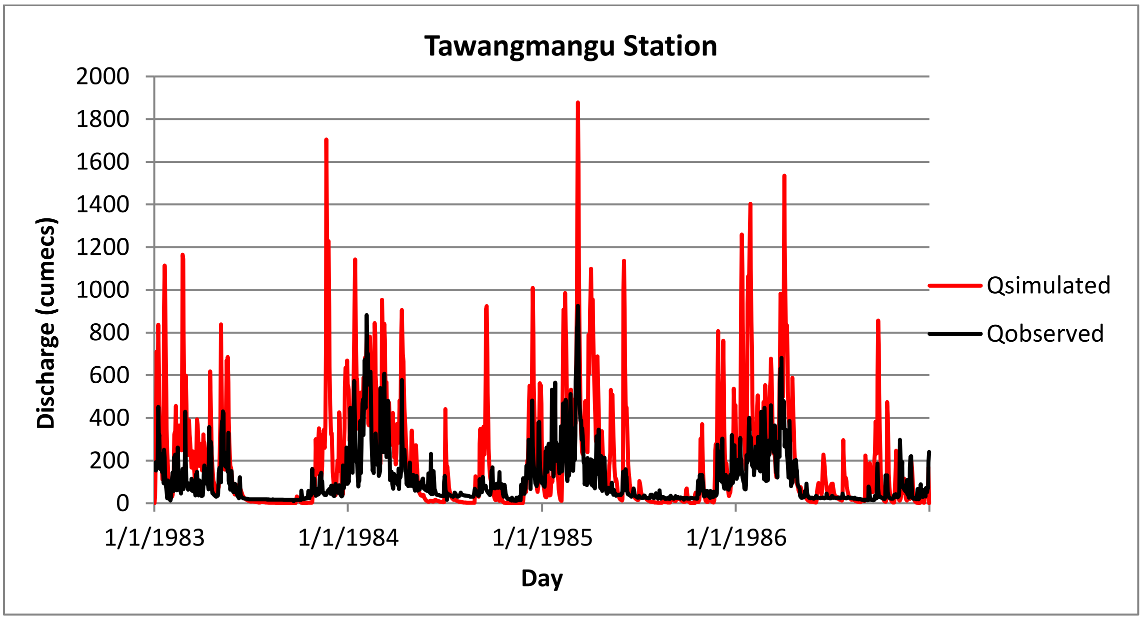


Figure 5. 7. Simulated and observed discharge with rainfall input from Tawangmangu station 1983 – 1986

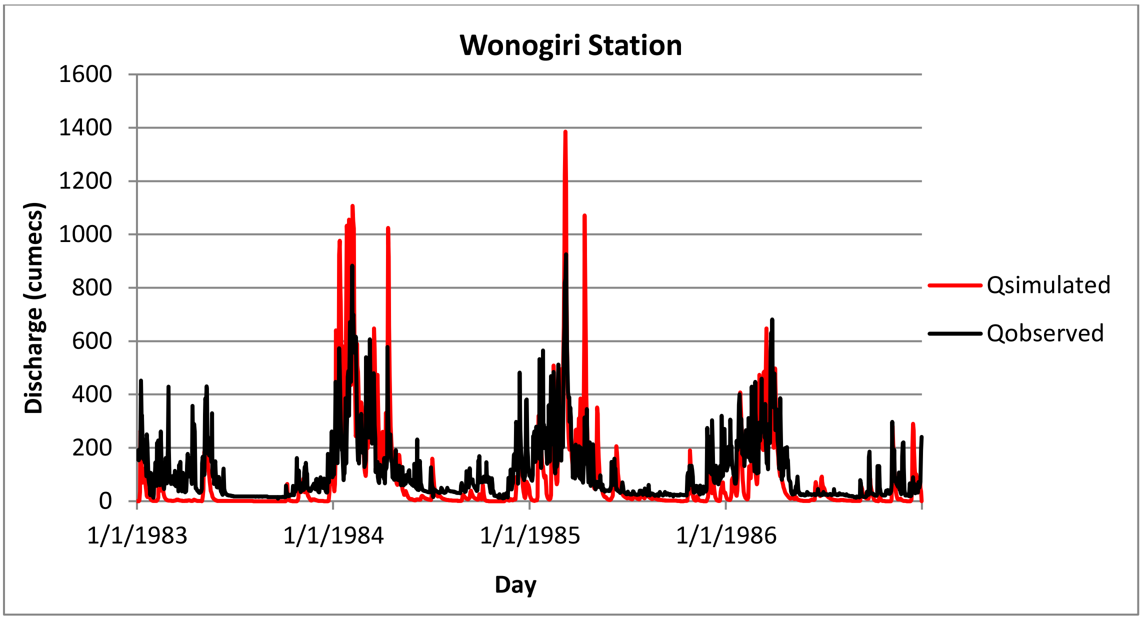


Figure 5. 8. Simulated and observed discharge with rainfall input from Wonogiri station 1983 – 1986

The Nash-Sutcliffe Efficiency (NSE) coefficient is widely used as a measure of goodness-of-fit that is independent of flow magnitude (Zhang et al., 2013). The other value to measure a model performance is the root mean square error (RMSE). The RMSE value demonstrates how much the simulations overestimate or underestimate observed values, stated as a percentage of the average value of the data collected (Đukić & Radić, 2014). RMSE is useful for modelling peak flows if they are the most important, whereas NSE covers all flows (including low flows which are common). The lower the root mean squared error (RMSE), the better the model's performance.

The NSE coefficient can be calculated using formula below.

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(X_{observed,i} - X_{simulated,i}\right)^2}{\sum_{i=1}^{n}\left(X_{observed,i} - mean[X_{observed}]\right)^2} \quad (5.3)$$

where :

NSE	:	Nash-Sutcliffe Efficiency value
$X_{observed}$	:	observed X values
$X_{simulated}$	:	simulated X values

NSE values range from - ∞ to 1. The closer the NSE value to 1, the more accurate the model is.

The RMSE value can be calculated using the following equation.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{observed,i} - X_{simulated,i}\right)^2}{n}} \qquad \textbf{(5.4)}$$

where :

RMSE	:	root mean squared value
$X_{observed}$	:	observed X values
$X_{simulated}$	:	simulated X values

The RMSE check was carried out by comparing the selected peak of observed discharge and the simulated discharge. The threshold x was determined using the following equation (Bezak et.al, 2014).

$$\mathrm{x} = \mu_x + k\sigma_x \qquad \textbf{(5.5)}$$

where:

x	:	the threshold value
μ_x	:	the mean of the observed discharge data
σ_x	:	the standard deviation of the observed discharge data
k	:	frequency factor.

Table 5.6 below presents the Nash-Sutcliffe Efficiency value for simulation using single rainfall input from 17 rain gauging stations in the Upper Bengawan Solo catchment.

Station's Number	Station's Name	NSE
1	Baturetno	0.12
2	Colo	0.01
3	Jatisrono	0.04
4	Kalijambe	-0.37
5	Kalinekuk	-0.01
6	Klaten	0.36
7	Nawangan	0.04
8	Nepen	-0.47
9	Ngancar	0.10
10	Pabelan	-0.18
11	Parangjoho	-0.40
12	Purwantoro	-0.75
13	Songputri	-3.95
14	Sragen	-0.30
15	Tawangmangu	-2.27
16	Wonogiri Dam	-0.03
17	Wonogiri	0.13

Table 5. 8. NSE value for simulation using single station rainfall input from rain gauging stations in Upper Bengawan Solo catchment

It can be seen from the table above that NSE values for simulation using single rainfall input are very low. The highest NSE value for simulation using single rainfall input is 0.36 with rainfall input from Klaten gauging station.

5.2.2. Simulation using multiple rainfall input

The first simulation used rainfall input from single station with rainfall data in 1983 – 1986. The period of 1983 – 1986 was selected by taking into account that during this period all the main stations in Upper Bengawan Solo catchment has complete in situ rainfall data. Using rainfall input from single station in initial SHETRAN simulation was applied because it is simpler than using multiple stations in the first experience of applying SHETRAN simulation in Jurug catchment. The result of simulation using rainfall input from single station produced very low NSE value as shown in Table 5.6, and it is unreliable to use this result to choose which stations would be included in the next simulation using rainfall input from multiple stations.

After implementing simulation using rainfall input using single station in the period of 1983 – 1986, the next simulation will use rainfall input from all stations in this period. Since there are several stations with unsatisfactory cross-correlation, it is required to remove the stations with lowest cross-correlation in the next simulation using rainfall data in 1983 – 1986. The combination of stations in the next simulation using rainfall data in 1983 – 1986 consists of 12, 11, 8, 7, and 5 stations. These combinations are selected based on the cross-correlation value obtained in Chapter 3.

The next simulation applied multiple rainfall input from selected gauging stations for the period of 1983 – 1986. SHETRAN simulation using multiple rainfall input requires setting Thiessen polygon which depends on the stations used as references. The Thiessen polygon is set up in *frd* files. The Thiessen polygon for the seven selected stations is shown in Figure 5.9.

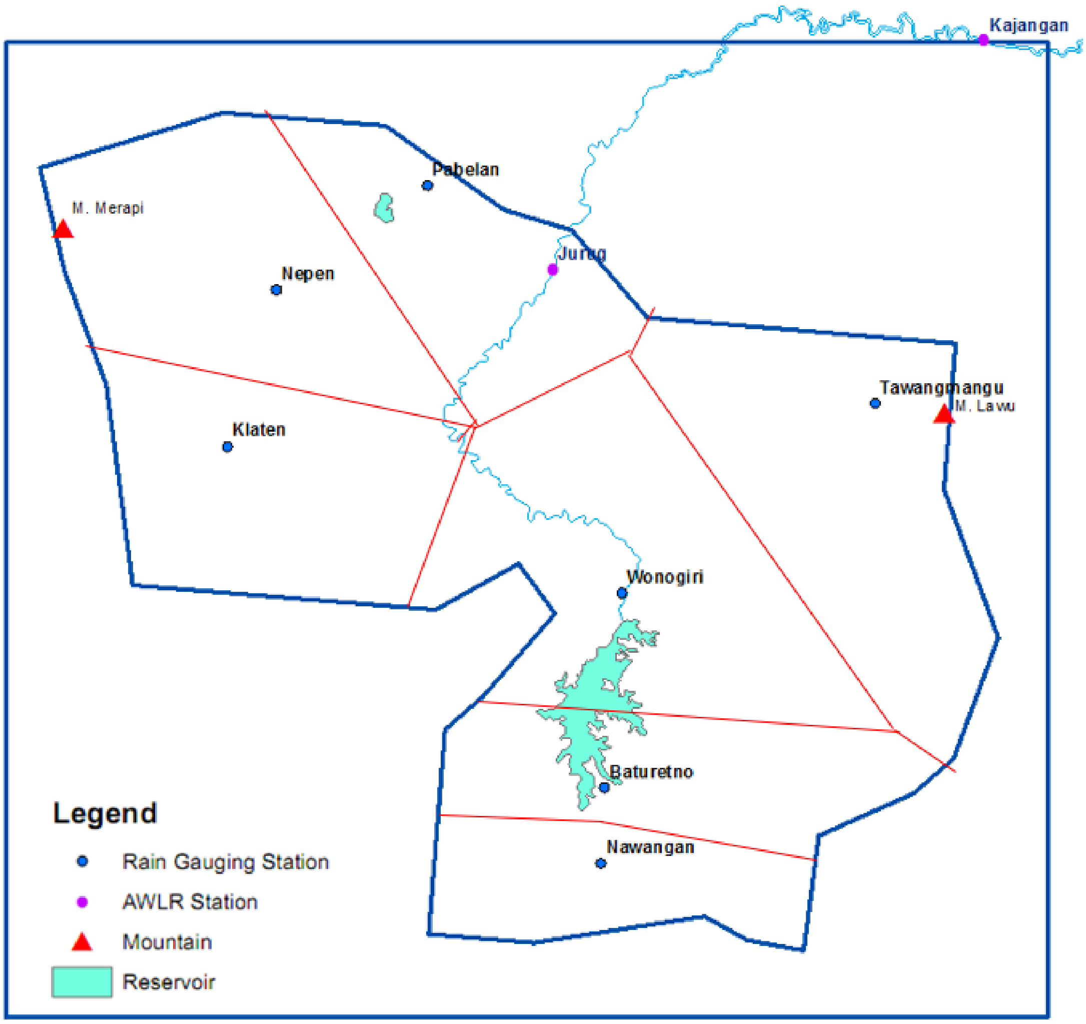


Figure 5. 9. Thiessen Polygon for Areal Rainfall in the Selected Stations.

Figures below show the results of simulation using 17 (all stations), 12, 11, 8, 7, and 5 rain gauging stations for the period of 1983 - 1986.

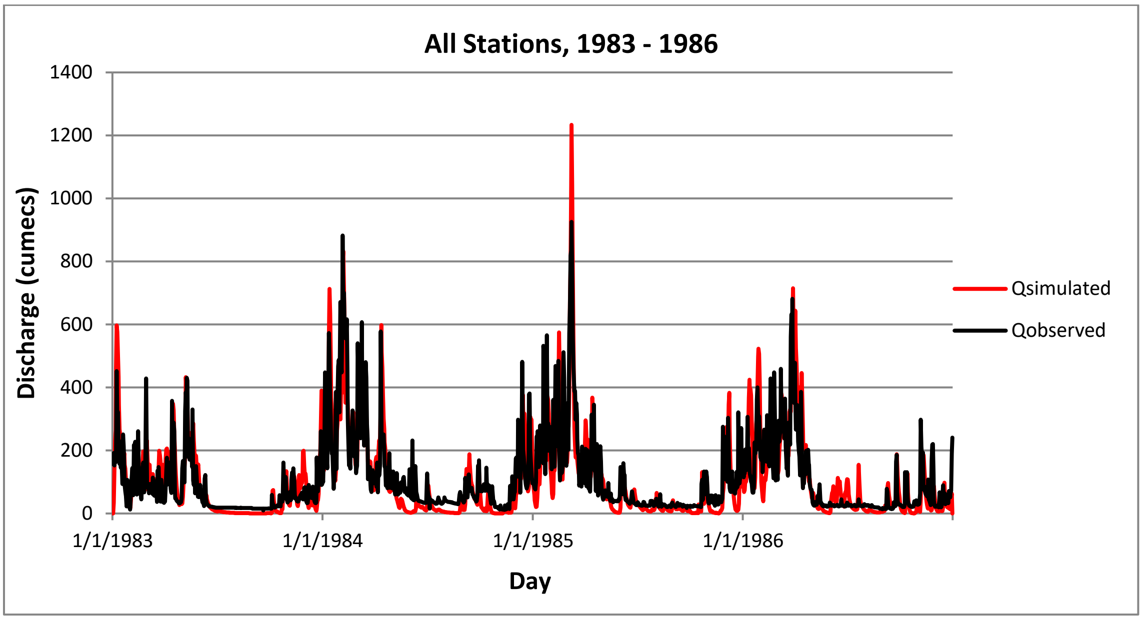


Figure 5. 10. Observed and simulated discharge with rainfall input from all stations in Upper Bengawan Solo catchment in 1983 – 1986

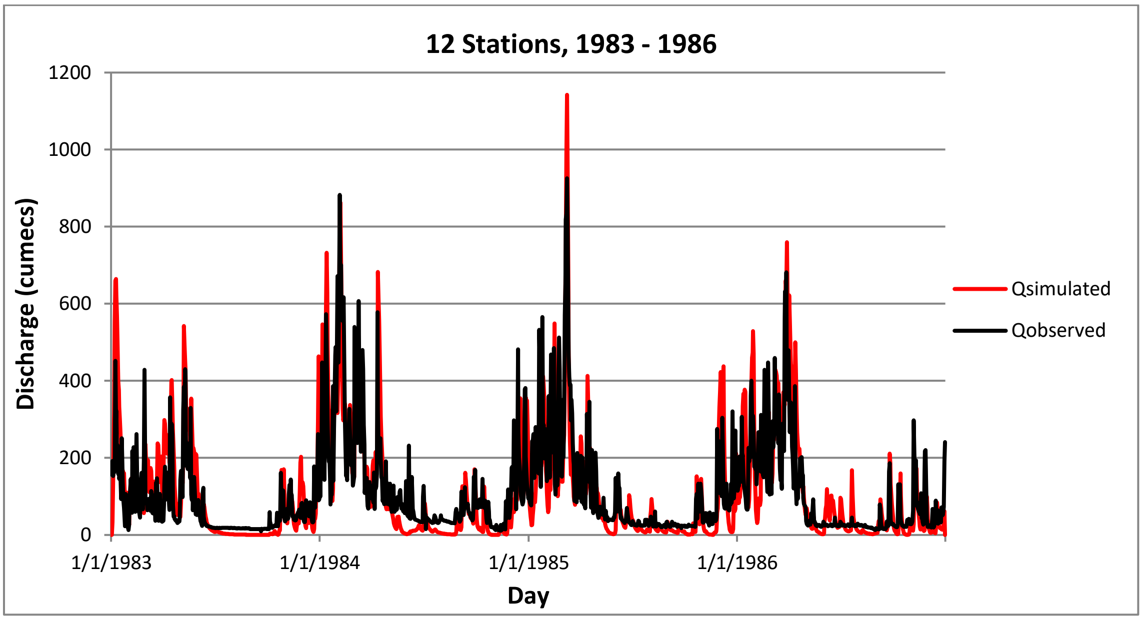


Figure 5. 11. Observed and simulated discharge with rainfall input from 12 stations (stations no. 1,2,3,5,7,8,9,10,12,13,14,17) in Upper Bengawan Solo catchment in 1983 – 1986

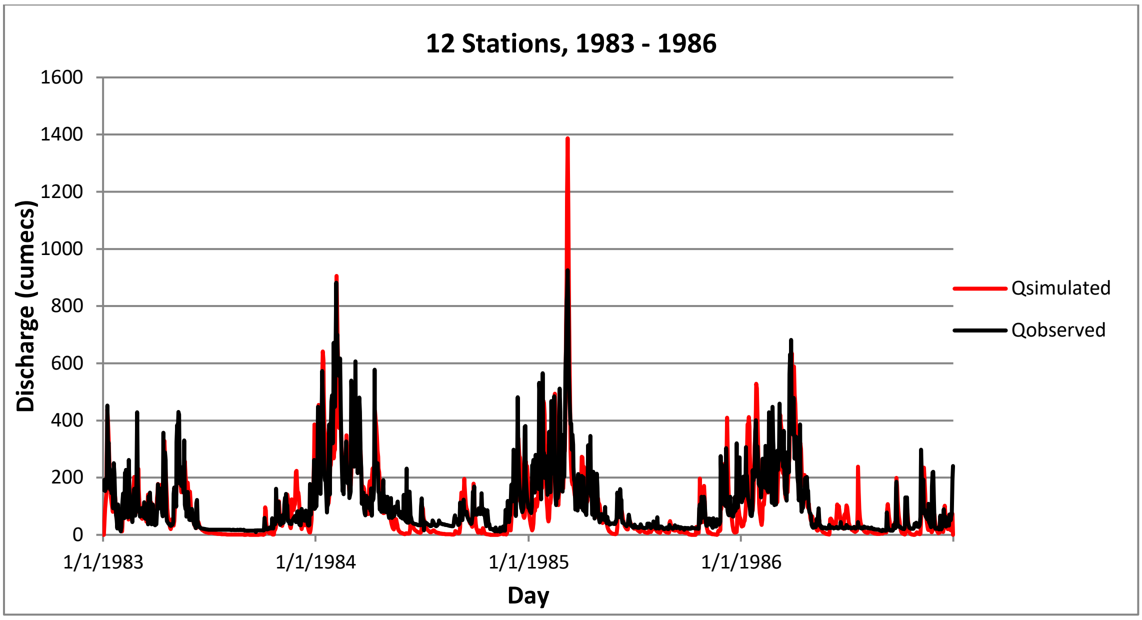


Figure 5. 12. Observed and simulated discharge with rainfall input from 12 stations (stations no. 1,2,3,4,5,6,9,10,11,13,15,16) in Upper Bengawan Solo catchment in 1983 – 1986

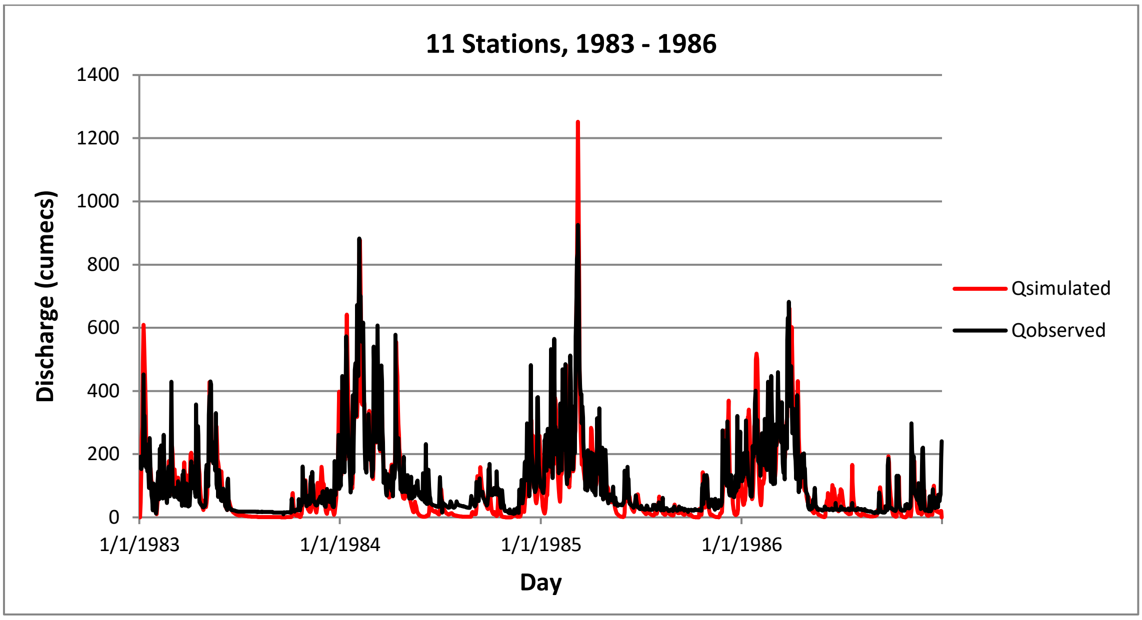


Figure 5. 13. Observed and simulated discharge with rainfall input from 11 stations (stations no. 1,2,3,5,6,7,8,9,10,15,17) in Upper Bengawan Solo catchment in 1983 – 1986

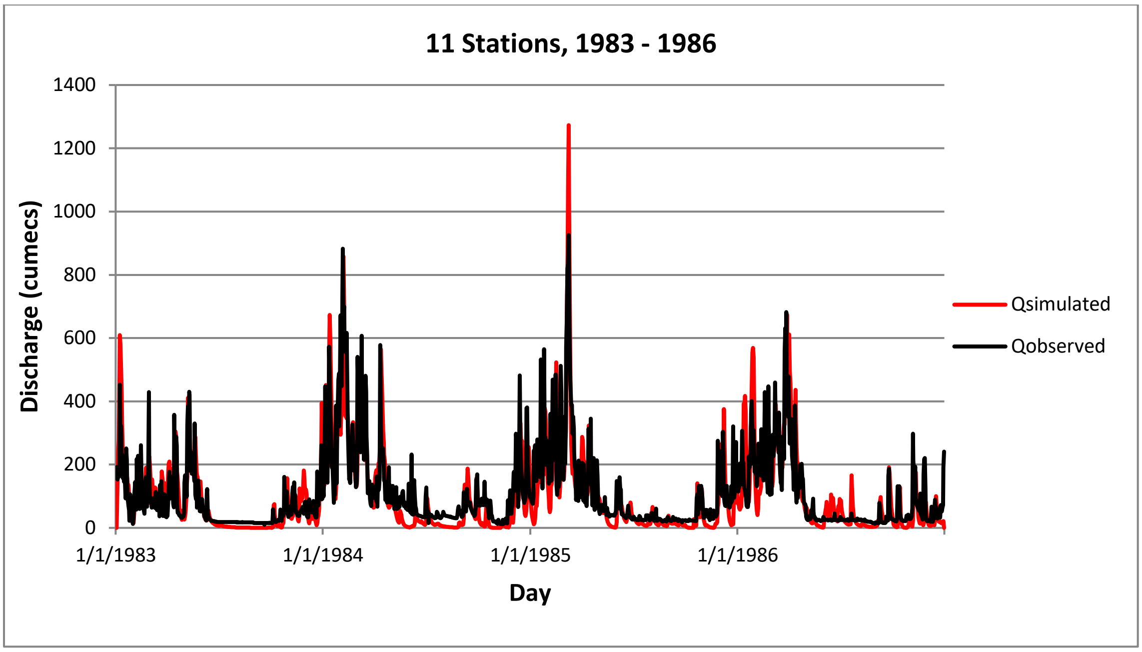


Figure 5. 14. Observed and simulated discharge with rainfall input from 11 stations (stations no. 1,2,3,5,6,8,9,10,11,15,17) in Upper Bengawan Solo catchment in 1983 – 1986

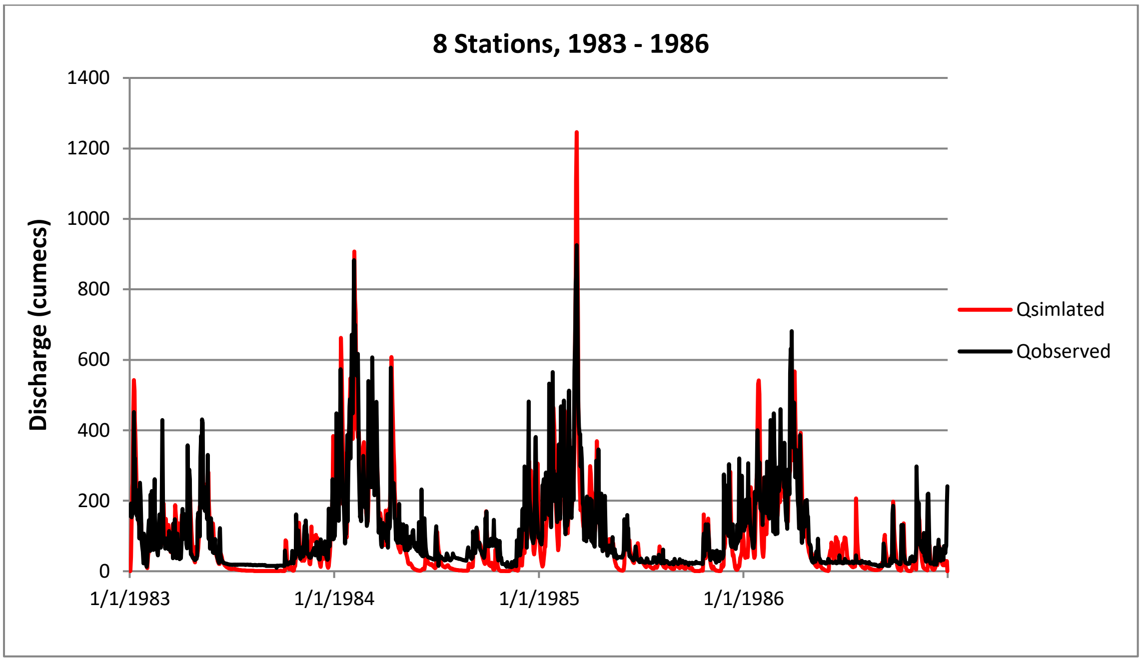


Figure 5. 15. Observed and simulated discharge with rainfall input from 8 stations (stations no. 1,3,6,7,8,10,15,17) in Upper Bengawan Solo catchment in 1983 – 1986

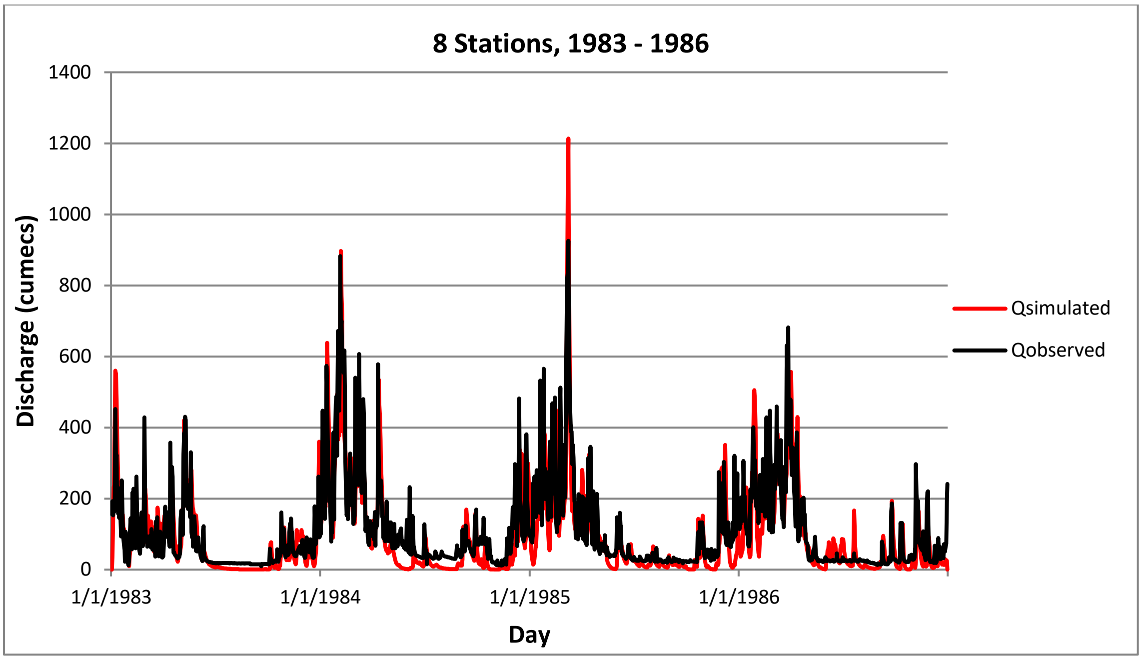


Figure 5. 16. Observed and simulated discharge with rainfall input from 8 stations (stations no. 2,3,6,7,8,10,15,17) in Upper Bengawan Solo catchment in 1983 – 1986

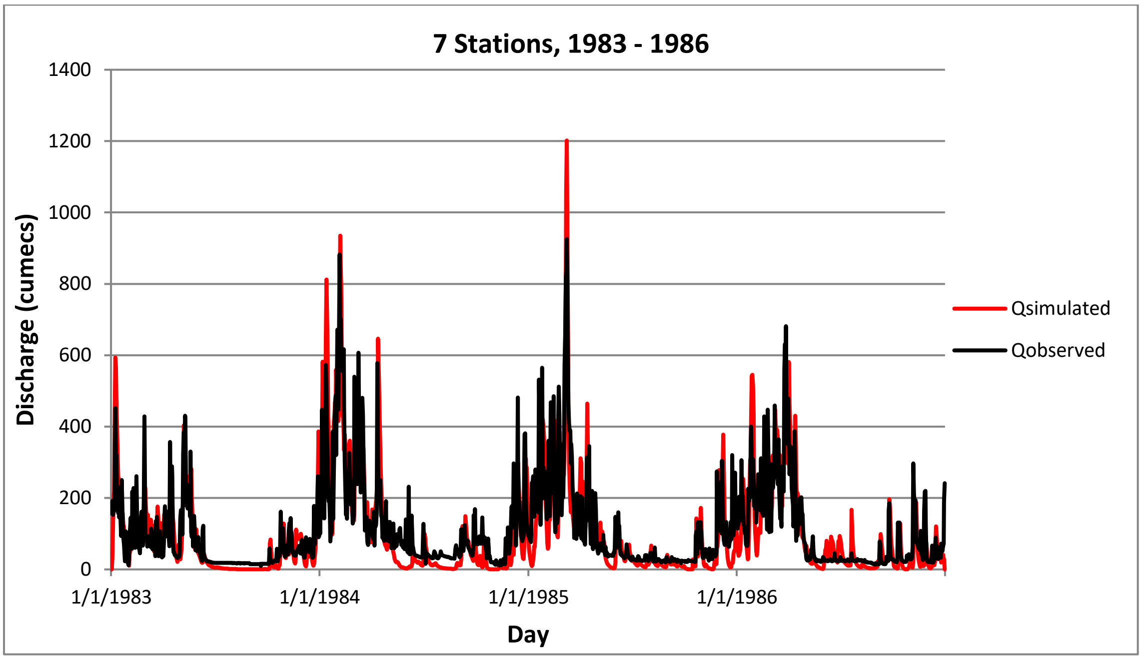


Figure 5. 17. Observed and simulated discharge with rainfall input from 7 stations (stations no. 2,3,6,8,10,15,17) in Upper Bengawan Solo catchment in 1983 – 1986

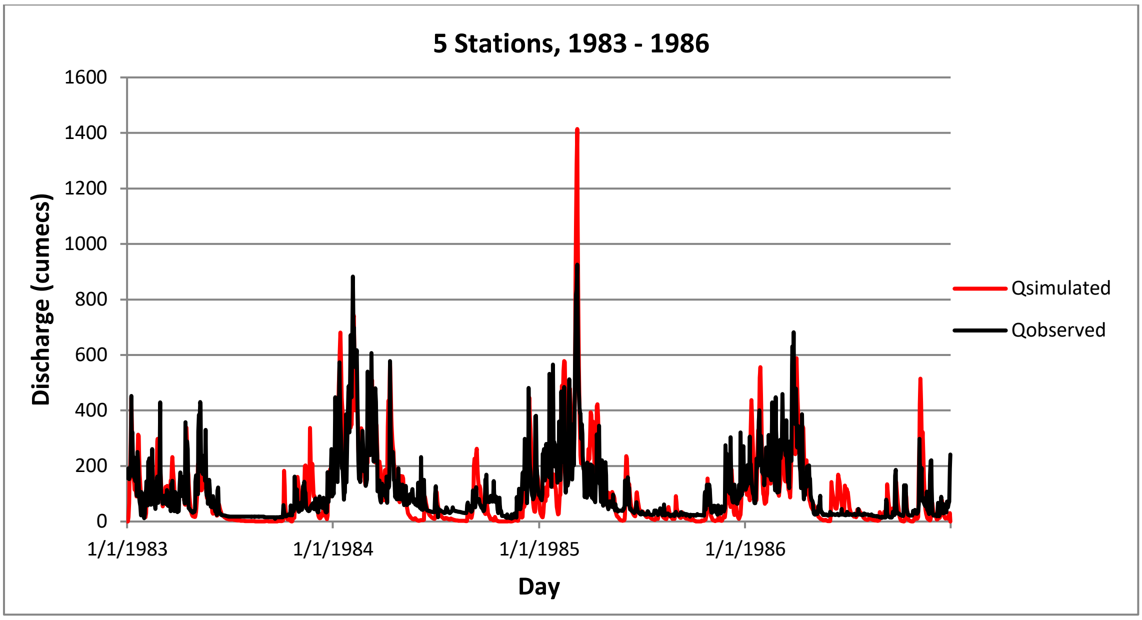


Figure 5. 18. Observed and simulated discharge with rainfall input from 5 stations (stations no. 4, 6, 11, 15, 16) in Upper Bengawan Solo catchment in 1983 – 1986

Charts for other simulation results using different combination of rain gauging stations can be seen in the Appendices.

The tables below show the summary of NSE values for simulation using different multiple rainfall input combination in from year 1983 - 1986.

No	Gauges	NSE
1	Stations : 4, 6, 11, 15, 16	0.59
2	Stations : 7, 8, 12, 14, 17	0.62
3	Stations : 6, 7, 10, 15, 16	0.66
4	Stations : 8, 11, 12, 14, 17	0.56
5	Stations : 4, 12, 13, 14, 16	0.48
6	Stations :1,2,3,5,7,8,9,10,12,13,14,17	0.66
7	Stations : 1,2,3,4,5,6,9,10,11,13,15,16	0.71
8	Stations : 1,2,3,4,5,8,9,11,12,13,14,17	0.62
9	Stations :1,2,3,4,5,6,7,9,10,13,15,16	0.72
10	Stations : 1,2,3,5,6,7,8,9,10,11,15,17	0.74

Table 5. 9. Summary of NSE values for simulation using rainfall input from 5 and 12 stations

For the simulation using rainfall input from 11, 8, and 7 selected rain gauging stations, the Nash-Sutcliffe Efficiency (NSE) value, correlation and RMSE are applied as measure of goodness-of-fit for simulation. Tables below show the summary of NSE, correlation and RMSE for multiple rainfall data in the selected rain stations.

The threshold to check the RMSE value was determined using equation (5.5), and the value is 478.015 cumecs.

Removed gauge	Gauges	NSE	Correlation	RMSE
1	Stations : 2,3,5,6,7,8,9,10,11,15,17	0.73	0.88	175.6
2	Stations : 1,3,5,6,7,8,9,10,11,15,17	0.66	0.86	199.6
3	Stations : 1,2,5,6,7,8,9,10,11,15,17	0.67	0.87	199.6
5	Stations : 1,2,3,6,7,8,9,10,11,15,17	0.74	0.88	182.7
6	Stations : 1,2,3,5,7,8,9,10,11,15,17	0.67	0.86	200.8
7	Stations : 1,2,3,5,6,8,9,10,11,15,17	0.73	0.88	187.0
8	Stations : 1,2,3,5,6,7,9,10,11,15,17	0.71	0.87	191.3
9	Stations : 1,2,3,5,6,7,8,10,11,15,17	0.74	0.88	172.4
10	Stations : 1,2,3,5,6,7,8,9,11,15,17	0.70	0.86	205.0
11	Stations : 1,2,3,5,6,7,8,9,10,15,17	0.75	0.89	179.6
15	Stations : 1,2,3,5,6,7,8,9,10,11,17	0.73	0.88	177.1

Table 5. 10. Summary of NSE, correlation and RMSE values for simulation using rainfall input from 11 stations

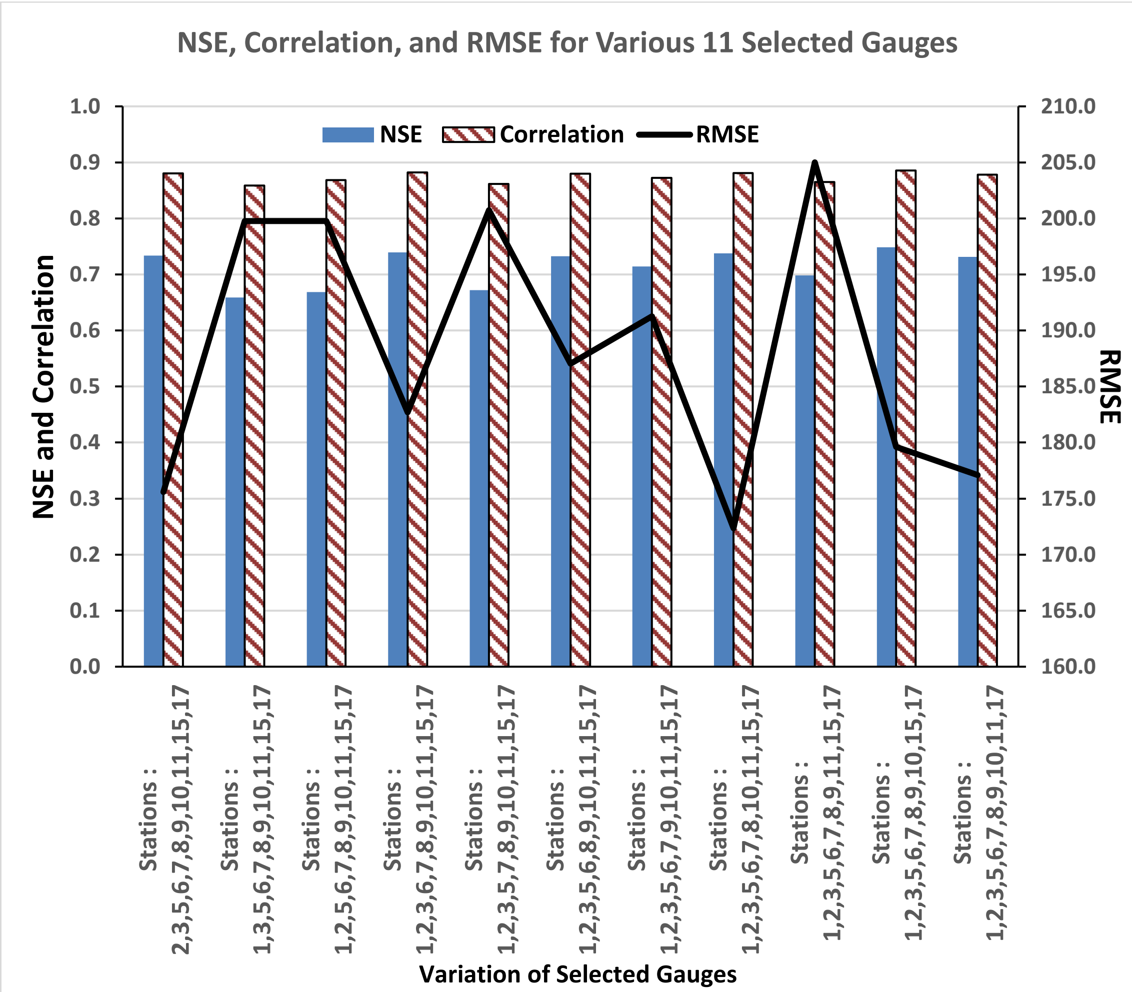


Figure 5. 19. NSE, correlation and RMSE values for simulation using rainfall data at 11 rain gauging stations.

Gauges	NSE	Correlation	RMSE
7 gauges	0.73	0.95	180.1
8 gauges #1	0.76	0.89	175.6
8 gauges #2	0.76	0.89	167.5
8 gauges #3	0.76	0.89	175.4
9 gauges	0.76	0.89	171.6

Table 5. 11. Summary of NSE, correlation and RMSE values for simulation using rainfall input from 10, 9, 8, and stations

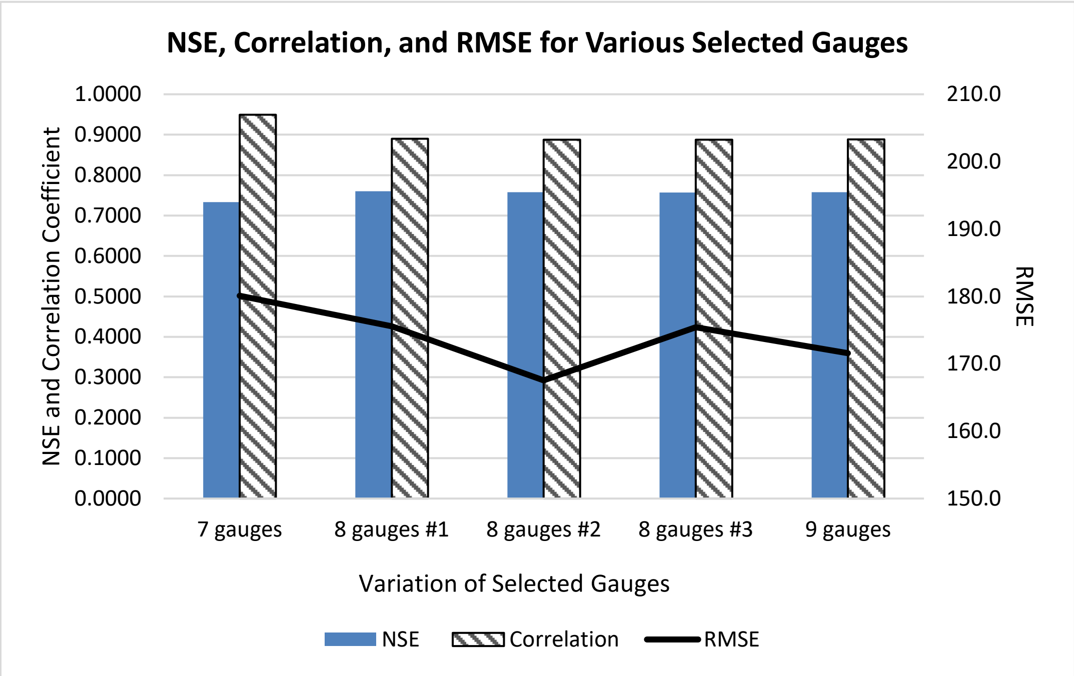


Figure 5. 20. NSE, correlation coefficient and RMSE values for simulation using rainfall data at selected 7, 8, and 9 rain gauging stations.

The simulation using rainfall input from 17 stations with data period of 1983 – 1986 resulted in the most satisfactory NSE value of 0.73.

In addition, simulation using rainfall input from 12 gauging stations in 1983 – 1986 produced NSE values range between 0.62 – 0.74. Whereas the simulation using rainfall input from 11 gauging stations resulted NSE values range between 0.67 – 0.75. The NSE value goes down when the simulation implemented using rainfall input from 5 gauging stations, with NSE values range between 0.48 – 0.66.

Based on the NSE and RMSE values, the best results were obtained using 8 rainfall stations. Whereas, the best result according to the correlation values was the simulation using rainfall data at the 7 rain gauging stations, i.e., 0.95. It is not entirely obvious why 8 stations is better than 7. It seems some of the rainfall stations had errors or missing values: this is considered in more detail in the next chapter.

Moreover, as described in Chapter 3, there are significant data gaps at some gauging stations in 1975 – 2009. In hydrological analysis involving rainfall input in a catchment, average rainfall from long record involving representative gauging networks in the catchment is an important parameter because the runoff flowing along the channel or river does not come from single point rainfall only. From 17 main gauging stations in the catchment, there are only 6 gauging stations have complete data in the longest period (1975 – 2009), i.e. Kalijambe, Klaten, Nawangan, Nepen, Pabelan, and Tawangmangu. From these 6 lists, Kalijambe station has the worst cross correlation.

The next chapter will described the SHETRAN simulation using longer periods of *in situ* rainfall input as well as the remotely sensed TRMM 3-hourly rainfall data for the period 1998 - 2000.

5.3. Summary

The parameters used in SHETRAN simulation for this research were set up based on the information obtained from SHETRAN Version 4 Data Requirements, Data Processing and Paramater values, with calibration for the several parameters such as Strickler roughness coefficient, soil saturated conductivities, and rice paddy field. The first SHETRAN simulation used single rainfall input from 17 rain gauging stations, with rainfall recorded in 1983 – 1986. This period was selected because all the rain gauging stations have complete record (with few months in-filled rainfall data in Baturetno). The simulation using single station rainfall input produced very low NSE value, with some of the stations provided minus NSE value. Thus it was unreliable to use this result as consideration to select the stations used for the next simulation using rainfall input from multiple gauging stations.

The simulation using rainfall input from 17 gauging stations with rainfall data from 1983 – 1986 produced satisfactory NSE value, i.e. 0.73. However, the record length was too short. Based on NSE result produced from simulation using different combinations of multiple stations, the simulation using 8 stations produced the most satisfactory NSE and RMSE values. Therefore, in the next simulation described in Chapter 6, these 8 rain gauging stations (i.e., Baturetno, Jatisrono, Klaten, Nawangan, Nepen, Pabelan, Tawangmangu, and Wonogiri) were selected for the rainfall input with longer data record.

Chapter 6. Improving rainfall input for SHETRAN simulation

This chapter describes the procedure of optimizing the choice of rainfall network for SHETRAN simulation and correcting the in situ discharge data which contains errors from 1990. Furthermore, the application of TRMM 3-hourly data in 1998 – 2000 as rainfall input for SHETRAN simulation is explained in this chapter.

6.1. Choosing an optimum rain gauge network

As described in the previous chapter, the rainfall data used in the simulation are those available in the Upper Bengawan Solo catchment. The chart below shows the cross correlation between all rain gauging stations (17 stations) in the Upper Bengawan Solo catchment, using rainfall data period of 1983 – 1986 which was used in the previous chapter.

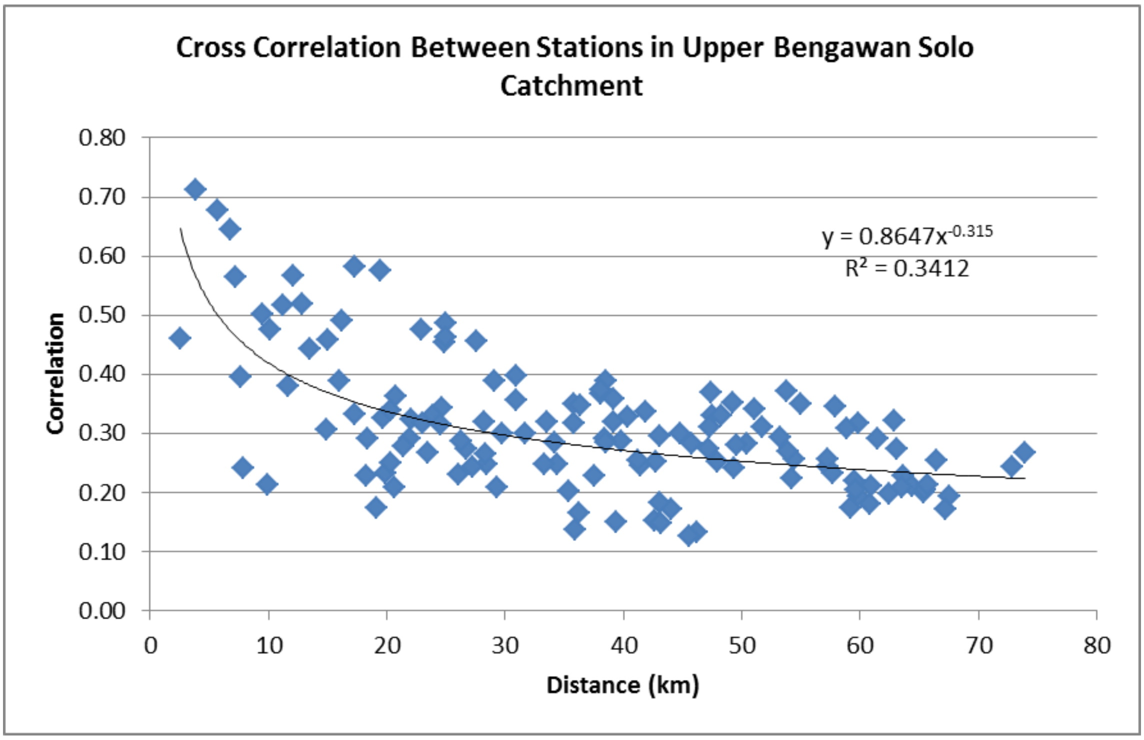


Figure 6. 1. Plot of cross correlation between rain gauging stations in Upper Bengawan Solo catchment

In this case, the rainfall data period is selected from 1983 – 1986 because the record is complete for all rain gauging stations in this period.

As expected, the cross-correlation between rainfall series falls off with the distance between rainfall stations according to a power law. As can be seen from Figure 6.1, the coefficient of determination (R^2) of the plot is 0.34, which indicates a high degree of scatter. The five highest cross correlation values are 0.71, 0.68, 0.64, 0.57 (2 pairs), and 0.56 which can be seen on the table in Chapter 3 and these are for pairs of nearest neighbour rainfall stations. The highest cross correlation occurs between Parangjoho and Songputri stations. The second highest occurs between Ngancar and Kalinekuk stations, followed by Kalinekuk and Baturetno, Parangjoho and Kalinekuk, Ngancar and Baturetno, and Nawangan and Baturetno. Burton *et al* (2013) estimated cross correlations for UK rainfall stations and found considerably higher values, with typical cross-correlation of around 0.6 for 100 km distance between stations in winter and 0.5 at the same distance in summer. In this catchment the correlation at 100 km is considerably lower at around 0.2. The localised convective nature of the rainfall in this catchment is the most likely cause and this makes the modelling of the catchment and choice of rainfall series more difficult.

In the case of gauging stations network in the Upper Bengawan Solo catchment, from Figure 6.1 it can be seen that there are some closer stations which have lower cross correlation value than stations with longer distance. The low cross correlation of rainfall data between rain gauging stations could be caused by various factors including human error in measurement or transcribing data, gauge relocation, damaged gauges or poor exposure. In a catchment area, generally there is more than one rain gauging station placed in the catchment. High quality rainfall data are essential for the hydrological which is being undertaken here.

From the initial simulations described in the previous chapter, simulation using single rainfall inputs produced low NSE values for all rain gauging stations used as a reference. In applying SHETRAN simulation, rainfall input is crucially important to obtain good simulation results, and particularly so for flood events. Considering that there are 17 rain gauging stations in the research location, and the cross correlation of rainfall between the stations is not satisfactory, the optimum stations network must be obtained to maximise the quality of the simulation results.

During the period 1983 – 1986, stations Kalinekuk, Ngancar, Songputri, Parangjoho contribute higher cross correlation than other gauging stations. However, the rainfall data series at these gauging stations are not as complete as other stations, with long data gaps. Therefore, these four stations have been removed from the list. The others to be removed due to data incompleteness are Colo, Kalijambe, Purwantoro, Sragen and Wonogiri Dam stations. Taking into account longer data series (20 years period), and considering the first SHETRAN simulation result described in previous chapter, 8 stations have been chosen to be used as references for rainfall data input in the next phase of simulation. These 8 rain gauging stations are Baturetno, Jatisrono, Klaten, Nawangan, Nepen, Pabelan, Tawangmangu, and Wonogiri. These rain gauging stations have complete daily rainfall data during period 1980 – 2000. However, there is a several month long data gap in Baturetno rain gauging station which has been infilled using the method described in Chapter 3.

The location of the selected stations is presented in the Figure 6.2 below.

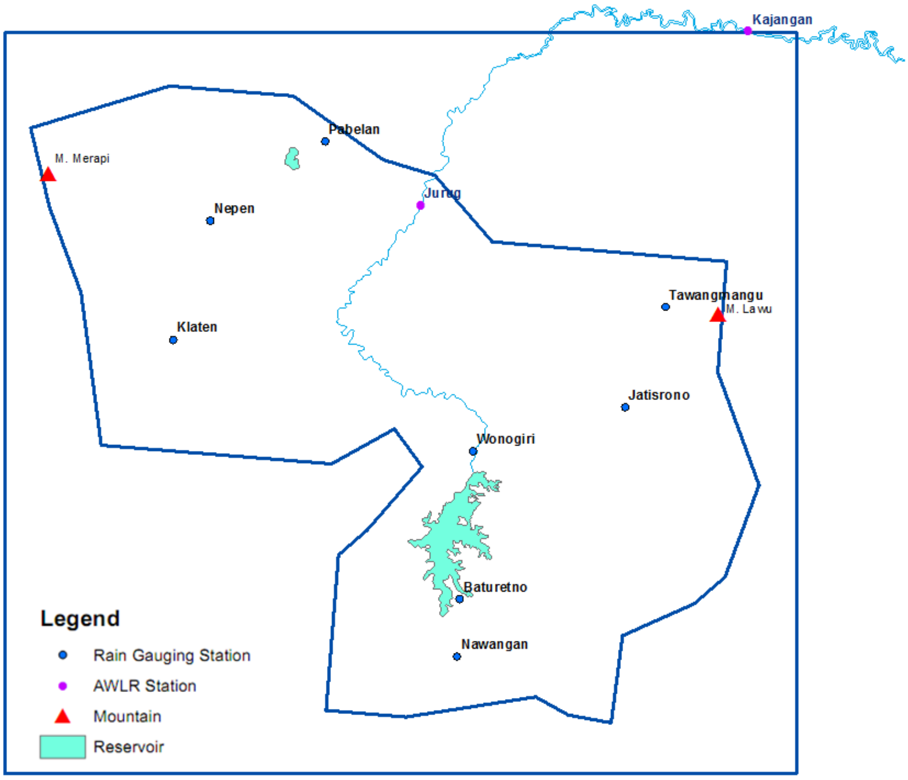


Figure 6. 2. Location of selected rain gauging stations in Upper Bengawan Solo catchment

Table 6.1 below shows the summary of mean and standard deviation of annual rainfall at the 8 rain gauging stations in 1980 – 2000. The period is divided into 4, *i.e.* in 1980 – 1984, 1985 – 1989, 1990 – 1994, and 1995 – 2000. It can be seen from the table that standard deviations at several stations in periods of 1990 – 1994 and 1995 – 2000 are higher than the previous periods.

Periods	Statistics	Preferred Rain Gauging Stations							
		Baturetno	Jatisrono	Klaten	Nawangan	Nepen	Pabelan	Tawangmangu	Wonogiri
1980 - 1984	Mean (mm)	1574.5	2245.4	1832.0	1676.0	2668.2	2413.4	2964.2	1655.5
	Standard deviation	385.3	518.3	287.1	323.6	320.6	89.0	473.0	635.5
1985 - 1989	Mean (mm)	1472.9	2155.6	1821.2	1572.8	2500.8	2226.7	3243.3	1920.9
	Standard deviation	95.5	263.8	231.9	201.1	258.4	232.8	198.1	287.8
1990 - 1994	Mean (mm)	1651.6	1941.6	1536.8	1619.1	1999.8	2187.9	2922.9	1718.9
	Standard deviation	456.9	381.7	332.7	194.0	416.6	344.8	534.3	452.3
1995 - 2000	Mean (mm)	1700.8	2166.8	1701.7	1829.0	2537.6	2071.8	3337.0	2083.1
	Standard deviation	482.7	445.6	362.6	789.4	865.2	636.0	602.2	516.8

Table 6. 1. Mean and standard deviation of annual rainfall at 8 selected rain gauging stations

The cross correlation values of rainfall data in 1980 – 2000 between the 8 selected rain gauging stations can be seen on the Table 6.2 below.

Stations	Baturetno	Jatisrono	Klaten	Nawangan	Nepen	Pabelan	Tawangmangu	Wonogiri
Baturetno	1.00							
Jatisrono	0.33	1.00						
Klaten	0.28	0.33	1.00					
Nawangan	0.42	0.33	0.30	1.00				
Nepen	0.23	0.29	0.34	0.22	1.00			
Pabelan	0.21	0.31	0.33	0.24	0.42	1.00		
Tawangmangu	0.30	0.41	0.35	0.33	0.29	0.30	1.00	
Wonogiri	0.28	0.32	0.28	0.26	0.24	0.23	0.30	1.00

Table 6. 2. Cross correlation value of rainfall data in 1980 – 2000 at 8 selected rain gauging stations.

The plot of cross correlation versus inter-station distance is presented in the figure below.

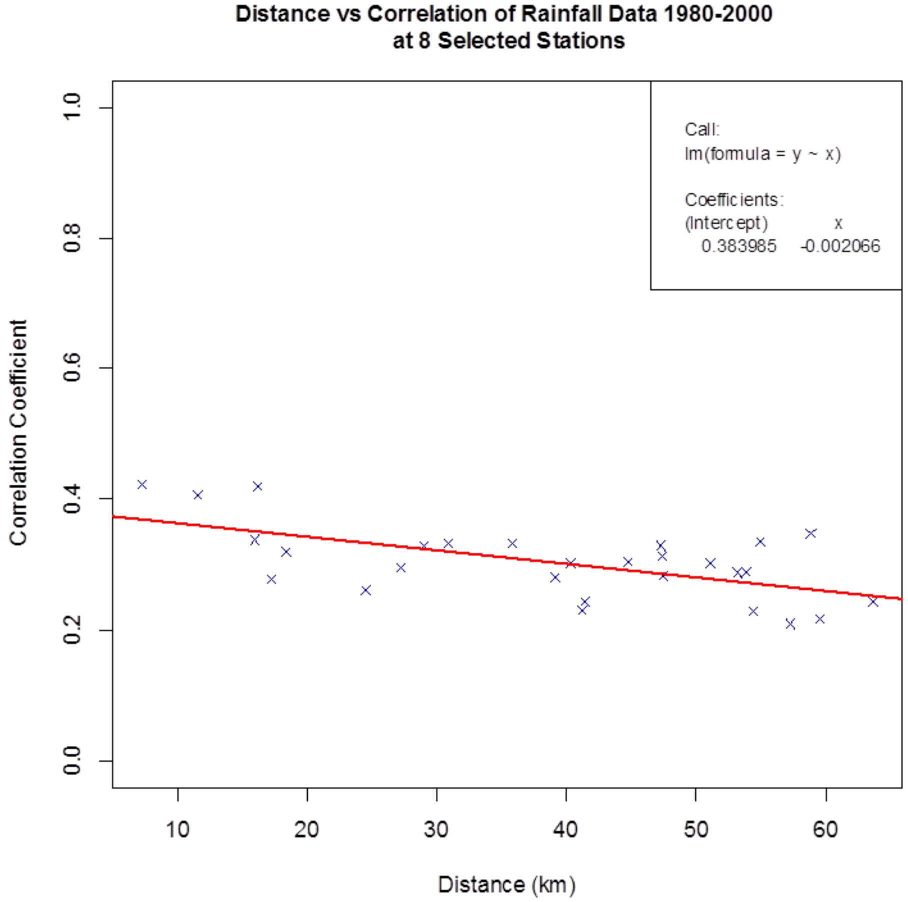


Figure 6. 3. Plot of cross correlation at 8 selected rain gauging stations

As can be seen on the Table 6.2 and Figure 6.3 above, the cross correlation between stations is below 0.5 although the data series in these rain gauging stations are more complete for longer periods than for the removed stations. However, these data were still used as rainfall input for SHETRAN simulation because the data are the only in situ data available from the research location.

Besides in situ rainfall data from selected rain gauging stations, the SHETRAN simulation in this phase applied existing original land use.as vegetation input. The original land use map and vegetation parameter can be seen in Chapter 5. The charts below show the result of SHETRAN simulation using existing original land use for the Jurug catchment and rainfall input from 8 selected rain gauging stations in 1980 – 1984, 1985 – 1989, 1990 – 1994, 1995 – 2000.

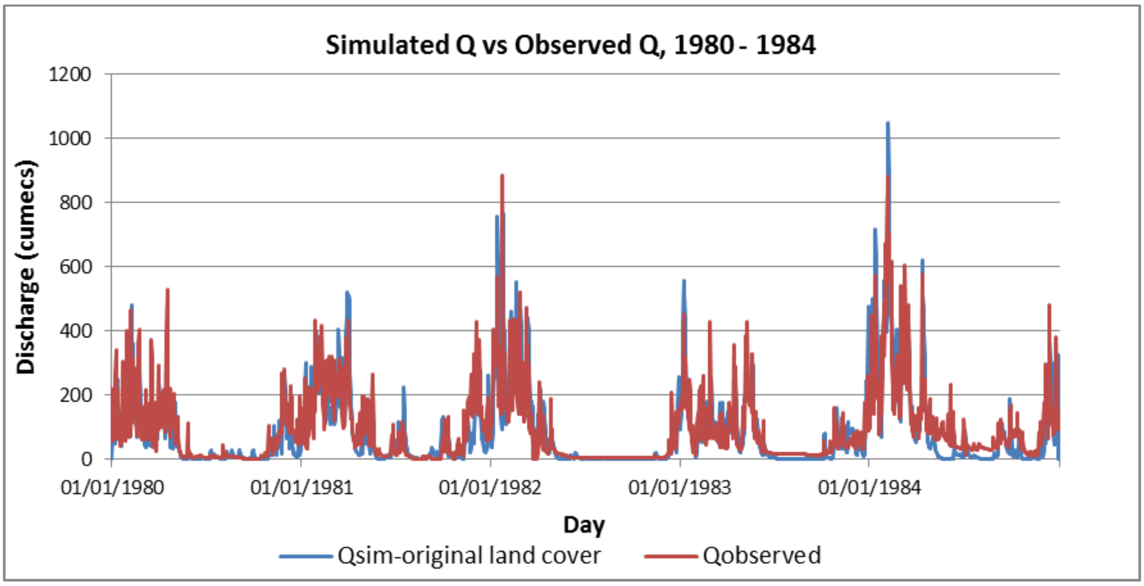


Figure 6. 4. Simulated versus observed discharge using rainfall input 1980 – 1984

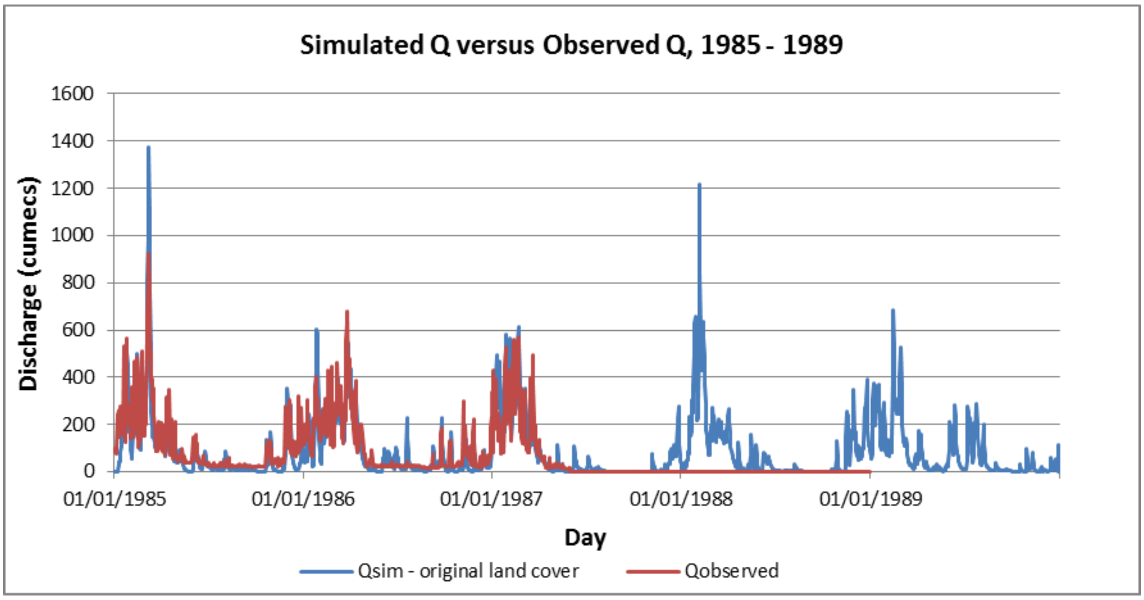


Figure 6. 5. Simulated versus observed discharge using rainfall Input 1985 – 1989

The observed discharge in 1987 – 1989 is zero because there is no water level data record during these periods.

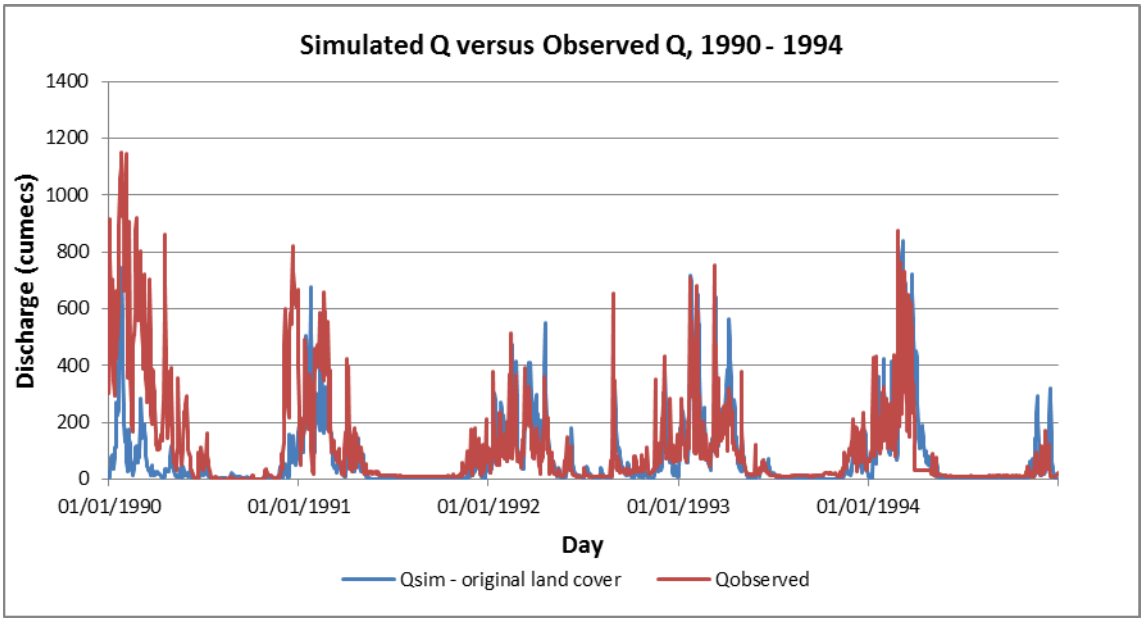


Figure 6. 6. Simulated versus observed discharge using rainfall input 1990 – 1994

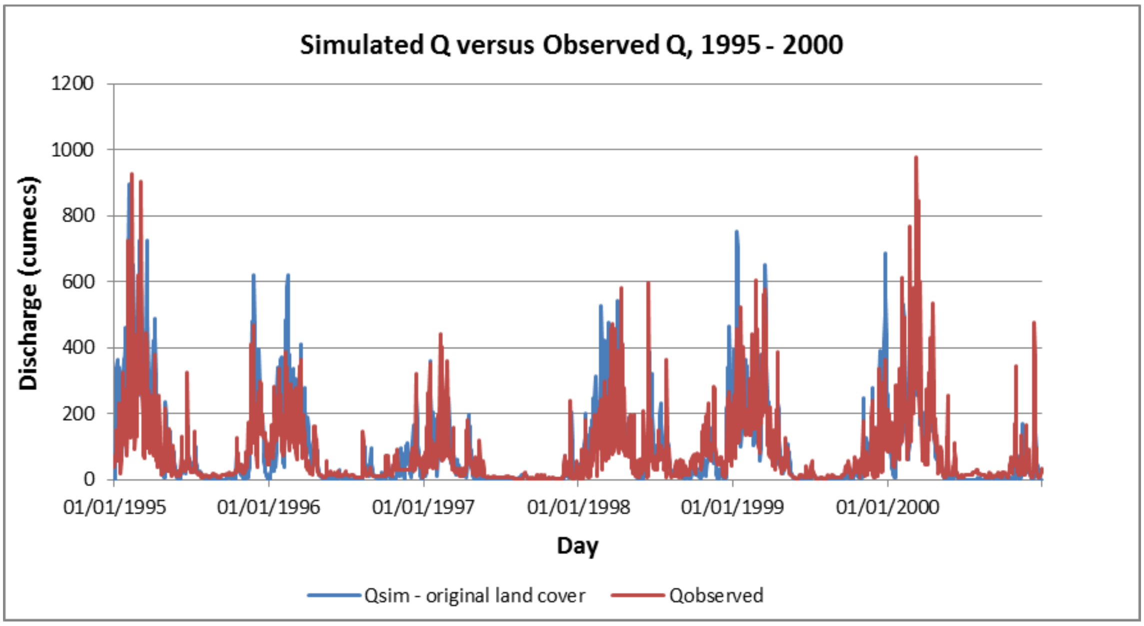


Figure 6. 7. Simulated versus observed discharge using rainfall input 1995 – 2000

Table 6.3 below shows the NSE value between simulated discharge and observed discharge of the simulation in this phase.

Period	NSE
1980 - 1984	0.73
1985 - 1989	0.71
1990 - 1994	0.58
1995 -2000	0.49

Table 6. 3. NSE value of simulation result with rainfall input from 8 Stations

It can be seen from Table 6.3 that the NSE values of simulation results using rainfall input during periods 1980 – 1984 and 1985 – 1989 are satisfactory, respectively 0.73 and 0.71. On the other hand, the simulation result using rainfall input from 1990 – 1994 and 1995 – 2000 gave lower NSE values, i.e. 0.58 and 0.49.

6.2. In situ discharge data correction

Based on the analysis of annual discharge from 1976 to 2009 as described previously in Chapter 3, the annual discharge in Jurug gauging station in 1990 and 1991 is different from the other years. The annual discharge in 1990 is much higher than other years. The observed discharge in this year is almost doubled compared to other years and it producing rainfall runoff ratios greater than 1.0 as can be seen in Figure 6.8 below. These data have therefore been removed. During the period of 1987 – 1989, there was no recorded discharge data in Jurug station, because of the broken gauge.

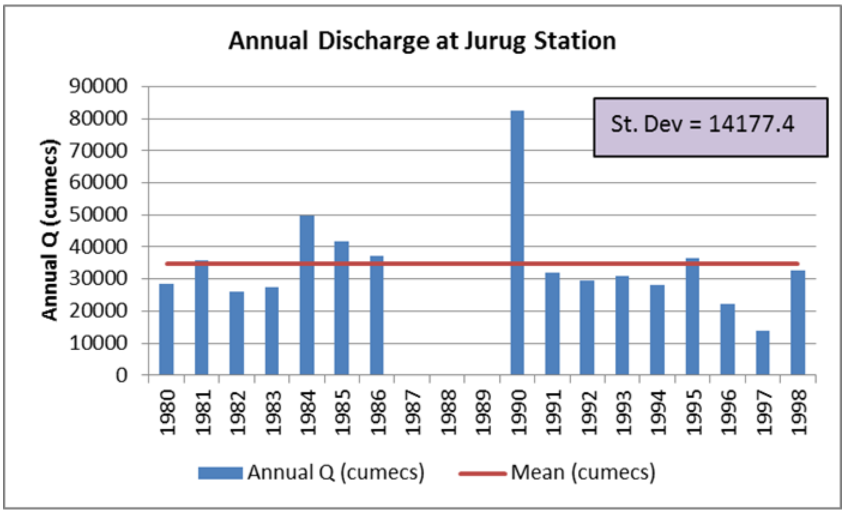


Figure 6. 8. Annual discharge at Jurug station in 1980 – 1998, with Q_{mean} = 34681.7 m^3 s^{-1} and standard deviation = 14177.1

However, there also seemed to be a problem with data from 1992 – 2000, so other discharges data from the nearest neighbouring station, i.e. Kajangan station, were used for comparison. Kajangan gauging station which is situated downstream of Jurug gauging station has a catchment area of about 5463 km^2. The comparison of annual discharge (in mm equivalent) at Jurug and Kajangan stations in 1980 – 1998 is presented in the chart below.

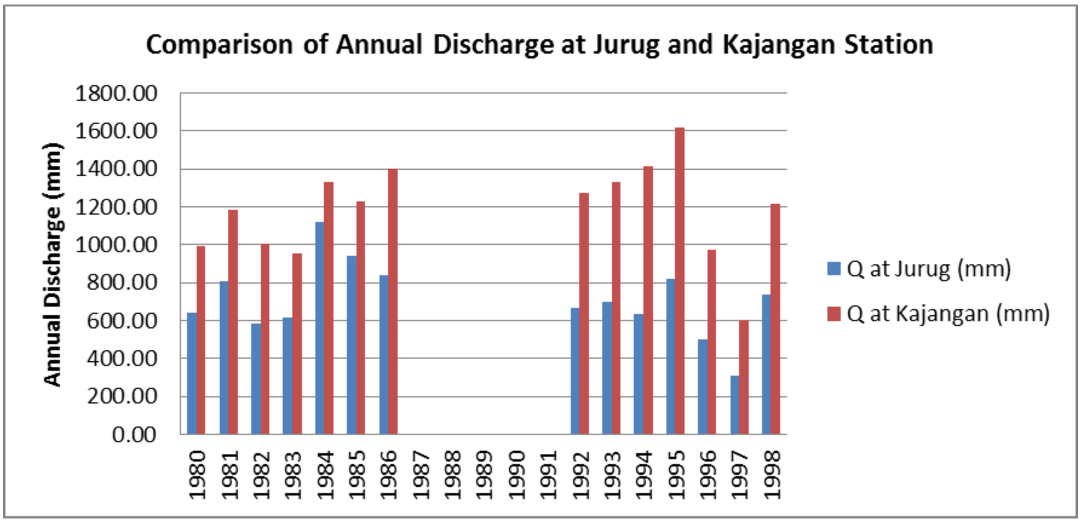


Figure 6. 9. Annual discharge at Jurug and Kajangan stations in 1980 – 1998

During the period 1980 – 1998, the data record at Kajangan gauging station is complete, whereas at Jurug gauging station, there are 5 years of data missing in that period. Therefore, the comparison was carried out for the period 1980 – 1986 and 1992 – 1998 where both gauging stations have a complete data record.

The ratio of difference between Jurug and Kajangan stations is obtained from:

$$\text{ratio} = \frac{Q_{\text{Kajangan}}}{Q_{\text{Jurug}}} \qquad \textbf{(6.1)}$$

where :

$Q_{Kajangan}$ = discharge at Kajangan station

Q_{Jurug} = discharge at Jurug station

The tables below show the ratio of difference between discharge per catchment area for Jurug and Kajangan stations, for years 1980 – 1986 and years 1992 – 1998.

Year	Q at Jurug (mm)	Q at Kajangan (mm)	Ratio
1980	638.95	989.19	1.55
1981	808.33	1182.47	1.46
1982	585.09	1001.71	1.71
1983	617.05	955.80	1.55
1984	1122.46	1329.87	1.18
1985	941.86	1230.49	1.31
1986	835.94	1397.97	1.67
		Average =	1.49

Table 6. 4. Annual discharge per catchment area for Jurug and Kajangan stations in 1980 – 1986

Year	Q at Jurug (mm)	Q at Kajangan (mm)	Ratio
1992	664.63	1270.94	1.91
1993	699.53	1329.31	1.90
1994	636.23	1411.21	2.22
1995	818.41	1616.65	1.98
1996	501.90	969.97	1.93
1997	312.18	605.65	1.94
1998	738.34	1217.64	1.65
		Average =	1.93

Table 6. 5. Annual discharge per catchment area for Jurug and Kajangan Stations in 1992 – 1998

Since the discharge at Jurug station in year 1990 seems to be in error which might be caused by human error or damaged gauge, a correction is required for the discharge at Jurug station from 1992 onwards. The correction is applied from 1992 onwards instead of from 1990, because the data for 1990 – 1991 are not complete. The ratio between periods 1980 – 1986 and 1992 – 1998 is applied as a correction factor calculated as: 1.93 / 1.49 = 1.30

The table below shows the discharge per catchment area in years 1992 – 1998 after being corrected by this factor, 1.30.

Year	Q at Jurug (mm)	Q at Kajangan (mm)	Ratio
1992	861.57	1270.94	1.48
1993	906.81	1329.31	1.47
1994	824.76	1411.21	1.71
1995	1060.92	1616.65	1.52
1996	650.62	969.97	1.49
1997	404.68	605.65	1.50
1998	957.12	1217.64	1.27
		Average =	1.49

Table 6. 6. Discharge at Jurug Station per catchment area after correction

The correction factor of 1.30 is used from year 1992 onwards at Jurug gauging station. Table 6.7 below shows the annual discharge in m^3/second (cumecs) at Jurug gauging station in 1992 – 1998 before and after correction.

Year	Discharge before correction (cumecs)	Discharge after correction (cumecs)
1992	29539.09	38400.82
1993	31090.12	40417.15
1994	28277.04	36760.15
1995	36373.92	47286.10
1996	22306.74	28998.76
1997	13874.47	18036.81
1998	32815.20	42659.76

Table 6. 7. Discharge at Jurug Station per catchment area after correction

Figure 6.10 and Figure 6.11 below show the curve of simulated and corrected observed discharge for period 1990 – 1994 and 1995 – 1998.

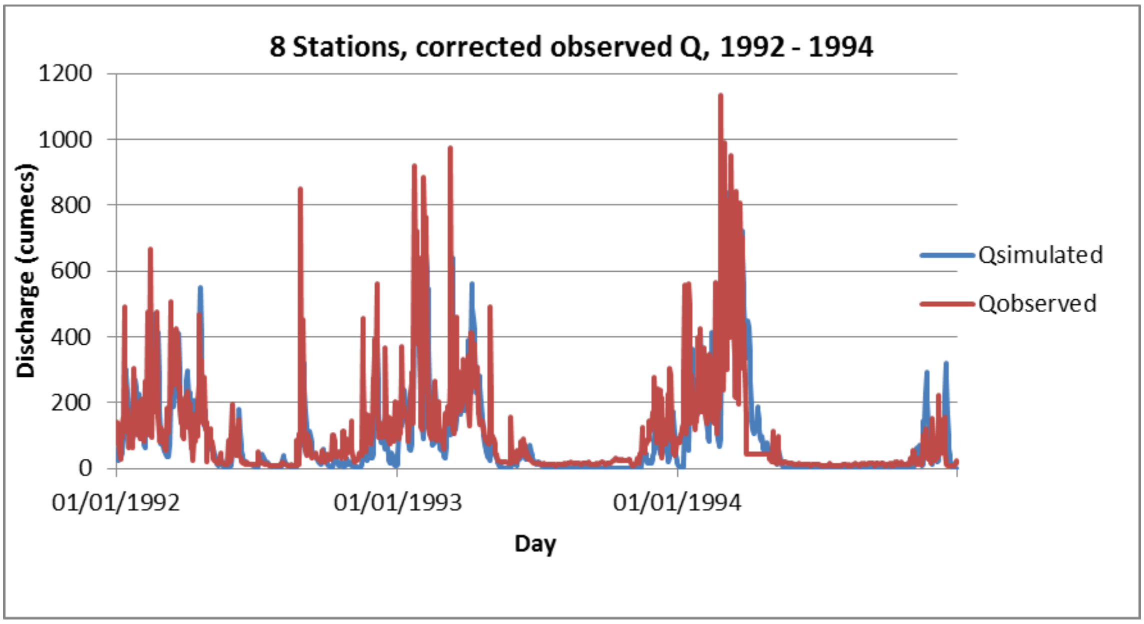


Figure 6. 10. Simulated discharge versus corrected observed discharge for 1992 – 1994

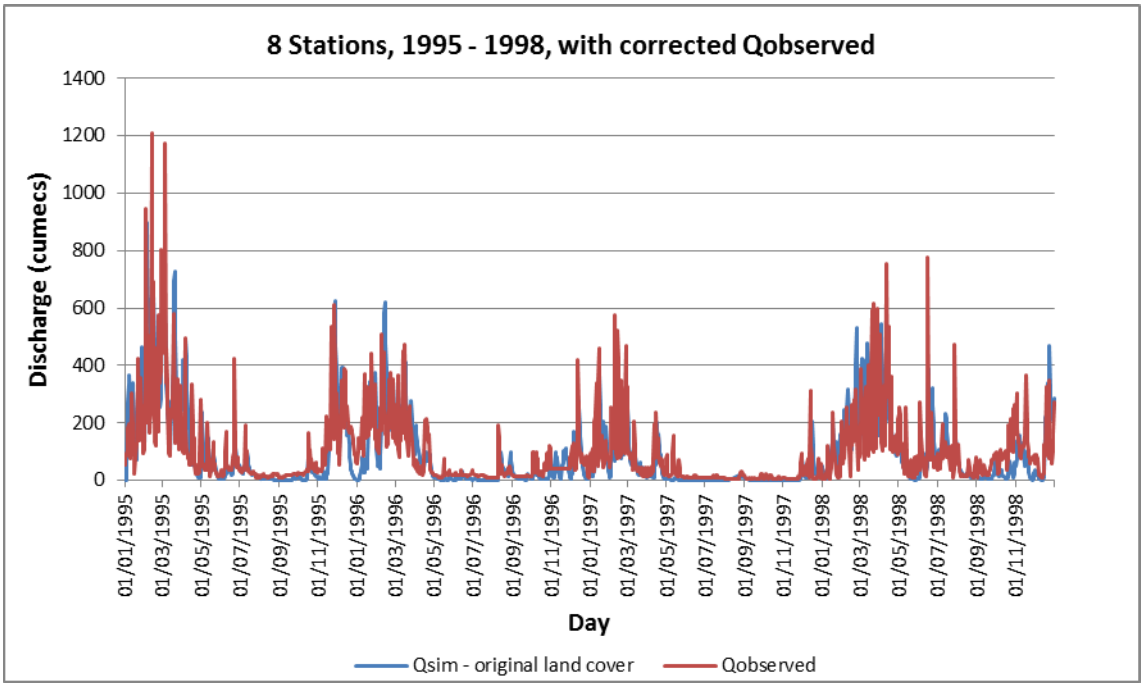


Figure 6. 11. Simulated discharge versus corrected observed discharge for 1995 – 1998

Table 6.8 below presents the NSE values for period 1992 – 1994 and 1995 – 2000, before and after correction of observed discharge.

Period	NSE before correction	NSE after correction
1992 - 1994	0.58	0.67
1995 - 2000	0.49	0.55

Table 6. 8. NSE values before and after correction of observed discharge

It can be seen from Table 6.8 that correcting the observed discharge with correction factor 1.30 has improved the SHETRAN simulation performance as measured by the NSE values in the period 1992 – 1994 and 1995 – 2000.

6.3. TRMM Data 1998 – 2000 for Rainfall Input

According to the previous analysis, the cross correlation between rain gauging stations in the research location is rather low, suggesting spatially variable rainfall fields of a convective nature. It is therefore likely that the rain gauge network does not satisfactorily sample the rainfall field, so alternative and complementary rainfall measurements will be considered next.

In the next phase of SHETRAN simulation implementation, TRMM 3-hourly rainfall data have been considered as rainfall input. There are several products of TRMM which are obtained by combining different instruments used in the algorithm estimation. This phase of research applied data from TRMM research product 3B42.

The 3B42 TRMM data are 3-hourly rain rate data in 0.25^o x 0.25^o grid intervals from latitude 50^oN to 50^oS and longitude from 180^oW to 180^oE. The data are 3-hourly averages centred at the middle of each 3-hour period. The data are compiled in the HDF file with dimensions for longitude and latitude of respectively 1440 and 400. The value "-9999.9" in the data package indicates missing data. The data can be downloaded free from this site http://disc.sci.gsfc.nasa.gov/daac-bin/DataHoldingsPDISC.pl.

6.3.1. Original TRMM 3-hourly data 1998 - 2000

In this phase, the original 3-hourly TRMM data were applied, with 5 points from the 3B42 data used as references. The 5 selected points and their relation to the rain gauging stations used as rainfall input in this research are shown in Table 6.9 below.

Latitude	Longitude	Point corresponds to station
7.75 S	110.5 E	Nepen and Klaten
8 S	110.5 E	Nawangan, Baturetno and Wonogiri
7.75 S	110.75 E	Pabelan
8 S	111.0 E	Jatisrono
7.75 S	111.0 E	Tawangmangu

Table 6. 9. Locations of 5 selected TRMM data points and related rain gauging stations

The in situ rainfall data are only available on a daily basis. To convert the 3-hourly rain rate in 3B42 to daily, each of 3-hourly rainfall rates is multiplied by 3 hours to get the total rainfall for each 3 hour period.

From the 3B42 TRMM 3-hourly data (original), the distribution of when the rain event typically occurred during the day in the research location in years 1998 – 2000 can be seen in the charts below.

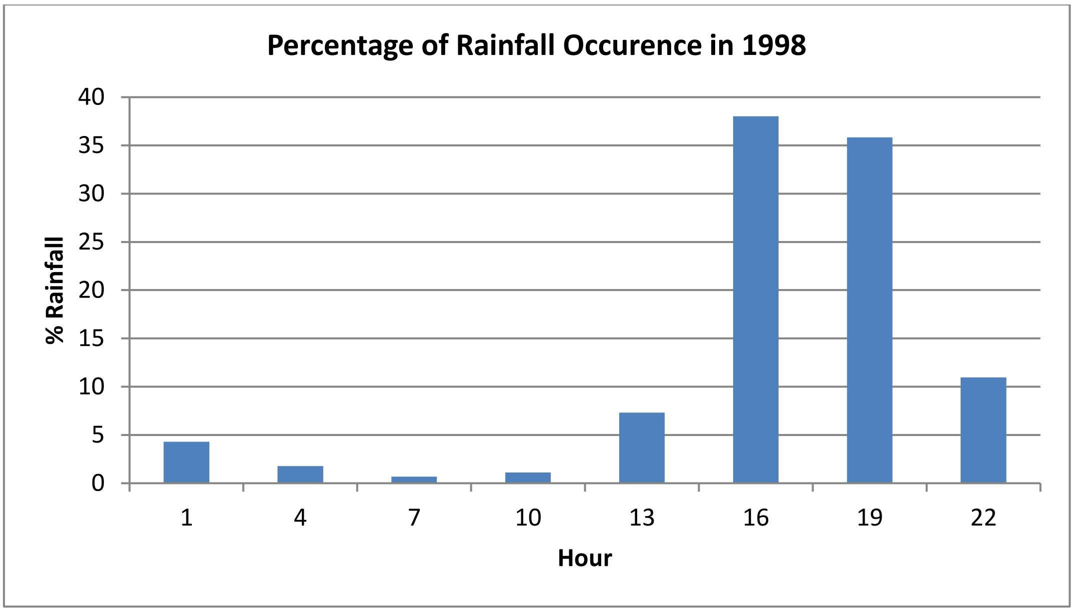


Figure 6. 12. The diurnal distribution of rainfall from 1998 TRMM data

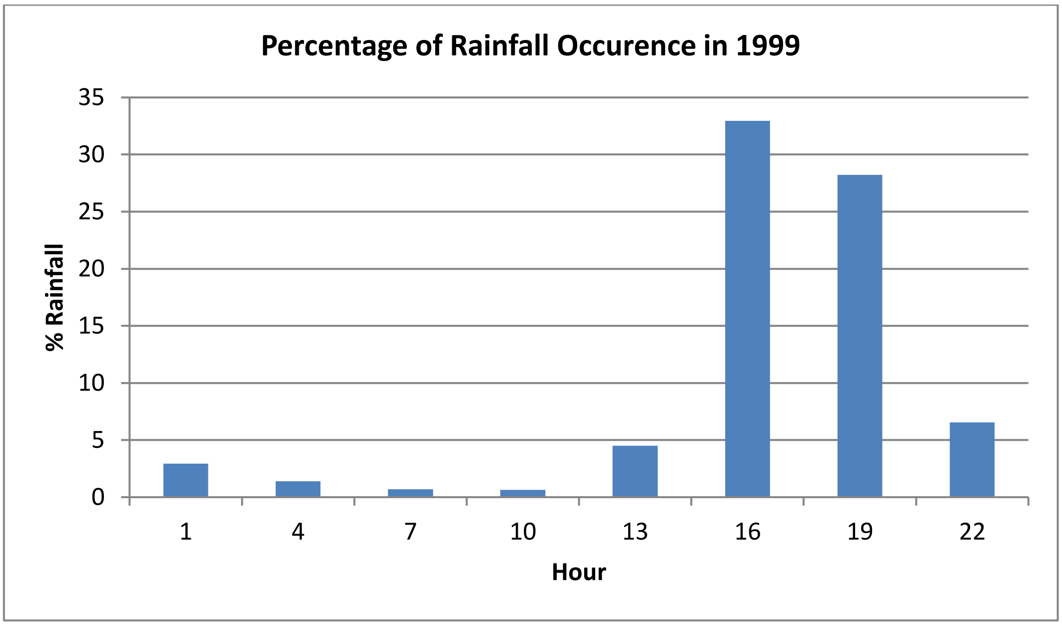


Figure 6. 13. The diurnal distribution of rainfall from 1999 TRMM data

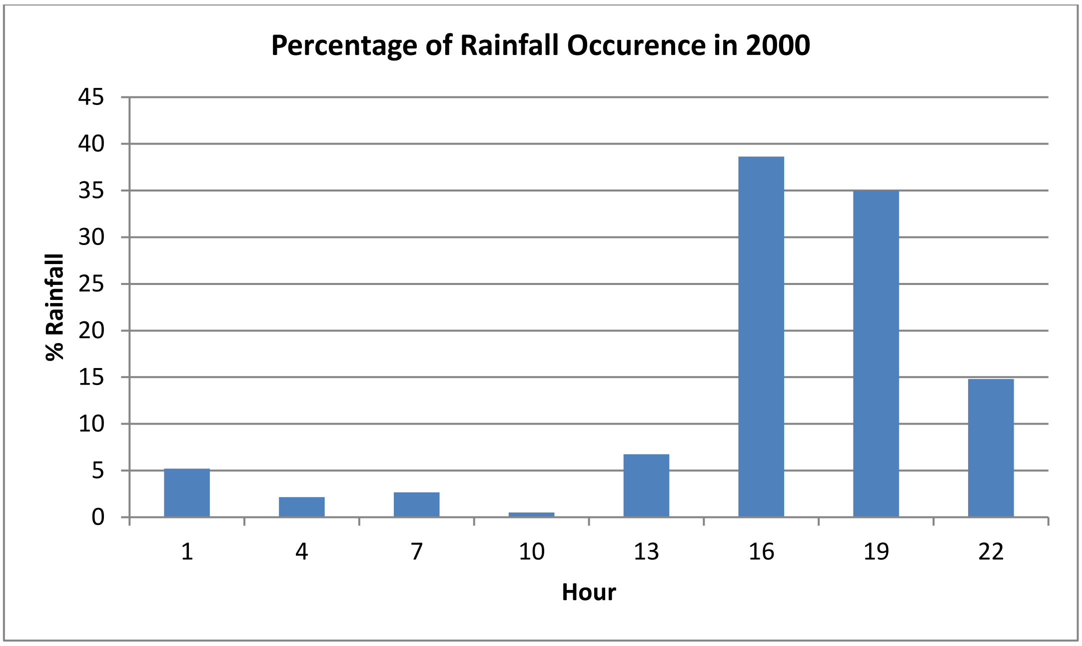


Figure 6. 14. The diurnal distribution of rainfall from 2000 TRMM data

It can be seen on the charts above that the heaviest rainfall typically occurs between 14.00 and 19.00. This information is useful in relation to the attempt to disaggregate the daily in situ rainfall data into 3-hourly data.

The result of the SHETRAN simulation for this phase using the 3-hr TRMM data directly can be seen in the chart below.

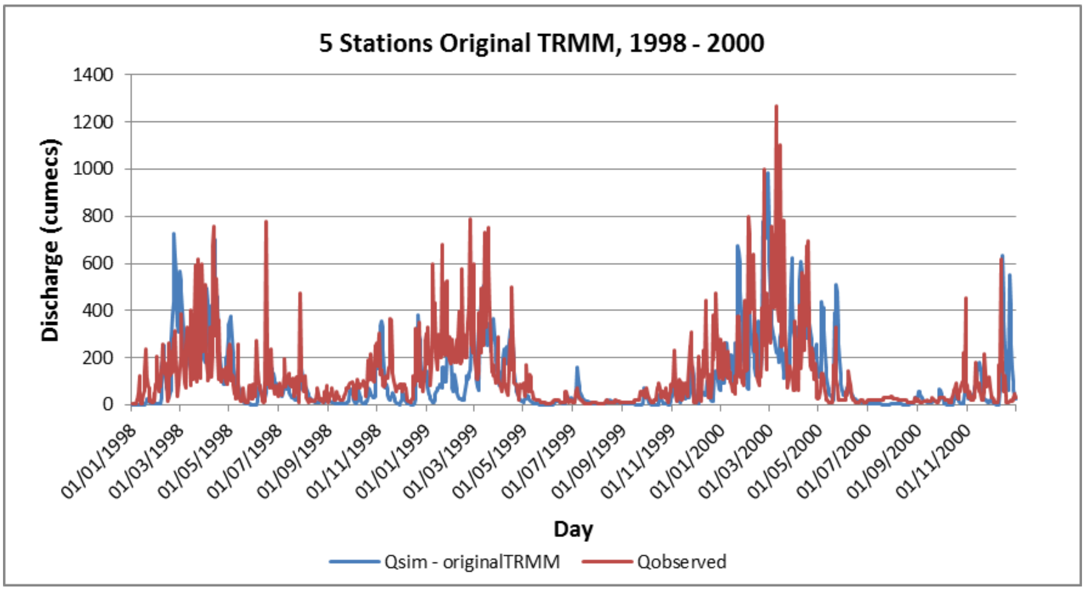


Figure 6. 15. The simulated and observed discharge of simulation using original 3-hourly TRMM data

The NSE value for the simulation result using original TRMM 3-hourly data in 1998 – 2000 is 0.21. Clearly the TRMM data do not provide a good estimate of the real rainfall and the SHETRAN simulation is much inferior to that obtained using the gauge data set. A better method of using the TRMM information was therefore sought.

6.3.2. Disaggregating daily in situ rainfall data with 3-hourly diurnal TRMM data 1998 - 2000

The mean diurnal cycle of rainfall can be estimated from the TRMM 3B42 data. Table 6.10 shows the average of 3-hourly rainfall based on diurnal cycle at 5 selected points in 1998 - 2000.

Hour	Average Rainfall (mm)	% of Rainfall
1	324	4.4
4	138	1.9
7	105	1.4
10	59	0.80
13	483	6.6
16	2855	38.6
19	2580	34.9
22	842	11.4

Table 6. 10. The average of 3-hourly diurnal cycle rainfall in 1998 – 2000

The disaggregation of daily in situ rainfall data using the 3-hourly diurnal cycle starts from hour 07:00, so the order of percentage for disaggregation based on Table 6.10 above is 1.4%, 0.80%, 6.6%, 38.6%, 34.9%, 11.4%, 4.4% and 1.9%. Table 6.11 shows the example of disaggregation of daily rainfall data at Tawangmangu station on 01/01/1998 and 02/01/1998 into 3-hourly diurnal cycle.

Date	Daily in situ rainfall (mm)	Hour	% Rainfall	Diurnal cycle rainfall (mm)	
01/01/1998	3	7	1.4	3 x 1.4% =	0.04
		10	0.8	3 x 0.8% =	0.02
		13	6.6	3 x 6.6% =	0.20
		16	38.6	3 x 38.6% =	1.16
		19	34.9	3 x 34.9% =	1.05
		22	11.4	3 x 11.4% =	0.34
		1	4.4	3 x 4.4% =	0.13
		4	1.9	3 x 1.9% =	0.06
02/01/1998	16	7	1.4	16 x 1.4% =	0.23
		10	0.8	16 x 0.8% =	0.13
		13	6.6	16 x 6.6% =	1.05
		16	38.6	16 x 38.6% =	6.18
		19	34.9	16 x 34.9% =	5.59
		22	11.4	16 x 11.4% =	1.82
		1	4.4	16 x 4.4% =	0.70
		4	1.9	16 x 1.9% =	0.30

Table 6. 11. An example of daily rainfall disaggregated to 3-hourly using the mean diurnal cycle

The result of SHETRAN simulation using disaggregated daily in situ data into 3-hourly diurnal cycle can be seen in Figure 6.16. The simulation produced a NSE value 0.54, which is an improvement on using the TRMM data directly, but not as high as using the daily gauge data.

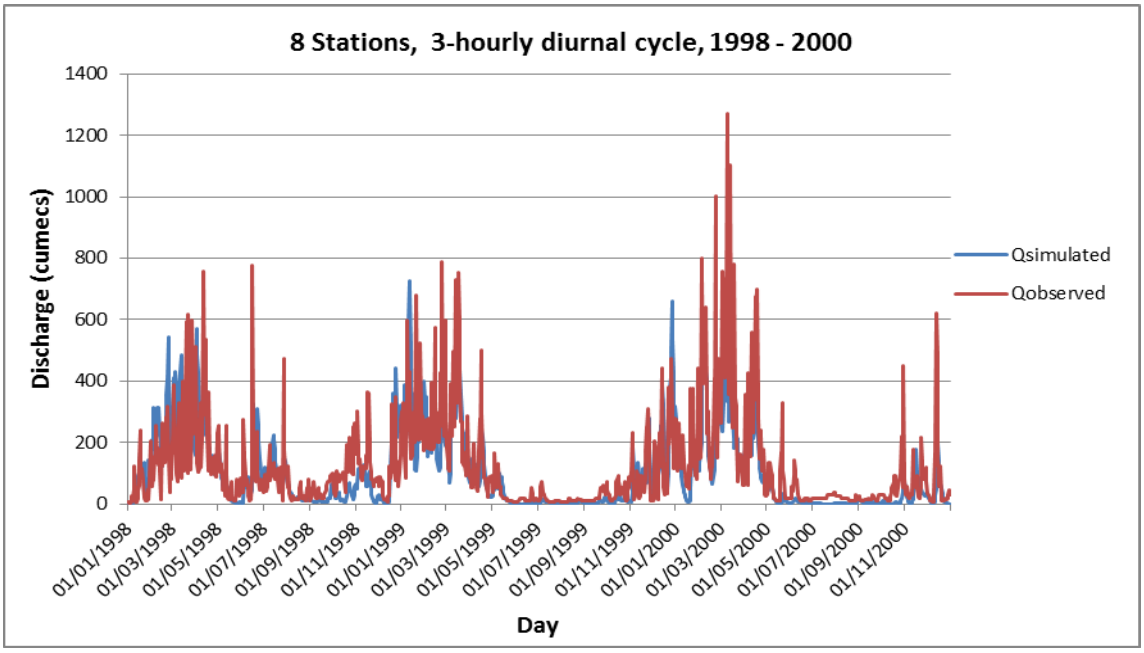


Figure 6. 16. Simulated versus observed discharge using 3-hourly diurnal cycle rainfall data

6.3.3. Disaggregating daily in situ rainfall data with original 3-hourly TRMM data 1998-2000

The next phase of SHETRAN simulation is to apply disaggregated in situ rainfall data into 3-hourly based on the original 3-hourly TRMM data. The original daily in situ data from 8 selected rain gauging stations was disaggregated into 3-hourly, using 5 selected points from original 3-hourly TRMM data as references. The example below describes the procedure to disaggregate daily rainfall data into 3-hourly data.

For example, point 7 of TRMM data corresponded to Klaten and Nepen stations is used as a reference. The example rainfall event occurred on 07/01/1998. The summary of the rainfall event at point 7 on that day can be seen in Table 6.12.

Date	Hour	Rainfall (mm)	Total rainfall (mm)	% Rainfall
07/01/1998	16.00 19.00	3.21 3.51	6.72	47.8 52.2

Table 6. 12. Rainfall event on 07/01/1998 at point 7 of TRMM 3-hourly data

From the example above, the rainfall event on 07/01/1998 occurred at hour 16.00 and 19.00 with percentages respectively 47.8% and 52.2%. Using this information, the daily rainfall at Klaten and Nepen stations can be disaggregated as shown in Table 6.13.

Station	Date	Total Rainfall (mm)	% Rainfall	Hour	Disaggregated rainfall (mm)	
Klaten	07/01/1998	31	47.8 52.2	16.00 19.00	31 x 47.8% = 31 x 52.2% =	14.8 16.2
Nepen	07/01/1998	3	47.8 52.2	16.00 19.00	3 x 47.8% = 3 x 52.2% =	1.4 1.6

Table 6. 13. Daily in situ data disaggregated into 3-hourly on 07/01/1998 at Klaten and Nepen stations

The comparison of observed and simulated discharge using disaggregated daily in situ data into 3-hourly can be seen in Figure 6.17 below. The simulation produced NSE value 0.54, whereas the simulation using original in situ data in 1998 – 2000 produced NSE value 0.55.

Simulations using the disaggregated TRMM data produce very similar results as for the daily gauge rainfall inputs. This is to be expected because the daily totals are kept the same and the daily discharges are compared in the overall NSE statistic.

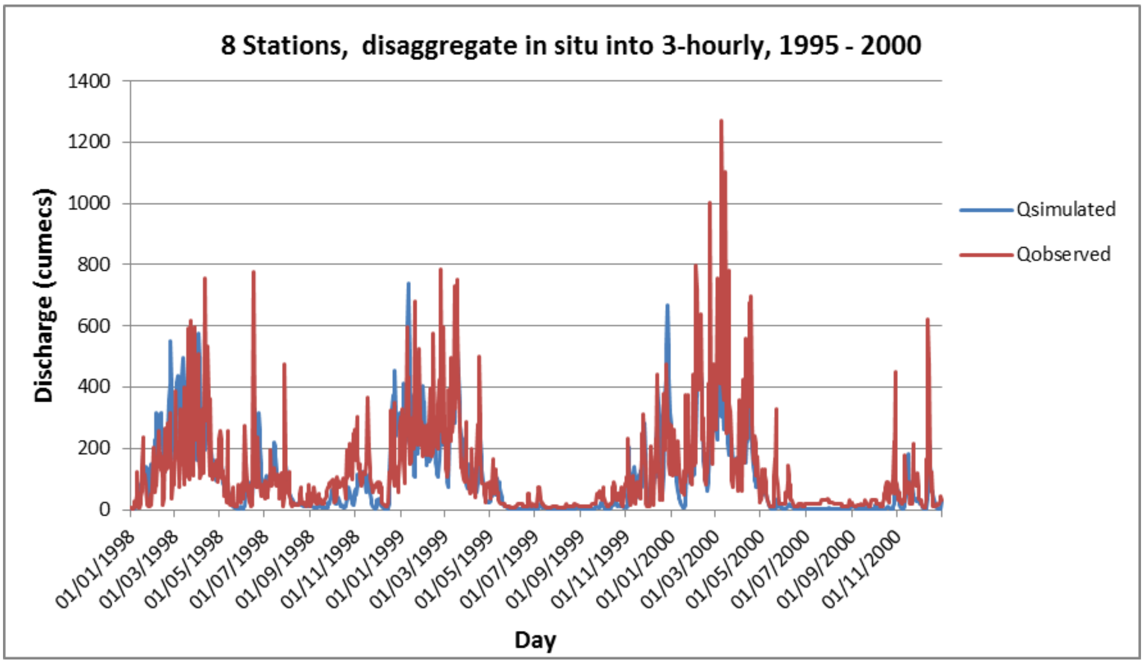


Figure 6. 17. The simulated and observed discharge of simulation using disaggregated in situ rainfall data

6.3.4. Selected hourly discharge events resulting from simulation using in situ and TRMM data

The previous results have considered the simulation efficiency for the overall hydrograph using the Nash Sutcliffe efficiency. Using the disaggregated rainfall series will generate higher intensity rainfall events (for 3 hour periods) and consequently we might expect to see higher resultant discharge peaks. These are not distinguished well using NSE, so a more detailed event-based analysis has been carried out. Figures 6.18 – 6.20 show the comparison of hourly-simulated discharge resulting from in situ rainfall and TRMM rainfall data inputs for selected events, i.e. on 10 January 1998, 10 January 1999, and 10 January

2000. Rainfall input using original TRMM data on 10/01/1998 and 10/01/1999 produced zero flow because there was no rainfall recorded on that dates. However, on 10/01/2000, rainfall input using original TRMM data resulted in discharge much higher than other rainfall inputs.

The simulated-discharge pattern produced by in situ rainfall input is different from the ones produced by TRMM rainfall input, because the in situ rainfall data is on a daily basis while the TRMM input is 3-hourly.

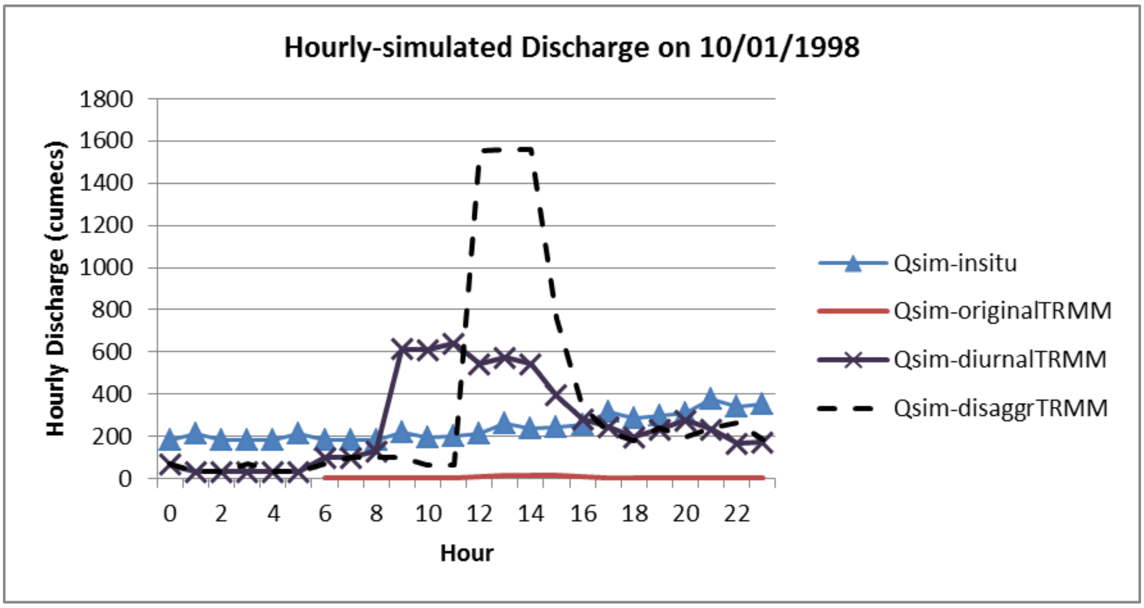


Figure 6. 18. Comparison of hourly-simulated discharge using different rainfall input on 10/01/1998

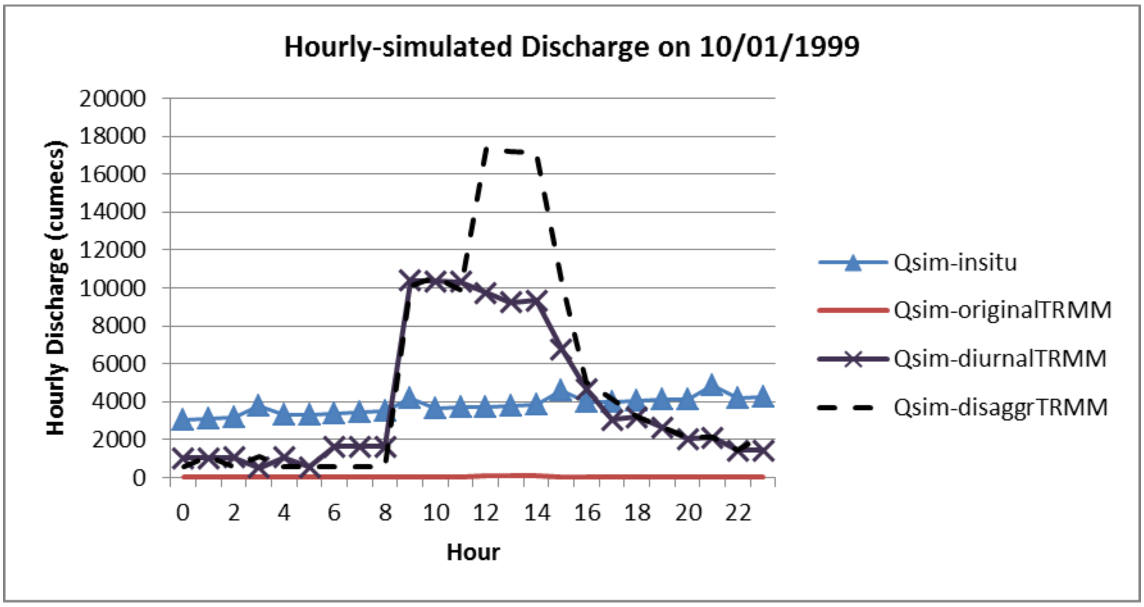


Figure 6. 19. Comparison of hourly-simulated discharge using different rainfall input on 10/01/1999

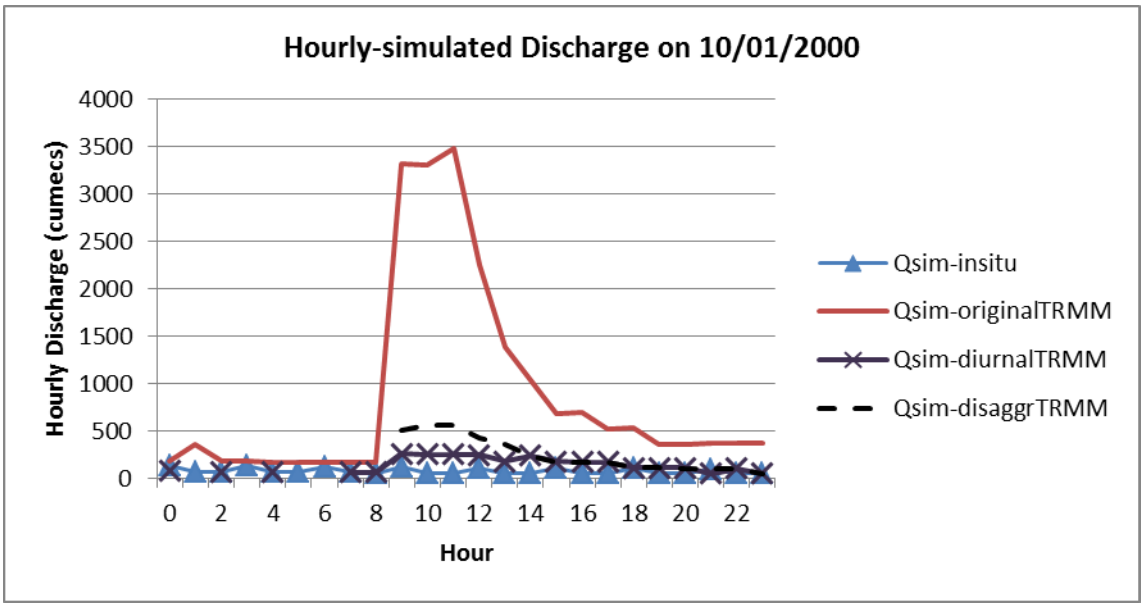


Figure 6. 20. Comparison of hourly-simulated discharge using different rainfall input on 10/01/2000

Figure 6.21 – 6.23 show the comparison of hourly-simulated discharge resulting from in situ rainfall and TRMM rainfall data inputs for selected events on 20/02/1998, 20/02/1999, and 20/02/2000. As can be seen in the charts, the patterns of peak discharge produced by TRMM rainfall inputs are similar.

Whereas simulation using in situ rainfall input produced different pattern of peak discharge compared to the simulation using TRMM rainfall inputs.

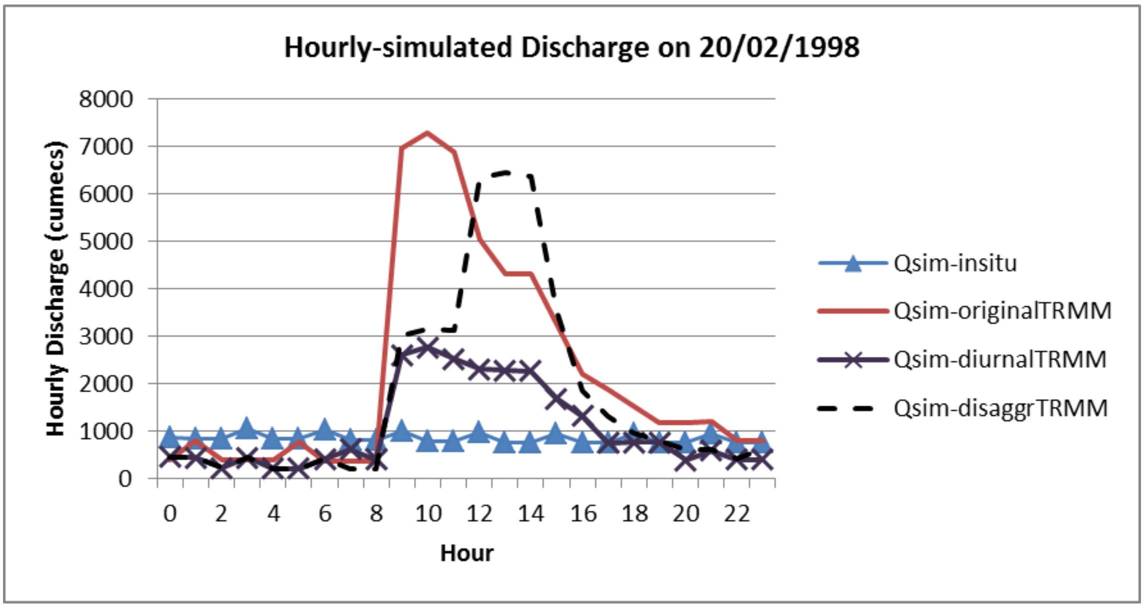


Figure 6. 21. Comparison of hourly-simulated discharge using different rainfall input on 20/02/1998

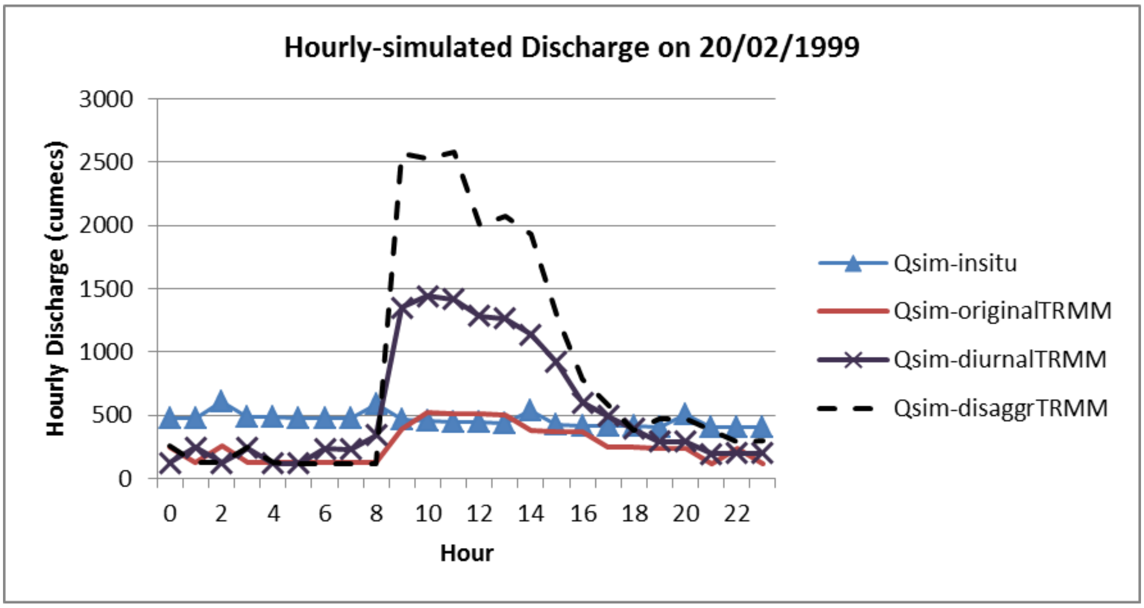


Figure 6. 22. Comparison of hourly-simulated discharge using different rainfall input on 20/02/1999

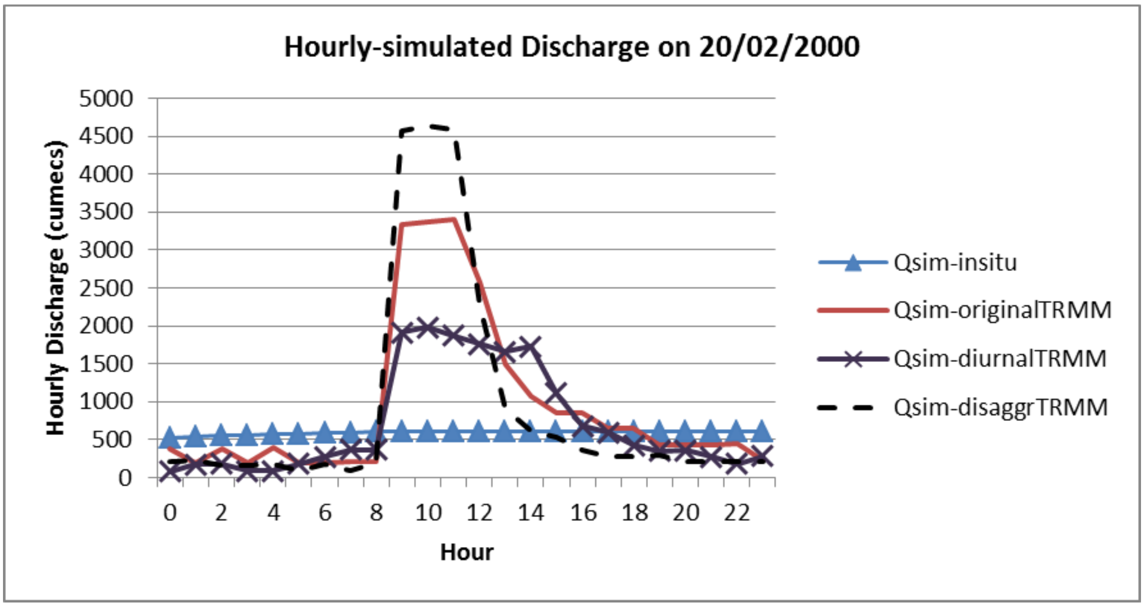


Figure 6. 23. Comparison of hourly-simulated discharge using different rainfall input on 20/02/2000

Figure 6.24 – 6.26 show the comparison of hourly-simulated discharge resulting from in situ rainfall and TRMM rainfall data inputs for selected events on 15/03/1998, 15/03/1999, and 15/03/2000.

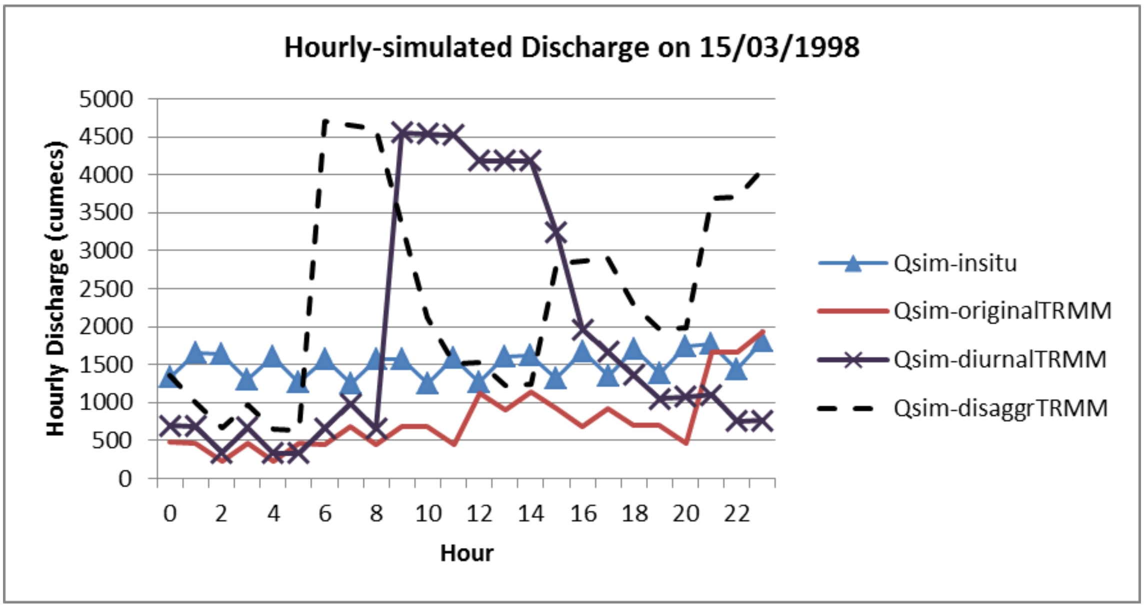


Figure 6. 24. Comparison of hourly-simulated discharge using different rainfall input on 15/03/1998

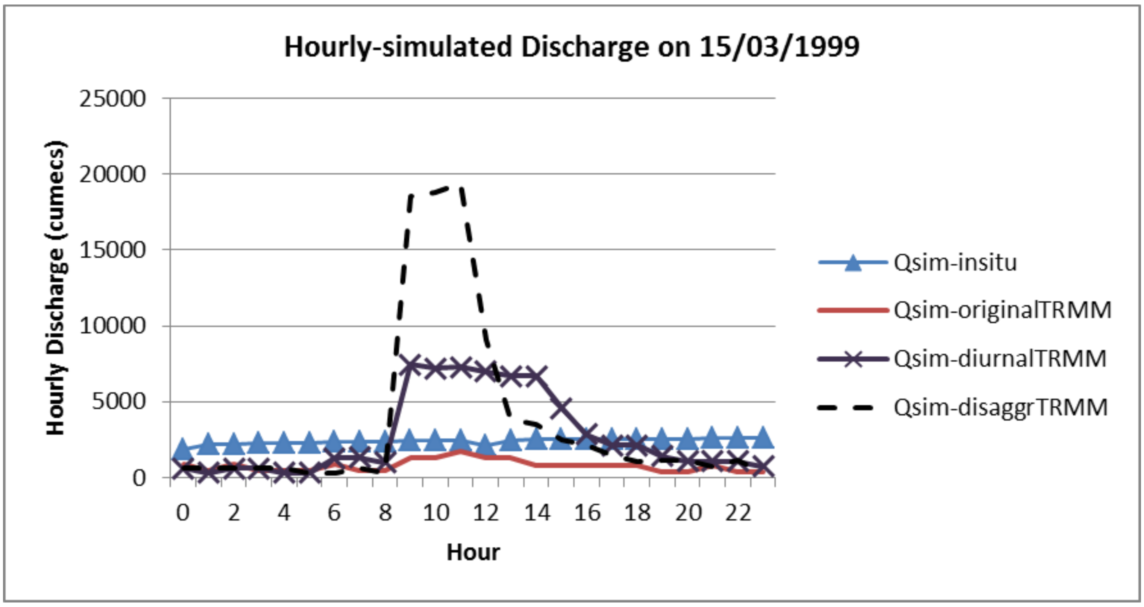


Figure 6. 25. Comparison of hourly-simulated discharge using different rainfall input on 15/03/1999

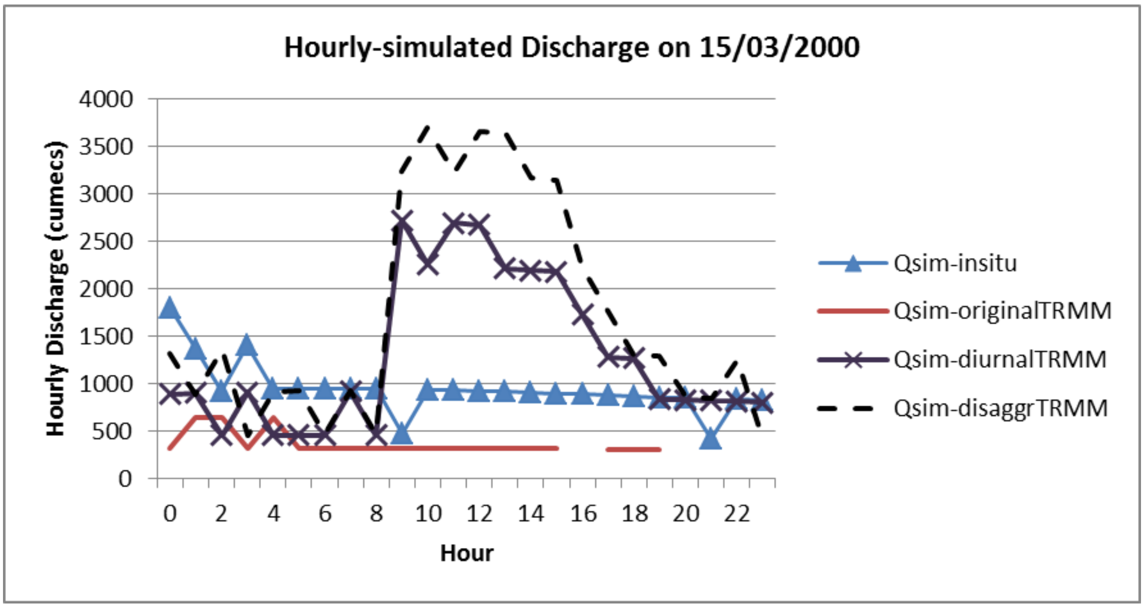


Figure 6. 26. Comparison of hourly-simulated discharge using different rainfall input on 15/03/2000

As can be seen in Figure 6.24 – 6.26, the pattern of discharge produced by simulation using in situ and original TRMM rainfall input is different from simulation using diurnal and disaggregated TRMM rainfall input. The discharge resulted from simulation using diurnal and disaggregated TRMM rainfall input is higher than the discharge resulted from in situ and original TRMM data. It would be more intriguing if in situ sub-daily discharge data is available to be compared with the simulated discharge resulting from the simulation. Unfortunately, the in situ sub-daily discharge data is unavailable in the research location. Therefore, it would be important to persuade the government and related institutions to improve the gauging networks and database for better flood management in the future.

6.3.5. Selected daily peak discharge events resulting from simulation using in situ and TRMM data

Figure 6.27 – 6.38 below show the comparison of selected daily peak discharge resulting from simulation using in situ and TRMM rainfall inputs. Figure 6.27 – 6.29 show the comparison of daily peak discharge in November (1998 – 2000). It can be seen from the charts that the pattern of daily peak discharge resulting from simulation using in situ, diurnal TRMM and disaggregated TMM rainfall inputs in November 1998 and 2000 are similar. While in November 1999, the daily peak discharge resulting from disaggregate TRMM rainfall input is higher than the others. Moreover, the simulation using original TRMM produced different daily peak discharge pattern on the selected periods.

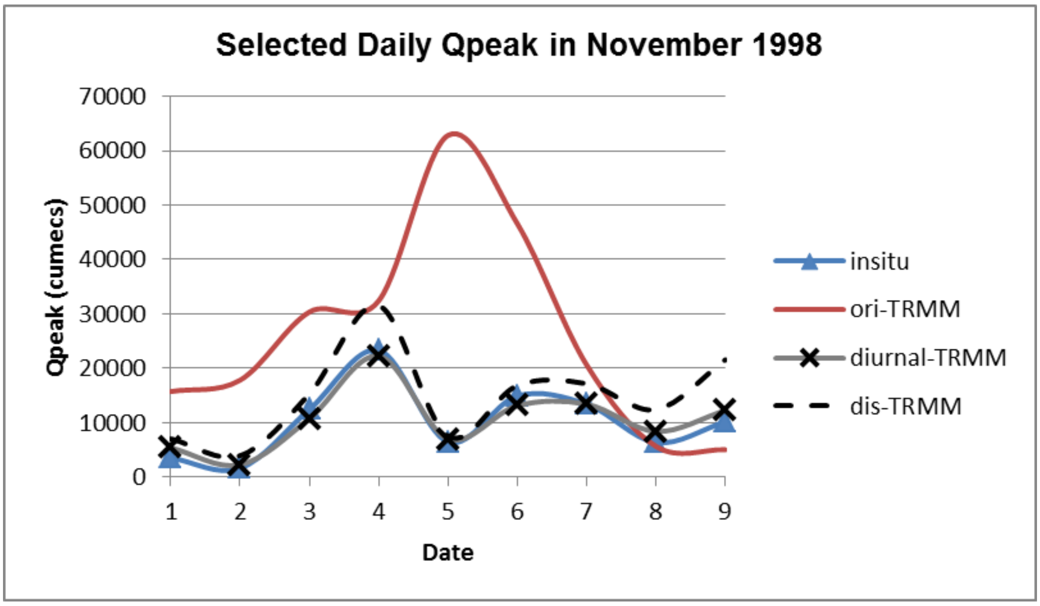


Figure 6. 27. Selected daily peak discharge in November 1998

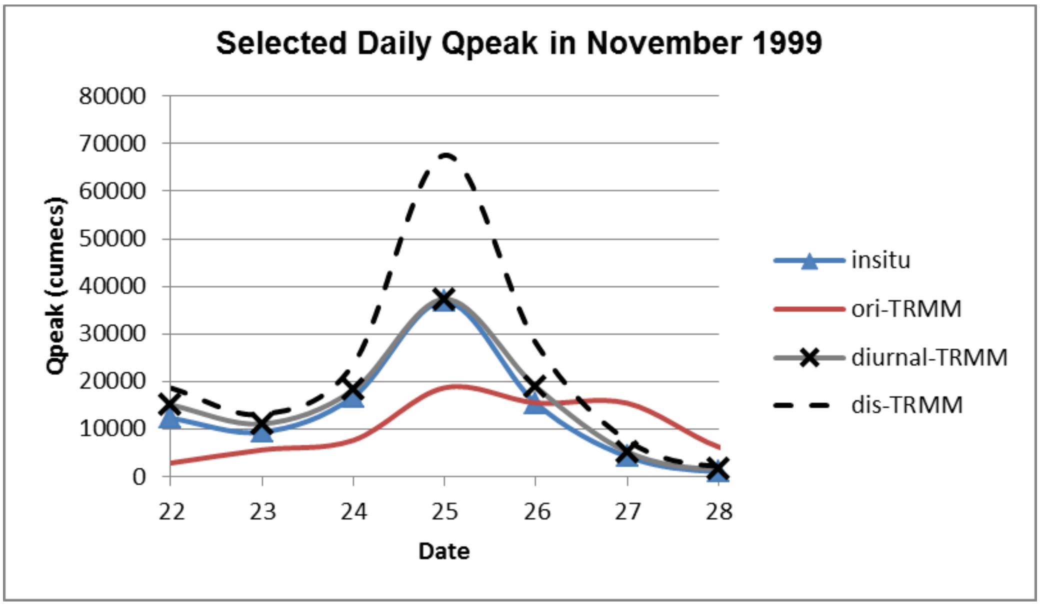


Figure 6. 28. Selected daily peak discharge in November 1999

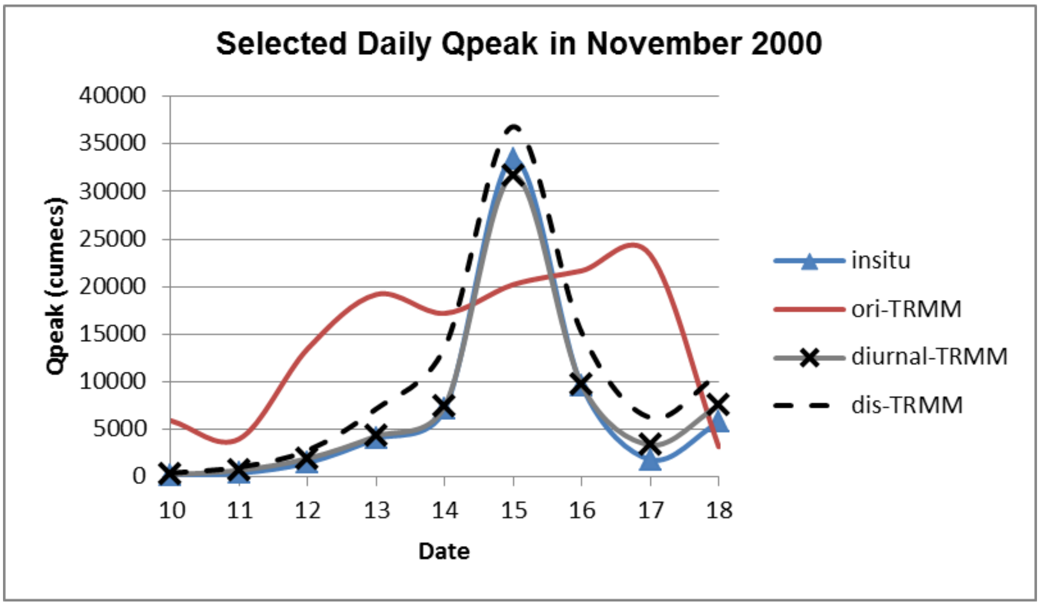


Figure 6. 29. Selected daily peak discharge in November 2000

Figure 6.30 – 6.32 show the comparison of daily peak discharge in December (1998 – 2000). During this period, the simulation using original TRMM rainfall input also produced different pattern of daily peak discharge, whereas the others rainfall inputs created similar pattern.

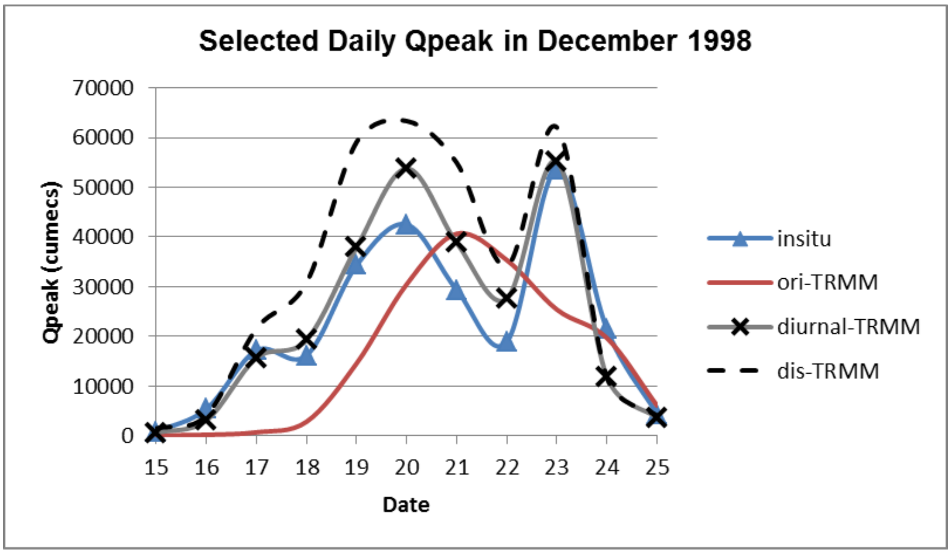


Figure 6. 30. Selected daily peak discharge in December 1998

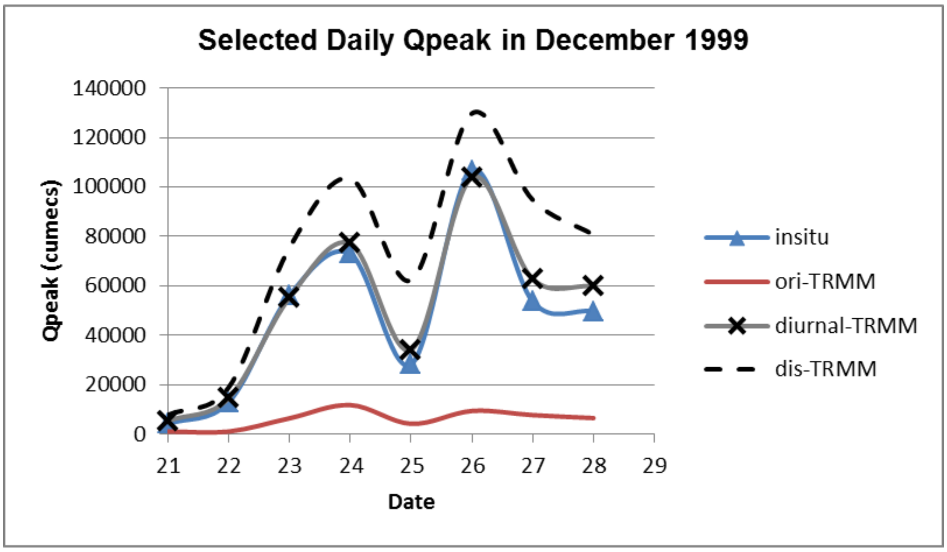


Figure 6. 31. Selected daily peak discharge in December 1999

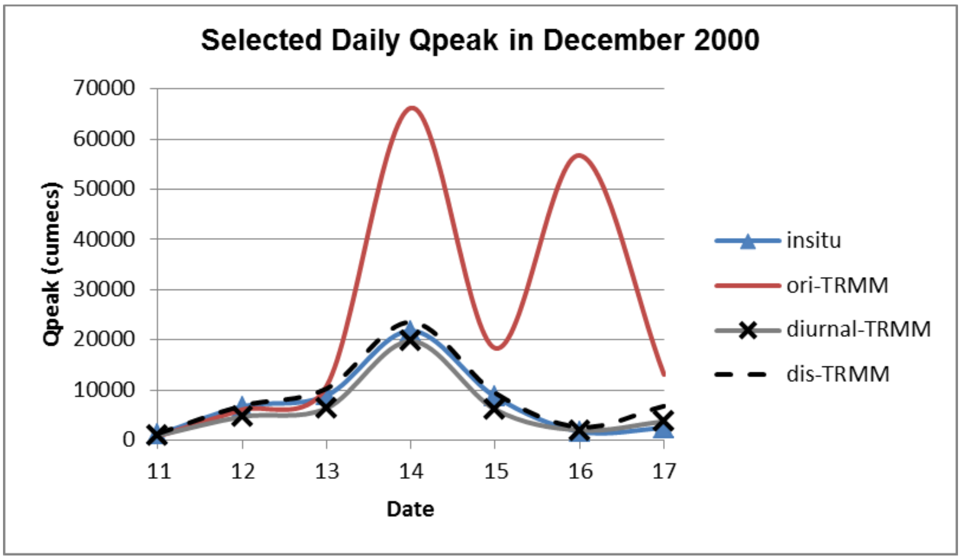


Figure 6. 32. Selected daily peak discharge in December 2000

Furthermore, Figure 6.33 – 6.35 show the comparison of daily peak discharge in January (1998 – 2000). In January 1998 - 1999, there is no rainfall recorded in the original TRMM data, therefore the discharge resulting from simulation is almost zero. While the original TRMM data in January 2000 produced higher daily peak discharge than the other rainfall inputs.

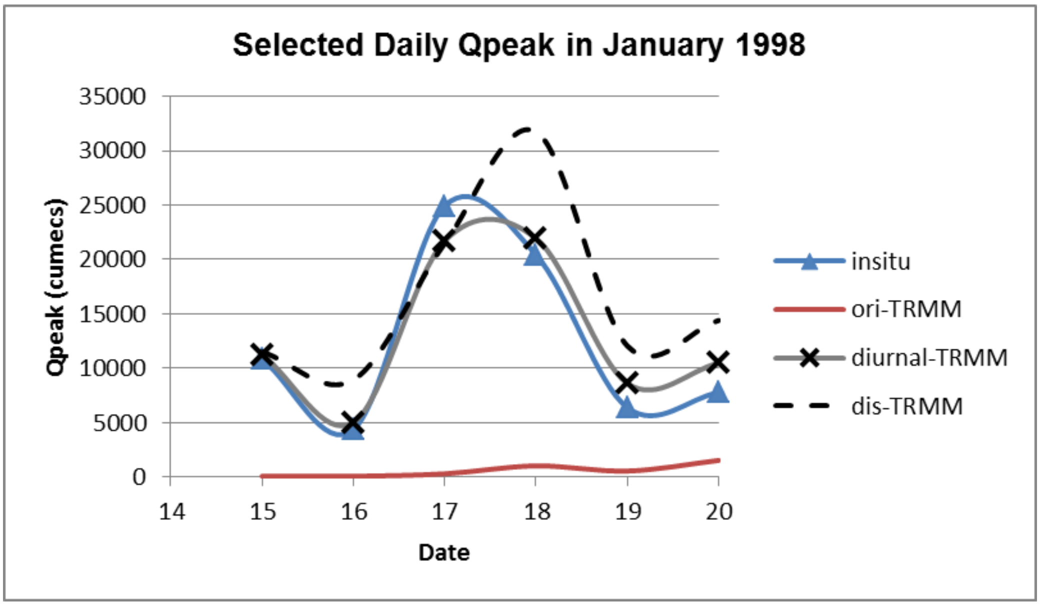


Figure 6. 33. Selected daily peak discharge in January 1998

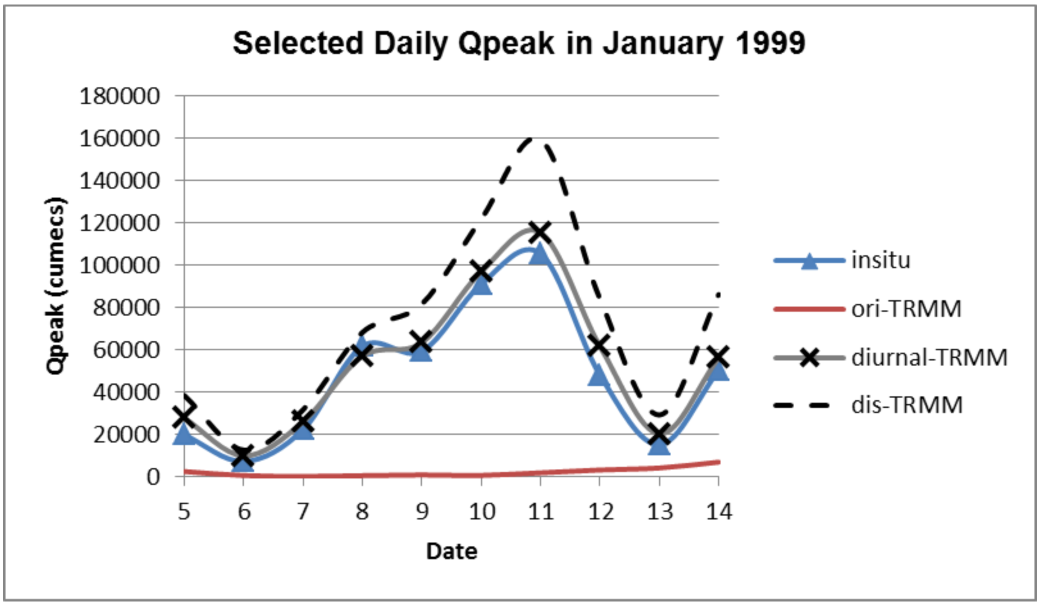


Figure 6. 34. Selected daily peak discharge in January 1999

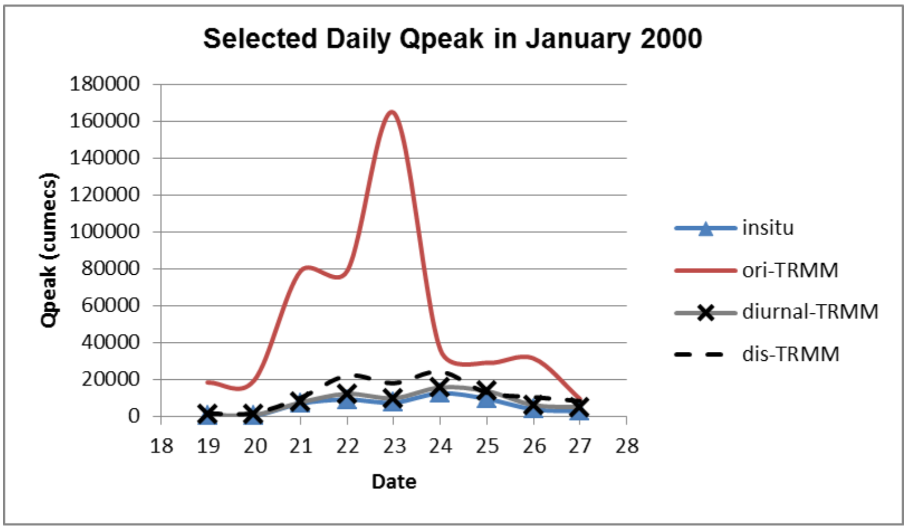


Figure 6. 35. Selected daily peak discharge in January 2000

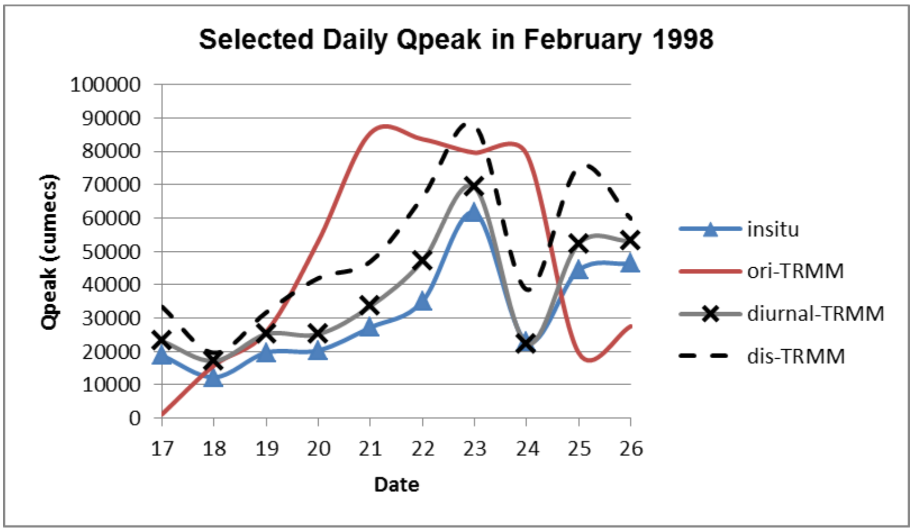


Figure 6. 36. Selected daily peak discharge in February 1998

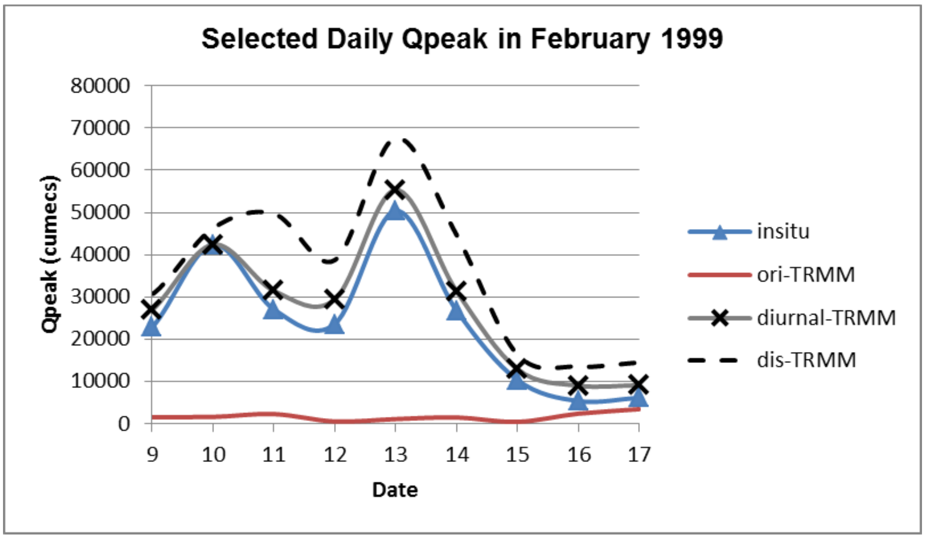


Figure 6. 37. Selected daily peak discharge in February 1999

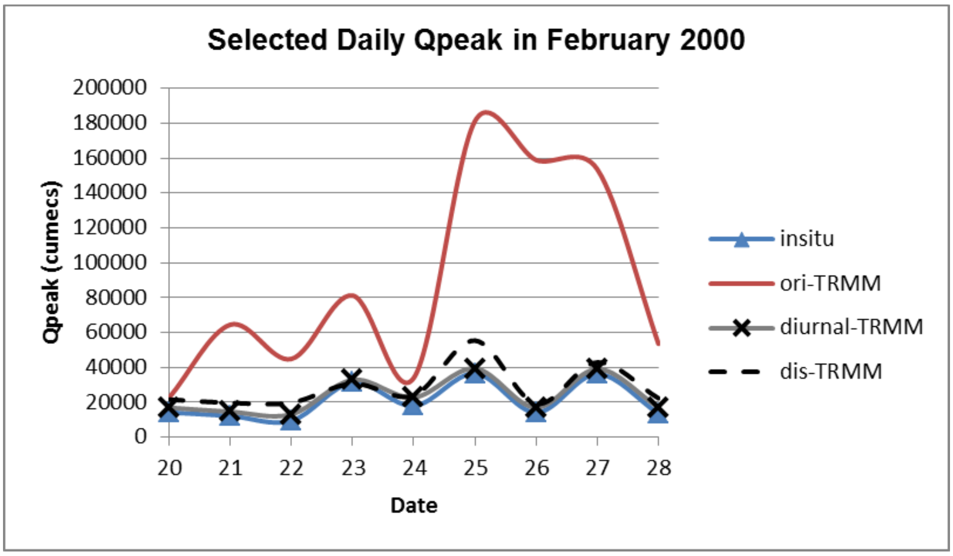


Figure 6. 38. Selected daily peak discharge in February 2000

As can be seen in the figures above, the simulation using in situ, diurnal and disaggregated TRMM rainfall inputs produced similar pattern of daily peak discharge at the selected events. In contrast, the simulation using original TRMM rainfall input produced different pattern of daily peak discharge.

The reliability of the TRMM data series depends on its root mean squared error ratio (% RMSE) and correlation coefficient (Condom *et al*, 2010; Duan *et al*, 2012). Duan *et al* (2012) suggested that the local calibration should be implemented first to improve the TRMM data for further application. For further research using TRMM data in Bengawan Solo river basin, the local calibration of TRMM data is recommended to be carried out.

6.4. Summary

The in-situ rainfall data used in this stage of SHETRAN simulation was selected based on the correlation between rain gauging stations, the completeness of the data series, and the result of the first SHETRAN simulation. The best NSE values were obtained in simulation using the in-situ rainfall data in 1980 – 1989. The simulation using in situ rainfall data in 1990 – 2000 produced lower NSE values than in 1980 – 1989. The NSE value for the simulation in 1990 – 2000 increased after correcting the in-situ discharge data in Jurug catchment (the catchment for the simulation) using correction factor derived from the comparison with in situ discharge data in neighbouring station (Kajangan station). However, the NSE values in 1990 – 2000 were still lower than in 1980 – 1989.

Simulation using 3-hourly TRMM rainfall data in 1998 – 2000 also produced NSE value almost similar with simulation using in situ rainfall data in 1995 – 2000, which is lower than in 1980 – 1989. It was not investigated in this research whether the in-situ discharge in Jurug catchment in 1990 – 2000 is wrongly recorded, or the rating curve used to derive the discharge was inappropriate, or the gauge was damaged. For further research, the investigation of the reliability of in situ discharge at Bengawan Solo river basin would be useful. In addition, the local calibration of TRMM rainfall data in Bengawan Solo river basin is recommended for further application.

Chapter 7. Land Use Change Sensitivity

The impact of land use change on run off has been the subject of a great deal of research worldwide. Some of the studies regarding the effect of land use and land use conversion on runoff were summarized by Camorani *et al* (2005). Hibbert (1967) reported that there is a noticeable increase in water yield due to forest cover reduction while he underlined the unpredictability of the response. Moreover, according to Hollis (1975), while small frequent floods are increased many times by urbanization, large rare floods are not significantly affected.

Fohrer *et al* (2001), who used a physically based model to examine and predict the impact of land use change on the modelled flows, stated that land use change has a direct effect on hydrological processes and type of ground cover has a massive impact on the initiation of surface runoff. Moreover, the study conducted by Wijesekara et al (2012) demonstrated that historical and forecasted land use changes in Alberta catchment in Canada progressively increase the impact on the hydrological processes in the catchment.

This chapter describes the SHETRAN simulation using different combinations of land use in Jurug catchment to investigate the impact of land use change on the flow in the catchment. The land use based on the data in the 1990s and 2006 as well as the hypothetical land use scenarios were used as input in the SHETRAN simulation in this stage.

7.1. Land use Changes in Simulation

7.1.1. Land use in the 1990s

According to the Catalogue of Rivers for Southeast Asia and the Pacific Volume I (UNESCO-IHP, 1995), in 1992 the land use in Bengawan Solo river basin (the whole river basin) consisted of 25.3% of other agriculture, 19.5% of forest, 0.9% of marsh and lake, 21.9% of rice paddy field, and 32.4% of settlement (urbanised area). Figure 7.1 below shows the land use map of Bengawan Solo river basin in 1992 as reported by UNESCO-IHP (1995).

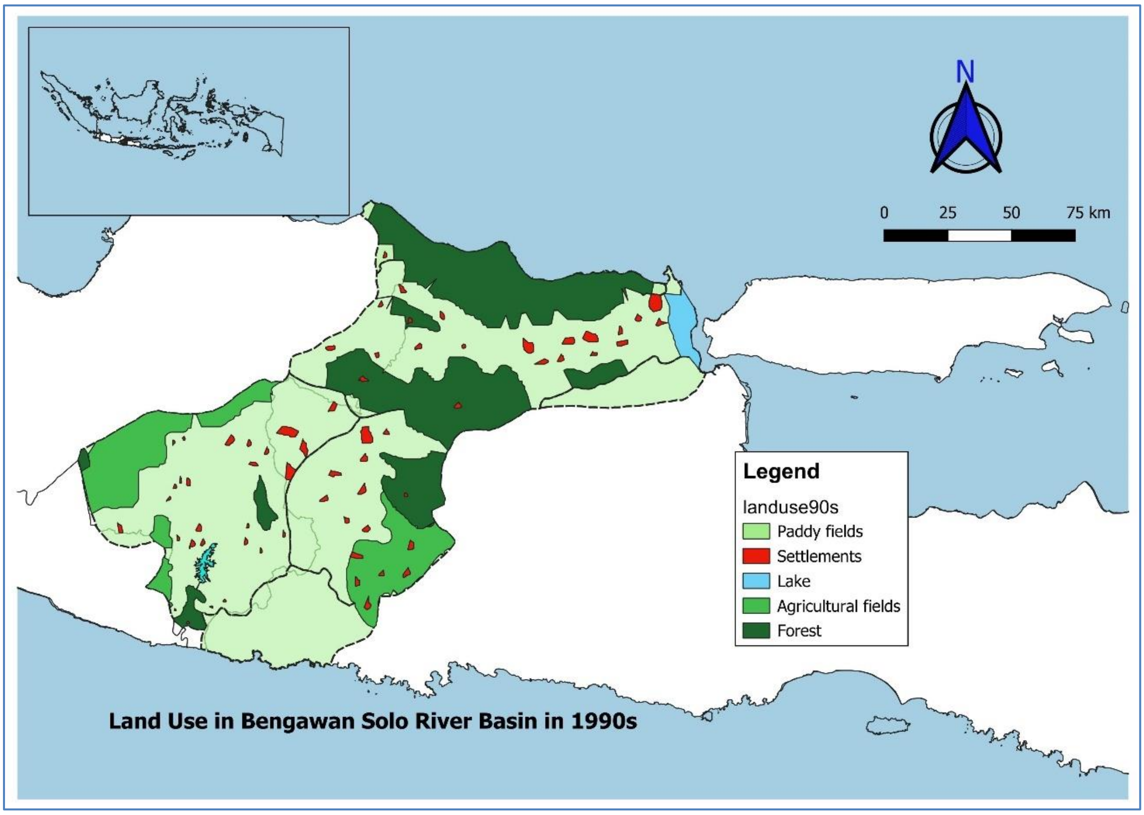


Figure 7. 1. Land use in Bengawan Solo river basin in 1990s (source: redrawn from River Catalogue, UNESCO-IHP, 1995)

This research used Jurug catchment which is situated in the Upper Bengawan Solo catchment for the application of SHETRAN simulation. As shown in Figure 7.1, in 1990s, the urbanised area in Jurug catchment is small, and the catchment was dominated by rice paddy field. The area of forest was also small in Jurug catchment in the 1990s. However, there is question for the map in Figure 7.1 because it shows that there is agricultural field very close to the volcano. It is also impossible that rice paddy field situated very close to the volcano. Using this information, for SHETRAN simulation using 1990s land use input, it is assumed that the land use combination in Jurug catchment in 1990s consisted of 31% of rice paddy field; 34% of bareground; 6% of urbanised area; 10% of forest; and 19% of grass / shrub. Urbanised area in Bengawan Solo river basin tipically consists of building, road, and other impervious area which reduce the capacity of the surface to absorp the rain water. In Bengawan Solo river basin, the highway mostly layered using bitumen/asphalt. Moreover, the porous pavement along the settlement is rare as mostly constructed using cement block. The green space is also very limited in the urbanised area in Bengawan Solo river basin.

Figure 7.2 below shows the land use combination in Jurug catchment in the 1990s.

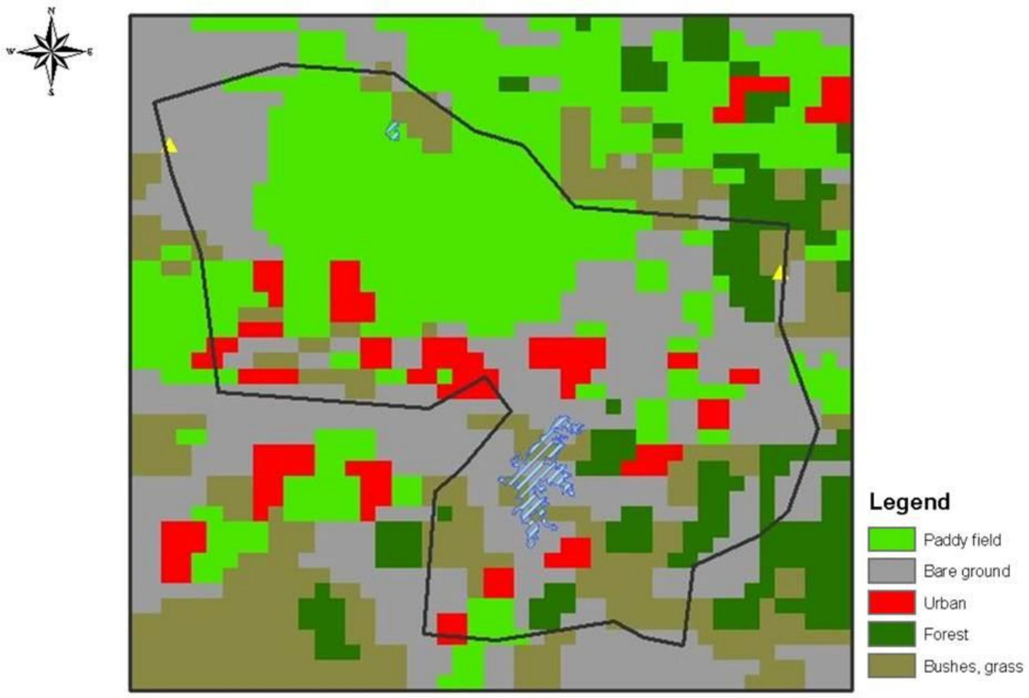


Figure 7. 2. The land use combination in Jurug catchment in 1990s.

The parameter of vegetation cover for each type of land use for SHETRAN simulation has been described in Chapter 5, with the more detail one provided in the Appendices. The SHETRAN simulation result using land use in the 1990s is presented in figures below.

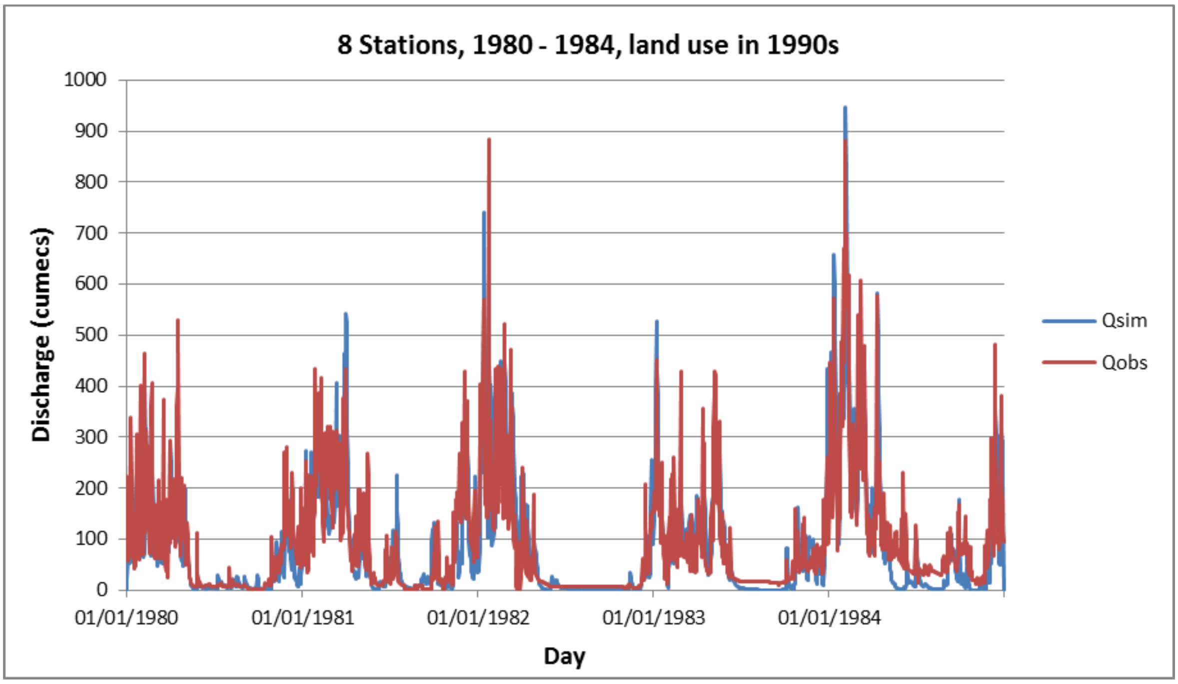


Figure 7. 3. Observed and simulated discharge in 1980 – 1984 with land use combination in the 1990s

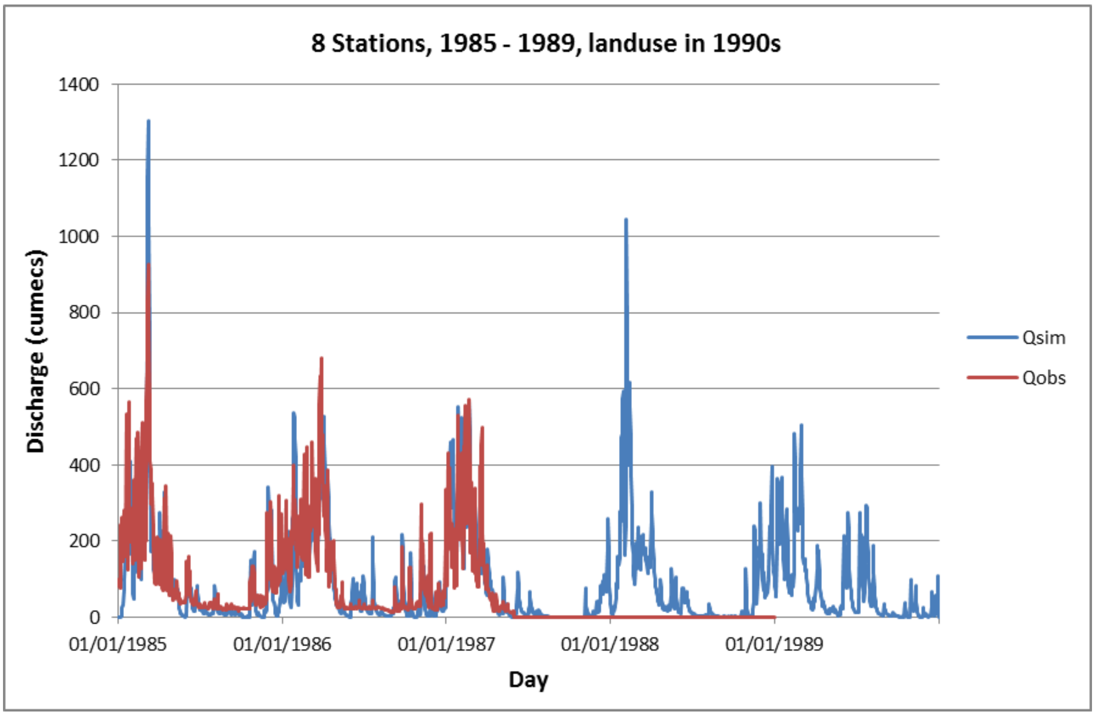


Figure 7. 4. Observed and simulated discharge in 1985 – 1989 with land use combination in the 1990s

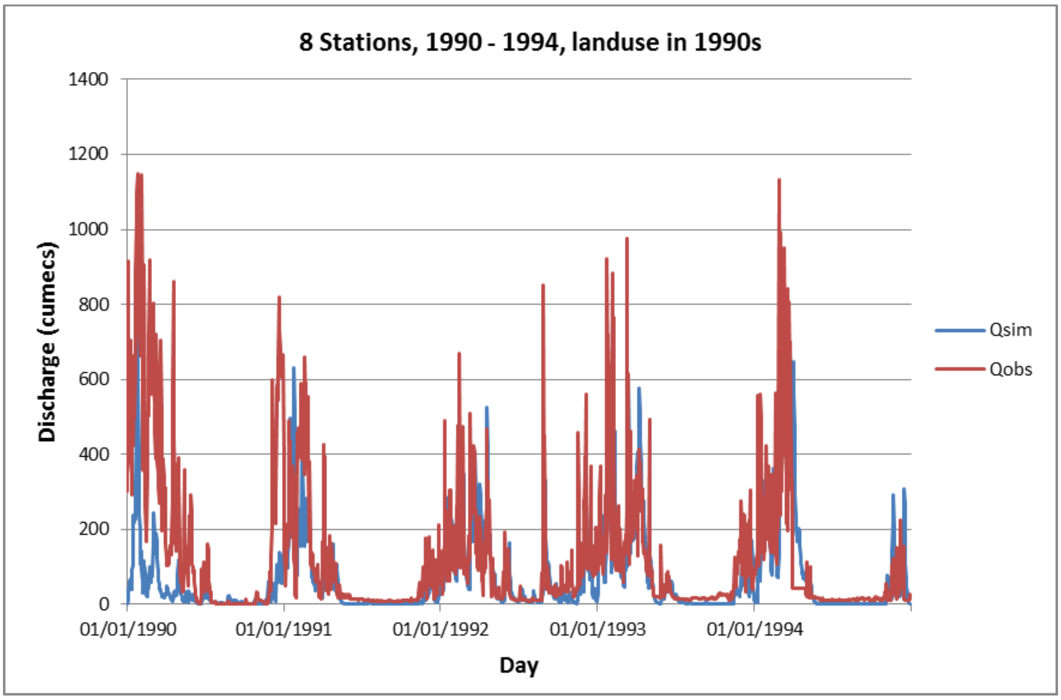


Figure 7. 5. Observed and simulated discharge in 1990 – 1994 with land use combination in the 1990s

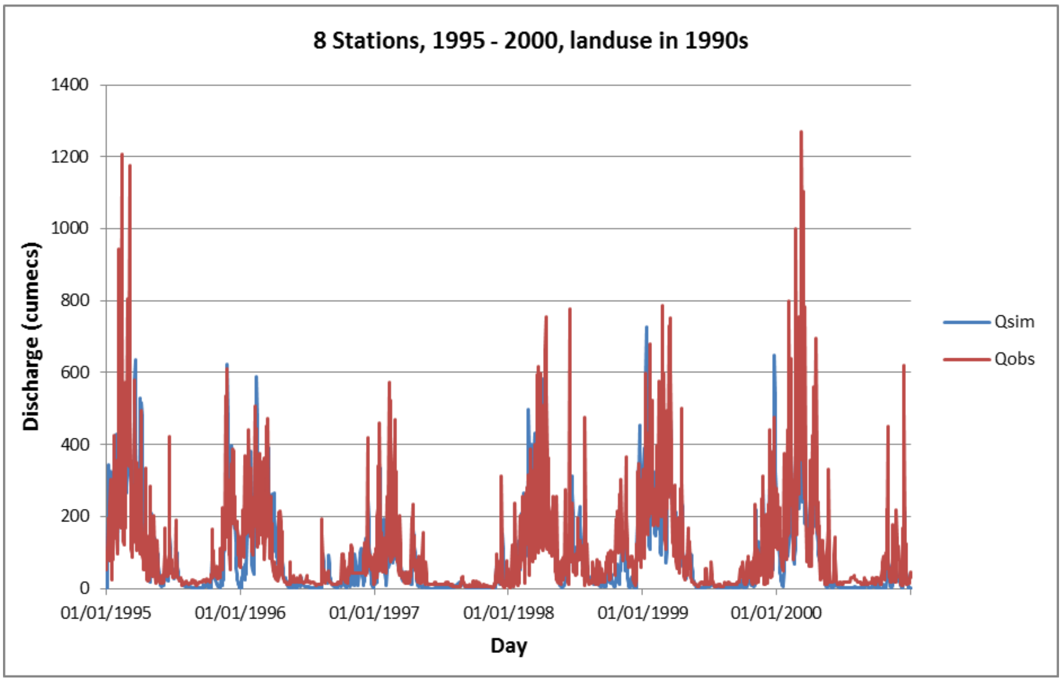


Figure 7. 6. Observed and simulated discharge in 1995 – 2000 with land use combination in the 1990s

The simulation using land use data in the 1990s produced NSE values 0.72, 0.71, 0.65, and 0.55 for each rainfall period, which are mostly similar to the NSE values produced by simulation using existing land use data.

7.1.2. The comparison of peak discharge from simulation using land use combination in 1990s and original existing land use (in 2006)

As explained previously in Chapter 5, the land use in Jurug catchment, which has an area of about 3850 km^2, is dominated by rice paddy field and bare ground. According to Wonogiri Regency Statistic Report (2011), the inhabitants of the catchment mostly work as farmers, producing various agricultural commodities including rice, cassava, corn, peanut, and local vegetables. The percentage of forest area is only 9% of the total area. Table 7.1 shows the percentage of original land use in Jurug catchment.

Land use type	% area
Paddy	29
Bare ground	29
Urban	14
Forest	9
Grass, shrub	19

Table 7. 1. Percentage of existing land use in Jurug catchment

Comparing the land use pattern in the 1990s and in 2006 (the existing original land use data applied in this research), the urbanised area in Jurug catchment in 2006 increased 8% from the condition in the 1990s. The rice paddy field in 2006 decreased 2%, and the bareground decreased 5% compared to the condition in the 1990s. The forest area in 2006 decreased 1%, while the the area of grass/shrub remain the same as in the 1990s.

Figures below show the comparison of selected peak discharge resulting from simulation using land use combination in 1990s and in 2006.

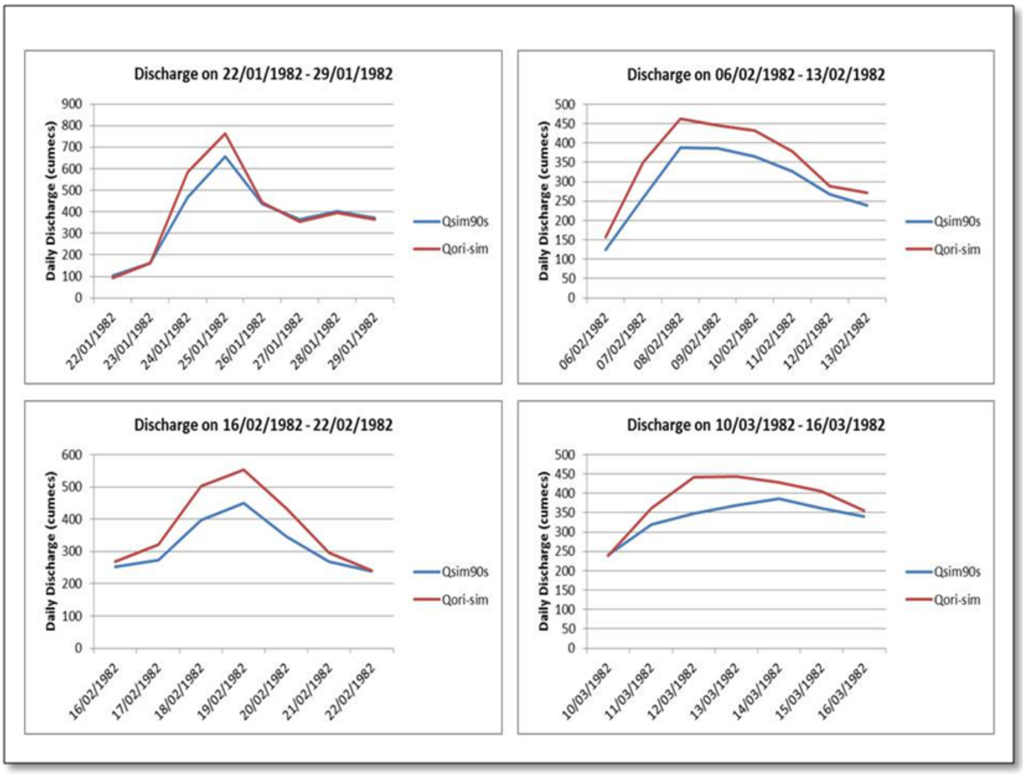


Figure 7. 7. Selected peak discharge in 1982 from simulation using land use data in the 1990s

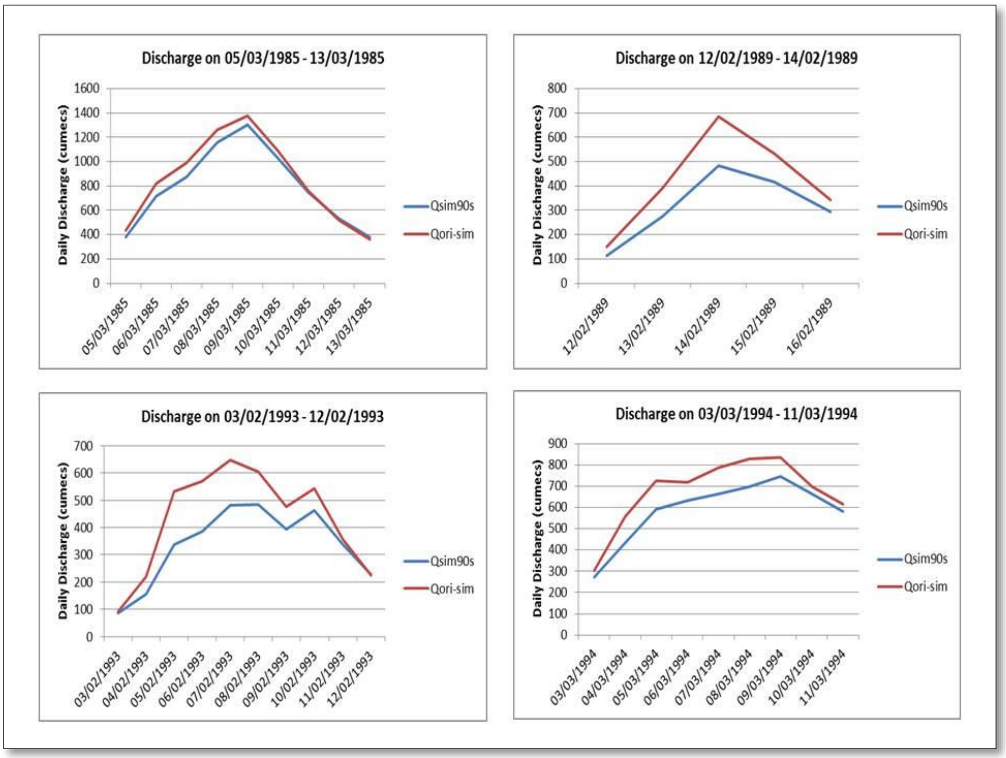


Figure 7. 8. Selected peak discharge from simulation using land use data in the 1990s

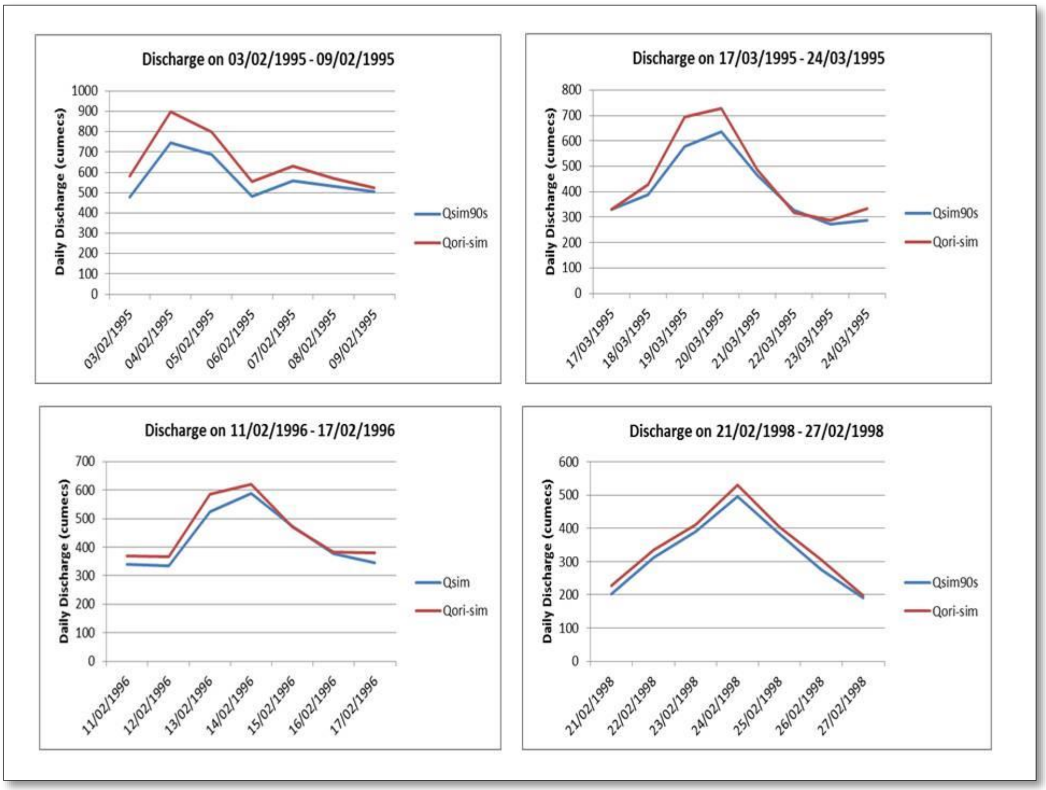


Figure 7. 9. Selected peak discharge from simulation using land use data in the 1990s

As shown in the figures above, the selected peak discharges from simulation using land use data in 2006 were higher than in the 1990s.

7.1.3. Future land use scenarios

To investigate the impact of land use change in the future to the flow in the catchment, the next SHETRAN simulations used different land use combinations for vegetation cover input. Hypothetical land use scenarios were applied in this research due to unavailable future land use plan data in the Jurug catchment. Information from local mass media was used as a reference to set up the land use scenarios. The Jurug catchment is situated in the Central Java Province. According to Tempo online media (2010), the area of agricultural fields in Central Java Province decreases by about 2,000 – 2,500 hectare every year. Moreover, according to Statistic Indonesia (2013), the number of population in Central Java

Province is increasing significantly in the future, therefore the demand of housing is increasing as well. As consequence, the area of agriculture field is predicted to decrease. The land use scenarios in this simulation was set up based on this information.

In this phase, there are 3 combinations of land use scenarios used for simulation. There is no change for the forest area because it has already been diminished and only 9% remains in the catchment. The land use types changed in this research are rice paddy field, bare ground, grass/shrub, and urban area. The 3 scenarios and percentage of land uses type for each can be seen in Table 7.2 and the figures.

Land Use	Percentages		
	Scenario 1	Scenario 2	Scenario 3
Rice paddy field	25	25	20
Bare ground	33	21	23
Urban	14	26	37
Forest	9	9	9

Table 7. 2. Percentages of land use type for 3 different land use scenarios

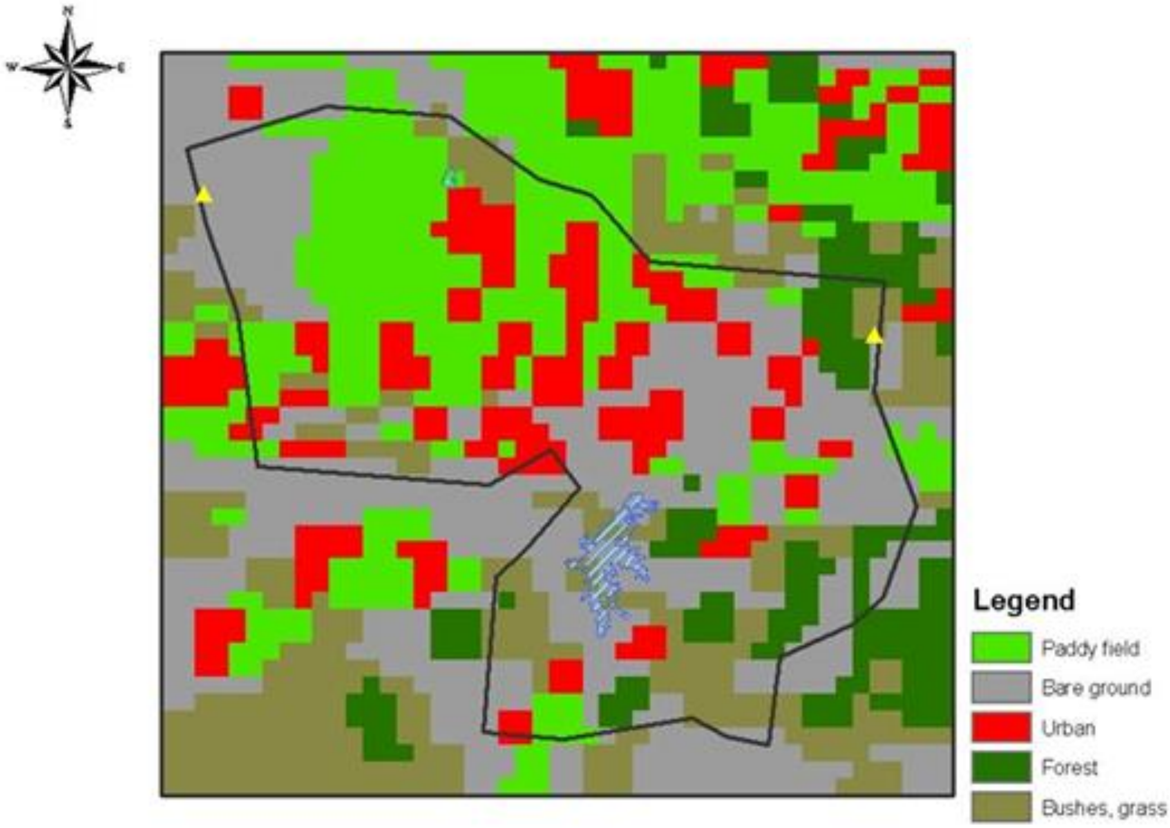


Figure 7. 10. Map of 1st land use scenario at Jurug catchment

Compared to the original land use, the area of rice paddy decreases to 25% while bare ground increases to 33% in the 1st land use scenario.

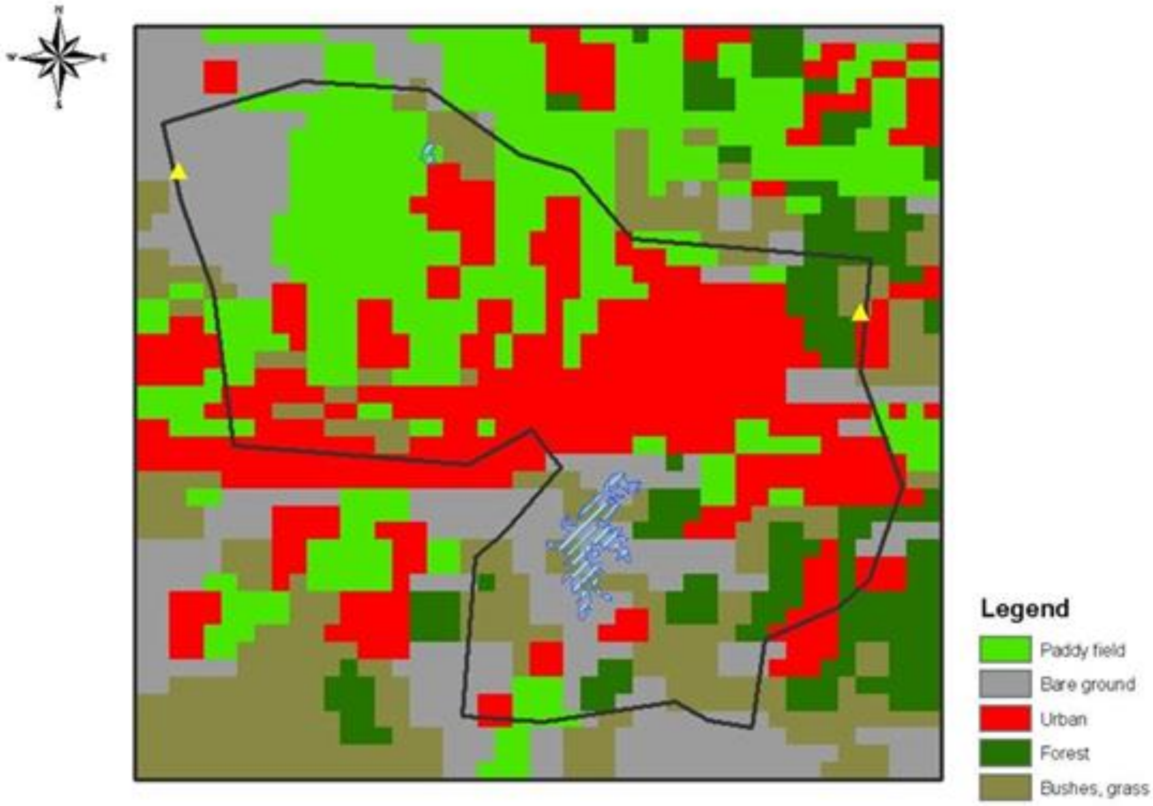


Figure 7. 11. Map of 2nd land use scenario at Jurug catchment

For 2nd land use scenario, the area of rice paddy and bare ground decrease to 25% and 21% respectively if compared to the original land use. Furthermore, the urban area goes up from 14% to 26%.

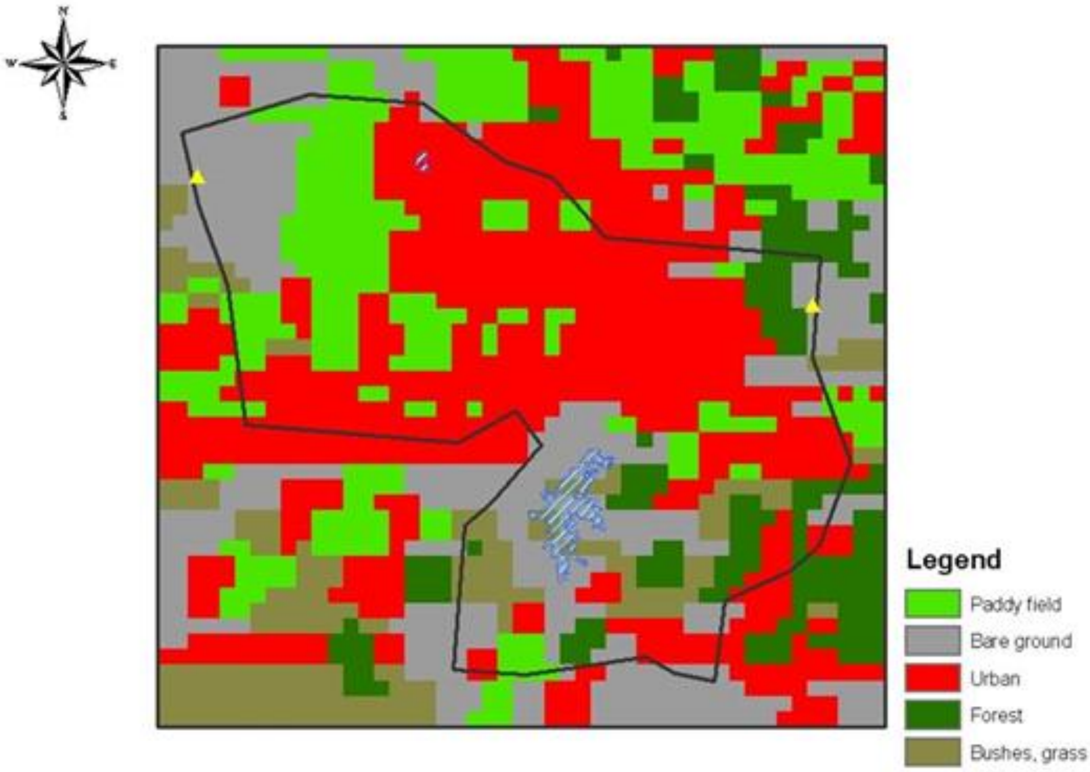


Figure 7. 12. Map of 3rd land use scenario at Jurug catchment

For the 3rd land use scenario, the area of rice paddy, grass/shrub and bare ground declines to 20%, 11% and 23% respectively, while the urban rises to 37% from 14%.

7.2. Effect of land use change on peak discharge

The peak discharges produced by simulation using land use in the 1990s and 2006 were different. Simulation using land use combination in the 1990s resulted lower peak discharge than simulation using land use in 2006. Table 7.3 below shows the comparison of selected peak discharge produced by simulation using land use combination in the 1990s and 2006.

From the Table 7.3, it can be seen that the peak discharge from simulation using land use in 2006 greater than in the 1990s with various percentage of increase discharge.

Date	Q_{sim} using landuse in 1990s (cumecs)	Q_{sim} using landuse in 2006 (cumecs)	% increase
24/01/1982	466.8	586.0	25.5
25/01/1982	657.0	765.3	16.5
19/02/1982	450.0	553.7	23.1
05/02/1984	766.9	866.5	13.0
06/02/1984	946.5	1049.5	10.9
07/03/1985	875.6	991.6	13.3
08/03/1985	1159.1	1262.7	8.9
27/01/1986	537.7	605.2	12.5
21/02/1987	564.2	612.4	8.5
06/02/1988	1044.5	1219.2	16.7
14/02/1989	482.3	686.4	42.3
25/01/1991	629.5	675.6	7.3
24/01/1993	633.9	716.0	12.9
07/02/1993	482.4	648.5	34.4
08/03/1994	699.8	829.8	18.6
04/02/1995	744.1	897.9	20.7

Table 7. 3. The comparison of selected peak discharge resulted from simulation using land use in the 1990s and 2006.

From the simulations performed using different future land use scenarios, the changes of simulated discharge are obvious. The simulation using the 3rd land use scenario where the urban area becomes 37% (increases 23% from the original one) of the total area resulted in significant increasing peak discharge in the catchment.

The value of peak discharge for selected peak events in 1980 - 1984 is presented in Table 7.4.

Date	Discharge (cumecs)			
	Original land use	1st land use scenario	2nd land use scenario	3rd land use scenario
23/01/1980	256.6	276.7	303.0	358.0
30/11/1980	265.6	286.4	313.7	370.6
07/12/1980	139.8	150.7	165.1	195.1
01/01/1981	116.4	125.5	137.5	162.4
09/01/1981	302.9	326.6	357.7	422.6
28/03/1981	390.9	421.5	461.7	545.5
30/11/1981	82.6	89.1	97.6	115.3
01/12/1981	168.0	181.1	198.4	234.4
02/12/1981	203.6	219.5	240.4	284.1
24/01/1982	586.0	631.8	692.0	817.6
18/02/1982	501.2	540.4	591.9	699.3
07/01/1983	431.7	465.5	509.8	602.4
04/02/1983	60.1	64.8	70.9	83.8
05/02/1983	69.8	75.3	82.5	97.4
08/02/1983	139.6	150.6	164.9	194.8
09/02/1983	125.2	135.0	147.9	174.7
10/02/1983	135.0	145.5	159.4	188.3
11/12/1984	102.8	110.8	121.4	143.4
12/12/1984	126.3	136.2	149.2	176.3
13/12/1984	194.5	209.8	229.8	271.5

Table 7. 4. Selected peak events resulting from simulation using original and land use scenarios from 1980 - 1984

The percentage increase in discharge resulting from the simulation using hypothetical land use scenarios in 1980 - 1984 compared to discharge resulting from the original land use can be seen in Table 7.5.

Year	Date	Q original land use (cumecs)	% of increasing discharge		
			1st land use scenario	2nd land use scenario	3rd land use scenario
1980	23/01/1980	256.6	8	18	40
	30/11/1980	265.6	3	14	28
	07/12/1980	139.8	7	26	36
1981	01/01/1981	116.4	16	53	73
	09/01/1981	302.9	8	21	31
	28/03/1981	390.9	4	11	27
	30/11/1981	82.6	25	100	116
	01/12/1981	168.0	15	54	65
	02/12/1981	203.6	14	39	48
1982	24/01/1982	586.0	2	0	30
	18/02/1982	501.2	1	2	26
1983	07/01/1983	431.7	10	17	28
	04/02/1983	60.1	13	70	90
	05/02/1983	69.8	9	59	72
	08/02/1983	139.6	18	25	59
	09/02/1983	125.2	16	20	47
	10/02/1983	135.0	25	29	39
1984	11/12/1984	102.8	31	54	51
	12/12/1984	126.3	16	41	48
	13/12/1984	194.5	9	24	39

Table 7. 5. Percentage increase in discharge at selected peak events from simulation using land use scenarios from 1980 - 1984

Moreover, the change in discharge resulting from the simulation using land use scenarios can be seen in Figure 7.4.

It can be seen that the highest increase in discharge due to land use change in 1980 – 1984 occurred on 30/11/1981, with 100% and 116% increment on 2nd hypothetical and 3rd land use scenario, respectively.

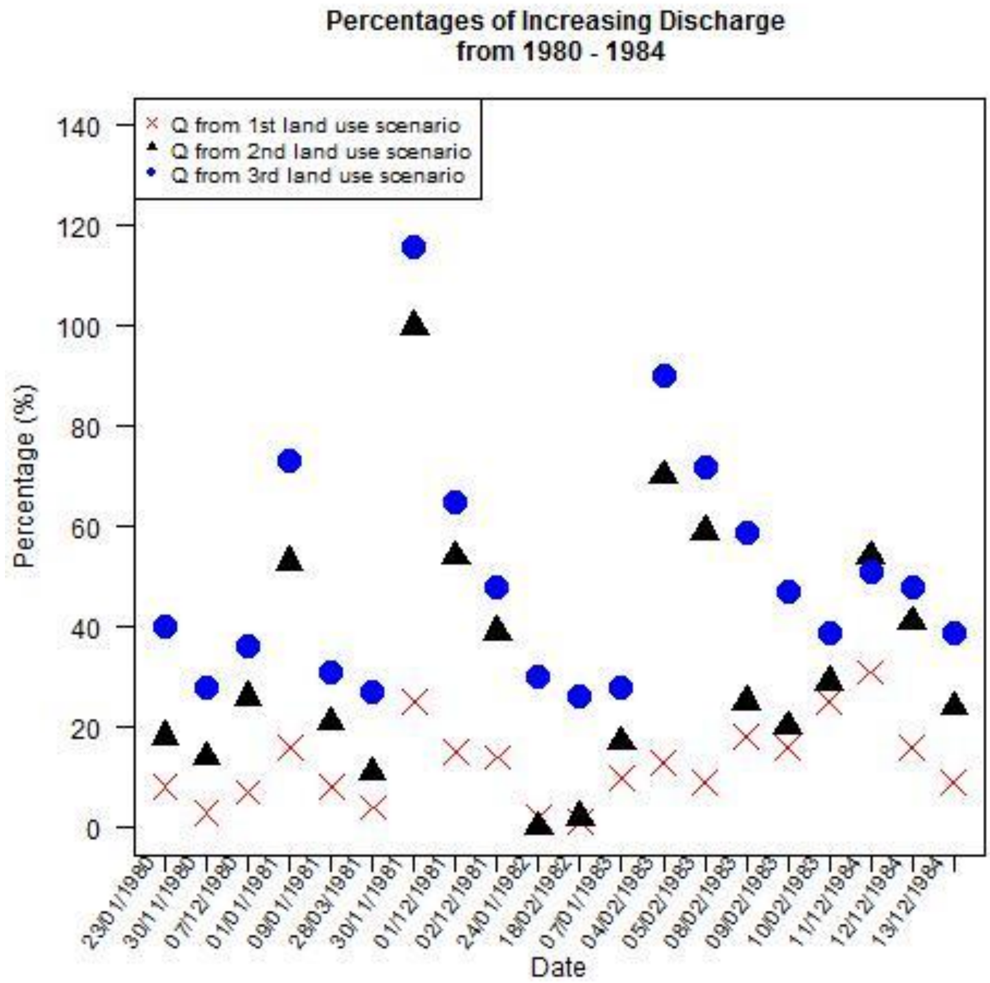


Figure 7. 13. Percentage increase in discharge for selected peak events from 1980-1984

For simulation using rainfall input in 1985 – 1989, the value of peak discharge and percentage of increase in discharge for selected peak events are presented in Tables 7.6 and 7.7, respectively.

	Discharge (cumecs)			
Date	Original	1st land use scenario	2nd land use scenario	3rd land use scenario
06/02/1985	170.4	170.5	174.1	240.0
29/11/1985	69.5	87.4	126.7	127.1
03/12/1985	279.4	301.1	356.6	355.3
07/12/1985	182.7	214.3	249.6	242.9
06/01/1986	69.3	76.0	81.5	100.4
10/01/1986	175.0	198.8	233.9	253.6
07/02/1986	200.9	205.4	201.0	314.6
15/12/1986	85.1	126.5	160.0	157.5
02/01/1987	208.1	258.4	293.9	356.9
05/01/1987	340.9	380.4	427.3	454.7
07/05/1987	104.2	154.4	183.3	188.3
11/12/1987	87.0	93.3	106.5	119.5
25/12/1987	198.5	206.1	221.3	255.3
18/01/1988	231.5	241.5	244.3	319.7
23/01/1988	306.8	329.0	388.3	406.4
09/03/1988	167.6	182.0	223.8	236.3
15/05/1988	114.3	144.0	215.3	260.5
23/05/1988	82.7	150.0	163.5	154.8
26/11/1988	158.8	186.7	217.8	218.7
07/12/1988	113.6	132.7	202.9	194.6
14/02/1989	686.4	710.6	746.2	901.1
28/03/1989	59.0	68.4	64.8	115.2
30/12/1989	112.7	115.7	120.0	152.1

Table 7. 6. Selected peak events resulting from the simulation using original and land use scenarios from 1985 – 1989

Year	Date	Q original land use (cumecs)	% increasing of discharge		
			1st land use scenario	2nd land use scenario	3rd land use scenario
1985	06/02/1985	170.4	0	2	41
	29/11/1985	69.5	26	82	83
	03/12/1985	279.4	8	28	27
	07/12/1985	182.7	17	37	33
1986	06/01/1986	69.3	10	18	45
	10/01/1986	175.0	14	34	45
	07/02/1986	200.9	2	0	57
	15/12/1986	85.1	49	88	85
1987	02/01/1987	208.1	24	41	71
	05/01/1987	340.9	12	25	33
	07/05/1987	104.2	48	76	81
	11/12/1987	87.0	7	22	37
	25/12/1987	198.5	4	11	29
1988	18/01/1988	231.5	4	6	38
	23/01/1988	306.8	7	27	32
	09/03/1988	167.6	9	34	41
	15/05/1988	114.3	26	88	128
	23/05/1988	82.7	81	98	87
	26/11/1988	158.8	18	37	38
	07/12/1988	113.6	17	79	71
1989	14/02/1989	686.4	4	9	31
	28/03/1989	59.0	16	10	95
	30/12/1989	112.7	3	6	35

Table 7. 7. Peak events and percentage increase in discharge resulting from simulation using hypothetical land use scenarios from 1985 – 1989

The highest percentage increase in discharge in period 1985 – 1989 occurred on 15/01/1988 where the discharge from simulation using the 3rd land use scenario increased by 128% compared to the simulation using the original land use.

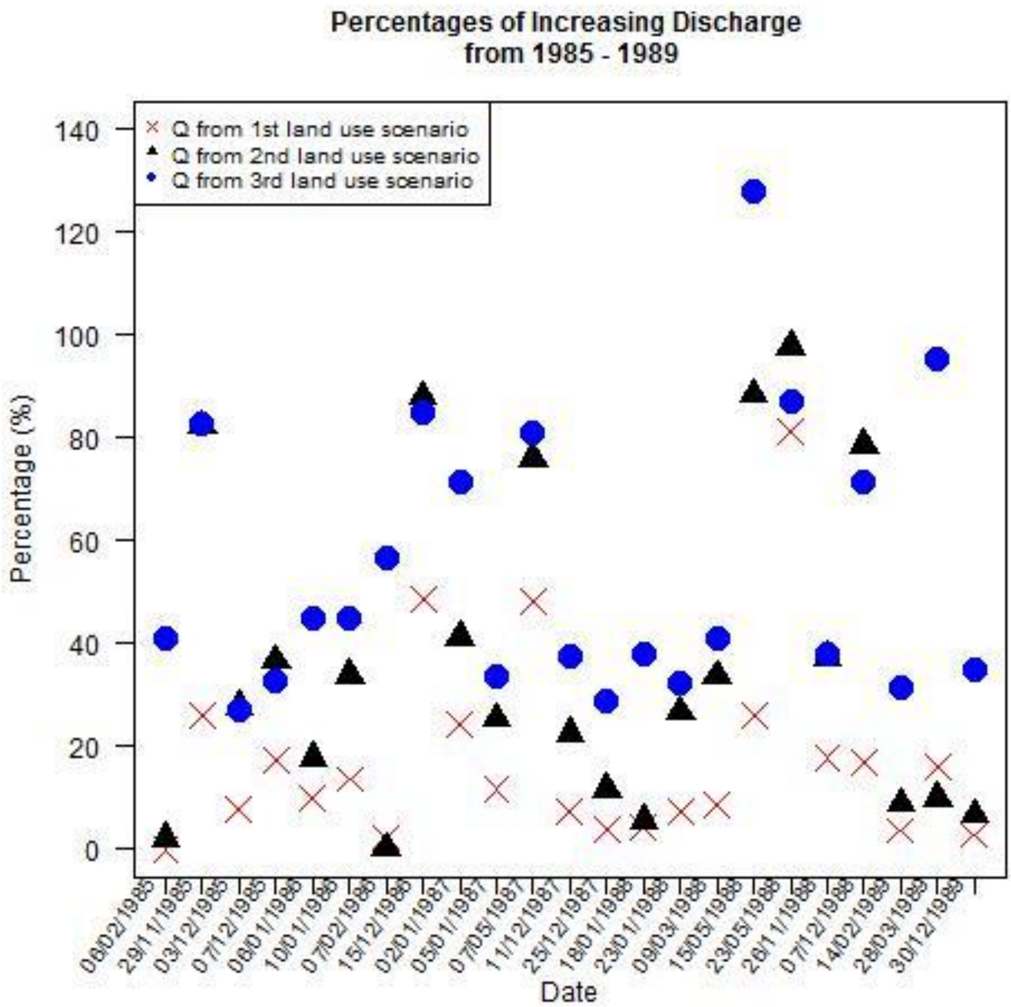


Figure 7. 14. Percentage increase in discharge for selected peak events from 1985- 1989

The value of peak discharge and the percentage increase in discharge for selected peak events in 1990 - 1994 are presented in Tables 7.8 and 7.9. In addition, the chart of the percentage increase in discharge can be seen in Figure 7.6.

Date	Discharge (cumecs)			
	Original	1st land use scenario	2nd land use scenario	3rd land use scenario
09/02/1990	173.7	182.6	203.6	250.2
02/03/1990	192.3	202.0	225.6	256.0
15/12/1990	157.5	169.2	167.4	231.6
09/04/1991	184.5	192.8	187.0	258.0
22/04/1991	103.7	118.5	163.2	160.0
08/12/1991	42.7	50.7	65.8	60.5
29/12/1991	110.7	143.9	215.3	245.7
12/01/1992	263.8	296.3	340.6	400.1
31/10/1992	20.5	29.6	36.4	34.4
04/11/1992	10.5	11.3	12.4	16.6
25/11/1992	45.3	70.8	130.9	135.1
03/12/1992	199.5	236.5	283.9	304.8
03/01/1993	112.3	123.3	181.6	184.7
20/01/1993	139.1	148.9	146.8	200.9
12/03/1993	335.1	372.3	462.3	518.5
03/12/1993	147.7	167.4	176.4	214.7
23/12/1993	112.3	138.3	161.2	189.5
10/01/1994	138.4	146.4	143.4	221.7
18/01/1994	263.8	299.7	358.5	398.2
28/02/1994	407.1	444.4	481.2	550.5
09/12/1994	141.5	147.8	142.6	188.5

Table 7. 8. Selected peak events resulting from simulation using original and land use scenarios from 1990 – 1994

The highest discharge from the simulation using rainfall period from 1990 – 1994 is 550.5 cumecs which occurred on 18/02/1994. However, as can be seen in Table 7.8, the highest percentage increase in discharge in the period from 1990 – 1994 occurred on 25/11/1992 where the discharge from the simulation using the 3rd land use scenario increased by 199% compared to the simulation using original land use. In addition, the simulation using 2nd land use scenario in this period produced an 189% increase in discharge.

Year	Date	Q original land use (cumecs)	% increasing of discharge		
			1st land use scenario	2nd land use scenario	3rd land use scenario
1990	09/02/1990	173.72	5	17	44
	02/03/1990	192.25	5	17	33
	15/12/1990	157.54	7	6	47
1991	09/04/1991	184.48	5	1	40
	22/04/1991	103.70	14	57	54
	08/12/1991	42.71	19	54	42
	29/12/1991	110.72	30	94	122
1992	12/01/1992	263.79	12	29	52
	31/10/1992	20.47	45	78	68
	04/11/1992	10.46	8	19	59
	25/11/1992	45.26	56	189	199
	03/12/1992	199.49	19	42	53
1993	03/01/1993	112.28	10	62	64
	20/01/1993	139.06	7	6	44
	12/03/1993	335.07	11	38	55
	03/12/1993	147.73	13	19	45
	23/12/1993	112.31	23	44	69
1994	10/01/1994	138.44	6	4	60
	18/01/1994	263.83	14	36	51
	28/02/1994	407.08	9	18	35
	09/12/1994	141.54	4	1	33

Table 7. 9. Peak events and the percentage increase in in discharge resulting from simulation using land use scenarios from 1990 – 1994

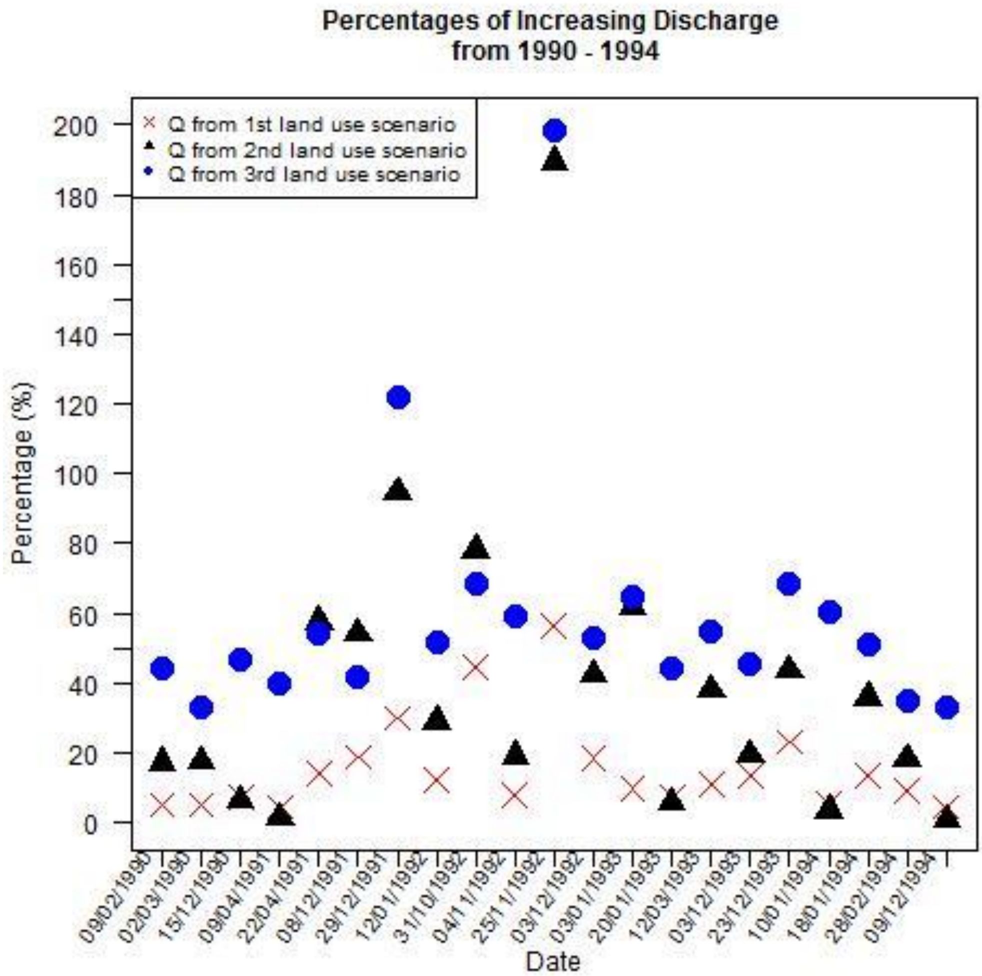


Figure 7. 15. Percentage increase in discharge for selected peak events from 1990 – 1994

The value of peak discharge and the percentage increase in discharge for selected peak events in 1995 - 2000 are presented in Tables 7.10 and 7.11. In addition, the percentage increase in discharge can be seen in Figure 7.7.

Date	Discharge (cumecs)			
	Original	1st land use scenario	2nd land use scenario	3rd land use scenario
05/01/1995	214.4	228.8	227.8	313.6
01/05/1995	96.3	109.2	119.4	197.2
03/06/1995	20.5	22.7	34.9	36.9
22/11/1995	481.9	562.1	662.2	691.0
10/01/1996	74.9	85.3	96.8	116.9
19/01/1996	195.4	240.6	256.9	303.4
18/04/1996	97.5	111.3	147.3	146.9
08/11/1996	98.3	108.0	130.4	142.4
23/11/1996	100.6	119.8	166.0	173.4
06/12/1996	116.8	145.2	186.0	203.2
24/03/1997	38.0	55.2	73.3	67.7
13/04/1997	49.2	86.5	107.1	104.0
16/12/1997	204.1	223.1	235.2	299.1
11/01/1998	65.8	78.3	110.9	114.2
02/02/1998	183.5	280.7	313.2	310.3
21/10/1998	64.4	77.5	99.9	101.4
05/11/1998	107.4	136.4	187.5	189.6
18/11/1998	88.1	108.0	139.5	140.7
20/12/1998	303.7	333.7	423.8	441.1
05/11/1999	248.2	336.6	351.4	337.7
19/11/1999	93.3	107.5	131.1	134.7
12/12/1999	322.2	413.3	512.0	521.5
23/01/2000	137.9	146.9	165.7	181.9
15/11/2000	151.9	174.7	216.3	236.5
20/11/2000	73.2	82.2	110.6	110.3
14/12/2000	182.4	226.5	286.3	304.1

Table 7. 10. Selected peak events resulting from simulation using original and land use scenarios from 1995 – 2000

Year	Date	Q original land use (cumecs)	% difference of discharge		
			1st land use scenario	2nd land use scenario	3rd land use scenario
1995	05/01/1995	214.44	7	6	46
	01/05/1995	96.29	13	24	105
	03/06/1995	20.45	11	71	80
	22/11/1995	481.85	17	37	43
1996	10/01/1996	74.92	14	29	56
	19/01/1996	195.35	23	32	55
	18/04/1996	97.46	14	51	51
	08/11/1996	98.34	10	33	45
	23/11/1996	100.63	19	65	72
	06/12/1996	116.82	24	59	74
1997	24/03/1997	38.02	45	93	78
	13/04/1997	49.17	76	118	111
	16/12/1997	204.08	9	15	47
1998	11/01/1998	65.76	19	69	74
	02/02/1998	183.52	53	71	69
	21/10/1998	64.43	20	55	57
	05/11/1998	107.42	27	75	76
	18/11/1998	88.06	23	58	60
	20/12/1998	303.71	10	40	45
1999	05/11/1999	248.16	36	42	36
	19/11/1999	93.29	15	41	44
	12/12/1999	322.15	28	59	62
2000	23/01/2000	137.87	7	20	32
	15/11/2000	151.90	15	42	56
	20/11/2000	73.22	12	51	51
	14/12/2000	182.39	24	57	67

Table 7. 11. Peak events and the percentage of increase in discharge resulting from simulation using land use scenarios from 1995 – 2000

The highest percentage increase in discharge in the period 1995 – 2000 occurred on 13/04/1997 where the discharge from the simulation using 2nd and 3rd land use scenarios increased by 118% and 111% compared to the simulation using original land use.

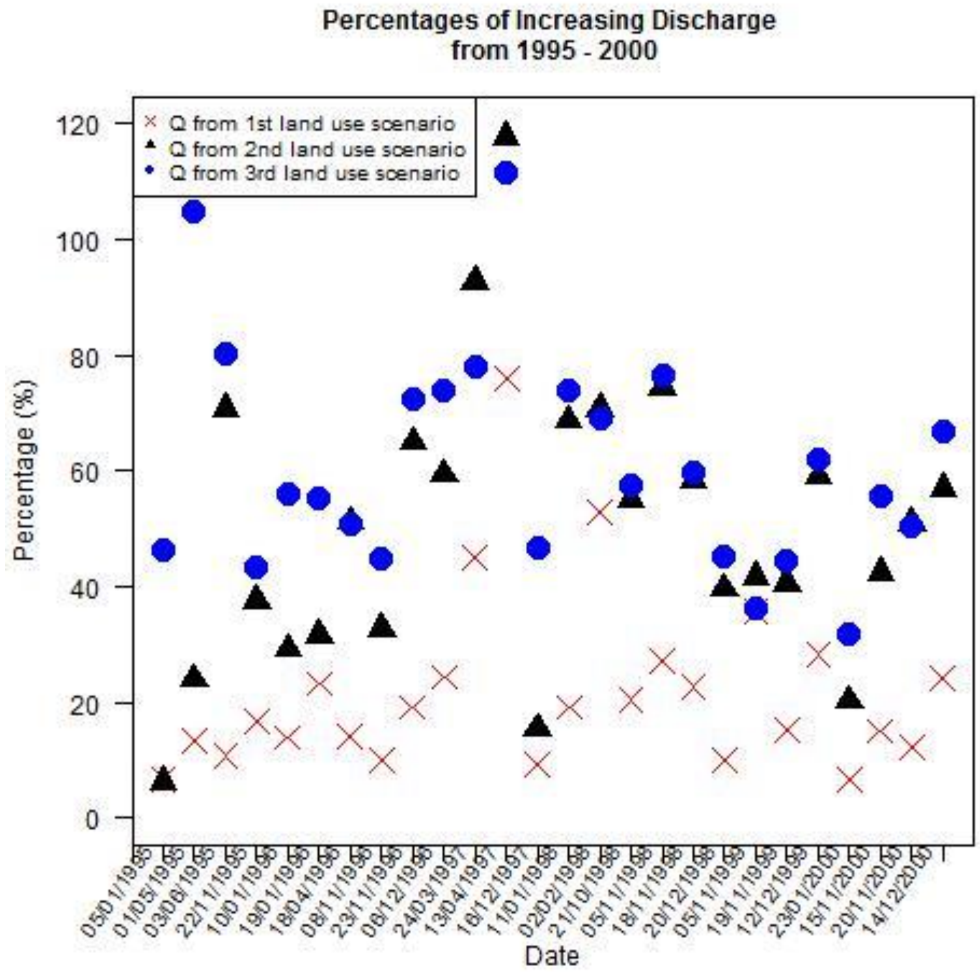


Figure 7. 16. Percentages increase in discharge for selected peak events 1995 – 2000

7.3. Sensitivity of annual mass balance to land use

Table 7.12 shows the annual discharge resulting from simulation using land use scenarios from 1980 – 2000, average annual rainfall, and annual potential evaporation (PE), in millimetre unit. Moreover, Figure 7.8 – 7.11 shows the charts of annual flow resulting from the simulation in periods from 1980 – 1984, 1985 – 1989, 1990 – 1994, and 1995 – 2000. As can be seen from the table and the charts, the highest average annual rainfall was occurred in 1995. As a result, the highest annual flow was produced in 1995.

The results show very little difference between the 3 different land use scenarios. The reason of this is that the change of land-use was mainly an increase in urban area and a decrease in bare ground, both of which have a similar actual evaporation and so annual discharge. Thus, the area of bare ground in the 2nd land use scenario is 12% lower than the 1st one, while the urban area in 2nd land use scenario is 12% higher than the 1st one. The areas of rice paddy field, forest, and grass / shrub are similar for both land use scenario. With the evaporation similar for both land-use types the annual discharge is similar. Whereas section 7.2 showed the urban area has a faster runoff and so significantly increased peak flows.

The daily peak discharge increased as the area of urban broaden. Larger urbanised area will increase impervious area which will reduce the capacity of the ground to absorb the rain water. Thus the amount of surface runoff is higher in the urbanised area, with shorter time to peak in the hydrograph.

Year	Q from 1st scenario (mm)	Q from 2nd scenario (mm)	Q from 3rd scenario (mm)	Average Annual Rainfall (mm)	Annual PET (mm)
1980	479	478	485	1949	2244
1981	711	710	723	2312	2244
1982	669	668	673	1777	2244
1983	592	591	607	2149	2244
1984	949	947	959	2493	2244
1985	749	748	765	2219	2244
1986	709	707	720	2237	2244
1987	669	668	686	1935	2244
1988	724	723	730	2288	2244
1989	615	614	628	2012	2244
1990	381	380	382	1529	2244
1991	501	500	508	1458	2244
1992	691	690	709	2074	2244
1993	716	714	721	1790	2244
1994	795	794	817	1733	2244
1995	1134	1133	1142	2745	2244
1996	594	592	603	2065	2244
1997	250	249	252	1354	2244
1998	906	904	932	2699	2244
1999	857	856	862	2395	2244
2000	623	622	631	1904	2244

Table 7. 12. Annual discharge resulting from simulation using land use scenarios, annual rainfall, and annual PE (mm)

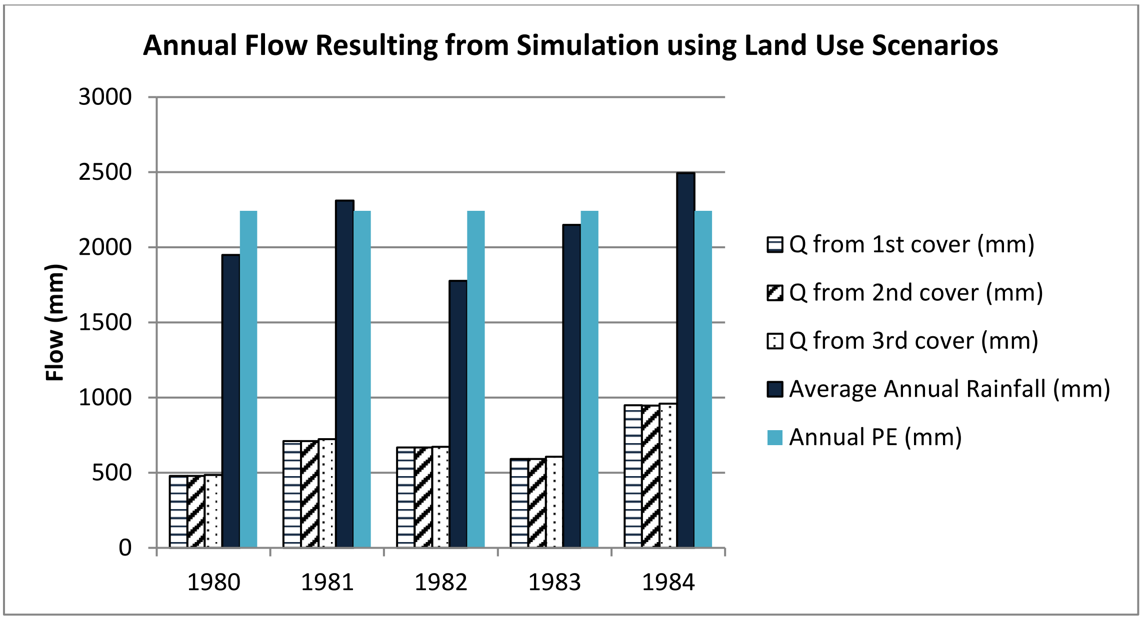


Figure 7. 17. Annual discharge, annual rainfall, and annual PE 1980 – 1984

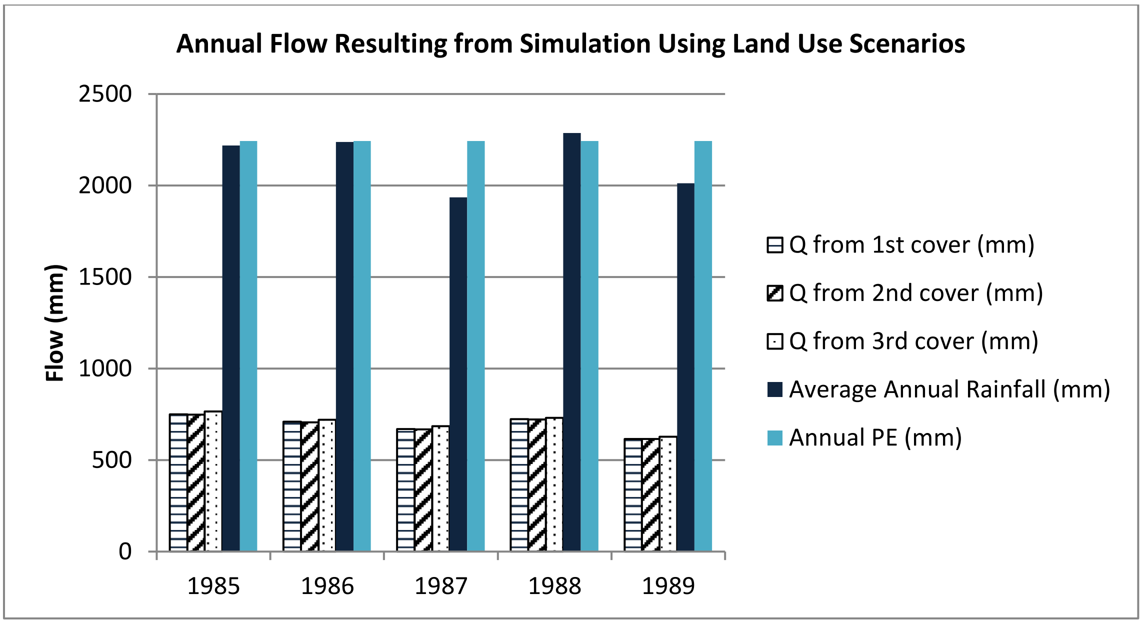


Figure 7. 18. Annual discharge, annual rainfall, and annual PE 1985 – 1989

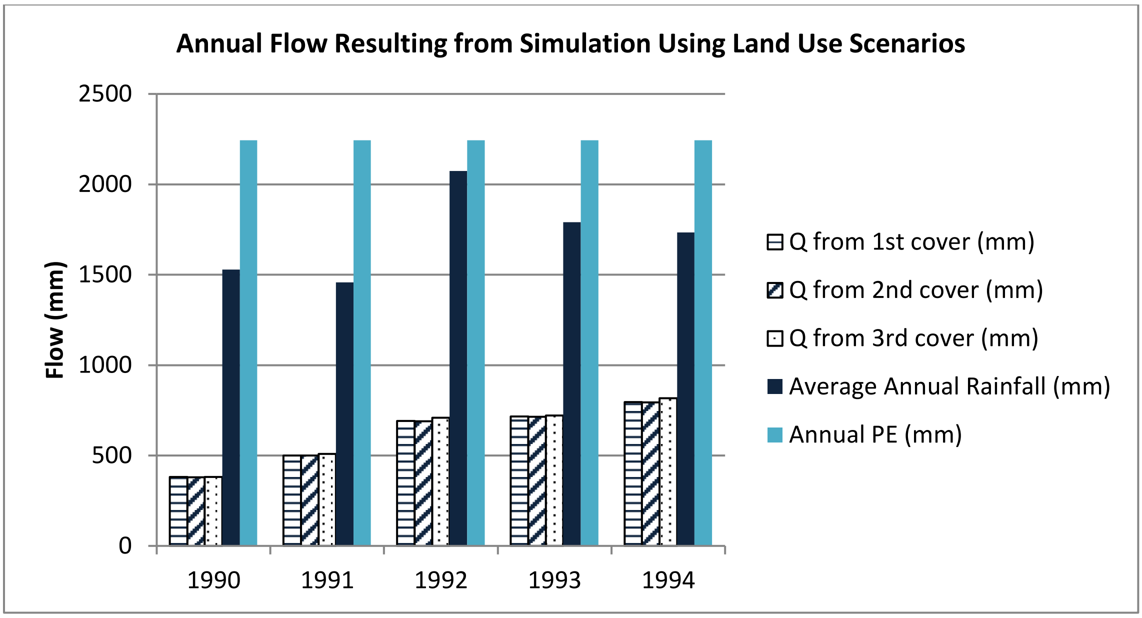


Figure 7. 19. Annual discharge, annual rainfall and annual PET 1990 – 1994

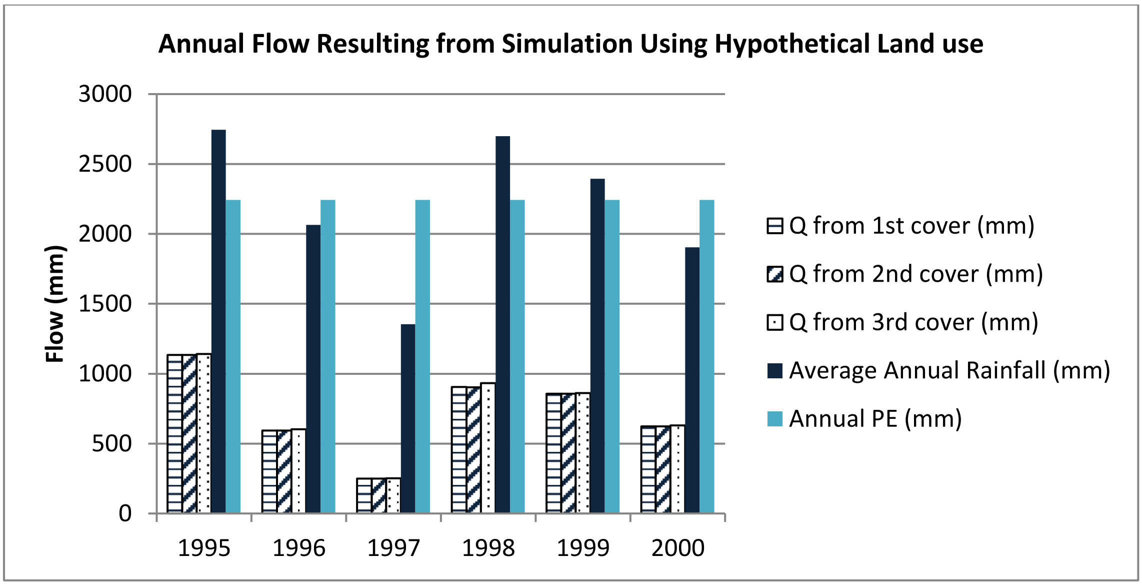


Figure 7. 20. Annual discharge, annual rainfall, and annual PET from 1995 – 2000

7.4. Summary

The existing land use data in Bengawan Solo river basin which was produced in 2006 shows different land use pattern compared to the land use data in the 1990s. In Jurug catchment which is situated in Upper Bengawan Solo cathment, during the 1990s period, the land use was dominated by rice paddy field and the urbanised area was relatively small. In 2006, the area of rice paddy field decreased and the urbanised area increased. The urbanised area in Bengawan Solo river basin tipically consists of settlement, public service building and its supporting infrastructure.

The SHETRAN simulation using different type of land use combinations produced different peak discharge. The land use combinations with wider urbanised area produced higher peak discharge. The urbanised area which usually consist of impervious surface inhibit the rain water to infiltrate into the ground. As a result, the surface runoff increases in the urbanised area.

To arrange robust flood management in river basin, the prediction of future peak discharge is one of the important attempts. Future peak discharge can be investigated using model such as SHETRAN. The performance of the model depends on the input data. In this research, the model performance for the period in 1990 – 2000 is less satisfactory than in 1980 – 1989, which might be caused by the quality of the data.

Chapter 8. Discussion and Conclusions

8.1. Discussion

8.1.1. Rainfall and discharge in Bengawan Solo river basin

The analysis in previous chapters has shown that the quality of rainfall and discharge data in the Bengawan Solo river basin is poor compared to some European and UK standards and has seriously limited the scope of the research originally proposed in this study. This issue is exacerbated by the heterogeneity of the convective rainfall prevalent in the basin. There are long data gaps in some rainfall and river gauging station records and the reliability of the stage-discharge relations is highly questionable. Therefore, the analysis of rainfall and discharge data in this research was applied only in selected gauging stations with complete data, and a number of investigations were carried out to improve the reliability of the data used for inputs and validation of the simulation components of the work.

Prior to undertaking investigations of the flood response of the basin, fundamental analyses of the rainfall data were carried out to check for changes or trends. Changes in rainfall extremes were identified using the Pettit test, which Busuioc and von Storch (1996) identify as a useful exploratory tool. In the case of annual maximum daily rainfall in the Upper Bengawan Solo catchment, the change point analysis detected a significant change at only one station, Klaten, in 1988. There was no change detected at the other stations, so the overall significance of this one result is low, and in the absence of any other major identified changes or trends in this research or in the literature, it is most likely that it was caused by human error, broken gauges, or relocated gauges.

Furthermore, the analysis of annual maximum daily rainfall within period of 1979 – 2009 in selected gauging stations (Baturetno, Klaten, Nawangan, Nepen, Pabelan and Tawangmangu) based on the Mann – Kendall test shows that there is no trend detected in annual maximum daily rainfall at any selected stations.

This is similar to the result of a study conducted by Satrio and Tanaka (2010) who applied the Mann – Kendall test to investigate the trend of annual maximum precipitation in Upper Bengawan Solo catchment using rainfall data from Klaten, Nepen, Pabelan, and Tawangmangu gauging stations. Satrio and Tanaka (2010) reported that there was no trend detected in annual maximum precipitation in the selected gauging stations in the catchment.

In addition, the highest maximum daily rainfall is 242 mm recorded at Baturetno gauging station on 26 December 2007. This event was followed by the most severe flooding in recent decades. According to a frequency analysis using the GEV distribution, the rainfall corresponding to a 25-year return period at the Baturetno station is approximately 165 mm. Similarly, using the Gumbel distribution, the daily rainfall with a return period of 25 years is approximately 150 mm. The maximum daily rainfall recorded at Baturetno station on 26 December 2007 exceeded the 25-year return period rainfall estimated using GEV and Gumbel distribution in this research.

In relation to discharge, the data series for the Bengawan Solo river basin are also unsatisfactory, and again only data series for a few selected gauging stations were used in this research. In the case of maximum discharge, the highest discharge in Lower Bengawan Solo catchment was 3249 m^3/s recorded at Napel station in 2007. Based on frequency analysis using GEV distribution, the maximum discharge with a return period of 25 year in Napel station is approximately 2630 m^3/s (or 2515 m^3/s using the Gumbel distribution). The discharge recorded at Napel station in 2007 when the big flood struck the river basin was higher than the 25-return period discharge estimated using GEV and Gumbel distribution.

Since 2007, the maximum daily rainfall as well as maximum discharge for the selected gauging stations has not exceeded these high levels. With no upward trend of maximum rainfall and discharge in the catchment, the flooding which has occurred annually since 2007 in the Bengawan Solo could also be triggered by factors such as river siltation, high sedimentation in drainage channels and reservoirs, and rapid increasing of impermeable surface in the basin. Indeed, Satrio and Tanaka (2010) reported that Surakarta city which is situated in Upper Bengawan Solo catchment, has flooded frequently (2007, 2008 and 2009) due to a combination of high rainfall, poor drainage system in Surakarta city, and insufficiency of main Bengawan Solo river to convey the peak discharge from the upstream area.

The rainfall and discharge data series used in this research is very limited, therefore the result of rainfall and discharge analysis might not be as perfect as expected before. The data series length is only available up to 20 - 30 years with many gaps in some gauging stations, therefore it is unreliable to estimate maximum rainfall and discharge for return period higher than 25 years. Integrated flood management requires reliable and qualified data to investigate the cause of flood and to plan the measures should be done in flood risk mitigation and reduction. The improvement of gauging networks and database system is very important in Bengawan Solo river basin, therefore reliable and qualified data required in flood risk management would be available.

8.1.2. Land use impacts on discharge

The investigation of land use change impacts on discharge in this research was achieved by applying SHETRAN simulations using multiple rainfall inputs from 8 selected rain gauging stations. The result of SHETRAN simulation using in situ rainfall input from year 1980 – 1989 is satisfactory, with NSE 0.72 – 0.73, whereas the result using rainfall input from 1990 – 2000 is less satisfactory with lower NSE value. The cause of lower NSE value in simulation using in situ rainfall input in 1990 – 2000 was not investigated, therefore it is unclear whether it caused by the low quality of in situ rainfall and discharge data or caused by uncertainty of the model.

During the 1990s, the land use in Bengawan Solo river basin was dominated by rice paddy field and other agricultural field, with urbanised area and forest in the whole river basin were approximately 32.4% and 19.5% of the total area respectively. In Jurug catchment which is situated in the Upper Bengawan Solo catchment, in the 1990s, the urbanised area was approximately 6% of the catchment. While based on land use data in 2006, the urbanised area in Jurug catchment increased 8% become 14% of the catchment area.

Based on the SHETRAN simulation result as described in Chapter 7, the discharge produced from simulation using land use in 2006 was higher than in the 1990s, particularly during wet season.

Moreover, there is no future projected land use data available in the Bengawan Solo river basin, therefore hypothetical scenarios were used to investigate the land use change impact on discharge. In the SHETRAN simulation using different land use scenarios, only in situ rainfall data were used as the rainfall input. It would be intriguing if sub-daily in situ rainfall and discharge data were available to compare the sensitivity of the simulation results for different land use scenarios. However, there are no sub-daily in situ rainfall and discharge data available in the study area.

The future land use scenarios in this research were estimated using the information from mass media which was very limited, therefore it might be less valid. In Indonesia, future plan of city or region is rarely set up. To estimate how the catchment responds to future flooding, the future plan of land use is one of the important information to be obtained. Therefore, it is suggested that the government should produce future land use in the region.

8.1.3. Peak discharge from SHETRAN simulation

In Chapter 7, the selected peak discharges resulting from simulation using land use combination in the 1990s, 2006 (existing land use data), and hypothetical scenarios were presented. In the period of 1998 – 2000, besides using in situ rainfall data, the 3-hourly TRMM data was used as well. It would be intriguing if sub-daily in situ rainfall data were available as rainfall input in the simulation using different land use scenarios, as these could be compared to the result of simulation using 3-hourly satellite-derived TRMM rainfall data. However, there are no 3-hourly in situ rainfall data available in the study area.

Reducing the area of rice paddy field, bare ground and grass/shrub, and broadening the urban area by 23% from the original condition, the peak discharge resulting from SHETRAN simulation using rainfall input in 1980 - 2000 was shown to increase considerably. The range of percentage of increase in selected peak discharge resulting from the simulation using rainfall input from 1980 – 2000 with different types of land use scenarios is presented in Table 8.1.

The highest increase of discharge resulted from the simulation using rainfall input in 1990 – 1994. It can be understood that the discharge resulted from simulation using rainfall input from 1990 – 1994 is the highest because the recorded rainfall during this year is also higher than the other periods. Increasing urban area will increase impervious area which reduces the capacity of the ground to absorb the water, thus increase the amount of surface runoff. In urbanised area with larger impervious area, lower evaporation and higher rainfall will produce higher surface runoff / peak discharge.

% increase of Q	Land use scenario			Land use scenario			Land use scenario			Land use scenario		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Minimum	1.0	-0.1	25.9	2.7	5.5	27.2	4.4	0.8	33.2	6.5	6.3	31.9
Maximum	30.6	99.6	116.2	81.4	97.7	128.0	56.4	189.3	198.6	75.9	117.8	111.4
Rainfall input	1980 – 1984			1985 – 1989			1990 – 1994			1995 – 2000		

Table 8. 1. The percentage of increase of discharge resulting from simulation using different types of hypothetical land uses and rainfall input in 1980 – 2000

Based on the SHETRAN simulation result, it is obvious that broadening the urban area increases the peak discharge considerably because the capability of the soil to infiltrate the water is diminished. Considering the fact that the housing and industrial area is broadening in the Bengawan Solo River Basin, it can be seen that the amount of surface runoff in the catchment is increasing which triggers flooding even in the absence of any trend of extreme rainfall in the catchment. In addition, the flood risk is likely to increase further in the basin because the growing population will increase the demand for housing and infrastructure which will increase the impervious area in the basin.

The performance of SHETRAN model in this research using rainfall data in 1980 – 1989 is satisfactory. However, for further implementation of SHETRAN model in Bengawan Solo river basin, there are some aspects should be taken into account such as for the large grid size, the changes across a grid cannot be incorporated and the model relies on the rainfall which misses some of the spatial variability. In addition, for rice paddy field which uses reduced Strickler coefficient, it would be useful to test it on a smaller sub-basin.

8.1.4. Existing flood management in Bengawan Solo river basin

As described in Chapter 1, following the major flood event of 2007, flooding in the Bengawan Solo river basin has become a continuing and serious problem as it happens annually. Indeed, in recent years, flood events have occurred twice a year. Generally speaking, the flood events create negative impacts as they destruct the public infrastructures, human settlement, agriculture land, and industries; and increase water-borne disease and displace people. In the past, the government relied on the dam constructed in the upper catchment, i.e., Wonogiri Dam. However, the dam performance is not satisfactory as expected due to high erosion and sedimentation rate in the upper catchment which is dominated by seasonal agricultural plantation.

The government also created “short-cuts” or channel diversions in some parts of Bengawan Solo River to drain the excessive water to the Java Sea more quickly. However, communities living downstream now complain that these interventions trigger floods downstream. Early warning systems have been set up in the Bengawan Solo River Basin, but do not work satisfactorily due to poor provision of electricity and internet service. In Indonesia, the electricity supply is typically subject to frequent interruptions, with deleterious consequences in many sectors.

Furthermore, to prevent flood damages to the community, the government has constructed embankments along the flood prone area from the upper to lower catchment. However, as reported by local mass media, some part of the embankment along the flood prone area in Bengawan Solo river basin has been used by local poor community for planting peanut, corn, and other seasonal vegetable, resulting in substantially reduced performance.

Bengawan Solo river basin is a trans-boundary river basin which belongs to 2 provinces, i.e., Central Java and East Java Provinces. Besides the local government, the national government also has responsibility in managing the river basin through the Ministry of Public Work which is represented by Balai Besar Sungai Bengawan Solo (Bengawan Solo River Basin Organisation). Since the implementation of decentralisation where each region in the country has autonomy to manage its own region, the coordination and cooperation between regions is likely to be weak. Implementing integrated flood risk management requires good coordination and cooperation among regions and authorities responsible for flood management, particularly in trans-boundary river basins.

One example of a trans-boundary river basin in Indonesia is the Ciliwung – Cisadane River Basin which is situated in provinces DKI Jakarta, West Java, and Banten. The city of Jakarta (the capital city of Indonesia) has experienced flooding annually since the Dutch colonial era. The local government and the related institutions in Jakarta supported by Dutch consultant have applied dredging along the main river as well as cleaning the drainage channel in Jakarta to minimize the flood risk. However, the capital city still experiences flooding which is more severe recently.

In the case of Jakarta flooding, Abbas et al (2012) reported that there is a lack coordination and cooperation among regions and authorities responsible for Jakarta flood management. This condition also occurs in other regions in Indonesia, including the regions where Bengawan Solo River Basin is situated. Bengawan Solo River Basin belongs to 2 provinces and 20 cities/regencies. Therefore, there are 2 governors, 20 mayors, and a significant numbers of agencies responsible to flood management in Bengawan Solo River Basin. With many bodies and agencies responsible to flood management in the basin, coordination and cooperation among them is essential to succeed the attempt in minimizing flood risk.

Furthermore, the regions situated in Bengawan Solo river basin have been implementing rapid economic development with less attention to environmental sustainability. The number of housing, industrial areas, and other building have increased significantly with very limited green space in the regions. The water bodies and infrastructures are also poor maintained. This condition shows that educating people and improving the capacity building of all stakeholders is required.

In the case of trans-boundary river basin, the authorities responsible for flood management in Indonesia might learn from the Mekong River Commission experiences. The Mekong River Commission (MRC) is an organisation managed by the countries situated in Mekong River Basin, i.e. Thailand, Vietnam, Cambodia, and Lao PDR. The MRC works to manage the river basin, including managing the flood and drought in the basin. As presented in MRC website, the MRC provides river monitoring services including flood forecasting to its member countries, and also provides facilitation on water and its related issues, capacity building, and technology transfer for flooding. In 2005, MRC established Flood Management and Mitigation Programme (FMPP). In the framework of FMPP, there have been several efforts made to minimize the flood risk in the Mekong River Basin such as setting up flood forecasting and early warning; supporting dialogue and knowledge production; and enhance cooperation among its member countries.

Regarding flood forecasting and early warning, the MRC use the data collected from 138 hydro-meteorological stations to predict the water levels at 23 forecast points on the Mekong River system. To communicate this information daily, the FMMP uses fax, e-mail, and updated MRC web pages. This daily warning programme provides the agencies and communities in Cambodia and Laos PDR with advanced notice of rising water levels. The FMMP also provides flood markers and community billboards to give clear information about current and predicted water levels. In addition, the FMMP also deliver online postings, radio communication, guidebooks and workshops.

Furthermore, according to Cap-Net (2011), a proper Integrated Urban Flood Management Plants (IUFMP) consists of four major sections i.e. policies (consists of objectives, principles, goals and scenarios); assessment of existing conditions related to floods; development of the measures (both non-structural and structural) to reduce the impacts and reach the goals; and delivering the outputs and outcomes for the city. The authorities and agencies responsible for flood management in Bengawan Solo River Basin could consider this approach or copy the effort done by the MRC with some modification appropriate for Bengawan Solo catchment conditions and configuration.

8.2. Conclusions

Flooding has become a serious problem in Indonesia and looks set to increase. The occurrence of flooding has spread widely across the country which has generated severe negative impacts. This research has investigated the properties and nature of flooding in the Bengawan Solo River Basin which is situated in East Java and Central Java Provinces with a view to assessing possible future changes and formulating advice for risk management. Considering the result from analysis using available data and SHETRAN simulation, it can be concluded as follows:

a) The environment in Bengawan Solo river basin has been degraded where the area of forest is very small, the river is poorly managed, and the economic development is less controlled.
b) Based on the Mann-Kendall and Pettit tests of annual and monthly maximum daily rainfall conducted in this research, it is clear that the tests produced different results. During the wet season, the Pettit test produced different results for annual maximum daily rainfall and monthly maximum daily rainfall. There is an abrupt change detected at Klaten station for the annual maximum daily rainfall, but no change is detected on a monthly basis. The Pettit test, on the other hand, was applied for maximum daily rainfall during rainy months (October - March) and detected an abrupt change at the Nepen station in March.

c) There is no trend of extreme rainfall detected in selected rain gauging stations in the Bengawan Solo River Basin using Mann-Kendall test.

d) Based on the frequency analysis conducted in this study, only the data series from the Klaten and Nawangan stations closely fit the Gumbel distribution. On the other hand, all of the stations are reasonably close to the GEV distribution's line of fit. The data series at Klaten, Nawangan, Pabelan, and Tawangmangu stations fit the GEV and Gumbel distributions well. However, due to the short record lengths, estimates for return periods longer than 20 years are uncertain. Based on this, more rain gauges with better quality control or satellite data are required for the better data.

e) The SHETRAN simulation result shows that increasing urbanised areas increases the peak discharge noticeably, therefore planning control of land use change and development is needed to avoid further problems. The availability of better hydrometry data is also required for better flood simulation.

f) The large flood event in December 2007 can be satisfactorily reproduced confirming that it was essentially related to the high rainfall (which is recorded as the highest maximum precipitation). However, flooding has continued to occur since 2007, with rainfall events of lesser magnitude than in December 2007.

g) Considering the result from the SHETRAN simulation and the fact that the number of buildings is increasing in Bengawan Solo River Basin, it can be understood that flooding will continue to occur even if climate change does not bring about increased frequency or severity of extreme rainfall.

h) Bengawan Solo river basin belongs to 20 regions and 2 provinces which have autonomy to manage their resources, and managed by several institutions responsible in water resources management. The governments and related institutions must cooperate and coordinate in managing the flood risk in the river basin.

i) Since flooding is likely to occur, attempts must be made to minimize the risk and reduce the severe impact of flooding. Such measures have been put in place by the Mekong River Commission and the approach introduced by Cap-

Net might be adopted by some modification appropriate to the Bengawan Solo River Basin situation. Providing early good flood forecasting and warning systems, conducting capacity building for all related stakeholders, enhance coordination and cooperation among related agencies and authorities, and development flood measure both structural and non-structural could be implemented to reduce the flood risk and minimize severe impact of flooding in Bengawan Solo River Basin.

8.3 Recommendations for future research

In this research, it can be seen in the previous chapters that there are several areas where shortcomings are apparent and where further research would be beneficial.

A key area of shortcomings is the availability and the quality of the data. Due to the limitation of the available data, this research result is not as satisfactory as expected before. To achieve successful flood risk management program, the availability and quality of the required data is very important. Learning from the experience during conducting this research, it is recommended that:

a) Persuade the government and related agencies or authorities to improve the hydrology, hydraulic, and meteorological gauging networks in Bengawan Solo River Basin and other river basins in Indonesia, particularly error-checking of the data obtained from the gauging networks. It is also important to improve the database system in related agencies / authorities as well as install more rain gauges in the river basins due to spatial variability of the rainfall.

b) Conduct further research regarding the impact of climate change on flooding in Bengawan Solo River Basin based on more reliable data, including further use of 3-hourly TRMM data in longer period. If the information of peak discharges is highly required rather than daily discharges, sub-daily rainfall data is needed, and TRMM data would be useful. Downloading the longer TRMM data from Indonesia might be difficult because of the limitation in the internet connection. However, it is worth using longer periods of 3-hourly TRMM for further research in the future.

c) Further research using SHETRAN simulation would be useful as well. Besides it is free downloadable, the advantage of SHETRAN software is the user can modify the parameter of input data as required based on the catchment characteristic. In the case of Indonesia, particularly in Java Island, SHETRAN software might need to be developed by considering other land use type such as the seasonal plantation to improve the simulation.

d) Taken into account the future climate change, future impact assessments would be useful if global climate model (GCM) outputs are available and reliable, although the urgent need is to deal with flooding under the present conditions.

References

Abhas K Jha, Robin Bloch, and Jessica Lamond (2012) 'Cities and flooding : a guide to integrated urban flood risk management for the 21st century', World Bank. Available at: http://www.gfdrr.org/sites/gfdrr.org/files/urbanfloods/pdf/Cities%20and%20Flooding%20Guidebook.pdf. (Accessed : 10 January 2013).

Adi, S. (2013) 'Characterization of Flash Flood Disaster in Indonesia Karakterisasi Bencana Banjir Bandang Di Indonesia', *Jurnal Sains dan Teknologi Indonesia*, 15(1), pp. 42–51.

Adnan, N.A. and Atkinson, P.M. (2010) 'Exploring the impact of climate and land use changes on stream flow trends in a monsoon catchment', *International Journal of Climatology*, Wiley Inter Science.

Azdan, M.D. (2011) 'Overview of Indonesia water system and policies', [Online]. Available at: http://www.oecd.org/tad/sustainable-agriculture/49213672.pdf (Accessed: 18 October 2013).

Bao, J.Z., Wang, G. et al (2012) 'Attribution for decreasing stream flow of the Haihe River Basin, Northern China: climate variability or human activities?', *Journal of Hydrology*, 460-461, pp. 117-129.

Bartholy, J. and Pongracz,R. (2007) 'Regional analysis of extreme temperature and precipitation indices for the Carpathian Basin from 1946 to 2001', *Global and Planetary Change*, 57, pp. 83-95.

Bates, B.C., Kundzewicz, Z.W., Wu, S., and Palutikof, J.P. (2008) 'Climate change and water: technical paper of the Intergovernmental Panel on Climate Change', *IPCC Secretariat*, Geneva, 210 pp.

Bathurst, J.C., Ewen, J., Parkin, G., O'Connell, P.E., and Cooper, J.D. (2004) 'Validation of catchment models for predicting land use and climate change impacts 3. blind validation for internal and outlet responses', *Journal of Hydrology*, 287, pp. 74-94.

Bathurst, J.C., Felipe Cisneros, et al (2011) 'Forest impact on floods due to extreme rainfall and snowmelt in four Latin American environments 1: field data analyses', *Journal of Hydrology*, 400, pp. 281-291.

BBWS Bengawan Solo (2008) 'Balai Besar Wilayah Sungai Bengawan Solo' [Online]. Available at: http://www.pu.go.id/satminkal/index.asp?Site_id=103220602 (Accessed: 20 October 2010)

Begueria, S. and Vicente-Serrano, S.M. (2005) ‘Mapping the hazard of extreme rainfall by Peaks Over Threshold extreme value analysis and spatial regression techniques’, *Journal of Applied Meteorology and Climatology*, 45, pp. 108-124.

Benito, G. et al (2010) 'The impact of Late Holocene climatic variability and land use change on the flood hydrology of the Guadalentín River, Southeast Spain', *Global and Planetary Change*, 70, pp. 53-63.

Birkinshaw, S.J. and Ewen, J. (2000) ‘Modelling nitrate transport in the Slapton Wood catchment using SHETRAN’, *Journal of Hydrology*, 230(1-2), pp. 18-33.

Birkinshaw, S.J., and Ewen, J. (2000) ’Nitrogen transformation component for SHETRAN catchment nitrate transport modelling’, *Journal of Hydrology*, 230(1-2), pp. 1-17.

Brath, A., Montanari, A., and Greta Moretti (2006) 'Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty)', *Journal of Hydrology*, 324, pp. 141-153.

Burton, A., Glenis, V., Jones, M.R., & Kilsby, C.G. (2013) ‘Model of daily rainfall cross-correlation for the United Kingdom’, Environmental Modelling & Software, 49, 22-33.

Cabello, A., Velasco, M., Barredo,J.I., Hurkmans, R.T.W.L. et al (2011) 'Assessment of future scenarios of climate and land use changes in the IMPRINTS test-bed areas', *Environmental Science & Policy*, 14, pp. 884-897.

Camorani, G., Castellarin, A., and Brath, A (2005) ‘Effects of land use changes on the hydrologic response of reclamation systems’, *Physics and Chemistry of the Earth*, Parts A/B/C, 30 (8–10), pp. 561-574.

Cap-Net (2011) ‘Integrated Urban Flood Management’ [online]. Available at: http://www.apfm.info/publications/manuals/Cap-Net%20WMO%20Integrated%20Urban%20Flood%20Management.pdf (Accessed: 12 March 2013)

Choi, W. and Brian M.D. (2008) 'Assessing hydrological impact of potential land use change through hydrological and land use change modelling for the Kishwaukee River Basin (USA)', *Journal of Environmental Management*, 88, pp. 1119-1130.

Condom, T., Rau, P. and Espinoza, J.C. (2010) ‘Correction of TRMM 3B43 monthly precipitation data over the mountainous areas of Peru during the period 1998 – 2007’, *Hydrological Processes*, John Wiley & Sons.

Croitoru, A.E., Chiotoroiu, B.C., Todorova, V.I., and Torica, V. (2013) ‘Changes in precipitation extremes on the Black Sea Western Coast’, *Global and Planetary Change*, 102, pp. 10-19.

De Roo, A., Odijk, M., G. Schmuck, E. Koster, A. Lucieer (2001) 'Assessing the effects of land use changes on floods in the Meuse and Oder Catchment ', *Physics and Chemistry of the Earth*, 26(7-8), pp. 593-599.

Descroix, L., Genthon, P., Okechukwu Amogu, Jean-Louis Rajot, Daniel Sighomnou, Michel Vauclin (2012) 'Change in Sahelian rivers hydrograph: the case of recent red floods of the Niger River in the Niamey region', *Global and Planetary Change*, 98-99, pp. 18-30.

Dinas Kependudukan dan Pencatatan Sipil Kota Surakarta (2012) [online]. Available at: http://dispendukcapil.surakarta.go.id/index.php/profilpenduduk/tahun-2012/90-kuantitaspenduduk/96-jumlahdanpersebaranpenduduk (Accessed: 10 November 2013)

Directorate Water Resources, Ministry of Public Work, Government of Republic Indonesia (2009) 'Peta Penggunaan Lahan Wilayah Sungai Bengawan Solo.'

Directorate Water Resources and Irrigation, National Development Planning Agency of Republic Indonesia (2013) 'Water Resources and Urban Flood Management in Indonesia',[Online]. Available at: http://www.unescap.org/esd/suds/egm/2013/urban-flood-management/documents/3-Country-Presentations/Indonesia.pdf (Accessed: 18 October 2013).

Dobler, C., Brüger, G., and Stötter, J. (2012) 'Assessment of climate change impacts on flood hazard potential in the Alpine Lech watershed', *Journal of Hydrology*, 460-461, pp. 29.39.

Duan, Z., Bastiaanssen, W.G.M and Liu, J. (2012) 'Monthly and annual validation of TRMM multi satellite precipitation analysis (TMPA) products in the Caspian Sea region for the period 1999 – 2003', a paper presented at IEEE IGARSS 2012, 22 – 27 July 2012, Munich, Germany.

Đukić, V. & Radić, Z. (2014) 'GIS Based Estimation of Sediment Discharge and Areas of Soil Erosion and Deposition for the Torrential Lukovska River Catchment in Serbia', *Water Resources Management*, 28(13), pp. 4567–4581.

Ewen, J., Parkin, G., and O'Connell, PE. (2000) SHETRAN: distributed river basin flow and transport modeling system. Proc. Am. Soc. Civ. Engrs., J. Hydrologic Engrg. 5, 250-258.

Fohrer, N., Haverkamp, S., Eckhardt, K.H., and Frede, G. (2001) 'Hydrologic response to land use changes on the catchment scale', *Physics and Chemistry of the Earth*, Volume 26, pp. 577-582.

Government of Indonesia (2011), 'Peraturan Pemerintah Republik Indonesia Tentang Sungai PP No. 38/2011'.

Gregersdotter, L. (2009) ‘Planning for sustainable settlements along the River Bengawan Solo, Java Island, Indonesia’. Master degree thesis for Master Program of Spatial Planning at Blekinge Institute of Technology, p. 42.

Gubareva, T.S., and Gartsman, B.I. (2010), ‘ Estimating distribution paramaters of extreme hydrometeorological characteristics by L-moments method’, Water Resources Vol 37. No 4, Pleiades Publishing, Ltd., pp. 437-445

Hidayat, F. (2009) 'Floods and climate change - observations from Java, Solo, Central Java, Indonesia', *crbom.org* [Online]. Available at: www.crbom.org (Accessed: 29 March 2010).

Hidayat, F. and Valiant, R. (2007) ‘Introduction to the study visit program: sedimentation problem and water allocation within the Bengawan Solo River Basin (Wonogiri Reservoir)’, Report for 3rd General Meeting of NARBO.

Hoekstra, P. (1988) 'Coastal hydrodynamics, geomorphology and sedimentary environments of two major Javanese river deltas: program and preliminary results from The Snellius-II Expedition (Indonesia) ', *Journal of Southeast Asian Earth Sciences*, 2(2), pp. 95 - 106.

Hoekstra, P.R.F.N. and Van der Sloot, H.A. (1989) 'Supply and dispersion of water and suspended matter of the Rivers Solo and Brantas into the coastal waters of East Java, Indonesia ', *Netherlands Journal of Sea Research*, 23(4), pp. 501 - 515.

Hosking, J.R.M. (1990) ‘L-moments: analysis and estimation of distributions using Linear Combination of order statistics’, *J.R. Statistic Society*, 52 (1), pp. 105-124.

Huilan, S., Yaning, C., and Weihong, L. et al (2010) ‘Variation and Abrupt Change of Climate in Ili River Basin, Xinjiang’, *Journal of Geography Sciences*, 20 (5), pp. 652-666.

Indonesia Ministry of Public Work (2008) [Online]. Available at: http://www.pu.go.id/publik/ind/produk/info_peta/rwnbanjir/bencana2008/3335indexbengawansolobanjir.htm (Accessed: 11 January 2012)

Indrani P. and Al-Tabbaa, T. (2009) 'Trends in seasonal precipitation extremes – an indicator of ‘climate change’ in Kerala, India', *Journal of Hydrology*, 367, pp. 62–69.

IPCC (2012) ‘Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaption : A Special report of working groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]’, *Cambridge University Press*, Cambridge, UK and New York, USA, 582 pp.

Jinkang Du, L.Q., Hanyi Rui, Tianhui Zuo, Dapeng Zheng, Youpeng Xu, C.-Y. Xu (2012) 'Assessing the effects of urbanization on annual runoff and flood events using an Integrated Hydrological Modeling System for Qinhuai River Basin, China', *Journal of Hydrology*, 464-465, pp. 127-139.

Jothityangkoon, C.H., Kowit Boonrawd, Murugesu Sivapalan (2013) 'Assessing the impact of climate and land use changes on extreme floods in a large tropical catchment ', *Journal of Hydrology*, 490, pp. 88-105.

Kabupaten Sragen (2012) ‘Sragen Dalam Angka’ [Online]. Available at: http://bappeda.sragenkab.go.id/home.php?page=28 (Accessed: 26 November 2013)

Kompas (2008) ‘Banjir Bengawan Solo Meluas’ [Online]. Kompas online, 3 March 2008 edition. Available at: http://regional.kompas.com/read/2008/03/03/17115751/banjir.bengawan.solo.meluas. (Accessed: 15 February 2010)

Kompas, T.E. (2008) ‘*Ekspedisi Bengawan Solo*.’, PT. Gramedia Pustaka, Jakarta.

Lukey, B.T., Sheffield, J., Bathurst, J.C., Hiley, R.A., and Mathys, N. (2000)’Test of the SHETRAN technology for modelling the impact of reforestation on bad lands runoff and sediment yield at Draix, France’, *Journal of Hydrology*, 235 (1-2), pp. 44-62.

Mekong River Commission Flood Management and Mitigation Programme [online]. Available at: http://www.mrcmekong.org/about-the-mrc/programmes/flood-management-and-mitigation-programme/ (Accessed: 10 February 2013)

Mellor, D., Sheffield, J., O’Connell, P.E., Metcalfe, A. V., 2000. A stochastic space-time rainfall forecasting system for real time flow forecasting II: Application of SHETRAN and ARNO rainfall runoff models to the Brue catchment. Hydrol. Earth Syst. Sci. https://doi.org/10.5194/hess-4-617-2000

Merz, B., Vorogushyn, S., Uhlemann, S., Delgado, J, and Hundecha, Y. (2012) ‘More efforts and scientific rigour are needed to attribute trends in flood time series’, *HESS Opinions* [Online]. Available at : http://www.hydrol-earth-syst-sci.net/16/1379/2012/hess-16-1379-2012.pdf (Accessed: 17 October 2012).

Millington, N., Samiran Das, Slobodan P. Simonovic (2011) ‘The comparison of GEV, Log-Pearson Type 3 and Gumbel distributions in the Upper Thames River watershed under Global Climate Models’, *Water Resources Research Report*, The University of Western Ontario, Department of Civil and Environmental Engineering.

Narisma, G.T., Foley, J.A., Licker, R., and Ramankutty, N. (2007) ‘Abrupt changes in rainfall during the Twentieth Century’, *Geophysical Research Letter*, Volume 34.

NASA 'TRMM : Explanation of Data Products', Precipitaton Measurement Missions [Online]. Available at: http://pmm.nasa.gov/data-access/data-products (Accessed: 4 November 2013).

NASA (1997) 'TRMM : Tropical Rainfall Measuring Mission', Precipitaton Measurement Missions [Online]. Available at: http://pmm.nasa.gov/TRMM (Accessed: 5 November 2013).

Nejc Bezak, Mitja Brilly & Mojca Šraj (2014) “Comparison between the peaks-over-threshold method and the annual maximum method for flood frequency analysis”, Hydrological Sciences Journal, 59:5, 959-977, DOI: 10.1080/02626667.2013.831174

Parkin, G., Birkinshaw, S.J., Younger, P.L., Rao, Z., and Kirk, S (2007) ‘A numerical modelling and neural network approach to estimate the impact of groundwater abstraction on river flows’, *Journal of Hydrology*, 339, pp. 15-28.

Pawitan, H. and Haryani, G.S. (2012) 'Water resources, sustainability and societal livelihoods in Indonesia', *Ecohydrology and Hydrobiology*, 11(3-4), pp. 231 - 243.

Posthumus, H., Hewett, C.J.M, Morris, J., and Quinn, P.F. (2008) ‘Agricultural land use and flood risk management: Engaging with stakeholders in North Yorkshire’, *Agricultural Water Management*, 95, pp. 787-798.

Saleth, R.M. (2004) 'Strategic analysis of water institutions in India: application of a new research paradigm ', [Online]. Available at: http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/pub079/Report79.pdf (Accessed: 18 October 2013).

Sankarasubramanian, A. and Srinivasan, K. (1999),‘Investigation and comparison of sampling properties of L-moments and conventional moments’, *Journal of Hydrology*, 218, pp. 13-34.

Satrio, R.P., and Tanaka, S. (2010) ‘Flood Characteristic of Upper Solo River Sub-basin, Case Study: Surakarta City’, [Online]. Available at http://www.icharm.pwri.go.jp/training/master/pubilication/pdf/2010/panji.pdf (Accessed: 10 January 2012).

Shaw, E.M (1983) ‘Hydrology in Practice (Second Edition)’, Chapman and Hall Publisher, London, pp. 525-526.

Sobriyah (2005) 'Model perkiraan banjir DAS besar dari sintesa beberapa persamaan terpilih', *Media Teknik Sipil UNS*, 71.

Sobriyah, S., Sriharto, B. and Legono, D. (2001) 'Pendekatan pemilihan stasiun hujan untuk dasar perhitungan debit banjir kasus DAS Bengawan Solo', *Forum Teknik UGM*, 25(2).

Suriya, S. and Mudgal, B.V. (2012), 'Impact of urbanization on flooding: the Thirusoolam sub watershed – a case study', *Journal of Hydrology*, 412-413, pp. 210-219.

Suroso, D.S.A., Kombaitan, B. and Setiawan, B. (2013) 'Exploring the use of Risk assessment approach for climate change adaptation in Indonesia: case study of flood risk and adaptation assessment in the South Sumatra Province.', *Procedia Environmental Sciences*, 17, pp. 372-381.

Taqobalallah, R. (2009) 'Banjir Bengawan Solo tahun 1966: dampak dan respons masyarakat kota Solo', Fakultas Sastra dan Seni Rupa, Universitas Sebelas Maret, Surakarta. [Online]. Available at: http://eprints.uns.ac.id/8347/1/144771308201011041.pdf (Accessed: 27 November 2013)

Tarboton, D.G. (2003) 'Chapter 2: Runoff Generation Mechanisms', in *Rainfall-Runoff Processes*. [Online]. Utah State University. pp. 1–19.

The World Meteorological Organization and The Global Water Partnership (2007) *Conducting flood loss assessments. Integrated flood management tools Series No. 2*. (2) p.p. 48.

Thomas, B., Steidl, J., Dietrich, O., and Lischeid, G (2011) 'Measures to sustain seasonal minimum runoff in small catchments in the Mid-Latitudes: a review', *Journal of Hydrology*, 408, pp. 296-307.

Thompson, J.R., Green, A.J., Kingston, D.G., and Gosling, S.N (2013) 'Assessment of uncertainty in river flow projections for the Mekong River using multiple GCMs and hydrological models', *Journal of Hydrology*, 486, pp. 1-30.

Tomozeiu, R., Busuioc, A., Marletto, V., Zinoni, F., and Cacciamani, C. (2000) 'Detection of changes in the summer precipitation time series of the region Emilia-Romagna, Italy.', *Theoretical and Applied Climatology*, 67, pp. 193-200.

UNESCO-IHP (1995) 'Catalogue of rivers for Southeast Asia and the Pacific – Volume I', Edited by K.Takeuchi, A.W.Jayawardena, and Y.Takahasi. [Online] Available at http://flood.dpri.kyoto-u.ac.jp/ihp_rsc/riverCatalogue/Vol_01/index.html (Accessed: 19 February 2014)

UN-Habitat (2009) 'The Slum Upgrading Facility (No. 7)',[Online]. Available at: www.unhabitat.org/pmss/ (Accessed: 29 March 2010).

University of Newcastle upon Tyne (2009) ‘SHETRAN Standard Version – V4.4.1 User Guide and Data Input Manual’, United Kingdom. Available at www.ceg.ncl.ac.uk/shetran/ (Accessed: 10 July 2011).

University of Newcastle upon Tyne (2009) ‘SHETRAN Version 4: Data Requirements, Data Processing, and Parameter Values’, United Kingdom. Available at www.ceg.ncl.ac.uk/shetran/ (Accessed: 22 January 2012).

Villarini, G., Smith, J.A., Baeck, M.L, Vitolo, R., Stephenson, D.B., and Krajewski, W.F (2011) 'On the frequency of heavy rainfall for the Midwest of the United States', *Journal of Hydrology*, 400, pp. 103–120.

Wang, D., Hagen, S.C., and Alizad, K. (2013) 'Climate change impact and uncertainty analysis of extreme rainfall events in the Apalachicola River Basin, Florida', *Journal of Hydrology*, 480, pp. 125–135.

Wheater, H.E.E. (2009) 'Land use, water management and future flood risk', *Land Use Policy*, 26S, pp. S251–S264.

Wijesekara, G.N., Gupta, A., Valeo, C., and Hasbani, J.G et al (2012) ‘Assessing the impact of future land use changes on hydrological processes in the Elbow River watershed in Southern Alberta, Canada.’, *Journal of Hydrology*, 412 – 413, pp. 220-232.

Wu, F., Wang, X., Cai, Y., and Li, C. (2013) ‘Spatiotemporal analysis of precipitation trends under climate change in the Upper Reach of Mekong River Basin.’, *Quaternary International*, pp. 1-10.

Xie, Z., Su, F., Liang, X., Zeng, Q., Hao, Z. & Guo, Y. (2003) ‘Applications of a surface runoff model with Horton and Dunne runoff for VIC’, *Advances in Atmospheric Sciences*, 20(2), pp. 165–172

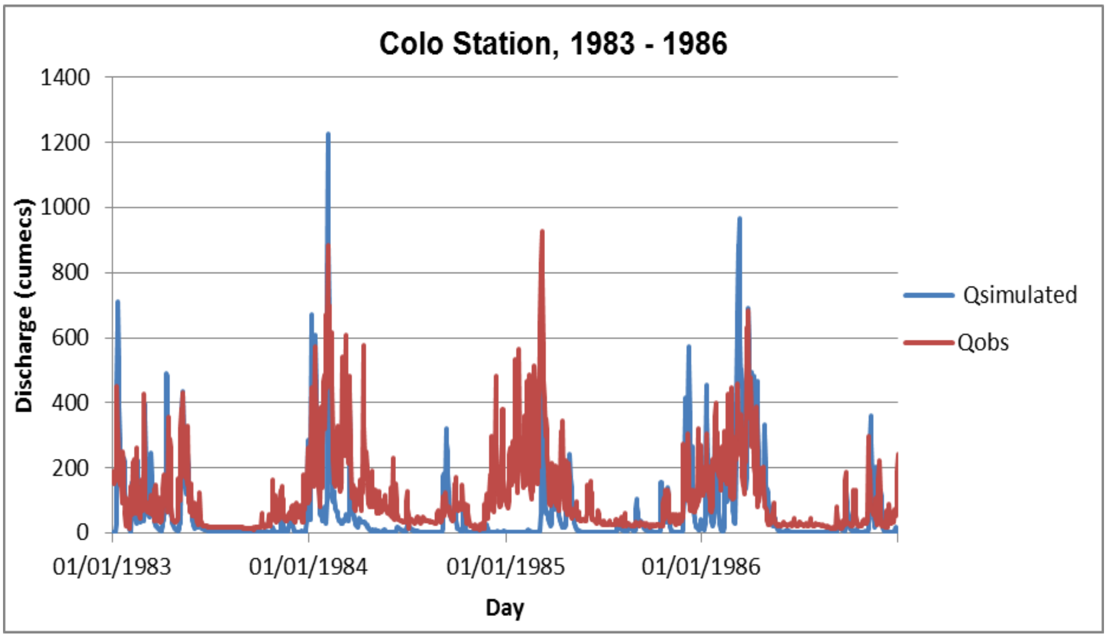
Xu, Y.P., Zhang, X., Ran, Q., and Tian, Y. (2013) ‘Impact of climate change on hydrology of Upper Reaches of Qiantang River Basin, East China.’, *Journal of Hydrology*, 483, pp.41-50.

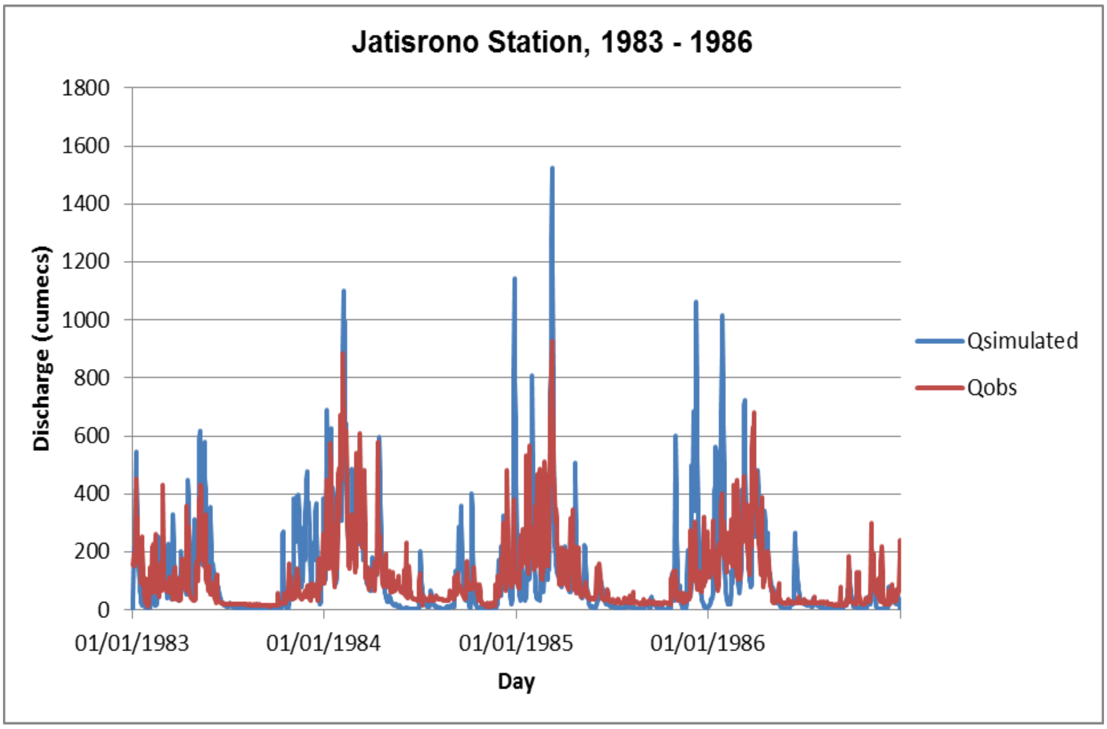
Zhang, Q., Xu, C.Y., and Becker, S. et al (2009) ‘Trends and abrupt changes of precipitation maxima in the Pearl River Basin, China’, *Atmospheric Science Letters*, Wiley Inter Science.

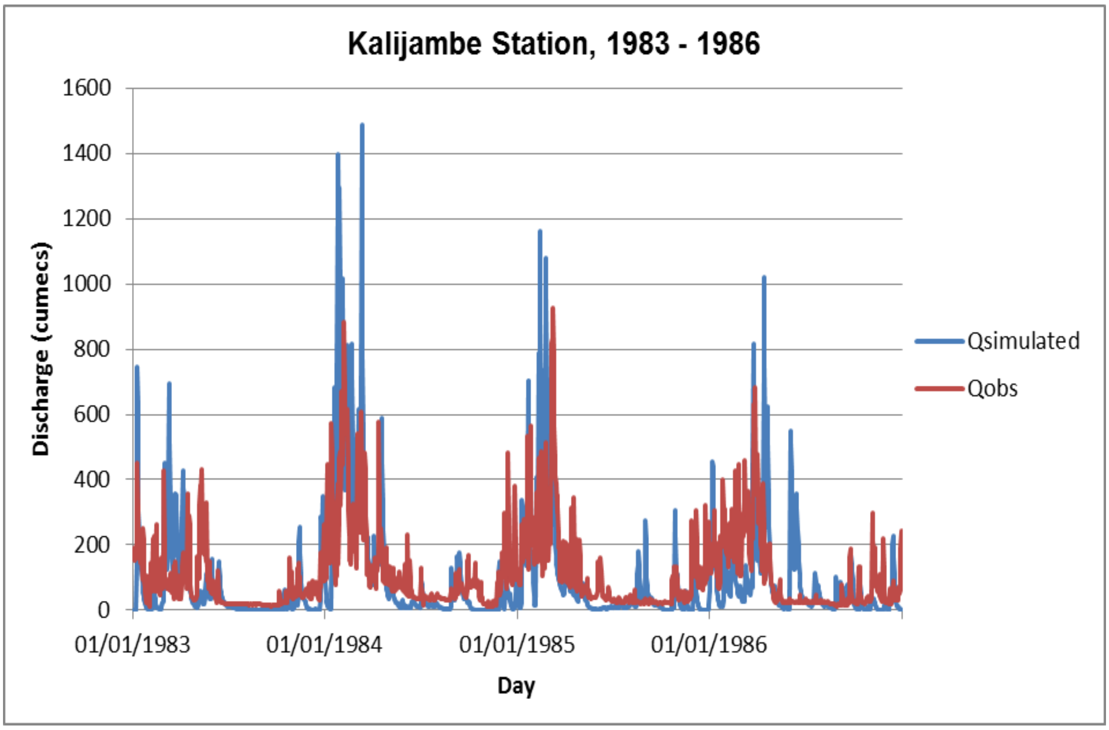
Zhang, R., Santos, C.A.G., Moreira, M., Freire, P.K.M.M. & Corte-Real, J. (2013) ‘Automatic Calibration of the SHETRAN Hydrological Modelling System Using MSCE’, *Water Resources Management*, 27(11), pp. 4053–4068

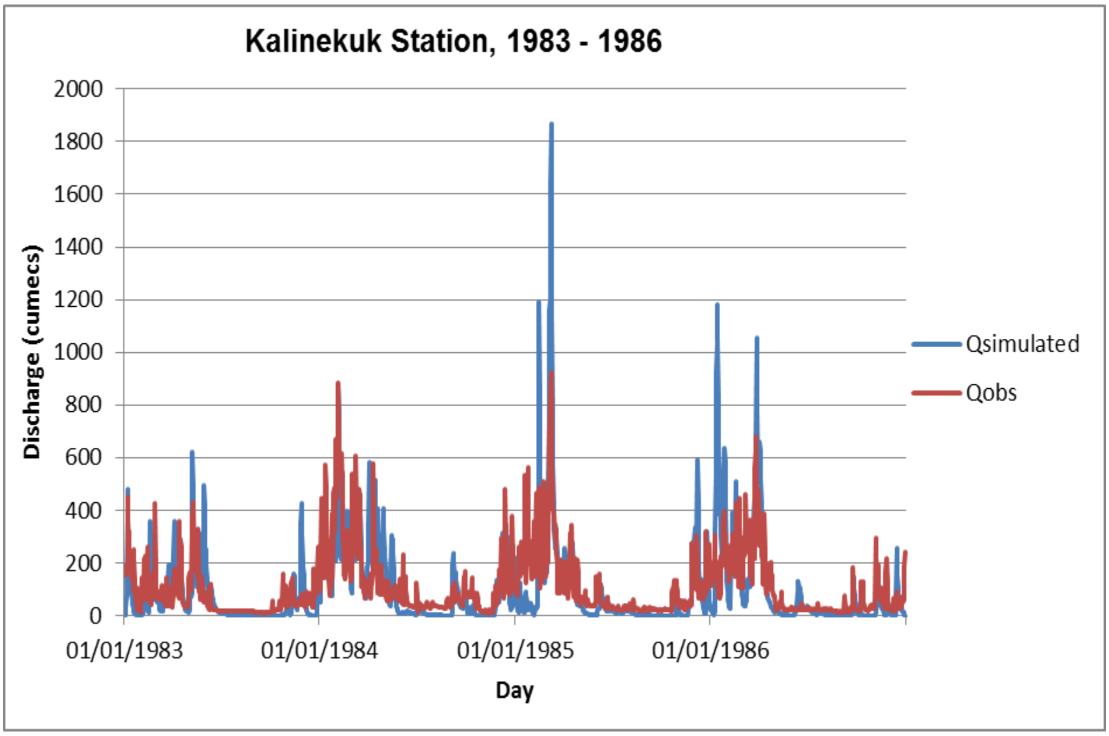
Appendix

Appendix 1 Charts of observed versus simulated discharge using single station rainfall input in Upper Bengawan Solo catchment in 1983 - 1986.

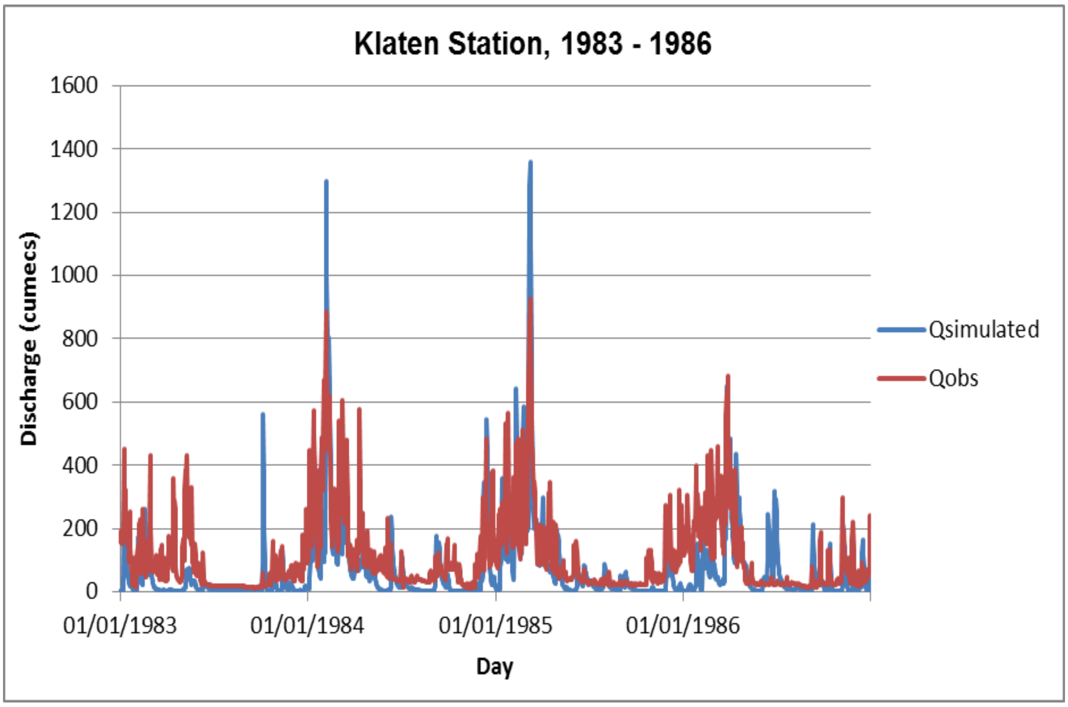


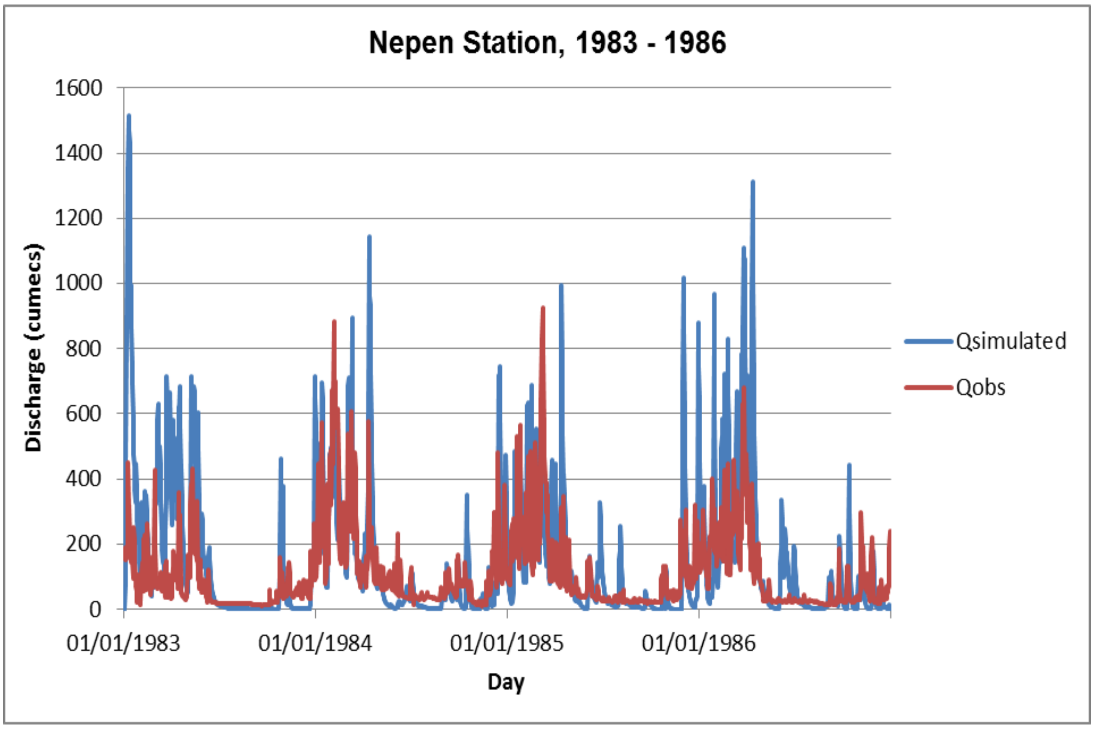



Kalijambe Station, 1983 - 1986
1600
1400
1200
1000
800
600
400
200
0
Discharge (cumecs)
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

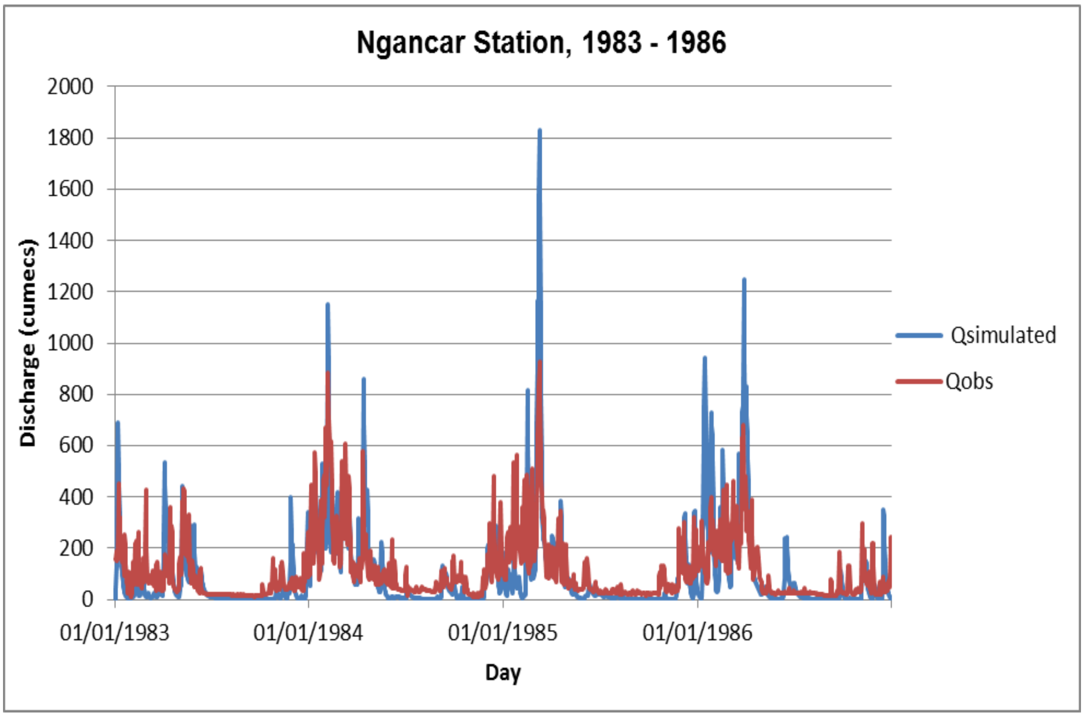

Kalinekuk Station, 1983 - 1986
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Discharge (cumecs)
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

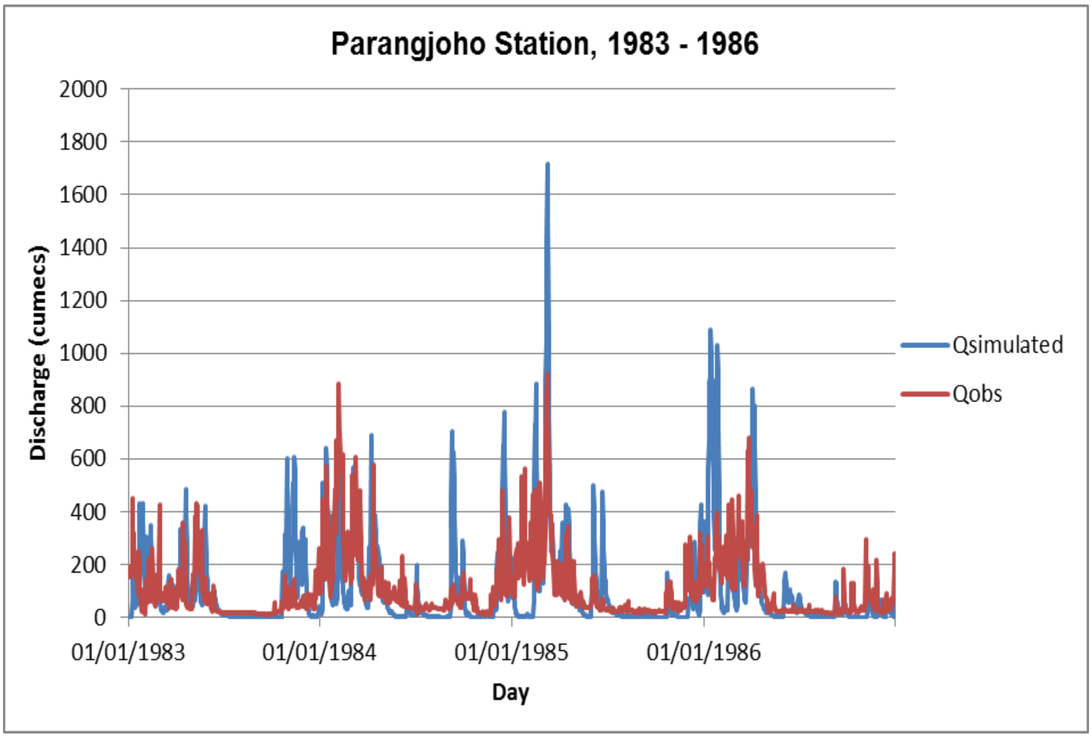
Appendix 1


Klaten Station, 1983 - 1986
Discharge (cumecs)
1600
1400
1200
1000
800
600
400
200
0
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

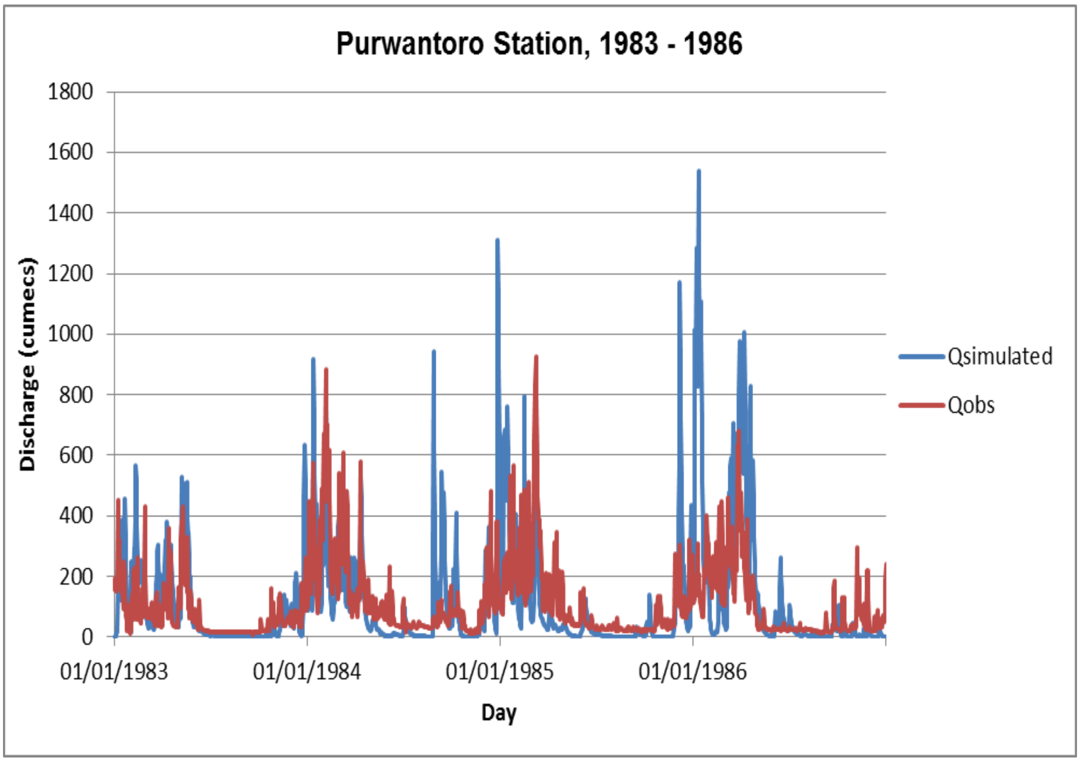

Nepen Station, 1983 - 1986
Discharge (cumecs)
1600
1400
1200
1000
800
600
400
200
0
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

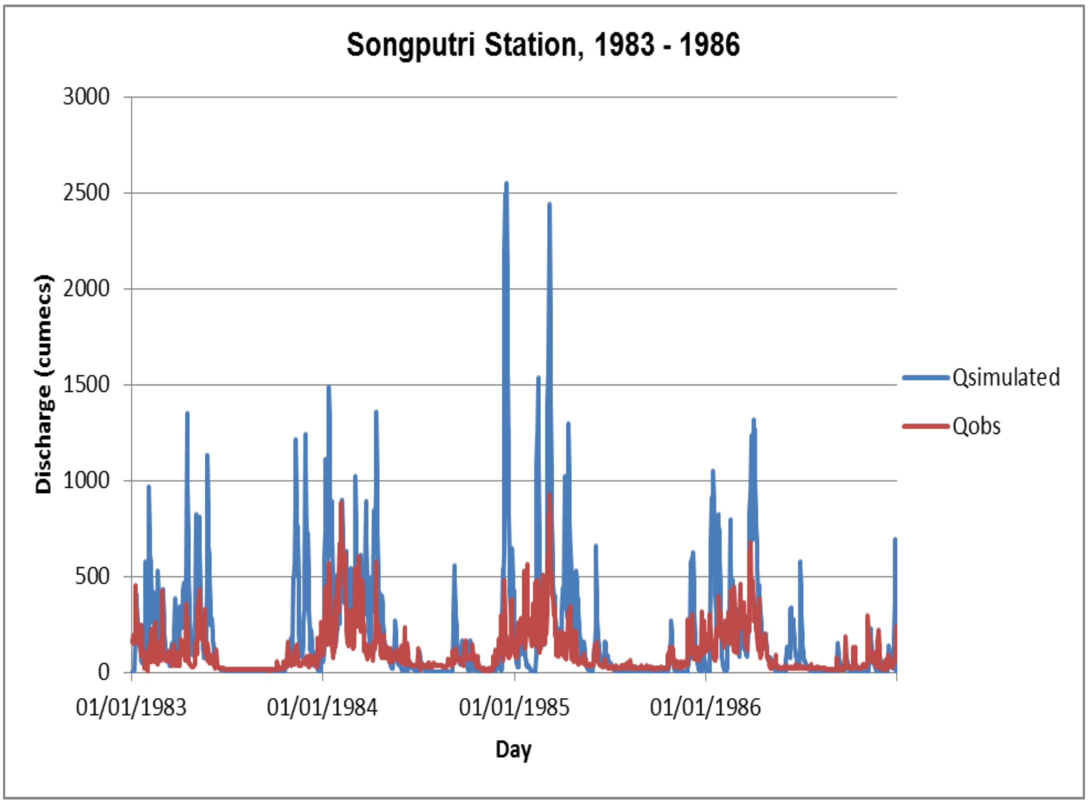
Appendix 1

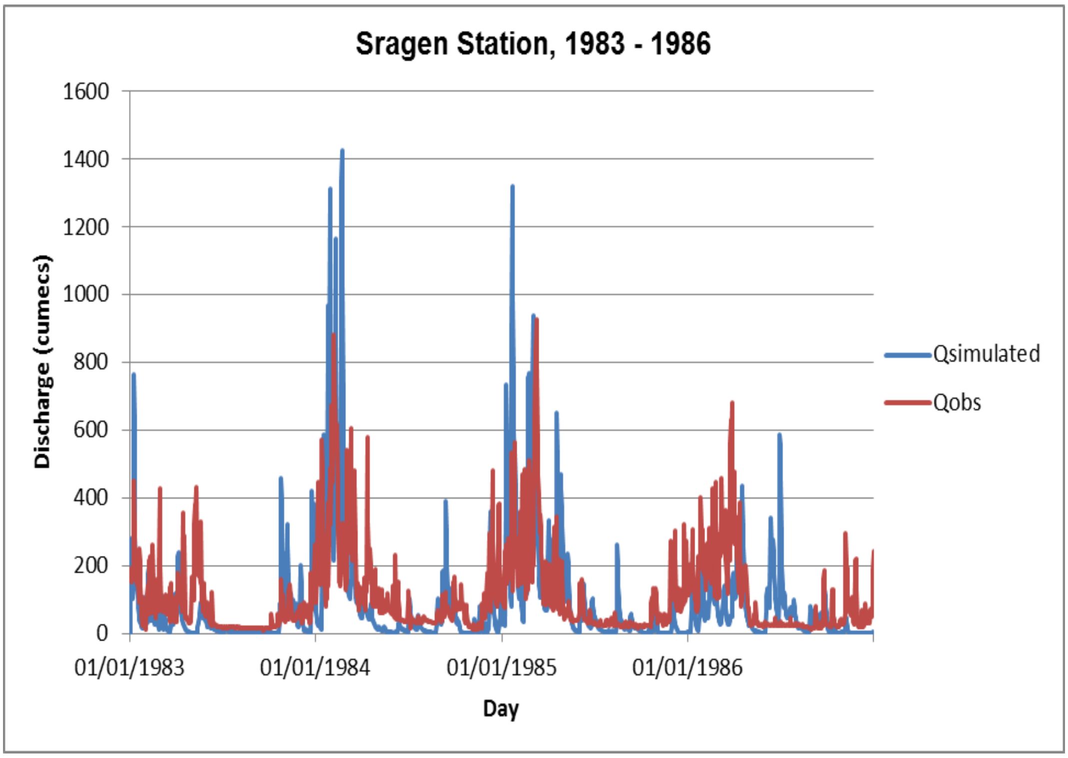

Ngancar Station, 1983 - 1986
Discharge (cumecs)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

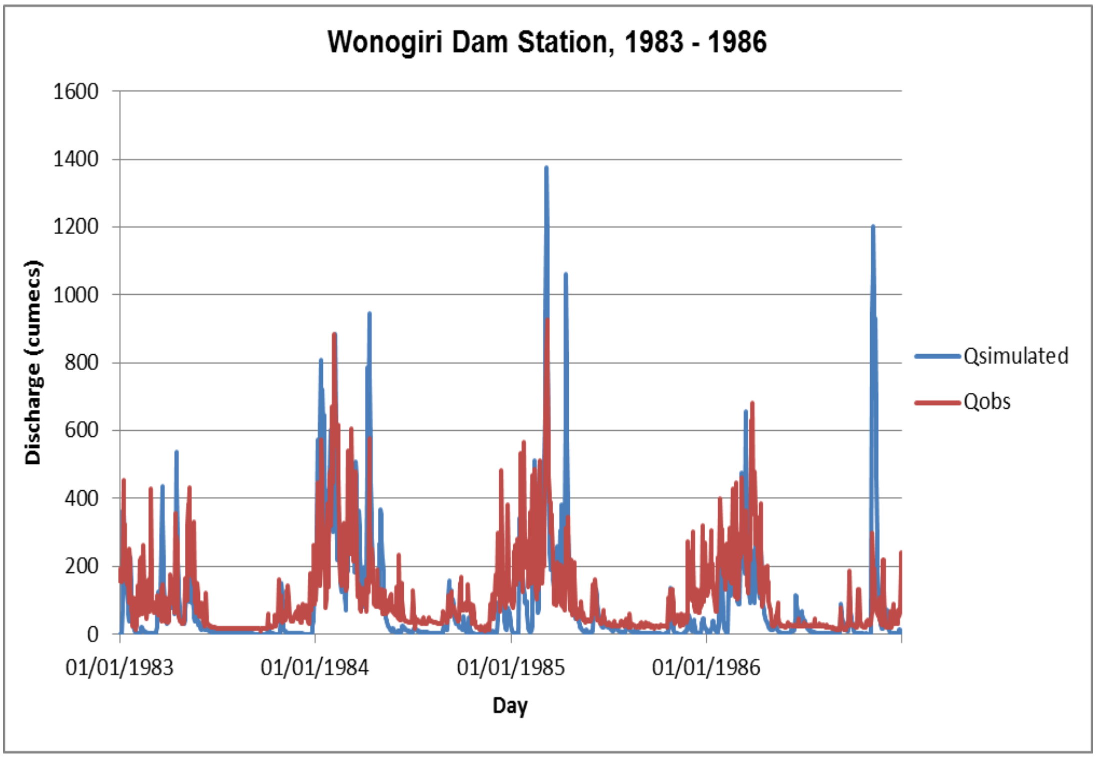

Parangjoho Station, 1983 - 1986
Discharge (cumecs)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

Appendix 1

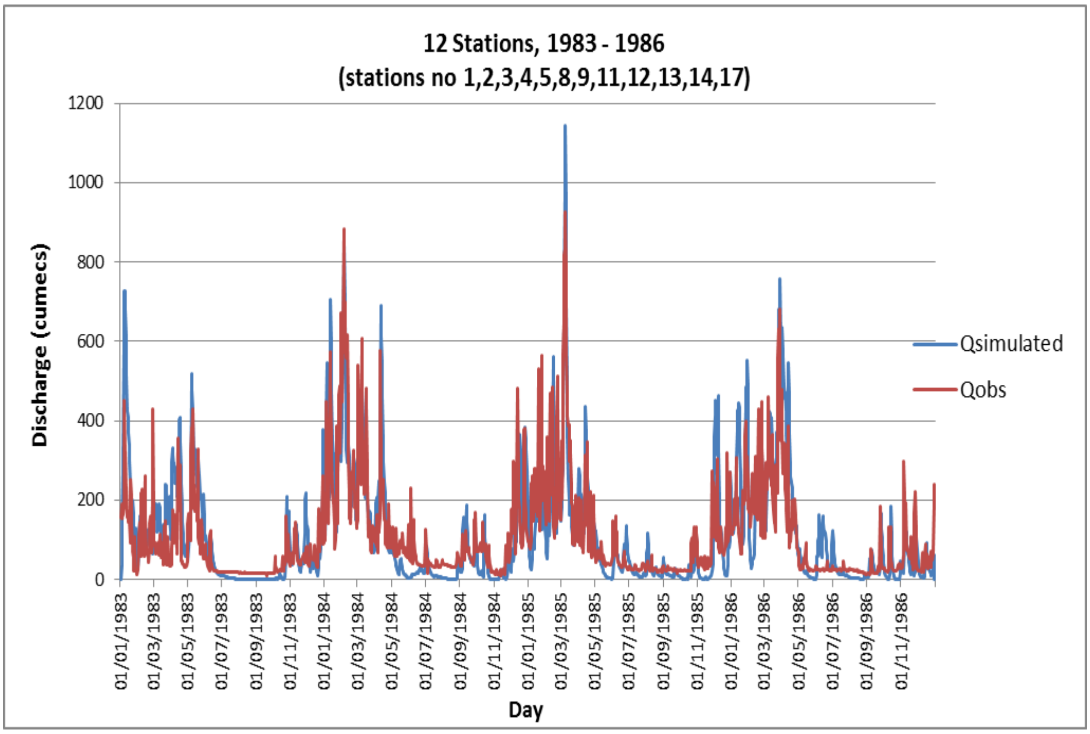

Purwantoro Station, 1983 - 1986
1800
1600
1400
1200
1000
800
600
400
200
0
Discharge (cumecs)
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

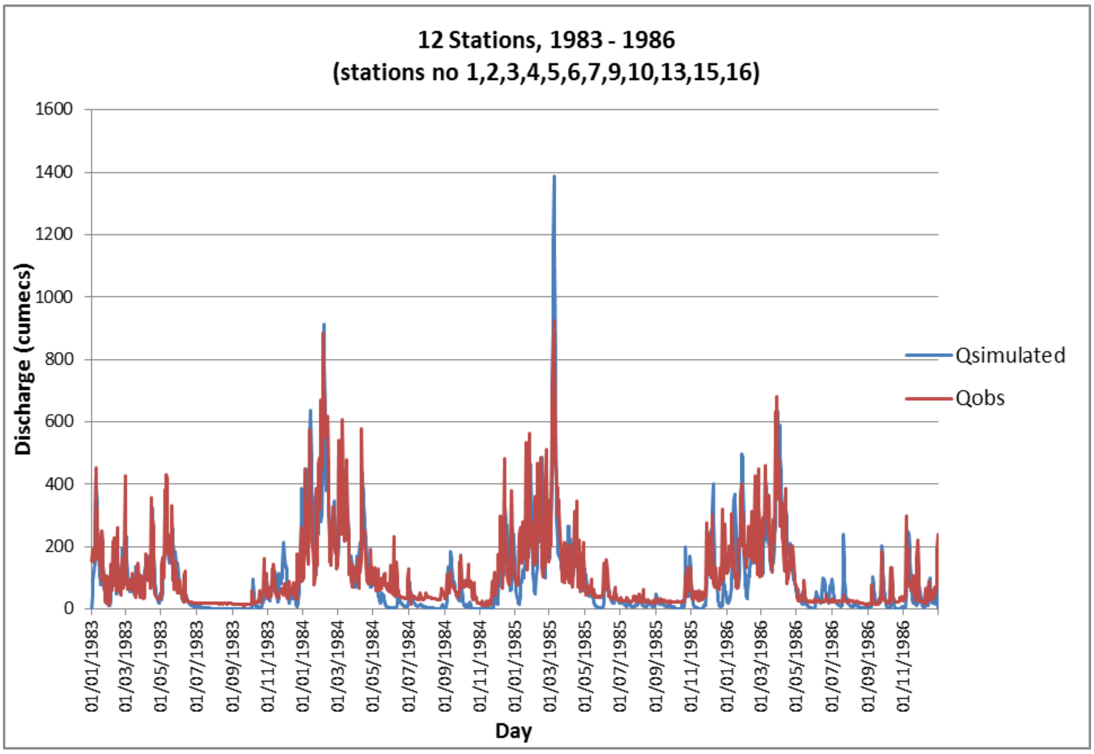

Songputri Station, 1983 - 1986
3000
2500
2000
1500
1000
500
0
Discharge (cumecs)
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

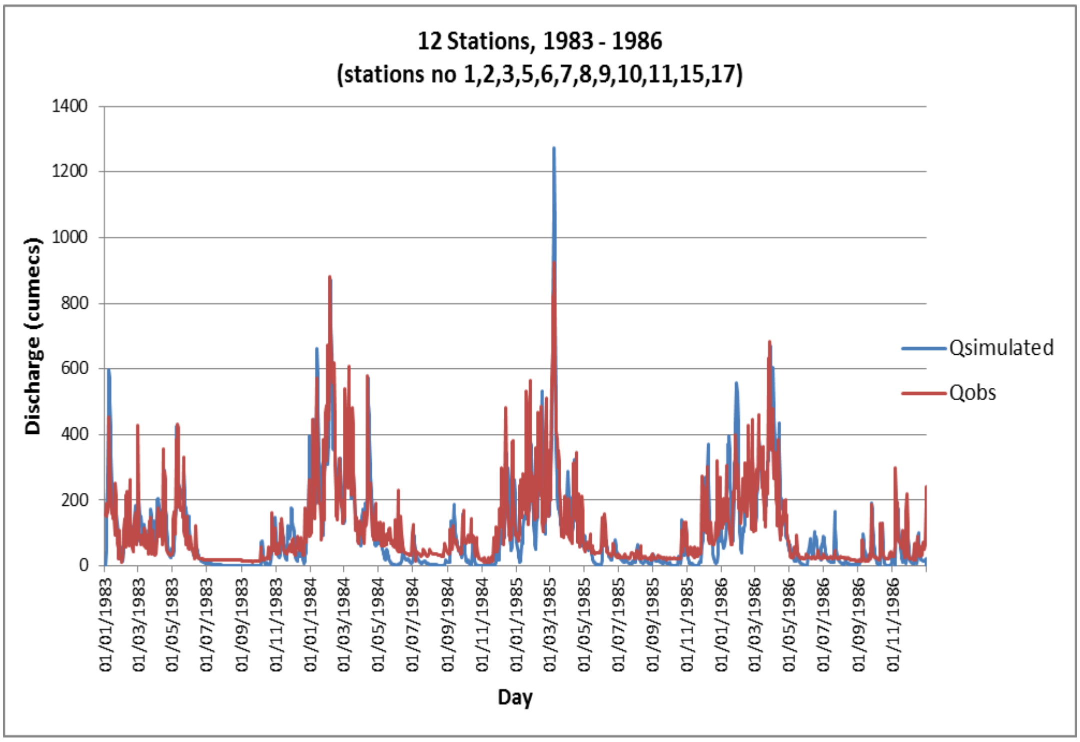

Sragen Station, 1983 - 1986
1600
1400
1200
1000
800
600
400
200
0
Discharge (cumecs)
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs


Wonogiri Dam Station, 1983 - 1986
1600
1400
1200
1000
800
600
400
200
0
Discharge (cumecs)
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

Appendix 2 Charts of observed versus simulated discharge using 12 stations rainfall input in Upper Bengawan Solo catchment in 1983 - 1986.

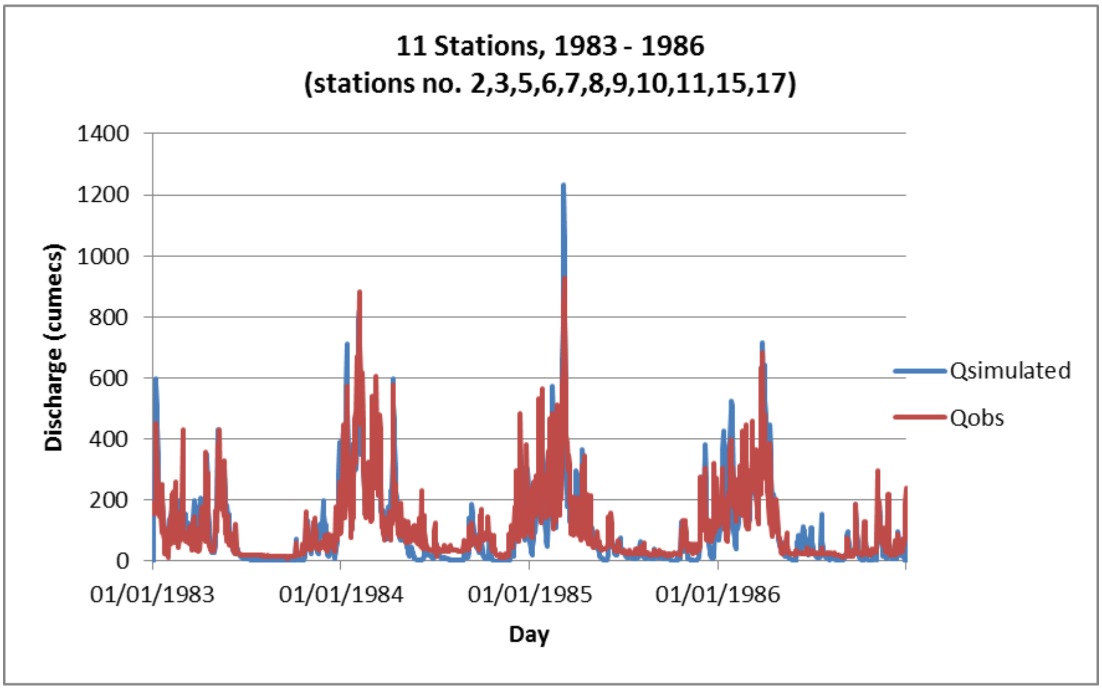


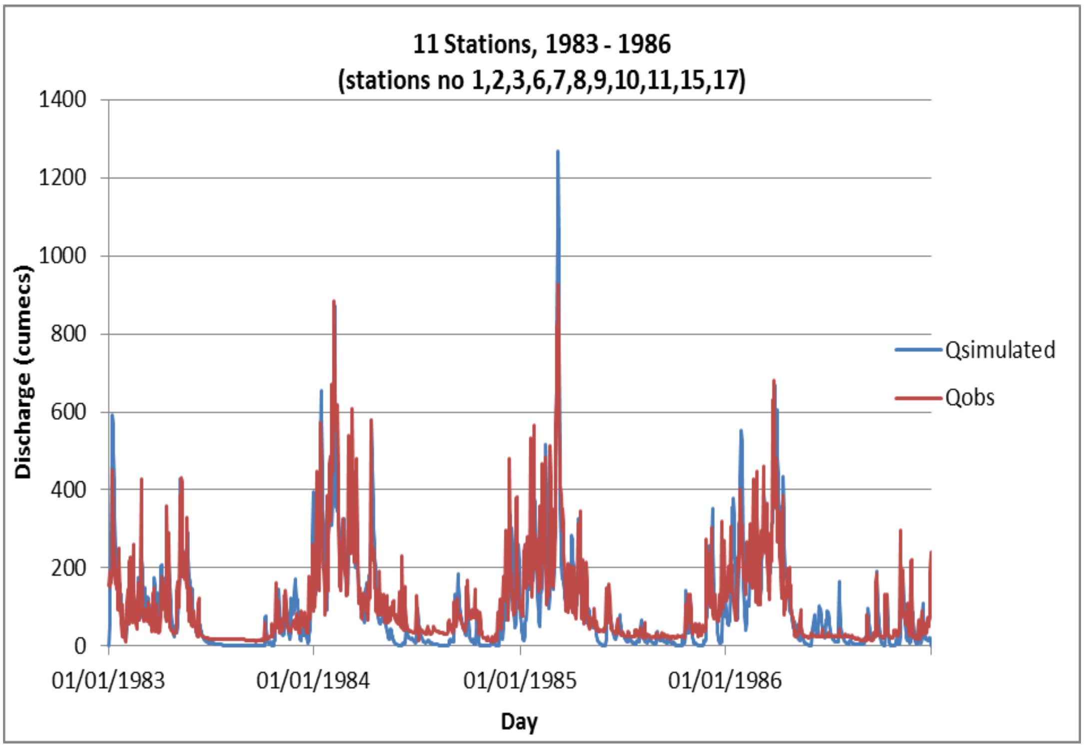


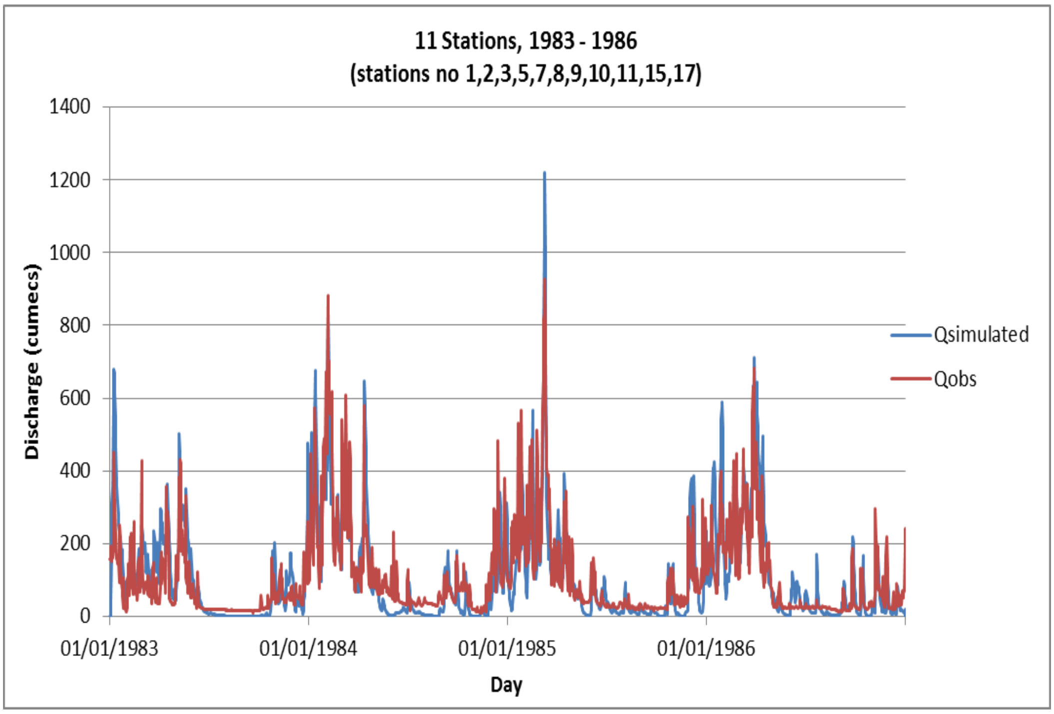

12 Stations, 1983 - 1986
(stations no 1,2,3,5,6,7,8,9,10,11,15,17)
1400
1200
1000
800
600
400
200
0
Discharge (cumecs)
01/01/1983
01/03/1983
01/05/1983
01/07/1983
01/09/1983
01/11/1983
01/01/1984
01/03/1984
01/05/1984
01/07/1984
01/09/1984
01/11/1984
01/01/1985
01/03/1985
01/05/1985
01/07/1985
01/09/1985
01/11/1985
01/01/1986
01/03/1986
01/05/1986
01/07/1986
01/09/1986
01/11/1986
Day
Qsimulated
Qobs

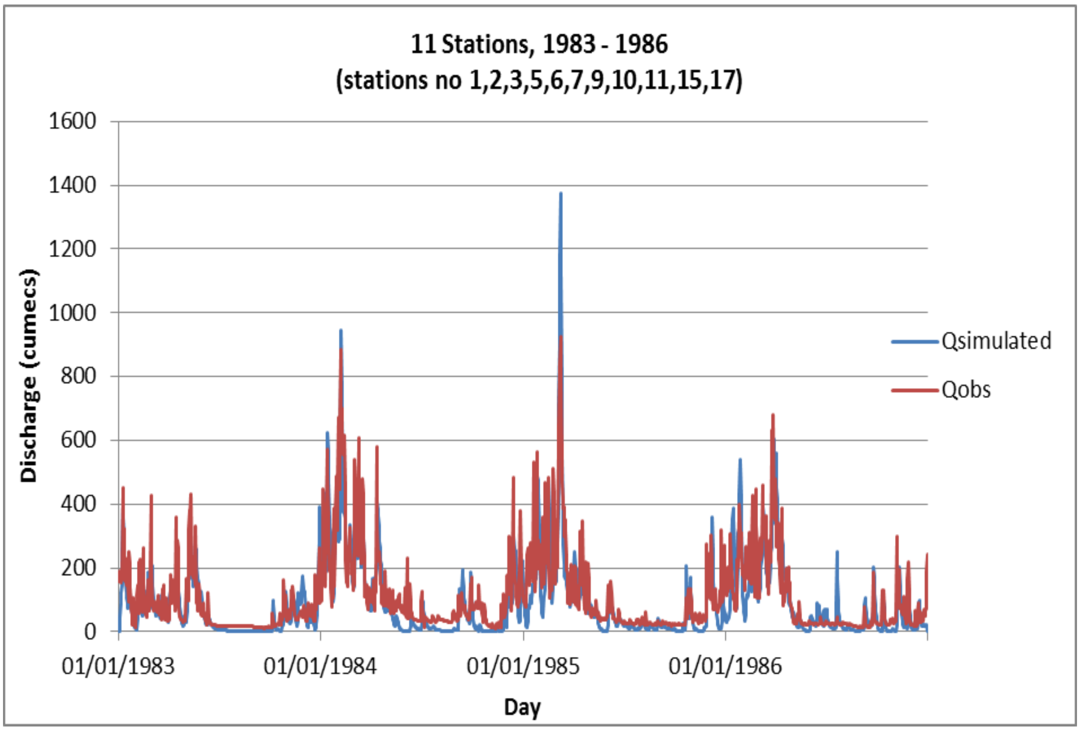
Appendix 2

Appendix 3 Charts of observed versus simulated discharge using 11 stations rainfall input in Upper Bengawan Solo catchment in 1983 - 1986.

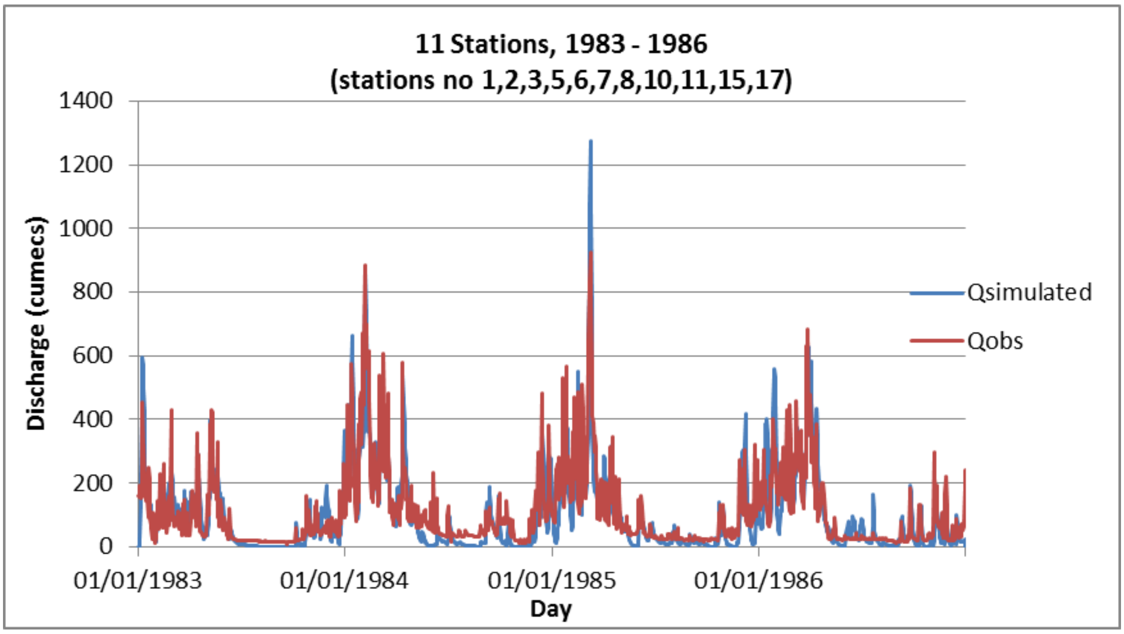


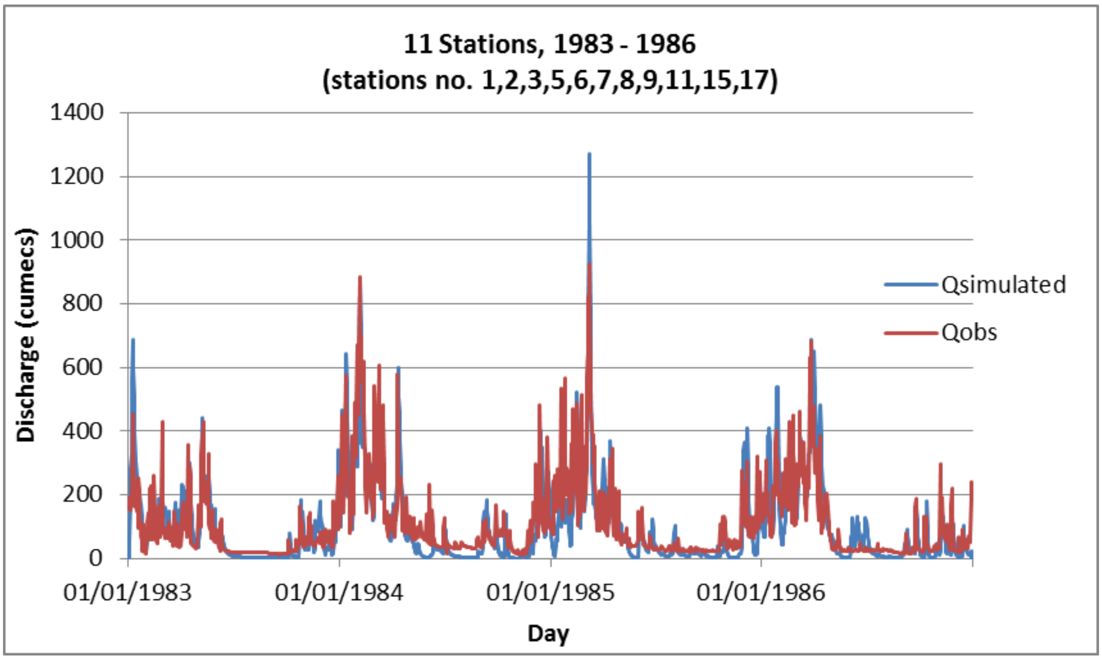


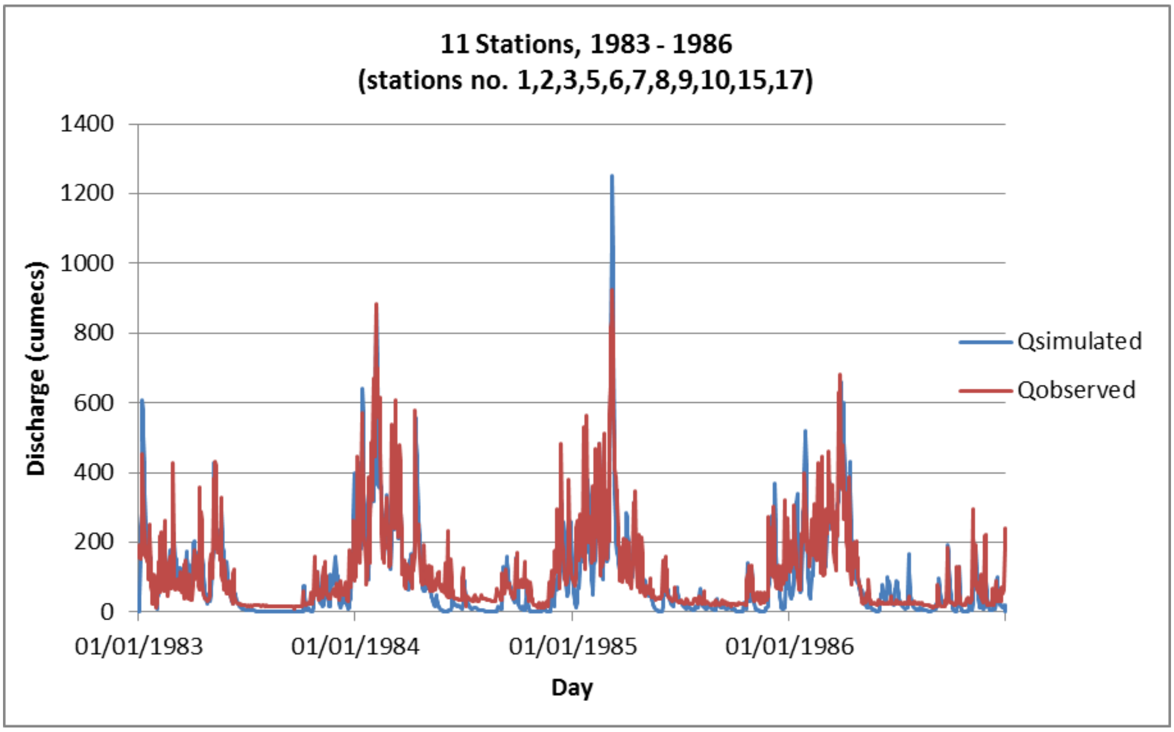

11 Stations, 1983 - 1986
(stations no 1,2,3,5,7,8,9,10,11,15,17)
Discharge (cumecs)
0
200
400
600
800
1000
1200
1400
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

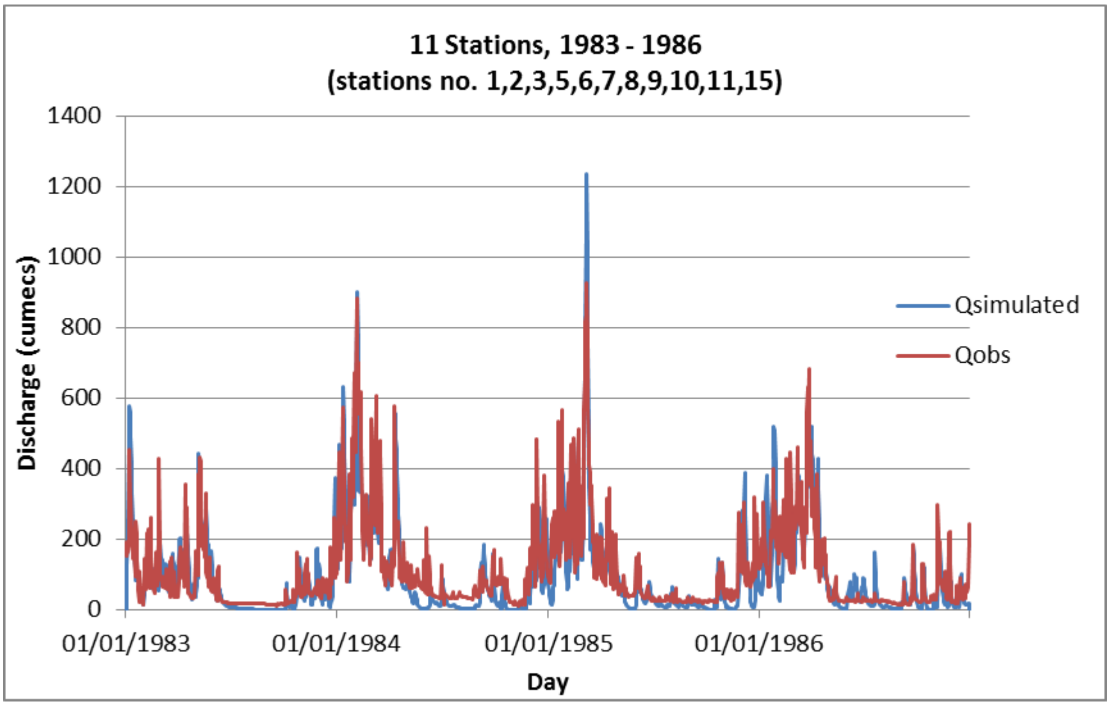

11 Stations, 1983 - 1986
(stations no 1,2,3,5,6,7,9,10,11,15,17)
Discharge (cumecs)
0
200
400
600
800
1000
1200
1400
1600
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

Appendix 3

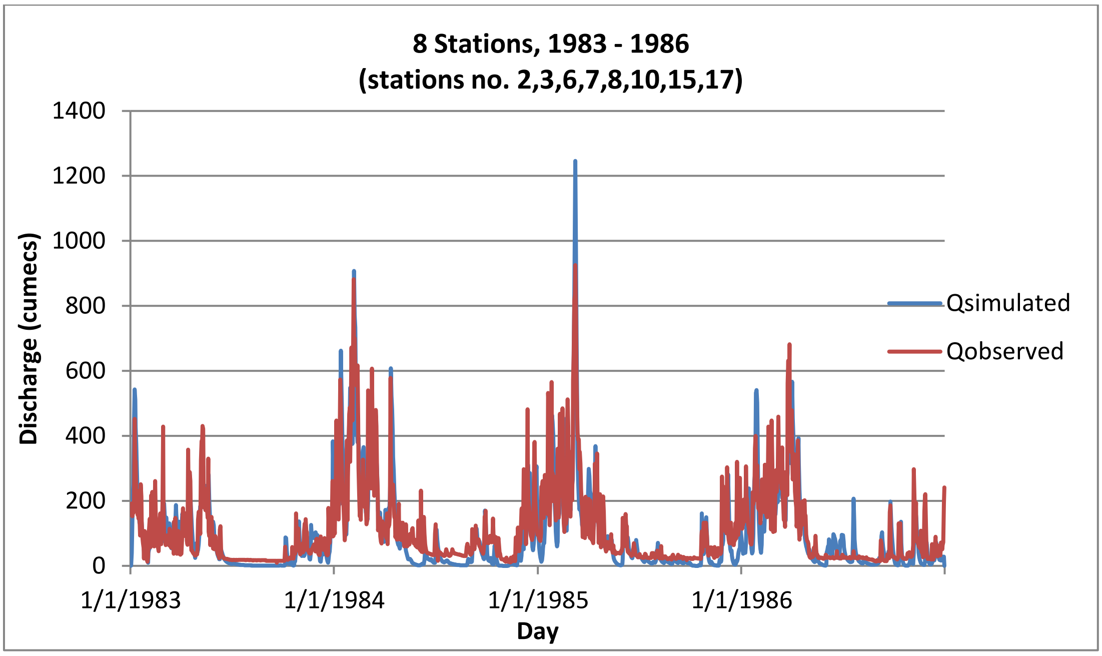

11 Stations, 1983 - 1986
(stations no 1,2,3,5,6,7,8,10,11,15,17)
Discharge (cumecs)
1400
1200
1000
800
600
400
200
0
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs


11 Stations, 1983 - 1986
(stations no. 1,2,3,5,6,7,8,9,11,15,17)
Discharge (cumecs)
1400
1200
1000
800
600
400
200
0
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

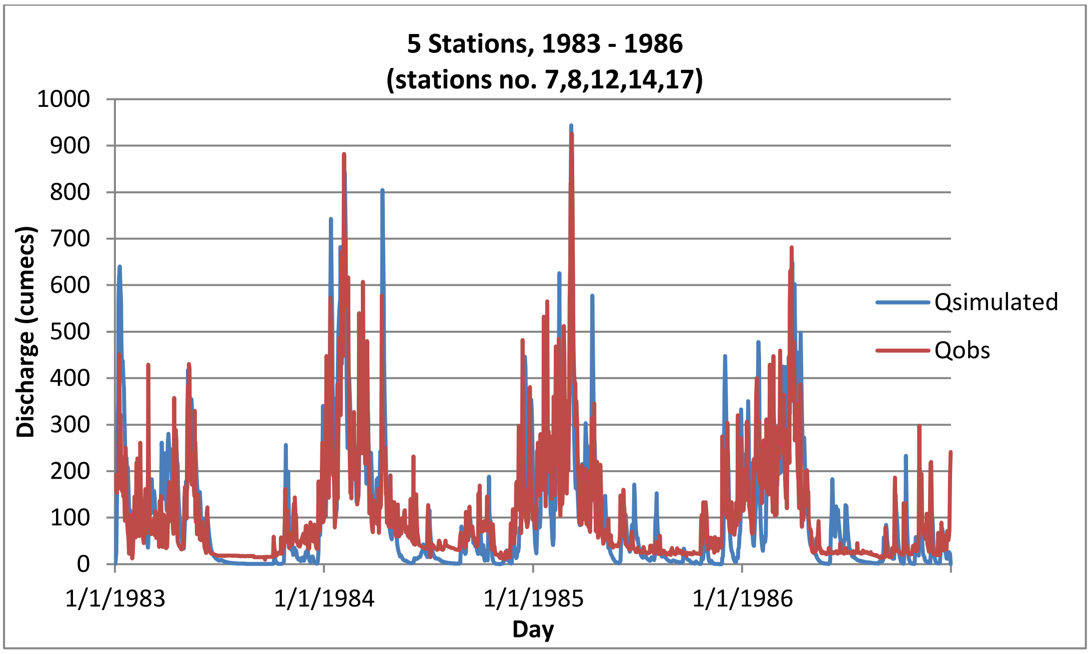

11 Stations, 1983 - 1986
(stations no. 1,2,3,5,6,7,8,9,10,15,17)
1400
1200
1000
800
600
400
200
0
Discharge (cumecs)
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobserved

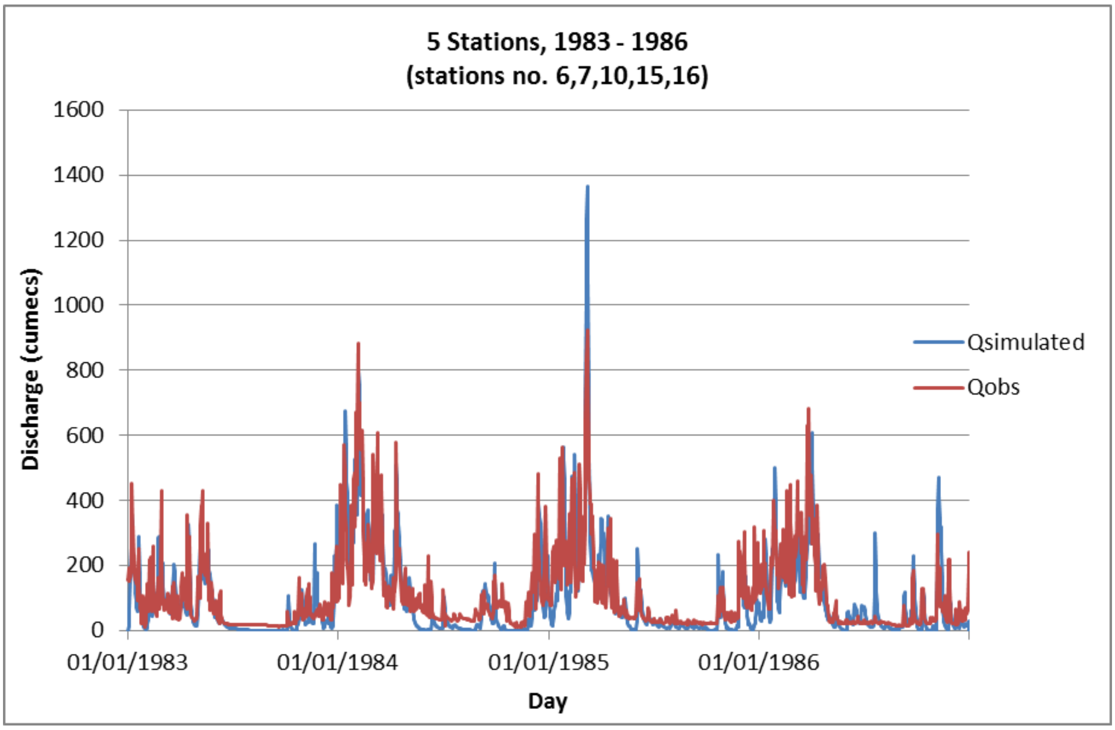

11 Stations, 1983 - 1986
(stations no. 1,2,3,5,6,7,8,9,10,11,15)
1400
1200
1000
800
600
400
200
0
Discharge (cumecs)
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

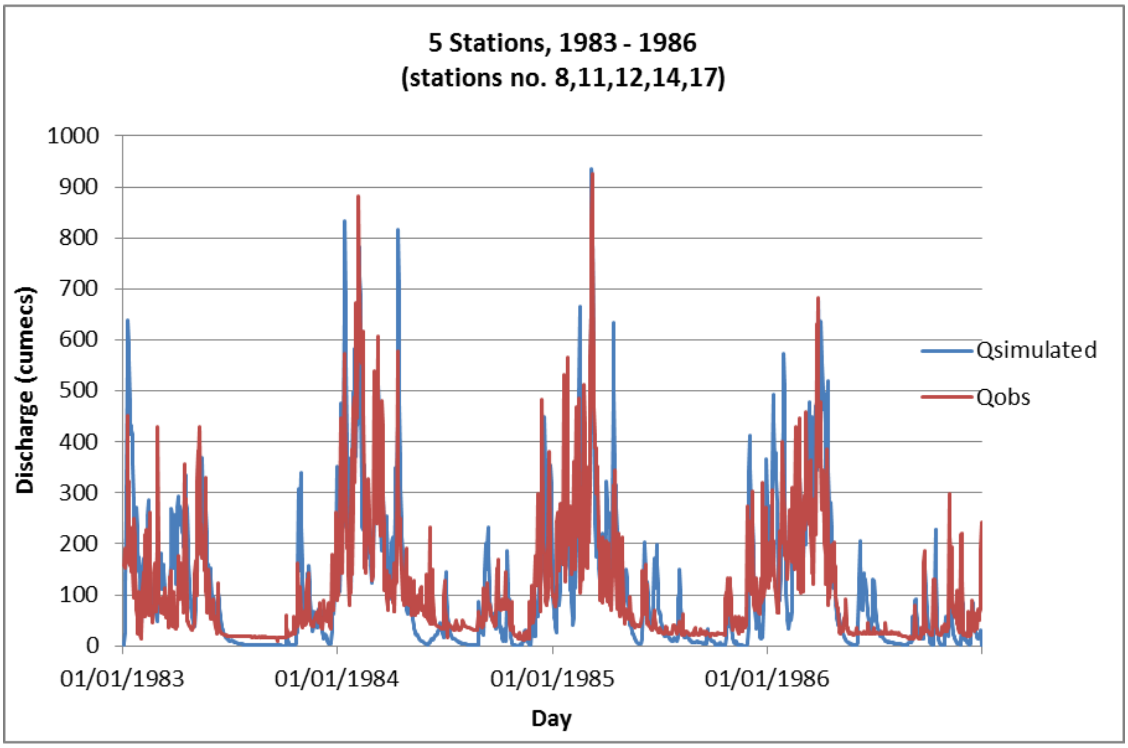
Appendix 4 Chart of observed versus simulated discharge using 8 stations rainfall input in Upper Bengawan Solo catchment in 1983 - 1986.

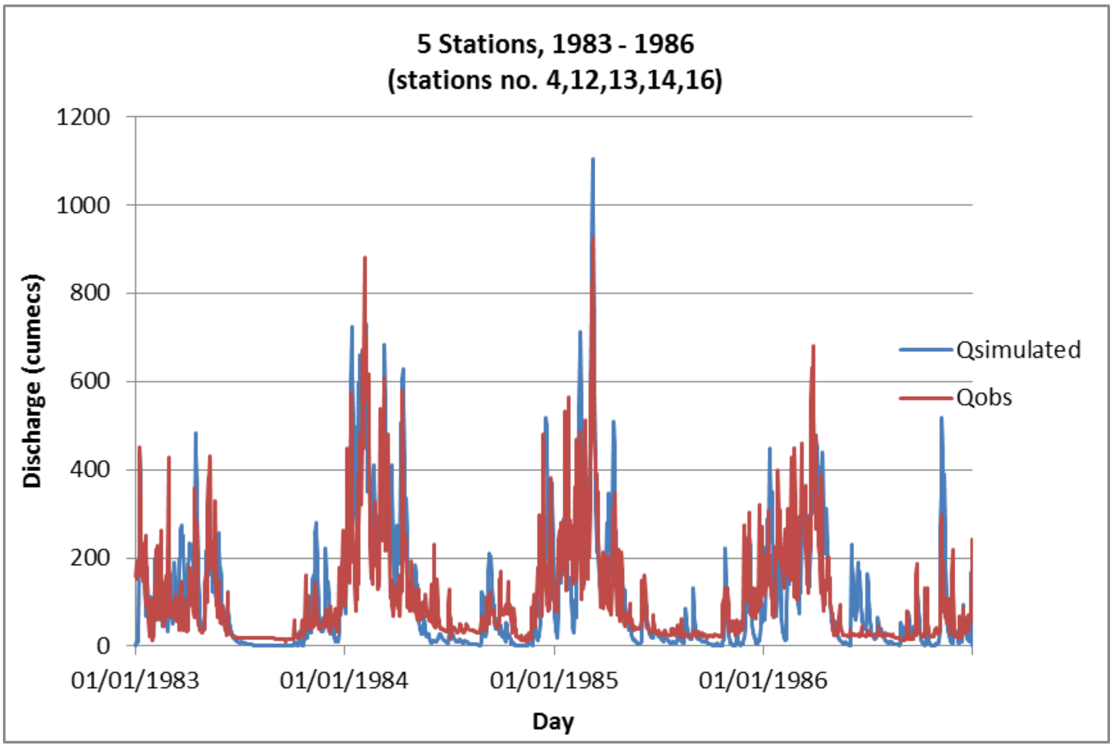


Appendix 5 Charts of observed versus simulated discharge using 5 stations rainfall input in Upper Bengawan Solo catchment in 1983 - 1986.






5 Stations, 1983 - 1986
(stations no. 8,11,12,14,17)
Discharge (cumecs)
1000
900
800
700
600
500
400
300
200
100
0
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs


5 Stations, 1983 - 1986
(stations no. 4,12,13,14,16)
Discharge (cumecs)
1200
1000
800
600
400
200
0
01/01/1983
01/01/1984
01/01/1985
01/01/1986
Day
Qsimulated
Qobs

Appendix 5

Appendix 6 Example of rundata file for SHETRAN simulation.

Rundata file -Test data
10: frame ---------- INPUT DATA
input_B5_frd.txt
11: VSS input data
input_t1_vsd.txt
12: overland/channel
input_t1_ocd.txt
13: evapotranspiration
input_t1_etd.txt
14: post-processing data definition (no longer used)

15: snowmelt

16: bank element data

17: sediment yield input

18: contaminant input

19: hourly met. data ---------- MET. DATA

20: precipitation data
rain-17gauges.txt
21: potential evaporation data
beng_j_epd.txt
22: time counter file ---------- OUTPUT DATA
output_t1_tim.txt
23: water flow print output
output_t1_pri.txt
24: sediment yield print

25: contaminant print

26: debug output

27: main unformatted results file (no longer used

28: hostart file -------INITIAL CONDITIONS

29: VSS initial conditions

30: time-varying vegetation (VED)-----TIME-SERIES DATA

31: well extraction (WLD)

32: lateral subsurface flow boundary condition (LFB)

33: lateral subsurface head boundary condition (LHB)

34: lateral subsurface head gradient boundary condition (LGB)

35: column base flow boundary condition (BFB)

36: column base head boundary condition (BHB)

37: overland/channel flow boundary condition (OFB)

38: overland/channel head boundary condition (OHB)

39: contaminant time-series 1 (CMT)

40: contaminant time-series 2 (CMB)

41: discharge at the outlet --------ADDITONAL OUTPUT
output_B5_discharge_sim_daily.txt
42: vsi data for initial conditions
output_B5_vsi.txt
43: mass balance data
output_B5_mb.txt
44: discharge at the outlet
output_B5_discharge_sim_everytimestep.txt
45: not used

46: not used

47: not used

48: visualisation plan ------VISUALISATION OUTPUT
input_t1_visualisation_plan.txt
49: check visulisation plan
output_t1_check_vis_plan.txt
50: HDF output
output_t1_shegraph.h5

Appendix 6

Appendix 7 Example of frame data file for SHETRAN simulation.

```
:FR1 - TEST CATCHMENT- FR COMPONENT DATA SET
:FR2 - GRID SQUARES IN THE X Y DIRECTIONS
    47    44
:FR4 - START TIME OF WATER FLOW COMPONENT SIMULATION
  1983     1     1     0     0
:FR6 - END TIME OF WATER FLOW COMPONENT SIMULATION
  1986    12    31     0     0
:FR7a - START TIME OF SEDIMENT TRANPORT COMPONENT SIMULATION
  2005     1     1     0     0
:FR7c - START TIME OF CONTAMINANT MIGRATION COMPONENT SIMULATION
  2005     1     1     0     0
:FR8 - GRID SPACING IN X DIRECTION
 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0
 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0
 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0
 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0
 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0
:FR10 - GRID SPACING IN Y DIRECTION
 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0
 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0
 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0
 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0 2000.0
 2000.0 2000.0 2000.0
:FR12 - PRINT CONTROL PARAMETERS
 1.0000     2     T     F     F     F 20000.
:FR20 - BASIC TIMESTEP DATA
 0.5000 0.0500 9999.0  8.000     T
:FR22 - PRINT CONTROL PARAMETERS
     F     F     F     F     F     F     F     F     F     F
:FR24 - COMPONENT EXECUTION CONTROL PARAMETERS (SM,BK,SY,CM)
     F     F     F     F
:FR26 - HOTSTART PARAMETERS
     F     F   0.0    0.0
:FR28 - NO. OF MET./RAINFALL STATIONS, VEG./SOIL TYPES AND SOIL LAYER CAT.
     5    17     5     1     1
:FR30 - RIVER LINING PARAMETERS
     F 0.1000    0.0     F
:FR32 - DEFAULT VALUES FOR MET,RAINFALL,VEG,SOIL LAYER CATEGORIES
     0     0     0     1
:FR34 - COMPUTATIONAL GRID DEFINITION
    44 00000000000000000000000000000000000000000000000
    43 00000000000000000000000000000000000000000000000
    42 00000000000000000000000000000000000000000000000
    41 00000000011111000000000000000000000000000000000
    40 00000111111111111100000000000000000000000000000
    39 00111111111111111111000000000000000000000000000
```

38 00111111111111111111100000000000000000000000000
37 00111111111111111111110000000000000000000000000
36 00111111111111111111111111000000000000000000000
35 00111111111111111111111111000000000000000000000
34 00011111111111111111111111100000000000000000000
33 00011111111111111111111111110000000000000000000
32 00011111111111111111111111111100000000000000000
31 00001111111111111111111111111111111111111100000
30 00001111111111111111111111111111111111111110000
29 00000111111111111111111111111111111111111110000
28 00000111111111111111111111111111111111111110000
27 00000111111111111111111111111111111111111110000
26 00000111111111111111111111111111111111111100000
25 00000111111111111111111111111111111111111100000
24 00000111111111111111111111111111111111111100000
23 00000111111111111111111111111111111111111110000
22 00000111111111111111111111111111111111111110000
21 00000011111111111111111111111111111111111111000
20 00000011111111111111100011111111111111111111000
19 00000000000000000011000001111111111111111111000
18 00000000000000000000000011111111111111111111100
17 00000000000000000000000111111111111111111111100
16 00000000000000000000001111111111111111111111000
15 00000000000000000000001111111111111111111111000
14 00000000000000000000111111111111111111111110000
13 00000000000000000000111111111111111111111110000
12 00000000000000000000111111111111111111111110000
11 00000000000000000000111111111111111111111000000
10 00000000000000000000111111111111111111110000000
9 00000000000000000001111111111111111110000000000
8 00000000000000000001111111111111111110000000000
7 00000000000000000001111111111111111100000000000
6 00000000000000000001111111111111111100000000000
5 00000000000000000001111111111110111000000000000
4 00000000000000000000001110000000011100000000000
3 00000000000000000000000000000000000000000000000
2 00000000000000000000000000000000000000000000000
1 00000000000000000000000000000000000000000000000
:FR35a - E-W FLOW CODES (n-s links)
44 ....
43 ....
42 ....
41 ....R..................................
40 ........R....R.................................
39 ....R..............................
38 .....R.R.........R.R...........................
37 ................R...R..........................
36 ................R.R..R...W.....................
35 .....................R..R......................

34 ......................R..R......................
33 ....R.......................
32 .....R..................R.......................
31 .....R...............R..R.......................
30 .....R...............R..R......R.R.R.R.R........
29 .....R.................R..R.R.R.R.R.R.R.........
28 .....R.................R........................
27 .....R.....R...R.R.R...R................R.......
26 .....R.....R.......R..R.R.......................
25 .....R.....R.R.R.R.R....R.......................
24 .....R.....R.R.R..R....R.R...R..................
23 ......R....R......R....R..R..R.........R.R......
22 ..........R.R.....R.......R..R.........R.R......
21 ..........R........R......R..R.........R.R......
20 ...................R.........R.........R.R......
19 .............................R.........R.R......
18 .............................R.R.R.....R.R.R....
17 .............................R.R.R.....R.R......
16 ............................R.........RR.RR.....
15 .........................R..R.........RR.R......
14 .........................R..R...................
13 .......................R....R.........R.........
12 ........................R.R.R..R..R...R.........
11 ........................R.R.R.....R.............
10 ..........................R.R...................
9 .........................R..R...................
8 ........................R....R.RR..............
7 .......................R.R...R.RR...............
6 .......................R.R...R...R.............
5 .........................R.......R..............
4 ....
3 ....
2 ....
1 ....
:FR35c - N-S FLOW CODES (e-w links)
45 ....
44 ....
43 ....
42 ....
41 ....
40 ....RRRRRRRRR.............................
39 ....R.R..........RR............................
38 ....RRRRRRRRRRRRRR..R..........................
37 ....RRR.........................
36 ....RRRRRRRRRRRRR..............................
35 ....RRR........................
34 .....RRRRRRRRRRRRRRRRRRRR......................
33 ....RR......................
32 .......RRRRRRRRRRRRRRR...RRRRRR................

31 .....................RRR.......R.R.R.R.R.......
30 ..........RRRRRRRRRRR..RRRRRRRRRRRRRRRRRR......
29 .....RR................RR.R.R.R.R.R.R.R........
28 .............RR.R.R.RRR.................R......
27 .....RRRR......RRRR...RRRRRRRRRRRRRRRRRRR......
26 ....RRR.........................
25 .....RRRR........RR..RRRRRRR.RRRRRRRRRR........
24 .....R.....RRRRRRR.......R.....................
23 ......RRRRRR............RRRRRRRRRRR............
22 ............R.RRRRR............................
21 .............................RRRR....RR..RR....
20 ....
19 ...............................R...RRRR....R...
18 ....RR....
17 ............................RRRRRRRRRRRRRR.....
16 ....RRRRR...................
15 ....RR...................
14 ......................R...............RRRR.....
13 .....................RRRRRRRRRRRRRRRRR.........
12 ............................RR.R......RR.......
11 ....
10 ....R.....................
9 ........................R...RRRRRRR............
8 ....RRRRR......................
7 ....R..............
6 ....RR........................
5 ....RRR...........
4 ....
3 ....
2 ....
1 ....

:FR37 - GROUND SURFACE ELEVATION

44
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0

43
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0

42
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0
41
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 545.64
498.01 453.99 341.89 240.15 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
40
0.0 0.0 0.0 0.0 0.0 879.95 758.68 662.22 595.81 536.50
450.70 375.36 287.04 223.38 206.60 174.82 169.51 163.69 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
39
0.0 0.0 2070.4 1432.5 1103.5 892.37 757.66 666.57 588.24 513.60
428.55 379.44 332.30 287.39 221.03 186.40 187.18 159.49 139.82 128.40
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
38
0.0 0.0 1866.1 1445.9 1163.3 890.43 750.39 668.19 574.48 486.94
412.75 351.94 317.38 273.47 215.79 179.72 165.52 160.37 142.62 127.69
122.87 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
37
0.0 0.0 1594.7 1405.9 1170.0 921.12 794.68 675.95 567.66 485.18
414.86 358.41 306.25 258.01 200.46 171.72 155.78 143.89 128.88 117.47
114.92 115.75 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
36
0.0 0.0 1823.5 1429.5 1168.4 977.73 825.89 682.53 570.91 483.04
435.35 352.54 279.78 228.10 188.14 164.92 152.80 138.93 126.53 119.00
111.10 106.34 120.29 131.20 113.54 90.245 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
35
0.0 0.0 2210.3 1507.5 1163.4 960.86 795.44 654.98 547.34 467.70
397.68 327.86 272.07 226.71 188.51 160.95 147.84 135.23 124.18 116.33
107.38 101.94 105.47 121.50 107.51 92.445 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
34
0.0 0.0 0.0 1352.2 1085.1 891.81 753.15 634.19 533.19 449.08
377.60 318.91 263.98 218.44 178.15 151.99 140.95 131.31 120.95 111.06
105.61 99.690 99.552 101.05 99.348 97.448 102.73 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0

33
0.0 0.0 0.0 1088.3 934.38 801.99 682.79 594.97 507.66 430.19
360.05 301.35 246.34 205.65 173.60 151.16 135.85 125.24 116.76 108.10
102.40 99.552 99.452 99.415 99.355 99.510 108.52 116.89 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
32
0.0 0.0 0.0 903.45 795.09 694.94 597.98 525.99 462.80 399.36
340.92 284.06 232.68 192.90 165.41 148.77 135.12 124.47 115.76 107.29
100.11 99.555 99.455 99.452 99.455 104.39 114.47 124.89 138.61 158.00
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
31
0.0 0.0 0.0 0.0 670.82 605.37 532.62 468.03 410.86 358.11
313.30 267.15 221.13 186.26 161.49 146.82 131.42 120.91 111.81 106.17
99.975 99.615 99.515 99.455 99.555 107.16 116.24 127.06 141.21 159.65
188.99 221.65 274.34 361.77 439.12 503.11 593.97 691.92 826.73 1035.3
1446.0 1961.7 0.0 0.0 0.0 0.0 0.0
30
0.0 0.0 0.0 0.0 569.14 517.71 463.14 411.42 366.27 317.18
277.97 241.15 205.60 176.59 152.93 136.15 126.29 116.12 107.72 101.34
99.655 99.555 99.552 99.515 99.615 104.67 113.32 127.49 145.24 164.38
195.38 231.00 275.80 333.10 397.61 464.03 613.69 723.60 849.80 1114.7
1572.0 2093.3 2791.1 0.0 0.0 0.0 0.0
29
0.0 0.0 0.0 0.0 0.0 436.29 397.10 352.11 318.18 279.27
243.76 218.05 188.42 161.18 140.78 127.21 118.64 111.75 104.16 99.855
99.755 99.655 99.652 99.615 99.715 104.88 117.61 132.43 159.88 180.41
211.21 251.35 296.86 343.73 401.29 474.60 623.87 735.26 876.28 1080.7
1401.0 1815.6 2197.2 0.0 0.0 0.0 0.0
28
0.0 0.0 0.0 0.0 0.0 359.66 329.53 296.53 271.15 239.14
214.09 193.91 171.03 151.43 133.86 119.93 112.90 107.79 103.43 99.955
99.855 99.755 99.752 99.715 102.41 108.02 119.29 138.19 162.23 191.50
226.29 265.39 311.86 381.09 443.40 509.32 609.19 719.95 869.69 1047.8
1333.6 1609.7 1820.9 0.0 0.0 0.0 0.0
27
0.0 0.0 0.0 0.0 0.0 297.54 269.08 241.52 221.31 203.83
188.12 175.50 157.74 142.85 128.33 117.32 113.28 106.08 102.15 100.05
99.955 99.855 99.852 101.46 104.10 110.40 120.93 138.74 165.86 193.91
228.51 270.64 318.76 379.76 449.86 538.09 657.78 774.15 924.97 1127.7
1355.6 1610.5 1974.4 0.0 0.0 0.0 0.0
26
0.0 0.0 0.0 0.0 0.0 246.20 228.38 206.47 187.75 176.60
165.01 157.68 144.76 132.08 119.27 110.07 105.39 104.86 102.13 100.03
100.01 99.955 99.935 100.09 104.49 114.38 127.99 146.99 170.12 199.73
239.82 282.45 329.66 386.79 455.58 544.81 672.61 782.90 927.67 1070.8
1286.6 1607.5 0.0 0.0 0.0 0.0 0.0
25

0.0 0.0 0.0 0.0 0.0 204.54 193.38 179.00 167.03 158.70
146.92 140.36 131.38 120.65 113.68 107.96 106.93 104.61 103.23 100.13
100.11 100.05 100.63 100.99 103.71 111.98 126.07 147.84 173.07 203.20
238.00 279.27 325.06 376.76 442.40 525.62 627.65 753.64 869.00 992.15
1218.3 1544.4 0.0 0.0 0.0 0.0 0.0
24
0.0 0.0 0.0 0.0 0.0 171.38 165.21 157.13 150.32 146.06
137.16 135.68 133.98 119.80 108.57 107.94 105.66 104.35 102.33 101.62
102.75 105.47 102.02 106.11 105.62 108.65 118.69 135.93 161.96 193.97
230.21 267.12 309.85 365.06 430.55 497.79 578.22 691.32 780.55 882.05
1091.0 1193.3 0.0 0.0 0.0 0.0 0.0
23
0.0 0.0 0.0 0.0 0.0 149.22 145.41 138.66 136.06 135.96
135.86 135.76 151.06 118.91 115.63 109.53 107.71 105.35 103.43 123.36
148.90 138.51 129.41 115.47 113.47 110.35 114.86 134.04 146.12 171.54
208.44 247.57 293.13 346.61 398.39 459.50 536.03 615.44 675.92 778.80
906.99 956.16 991.94 0.0 0.0 0.0 0.0
22
0.0 0.0 0.0 0.0 0.0 185.94 136.36 136.26 136.16 136.06
135.96 138.13 139.23 150.44 123.47 107.94 105.61 105.42 105.66 122.46
192.82 229.71 221.67 132.67 118.74 111.76 118.10 169.14 146.22 157.59
197.26 239.44 280.26 330.82 388.62 447.48 500.29 530.10 570.84 650.84
731.28 767.34 792.40 0.0 0.0 0.0 0.0
21
0.0 0.0 0.0 0.0 0.0 0.0 162.59 177.99 229.04 136.16
136.06 136.16 136.26 137.68 125.06 108.57 116.15 114.67 107.60 115.32
190.72 303.14 377.38 347.66 133.98 142.14 129.30 146.43 146.31 151.73
193.27 232.54 278.20 319.55 362.67 408.23 442.12 445.74 487.36 536.03
592.35 614.77 674.31 657.26 0.0 0.0 0.0
20
0.0 0.0 0.0 0.0 0.0 0.0 292.79 284.96 246.98 234.33
263.33 286.25 282.42 276.11 270.19 208.16 223.31 192.13 116.31 130.37
203.82 0.0 0.0 0.0 261.86 196.66 168.59 184.76 146.31 152.36
184.49 220.45 256.08 291.55 326.58 355.31 377.12 383.04 420.75 457.02
500.18 521.44 552.73 548.13 0.0 0.0 0.0
19
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 156.30 175.97
0.0 0.0 0.0 0.0 0.0 488.84 390.92 240.85 146.33 153.80
180.65 207.70 235.70 263.95 287.34 310.49 317.05 334.83 362.12 404.32
424.36 449.23 458.40 464.06 0.0 0.0 0.0
18
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 335.16 405.60 433.08 266.43 146.41 146.51
166.58 198.59 219.41 236.39 253.24 273.40 272.39 294.49 318.54 348.20
364.24 385.74 388.30 403.77 593.07 0.0 0.0
17
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 212.48 220.91 212.40 177.64 146.43 146.41 160.34
168.67 172.52 196.62 205.80 307.29 244.68 238.89 260.62 283.21 302.80
321.43 335.45 340.68 418.51 691.52 0.0 0.0
16
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 248.47 178.45 166.16 158.77 146.61 146.51 164.07 206.88
244.15 276.33 232.72 224.96 238.63 238.69 238.79 238.89 254.28 265.65
287.44 326.40 396.21 599.77 0.0 0.0 0.0
15
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 274.59 210.65 153.87 146.71 146.61 146.51 146.61 174.05
307.24 314.39 328.46 457.00 491.68 367.61 242.91 238.99 239.09 285.04
509.82 607.38 727.91 784.95 0.0 0.0 0.0
14
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
571.29 375.86 276.27 186.96 146.81 146.71 146.61 146.53 146.63 155.06
239.32 271.87 349.94 385.92 513.17 554.96 500.26 469.26 395.89 422.61
615.44 692.10 906.99 0.0 0.0 0.0 0.0
13
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
453.20 282.71 265.97 183.15 151.84 146.81 146.71 146.63 149.78 152.13
152.23 161.06 171.30 191.31 228.60 254.12 325.76 292.04 299.82 476.12
689.26 859.05 986.61 0.0 0.0 0.0 0.0
12
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
506.97 421.66 249.23 183.15 148.82 147.91 147.81 147.73 160.42 176.29
211.48 269.17 266.78 271.18 228.68 228.78 228.88 284.27 480.28 745.00
999.45 1044.4 1083.3 0.0 0.0 0.0 0.0
11
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
556.03 545.41 304.03 193.88 158.10 149.01 148.91 148.83 150.49 166.10
219.28 289.31 347.17 318.40 337.98 371.24 366.33 501.36 719.12 851.74
972.45 0.0 0.0 0.0 0.0 0.0 0.0
10
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
560.58 550.36 345.67 189.59 159.22 149.11 149.01 149.66 156.52 200.32
334.14 309.33 333.01 330.97 455.58 600.37 707.36 778.30 947.40 933.33
0.0 0.0 0.0 0.0 0.0 0.0 0.0
9
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 427.02

444.19 447.88 324.29 177.54 154.52 151.35 151.87 149.49 152.98 200.19
259.57 445.38 385.21 397.48 413.61 560.75 837.44 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
8
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 401.71
313.51 282.56 208.71 166.51 156.14 161.40 190.87 252.58 168.40 183.82
200.32 224.09 224.19 301.44 404.31 575.99 792.94 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
7
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 398.22
321.56 260.91 199.43 171.32 162.49 182.15 257.57 351.13 274.13 299.52
229.28 224.19 224.29 412.49 466.58 550.49 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
6
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 377.11
323.27 282.36 227.41 190.84 177.73 198.34 286.16 427.42 363.06 418.39
388.74 229.52 224.39 423.71 474.00 433.85 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
5
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 354.54
322.26 306.17 276.86 231.51 210.30 251.71 375.17 387.64 396.09 420.28
424.47 0.0 248.76 276.43 299.89 346.83 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
4
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 291.42 302.15 275.49 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 398.11 372.66 418.97 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
3
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
2
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
1
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0
:FR43 - met stations
44 22222222111111211111111222111111111113111114344
43 22222222111111211111111222111111111113111114344
42 22222222122222122211111222111111111133311411433
41 22222222122222222221111122211111313313111444441 1
40 22222222132222211111111222111131131111114441111
39 22222222122211111111111551111111111111114431111
38 22222222221211111111111521111111111111111111133
37 22222222222221111111111551111111111111111111133
36 22222222222111111111111551111111111111555111144
35 22222222222111111111111555111111111111551111111
34 55522222222221111111113115111111111441155511111 11
33 55522222222111111111111133111111111444125511334 11
32 22222222222211111111333331111111444442555114554 4
31 22222222221111111111111331111131444442255544455 5
30 22222222221111111111111313111133144444222444555 5
29 22222222211111111111113311131311111444242444554 4
28 44444222211111111111113313331332221111444244444 44
27 44441222221111111111131111113332222211113334442 2
26 44441442221111313111131131133222222222123555422 22
25 44441111111111131111111311123322222222225554442 2
24 44441311111113111111113113122222322222222544222 2
23 44443331111131133111111111132223333222222224552 22
22 44441333114444113311133313322222232242222255522 2
21 44441333131331141113222121135223223222222225222 2
20 44441333131331141111225221132223222322322222333
19 44441333131331141111332521122232222222322222222
18 44441333131331141111213552221332332222122112222
17 44441333131331141111222255513332223222212122222
16 44441333131331141111222222211122222222112212224 4
15 11111133131331141111222222211112222214122212223 44
14 11111133131331141111552221111111555122223222241 1
13 11111133131331141111555422111111225441212242424 4
12 11111133131331141111555231111111555544114444424 4
11 11111111111111111111555522111111111111111222222 22
10 11111111111111111111222255311111344411111222225522
9 11111111111111111111222255131113144414112222 55555
8 11111111111111111112222555111331442144422222525 5
7 11111111111111111112222155111324222555555522222 2
6 11111111111111111112222221111152555545555555522 44
5 11111111111111111112222311115524545445555555224 4
4 11111111111111111112222311125522445555255555222 2
3 11111111111111111112222222222555555555225255222 22
2 11111111111111111112222222225555554222222225222 22
1 11111111111111111112222222225555554222222225222 22
:FR46 - rainfall stations
44

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
43
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 0
42
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 0
41
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 0
40
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 0
39
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 0
38
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 0
37
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 0
36
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 0
35
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 0
34
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 0
33
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 0
32
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 12 12 0
31
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 14 14 14 14 14 14 14 14 14 14 14 14 14 14 14 12 12 12 0
30
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 16
16 16 16 16 16 14 14 14 14 14 14 14 14 14 14 12 12 12 12 12 0
29
0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 16 16 16 16
16 16 16 16 16 16 16 16 16 14 14 14 14 14 12 12 12 12 12 12 12 0
28

0 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 16 16 16 16 16 16 16 16
16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12 12 12 0
27
0 4 4 4 4 4 4 4 4 4 4 4 4 16 16 16 16 16 16 16 16 16 16 16
16 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12 12 12
0
26
0 4 4 4 4 4 4 4 4 4 16 16 16 16 16 16 16 16 16 16 16 16 16 16
16 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12 12 12
0
25
0 13 13 13 13 13 13 13 16 16 16 16 16 16 16 16 16 16 16 16 16 16
16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
24
0 13 13 13 13 13 13 13 13 16 16 16 16 16 16 16 16 16 16 16 16 16
16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
23
0 13 13 13 13 13 13 13 13 13 13 16 16 16 16 16 16 16 16 16 16 16
16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
22
0 13 13 13 13 13 13 13 13 13 13 13 13 16 16 16 16 16 16 16 16 16
16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
21
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 16 16 16 16 16 16 16
16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
20
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 16 16 16 16 16 16
16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
19
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 16 16 16 16
16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
18
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 16 16
16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
17
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 16
16 16 16 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
16

0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 16 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
15
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 16 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
14
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 16 16 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
13
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 13 13 16 16 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
12
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 13 13 13 13 16 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
11
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 13 13 13 13 13 16 16 16 16 16 16 12 12 12 12 12 12 12
12 12 0
10
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 13 13 13 13 13 13 13 16 16 16 16 12 12 12 12 12 12 12
12 12 0
9
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 13 13 13 13 13 13 13 13 13 16 16 12 12 12 12 12 12 12
12 12 0
8
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 13 13 13 13 13 13 13 13 13 13 16 12 12 12 12 12 12 12
12 12 0
7
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 12 12 12 12 12 12 12
12 12 0
6
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 12 12 12 12 12 12
12 12 0
5
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 12 12 12 12 12 12
12 12 0
4

0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 12 12 12 12 12 12
12 12 0
3
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 12 12 12 12 12
12 12 0
2
0 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13
13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 13 12 12 12 12 12
12 12 0
1
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
:FR49 - VEGETATION TYPES
44 2222222211111121111111222111111111311111 4344
43 22222222111111211111112221111111113111114344
42 22222222122222122211111222111111111333114114 33
41 22222222122222222221111122211111313313111444 4411
40 22222222132222211111111222111131131111111444 1111
39 22222222122211111111111551111111111111114431111
38 22222222221211111111111521111111111111111111133
37 22222222222221111111111551111111111111111111133
36 22222222222111111111111551111111111111555111144
35 22222222222111111111111555111111111111551111111
34 55522222222221111111111311511111111144115551111111
33 55522222222111111111111331111111114441255113 3411
32 22222222222111111113333311111114444425551145544
31 22222222221111111111113311111314444422555444555
30 22222222221111111111113131111331444442224445555
29 22222222211111111111133111313111114442424445544
28 44444222211111111111331333133222111444244 44444
27 44441222221111111111131111113332222211113334 4422
26 44441442221111313111131131133222222222123555 4222
25 44441111111111131111111311123322222222225554 4422
24 44441311111113111111113113122222322222225442222
23 44443331111131133111111111132223333222222224552 22
22 44441333114444113311133313322222232242222555222
21 44441333131331141113222121135223223222222225 2222
20 44441333131331141111225221132223222322322222333
19 44441333131331141111332521122232222222322222222
18 44441333131331141111213552221332332222122112222
17 44441333131331141111222255513332223222212122222
16 44441333131331141111222222211122222221122122244
15 11111133131331141111222222111122221412221222344
14 11111133131331141111552221111115551222232222411
13 11111133131331141111555422111112254412122424244
12 11111133131331141111555231111115555441144444244
11 11111111111111111115555221111111111111112222222 2

10 11111111111111111122225531111344411111222225522
9 11111111111111111122225513111314441411222255555
8 11111111111111111122225551113314421444222225255
7 11111111111111111122221551113242225555555222222
6 11111111111111111122222111115255554555555552244
5 11111111111111111122223111155245454455555552244
4 11111111111111111122223111255224455552555552222
3 11111111111111111122222222555555555522525522222
2 11111111111111111122222222555555422222222522222
1 11111111111111111122222222555555422222222522222

Appendix 8 Example of etd data file for SHETRAN simulation.

```
:ET1 - TEST CATCHMENT- ET COMPONENT DATA SET
    F     F     T
:ET3 - DTMET : TIMESTEP FOR INPUT OF RAIN AND MET. DATA
  1.0 24.000 730.00
:ET5 - MEASPE (0 NOT MEASURED, 1 MEASURED)
    1     1     1     1     1
:ET7 - VEGETATION TYPE rice paddy's
    F     0.     0.     0.     0.     0.     3
    7 1.0000 5.00001.40E-5 5.1000      3 4.0000      0      0
:ET9 - CONTROLS FOR TIME VARYING PARAMETERS FOR VEGETATION TYPE
    1     0     0     0
:ET11 - time varying canopy storage
  106
:ET13 - time varying canopy storage
1.0000 1.0
1.0000 90.0
0.0001 91.0
0.0001 330.0
1.0000 455.0
0.0001 456.0
0.0001 695.0
1.0000 820.0
0.0001 821.0
0.0001 1060.0
1.0000 1185.0
0.0001 1186.0
0.0001 1425.0
1.0000 1550.0
0.0001 1551.0
0.0001 1790.0
1.0000 1915.0
0.0001 1916.0
0.0001 2155.0
1.0000 2280.0
0.0001 2281.0
0.0001 2520.0
1.0000 2645.0
0.0001 2646.0
0.0001 2885.0
1.0000 3010.0
0.0001 3011.0
0.0001 3250.0
1.0000 3375.0
0.0001 3376.0
0.0001 3615.0
1.0000 3740.0
```

0.0001 3741.0
0.0001 3980.0
1.0000 4105.0
0.0001 4106.0
0.0001 4345.0
1.0000 4470.0
0.0001 4471.0
0.0001 4710.0
1.0000 4835.0
0.0001 4836.0
0.0001 5075.0
1.0000 5200.0
0.0001 5201.0
0.0001 5440.0
1.0000 5565.0
0.0001 5566.0
0.0001 5805.0
1.0000 5930.0
0.0001 5931.0
0.0001 6170.0
1.0000 6295.0
0.0001 6296.0
0.0001 6535.0
1.0000 6660.0
0.0001 6661.0
0.0001 6900.0
1.0000 7025.0
0.0001 7026.0
0.0001 7265.0
1.0000 7390.0
0.0001 7391.0
0.0001 7630.0
1.0000 7755.0
0.0001 7756.0
0.0001 7995.0
1.0000 8120.0
0.0001 8121.0
0.0001 8360.0
1.0000 8485.0
0.0001 8486.0
0.0001 8725.0
1.0000 8850.0
0.0001 8851.0
0.0001 9090.0
1.0000 9215.0
0.0001 9216.0
0.0001 9455.0
1.0000 9580.0
0.0001 9581.0

```
0.0001 9820.0
1.0000 9945.0
0.0001 9946.0
0.0001 10185.0
1.0000 10310.0
0.0001 10311.0
0.0001 10550.0
1.0000 10675.0
0.0001 10676.0
0.0001 10915.0
1.0000 11040.0
0.0001 11041.0
0.0001 11280.0
1.0000 11405.0
0.0001 11406.0
0.0001 11645.0
1.0000 11770.0
0.0001 11771.0
0.0001 12010.0
1.0000 12135.0
0.0001 12136.0
0.0001 12375.0
1.0000 12500.0
0.0001 12501.0
0.0001 12740.0
:ET15 - PSI/RCF/FET FUNCTION FOR VEGETATION TYPE
 -1000.     0.    0.0
 -150.0     0. 0.0200
 -50.00     0. 0.0200
 -20.00     0. 0.0200
 -10.00     0. 0.0200
 -1.000     0. 0.0200
 -0.100     0. 0.0200
:ET17 - DEPTH/RDF FOR VEGETATION TYPE
 0.1000 0.5000
 0.2000 0.3000
 0.3000 0.2000
:ET7 - VEGETATION TYPE BareGround
     F     0.     0.     0.     0.     0.      3
     7    0.8    3.01.40E-5 5.1000      1 1.0000      0      0
:ET9 - CONTROLS FOR TIME VARYING PARAMETERS FOR VEGETATION TYPE
     0      0      0      0
:ET15 - PSI/RCF/FET FUNCTION FOR VEGETATION TYPE
 -1000.     0.    0.0
 -150.0     0. 0.0200
 -50.00     0. 0.3000
 -20.00     0. 0.5000
 -10.00     0. 0.8000
 -1.000     0. 1.0000
```

```
 -0.100     0. 1.0000
:ET17 - DEPTH/RDF FOR VEGETATION TYPE
 0.1000 1.0000
:ET7 - VEGETATION TYPE Urban
     F     0.     0.     0.     0.     0.      3
     7 0.8000    1.01.40E-5 5.1000      3 1.0000      0      0
:ET9 - CONTROLS FOR TIME VARYING PARAMETERS FOR VEGETATION TYPE
     0      0      0      0
:ET15 - PSI/RCF/FET FUNCTION FOR VEGETATION TYPE
 -1000.     0.    0.0
 -150.0     0. 0.0200
 -50.00     0. 0.1000
 -20.00     0. 0.2000
 -10.00     0. 0.6000
 -1.000     0. 0.8000
 -0.100     0. 0.8000
:ET17 - DEPTH/RDF FOR VEGETATION TYPE
 0.1000 0.5000
 0.2000 0.3000
 0.3000 0.2000
:ET7 - VEGETATION TYPE Forest
     F     0.     0.     0.     0.     0.      3
     7 1.0000 5.00001.40E-5 5.1000      3 6.0000      0      0
:ET9 - CONTROLS FOR TIME VARYING PARAMETERS FOR VEGETATION TYPE
     0      0      0      0
:ET15 - PSI/RCF/FET FUNCTION FOR VEGETATION TYPE
 -1000.     0.    0.0
 -150.0     0. 0.0200
 -50.00     0. 0.3000
 -20.00     0. 0.5000
 -10.00     0. 0.8000
 -1.000     0. 1.0000
 -0.100     0. 1.0000
:ET17 - DEPTH/RDF FOR VEGETATION TYPE
 0.1000 0.5000
 0.2000 0.3000
 0.3000 0.2000
:ET7 - VEGETATION TYPE Grass/shrub
     F     0.     0.     0.     0.     0.      3
     7 1.0000 2.50001.40E-5 5.1000      3 6.0000      0      0
:ET9 - CONTROLS FOR TIME VARYING PARAMETERS FOR VEGETATION TYPE
     0      0      0      0
:ET15 - PSI/RCF/FET FUNCTION FOR VEGETATION TYPE
 -1000.     0.    0.0
 -150.0     0. 0.0200
 -50.00     0. 0.3000
 -20.00     0. 0.5000
 -10.00     0. 0.8000
 -1.000     0. 1.0000
```

-0.100   0. 1.0000
:ET17 - DEPTH/RDF FOR VEGETATION TYPE
0.1000 0.5000
0.2000 0.3000
0.3000 0.2000