



Effects of changes in land use and climate on water availability of a tropical catchment

Hero Marhaento |



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**EFFECTS OF CHANGES IN LAND USE AND CLIMATE
ON WATER AVAILABILITY OF A TROPICAL CATCHMENT**

DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the rector magnificus,
prof. dr. T.T.M. Palstra,
on account of the decision of the graduation committee,
to be publicly defended
on Thursday 22 February 2018 at 14:45 hrs

by

Hero Marhaento

Born on April 5th, 1982
in Yogyakarta, Indonesia

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Verify, after hardship comes ease

[Quran 94:5]

I dedicate this book to my parents, wife and son

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Hero Marhaento

Summary

Introduction. Land use changes such as deforestation and urbanization influence the hydrology of catchments and hence water availability. Together with climate change, land use changes can affect the frequency of floods or droughts and thus threaten local or regional socio-economic development. For Indonesia, the effects of changes in land use and climate have been projected to cause a food crisis and eventually increase the degree of poverty in the future. In order to mitigate future risks, knowledge on the extent and directions of land use change and climate change impacts on water availability is essential.

The objective of this research is to assess the effects of land use change and climate change on the water availability in the Samin catchment (278 km²) in Java, Indonesia. The research is divided into four parts (papers). The first two papers address the attribution of observed changes in hydrological processes to land use change and climate change, using a data-based approach (first paper) and a modelling approach (second paper). In the third paper, the future hydrological response due to expected land use change and climate change is estimated. Finally, in the fourth paper, the effects of different land use patterns on streamflow characteristics are assessed.

Attribution of changes in streamflow to land use change and climate change in a mesoscale tropical catchment in Java, Indonesia. Changes in the streamflow of the study catchment have been attributed to land use change and climate change using a method based on the changes in the proportion of excess water relative to changes in the proportion of excess energy. The results show that 72% of the increase in streamflow in the period 1990-2013 can be attributed to land use change and 28% to climate change. The results were corroborated by statistical trend analyses (i.e. Mann-Kendall trend analysis and Sen's slope estimator) and land use change analysis based on two Landsat imageries for 1994 and 2013. The results of the statistical trend analysis are in the same direction as the results of the attribution analysis, where climate change was relatively small compared to the significant land uses changes due to deforestation during the period 1994-2013. It was concluded that changes in streamflow in the study catchment can be mainly attributed to land use change rather than climate change.

Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model. Changes in the water balance of the study catchment have been attributed to land use change using the Soil Water Assessment Tool (SWAT) and a baseline-altered method. The simulation period 1990–2013 was divided into four equal periods to represent baseline conditions and altered land use conditions. A SWAT model was calibrated for the baseline

period and applied to the altered periods with and without land use change acquired from Landsat and Aster satellite imageries for the years 1994, 2000, 2006 and 2013. The results show that the model performance for simulations with land use change is better than the model performance without land use change, confirming that land use change is an explanatory factor for observed changes in the water balance. Land use changes during 1994–2013, which included a decrease in forest area from 48.7% to 16.9%, an increase in agriculture area from 39.2% to 45.4% and an increase in settlement area from 9.8% to 34.3%, have resulted in an increase of the ratio of streamflow to precipitation from 35.7% to 44.6%, a decrease in the ratio of evapotranspiration to precipitation from 60% to 54.8%, an increase in the ratio of surface runoff to streamflow from 26.6% to 37.5% and a decrease in the ratio of base flow to streamflow from 40% to 31.1%. At sub-catchment level, the effects of land use changes on the water balance varied in different sub-catchments depending on the scale of changes in forest and settlement areas.

Hydrological response to future land use change and climate change in a tropical catchment. Future hydrological response in the study catchment has been simulated using the validated SWAT model, predicted land use distributions for the period 2030–2050, and outputs from a bias-corrected Regional Climate Model (RCM) and six Global Climate Models (GCMs) to include climate model uncertainty. Two land use change scenarios, namely a business-as-usual (BAU) scenario, where no measures are taken to control land use change, and a controlled (CON) scenario, where the future land use follows the land use planning, were used in the simulations together with two climate change scenarios, namely Representative Concentration Pathways (RCPs) 4.5 and 8.5. It was predicted that, in the period 2000–2050, settlement and agriculture areas of the study catchment will increase by 33.9% and 3.5%, respectively, under the BAU scenario, whereas agriculture area and evergreen forest will increase by 15.2% and 10.2%, respectively, under the CON scenario. In comparison to the baseline conditions (1983–2005), the mean annual maximum and minimum temperature in 2030–2050 are expected to increase by an average of +1°C, while predicted changes in the mean annual precipitation range from -20% to +19% under RCP 4.5 and from -25% to +15% under RCP 8.5. The results show that land use change and climate change individually will cause changes in the water balance components, but that more pronounced changes are expected if the drivers are combined in the modelling approach, in particular for changes in annual streamflow and surface runoff. Furthermore, under the CON scenario the annual streamflow and surface runoff could be potentially reduced by up to 10% and 30%, respectively indicating the effects of applied land use planning.

Sensitivity of streamflow characteristics to different spatial land use configurations in a tropical catchment. While the previous chapters have focused on the impact of changes in types of land use on hydrological processes, this chapter assesses the effects of changes in the spatial configuration of land use on streamflow characteristics. The land use distribution in the period 1982-2013 was reconstructed based on satellite images and used to estimate land use pattern characteristics for the years 1982, 1994, 2000, 2006 and 2013. A validated SWAT model was employed using the land use distributions for the mentioned years as inputs and a correlation analysis was applied to identify relations between changes in land use pattern characteristics and simulated streamflow characteristics. Furthermore, a future land use scenario analysis was carried out to assess the sensitivity of streamflow characteristics to different land use patterns. The results show that changes in the percentages of different land use types and the physical connectivity between patches of similar land use types appear as dominant drivers for changes in streamflow characteristics. When the relative presence of different land use types is fixed but the physical connectivity of patches is changed, simulation results indicate that an increase in the settlement connectivity can result in an increase in the ratio of surface runoff to streamflow and a decrease in the ratio of dry-season streamflow to wet-season streamflow, and vice versa, while changes in the forest connectivity have less impact on streamflow characteristics.

Conclusions. The research provides insight in the impacts of changes in land use and climate on water availability in a tropical catchment in the past and future. Beside contributing to the advancement of the scientific field of hydrology through proposed methods used in this thesis, findings of this study can be useful for supporting the authorities for mitigating future water stress through appropriate land use management.

Samenvatting

Introductie. Veranderingen in landgebruik zoals ontbossing en verstedelijking beïnvloeden de hydrologie van stroomgebieden en daarmee de waterbeschikbaarheid. Samen met klimaatveranderingen kunnen veranderingen in landgebruik invloed hebben op de frequentie van desastreuze gebeurtenissen (bijv. overstromingen en droogte), wat kan leiden tot bedreigingen voor lokale, regionale en globale socio-economische ontwikkeling. In Indonesië zijn de gevolgen van veranderingen in landgebruik en klimaat de oorzaken van een voedselcrisis wat uiteindelijk resulteert in een toename van de mate van armoede in de toekomst. Kennis over de grootte en richting van landgebruiks- en klimaatveranderingen is noodzakelijk om toekomstige risico's op waterbeschikbaarheid te beperken.

De doelstelling van dit onderzoek is om de effecten van veranderingen in landgebruik en klimaat op waterbeschikbaarheid in het stroomgebied van de Samin (278 km²) in Java, Indonesië, te beoordelen. Dit onderzoek is opgesplitst in vier delen (artikelen). De eerste twee artikelen richten zich op de toekenning van waargenomen veranderingen in hydrologische processen op veranderingen in landgebruik en klimaat, gebruikmakende van een data-gedreven benadering (eerste artikel) en een modelleerbenadering (tweede paper). In het derde artikel worden de toekomstige hydrologische reacties ten gevolge van verwachte landgebruiks- en klimaatveranderingen geschat. In het vierde artikel worden de effecten van verschillende patronen van landgebruik op de afvoercharacteristieken beoordeeld.

Toekenning van veranderingen in afvoer aan landgebruiksveranderingen en klimaatveranderingen in een mesoschaal stroomgebied in Java, Indonesië. Veranderingen in de afvoer van het studiegebied zijn toegekend aan landgebruiks- en klimaatveranderingen gebruikmakende van een methode gebaseerd op de veranderingen in het aandeel van overtollig water ten opzichte van veranderingen in het aandeel van overtollige energie. De resultaten laten zien dat 72% van de toename in afvoer in de periode 1990-2013 kan worden toegeschreven aan veranderingen in landgebruik en 28% kan worden toegekend aan klimaatverandering. De resultaten werden bevestigd door statische trendanalyses (Mann-Kendall trend analyse en Sen's slope estimator) en een analyse van landgebruiksveranderingen gebaseerd op Landsat satelietbeelden uit 1994 en 2013. De resultaten van de statische trendanalyses komen overeen met de resultaten van de toekenningsanalyse waar klimaatveranderingen relatief klein waren in vergelijking met de significante landgebruiksveranderingen ten gevolge van ontbossing in de periode 1994-2013. Er werd geconcludeerd dat de veranderingen in afvoer in het studiegebied voornamelijk kunnen worden

toegeschreven aan de veranderingen in landgebruik in plaats van klimaatveranderingen.

Toekenning van veranderingen in de waterbalans van een tropisch stroomgebied aan landgebruiksveranderingen gebruikmakende van het SWAT model. Veranderingen in de waterbalans van het studiegebied zijn toegekend aan landgebruiksveranderingen gebruikmakende van de Soil Water Assessment Tool (SWAT) en een gewijzigde baseline methode. De 1990-2013 simulatieperiode was opgesplitst in vier gelijke periodes om de baseline condities en gewijzigde condities in landgebruik weer te geven. Een SWAT model was gekalibreerd en gevalideerd voor de baseline periode en toegepast op de gewijzigde periodes met en zonder landgebruiksveranderingen verkregen van Landsat en Aster satellietbeelden voor de jaren 1994, 2000, 2006 en 2014. De resultaten laten zien dat modelprestaties voor de simulaties met landgebruiksveranderingen beter zijn dan de modelprestaties zonder veranderingen in landgebruik, waarmee wordt bevestigd dat landgebruiksveranderingen een verklarende factor is voor de waargenomen veranderingen in de waterbalans. Veranderingen in landgebruik tijdens de periode 1994-2013 met een afname van bosgebieden van 48,7% naar 16,9%, een toename in landbouwgebieden van 39,2% naar 45,4% en een toename in verstedelijking van 9,8% naar 34,4%, resulteerde in een toename van de ratio van afvoer tot neerslag van 35,7% naar 44,6%, een afname van de ratio van evapotranspiratie tot neerslag van 60% naar 54,8%, een toename van de ratio van oppervlakte-afvoer tot afvoer van 26,6% naar 37,5%, en een afname van de ratio basisafvoer tot afvoer van 40% tot 31,1%. De effecten van landgebruiksveranderingen op de waterbalans varieerden voor de verschillende deelstroomgebieden afhankelijk van de mate van veranderingen in bosgebieden en verstedelijking.

Hydrologische reactie op toekomstige veranderingen in landgebruik en klimaat in een tropisch stroomgebied. De toekomstige hydrologische reactie in het studiegebied is gesimuleerd met behulp van het gevalideerde SWAT model. Een voorspelde verdeling van landgebruik in de periode 2030-2050 is gebruikt als invoer, en uitvoer van een bias gecorrigeerd Regional Climate Model (RCM) en uitvoer van zes Global Climate Models (GCMs) zijn gebruikt om de onzekerheid van het klimaatmodel te verdisconteren. Twee landgebruikscenario's, namelijk een business-as-usual (BAU) scenario waarin geen maatregelen zijn genomen om landgebruiksveranderingen te beheersen, en een gecontroleerde (CON) scenario waarin toekomstige landgebruik de landgebruiksplanning volgt, waren gebruikt in de simulaties samen met twee klimaatveranderingsscenario's, namelijk de Representative Concentration Pathways (RCPs) 4.5 en 8.5. Er werd voorspeld dat in 2050 verstedelijking en

landbouwgrond in het studiegebied met respectievelijk 33,9% en 3,5% zullen toenemen in het BAU scenario en landbouwgrond en groenblijvend bos zullen toenemen met respectievelijk 15,2% en 10,2% in het CON scenario. In vergelijking met de baseline condities (1983-2005) zal de verwachte gemiddelde jaarlijkse maximum en minimum temperatuur in 2030-2050 toenemen met een gemiddelde van +1°C, terwijl veranderingen in de gemiddelde jaarlijkse neerslag variëren tussen -20% en +19% onder RCP 4.5 en tussen -25% en +15% onder RCP 8.5. De resultaten laten zien dat veranderingen in zowel landgebruik als in klimaat leiden tot veranderingen in de waterbalanscomponenten, maar de verwachte veranderingen zijn groter als beide oorzaken worden gecombineerd, met name voor veranderingen in de jaarlijkse afvoer en oppervlakte-afvoer. Daarnaast kunnen de jaarlijkse afvoer en oppervlakte-afvoer mogelijk afnemen met respectievelijk 10% tot 30% in het CON scenario.

Gevoeligheid van afvoercharacteristieken voor verschillende ruimtelijke landgebruikconfiguraties in een tropisch stroomgebied. Terwijl in de vorige hoofdstukken de focus was op het effect van veranderingen in type landgebruik op hydrologische processen, beoordeelt dit hoofdstuk het effect van veranderingen in de ruimtelijke configuraties van landgebruik op afvoercharacteristieken. De landgebruiksverdeling uit de periode 1982-2013 was gereconstrueerd met behulp van satellietbeelden en gebruikt om een schatting te maken van de karakteristieken van landgebruikspatronen voor de jaren 1982, 1994, 2000, 2006 en 2013. Een gevalideerd SWAT model was toegepast gebruikmakende van de landgebruiksverdelingen voor de genoemde jaren als invoer en een correlatieanalyse was toegepast om de relaties tussen veranderingen in karakteristieken van landgebruikspatronen en gesimuleerde afvoercharacteristieken te bepalen. Daarnaast was een toekomstige landgebruiksscenario analyse uitgevoerd om de gevoeligheid van afvoercharacteristieken voor verschillende landgebruikspatronen te bepalen. De resultaten laten zien dat veranderingen in de percentages van verschillende landgebruikstypes en de fysische verbinding tussen gebieden met hetzelfde landgebruik de meest dominante oorzaken blijken te zijn voor veranderingen van de afvoercharacteristieken. Uit simulaties blijkt dat wanneer het relatieve voorkomen van verschillende landgebruikstypes is vastgelegd, maar de fysische locaties van de gebieden zijn veranderd, een toename in verbindingen van stedelijke gebieden kan leiden tot een toename in de ratio van oppervlakte-afvoer tot afvoer en tot een afname van de ratio van de afvoer in het droge seizoen tot de afvoer in het natte seizoen en vice versa, terwijl veranderingen in verbindingen van bosgebieden minder impact hebben op de afvoercharacteristieken.

Conclusie. Het onderzoek geeft inzicht in het effect van veranderingen in landgebruik en klimaat op waterbeschikbaarheid in een tropisch stroomgebied voor het verleden en de toekomst. Daarnaast draagt het bij aan de vooruitgang van het wetenschappelijke inzicht op het gebied van hydrologie door middel van de gebruikte methodes in dit proefschrift en kunnen de bevindingen van deze studie nuttig zijn om autoriteiten te ondersteunen voor het verzachten van toekomstige waterstress door middel van passende ruimtelijke ordening.

Chapter 1

Introduction

1.1. Background

Effects of land use change and climate change on the local, regional, and global water balance have been of interest among hydrologists for decades. Numerous studies have been carried out to quantify and simulate the effects of land use change on hydrological processes in catchments under various climatic conditions using methods such as paired catchment studies (i.e. comparison studies between control catchments and catchments under treatment) (e.g. Bosch and Hewlett, 1982; Brown et al., 2005; Suryatmojo et al., 2011; Zhao et al., 2012), a single model framework (e.g. Niehoff et al., 2002; Ashagrie et al., 2006; Breuer et al., 2009; Menzel et al., 2009; Suarez et al., 2013) and multiple models (ensemble modeling) (e.g. Huisman et al., 2009). Most studies found that, at the local scale, effects of land use change on hydrological processes are more pronounced than the effects of climate change (Bosch and Hewlett, 1982; Brown et al., 2005, O'connell et al., 2007; Wohl et al., 2012; Gallo et al., 2015). For large scales ($>100 \text{ km}^2$), the effects of land use change on hydrological processes are often contradictory and inconsistent because of e.g. climatic interference (Calder et al., 2001; Blöschl et al., 2007; Beck et al., 2013). Several studies show that the combination of land use and climate changes does not necessarily result in accelerating changes in hydrological processes (Legesse et al., 2003; Khoi & Suetsugi, 2014), since the effects of both drivers may also offset each other (Zhang et al, 2016). In addition, feedback mechanisms between land use change and climate change may be operative in larger catchments, however to what extent and in which direction is not very well understood (Pielke, 2005; Blöschl et al., 2007; Wohl et al., 2012).

One of the major challenges in the study of hydrology is to assess the attribution of changes in water availability to land use and climate changes (Romanowicz & Booij, 2011). A widespread belief exists in the hydrological community that forest reduction due to agricultural and settlement developments is the main cause of an increasing number of disasters (floods and droughts) (Andréassian, 2004; Marfai et al., 2008). It is generally agreed that forest reduction may significantly reduce canopy interception and soil infiltration capacity, resulting in a larger fraction of precipitation being transformed into surface runoff rather than recharge to groundwater (Bruijnzeel, 1989; 2004; Ibanez et al., 2002; Ogden et al.; 2013). However, some studies in tropical regions found that the influence of climate change (particularly changes in temperature and precipitation) on water

availability in catchments is larger than the influence of land use change (Legesse et al., 2003; Khoi & Suetsugi, 2014). In addition, several reports argue that forests act like a 'pump' that consumes (evaporates) a lot of water during the dry season rather than like a 'sponge' that supplies water to streamflow in the dry season (Calder et al., 1998; Calder, 2001). These findings call for further investigations on the effects of land use change and climate change on hydrological processes of catchments. Knowledge on the relative impacts of land use change and climate change on water availability can provide a better understanding of the single effect of land use change and climate change, and thus will be helpful in estimating the effectiveness of land use management practices at landscape level.

Hydrology in tropical regions differs from other regions in having greater energy inputs with large spatial and temporal variability and a fast rate of change including human-induced change (Wohl et al., 2012). Several studies have projected that land use and climate conditions of tropical regions in the future are generally characterized by a continuous reduction of tropical forest area due to cropland expansions, an increase in the average temperature (similarly to all regions in the world) and changes in the spatial and temporal precipitation variability at an uncertain magnitude (Thomson et al., 2010; Wohl et al., 2012; Nobre et al., 2016). As a result, the frequencies of droughts and floods in tropical regions related to land use and climate change are predicted to increase, resulting in threats to local or regional socio-economic development (IPCC, 2007; 2012). For Indonesia, it was projected that land use change and climate change may cause a food crisis in the future due to a decrease in crop production resulting from a warming climate (Amien et al., 1996; Naylor et al., 2007; Syaukat, 2011). Furthermore, poverty in Indonesia could increase in the future because food insecurity usually correlates with poverty (Slater et al., 2007; Syaukat, 2011). For these reasons, the Government of the Republic of Indonesia (GoI) has initiated numerous policies that engage all sectors to mitigate future risks associated with land use change and climate change (MoE, 2010). In the water resources sector, GoI has enacted National Law No. 7/2004 on water resources which aims at the integration between land use planning and water management (Fulazzaky, 2014; Putra & Han, 2014).

Integration between land use planning and water management has been acknowledged worldwide as a measure to achieve sustainable water resources use (Wheater & Evans, 2009). Land use planning can be an effective way to mitigate future risks associated with changes in land use and climate because different land use distributions may result in different water use and water storage characteristics (Bruijnzeel, 1989, 2004; Legesse et al., 2003; Memarian et al., 2014). However, it is a challenge to effectively implement the integration

between land use planning and water management. Population growth followed by an increasing demand for land for food and settlement increases the pressure on land, since more land is likely allocated for economic purposes (e.g. agricultural and industrial area expansions) than for soil and water protection purposes (Carter et al., 2005; Wheeler & Evans, 2009). In addition, land use planning is often applied without information on its effectiveness to reduce risks for future water stress (Carter et al., 2005; Fulazzaky, 2014). For these reasons, it is necessary to gain knowledge on the extent and directions of future hydrological processes as affected by ongoing trends of land use change under various climate conditions.

Summarizing, the effects of land use change and climate change on water availability in tropical regions are not well understood yet and call for further investigations. This study intends to provide a better insight in the impacts of land use change and climate change on water availability in tropical regions, in particular for the chosen study catchment in Java, Indonesia. Even though this research was conducted for a single catchment, it is thought to represent problems that are characteristic for tropical developing countries, particularly in South-East Asia, where quite similar climate and land use conditions can be found.

1.2. Research objective

The main objective of this thesis is to assess the effects of land use change and climate change on the water availability in the Samin catchment (278 km²) in Java, Indonesia. The Samin catchment is selected as the study catchment because of data availability and the fact that it is representative for many catchments in Java, but also for other catchments of Indonesia and South-East Asia (in terms of experiencing massive land use changes during the last 30 years).

1.3. Research questions

In order to achieve the research objective, the following research questions are identified.

1. What is the attribution of changes in streamflow to land use change and climate change?
2. What is the attribution of changes in water balance components such as evapotranspiration, streamflow, surface runoff, lateral flow and base flow to land use change?

3. What is the future hydrological response of the study catchment under different land use change and climate change scenarios?
4. What are the effects of different spatial land use configurations on streamflow characteristics?

1.4. Research approach

This study started with an extensive literature study that resulted in an overview of methods to attribute changes in water availability to land use change and climate change. In general, two groups of methods were identified namely data-based approaches and modelling approaches. While modelling approaches are able to simulate hydrological processes under changing conditions (i.e. land use change and climate change), they are accompanied by the need for large amounts of data and time-consuming model calibration and validation. Data-based approaches require less data and are relatively faster than modelling approaches, but suffer from lacking the ability to describe underlying hydrological processes under land use and climate changes. However, both approaches may provide mutual benefits to assess the attribution of changes in water availability to land use change and climate change. In this study, both approaches were applied for the same study catchment (**Q1** and **Q2**) in order to give insight on the effects of land use and climate changes on water availability assessed using different approaches.

The data-based approach only uses observed time series of precipitation, streamflow and calculated potential evapotranspiration. Furthermore, a quantitative measure is developed to use those datasets to attribute changes in streamflow to land use change and climate change based on the changes in the proportion of excess water relative to changes in the proportion of excess energy (**Q1**). The results of the data-based approach will provide general knowledge on the relationship between land use change, climate change and streamflow alteration. To obtain a better understanding of the effects of land use change on the other water balance components such as actual evapotranspiration and the fraction of precipitation becoming surface runoff, lateral flow and base flow, a modelling approach is required (**Q2**). In this study, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) was used to simulate hydrological processes. The SWAT model was calibrated and validated using observed streamflow data and simulated with and without land use change conditions to investigate whether land use change is the main driver for changes in streamflow.

With a good knowledge on the relations between past land use change, climate change and their impacts on hydrological processes in the study catchment,

future water availability of the study catchment can be predicted (**Q3**). The validated SWAT model was run using as inputs simulated future land use distributions following a business-as-usual scenario and a land use planning scenario, and the outputs of climate models for two climate change scenarios namely Representative Concentration Pathway (RCP) 4.5 and 8.5. As a result, the individual and combined impacts of land use change and climate change on water availability including the effectiveness of applied land use planning can be assessed.

While previous research activities focused primarily on assessing the impacts of changes in land use type on water availability, it is interesting to know how changes in the spatial land use configurations may affect streamflow characteristics as well (**Q4**). For this purpose, the validated model was run under different land use scenarios with different spatial pattern characteristics, while the percentages of different land use types were fixed. In this scenario analysis, the land use planning was used as a baseline scenario so that the results can be used to explore potential hydrological impacts of alternative land use planning.

1.5. Thesis outline

Chapter 2 quantifies the relative contribution of land use change and climate change to streamflow alteration in the study catchment based on the relations between precipitation, actual evapotranspiration and potential evapotranspiration. Hydro-climatic data covering the period 1990-2013 and land use data acquired from Landsat satellite imageries for the years 1994 and 2013 were used and analyzed using a method based on the changes in the proportion of excess water relative to changes in the proportion of excess energy. Furthermore, land use change analysis and statistical trend analysis (i.e. the Mann-Kendall trend analysis and Sen's slope estimator) for the mean annual precipitation, potential evapotranspiration and streamflow were carried out to corroborate the attribution results.

Chapter 3 analyses the attribution of changes in the water balance of the study catchment to land use change using the Soil Water Assessment Tool (SWAT) and the baseline-altered method. The simulation period 1990–2013 was divided into four equal periods to represent baseline conditions and altered land use conditions. The past land use evolution from 1994-2013 was acquired from Landsat and Aster satellite imageries and used as inputs in the validated SWAT model with and without land use change to investigate the contribution of land use change to changes in streamflow. Furthermore, causal relationships between land use change and water balance components were investigated.

Chapter 4 analyses potential changes in hydrological processes to expected future changes in land use and climate. Hydrological processes in the future period 2030-2050 were simulated under both land use change and climate change scenarios. Two land use change scenarios, namely a business-as-usual (BAU) scenario, where no measures are taken to control land use change, and a controlled (CON) scenario, where the future land use follows the governmental land use planning, were used in the simulations together with two climate change scenarios, namely Representative Concentration Pathways (RCPs) 4.5 and 8.5. For climate change, the output of a bias-corrected Regional Climate Model and the outputs of six Global Climate Models were used to include climate model uncertainty.

Chapter 5 analyses the impacts of changes in land use pattern characteristics on streamflow characteristics of the study catchment. Changes in fifteen landscape metrics from past land use distributions in the period 1982-2013 were investigated to determine which land use pattern characteristics significantly affected the ratio of surface runoff to streamflow and the ratio of streamflow in the dry season to streamflow in the wet season. Furthermore, a validated SWAT model was applied using inputs from different land use pattern scenarios based on the land use planning to explore potential hydrological impacts of different land use patterns.

Chapter 6 concludes the thesis by summarizing the main findings, providing research limitations and future research directions, and explaining how this thesis contributes to hydrological science.

Chapter 2

Attribution of changes in streamflow to land use change and climate change in a mesoscale tropical catchment in Java, Indonesia¹

Abstract

Changes in the streamflow of the Samin catchment (277.9 km²) in Java, Indonesia, have been attributed to land use change and climate change. Hydro-climatic data covering the period 1990–2013 and land use data acquired from Landsat satellite imageries for the years 1994 and 2013 were analysed. A quantitative measure is developed to attribute streamflow changes to land use and climate changes based on the changes in the proportion of excess water relative to changes in the proportion of excess energy. The results show that 72% of the increase in streamflow might be attributed to land use change. The results are corroborated by a land use change analysis and two statistical trend analyses namely the Mann-Kendall trend analysis and Sen's slope estimator for mean annual discharge, precipitation and potential evapotranspiration. The results of the statistical trend analysis are in the same direction as the results of the attribution analysis, where climate change was relatively minor compared to significant land uses change due to deforestation during the period 1994–2013. This study concludes that changes in streamflow can be mainly attributed to land use change rather than climate change for the study catchment.

¹ This chapter is based on a paper that has been published as: Marhaento, H., Booij, M. J., & Hoekstra, A. Y. (2017). Attribution of changes in streamflow to land use change and climate change in a mesoscale tropical catchment in Java, Indonesia. *Hydrology Research*, 48(4), 1143-1155

2.1. Introduction

Hydrology in tropical regions differs from that in other regions in having greater energy inputs and faster rates of change, including human-induced changes (Wohl et al., 2012). Despite high annual precipitation, water availability is often insufficient for human use in tropical regions because of seasonality, droughts, and increasing water demands resulting from rapid population growth. Bruijnzeel (1990) and Douglas (1999) argue that high rates of deforestation, urbanization and intensive land tillage, which are commonly found in tropical regions, have large impacts on water availability.

Bosch and Hewlett (1982) and Brown et al. (2005) reviewed the results of numerous catchment model experiments (e.g. paired catchment studies) throughout the world, including in the tropics, and found that changes in land use type through deforestation and afforestation can significantly affect the mean annual flow and the variability of annual flow (flow duration and seasonal flow). The annual water yield in tropical regions probably increases with deforestation, with maximum gains in water yield following total clearing (Bruijnzeel, 1990). However, these clear signals of how land use change affects hydrology were mostly found for small catchments. Evidence of land use change effects on water availability in larger catchments ($>100 \text{ km}^2$) in tropical regions is less consistent (Costa et al., 2003; Beck et al., 2013).

Apart from land use changes, climate change is the other main driver that influences water availability in tropical regions. Several studies have argued that climate change (particularly changes in temperature and precipitation) has a larger influence on water availability than land use change (Legesse et al., 2003; Khoi & Suetsugi, 2014; Yan et al., 2015). Blöschl et al. (2007) argue that climate change impacts on water availability vary depending on the spatial scale, due to direct and indirect influences through feedback mechanisms between land use and climate changes. Hejazi & Moglen (2008) found that the combination of land use change and climate change might result in more significant hydrological changes than either driver acting alone.

A major challenge in the study of tropical hydrology is to assess the attribution of changes in water availability to land use and climate changes (Romanowicz & Booij, 2011). A widespread belief exists among hydrologists in tropical countries that land use changes (e.g. deforestation) are the main cause of an increasing number of floods (Andréassian, 2004). Only a quantitative approach that combines the effects of land use and climate change can provide a better understanding of the single effect of land use change. Knowledge on the relative impacts of changes in land use and climate on water availability will be helpful in

estimating the effectiveness of land use management practices at the landscape level.

According to Zhang et al. (2012), there are two ways to distinguish the impacts of land use and climate changes on hydrology: a modelling and a non-modelling approach. The modelling approach has been widely used to measure the relative effects of land use and climate change on hydrology (Li et al., 2009; Khoi & Suetsugi, 2014; Zhan et al., 2013). However, the ability to simulate realistic conditions is accompanied by the need for large amounts of data. Several non-modelling approaches were introduced to assess the contribution of land use and climate changes on hydrology. Wei and Zhang (2010) and Zhang et al. (2012) used the modified double mass curve to exclude the effect of climate change on runoff generation in a deforested area. Tomer and Schilling (2009), Ye et al. (2013) and Renner et al. (2014) used a coupled water-energy budget approach to distinguish relative impacts of land use and climate change on watershed hydrology. A classical non-modelling approach is to employ trend analysis and change detection methods (Rientjes et al., 2011; Zhang et al., 2014).

This study aims to attribute changes in streamflow to land use and climate changes in the Samin catchment in Java, Indonesia. A non-modelling approach is used to achieve the research objective. An adaptation of the Tomer & Schilling (2009) approach is proposed to distinguish the impacts of land use and climate change on streamflow based on the relations between precipitation, actual evapotranspiration and potential evapotranspiration. Subsequently, statistical trend analysis (i.e. the Mann-Kendall trend analysis and Sen's slope estimator) and land use change analysis were carried out to validate the attribution results. The measures used for attribution analysis and the validation of the attribution results by means of statistical analyses and land use change analysis are the novelty of the present study. The study area and data availability are then described, followed by an explanation of the methods used in the study. Subsequent sections then discuss the key findings of the study and finally, conclusions are drawn.

2.2. Study area and data availability

2.2.1. Catchment description

The Samin River is one of the tributaries of the Bengawan Solo River, which plays an important role to support life within its surrounding area. It is located in the western part of Central Java Province, Indonesia. The catchment area of the Samin River extends over 277.9 km² and is located between latitude 7.6⁰–7.7⁰

South and longitude 110.8⁰–111.2⁰ East (see Figure 2.1). The highest part of the catchment is located in the Lawu Mountain with an altitude of 3,175 meter above mean sea level and the lowest part is located near the Bengawan Solo river with an altitude of 84 meter above mean sea level. The average slope in the Samin catchment is 10.2%, and the stream density is around 2.2 km/km². According to the global soil map from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012), two soil classes namely Luvisols and Andosols are dominant in the Samin catchment, which occupy 57% and 43% of the study area, respectively. Luvisols are developed from parent material of accumulated silicate clay and Andosols are developed from parent material of the volcanic Lawu Mountain. Seasons in the Samin catchment are influenced by monsoon winds, where the dry season is influenced by Australian continental wind masses and generally extends from May to October and the wet season is influenced by Asian and Pacific Ocean wind masses and generally extends from November to April.

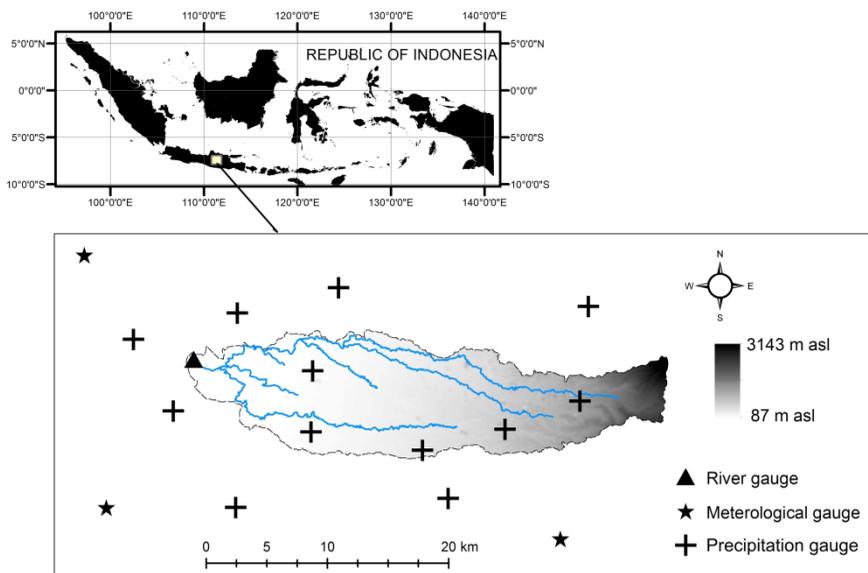


Figure 2.1. Location of the Samin catchment in Java, Indonesia.

2.2.2. Discharge data

The Bengawan Solo River Basin office provided daily water level data of the Samin catchment for the period 1990–2013. The daily discharge data have been

obtained by converting daily water level data to discharge values using the rating curves provided by the Bengawan Solo River Basin office. To test the reliability of the dataset, a quality check has been performed. A data screening process and a visual check of the hydrograph were carried out to identify missing and unrealistic values (outliers). An absolute error was found in the measured water level data where all daily water level data were systematically overestimated in the periods 1995-2008 and 2009-2013 (see Figure 2.2). The data provider confirmed that this error is probably due to a change of the gauge location.

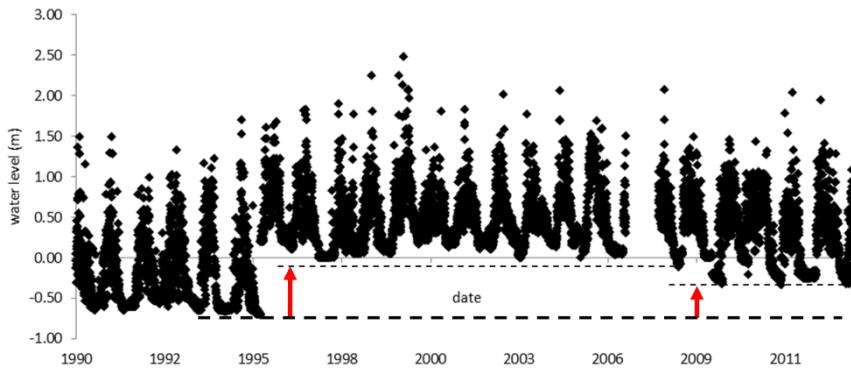


Figure 2.2. Original daily water level data acquired from the data provider. The arrow shows a systematic error (shifting upward) in the water level data. Data for the entire year 2007 are missing.

A correction of the water level was carried out based on the height difference between the lowest water level of both error periods. The annual minimum 7-day average was used to define the lowest value in both periods. Correction values of -0.6 meter and -0.4 meter were found for the daily water level data within the period 1995–2008 and 2009–2013, respectively. Subsequently, the missing discharge data were completed using a non-linear recession model (Wittenberg, 1994). A non-linear recession model was selected after Pearson's test showed low correlation coefficients between the Samin discharge station and adjacent discharge stations (i.e. Keduang and Pidekso stations), which inhibited the use of widely used regional regression models to estimate the discharge. Note that this method was applied to fill-in data of maximum fifteen consecutive days of missing discharge values. Streamflow data that were unavailable for more than fifteen consecutive days were excluded from the analysis. This fill-in procedure concerns less than 5% of the data. The discharge data included missing daily discharge values for the entire year 2007.

2.2.3. Precipitation and Climatological data

Daily precipitation from eleven precipitation stations and meteorological data from three meteorological stations (Adi Sumarmo station, Pabelan station and Jatisrono station) were provided by the Bengawan Solo River Basin Organization for the period 1990–2013. Outliers and missing values of precipitation and meteorological data were identified and corrected. The data were checked for errors related to data processing (e.g. human errors) since most of the precipitation and meteorological data were manually recorded from the gauges. Doubtful precipitation values, such as negative precipitation values, unrealistic values and missing data were corrected using the normal ratio method (Paulhus & Kohler, 1952).

To obtain catchment average precipitation depths, daily precipitation values were averaged using the Thiessen polygon approach with elevation correction (TEC). The TEC method was selected after the results from the TEC approach were compared with three other widely known interpolation methods namely Inverse Distance Weighting (IDW), Ordinary Kriging (OK) and Ordinary Co-kriging (OCK) using 72 randomly selected sample points of mean monthly precipitation. It was found that the Root Mean Square Error (RMSE) of TEC of 67 mm was comparable with the RMSE of IDW (56 mm), OK (69 mm) and OCK (60 mm) and for all methods the $R^2 > 0.8$. Moreover, the TEC method is the simplest method to compute average precipitation values. The elevation correction for the TEC approach is based on a simple linear regression between the mean annual precipitation and elevation of thirteen precipitation stations in the surrounding catchment. This resulted in a correction factor for the Thiessen polygon method of 153 mm increase of annual precipitation per 100 m increase of elevation.

The reference evapotranspiration (ET_0) was calculated in each meteorological stations using the Penman-Monteith method as recommended by the Food and Agricultural Organization (Smith and Allen, 1992). However, the daily meteorological data for Pabelan station and Jatisrono station were only available from 2008 to 2013. To complete the meteorological values in these stations, daily meteorological data from the National Centers for Environmental Prediction Climate Forecast System Reanalysis (Saha et al., 2010) were used. They provide daily climate data at a resolution of $0.25^0 \times 0.25^0$ from 1979 to 2010. Furthermore, daily ET_0 for the study catchment were averaged using the Thiessen polygon approach. An elevation correction for ET_0 was not used since the data availability was not sufficient to determine the correlation between potential evapotranspiration and elevation. However, the elevation gap between the mean elevation of the catchment and the meteorological stations is minor. Figure 2.3 shows the mean annual precipitation, potential evapotranspiration and discharge of the study catchment.

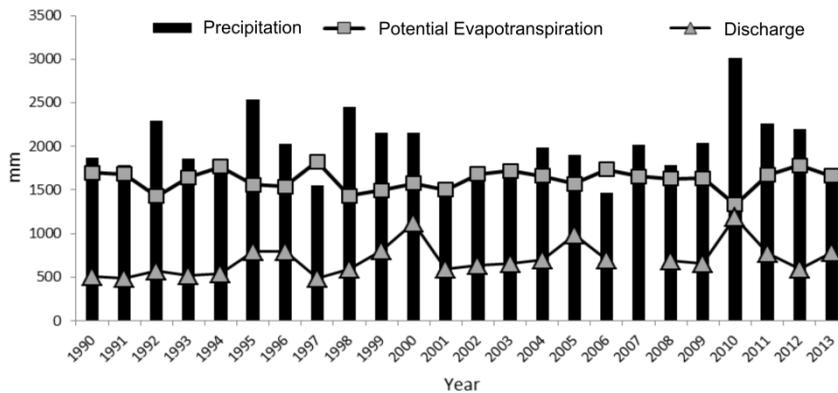


Figure 2.3. Mean annual precipitation, potential evapotranspiration and discharge for the period 1990–2013 in the Samin catchment. The data include a missing discharge value for the year 2007.

2.2.4. Spatial data

Landsat imageries from 1994 and 2013 were available for the study area through the United States Geological Survey archives (USGS, 2016). The data scene (path/row) number is 119/65 and the acquisition dates are September 1, 1994 and October 7, 2013. Both images have cloud cover of less than 5% so are sufficient for further analysis of land use images classification. The catchment boundaries and the stream network of the study area were delineated based on a Digital Elevation Model (DEM) from a contour map with a Contour Interval (CI) of 12.5 meters that was available from the Geospatial Information Agency of Indonesia.

2.3. Methods

2.3.1. Separating effects of land use and climate change on streamflow

This study extends the idea of Tomer and Schilling (2009) who distinguish the impacts of land use and climate change on hydrology using the changes in the proportion of excess water relative to changes in the proportion of excess energy. The amount of excess water within the system (i.e. catchment) can be expressed as precipitation (P) minus actual evapotranspiration (ET) and the amount of excess energy as potential evapotranspiration (ET_0) minus actual evapotranspiration (ET). The amounts of excess water and excess energy

divided by the available water and energy amounts result in dimensionless values P_{ex} and E_{ex} on a scale of 0 to 1, which can be expressed as follows:

$$P_{ex} = 1 - ET/P \quad (\text{eq. 2.1})$$

$$E_{ex} = 1 - ET/ET_0 \quad (\text{eq. 2.2})$$

where P_{ex} is the proportion of excess water, E_{ex} the proportion of excess energy, P the precipitation, ET_0 the potential evapotranspiration and ET the actual evapotranspiration.

The Tomer and Schilling (2009) framework follows two basic assumptions for separating land use and climate change impacts on hydrology based on excess water and energy. First, land use changes will affect ET, which will decrease or increase P_{ex} and E_{ex} simultaneously because ET is in the numerator of both fractions. As a result, P_{ex} and E_{ex} will move creating an angle close to 45° or 225° compared to the x-axis (see Figure 2.4) if there is a change in land use while climate is unchanged (i.e. $\Delta P \sim 0$ and $\Delta ET_0 \sim 0$). A movement creating an angle of 45° indicates a decrease of water and energy consumption (e.g. less ET because of a less vegetated area), while a movement creating an angle of 225° indicates an increase of water and energy consumption (e.g. more ET because of a more densely vegetated area). Second, climate change will affect P and/or ET_0 , which will be reflected by a change in the ratio of P to ET_0 . If the ratio of P to ET_0 increases while ET remains unchanged (i.e. no land use changes), the P_{ex} value will increase and/or the E_{ex} value will decrease, and vice versa, creating a movement along a line with an angle close to 135° or 315° compared to the x-axis (see Figure 2.4). Within the framework, a change in streamflow can be equally attributed to land use change and climate change if movements of P_{ex} and E_{ex} are parallel to the P_{ex} axis or E_{ex} axis. A reference is made to Tomer and Schilling (2009) for a more detailed explanation about the concept.

However, Renner et al. (2014) argue that the Tomer and Schilling (2009) concept cannot be applied to all hydro-climatic conditions and works only for a region where precipitation equals evaporative demand. They proposed an adaptation of the concept by considering the aridity index (ET_0/P) to determine the climatic state of the study catchment. Within their improved concept, a land use change impact on hydrology is defined as a change in ET, but with a constant aridity, and a climate change impact on hydrology is defined as changes in the average supply of water and energy. As a result, a change of P_{ex} and E_{ex} for the same aridity index is considered as a land use change impact and a change of P_{ex} and E_{ex} moving away from a constant aridity index is considered as a climate change impact.

This study extended the framework adapted by Renner et al. (2014) by developing quantitative measures to estimate the land use and climate change impacts on streamflow alteration based on the changes of P_{ex} and E_{ex} . The period of analysis 1990–2013 for which hydro-meteorological time series were available was divided into two periods: a baseline and an altered period, when land use change and climate change might have contributed to streamflow change. The years 1990–1997 and 2006–2013 were regarded as the baseline period and the altered period, respectively, since during the period 1998–2003 significant land use changes have occurred due to deforestation. In 1998, which is considered to be the starting year of the ‘reformation era’, many local communities reclaimed their customary rights inside state forests and converted forest area to other land uses as alternative sources of livelihood after the economic crisis in Indonesia (Resosudarmo et al., 2012). Subsequently, P_{ex} and E_{ex} for the baseline period and altered period, later symbolized as point M_1 (P_{ex1}, E_{ex1}) and M_2 (P_{ex2}, E_{ex2}), were compared and the change of P_{ex} and E_{ex} relative to the long-term aridity index ($\overline{ET_0}/\overline{P}$) of the study catchment (Figure 2.4) were determined.

The magnitude of land use and climate change impacts that causes a shift from point M_1 (P_{ex1}, E_{ex1}) to M_2 (P_{ex2}, E_{ex2}) is estimated based on three measures: (1) the resultant length (R); (2) the angle (θ) of change; and (3) the attribution (in %) to land use change and climate change. The resultant length (R) indicates the magnitude of the changes of excess water and energy where a higher resultant length (R) represents a higher magnitude of changes of excess water and energy. A higher change of excess water and energy then corresponds to a higher rate of land use and climate change impacts on streamflow change. The magnitude of the resultant length (R) from M_1 to M_2 can be calculated based on Pythagoras’ theorem as follows:

$$R = \sqrt{(E_{ex2} - E_{ex1})^2 + (P_{ex2} - P_{ex1})^2} \quad (\text{eq. 2.3})$$

The angle (θ) of change indicates the contribution of land use and climate changes with a higher slope reflecting a higher contribution of climate change. The angle (θ) can be calculated based on the gradient of the vector M_1 - M_2 relative to the gradient of the long term aridity index using the following equations:

$$\tan(\theta) = \frac{\left| \frac{\overline{ET_0}}{\overline{P}} - \frac{P_{ex2} - P_{ex1}}{E_{ex2} - E_{ex1}} \right|}{1 + \left(\frac{\overline{ET_0}}{\overline{P}} \right) * \left(\frac{P_{ex2} - P_{ex1}}{E_{ex2} - E_{ex1}} \right)} \quad (\text{eq. 2.4})$$

$$\theta = \arctan(\theta) \quad (\text{eq. 2.5})$$

The attribution (in %) of streamflow changes to land use change and climate change is measured by determining the length of the changes along the aridity index line and the line perpendicular to the aridity index line, which are denoted as LUC and CC respectively. The lengths of LUC and CC can be calculated as follows:

$$LUC = R * \cos \theta \quad (\text{eq. 2.6})$$

$$CC = R * \sin \theta \quad (\text{eq. 2.7})$$

The relative magnitudes of *LUC* and *CC* are denoted as *L* (%) and *C* (%) and calculated using the following equations.

$$L(\%) = \frac{LUC}{LUC + CC} * 100\% \quad (\text{eq. 2.8})$$

$$C(\%) = \frac{CC}{LUC + CC} * 100\% \quad (\text{eq. 2.9})$$

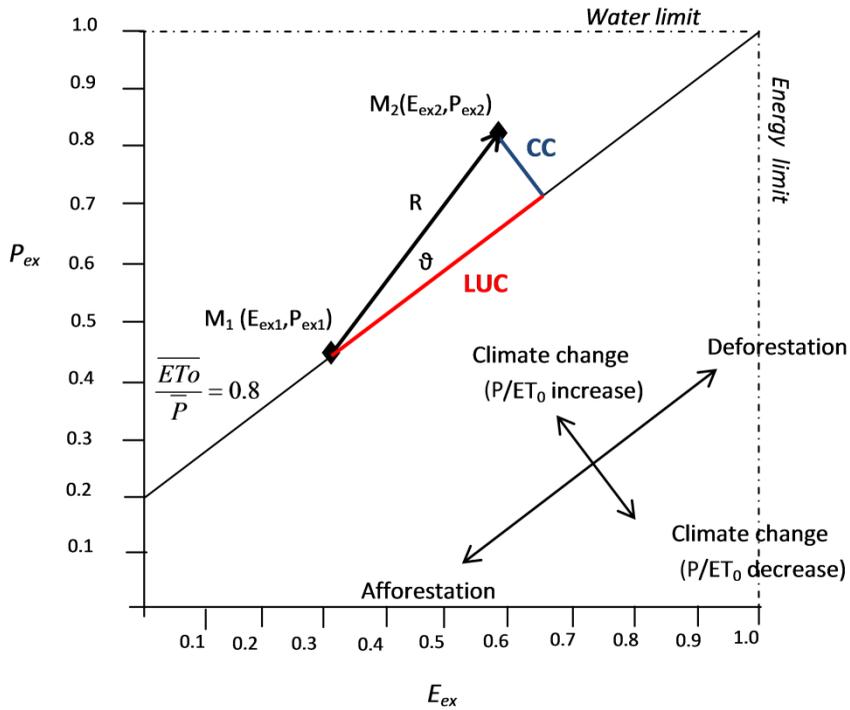


Figure 2.4. Adapted Tomer and Schilling (2009) framework to illustrate how the fractions of excess water and energy respond to land use changes and climate change. The points M_1 and M_2 are the fractions of excess water and energy of the baseline period (P_{ex1}, E_{ex1}) and altered period (P_{ex2}, E_{ex2}). The contribution of land use and climate change to streamflow changes is estimated based on the changes of P_{ex} and E_{ex} relative to the long-term aridity index line ($\overline{ET_0}/\overline{P}$). For example, if the long-term aridity index is 0.8, the change along the constant aridity index line (i.e. LUC line) is attributed to land use change and the line perpendicular to this line (i.e. CC line) is attributed to climate change. The movement direction will determine whether land use change or climate change has a more dominant contribution to changes in streamflow.

2.3.2. Validation of attribution assessment

Two analyses were carried out to validate the results of the attribution analysis: a statistical trend analysis to validate the contribution of climate change to streamflow change and a land use change analysis to validate the contribution of land use change to streamflow change.

2.3.2.1. Trend analysis of climate variables

Trend analysis was performed to check whether the mean annual discharge (Q), precipitation (P) and evapotranspiration (ET_0) have significantly changed over time (long-term). It was hypothesized that if climate change has a larger contribution than land use change to streamflow alteration, the trends in climate variables (P and ET_0) will be in the same direction and have the same magnitude as the streamflow trend. The trend direction and magnitude were determined using the Mann-Kendall test and Sen's slope estimator. The Mann-Kendall test and Sen's slope estimator were selected since they are widely used to detect trends in long-time series of hydrological and climatological data (Rientjes et al., 2011; Zhang et al., 2014).

2.3.2.2. Land use change analysis

Land use change analysis was carried out to measure the rate of land use change in the study catchment, and to validate the contribution of land use change to streamflow changes. It was hypothesized that if land use change has a larger contribution than climate change to streamflow alteration, the type of change in land use will be in line with the attribution results, e.g. deforestation will affect to increase P_{ex} and E_{ex} simultaneously.

Landsat imageries from the years 1994 and 2013 were used to assess land use changes within the study area. These two imageries represent the land use condition of the baseline period (1990–1997) and altered period (2006–2013). Before image processing, a pre-processing analysis had been applied for the selected images including geometric correction to avoid distortion on map coordinates and masking analysis to obscure the area beyond our study area. After the pre-processing analysis was completed, a maximum likelihood algorithm was applied to retrieve the land cover map using a thousand sample points that were generated from an institutional land use map (scale 1:25,000) from the Geospatial Information Agency of Indonesia. The sample points were divided into two parts: half of the sample points were used to perform image classification and another half was used to perform accuracy assessment. An error matrix (Congalton, 1991) was made to calculate the accuracy using four measures: the producer's accuracy, the user's accuracy, the overall accuracy and the Kappa coefficient. The producer's accuracy is to measure how well a certain area can be classified. The user's accuracy is to measure how well labels on a map represent each category on the ground. The overall accuracy is to measure the total number of correct samples divided by the total number of samples. The Kappa coefficient is the coefficient of agreement between the classification map and the reference data. Subsequently, land use change

analysis was performed based on the area differences of each land use class from different years.

2.4. Results

2.4.1. Attribution of changes in streamflow to land use change and climate change

The results for the three measures (see Table 2.1 and Figure 2.5) show a simultaneous increase of P_{ex} and E_{ex} in the study catchment. The increase of P_{ex} and E_{ex} occurred because ET has significantly decreased, which is probably due to deforestation, while P and ET_0 remain relatively unchanged. The aridity index was found to be 0.8 and the movement of P_{ex} and E_{ex} relative to the aridity index line has created an angle of 21° . The angle is less than 45° indicating that climate change (P and ET_0) is minor and has a smaller contribution than land use change on the streamflow alteration. In addition, the change of P_{ex} and E_{ex} is relatively low with a Resultant value (R) of 0.1. The attribution of changes in streamflow to land use change and climate change was estimated to be about 72% and 28%, respectively. Note that the discharge data includes uncertainty during measurements that might influence the attribution results considerably. Using the original discharge data (i.e. before the mean annual discharge has been corrected by a decrease of 60% for the years 1995–2008 and a decrease of 40% for the years 2009–2013 due to a systematic error), the attribution results were found to be 98% and 2% for land use change and climate change contribution, respectively.

Table 2.1. Measures of the attribution of changes in streamflow to land use and climate changes

Period	P	ET_0	Q	ET	P_{ex}	E_{ex}	R	ϑ	L	C
1990 - 1997	1,962	1,644	588	1,374	0.30	0.16				
2006 - 2013	2,072	1,639	771	1,301	0.37	0.20	0.1	21.0	72	28

P = mean annual precipitation (mm), ET_0 = mean annual potential evapotranspiration (mm), Q = mean annual discharge (mm), ET = mean annual evapotranspiration (mm), P_{ex} = excess water divided by available water, E_{ex} = excess energy divided by available energy, R = Resultant length (dimensionless), ϑ = angle of changes (degrees), L = Attribution to land use change (%), C = Attribution to climate change (%)

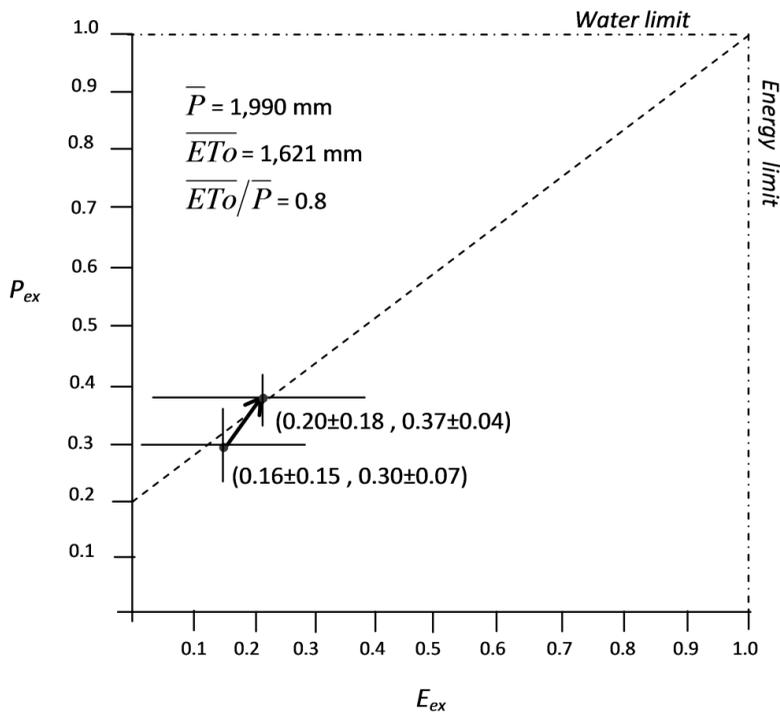


Figure 2.5. Change of excess water (P_{ex}) and excess energy (E_{ex}) relative to long term aridity index line ($\overline{ET_0}/\overline{P}$). The arrow shows the change of P_{ex} and E_{ex} between the baseline period (1990–1997) and the altered period (2006–2013). The natural variations of P_{ex} and E_{ex} for each period are represented by the standard deviation lines.

2.4.2. Trend analysis of climate variables

The trend analysis was carried out for mean annual climate variables (i.e. P and ET_0) and discharge (Q). The results of the Mann-Kendall test and Sen's slope estimator (see Table 2.2) show that the trends in P and ET_0 are not significant while the trend in Q is significant at a significance level of 5%. The trend magnitude determined by Sen's slope for Q (i.e. Sen's slope = 12.1 mm/year) is larger than for ET_0 (i.e. Sen's slope = 1.3 mm/year) and P (i.e. Sen's slope = 2.0 mm/year). In general, the statistical results from the Mann-Kendall trend test and Sen's slope estimator showed that the mean annual precipitation and potential evapotranspiration have not significantly changed while the mean annual discharge has changed significantly. The results are in line with the attribution results, which generally revealed a small contribution of climate change to changes in streamflow.

Table 2.2. Results of statistical trend analysis for mean annual precipitation, mean annual potential evapotranspiration and mean annual discharge for the period 1990-2013

Analysis	Precipitation	ET ₀	Discharge
Mann-Kendall Z-statistic	0.1	0.4	2.7*
p-value	1.0	0.4	0.01*
Sen's slope	2.0	1.3	12.1

An asterisk indicates that trend is significant at 5%

2.4.3. Land use change detection

Following the land use classification from the Geospatial Information Agency of Indonesia, eight dominant land use classes were found in the study area: evergreen forest, mixed garden, settlement, paddy field, dryland farming, shrubs, bare land and water body. Evergreen forest is homogeneous forest area that consists of *Pinus merkusii* tree species. Mixed garden is community forest that consists of multipurpose trees (e.g. fruits, fuel woods, etc.) and often combined with seasonal crops on the same unit of land. Settlement is build-up area and its surroundings. Paddy field is agricultural area that consists of paddy rice fields with an intensive irrigation system. Dry land farming is agricultural area for seasonal crops production. Shrub is abandoned area covered by herbaceous plants. Bare land is rocky abandoned area without vegetation cover. Water body refers to rivers and ponds. By applying an error matrix (Congalton, 1991) using 500 (unit) samples, it was found that the average producer's accuracy is 87.6%, the average user's accuracy is 91.5%, the overall accuracy is 89.3% and the Kappa coefficient is 87.6%. According to Anderson et al. (1976), these accuracy assessment results may represent a strong agreement and high accuracy for producing a land use map.

Land use change analysis was performed based on the area differences for each land use class from different years. Furthermore, the eight land use classes were reclassified into four land use classes to have more general land use classes namely forest area (i.e. combination of evergreen forest and mixed garden), agricultural area (i.e. combination of paddy field and dry land farming), settlements and others (i.e. combination of shrub, bare land and water body) (see Table 2.3). The results show that settlements and agricultural area have increased by 24% and 6%, respectively during the period 1994–2013. These expansions caused large scale deforestation by decreasing the forest area with 32%. Since climate changes have a minor contribution to the streamflow alteration, significant changes in land use (i.e. deforestation) validate the results of the attribution analysis, which revealed a larger contribution of land use

change than climate change to streamflow alteration. Figure 2.6 shows the land use maps for the years 1994 and 2013.

Table 2.3. Land use distribution of the Samin catchment in the year 1994 and 2013 including its change

Land Use Class	1994		2013		Change (%)
	(in hectare)	%	(in hectare)	%	
Forest area	13,542.7	49	4,687.1	17	-32
Agriculture area	10,896.6	39	12,628.6	45	6
Settlements	2,711.6	10	9,531.5	34	24
Others	647.1	2	950.9	4	2
Total	27,798.0	100	27,798.0	100	0

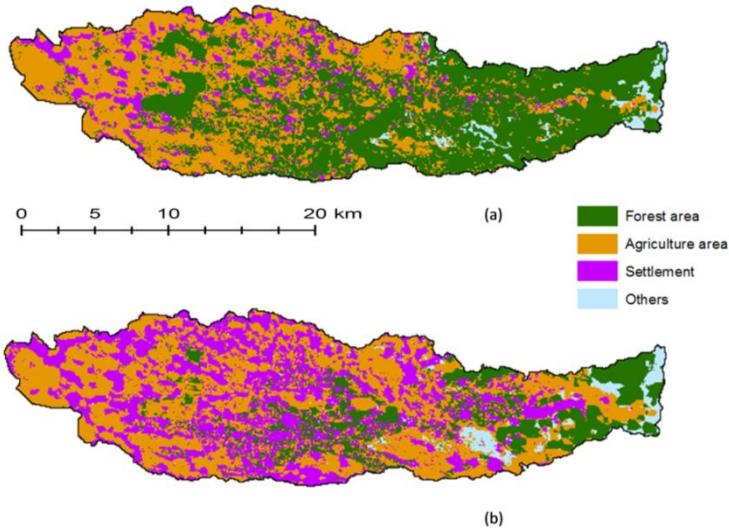


Figure 2.6. Land use maps in the Samin catchment for 1994 (a) and 2013 (b)

2.5. Discussion

Land use changes, which are related to deforestation due to expansion of agriculture areas and settlement areas, were probably the cause of significant changes in streamflow generation. Using the three measures developed in this study, land use change has found to contribute to about 72% of the streamflow alteration in the study catchment. These results are in the same direction as the

results of the statistical trend analysis, where the annual ET_0 and P have not significantly changed (at a significance level of 5%) over the period of analysis. In contrast, the annual Q has significantly changed (at a significance level of 5%) and at the same time, land use has dramatically changed, where a large increase of settlements and agricultural area has decreased the forest area during the period 1990–2013. These findings corroborate the attribution results where changes in streamflow can be largely attributed to land use changes rather than to climate change in the Samin catchment. Numerous studies argue that a continuous decline of tree-areas in catchments may lower the infiltration rate, reduce the groundwater recharge and inhibit water to be stored in the soil (Bosch and Hewlett, 1982; Brown et al., 2005). As a result, a larger volume of precipitation was transformed into surface runoff.

Despite the fact that the impacts of land use change and climate change on streamflow alteration were evident, the magnitude of change in excess water and energy represented by the Resultant (R) length, was relatively low. Besides land use and climate change, the magnitude of change in streamflow seems to be affected by other factors for instance by the catchment size, the slope variation and the soil type. Several studies reported the impacts of land use change on streamflow generation for different catchment sizes (e.g. D'Almeida et al., 2007; Blöschl et al., 2007; Gallo et al., 2015). These studies generally argue that the magnitude of land use change impacts on hydrology became smaller with increasing catchment area. In addition to the catchment size, the slope variation may also influence the impact magnitude. Van Dijk et al. (2007) argue that a larger topographic variation results in shallower soils, less infiltration and therefore generating more runoff. Thus, the impact of land use change on streamflow generation in a catchment with a large topographic variation will be amplified and vice versa. Bruijnzeel (2004) addressed the role of soil conditions on the magnitude of land use change impacts on hydrology in tropical regions. He argues that soil protection measures following deforestation, for instance by applying the Reduce Impact Logging (RIL) technique during land clearing for agriculture or plantations, might decrease the impact magnitude of forest removal in hydrological processes. Nonetheless, underlying natural geology and soil types in a system are important to control catchment hydrological behaviour after land use has changed. A porous soil of volcanic deposits in the study area might have a lower impact magnitude than an area with similar land use change condition having a low porosity and low hydraulic conductivity. However, the influence of these factors (i.e. catchment size, slope variation and soil type) on the resultant value could not be assessed in the present study due to limited data availability in other catchments. More research is needed to test the applicability of the resultant value under different catchment conditions.

The present study proposes a framework to quantitatively assess the attribution of changes in streamflow to land use and climate changes. Although promising results were obtained, two challenges were addressed for further study.

First, the basic conceptual design proposed by Tomer and Schilling (2009) depends on rigorous assumptions, which are not realistic in the real world. The framework uses the assumption that climate change only results in changes in P and ET_0 and land use change only results in changes in ET. In this way, the basic concept neglects the natural complex system where changes in ET are caused by an interaction between climate change and land use change (Budyko, 1974; Wang, 2014; Jiang et al., 2015). Furthermore, the basic concept used the assumption of a linear correlation between the fractions of excess water and energy that is represented by a straight line in a 2-D plot. This simplification differs from the widely known Budyko curve (Budyko, 1974), but is in line with the study of Pike (1964). Renner et al. (2012) argue that the concept of Tomer and Schilling (2009) is not valid for wet catchments (i.e. P is much higher than ET_0) or dry catchments (i.e. P is much lower than ET_0) so that is not applicable in many parts of the world. The basic concept that was originally developed for a temperate climate only works for conditions where precipitation meets evaporative demand (i.e. the middle part of the Budyko curve). Using the aridity index as a correction for the basic concept (Renner et al., 2014), the results have improved but do not reduce the uncertainty inherent in the basic assumption. The proposed approach requires a condition in which changes in the water supply have the same impacts as a change in energy supply, but in opposite directions (i.e. $\Delta P = -\Delta ET_0$). Thus, for conditions where P and ET_0 changes in the same direction (i.e. both decrease or increase), the attribution of changes in streamflow to climate change will interfere with land use change impacts. The results of the present study were found convincing, because the hydro-climatic state of our study catchment met the conditions imposed. Although a sharp attribution is not possible due to the assumptions used, the movements of P_{ex} and E_{ex} compared to the aridity index line can provide a rough indication. A validation through trend analysis of climate variables (i.e. P and ET_0) and land use change analysis as applied in this study appears to be useful to verify the attribution results. The proposed method needs more practical applications across various climatic regions to make the approach more reliable and robust.

Second, this study agrees with Tomer and Schilling (2009), Ye et al. (2013) and Renner et al. (2014) that the basic concepts of excess water and energy are sensitive to the data quality, particularly for precipitation, potential evapotranspiration and streamflow data. Reliable time series of hydrological data are rarely found in developing countries, including Indonesia (Douglas, 1999). However, performing data checks for errors and making data corrections using

well-established methodologies (as demonstrated in this study) can be useful to arrive at more reliable datasets. Moreover, data analysis in this study was carried out over a long time period and on an annual basis, which may reduce random errors. More convincing results, however, are expected if hydrological datasets are available for a long time period and data gauges are well distributed over the area of interest.

2.6. Conclusions

A quantitative assessment of land use and climate change contribution to streamflow alteration has been carried out using measures described in this paper. The results show that changes in streamflow of the Samin catchment during the period 1990–2013 can be attributed to land use change for 72% and climate change for 28%. The results were corroborated by the results of statistical trend analyses (Mann-Kendall trend analysis and Sen's slope estimator), and land use change analysis. The results of the statistical trend analyses show that the climate (i.e. mean annual P and ET_0) has not significantly changed while the mean annual discharge has significantly changed at a confidence level of 5%. At the same time, land use has significantly changed due to deforestation where the forest area has decreased by 32% mostly due to an increase of settlements and agricultural area of 24% and 6%, respectively. Our results are in line with the results from other tropical hydrological studies on the contribution of land use and climate change to streamflow alteration ranging from small-scale experiments (Bosch and Hewlett, 1982; Bruijnzeel, 1990; Brown et al., 2005) to large-scale modelling studies (Thanapakpawin et al., 2007; Alansi et al., 2009).

Chapter 3

Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model²

Abstract

Changes in the water balance of the Samin catchment (277.9 km²) on Java, Indonesia, can be attributed to land use change using the Soil Water Assessment Tool model. A baseline-altered method was used in which the simulation period 1990–2013 was divided into 4 equal periods to represent baseline conditions (1990–1995) and altered land use conditions (1996–2001, 2002–2007, and 2008–2013). Land use maps for 1994, 2000, 2006, and 2013 were acquired from satellite images. A Soil Water Assessment Tool model was calibrated for the baseline period and applied to the altered periods with and without land use change. Incorporating land use change resulted in a Nash–Sutcliffe efficiency of 0.7 compared to 0.6 when land use change is ignored. In addition, the model performance for simulations without land use change gradually decreased with time. Land use change appeared to be the important driver for changes in the water balance. The main land use changes during 1994–2013 are a decrease in forest area from 48.7% to 16.9%, an increase in agriculture area from 39.2% to 45.4%, and an increase in settlement area from 9.8% to 34.3%. For the catchment, this resulted in an increase of the ratio of streamflow to precipitation from 35.7% to 44.6% and a decrease in the ratio of evapotranspiration to precipitation from 60% to 54.8%. More pronounced changes can be observed for the ratio of surface runoff to streamflow (increase from 26.6% to 37.5%) and the ratio of base flow to streamflow (decrease from 40% to 31.1%), whereas changes in the ratio of lateral flow to streamflow were minor (decrease from 33.4% to 31.4%). At sub-catchment level, the effect of land use changes on the water balance varied in different sub-catchments depending on the scale of changes in forest and settlement area.

² This chapter is based on a paper that has been published as: Marhaento, H., Booij, M. J., Rientjes, T. H. M., & Hoekstra, A. Y. (2017). Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model. *Hydrological Processes*, 31(11), 2029-2040.

3.1. Introduction

Attributing changes in streamflow to land use and climate change has been of interest for decades. Numerous studies have been carried out throughout the world focusing on the relationship between changes in streamflow and changes in land use and climate. Zhang et al. (2012) distinguishes two approaches to attribute changes in streamflow to land use change: a modelling and non-modelling approach. The latter is often carried out based on paired catchment studies (Bosch and Hewlett, 1982; Brown et al., 2005) or long-term hydrological data analyses (Rientjes et al., 2011; Zhang et al., 2014; Marhaento et al., 2017b). The modelling approach can be based on a single model (Niehoff et al., 2002; Rodriguez Suarez et al., 2014) or multiple models (ensemble modeling) (Huisman et al., 2009). Surprisingly, very few studies investigated hydrological behavior under changing conditions in tropical regions (Douglas, 1999; Wohl et al., 2012). The impact of land use change and climate change on streamflow can be significant for tropical regions having greater energy inputs and faster rates of change, including human-induced changes (Wohl et al., 2012).

In the 1990s, Indonesia was among countries having the largest land use changes in terms of forest lost in the world, behind Brazil (Hansen et al., 2009). A high demand of land resources to accelerate the economic development and meet local needs for food and settlements resulted in land use changes at different scales. Several hydrological studies have been carried out in Indonesia to investigate the impacts of land use change on water resources (Valentin et al., 2008; Remondi et al., 2015), showing that deforestation and urbanization were the two land use changes mostly reported to affect streamflow. Deforestation and urbanization caused increases in peak flows enhancing the flood risk during the wet season and decreases in base flow in the dry season following the loss of forest area (Bruijnzeel, 2004).

Douglas (1999) argues that most of the hydrological studies in tropical regions, including Indonesia, focus on the impacts of land use change on streamflow (e.g. seasonal flow and annual flow) and sediment yield based on small-scale plot measurements. In addition, land use change can also affect other water balance components such as evapotranspiration, soil water content and groundwater recharge. Yet, only few studies have attempted to assess the attribution of changes in the water balance to land use change in tropical regions. Moreover, some of the results are contradictory and inconsistent, in particular for large catchments (>100 km²; Calder et al., 2001; Beck et al., 2013).

In order to assess the impacts of land use change on the water balance, a modelling approach is typically used. Models can be used to assess impacts of historic as well as future land use changes on hydrological conditions

(Thanapakpawin et al., 2007; Huisman et al., 2009). A wide range of models has been used to simulate land use change impacts on the water balance, e.g. SWAT (Arnold et al., 1998), MIKE-SHE (Refsgaard and Storm, 1995), or DHSVM (Wigmosta et al., 1994). However, the contribution of land use change to changes in the catchment water balance is still not fully understood due to climatic interferences (Wang, 2014), requiring further study. A challenge is to attribute changes in the water balance to land use change under varying climatic conditions (Romanowicz and Booij, 2011).

Against this background, the goal of this study is to attribute changes in the water balance of a tropical catchment in Indonesia to land use change using a modelling approach. First, changes in streamflow of the Samin catchment in Java, Indonesia are attributed to land use change for the time period 1990–2013, using the semi-distributed physically based SWAT model (Soil and Water Assessment Tool) (Arnold et al., 1998) and a baseline-altered method. Second, causal relationships between land use change and water balance alteration in the study catchment are assessed. A diagnostic approach is followed using two widely used statistical analyses, namely Mann-Kendall trend analysis and Pearson's test, to investigate whether the water balance has statistically changed over the study period due to land use change. This study considers the water balance in terms of five water balance ratios: the ratio of streamflow to precipitation (the runoff coefficient, Q/P), the ratio of evapotranspiration to precipitation (ET/P), the ratio of surface runoff to streamflow (Q_s/Q), the ratio of lateral flow to streamflow (Q_l/Q) and the ratio of base flow to streamflow (Q_b/Q).

The use of attribution analysis to test whether land use change is the main driver for changes in streamflow prior to assess the impact of land use change on the overall water balance is proposed. In addition, a diagnostic approach may provide insight on the relationship between land use change and water balance alteration that is rarely investigated in tropical regions. This study complements the study of Marhaento et al. (2017b) who conducted attribution analysis of changes in streamflow to land use and climate change using a non-modelling approach for the same catchment.

The structure of the paper is as follows. Section 3.2 presents a description of the study area and the data availability. Section 3.3 describes the methods used and Sections 3.4 and 3.5 give the results and discussion of the key findings. Finally, conclusions are addressed in Section 3.6.

3.2. Study area and data

3.2.1. Catchment description

The Samin River, with a total length of about 53 km, is of the Bengawan Solo River, which plays an important role to support life within its surrounding area. The catchment area of the Samin River extends over 277.9 km² and ranges between southern latitude 7.6⁰–7.7⁰ and eastern longitude 110.8⁰–111.2⁰ (see Figure 3.1). The main economic activity in this catchment is agriculture, which is supported by the water availability within the catchment. The highest part of the catchment is the Lawu Mountain, with an altitude of 3,175 meter above mean sea level and the lowest part is near the Bengawan Solo river in Sukoharjo district, with an altitude of 84 meter above mean sea level. The average slope in the Samin catchment is 10.2% where higher slopes are mostly in the upstream part near the foothill of the Lawu Mountain. The stream density is around 2.2 km/km² and streams form a parallel drainage pattern, where the tributaries tend to stretch out from east to west following the surface slope. According to the soil map from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012), two soil classes, namely Luvisols and Andosols, are dominant in the Samin catchment, which cover 57% and 43% of the study area, respectively. Luvisols are developed from parent material of accumulated silicate clay that is dominant in the midstream to downstream area. These soils are characteristic for the forested area where a leafy humus horizon can be found at the top of the soil layers. Andosols are developed from parent material of the volcanic Lawu Mountain and are mainly dominant in the upstream area. These soils are typically highly porous and fertile due to volcanic deposits from the Lawu Mountain.

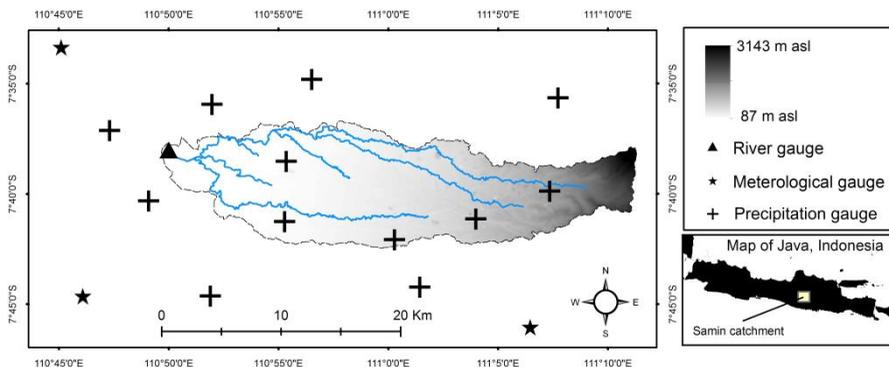


Figure 3.1. Samin catchment in Java, Indonesia, with the locations of hydrological gauges

3.2.2. Hydro-climatic conditions

The climate of the Samin catchment is tropical monsoon with distinct dry and wet seasons. The dry season is influenced by Australian continental masses and generally extends from May to October whereas the wet season is influenced by Asian and Pacific Ocean wind masses and generally extends from November to April. The spatial precipitation pattern likely follows the orography, with a larger amount of precipitation in the upstream area than in the downstream area. Based on a simple linear regression between the mean annual precipitation and elevation of thirteen precipitation stations in the surrounding catchment, it was found that the mean annual precipitation increases about 150 mm per 100 m increase of elevation. This is comparable with the finding of Subarna et al. (2014) who estimated an increase in the mean annual precipitation of about 140 mm per 100 m increase of elevation for the Cisangkuy catchment in West Java, Indonesia. The mean daily temperature is approximately 26 °C with a mean daily minimum of about 21.5 °C and a mean daily maximum of about 30.5 °C. The daylight length is approximately 13 hours with a small difference between the wet and dry seasons resulting in a mean daily solar radiation of about 17 MJ/m². During the period 1990–2013, the annual precipitation, potential evapotranspiration and streamflow of the Samin catchment ranged from 1,500 mm – 3,000 mm, 1,400 mm – 1,700 mm and 500 mm – 1,200 mm, respectively where a high Q/P (i.e. >0.5) was found for the years 2000 and 2005 (see Figure 3.2). The trend analysis of the mean annual precipitation, potential evapotranspiration and streamflow showed an increase of approximately 48 mm, 31.2 mm and 290 mm, respectively (Marhaento et al., 2017b). Whereas long-term changes in the mean annual precipitation and potential evapotranspiration were statistically not significant, changes in the mean annual streamflow were significant at a significance level of 5%. Figure 3.2 shows the mean annual precipitation, potential evapotranspiration, and streamflow of the Samin catchment for the period 1990-2013.

3.2.3. Data collection

The SWAT model requires a Digital Elevation Model (DEM), land use data, soil data and climate data as model inputs. The DEM data were generated from a contour map with a contour interval of 12.5 meters, which was made available by the Indonesia Geospatial Information Agency. Land use information was available for a 30 m resolution for the years 1994 and 2013 from Marhaento et al. (2017b).

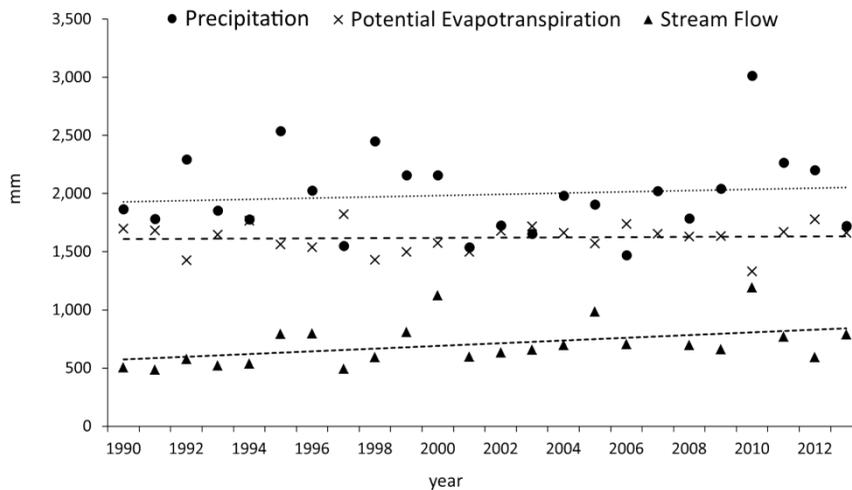


Figure 3.2. Mean annual precipitation, potential evapotranspiration, and streamflow for the period 1990–2013 in the Samin catchment (after Marhaento et al, 2017b)

Two additional land cover images were acquired from the Landsat satellite (USGS, 2016) for September 9, 2000 and Aster images (ERSDAC, 2016) for November 9, 2006 to represent land use for the years 2000 and 2006. Soil data were taken from the Harmonized World Soil Database (FAO et al., 2012). The soil characteristics required as SWAT input that were not available in the global soil map (i.e. available water content, saturated hydraulic conductivity and bulk density), were obtained from the Soil-Plant-Atmosphere-Water (SPAW) model (Saxton & Willey, 2005).

The SPAW model uses pedotransfer functions including information on soil texture, soil salinity, organic matter, gravel and soil compaction to determine water retention characteristics. The model has been developed based on an extensive number of laboratory datasets of soil characteristics from the USDA/NRCS National Soil Characterization database and has been validated using thousands of sample subsets (Saxton & Willey, 2005). Even though the SPAW model has been developed in the United States, the application of the SPAW model is worldwide and often performed with a model calibration (Botula et al., 2014).

For model calibration, daily streamflow data were used. The Bengawan Solo River Basin office provided daily water level data in the Samin catchment for the period 1990–2013. The daily discharge data have been obtained by converting the daily water level data to discharge values using the rating curves provided by

the Bengawan Solo River Basin office. It was assumed that the available rating curve is sufficient to represent the river flows (i.e. high flows and low flows) considering the limited information on how the rating curve has been checked and updated by the data provider. This study used the same discharge and climate data as Marhaento et al. (2017b) who have corrected erroneous water level data due to shifts in gauge location and corrected precipitation data based on the relationship between precipitation and elevation. In addition, the missing discharge data were completed using a non-linear recession model (Wittenberg, 1994) that was applied to fill-in data of maximum fifteen consecutive days of missing discharge values. Streamflow data that were unavailable for more than fifteen consecutive days were excluded from the analysis. This fill-in procedure concerns less than 5% of the data. For the missing climate data, a normal ratio method based on values from surrounding stations was used.

3.3. Methods

3.3.1. Land use changes

Because land use information for the years 1994 and 2013 is available from Marhaento et al. (2017b), additional satellite image analysis was carried out for Landsat and Aster images for the years 2000 and 2006. These images were completed by pre-processing analysis through a non-systematic geometric correction to avoid distortion on map coordinates and masking analysis to remove the area beyond the study area. The Aster image resolution was resampled from $15 \times 15 \text{ m}^2$ grid-size to $30 \times 30 \text{ m}^2$ grid-size to be similar to the grid size of Landsat images. A maximum likelihood approach was used to perform image classification using thousand ground-control points (GCPs; see Marhaento et al., 2017b), and then a confusion matrix was made to measure classification accuracy. The GCPs were divided into two sets: half of the GCPs were used to perform image classification and half of them were used to perform accuracy assessments by means of the overall accuracy and the Kappa coefficient. The overall accuracy is defined as the number of correct samples divided by the total number of samples. The Kappa coefficient measures the agreement between the classification map and the reference data. Land use change analysis was performed based on differences in areal coverage of each land use class between different years.

3.3.2. SWAT model set up and calibration

3.3.2.1. Water balance estimation

This study used the water quantity module of the SWAT model, a physically based semi-distributed model operating on a daily time step with proven suitability for hydrologic impact studies around the world (Wagner et al., 2013; Memarian et al., 2014). The SWAT model divides a catchment into sub-catchments and then further divides each sub-catchment into hydrological response units (HRUs) for which a land-phase water balance is calculated (Neitsch et al., 2011). A HRU is defined as a lumped area within a catchment assumed to have uniform behavior and is characterized by a dominant land use type, soil type and slope conditions (Arnold et al., 1998). For each simulation time step (daily in this study), a water balance is computed for each HRU and for each sub-catchment. Runoff is routed through channels to the catchment outlet and used to calculate the catchment water balance.

This study focused on the land-phase water balance where land use change has its main impact. The components of the land-phase water balance in the SWAT model include inflows, outflows and variations in storages. Precipitation (P) is the main inflow in the model. The outflows are actual evapotranspiration (ET), surface runoff (Q_s), lateral flow (Q_l) and base flow (Q_b). There are four water storage possibilities in SWAT namely snowpack, soil moisture (SM), shallow aquifer (SA) and deep aquifer (DA). The snowpack storage was excluded in the analysis because snowfall is not relevant in the study area. Flows between storages are percolation from the soil moisture storage to the shallow aquifer storage (Perc), water movement upward from the shallow aquifer to the soil moisture storage (Revap) and deep aquifer recharge (DA_Rchg). Figure 3.3 shows the SWAT model schematization used in this study. For a more detailed description of the SWAT model, reference is made to Neitsch et al. (2011).

3.3.2.2. Model setup

The DEM was used to delineate boundaries of the catchment and was used to divide the catchment into sub-catchments. A stream network from the Indonesia Geospatial Information Agency was used to “burn-in” the stream network to create accurate flow routing and to delineate sub-catchments. This procedure resulted in 11 sub-catchments, ranging in size from 0.12 km² to 83 km². In addition, the DEM was used to generate a slope map based on the slope classification from the Guideline of Land Rehabilitation from the Ministry of Forestry (1987).

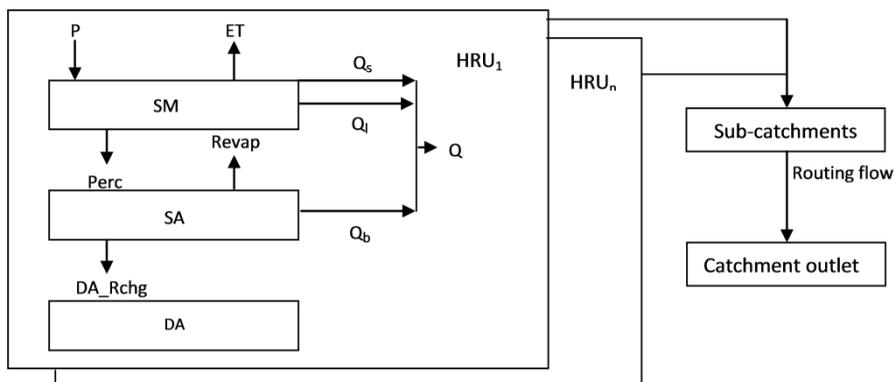


Figure 3.3. The Soil Water Assessment Tool model structure. DA = deep aquifer; ET = evapotranspiration; HRU = hydrological response unit; Q_b = base flow; Q_l = lateral flow; Q_s = surface runoff; SA = shallow aquifer; SM = soil moisture

Land use codes from the SWAT database, namely AGRR, FRSE, FRST, RICE, URMD and LBL5, were assigned to denote dryland farming, evergreen forest, mixed garden, paddy field, settlement and shrub, respectively. For the settlement, this study used the assumption that the settlement area is not fully impervious providing some pervious spaces in between the houses that are often used for house yards. Thus, the class Urban Residential Medium Density (URMD) in the SWAT model was used to assign parameters in the settlement area. URMD assumes an average of 38% impervious area in the settlement area (Neitsch et al., 2011), which is relatively similar to the settlement conditions in the study catchment. In addition, as a typical rural area in Java, the artificial drainage network in the study area is not well developed. Thus, the impacts of the artificial drainage network of the settlements on the long-term water balance of the system are assumed to be not significant. Furthermore, the SWAT crop and management database were modified for each land use type in order to match the conditions in a tropical region. It should be noted that SWAT is designed for temperate regions so that it is necessary to modify the crop parameters for application in a tropical region (Kilonzo, 2013; Griensven et al. 2014). Table 3.1 shows the adjusted values in the SWAT crop and management database applied in this study. Forest includes evergreen forest and mixed garden, whereas agriculture includes paddy field and dry-land farming.

HRUs were created by spatially overlying maps of land use, soil and slope classes. The Penman-Monteith method was used to calculate reference evapotranspiration. For runoff simulations, the Soil Conservation Service Curve Number (SCS-CN) method was selected because it has a direct link to land use types. In addition, the CN values were adjusted for slope effects based on the

equation from William (1995), since the default CN value in the SWAT model is only suitable for a slope up to 5%, which is not appropriate for the study catchment. For flow routing, the Muskingum method that models the storage volume as a combination of wedge and prism storage (Neitsch et al., 2011) was used.

Table 3.1. Adjusted values in the SWAT crop and management database (adapted from Kilonzo, 2013).

Variable	Land use/land cover class					
	Forest		Shrub		Agriculture	
	Original	Adjusted	Original	Adjusted	Original	Adjusted
LAI_INIT (-)	0	5	0	3	0	3
BIO_INIT (kg/ha)	0	1,000 ^a	0	0	0	0
PHU_LT (-)	0	3,500 ^a	0	3,500 ^a	0	3,500 ^a
GSI (mm/s)	2	7	5	5	7	7
CANMX (mm)	0	5	0	2	0	2

Note. Definitions for each variable are available in Neitsch et al. (2011). ^aThe maximum value allowed in SWAT. (-) means no units

3.3.2.3. Model calibration

Model calibration aims to produce a robust SWAT model that is able to simulate land use change impacts on the water balance. Identification of SWAT parameters to be calibrated was based on the procedure from Abbaspour et al. (2015). Within the procedure, the SWAT model was executed using the default SWAT parameters. The simulated hydrograph was visually compared with the observed hydrograph. Based on the characteristics of the differences between observed and simulated hydrograph (e.g. underestimation/overestimation discharge and shifted discharge), relevant SWAT parameters were identified. Furthermore, one at a time sensitivity analysis was carried out to detect the most sensitive parameters among the relevant parameters.

The model was calibrated using the Latin Hypercube Sampling approach from the Sequential Uncertainty Fitting version 2 (SUFI-2) in the SWAT-Calibration and Uncertainty Procedure (SWAT-CUP) package. First parameter ranges were determined based on minimum and maximum values allowed in SWAT. A number of iterations were performed where each iteration consisted of 1,000 simulations with narrowed parameter ranges in subsequent calibration rounds. The new parameter ranges were determined based on the lowest and highest parameter value of the 10% best parameter sets according to the objective

function value. The calibration process was stopped and the optimum parameter values were obtained after the objective function value showed insignificant changes (smaller than 0.01). Simulations for model calibration were assessed on a monthly basis and the Nash Sutcliffe Efficiency (NSE) (Eq.3.1) was used as the objective function.

$$NSE = 1 - \frac{\sum_{i=1}^{i=N} [Qs(i) - Qo(i)]^2}{\sum_{i=1}^{i=N} [Qo(i) - \overline{Qo}]^2} \quad (\text{Eq. 3.1})$$

where i is the time step, N the total number of time steps, Qs the simulated discharge, Qo the observed discharge and \overline{Qo} the mean of Qo over the period of analysis.

3.3.3. SWAT simulations

The SWAT simulations were carried out in two steps. The first step included simulations to attribute changes in streamflow to land use change. These simulations aimed to investigate whether land use change is the main driver for changes in streamflow. This study used a baseline-altered approach, which divides the dataset into four sequential periods: the first period is regarded as the baseline period, and other periods are regarded as altered periods, periods when the hydrological regime within a catchment is expected to be changed due to land use changes. The method assumes that by calibrating a model in the baseline period and applying the calibrated model in the altered periods using updated land use maps will enable the simulation of impacts of land use change on streamflow (Li et al., 2009 and Wagner et al., 2013).

In the present study, the simulation period (1990–2013) was divided into four equal periods to accommodate gradual changes in land use in the study catchment. The first period (1990–1995) was regarded as the baseline period and the other periods (1996–2001, 2002–2007 and 2008–2013) were regarded as altered periods. The four land use maps available for the years 1994, 2000, 2006 and 2013 represent the land use conditions for each period. The calibrated SWAT model was run for the baseline period (1990–1995) using land use of the year 1994 and then was applied for the altered periods. This study carried out two simulations for the altered periods i.e. with land use change (using land use maps of 2000, 2006 and 2013) and without land use change in order to investigate the attribution of changes in streamflow to land use change. This

study followed the method from Refsgaard et al. (1989) and Lørup et al. (1998), which used model performances as an indicator of land use change impacts. Land use change is regarded as the important driver to changes in streamflow when model simulations with land use changes show a better model performance than simulations without land use change. Updating land use cover in the simulations will adapt the HRU information in the simulation and thus affect streamflow simulation. Figure 3.4 shows the hypothetical scenario of the simulations. It should be noted that the changes in the model performance values are not necessarily linearly related to changes in land use as suggested by the straight lines in the diagram. To incorporate land use change in the simulations, the Land Use Update (LUP) tool in ArcSWAT was used.

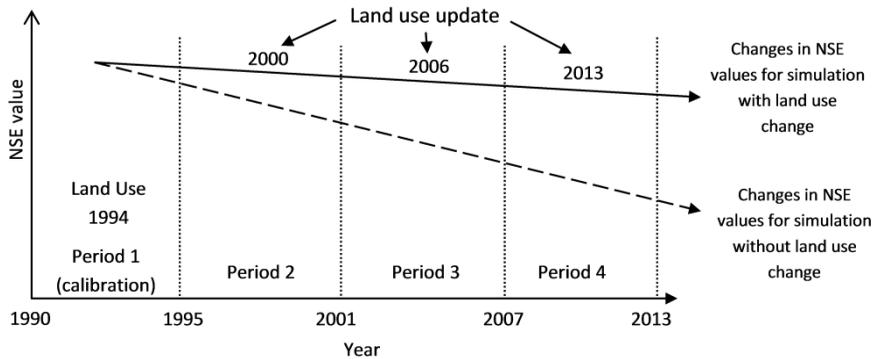


Figure 3.4. A hypothetical scenario for the model simulations to test the hypothesis regarding the effects of land use changes on the model performance. NSE = Nash–Sutcliffe efficiency

The first step of the simulations shows the land use change contribution to changes in streamflow. As a second step in the study, the changes in the mean annual water balance as a result of land uses change were assessed at both catchment level and sub-catchment level. This study focused on five water balance ratios, namely the ratio of streamflow to precipitation (the runoff coefficient, Q/P), the ratio of evapotranspiration to precipitation (ET/P), the ratio of surface runoff to streamflow (Q_s/Q), the ratio of lateral flow to streamflow (Q_l/Q) and the ratio of base flow to streamflow (Q_b/Q). A diagnostic approach using statistical analyses (Mann-Kendal statistic and Pearson statistic) was carried out to test the statistical significance of the long-term trends in the mean annual water balance ratios and to investigate the correlation between changes in the water balance and land use change.

3.4. Results

3.4.1. Land use change analysis

Table 3.2 shows the relative areas of each land use class for the years 1990, 2000, 2006 and 2013. In general, there was an increasing human influence in the Samin catchment through the development of settlements and agriculture area (i.e. paddy field and dryland farm). Figure 3.5 shows that in the period 1994–2000, agriculture area was converted to settlements in the downstream area and evergreen forest area was converted to mixed garden in the upstream area. However, these changes do not significantly reduce the tree-dominated area because the conversion of evergreen forest into mixed garden area basically is a change from a state forest into a community forest. A dramatic change has occurred in the period 2000–2006 when agriculture land was converted to mixed garden area in the upstream area that resulted in a major decrease of tree-covered area in the Samin catchment. At the same time, the settlement area significantly increased in the downstream area converting agricultural area into impervious area. In the period 2006–2013, the development of settlement areas expanded in the upstream part of the catchment at the expense of mixed garden area resulting in major deforestation. In total, during the period 1994–2013, deforestation by decreasing evergreen forest area and mixed garden area was about 30%. At the same time, settlements and agricultural area have increased by 25% and 6%, respectively. It should be noted that the average overall accuracy and Kappa coefficient of land use maps used for this study were 89% and 87%, respectively, which is sufficient for producing a land use map (Congalton, 1991). Detailed descriptions of each land use class are available in Marhaento et al. (2017b).

Table 3.2. Area percentage (%) of each land use class in the year 1994, 2000, 2006 and 2013

Land use class	1994	2000	2006	2013
1. Forest area	48.7	42.2	26.0	16.9
a. Evergreen forest	16.1	3.0	2.4	2.3
b. Mixed garden	32.6	39.2	23.6	14.6
2. Agriculture area	39.2	36.9	44.3	45.4
a. Paddy field	30.2	28.2	28.9	28.0
b. Dryland farm	9.0	8.7	15.4	17.4
3. Settlements	9.8	16.3	25.6	34.3
4. Shrub	2.0	4.3	3.8	3.1
5. Water body	0.3	0.3	0.3	0.3

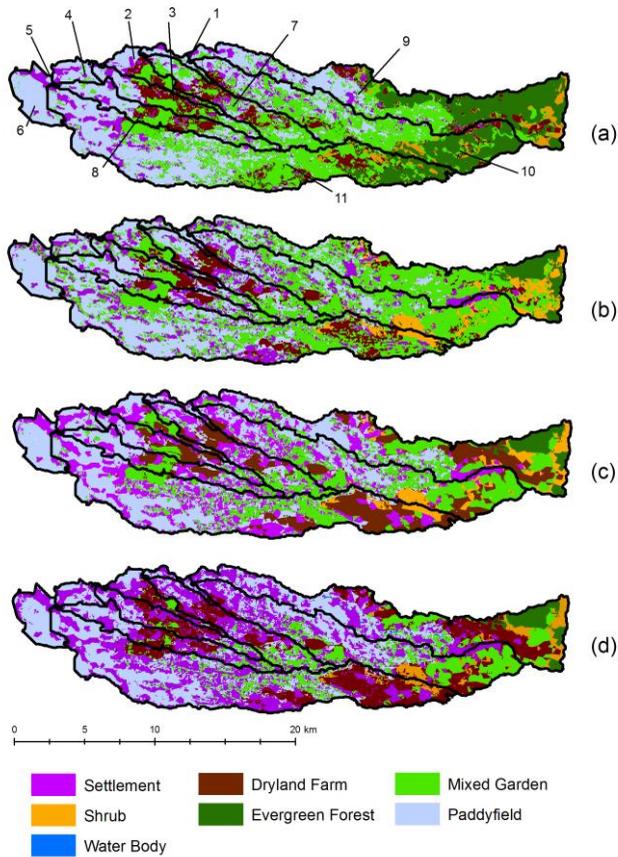


Figure 3.5. Land use distribution in the Samin catchment in the years 1994 (a), 2000 (b), 2006 (c) and 2013 (d). Numbers in Figure 3.5a show the sub-catchment identity number.

3.4.2. Model calibration and simulations

3.4.2.1. Model calibration

Six SWAT parameters were calibrated, namely CN2, SOL_AWC, ESCO, CANMX, GW_DELAY and GW_REVAP. CN2 is the curve number parameter, which controls the fraction of water to infiltrate into the soil or to generate surface runoff by overland flow. A large CN value causes less infiltration and results in more surface runoff. SOL_AWC is the available water capacity of the soil layer. It controls the soil water storage between soil moisture conditions at field capacity and permanent wilting point. GW_DELAY is the ground water delay time. It controls the lag time between water leaving the soil layers and entering the shallow aquifer. A larger GW_DELAY will enable more evaporation from the

unsaturated zone. GW_REVAP is the ground water revap coefficient, a SWAT term to describe the movement of water into overlying unsaturated layers as a function of water demand for evapotranspiration. The GW_REVAP parameter controls the amount of water in the capillary fringe that separates the unsaturated zone and the saturated zone to move upward (to fulfill evaporative demand). A larger GW_REVAP value results in a larger transfer rate from the shallow aquifer to the unsaturated zone. ESCO is the soil evaporation compensation factor and controls the soil evaporative demand that is to be met. When the value of ESCO gets closer to zero, the model will receive more water from the lower soil level to fulfil evaporative demand. CANMX is the maximum canopy storage to intercept precipitation. It controls the density of plant cover so that it significantly affects infiltration and evapotranspiration. A larger CANMAX results in a larger plant canopy capacity. CANMX was calibrated only for forested areas (i.e., FRSE and FRST).

These parameters were calibrated in different ways. For parameters CN2 and SOL_AWC, a scaling value at the HRU level was calibrated so that the default parameter value was multiplied by (1+ calibrated scaling value). In this way, the default parameters will not lose their original spatial patterns. For parameters GW_DELAY, GW_REVAP, ESCO and CANMX, parameter values were calibrated at the catchment level so that the calibrated parameter values are homogeneous over the entire catchment. After three rounds of calibration, this study found optimum calibrated parameter values with a NSE value of 0.78 (see Figure 3.6). Table 3.3 shows the calibrated values used in this study.

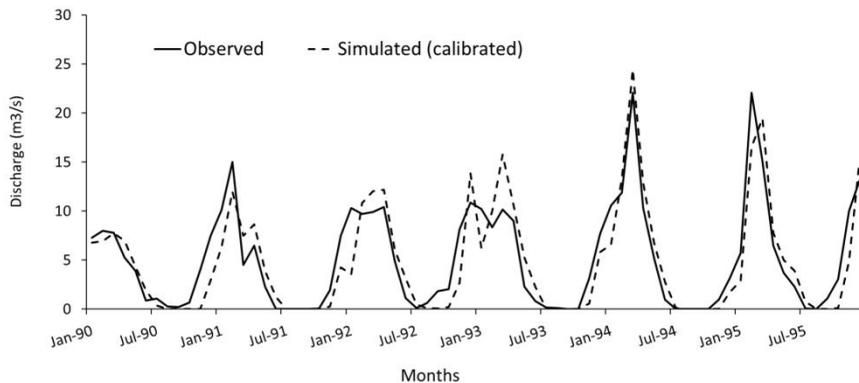


Figure 3.6. Hydrograph of simulation with calibrated parameter values for the baseline period

Table 3.3. Values of calibrated Soil Water Assessment Tool parameters

Parameters	Units	Prior range	Default value	Calibrated values
CN2	-	-0.3 – 0	0	- 0.1
SOL_AWC	mm	0 – 1	0	0.6
ESCO	-	0 – 0.5	0.95	0.1
GW_DELAY	Days	30 – 80	31	55
GW_REVAP	-	0.02 – 0.1	0.02	0.05
CANMX	mm	0 - 10	5	9

(-) means no units

3.4.2.2. Performance of model simulations with and without land use changes

Table 3.4 shows the model performance for simulations with and without land use changes for the altered periods. The results of the simulations without land use change show that the NSE value has continuously decreased, with a significant decrease in the period 2008–2013 (Figure 3.7). In this period, the calibrated model fails to simulate peak flows, which explains the relatively low value of NSE (<0.6). After land use change was incorporated in the simulations, the NSE values of the altered periods (periods 2, 3 and 4) were higher than the NSE values from simulations without land use changes. The simulated peak flows and low flows of the simulations with land use change are better than in the simulations without land use change. While the mean NSE value of simulations without land use change is around 0.6, the mean NSE value of simulations with land use change is around 0.7.

Table 3.4. NSE values of simulations with and without land use update

Simulations	Baseline period		Altered periods	
	1990–1995	1996–2001	2002–2007	2008–2013
Without land use update	0.78	0.70	0.65	0.53
With land use update	0.78	0.72	0.71	0.68

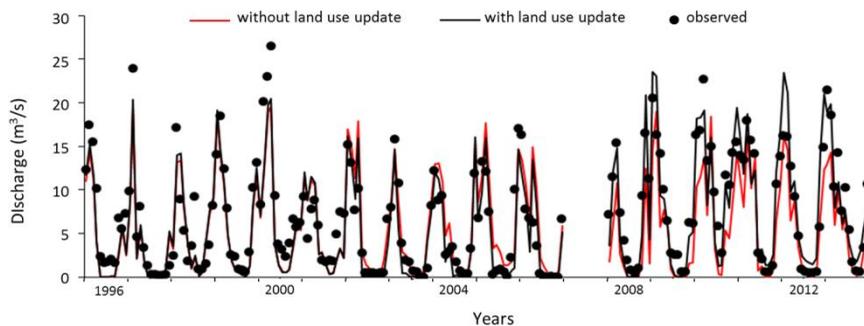


Figure 3.7. Hydrograph of simulations with and without land use change for the altered periods.

In order to validate the method, a similar procedure was applied in an independent sub catchment namely Tapan catchment (± 200 ha), that is located in the upstream part of the study catchment. The streamflow data of the Tapan catchment were made available by Retnowati (2012) at annual basis from the period 1993 to 2007. A new outlet was created in the simulated catchment that is similar to the outlet location of the Tapan catchment, and then the model was executed with and without land use change. Furthermore, the NSE values between simulations with and without land use change for the period 1993–2007 were compared. The results show that simulation with land use change has a better performance than the simulation without land use change with NSE values of -0.75 and -4.03, respectively (see Figure 3.8). Although the model showed a poor performance, a better model performance for simulations with land use change than simulations without land use change could be an indication of the importance of land use change to changes in streamflow.

3.4.3. Changes in water balance ratios

A good model performance of simulations with land use change confirmed the contribution of land use change to changes in streamflow. The results of the simulation with land use change showed that the water balance of the Samin catchment has changed in the 24-year time period at both catchment and sub-catchment level. At the catchment level, the Mann Kendall trend analysis showed that the changes in the runoff coefficient and ET/P were not significant at a significance level of 5%.

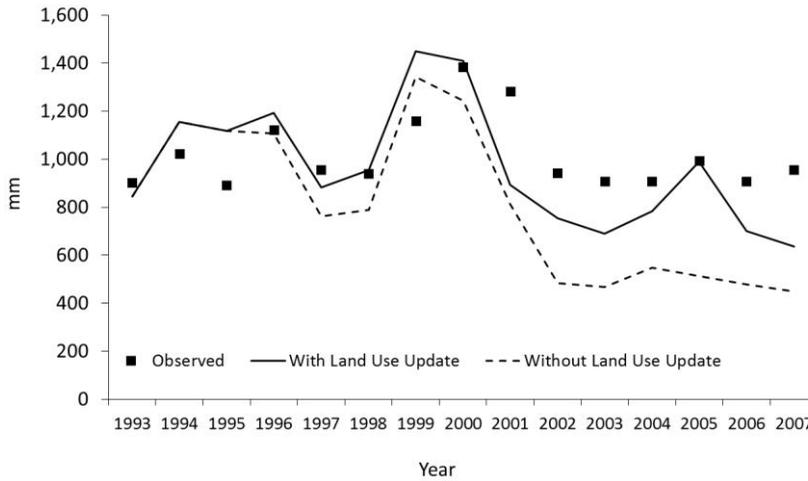


Figure 3.8. Hydrograph simulations with and without land use change for years 1993-2007 in the validation catchment

Between period 1 and period 4, the runoff coefficient has increased from 35.7% to 44.6% and ET/P has decreased from 60% to 54.8%. The results of this study are in line with the findings from Marhaento et al. (2017b) but this study found smaller increases for the mean annual streamflow. Despite changes in runoff coefficient were not statistically significant, changes in Q_s/Q and Q_b/Q were significant at a significance level of 1%. Between period 1 and period 4, Q_s/Q has increased from 26.6% to 37.5% whereas Q_b/Q has decreased from 40% to 31.1%. For Q_i/Q , the long-term changes were not significant at a significance level of 10% (decrease from 33.4% to 31.4%). Figure 3.9 shows the long-term changes in the water balance ratios for the period 1990–2013.

At the sub-catchment level, long-term trends were consistent for three water balance ratios namely runoff coefficient, Q_s/Q and Q_b/Q . It was found that the runoff coefficient and Q_s/Q increased while Q_b/Q decreased for all sub-catchments. However, long-term trends were not consistent for the other two water balance ratios ET/P and Q_i/Q . Several sub-catchments experienced a positive trend of ET/P as well as Q_i/Q while other sub-catchments showed negative trends. The opposite directions of ET/P and Q_i/Q at sub-catchment level have balanced each other so that the differences of ET/P and Q_i/Q at catchment level were minor. As a result, changes in ET/P were not equal to changes in Q_i/Q at catchment level indicating that there was a change in the water storage (ΔS). Table 3.5 shows the results of the Mann Kendall trend analysis of the water balance ratios at sub-catchment level.

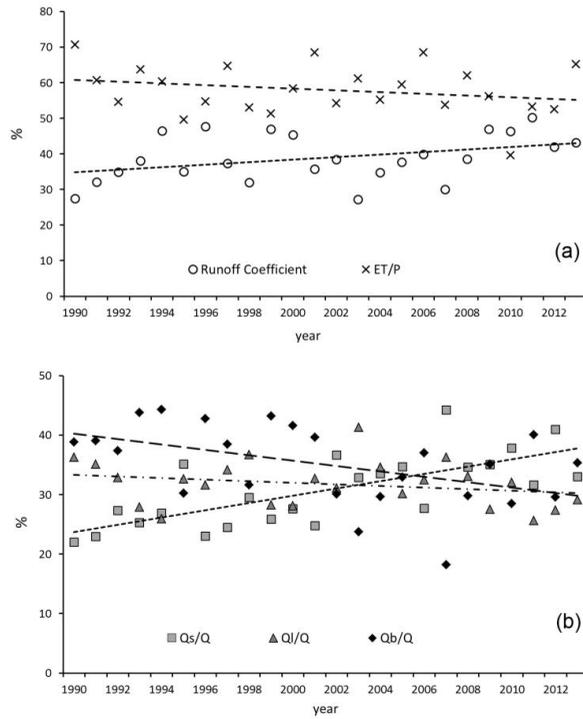


Figure 3.9. (a) Simulated runoff coefficient (Q/P) and ET/P and (b) simulated Q_s/Q , Q_i/Q and Q_b/Q including their long-term trend for the period 1990-2013 in the Samin catchment

Table 3.5. Trend directions from the Mann Kendall trend analysis for the water balance ratios per sub-catchment for the period 1990-2013.

Sub-catchment	Area (km ²)	ET/P	Q/P	Q_s/Q	Q_i/Q	Q_b/Q
1	2.5	-	+	+	-	-
2	8.2	-	+	+	-	-
3	13.7	-	+	+	-	-
4	4.6	+	+	+	+	-
5	0.1	+	+	+	+	-
6	9.5	+	+	+	+	-
7	21.3	-	+	+	-	-
8	17.8	-	+	+	-	-
9	60.8	-	+	+	-	-
10	55.4	-	+	+	+	-
11	84.0	-	+	+	-	-

A (-) shows a decreasing trend, while a (+) shows an increasing trend. Shading means that the trend is significant at a significance level of 5%.

3.4.4. Effect of land use change on the water balance

In order to relate changes in the water balance and changes in land use, Pearson correlation tests were performed at the sub-catchment level. The results showed that changes in the water balance were significantly correlated with changes in forest area (i.e. combination of evergreen forest and mixed garden) and settlements, whereas the other land use classes did not show a correlation with the water balance ratios at a significance level of 5%. Figure 3.10 shows the changes in the water balance ratios as a function of changes in forest and settlement area. Changes in the forest area had a positive correlation with the runoff coefficient and a negative correlation with ET/P at a significance level of 1%. In addition, changes in the settlement area had a positive correlation with the runoff coefficient at a significance level of 1%, but relatively low impacts on ET/P. Changes in the runoff coefficient and ET/P at sub-catchment level were higher than changes at catchment level. For the fractions of streamflow, changes in the Q_s/Q could be related to changes in the settlement area with a positive correlation at a significance level of 5%. Changes in Q_b/Q had the same magnitude but in an opposite direction than changes in Q_s/Q . The contribution of changes in forest area to changes in Q_s/Q and Q_b/Q were minor in particular for the latter. Changes in forest area significantly affected changes in Q_l/Q with a positive correlation at a significance level of 5%.

3.5. Discussion

Based on hydrological modelling, this study provides a strong indication that changes in land use altered the water balance in the Samin catchment. Findings show that land use change due to deforestation and expansions of settlement area (i.e. urbanization) have reduced the mean annual evapotranspiration and increased the mean annual streamflow. Moreover, the fraction of the streamflow originating from surface runoff has significantly increased compensated by a decrease in base flow. The directions of changes in the water balance by land use change (i.e. deforestation and urbanization) in this study are in line with hydrological studies in tropical regions from Bosch and Hewlett (1982), Bruijnzeel (2004) and Brown et al. (2005). It is well known that a reduction of forest area may cause not only a reduction in the tree stands which significantly reduces evapotranspiration from both canopy interception and plant transpiration, but also diminishes ground vegetation and leaf litter. The absence of ground vegetation and leaf litter affects top soils to lose protection from raindrop splashes and to have less biotic activity (Guevara-Escobar et al., 2007). Thus, processes in the top soil resulting in lower organic matter contents cause a lower permeability and storage capacity resulting in a lower infiltration capacity.

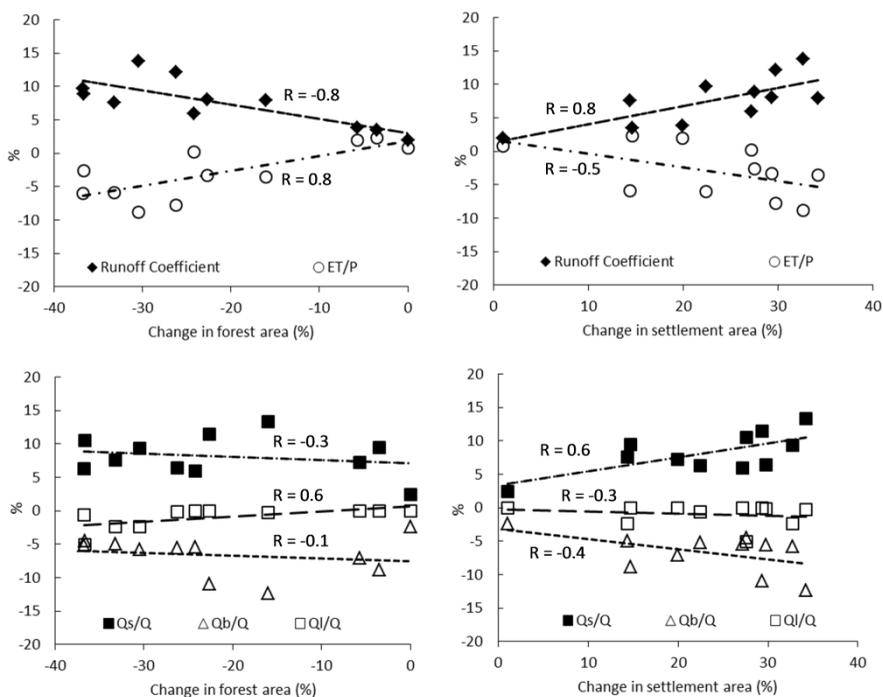


Figure 3.10. Changes in water balance components as a function of changes in forest area and settlements, including Pearson correlation coefficients (R). ET/P = ratio of evapotranspiration to precipitation; Q_b/Q = ratio of base flow to streamflow; Q_l/Q = ratio of lateral flow to streamflow; Q_s/Q = ratio of surface runoff to streamflow

As a result, a larger fraction of precipitation is transformed into surface runoff. In the present study, it is found that changes in forest area significantly contributed to changes in ET/P and Q_l/Q whereas changes in the Q_s/Q and Q_b/Q were profoundly affected by the expansion of settlement area. A rapid increase of settlement area (see Table 3.2) is probably the main reason of the significant impacts on the water balance. Expansion of impervious area (e.g. buildings, roads) can alter both surface and subsurface flow as a result of reduced infiltration. As impervious area increases, less water infiltrates into the soil resulting in lower soil water storage. Several studies have investigated the correlation between urbanization and the water balance in tropical regions (Wagner et al., 2013; Gumindoga et al., 2014a; Remondi et al., 2016) and results are similar to ours.

In this study, changes in the water balance due to land use change occurred at both catchment and sub-catchment level. However, it was found that changes at sub-catchment level were diverse where some sub-catchments showed different directions of change in the water balance ratios compared to others. Apparently, the positive and negative trends on ET/P and Q_i/Q at sub-catchment level have compensated each other, so that long-term changes of those variables at catchment level were relatively small. This is similar to the findings from Wagner et al. (2013) and Wilk and Hughes (2002) who argue that the complexity of large catchments that can mask the impacts of land use changes on hydrological processes at the local scale. Furthermore, the land use change impacts on the water balance differ for each sub-catchment. The changes in the downstream area, where land conversion from agriculture to settlement is dominant, are larger than in the upstream area, where land conversion from forest to agriculture is dominant. The rapid increase of impervious area is probably the main cause for changes in the overall water balance. This study agrees with Wagner et al. (2013) who argue the significant impacts of urban expansion to changes in the surface runoff and streamflow. In addition to these factors, Van Dijk et al. (2007) and Bruijnzeel (2004) mention slope variation, soil types and geological conditions which could contribute to the impact of land use change on the water balance. Nonetheless, changes in climate can also accelerate changes in the water balance of the study catchment. Aldrian and Djamil (2008) argue that the climate in East Java has changed over the past decades with a decrease in the accumulated monthly precipitation and annually, an increase of the ratio of total precipitation in the wet season to the total annual precipitation and an increase of the dry spell period. However, climate changes in East Java likely occurred in the low altitude area closer to the seashore and relatively less in the mountainous area due to regular orographic effects. Marhaento et al. (2017b) argue that the contribution of climate change to changes in the streamflow in the study catchment is less significant than the contribution of land use change but not negligible. As can be seen in Figure 3.2, the runoff coefficient of the years 2000 and 2005 was higher than in other years, which is probably due to climatic variability (e.g. higher precipitation intensity) rather than land use. Thus, combination of land use change and climate change might result in more significant hydrological changes than either driver acting alone (Hejazi & Moglen, 2008). A more thorough study, however, need to be done in the future focusing on the role of climate change (e.g. changes in the precipitation intensity, extreme precipitation events) to changes in the water balance of the study catchment.

The SWAT model used in the present study has been successful to attribute changes in the water balance to land use changes. However, a good model performance only was found at the catchment level, for which the model

calibration has been carried out. At the sub catchment level, the model errors increased. A significant deterioration of the model performance at smaller scale sub catchments probably result from model parameters that cannot represent detailed hydrological processes at a finer scale such as flow concentration during heavy downpours. In addition, accumulation of errors from the model structure (e.g. model assumptions, equations) as well as data inputs (e.g. lack of relevant spatial and temporal variability of data inputs from precipitation, soils, land uses and DEM) was increasing when the model was applied under changing conditions (e.g., land use change; Ewen et al., 2006)

It should be noted that parameterization is the key yet most challenging part in the model simulation. Identification of parameters to be calibrated was essential for the subsequent steps. This study followed the guideline from Abbaspour et al. (2015) to select parameters to be calibrated based on the model performance of the default simulation. However, these parameters were different from the parameters that were found by the global sensitivity analysis in the SWAT-CUP package (CN2, CH_N2, GWQMN, GW_DELAY, GW_REVAP and CNCOEFL1). Calibration of both parameter sets resulted in a comparable model performance in terms of NSE, where parameters from the global sensitivity analysis resulted in an average NSE value of 0.77 for simulations with land use change and 0.6 for simulations without land use change. Although a similar conclusion could be drawn by using the parameter set from the global sensitivity analysis, it was found that the model simulated a (very) low ratio of catchment averaged evapotranspiration to precipitation (in mm) with an average annual value of 34%. According to Bonell et al. (2005), in forested tropical catchments with distinct wet and dry seasons, the average annual ET is more than 50% of the annual precipitation. Findings of this study resemble Griensven et al. (2012), who reported the equifinality problem in SWAT simulations for tropical regions where satisfactory simulated discharges does not guaranty a good performance of the ET simulation.

The SWAT model has been developed for temperate regions and the default SWAT database is not applicable to other regions including the tropics. The SWAT model considers dormancy for the perennial trees (Neitsch et al., 2011), which is not the case in a tropical forest. Because of the dormancy, the Leaf Area Index (LAI) for the tree species is set to a minimum value during the dormancy period and this result in a low annual ET. Kilonzo (2013) argues to adjust several crop SWAT parameters (initial Leaf Area Index, initial biomass, heat units for perennial trees and plant-harvest schedule for crops) necessary to simulate streamflow in forested areas of tropical regions. In addition, Griensven et al. (2014) argue that parameters of the maximum canopy storage (CANMX) and maximum stomatal conductance at high solar radiation and low vapor

pressure deficit (GSI) are sensitive to evapotranspiration and therefore it is necessary to adjust the values in order to increase ET. Adjusting the crop parameters and management database as seen in Table 3.1 prior to model calibration has resulted in a more realistic simulation as demonstrated in this article. This adjustment caused an increase of ET by 10% compared to default crop parameters.

For further research on the impacts of land use change on the water balance in tropical regions, this study suggests to include ET in the calibration process. The use of remote sensing products to generate spatially and temporally distributed ET can contribute to this process (Rientjes et al., 2013 and Griensven et al., 2014).

3.6. Conclusions

This study was able to attribute changes in the water balance to land use change in the Samin catchment using the approach described in this paper. The results show that land use change was the dominant driver for changes in the water balance as shown by the better model performance for a simulation with land use change compared to a simulation without land use change. The simulation without land use change generally failed to simulate peak flows where the error was increasing in time and thus resulted in a worsening model performance.

Land use change in the study catchment was mainly shown as an increase in settlement area and a decrease in forested area. At catchment level, these land use changes caused an increase in the runoff coefficient and decrease in the ratio of evapotranspiration to precipitation. The ratio of surface runoff to streamflow substantially increased and the ratio of base flow to streamflow substantially decreased. At the sub-catchment level, the impacts of land use changes on the water balance were diverse for the ratio of evapotranspiration to precipitation and the ratio of lateral flow to steam flow. Positive and negative trends at sub-catchment level have compensated each other, so that long-term changes of those variables at catchment level were relatively small. In addition, changes in forest and settlement area have resulted in different impacts on the water balance. A reduction in the forest area significantly contributed to a higher runoff coefficient and lower ratios of evapotranspiration to precipitation and lateral flow to streamflow. An increase in the settlement area significantly contributed to a higher runoff coefficient and ratio of surface runoff to streamflow and a lower ratio of base flow to streamflow.

Chapter 4

Hydrological response to future land use change and climate change in a tropical catchment³

Abstract

Hydrological response to expected future changes in land use and climate in the Samin catchment (278 km²) in Java, Indonesia, has been simulated using the Soil and Water Assessment Tool model. Changes between the baseline period 1983–2005 and the future period 2030–2050 under both land use change and climate change are analyzed. This study uses the output of a bias-corrected Regional Climate Model and the outputs of six Global Climate Models to include climate model uncertainty. The results show that land use change and climate change individually will cause changes in the water balance components, but that more pronounced changes are expected if the drivers are combined, in particular for changes in annual streamflow and surface runoff. The findings of this study will be useful for water resource managers to mitigate future risks associated with land use and climate changes in the study catchment.

³ This chapter is based on a paper that has been submitted as: Marhaento, H., Booij, M. J., & Hoekstra, A. Y. Hydrological response to future land use change and climate change in a tropical catchment.

4.1. Introduction

Climate change and land use change are key factors determining changes in hydrological processes in catchments. Numerous studies have been carried out to evaluate the impacts of land use and climate change on water resources (Legesse et al., 2003; Li et al., 2009; Mango et al., 2011; Wang, 2014; Marhaento et al., 2017a; 2017b; Shrestha & Htut, 2016; Zang et al., 2016). Most findings show that changes in land use and climate affect hydrological processes such as evapotranspiration, interception and infiltration, resulting in spatial and temporal alterations of surface and subsurface flows patterns (Legesse et al., 2003; Bruijnzeel, 2004; Thanapakpawin et al., 2007; Khoi & Suetsugi, 2014; Marhaento et al., 2017a). According to Wohl et al. (2012), hydrological processes in the humid tropics differ from other regions in having greater energy inputs and faster rates of change, including human-induced changes, and therefore require additional study. IPCC (2007) reported that tropical regions, including Indonesia, are one of the most vulnerable areas for future water stress due to extensive land use and climate changes.

With a population of more than 130 million (in 2010), Java, Indonesia, is one of the most densely populated islands of the world. Over the last century, land use on Java has changed rapidly, following the rapid growth of human population (Verburg and Bouma, 1999), which has resulted in significant changes in the water system. Bruijnzeel (1989) observed higher flows during rainy seasons and lower flows during dry seasons after a fair proportion of forest area was transformed into settlements and agriculture in the Konto catchment (233 km²) in East Java. Studies from Remondi et al. (2016) and Marhaento et al. (2017a) present similar results, showing that land use change due to deforestation and expansions of settlement area have reduced mean annual evapotranspiration and increased mean annual streamflow. In addition, the fraction of streamflow originating from surface runoff significantly increased, compensated by a decrease in base flow.

Besides land use change, Java has experienced climate change in the past decades. Aldrian & Djamil (2008) found a significant change in the spatial and temporal climate variability over the Brantas catchment (12,000 km²) in East Java over the period 1955–2005. They found a decrease in annual precipitation, an increase of the precipitation intensity during the wet season and an increase of the dry spell period. More pronounced changes likely occurred in the low altitude area closer to the seashore. Their findings resemble those of Hulme and Sheard (1999), who found that most islands of Indonesia have become warmer since 1900, reflected in an increase of the annual mean temperature by about 0.3°C. Moreover, the mean annual precipitation has likely declined in the

southern regions of Indonesia including Java, resulting in a significant change in the water availability.

Changes in land use and climate in Java have threatened local and regional socio-economic development. Amien et al. (1996) and Naylor et al. (2007) argue that land use and climate change in Java have caused a decrease in the rice production resulting from a warming climate as well as a decreasing farming area. In addition, many reservoirs have failed, having a lower life span and water supply capacity than expected due to sedimentation from deforested upstream areas (Moehansyah et al., 2002). Furthermore, the frequency of disastrous events related to land use and climate change (e.g. droughts and floods) has increased, resulting in major economic losses in Java during the last decades (Marfai et al., 2008). Without taking any mitigation measures, Java is projected to have a severe food crisis by the year 2050 due to land use and climate changes (Syaukat, 2011).

Land use planning can be an effective way to mitigate future risks associated with changes in land use and climate (Memarian et al., 2014). Numerous studies argue that different types of land use have different water use and water storage characteristics (Bruijnzeel, 1989, 2004; Legesse et al., 2003; Memarian et al., 2014). However, it is a challenge to measure the effectiveness of land use planning for improving availability of water resources due to climatic interference. Complex interactions between land use and climate changes may not only result in accelerating changes in hydrological processes (Legesse et al., 2003; Khoi & Suetsugi, 2014), but may also offset each other (Zhang et al, 2016), which requires further study.

In order to provide insight in land use and climate change impacts on hydrological processes, coupled models are typically used. For example, Zhang et al. (2016) used a combination of a Markov chain model and a Dynamic Conversion of Land Use and its Effects (Dyna-CLUE) model to simulate future land uses, climate change scenarios to predict future climate variability and the Soil and Water Assessment Tool (SWAT) model to simulate hydrological processes in order to quantify the hydrological impacts of land use and climate changes. However, very few studies have assessed hydrological impacts due to land use and climate changes in tropical regions, which is mainly due to limited hydrological data in tropical regions for model calibration and validation purposes (Douglas, 1999). Furthermore, the results are often contradictory and inconsistent, in particular for large catchments (>100 km²) where interference from climate change becomes more important (Calder et al., 2001; Beck et al., 2013).

The present study aims to assess future hydrological response to changes in land use and climate in the Samin catchment (278 km²) in Java, Indonesia. The

Samin catchment is selected following prior studies from Marhaento et al. (2017a; 2017b), who argue that historic land use change in the Samin catchment has significantly affected the hydrological processes in this catchment. Central Java Provincial Government (2010) has introduced a spatial land use planning for the Samin catchment through a regional regulation, which motivated this study to assess its effectiveness to mitigate future risks of water resources under different climatic circumstances. This study assesses the separate and combined effects of land use change and climate change on water balance components for the period 2030–2050 through plausible future land use and climate change scenarios.

4.2. Study Area and Data Availability

4.2.1. Catchment description

The Samin catchment (278 km²) is part of the Bengawan Solo catchment, the largest catchment in Java, Indonesia, which plays an important role to support life of more than half a million people within its area. It is located between 7.6^o–7.7^o southern latitude and 110.8^o–111.2^o eastern longitude. The highest part of the catchment is the Lawu Mountain (3,175 meter above sea level) and the lowest part is near the Bengawan Solo river (84 meter above sea level; see Figure 4.1). The upper part of the Samin catchment is characterized by steep terrain (>25%) and predominantly covered by evergreen forest. A less undulated terrain is in the middle part of the catchment, which is mostly covered by mixed garden, agricultural crops and settlements. In the downstream part, agriculture (mainly paddy fields) and settlements are dominant. According to the soil map from the Harmonized World Soil Database (FAO et al., 2012), the soil distribution of the Samin catchment is predominantly Luvisols (a leafy humus soil) and Andosols (a volcanic soil of the Mount Lawu), which cover 57% and 43% of the study area, respectively. Geologically, the Samin catchment is located in the depression zone filled by Mount Lawu volcano's deposits that resulted in deep and fertile soils and thus are suitable for agriculture.

The Samin catchment experiences a tropical monsoon climate with distinct dry and wet seasons, whereby the former generally extends from May to October and the latter from November to April. Mean annual precipitation can be 1,500 mm in dry years and reaches 3,000 mm in wet years. The spatial precipitation pattern likely follows the orography, with a larger amount of precipitation in the upstream than in the downstream area. The mean daily temperature is approximately 26 °C, with a mean daily minimum of 21.5 °C and a mean daily maximum of 30.5 °C. The annual potential evapotranspiration in the catchment ranges from 1,400 to 1,700 mm (Marhaento et al., 2017b). According to the

Indonesia Statistical Bureau (BPS, 2017), the population size at the sub-district level in the Samin catchment is about 800.000 inhabitants, with an average annual population growth over the period 1994–2010 of about 0.8%. In the same period, land use has significantly changed, with an increase in the settlement area and a decrease in the forest area (Marhaento et al., 2017a). Population growth in the Samin catchment has been projected to decrease over time, reaching 0.1% per year in 2035, as a result of a successful birth control programme as well as a transmigration programme (BPS, 2013), which may affect future land use change in the study catchment.

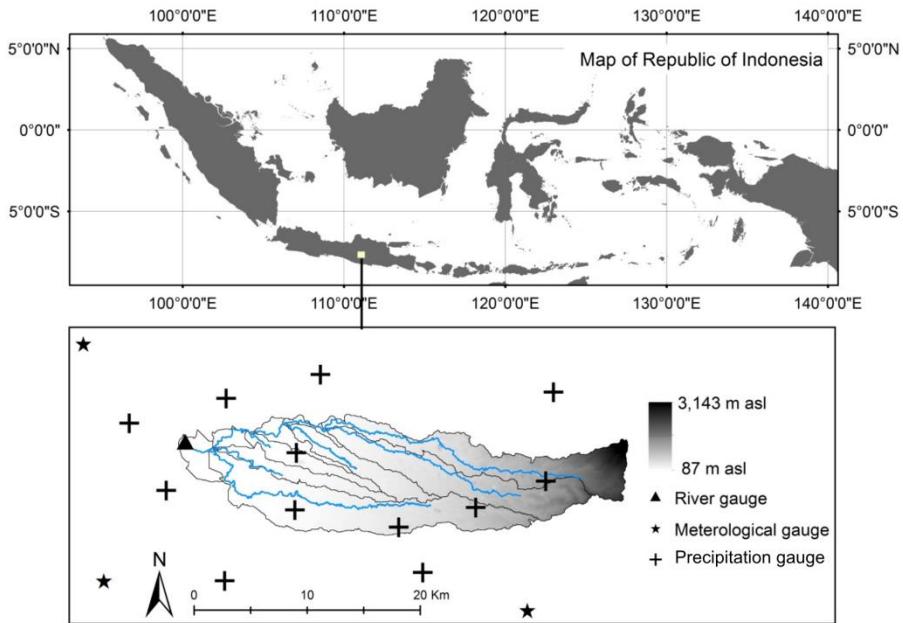


Figure 4.1. Samin catchment in Java, Indonesia, with the locations of hydrological gauges

4.2.2. Data Availability

To set up the hydrological model, spatial and non-spatial data were used. For the spatial data, land use maps with 30-meter spatial resolution for the years 1994, 2000, 2006 and 2013 were available for the study area from Marhaento et al. (2017a). A land use spatial planning map of the study area for the period 2009–2029 was available from Central Java Provincial Government (2010). The topographic map contains information related to elevation, roads and locations of public facilities (e.g. hospitals, schools, and offices) and is available from the

Geospatial Information Agency of Indonesia at 1:25,000 scale. A soil map at 30 arc-second spatial resolution was taken from FAO et al. (2012).

For the non-spatial data, daily water level data for the period 1990–2013 were available from the Bengawan Solo River Basin organization and converted into daily discharge data using the rating curves provided by the data provider. Daily climate data were available from eleven precipitation stations and three climate stations within the surrounding catchments for the period 1983–2013. Future climate data for the period 2030–2050 for different emission scenarios were made available from SEACLID/CORDEX Southeast Asia (CORDEX-SEA), a consortium consisting of experts from 14 countries and 19 institutions that aim to downscale a number of Global Climate Models (GCMs) from the Fifth Coupled Model Inter-comparison Project (CMIP5) for the Southeast Asian region. For Indonesia, the Indonesian Agency for Meteorological, Climatological and Geophysics (BMKG) provided the Regional Climate Model (RCM) RegCM4 data at 25×25 km² resolution (Ngo-Duc et al., 2016), downscaled from the CSIRO Mk3.6.0 GCM. The precipitation and maximum and minimum temperature data are available on a daily basis for the period 1983–2005 to represent the baseline period and for 2030–2050 to represent the future period. Two scenarios for the radiative forcing of future greenhouse gas emissions were applied, namely Representative Concentration Pathway (RCP) 4.5 and 8.5 to represent low emission and high emission scenarios, respectively. In addition to the RCM dataset, this study also used six additional GCMs from different sources in order to include the effect of climate model uncertainty. This study used GCMs rather than other RCMs to include climate model uncertainty because other RCMs are not available for the study catchment. Table 4.1 shows the characteristics of each GCM used in this study. These GCMs were selected after comparison of the mean annual precipitation in the study catchment from 26 GCMs listed in CMIP5, which showed significantly different changes in precipitation (even in the direction of change) between the baseline and future periods resulting in a large uncertainty band in future climate variability.

4.3. Methods

4.3.1. Land use change model

Future land use distributions in the study catchment are based on two land use scenarios namely a business-as-usual (BAU) scenario and a controlled (CON) scenario. The BAU scenario represents a future situation where no measures are taken to control land use change in the study catchment, whereas the CON scenario represents idealized land use conditions that follow the spatial planning regulation.

Table 4.1. List of GCMs used and their characteristics.

Model	Resolution (Lon x Lat)	Country origin	Signs*	References
GFDL-ESM2M	2.5 ⁰ × 2.0 ⁰	USA	- - -	Dunne et al. (2012)
CanESM2	2.81 ⁰ × 2.79 ⁰	Canada	- -	Arora et al. (2011)
CSIRO-Mk3.6.0	1.875 ⁰ × 1.86 ⁰	Australia	-	Collier et al. (2011)
MPI-ESM-LR	1.875 ⁰ × 1.85 ⁰	Germany	+	Giorgetta et al. (2013)
MIROC5	1.41 ⁰ × 1.39 ⁰	Japan	++	Watanabe et al. (2010)
NorESM1-M	2.5 ⁰ × 1.875 ⁰	Norway	+++	Bentsen et al. (2013)

*Differences between baseline and future conditions, where the (-) sign indicates that the mean annual precipitation in the future period is smaller than in the baseline period and the (+) sign shows that the mean annual precipitation in the future period is larger than in the baseline period

4.3.1.1. Business as usual (BAU) scenario

Attempts were made to ensure that future land use in the study catchment under the BAU scenario is in accordance with the ongoing trends of land use change. An integration of a Markov Chain and a Cellular Automata model with Multi Criteria Evaluation (MCE) was used to predict land use changes in the catchment for the future period (i.e. 2030-2050). A combination between a Markov Chain and a Cellular Automata model, later called CA-Markov, has been widely used to simulate land use changes throughout the world (Myint & Wang, 2006; Hyandye & Martz, 2017). Compared to other models with a similar aim (e.g. GEOMOD, CLUE), the CA-Markov model has a high ability to simulate multiple land use covers and complex patterns with less data and computational efforts (Eastman, 2012). Along with CA-Markov, a multi criteria decision-making (MCE) technique was used to support the decision processes of land allocations using different criteria of land use suitability (Behera et al., 2012). MCE uses factors and constraints for each land use category. Factors indicate the relative suitability of a specific land use type that is generally based on a measured dataset (e.g. slope gradient, elevation, and road distances), whereas constraints are used to exclude certain areas from consideration (e.g. protected area and water bodies).

Factors and constraints of each land use type were selected based on the available spatial data (see Table 4.2). In order to make factors and constraints spatially comparable, the selected factors and constraints were standardized using fuzzy membership functions with a range between 0–1, where a value closer to 1 indicates a stronger membership.

Table 4.2. Factors, membership functions, control points and constraints of the different land use classes.

Land use class	Factors	Membership functions	Control points	Constraints
Dryland	Slope gradient	MIS	a=0, b=15, c=25, d=45	▪ Protected area
	Distance from road	MDL	a=0, b=maximum	▪ Water body
Forest	Slope gradient	MIL	a=25, b=maximum	▪ Existing settlement
	Distance from road	MIL	a=500, b=maximum	▪ Existing paddy field
	Elevation (DEM)	MIL	a=1500, b=maximum	▪ Water body
Mixed garden	Slope gradient	MIS	a=8, b=25, c=25, d=45	▪ Protected area
	Distance from road	MDL	a=100, b=maximum	▪ Water body
	Distance from existing settlement	MDL	a=100, b=maximum	▪ Existing settlement
Paddy field	Slope gradient	MIS	a=0, b=15, c=25, d=45	▪ Protected area
	Distance from road	MDL	a=0, b=maximum	▪ Water body
	Distance from existing settlement	MDL	a=0, b=maximum	▪ Existing settlement
Settlement	Distance from road	MDL	a=0, b=maximum	▪ Protected area
	Distance from existing settlement	MDL	a=0, b=maximum	▪ Water body
	Slope gradient	MDL	a=0, b=45	
	Distance from urban facilities	MDL	a=0, b=maximum	
Shrub	Slope gradient	MIL	a=15, d=maximum	▪ Protected area
	Distance from road	MIL	a=500, b=maximum	▪ Water body
	Distance from existing settlement	MIL	a=500, b=maximum	▪ Existing settlement
Water body	Existing water body	-	-	-

MIL = monotonically increasing linear function, MDL = monotonically decreasing linear function, MIS = monotonically increasing symmetric function

Three types of fuzzy membership functions were used, namely a monotonically increasing linear function, a monotonically decreasing linear function and a monotonically increasing symmetric function. Subsequently, four fuzzy control points were determined in which the first point marks the location where the membership function begins to rise above 0, the second point indicates where it reaches 1, the third point indicates the location where the membership function drops again below 1, and the fourth point marks the point where it returns to 0. The four control points of fuzzy membership function for each land use class used in this study were adapted from Hyandye & Martz (2017). However, some changes were made for this study considering the local conditions (e.g. agriculture area was divided into paddy field and dry land farm) and data availability (e.g. population density was not included as a factor).

In this study, the Markovian transition area matrix was generated using two recent land use maps for the years 2006 and 2013. However, a boundary condition was applied for the settlement area by determining the settlement area in 2050 based on a linear relation between the changes in settlement area estimated from historical land use maps (Marhaento et al., 2017a) and population size in the same years (see Figure 4.2a). Population in 2050 was predicted using a second order polynomial function that can represent a decrease in the population growth in the future, following the prediction from the Indonesia Statistical Bureau (BPS, 2013) (Figure 4.2b). The results show that the settlement area in the study catchment in 2050 will be 50.2% of the study area.

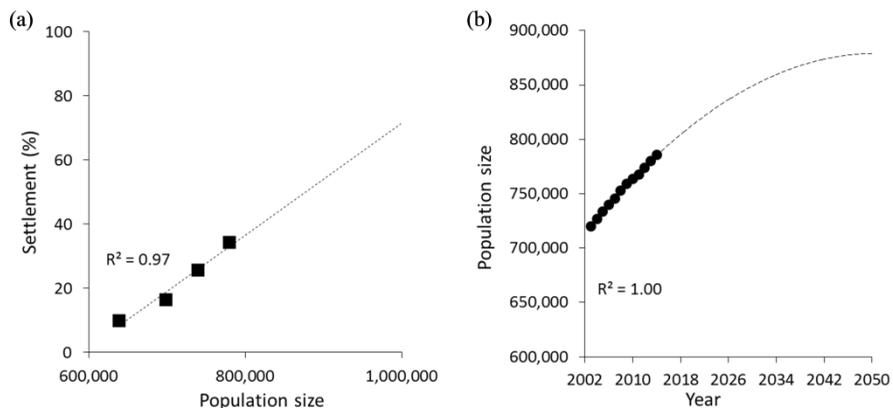


Figure 4.2. A linear relation between the settlement area (in %) and population size (a). A second order polynomial function of the population growth in the Samin catchment (b).

This boundary condition was applied in the simulation through a modification of the time lags of the model simulation until the model closely predicted a settlement area in 2050 of about 50% of the study area. The predicted annual land use distributions from 2030 to 2050 resulting from the fitted model were used as land use inputs in the SWAT simulations under the BAU scenario. For this study, spatial data preparation and land use simulations were executed using IDRISI Selva v.17 software (Eastman, 2012).

4.3.1.2. Controlled scenario

In this scenario (i.e. CON scenario), future land use in the study catchment was assumed to follow the spatial planning map. A pre-processing analysis has been carried out in order to convert a printed map of the spatial planning map into a digital map. Furthermore, the classification of the spatial planning map was changed to be comparable with the land use classification from Marhaento et al. (2017a). Figure 4.3 shows the spatial planning map of the study catchment with reclassified land use types. According to the spatial planning map, in the year 2029, agriculture area (i.e. paddy field and dryland farm) is the dominant land use type in the study catchment, covering 55% of the study area, followed by forest area (i.e. evergreen forest and mixed garden, 31%) and settlements (14%). Forest area is dominant in the upstream area, whereas agriculture area and settlements are dominant in the downstream area. This study used the predicted land use distribution in 2029 from the spatial planning map and the land use map for the year 2013 as inputs in the CA-Markov model in order to simulate annual land use distributions in the future period (i.e. 2030-2050). Output of the model was used as land use input in the SWAT simulations under the CON scenario.

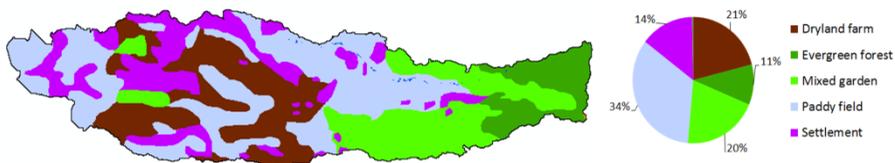


Figure 4.3. Predicted land use map of the Samin catchment in the year 2029 according to the spatial planning map from the Central Java Provincial Government.

4.3.2. Climate change model

GCM and RCM outputs are generally biased, which hampers the direct use of GCM or RCM data to assess the impact of climate change on hydrological processes (Teutschbein and Seibert, 2012). Thus, there is a need to correct these outputs before they can be used for regional impact studies. In this study, different bias correction methods were used to correct RCM and GCM output. For the RCM data, the distribution mapping method and the variance scaling method were used to correct biases in precipitation and maximum and minimum temperature, respectively. These methods were selected after performing an accuracy assessment based on a split sample test (Klemeš, 1986) for different bias correction methods (i.e. linear scaling, power transformation, distribution mapping). It was found that these methods outperformed other methods based on their coefficient of determination (R^2) against the observed precipitation and maximum and minimum temperature. For precipitation, the distribution mapping method resulted in a R^2 of 0.77, whereas the linear scaling method and power transformation method resulted in a R^2 of 0.53 and 0.56, respectively. For the maximum and minimum temperature, the variance scaling method resulted in a R^2 of 0.62, whereas the linear scaling method and distribution method resulted in a R^2 of 0.51 and 0.48, respectively. However, it should be noted that all bias correction methods improved the raw RCM-simulated precipitation and maximum and minimum temperature. For the six additional GCMs, a delta change method was applied to correct biases of the GCM-simulated precipitation and maximum and minimum temperature. Rather than using the GCM simulations of future conditions directly, the delta change method uses the differences between GCM-simulated historic and future conditions (anomalies) for a perturbation of observed data. For a detailed description of each method, references are made to Teutschbein & Seibert (2012) and Fang et al. (2015).

4.3.3. Hydrological model

The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) was used to simulate hydrological processes in the study catchment. The SWAT model is a physically based semi-distributed model that divides a catchment into sub-catchments and then further into hydrological response units (HRUs) for which a land-phase water balance is calculated (Neitsch et al., 2011). Runoff from each HRU (i.e. combinations of land use, soil and slope) is aggregated at sub-catchment level and then routed to the main channel for which the catchment water balance is calculated. In a previous study, Marhaento et al. (2017a) showed the suitability of SWAT to attribute changes in the water balance to land use change in the Samin catchment. The SWAT model set up in the

present study used the same settings as in Marhaento et al. (2017a). Since details of the model setup and parameterization are available in the previous study, this study only presents a brief summary of the model calibration results.

The calibration period is 1990–1995 assuming that this period is a reference period when land use change and climate change had small impacts on hydrological processes (Marhaento et al., 2017a). Six SWAT parameters were calibrated on a monthly basis. The initial parameter ranges were determined based on minimum and maximum values allowed in SWAT. Four iterations were performed where each iteration consisted of 1,000 simulations with narrowed parameter ranges in the subsequent calibration rounds. The Nash Sutcliffe Efficiency (NSE) was used as objective function, similarly as in for instance Setegn et al. (2011) and Zhang et al. (2015). The results of the model calibration show that the simulated mean monthly discharge in the calibration period agrees well with the observed records with a NSE value of 0.78. In the validation period (1996–2013), the NSE model performance of the calibrated SWAT model is 0.7 (Marhaento et al., 2017a).

4.3.4. Future hydrological responses to land use and climate change scenarios

Future hydrological processes in the study catchment were simulated using the validated SWAT model, using inputs from the bias-corrected RCM and GCMs for the period 2030–2050 and the predicted land use distributions. For the baseline conditions, this study used the output of the SWAT simulations forced by the bias-corrected RCM data and the observed data, where both data sets cover the period 1983–2005. The baseline condition simulated with the bias-corrected RCM data was used as a baseline condition for the future simulation forced by the RCM dataset, whereas the baseline condition simulated by the observed data was used as a baseline condition for the future simulation forced by the GCM dataset. In addition, two land use distributions for the years 1994 and 2000 were used in the simulation to represent land use conditions in the baseline period. The Land Use Update (LUP) tool in ArcSWAT (Marhaento et al., 2017a) was used to incorporate land use change in the SWAT simulations, whereby land use was initially assumed as the land use reported for 1994, and updated by the land use for 2000 when the simulation date entered 1st January 2000. The LUP tool was also used to incorporate land use change in the simulations for future period (i.e. 2030-2050). Table 4.3 shows the scenario simulations executed in this study including the assessment of the effects of land use change only (LUC), climate change only (CC) and the combined land use and climate change (LUC+CC) scenario on hydrological processes. For each

scenario, several hydrological components namely precipitation (P), potential evapotranspiration (PET), streamflow (Q), actual evapotranspiration (ET), surface runoff (Q_s), lateral flow (Q_l) and base flow (Q_b) were calculated and compared to the baseline conditions.

Table 4.3. Future land use and climate change scenarios as inputs for the SWAT model.

Scenarios		Land use change		
		NLUC	BAU	CON
Climate change	NCC	Baseline	BAUNC ¹	CONNC ¹
	RCP 4.5	NC4.5 ²	BAU4.5 ³	CON4.5 ³
	RCP 8.5	NC8.5 ²	BAU8.5 ³	CON8.5 ³

NLUC = No land use change, NCC = No climate change, BAU = Business as usual land use scenario, CON = Controlled land use scenario, RCP 4.5 = Climate change scenario under Representative Concentration Pathway 4.5, RCP 8.5 = Climate change scenario under Representative Concentration Pathway 8.5. ¹LUC scenarios, ²CC scenarios, ³LUC+CC scenarios

4.4. Results

4.4.1. Land use change

As shown in Table 4.4, land use in the study catchment in 2050 under the BAU scenario is predominantly settlements (50.2%), followed by paddy field (22.2%), dryland farm (18.2%), mixed garden (4.9%), evergreen forest (2.3%), shrub (1.9%) and water body (0.3%). In comparison to the year 2000, forest area (i.e. evergreen forest and mixed garden) and shrub have decreased by 35% and 2.4%, respectively, while agriculture area (i.e. paddy field and dryland farm) and settlements have increased by 3.5% and 33.9%, respectively. The settlement area significantly increased in the down- and middle stream area converting mixed garden and paddy field area into impervious area. In the upstream area, the dryland farm has mainly converted mixed garden and shrub area, as shown in Figure 4.4b.

Under the CON scenario, land use in 2050 is predominantly paddy field (34%), followed by dryland farm (18.1%), settlements (17.3%), mixed garden (17.1%), evergreen forest (13.2%) and water body (0.3%). In comparison to the year 2000, mixed garden and shrub have decreased by 22.1% and 4.3%, respectively, while agriculture area (i.e. paddy field and dryland farm), evergreen forest and settlements have increased by 15.2%, 10.2% and 1%, respectively. Figure 4.4c shows that under the CON scenario, forests (i.e. evergreen forest and mixed garden) are located in the upstream area, while agriculture area (i.e.

dryland farm and paddy field) and settlement are in the down- and middle stream area. It should be noted that within this scenario the evergreen forest area will increase but at the other hand the mixed garden area will decrease resulting in a net decrease in the forest area by 11.9%.

Table 4.4. Land use distribution (in %) in the years 2000 and 2050 for different scenarios.

Land use class	Reference (year 2000)	Future (year 2050)			
		BAU Scenario		CON Scenario	
	LU 2000	LU 2050	Δ	LU 2050	Δ
Forest area	42.2	7.2	-35	30.3	-11.9
a. Evergreen forest	3.0	2.3	-0.7	13.2	10.2
b. Mixed garden	39.2	4.9	-34.4	17.1	-22.1
Agriculture area	36.9	40.4	3.5	52.1	15.2
a. Paddy field	28.2	22.2	-6	34	5.8
b. Dryland farm	8.7	18.2	9.5	18.1	9.4
3. Settlement	16.3	50.2	33.9	17.3	1
4. Shrub	4.3	1.9	-2.4	0	-4.3
5. Water body	0.3	0.3	0	0.3	0

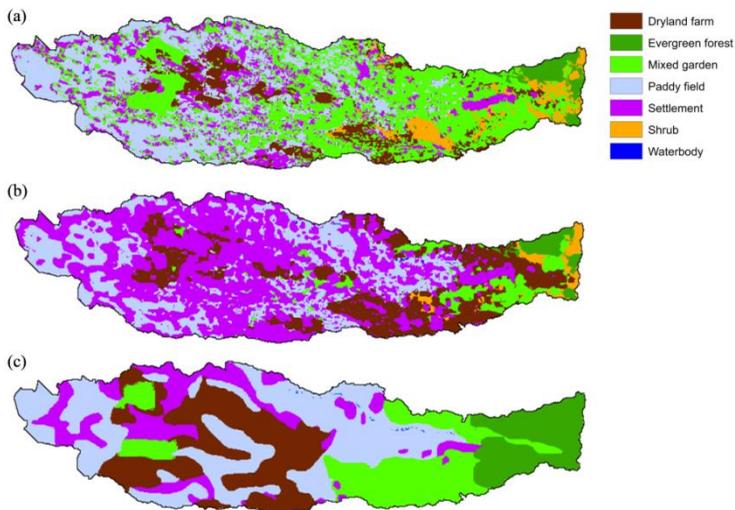


Figure 4.4. Land use cover of the Samin catchment in 2000 (a) and 2050 under business as usual (BAU) scenario (b) and controlled (CON) scenario (c).

4.4.2. Climate change

Figure 4.5 shows the changes in mean annual precipitation from the RCM and GCMs under RCP 4.5 and RCP 8.5 in the future period (2030–2050) relative to the baseline period (1983–2005). Based on the RCM, the mean annual precipitation in the study catchment is predicted to decrease by 412 mm (-20%) under RCP 4.5 and 505 mm (-25%) under RCP 8.5. The direction of change in the mean annual precipitation for the RCM is similar to the directions of change from three GCMs (i.e. GFDL-ESM2M, CanESM2 and CSIRO-Mk3.6.0), which predicted a decrease in mean annual precipitation ranging from 8 mm (-0.4%) to 193 mm (-18%) under RCP 4.5 and from 22 mm (-1%) to 343 mm (-17%) under RCP 8.5. On the contrary, three GCMs, namely MIROC5, MPI-ESM-LR and NorESM1-M, show an opposite direction of change in the mean annual precipitation over the study area. These GCMs predict an increase in mean annual precipitation in the future ranging from 91 mm (+5%) to 384 mm (+19%) under RCP 4.5 and from 87 mm (+4%) to 287 mm (+15%) under RCP 8.5. Although the RCM-simulated precipitation was downscaled from the CSIRO Mk.3.6.0 GCM, the magnitude of change of the two is different, in particular under the RCP 4.5 scenario. This is probably due to systematic biases in the RCM, which makes it independent from its driving datasets because of its physics parameterization (Murphy et al., 2004), and application of the bias-correction method (Themeßl et al., 2012).

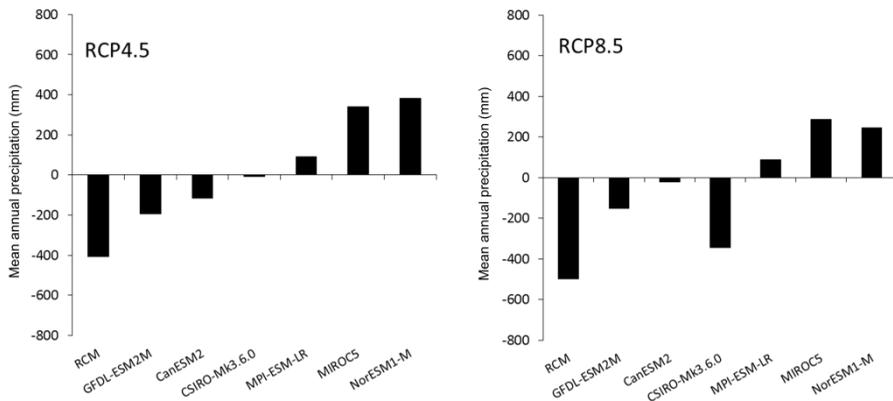


Figure 4.5. Changes in mean annual precipitation in the Samin catchment in the future period (2030–2050) relative to the baseline period (1983–2005) under RCP 4.5 and RCP 8.5 scenarios.

While different climate models show inconsistent directions of change for the future precipitation, all climate models predict a similar direction of change for the maximum and minimum temperature, although with slightly different magnitudes. For the RCM, the mean annual maximum and minimum temperatures increase for both scenarios, by $+1.0^{\circ}\text{C}$ and $+1.3^{\circ}\text{C}$, respectively, under RCP 4.5, and by $+0.7^{\circ}\text{C}$ and $+1.4^{\circ}\text{C}$, respectively, under RCP 8.5. All GCMs predicted an increase of about $+1^{\circ}\text{C}$ in the mean annual maximum and minimum temperature in the future period compared to the baseline period under both RCP 4.5 and RCP 8.5 scenarios.

4.4.3. Future hydrological response

4.4.3.1. Effects of land use change

In comparison to the baseline conditions (1983–2005), simulations under land use change scenarios indicate a decrease in the mean annual ET and an increase in the mean annual Q and Q_s (Figure 4.6a). However, the directions of change were different for Q_i and Q_b . Under BAU, Q_i increased and Q_b decreased while under CON, Q_i decreased and Q_b increased. It was found that under BAU the mean annual ET decreases by 15%, which is larger than the decrease of 7.4% under CON. A decrease in the mean annual ET under both scenarios is compensated by an increase in the mean annual Q with the same magnitude. More pronounced changes occur in the fraction of Q that becomes Q_s , Q_i and Q_b . Under BAU, the mean annual Q_s and Q_i increase by 40% and 20%, respectively, at the expense of Q_b , which decreases by 3%. Under CON, the mean annual Q_s increases by 16% and the mean annual Q_b by 6%, while the mean annual Q_i was relatively constant.

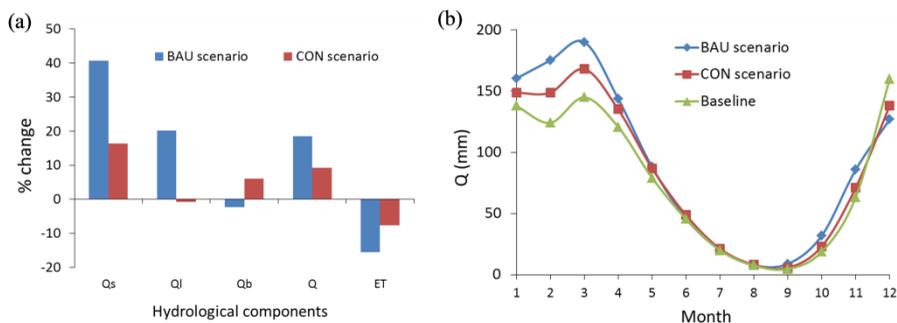


Figure 4.6 (a) Change in the mean annual water balance components under different land use change scenarios compared to the baseline period. (b) Mean monthly streamflow under different land use change scenarios.

At a monthly scale (Figure 4.6b), the simulated Q under both land use change scenarios is higher than in the baseline period during the wet season and similar to the baseline period during the dry season. The mean monthly Q under the BAU and CON scenarios reaches its peak in February, with a value of 175 mm (+41%) and 149 mm (+20%), respectively.

4.4.3.2. Effects of climate change

There is a large uncertainty in the future mean annual P for both RCP 4.5 and RCP 8.5, which causes a large variation in the predicted water balance components (Figure 4.7). Projected changes in the mean annual P under different RCP scenarios range from -20% to +19% under RCP 4.5 and from -25% to +15% under RCP 8.5. Together with an increase in the simulated PET of about 3%, changes in the mean annual P from both RCP scenarios cause a significant change in the mean annual Q as well as in the fractions of flow that become Q_s , Q_i and Q_b , while changes in ET are relatively minor. Under RCP 4.5, projections of the mean annual Q and ET range from -35% to +43% and from a -7% to +5%, respectively. Pronounced changes can be observed for the mean annual Q_s (ranging from -33% to +50%), Q_i (ranging from -32% to +38%) and Q_b (ranging from -38% to +39%). Under RCP 8.5, projections of the mean annual Q and ET range from -47% to +32% and from -10% to +5%, respectively, whereas changes in the mean annual Q_s , Q_i and Q_b range from -44% to +36%, from -41% to +29%, and -56% to +28%, respectively. The large ranges in the projections for the mean annual water balance components likely result from the differences in the predicted P from the different climate models. It should be noted that the RCM downscaled from a CSIRO Mk.3.6.0 GCM projected a (very) significant decrease in the mean annual P for both scenarios, resulting in pronounced changes in the mean annual Q, Q_s , Q_i and Q_b .

At a monthly scale, most climate models under RCP 4.5 and RCP 8.5 project a decrease in ET during the dry season and an increase during the wet season (Figure 4.8). A large uncertainty is found for the dry season, for which some climate models under RCP 8.5 project a significant decrease in the mean monthly ET, in particular for the simulation using the RCM data. For Q, a large uncertainty is found during the wet season, because different climate models project different directions of change, in particular under RCP 4.5. Under RCP 8.5, the direction of change is evident, with most climate models projecting a decrease of Q from April to December.

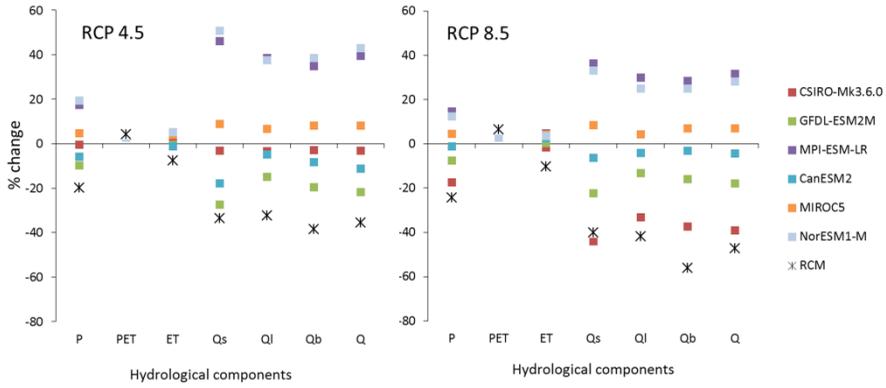


Figure 4.7. Changes in the water balance components (in %) compared to the baseline period under RCP 4.5 and RCP 8.5 scenarios for different climate models.

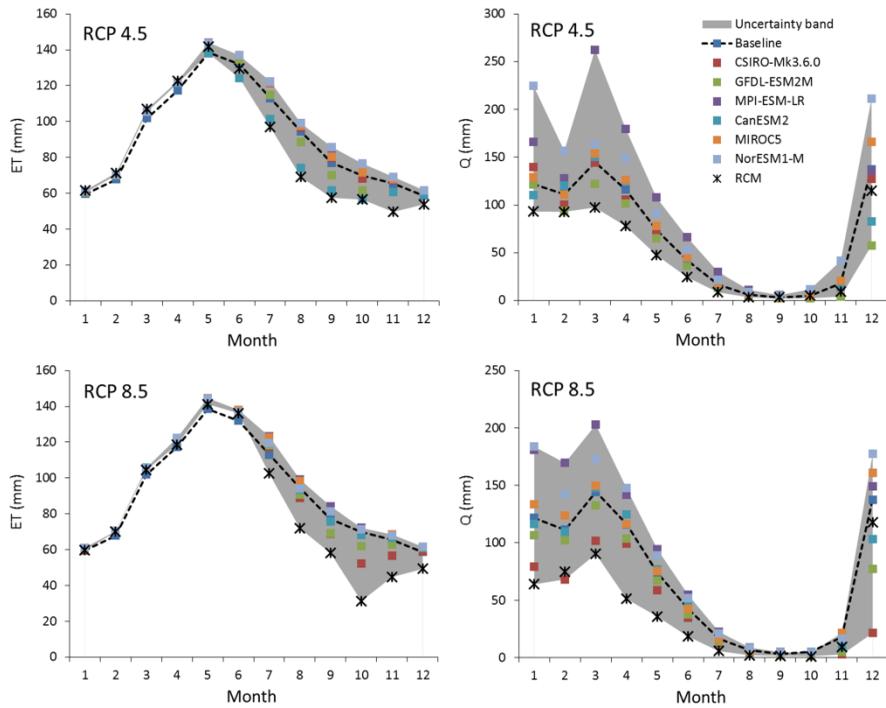


Figure 4.8. Mean monthly ET and Q from different climate models under RCP 4.5 and RCP 8.5 scenarios.

4.4.3.3. Combined effects of land use change and climate change

When land use and climate change scenarios are combined, the effects on the water balance components are pronounced as shown in Figure 4.9. Mean annual ET decreases, with the highest decrease under the BAU8.5 scenario (ranging from -10% to -25%) and the lowest decrease under the CON4.5 scenario (-1% to -14%). The direction of changes in the mean annual ET under combined climate and land use change scenarios are similar with the ET changes found when consider land use change only scenario. The mean annual Q is mostly predicted to increase under the BAU4.5 scenario (from -7% to +64%), whereby only the simulation with RCM data predicted a decrease in Q. Under the BAU8.5 and CON4.5 scenarios, the changes in the mean annual Q range from -18% to +53% and -19% to 52%, respectively. The largest uncertainty in change in the mean annual Q is found under the CON8.5 scenario, in which mean annual Q will change by -30% to +42%. An increase in the mean annual Q is observed under the BAU4.5 scenario, although some climate models predict a decrease in the mean annual precipitation. Changes in the mean annual Q due to land use change are amplified under wetting climate scenarios (prediction of an increase in the future precipitation from the climate models), where the mean annual Q increases by about 64% under scenario BAU4.5, which is about 40% more than under the land use change only scenario.

Similarly, there is a significant increase in the mean annual Q_s in particular under the BAU4.5 and BAU 8.5 scenarios, although the RCM and some GCMs predict a decrease in the mean annual precipitation. The mean annual Q_s is predicted to increase by +21% to +102% and by +2% to +91% under the BAU4.5 and BAU8.5 scenarios, respectively. Changes in the mean annual Q_s are pronounced for wetting climate scenarios, where the mean annual Q_s increases by about 100% compared to the baseline conditions, which is 60% more than under the land use change only scenario. For Q_b , it is observed that scenarios show increases as well as decreases in the mean annual Q_b , resulting in a large uncertainty. The directions of change in the mean annual Q_b under different scenarios are similar to those under the climate change only scenario. The CON4.5 scenario predicts the largest change in mean annual Q_b with a range from -30% to +46%, subsequently followed by the CON8.5, BAU4.5 and BAU8.5 scenarios.

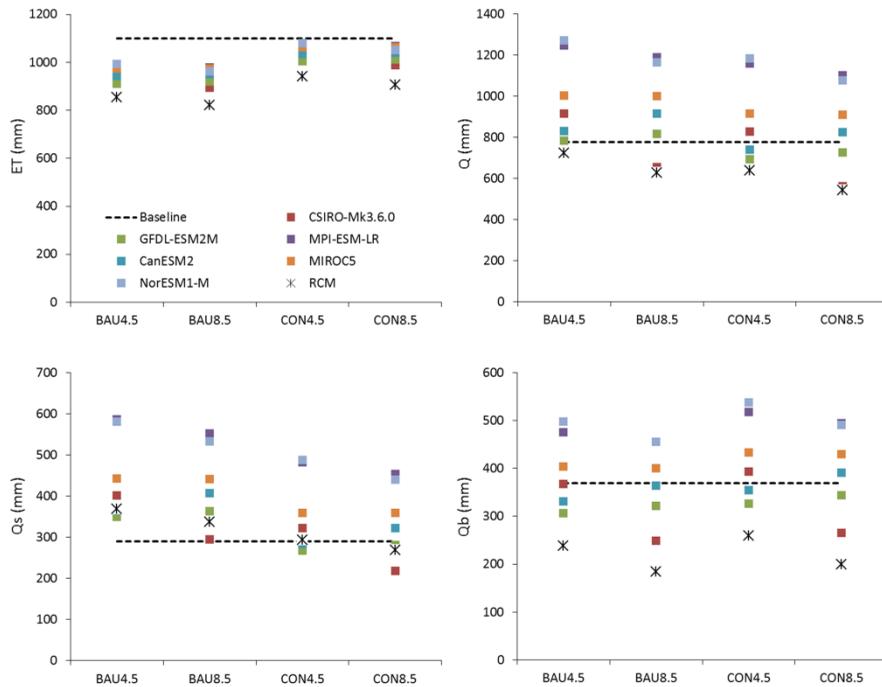


Figure 4.9. Predicted mean annual water balance components for different combinations of climate change and land use change scenarios.

At a monthly scale, most of the scenarios project an increase in the mean monthly Q from January to March, where changes in the mean monthly Q range from +60% to +120% compared to the baseline period (Figure 4.10). During the dry season, a large uncertainty is found for all scenarios, which predict decreases as well as increases in the mean monthly Q. At the start of the wet season (i.e. November), most scenarios predict a decrease in the mean monthly Q, whereby the largest decrease is found under the CON85 scenario (ranging from -84% to +14%), subsequently followed by BAU85, CON45 and BAU45.

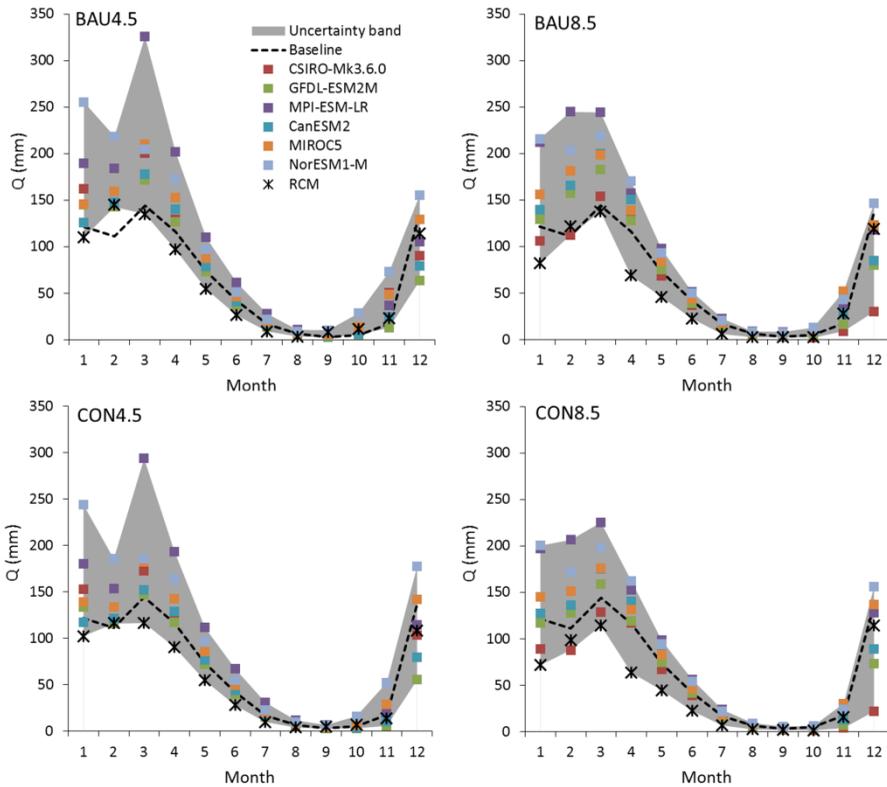


Figure 4.10. Mean monthly streamflow for different combinations of land use change and climate change scenarios

4.5. Discussion

In the Samin catchment, changes in land use are mainly controlled by internal factors, such as expansions of agriculture and settlements, whereas changes in climate variability are considered as externally driven. Both play a significant role in changing hydrological processes of the catchment. Using a modelling approach, this study assesses individual and combined effects of future land use and climate change on the water balance components in the Samin catchment.

4.5.1. Effects of future land use change

Findings show that when future land use changes under a business as usual (BAU) scenario, mean annual evapotranspiration will decrease, resulting in an increase in the mean annual streamflow. The mean annual surface runoff and

lateral flow are projected to increase almost twofold, but base flow will decrease. A massive land use conversion from vegetated area into settlement area as suggested by the BAU scenario will significantly reduce canopy interception and soil infiltration capacity, resulting a large fraction of precipitation being transformed into surface runoff (Bruijnzeel, 2004; Valentin et al., 2008; Marhaento et al., 2017a). As a result, under BAU, the Samin catchment will face an increasing risk for disastrous events such as flash floods, landslides and severe soil erosion. Those risks can be potentially reduced by introducing and enforcing a land use planning regulation. It was simulated that the allocation of forest area to the upstream part of the catchment and agriculture to the midstream part, while maintaining the settlement area, as suggested by the CON scenario, will significantly reduce the mean annual surface runoff and lateral flow, while the mean annual base flow will increase. A large fraction of vegetated area (i.e. evergreen forest) may lead to an increase in the water storage capacity of the soil due to greater root penetration and biotic activity in the upper soil layers, resulting in a larger infiltration rate and ground water recharge (Bruijnzeel 1989; 2004; Guevara-Escobar et al., 2007). With more water infiltrated and stored into the soil, a more balanced water distribution between wet and dry seasons can be expected. The directions of change in the water balance components by land use change in this study are in line with other studies in the tropics from Bruijnzeel (1989), Valentin et al. (2008), Remondi et al. (2016) and Marhaento et al. (2017a).

4.5.2. Effects of future climate change

When considering only climate change, findings show that changes in the mean annual precipitation may have large impacts on the water availability of the Samin catchment. An increase (or decrease) in the mean annual precipitation may result in a large increase (or decrease) in the streamflow and in the fractions of flow that become surface runoff, lateral flow and base flow, while changes in ET were relatively minor. However, small increases in precipitation are likely to have little impacts on the water balance. More significant impacts on the water balance can be observed if the changes in the mean annual precipitation are larger than 10%, where the impacts on streamflow and on the fractions of flow that become surface runoff, lateral flow and base flow can be twice the changes in precipitation. These findings are similar to the results of Mango et al. (2011) and Liu et al. (2011). The rising temperature causes an increase in the potential evapotranspiration, which may affect the mean annual ET due to an increase in the available energy (Budyko, 1974). However, this study finds that changes in annual ET are likely attributed to changes in annual precipitation, where the variations of ET follow the variations of precipitation. Thus, an increase in ET is

found during the wet season while a significant decrease in ET is found during the dry season. These findings are in line with Budyko (1974), who argues that changes in evapotranspiration are determined by the balance between precipitation and evaporative demands.

4.5.3. Combined effects of future land use change and climate change

The findings show that both land use change and climate change contribute to changes in the water balance components, but each driver has a specific contribution to the water balance alteration. Under combinations of land use and climate change scenarios, changes in the annual evapotranspiration are likely attributed to land use change, while changes in the annual base flow are likely attributed to climate change. It should be noted that this study used two completely different land use scenarios, where the BAU scenario represents deforestation and the CON scenario (partly) reforestation. Thus, changes in annual evapotranspiration under different land use change scenarios can be clearly observed, since trees are generally known to have higher evapotranspiration rates than other land uses (Bruijnzeel, 1989; 2004; Marhaento et al. 2017a). The presence of forests can increase the annual evapotranspiration from both canopy interception and plant transpiration, so that under the BAU scenario there will be a significant decrease in the annual evapotranspiration. However, one cannot neglect the role of climate variability to control changes in the annual evapotranspiration, since evapotranspiration is largely influenced by precipitation (Budyko, 1974; Liu et al., 2013). At a monthly scale, evapotranspiration is close to its potential value during the wet season, since precipitation supplies sufficient water, whereas in the dry season, the evapotranspiration capacity is mainly determined by the antecedent soil moisture and influenced by different land cover types (Liu et al., 2013).

The magnitude of changes in annual base flow is mainly determined by climate change (i.e. changes in precipitation), whereby the directions of change in annual Q_b under different scenarios are similar to those under the climate change only scenario. This study finds a small effect of land use change on the changes in the annual base flow, whereby a larger base flow is found under the CON scenario. However, the magnitude of changes in base flow under different land use scenarios was smaller than expected. According to Ilstedt et al. (2007), the presence of forests can result in more base flow due to an enhanced groundwater recharge. Apparently, in this catchment, the effects of land use change on the base flow are offset by climate change. Thus, more research is needed to assess the attribution of changes in the base flow to land use change and climate change.

Combined land use change and climate change have more pronounced effect on the streamflow and surface runoff. A projected increase in precipitation accompanied by the deforestation scenario (BAU scenario) will have more significant impacts on streamflow and surface runoff than land use change or climate change acting alone (Legesse et al., 2003; Hejazi & Moglen, 2008; Khoi & Suetsugi, 2014). Moreover, at a monthly scale, the streamflow originating from surface runoff significantly increases during the wet season and decreases during the dry season, indicating that more extreme events (i.e. droughts and floods) can potentially occur in the future. Under the land use planning scenario (CON scenario), the effects can be reduced, but only by less than 20%. Thus, more measures (e.g. soil conservation) are required in addition to land use planning in order to enhance infiltration and aquifer recharge and subsequently reduce risks due to land use and climate change impacts.

4.5.4. Limitations and uncertainties

This study couples a land use change model, climate change model and hydrological model, whereby each model can be a source of uncertainty affecting the results. For the land use change model, an integration of the CA-Markov and MCE techniques was used to project future land use distributions. However, this method predicts land use in the future based on extrapolation of trends, while future trends obviously are uncertain due to uncertainties in e.g. future population growth. For this reason, this study used a control condition in the simulations to constrain the predictions of the future land use distributions. For the climate change model, large model uncertainties occur due to model choices, where different climate models result in different directions of change in the projected precipitation. For this reason, this study employs six additional GCMs that were selected based on different directions of change in future precipitation to include climate model uncertainty. However, uncertainties from the climate models can be larger due to other sources of uncertainty, for instance from the model structure (e.g. choices of spatial resolution, the set of processes included in the model, basic assumptions on parameterization) and application of statistical downscaling methods (Murphy et al., 2004). For the hydrological model, sources of uncertainty can be present due to the model structure (e.g. model assumptions, equations) as well as data inputs (e.g. lack of relevant spatial and temporal variability of data on precipitation, soils, land uses and topography). Moreover, the scenario settings used in this study follow a single-factor fixed method, which does not take into account atmospheric feedbacks of land surface processes (Blöschl et al., 2007).

4.6. Conclusions

This study assessed the separate and combined impacts of future changes in land use and climate on the water balance components in the Samin catchment. Results based on the SWAT modelling approach show that both land use and climate change can result in changes in the water balance components, but that more pronounced changes will occur if the drivers are mutually considered, this in particular for the mean annual stream flow and surface runoff. When combining the RCP 4.5 climate scenario and BAU land use scenario, the mean annual streamflow and surface runoff are expected to change by -7% to +64% and +21% to +102%, respectively, which is 40% and 60% more than when land use change is acting alone. When the BAU land use scenario is replaced by the CON land use scenario, the mean annual streamflow and surface runoff reduce by up to 10% and 30%, respectively, while the mean annual base flow and evapotranspiration increase by about 8% and 10%, respectively. The findings show that land use planning can be one of the measures to reduce future water-related risks in the Samin catchment. However, it remains a challenge to accurately predict the hydrological changes due to land use and climate change since there are various uncertainties, in particular associated with future climate change scenarios.

Chapter 5

Sensitivity of streamflow characteristics to different spatial land use configurations in a tropical catchment⁴

Abstract

This paper analyses the impact of the spatial configuration of specific forms of land use, like forest and settlements, on streamflow in the Samin catchment, Indonesia. Land use distributions in the past have been reconstructed based on satellite images and used to assess land use pattern characteristics for the years 1982, 1994, 2000, 2006 and 2013. Hydrological processes of the study catchment are simulated using a validated Soil and Water Assessment Tool (SWAT), taking land use distribution for the mentioned years as inputs. Next, a correlation analysis between changes in land use pattern characteristics and simulated streamflow characteristics was carried out. A land use scenario analysis was done to assess the sensitivity of streamflow characteristics to different future land use patterns. The results show that changes in the streamflow characteristics of the study catchment can be attributed to changes in the percentages of different land use types and changes in the physical connectivity between patches of similar land use types. When the relative presence of different land use types is fixed but the physical connectivity of patches is changed, it is found that an increase in the settlement connectivity can result in an increase in the ratio of surface runoff to streamflow and a decrease in the ratio of dry-season streamflow to wet-season streamflow, and vice versa, while changes in the forest connectivity have less impact on streamflow characteristics. The results suggest that land use pattern management can be an important component in water management.

⁴ This chapter is based on a paper that has been submitted as: Marhaento, H., Booij, M. J., Rientjes, T. H. M., & Hoekstra, A. Y. Sensitivity of streamflow characteristics to different spatial land use configurations in a tropical catchment.

5.1. Introduction

In the last decades, the impacts of land use changes on catchment hydrology have received a lot of attention. Numerous studies argue that different types of land use have different water use and water storage characteristics, thus different land use distributions may result in different distributions of water in space and time (Bruijnzeel, 1989; 2004; Sahin & Hall, 1996; Brown et al., 2005; Romanowicz & Booij, 2011; Gumindoga et al., 2014a; Zhang et al., 2016; Marhaento et al., 2017a). Studies in tropical regions have shown that changes from vegetated areas into settlements may significantly reduce canopy interception and soil infiltration capacity, resulting in a large fraction of precipitation being transformed into surface runoff (Bruijnzeel, 2004; Valentin et al., 2008; Marhaento et al., 2017a). In addition, the spatial distribution of different land uses may affect the hydrological response of catchments, for example the velocity and volume of surface flow entering a stream (Wheater & Evans, 2009; Su et al., 2014). Hence, land use management can be used as a measure in water management practice for flood prevention and drought mitigation (Wheater & Evans, 2009 and Zhang et al., 2013).

Given the rapid growth of populations and associated demand for settlements and agricultural lands, land use policy can be a relevant factor in water management (Carter et al., 2005). Increased demands for settlements and farming areas can be in conflict with an increased demand for water resources. For instance, agricultural intensification and settlement development can lead to a reduction in soil infiltration rates and base flow and an increase of surface runoff and soil erosion. Therefore, future land allocation and land use management should be designed based on a proper understanding of how land use changes may affect catchment hydrology (see Carter et al., 2005).

Most studies assessing the effects of land use change on hydrological processes focused on the impact of changes in the relative presence of different land use types. Less attention has been given to the impacts of changes in spatial land use configurations (e.g. shape and connectivity of land use types). The impact of the spatial land use pattern on water resources, however, is relevant when selecting a particular land use management strategy (Azevedo et al., 2005; O'Connell et al., 2007; Bakker et al., 2008). Relevant questions are, for example: what is the effect of choosing different locations for certain new land uses (e.g. high vs. low elevations), and what is the effect of different spatial configurations (e.g. small-scattered vs. large-clustered) of forest planting and harvesting strategies? A better understanding will give insight in the potential effects of alternative land use decisions on water availability at catchment scale (Lin et al., 2007). Figure 5.1 depicts different spatial land use patterns which may result in different hydrological responses.

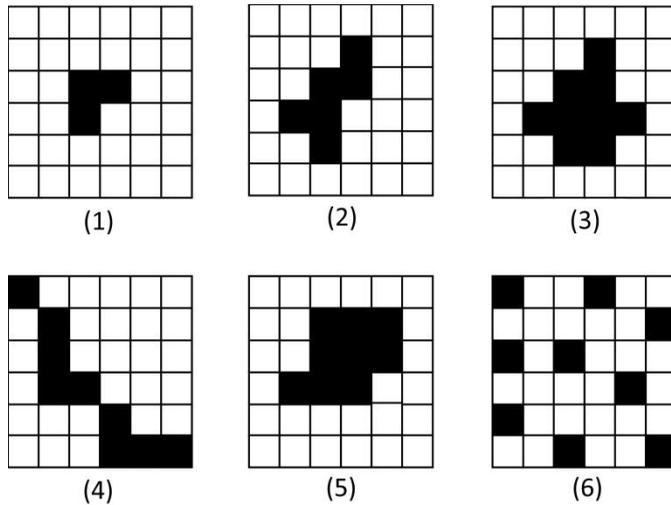


Figure 5.1. Six grids of 6 x 6 cells showing differences in abundance of a certain land use type (e.g. settlements) and differences in spatial configuration of this land use type in the landscape. Grids 1 to 3 show an increase in abundance, from 3/36 to 6/36 to 9/36 of the total area, respectively. Grids 4 to 6 show changes in the spatial patterns (e.g. shape and connectivity) while the fraction of patches to the total area is maintained at 9/36.

The impact of land use patterns on hydrological processes is often studied by means of a paired catchment approach, in which land use in the control catchment is held constant while land use in the treatment catchment, having similar physical conditions, is changed. Measurements then focus on the differences in hydrological response between the control and treatment catchment (Fohrer et al., 2005). Suryatmojo et al. (2011) used this approach to assess the impacts of different forest harvesting strategies (i.e. selective logging) on the streamflow characteristics in Central Kalimantan, Indonesia, and found that applications of different forest harvesting strategies resulted in different hydrological responses (i.e. peak flows). Sahin and Hall (1996) and Brown et al. (2005) reviewed the results of numerous paired catchment studies worldwide and found that changes in land use through deforestation, afforestation, re-growth and forest conversion can affect annual streamflow, which is likely to increase with the percentage of forest removed. Although a paired catchment study can provide relevant information of changes in hydrological processes due to changes in land use, this method is only applicable to small catchments (<25 km²), for which uncertainties due to spatial heterogeneity are relatively small (Fohrer et al., 2005; Brown et al., 2005).

For larger catchments ($>100 \text{ km}^2$), a modelling approach is typically used. Zhang et al. (2013) generated various hypothetical land use patterns using a land use change model and used these as input for a grid-based hydrological model to assess the impacts of land use patterns on streamflow in the Yong Ding catchment (300 km^2), China. They found that land use fragmentation may affect streamflow characteristics at different spatial resolutions. At fine scale ($30 \times 30 \text{ m}^2$), fragmented grassland positively correlated with peak flow and total streamflow, while at coarse scale ($1,200 \times 1,200 \text{ m}^2$), fragmented forest positively correlated with peak flow and total streamflow. Li and Zhou (2015) assessed the correlation between various land use pattern characteristics and hydrological variables (i.e. streamflow and sediment yield) in the Yanhe catchment ($7,725 \text{ km}^2$), China, and found that changes in the land use patterns significantly changed the sediment yield but did not significantly change the streamflow. Bormann et al. (2009) used different hydrological models (i.e. WASIM, TOPLATS and SWAT) to assess the sensitivity of water balance components to changes in different land use patterns in the Dill catchment (693 km^2), Germany, and found that land use redistribution slightly affected the water balance components. These studies show that the relationships between land use patterns and hydrological processes at the catchment scale are sometimes contradictory, requiring further study.

This paper aims to assess the impacts of land use patterns on streamflow characteristics of the Samin catchment (278 km^2) in Java, Indonesia. Hydrological processes of the study catchment were simulated using the semi-distributed physically based Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998). In the first part of this study, land use patterns over the period 1982-2013 have been reconstructed. Landsat images from the years 1982, 1994, 2000, 2006 and 2013 were used to assess past land use patterns. Different landscape metrics were calculated using FRAGSTAT (McGarigal & Marks, 1995) to define spatial land use pattern characteristics for each year. In the second part of this study, correlations between land use metrics and streamflow characteristics were determined. Two streamflow characteristics, the ratio of surface runoff to streamflow (Q_s/Q) and the ratio of streamflow in the dry season to streamflow in the wet season ($Q_{\text{dry}}/Q_{\text{wet}}$) were simulated using a validated SWAT model (Marhaento et al., 2017a) with different land use distributions. For the third part of this study, hypothetical land use scenarios were developed in order to assess the sensitivity of streamflow characteristics to different spatial land use configurations. In this scenario analysis, land use planning for the study catchment available from the Central Java Provincial Government (2010) was used as a baseline scenario and its spatial configuration was changed while maintaining the percentage of each land use type. Finally, this study assessed the potential hydrological impacts of different land use patterns in the study

catchment. The study area and data used are described in Section 5.2. Section 5.3 covers the methods used in this study. Section 5.4 presents the results, Section 5.5 discusses the key findings, and Section 5.6 draws the conclusions from this study.

5.2. Study area and data availability

5.2.1. Catchment description

The Samin river is a tributary of the Bengawan Solo river, the longest river in Java, Indonesia. The source of the river is the Lawu Mountain (3,175 m above sea level). The Samin catchment area is about 278 km², situated between 7.6^o–7.7^o southern latitude and 110.8^o–111.2^o eastern longitude. The mean elevation of the catchment is 380 m, the mean slope 19.8%, and the stream density around 2.2 km/km². The soil composition of the Samin catchment is predominantly Luvisols, a leafy humus soil that can be mainly found in the midstream and downstream areas, and Andosols, a volcanic soil that can be mainly found in the upstream area near the Lawu Mountain. These soils cover 57% and 43% of the study area, respectively. The study catchment has a tropical monsoon climate with a distinct wet season (November to April) and dry season (May to October), with January-March being the wettest period and July-September the driest period of the year. In the period 1990-2013, the mean daily temperature varied between 21.5 °C and 30.5 °C, the annual precipitation varied between 1,500 mm and 3,000 mm, the annual potential evapotranspiration varied between 1,400 mm and 1,700 mm, and the annual streamflow varied between 500 mm and 1,200 mm (Marhaento et al., 2017b). Figure 5.2 shows the Samin catchment with its topography and the location of hydro-meteorological gauges.

5.2.2. Data availability

Various datasets are available for modelling hydrological processes of the study catchment, such as a Digital Elevation Model (DEM), land use data, soil data and climate data. The DEM was generated from a contour map with a contour interval of 12.5 meters, which was made available by the Indonesia Geospatial Information Agency. Furthermore, the DEM was used to delineate the catchment and sub-catchment boundaries and to generate a slope map. Land use maps with a spatial resolution of 30 m for the years 1994, 2000, 2006 and 2013 were available for the study area from Marhaento et al. (2017a). An additional land cover image for September 11, 1982 was acquired from the Landsat satellite (USGS, 2017) to represent land use for the year 1982.

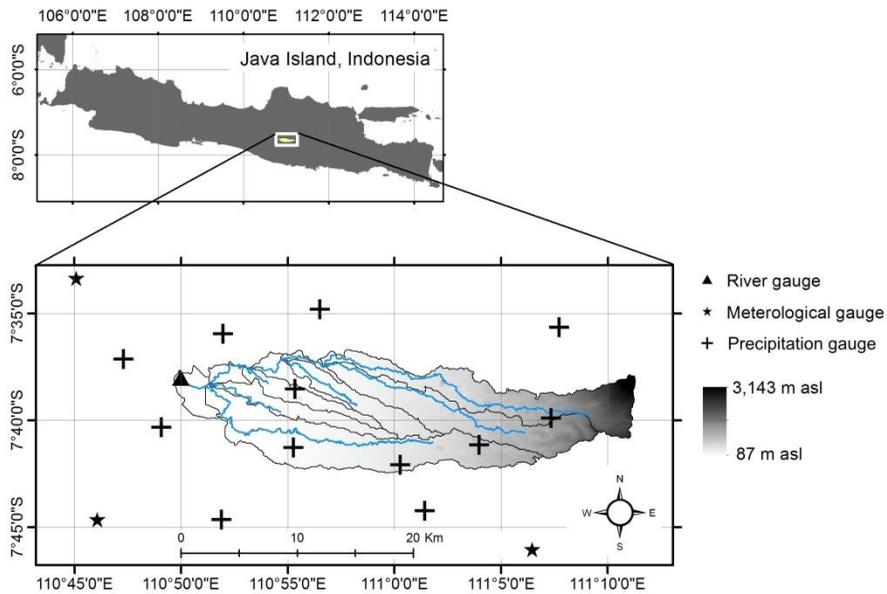


Figure 5.2. Location of the Samin catchment in Java, Indonesia, with locations of hydro-meteorological gauges.

A soil map at 30-arc second spatial resolution was available from the Harmonized World Soil Database (FAO et al., 2012). A land use spatial planning map of the study area for the period 2009–2029 was available with a spatial scale of 1:500.000 from the Central Java Provincial Government (2010). Daily climate data were available from eleven precipitation stations and three meteorological (see Figure 5.2) stations for the period 1983–2013, provided by the Bengawan Solo River Basin office and the Adi Sumarmo Airport. The Bengawan Solo River Basin office provided daily water level data in the Samin catchment for the period 1990–2013, including the rating curve to convert the water level data into discharge data for model calibration. This study used the same climate and discharge dataset as Marhaento et al. (2017b), who have filled and corrected time series of the daily climatological and discharge data of the Samin catchment.

5.3. Method

5.3.1. Reconstruction of past land use change

Land use patterns over the period 1982-2013 have been reconstructed based on Landsat images from the years 1982, 1994, 2000, 2006 and 2013, following the approach of Marhaento et al. (2017a). The Landsat images have been processed through two steps: pre-processing and image classification. Pre-processing included a non-systematic geometric correction to avoid distortion of map coordinates and a masking analysis to remove the area outside the study area. Image classification was performed using a maximum likelihood approach based on a thousand ground-control points (GCPs) from Marhaento et al. (2017a). For this study, land use classes in Marhaento et al. (2017a) are reclassified into four land use classes: forest area (combining evergreen forest and mixed garden), agricultural area (combining paddy field and dry land farming), settlements and other areas (combining shrub, bare land and water body). The latter covers less than 5% of the catchment area.

In order to characterize land use patterns for respective years, landscape metrics for each land use distribution were calculated using FRAGSTATS (McGarigal et al., 2012). Landscape metrics are quantitative indices that describe spatial aspects (e.g. size and edge, shape, connectivity) of landscapes based on spatial data (Kupfer, 2012). FRAGSTATS is software that can be used to calculate numerous landscape metrics simultaneously within a Geographical Information System. It has been widely used in landscape analysis including its relations with hydrological processes (Lin et al., 2007; Zhang et al., 2013; Li and Zhou, 2015).

There are different spatial levels at which landscapes can be analyzed, namely cell, patch, class, and landscape level. The selection of the appropriate level for analysis depends on the level of heterogeneity for the question under consideration (McGarigal et al., 2012). This study focuses on the class level since this study aims to analyze the spatial patterns for individual land use types within a catchment. Since there are numerous landscape metrics available with redundant information, this study selected fifteen metrics that represent a wide range of land use pattern characteristics and were previously reported having a relationship with hydrological processes (Lin et al., 2007; Zhang et al., 2013; Li and Zhou, 2015). These metrics include five metrics that describe landscape size and edge, namely percentage of land use type (PL), number of patches (NP), patch density (PD), largest patch index (LPI) and edge density (ED), five metrics that describe landscape shape (i.e. geometric complexity of patch types), namely perimeter-area ratio (PAR), shape index (SHI), fractal dimension index (FDI), related circumscribing circle (RCC) and contiguity index (CI), and five metrics that describe landscape aggregation (i.e. tendency of patch types to be spatially

aggregated), namely euclidian nearest neighborhood distance (ENN), proportion of like adjacencies (PLA), splitting index (SPI), landscape shape index (LSI) and patch cohesion index (PCI). A detailed description of these landscape metrics including their equations can be found in McGarigal and Marks (1995).

5.3.2. Hydrological model simulations

Hydrological processes were simulated using the SWAT model (Arnold et al., 1998), a physically based semi-distributed hydrological model operating at a daily time step, which has proven its suitability for hydrologic impact studies around the world (Wagner et al., 2013; Memarian et al., 2014, Marhaento et al., 2017a). The SWAT model divides a catchment into sub-catchments and further divides each sub-catchment into hydrological response units (HRUs), at which level a land-phase water balance is calculated (Neitsch et al., 2011). A HRU is defined as a lumped area within a catchment assumed to have uniform hydrological behavior and is characterized by a dominant land use type, soil type and slope (Arnold et al., 1998). A daily water balance is computed for each HRU for each sub-catchment, and runoff is routed through channels to the catchment outlet where the water balance of the catchment is calculated. A SWAT model calibrated and validated for the Samin catchment was available from a previous study (Marhaento et al., 2017a). In the current study, equal SWAT model settings were applied as in the previous study. However, since this study used a coarser land use classification, thus crop parameters for each land use class used in this study are averages (e.g. forest is a combination of evergreen forest and mixed garden). Here, a brief summary of the model setup and parameterizations is presented; a detailed description can be found in Marhaento et al. (2017a).

Eleven sub-catchments ranging in size from 0.12 km² to 83 km² have been generated from the DEM. A land use map with four classes (i.e. forest, settlement, agriculture and other areas), a slope map with five classes (i.e. 0-8%, 8-15%, 15-25%, 25-45%, >45%) and a soil map with three classes (i.e. luvisols, andosols and vertisols) were used to create Hydrological Response Units (HRUs), by spatially overlying maps of land use, soil and slope classes. The Penman-Monteith method and the Soil Conservation Service Curve Number (SCS CN) were used to calculate reference evapotranspiration and surface runoff, respectively. For flow routing, this study used the Muskingum method that models the storage volume as a combination of wedge and prism storages (Neitsch et al., 2011). Six SWAT parameters were calibrated based on the observed discharge using the Latin Hypercube Sampling approach from the Sequential Uncertainty Fitting version 2 (SUFI-2) in the SWAT-Calibration and Uncertainty Procedure (SWAT-CUP) package on a monthly basis. The

calibration period is 1990–1995 and the validation period is 1996-2013. The Nash Sutcliffe Efficiency (NSE) was used as objective function. The NSE values for model calibration and validation were 0.78 and 0.70, respectively.

5.3.3. Changes in land use patterns and streamflow characteristics

Effects of past land use changes on hydrological processes were simulated using the validated SWAT model, using as inputs land use distributions in the years 1982, 1994, 2000, 2006 and 2013 and observed meteorological time series in the period 1983-2013, with a 2-years “warming-up” period. Each land use distribution was simulated separately with the same meteorological input so that the differences obtained from the simulations are only due to the differences in land use. For each simulation, the ratio of mean annual surface runoff to streamflow (Q_s/Q) and the ratio of streamflow in the dry season to streamflow in the wet season (Q_{dry}/Q_{wet}) is determined. Following the mean monthly precipitation from 1983-2013, it was observed that July-September (JAS) is the driest period of the year and January-March (JFM) the wettest. For this reason, streamflow in the period JAS and JFM were accumulated to represent streamflow in the dry season and the wet season, respectively. While Q_s/Q is often used as an indicator for determining the severity of land degradation of the catchment, Q_{dry}/Q_{wet} can be used as a measure to represent the seasonal balance of water availability within the catchment. Furthermore, the relationships between changes in land use metrics and streamflow characteristics were analyzed using Pearson’s correlation statistic.

5.3.4. Simulation of land use scenarios

In order to explore changes in streamflow characteristics in relation to changes in land use patterns, hydrological processes were simulated under different land use scenarios. In this scenario analysis, the spatial patterns of the land use planning of the study area available from the Central Java Provincial Government (2010) were changed, while the percentages of different land use types remained unchanged (as depicted in Figure 5.1). The land use planning is used as a baseline scenario and provides spatial constraints for the land use scenarios. Land use planning was selected because it is assumed to be the future direction of land use management in the study area. Developing land use scenarios based on the land use planning can support the exploration of potential hydrological impacts of alternative land use planning. Land use scenarios were developed at a 250×250 m² spatial resolution following the spatial scale of the land use planning.

In line with the land use planning, settlements are located in the elevation range from 0 to 1,000 meter above sea level and slope range from 0% to 15%, agriculture is located in the elevation range from 0 to 1000 meter above sea level and slope range from 0 to 20%, and forest is located in the elevation range from 100 to 3,125 meter above sea level and slope range from 0% to 50%. Based on these spatial constraints, locations above 1,000 meter above sea level and slope >20% are only allocated to forest area, while other locations can be for every land use type, thus giving room to develop land use pattern scenarios. Within these constraints, two opposite land use scenarios were created to represent a wide range of possible configurations. In the “clustered land use scenario” each land use class was combined at sub-catchment level following the guideline from the Presidential Regulation of the Republic of Indonesia number 32 (1990), where settlements are grouped and positioned at low elevations and flat to middle slopes, agriculture is grouped and positioned at middle elevations and flat to middle slopes, and forest is grouped and positioned at high elevations and steep slopes. In the “scattered land use scenario” each land use class was split at sub-catchment level into several patches and spread within the catchment. It should be noted that in the land use redistribution process, the mean elevation and slope of each land use class were maintained so that land use classes in this scenario have a similar mean elevation and slope as in the land use planning.

5.4. Results

5.4.1. Past land use evolution

Figure 5.3 shows the land use distributions in the Samin catchment in different years in the period 1982-2013. The land use change over this period is characterized by a significant decrease in forest area (-36.1%), which mainly converted into settlement area (+29.6%) and agriculture area (+7.7%), while changes in other land use types were relatively small (-1.2%). The forest area decreased by 4.2% over the period 1982-1994, by 6.6% over 1994-2000, by 16.1% over 2000-2006 and by 9.2% over 2006-2013, while the settlement area increased by 5%, 6.5%, 9.4% and 8.7% over the four respective periods. Agriculture area increased by 1.5% in the period 1982-1994, then decreased by 2.4% in the period 1994-2000, and increased again by 8.6% in the period 2000-2013.

Changes in the distribution of land use types in the period 1982-2013 were accompanied by changes in spatial land use patterns. Table 5.1 shows the landscape metric values for 1982, 1994, 2000, 2006 and 2013 per land use type.

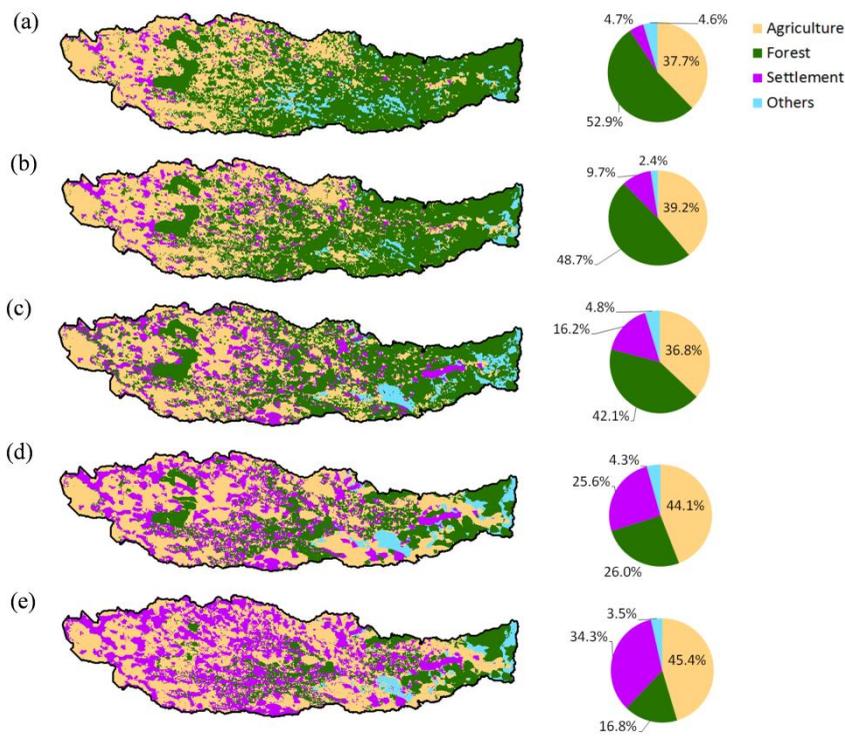


Figure 5.3. Land use distribution of the Samin catchment in 1982 (a), 1994 (b), 2000 (c), 2006 (d) and 2013 (e).

The decrease in the percentage of forest, is accompanied by a decrease in the largest patch index (LPI) and the patch cohesion index (PCI), while there is no clear relation with other metrics. LPI quantifies the percentage of the landscape comprised by the largest patch, while PCI quantifies the physical connectivity of patches from the corresponding land use type. The LPI value for forest was 41.5 in 1982, but decreased to 38.2 (1994), 17.2 (2000), 5.1 (2006) and 2.3 (2013), while the PCI value for forest was 99.8 in 1982, which decreased to 99.7 (1994), 99.2 (2000), 98.2 (2006) and 97 (2013). The increase in the percentage of settlement area, is accompanied by an increase in the edge density (ED) and the PCI values, while there is no clear relation with other metrics. ED quantifies the ratio of edge segment length to total area. The ED value for settlement was 10.8 in 1982 and increased to 24.3 (1994), 39.9 (2000), 41.9 (2006) and 53.9 (2013), while the PCI value of settlement was 91.1 in 1982 and increased to 91.3 (1994), 92.5 (2000), 96.2 (2006), 98.8 (2013). For agriculture, there is no clear relation between changes in the percentage of land use and changes in the other metrics.

Table 5.1. Landscape metrics for 1982, 1994, 2000, 2006 and 2013 at class level.

Metrics*	PL	NP	PD	LPI	ED	PAR	SHI	FDI	RCC	CI	ENN	PLA	SPI	LSI	PCI
Agriculture															
1982	37.8	390	1.4	28.9	49.1	508	1.5	1.1	0.6	0.6	140	90.2	12	33.3	99.7
1994	39.2	764	2.7	27.6	60.1	639	1.4	1.0	0.5	0.5	104	88.5	13	39.9	99.6
2000	36.9	791	2.8	13.5	55.8	635	1.4	1.1	0.5	0.5	102	88.7	36	38.3	99.1
2006	44.3	702	2.5	19.6	49.9	599	1.3	1.0	0.5	0.5	106	91.5	23	31.2	99.2
2013	45.5	690	2.5	31.7	60.5	609	1.4	1.0	0.5	0.5	99	90.0	10	37.3	99.6
Settlement															
1982	4.7	262	0.9	0.3	10.8	438	1.4	1.1	0.6	0.6	247	82.8	24,185	20.6	91.1
1994	9.7	856	3.1	0.9	24.3	604	1.2	1.0	0.5	0.5	140	81.2	6,409	32.5	91.3
2000	16.1	997	3.6	0.8	39.9	611	1.4	1.1	0.5	0.5	108	81.4	3,933	41.4	92.5
2006	25.4	629	2.3	1.4	41.9	462	1.4	1.1	0.5	0.6	110	87.6	837	34.6	96.2
2013	34.2	821	3.0	10.4	53.9	536	1.3	1.0	0.5	0.5	110	88.2	76	38.4	98.8
Forest															
1982	52.9	655	2.4	41.5	52.0	580	1.3	1.0	0.5	0.5	118	92.6	6	29.8	99.8
1994	48.7	720	2.6	38.2	55.7	579	1.3	1.0	0.5	0.5	124	91.4	7	33.2	99.7
2000	42.2	698	2.5	17.2	62.4	497	1.5	1.1	0.5	0.6	110	88.9	24	40.0	99.2
2006	25.9	661	2.4	5.1	36.8	553	1.3	1.0	0.5	0.5	132	89.4	167	30.1	98.2
2013	16.8	711	2.6	2.3	29.4	623	1.3	1.0	0.5	0.5	145	86.9	545	29.9	97.0

* PL = Percentage of land use type (%), NP = Number of patches (-), PD = Patch density (number per 100 hectare), LPI = Largest patch index (%), ED = Edge density (meter/hectare), PAR = Perimeter-area ratio (-), SHI = Shape index (-), FDI = Fractal dimension index (-), RCC = Related circumscribing circle (-), CI = Contiguity index (-), ENN = Euclidian nearest neighborhood distance (meter), PLA = Proportion of like adjacencies (%), SPI = Splitting index (-), LSI = Landscape shape index (-), PCI = Patch cohesion index (-).

5.4.2. Correlations between land use patterns and streamflow characteristics

Figure 5.4 shows that land use changes in the period 1982-2013 have affected simulated streamflow characteristics. The long-term average ratio of mean annual surface runoff to streamflow (Q_s/Q) increased from 0.28 in 1982 to 0.31 (1994), 0.33 (2000), 0.36 (2006) and 0.39 (2013), whereas the long-term average ratio of dry-season to wet-season streamflow (Q_{dry}/Q_{wet}) decreased from 0.13 in 1982 to 0.12 (1994), 0.11 (2000), 0.1 (2006) and 0.09 (2013). A consistent increase of Q_s/Q and a consistent decrease of Q_{dry}/Q_{wet} is in line with the direction of changes in forest and settlement area, where forest has significantly decreased and settlement has significantly increased in the period 1982-2013.

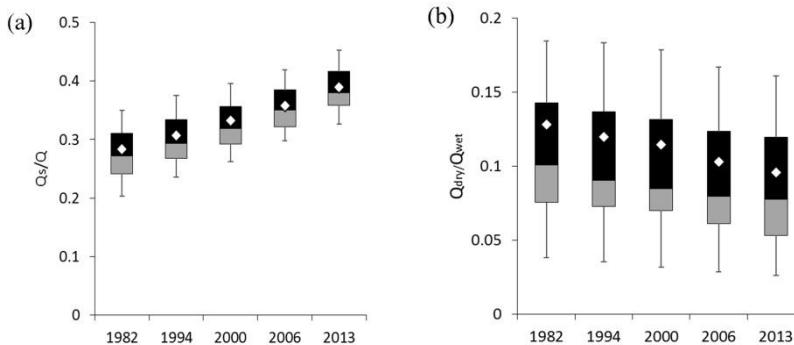


Figure 5.4. (a) Box-whisker plot of the ratio of mean annual surface runoff to streamflow (Q_s/Q) and (b) box-whisker plot of the ratio of mean annual streamflow in the dry season to streamflow in the wet season (Q_{dry}/Q_{wet}) from simulations using land use distributions from different years.

Based on the results of Pearson's correlation analysis between various landscape metrics and streamflow characteristics, it is found that the percentage of forest (PL_f) negatively correlates and the percentage of settlement (PL_s) positively correlates with Q_s/Q , at a significance level of 1%. The cohesion of forest area (PCI_f) negatively correlates and the cohesion of settlement (PCI_s) positively correlates with Q_s/Q , at a significance level of 1%. For Q_{dry}/Q_{wet} , the percentage of forest (PL_f) positively correlates, while the percentage of settlement (PL_s) and the cohesion of settlement (PCI_s) negatively correlate, at a significance level of 1%. Figure 5.5 shows the estimated Pearson's correlation coefficients between landscape metrics and streamflow characteristics. It should

characteristics independent of the percentage of settlement and forest area was assessed using the scenario analysis. Figure 5.6 shows the land use distribution of the baseline scenario (i.e. land use planning), the clustered land use scenario and the scattered land use scenario, and Figure 5.7 shows the differences of PCI values for each land use scenario compared to the baseline scenario. It is shown that the clustered scenario has larger PCI values and the scattered scenario smaller PCI values than the baseline scenario.

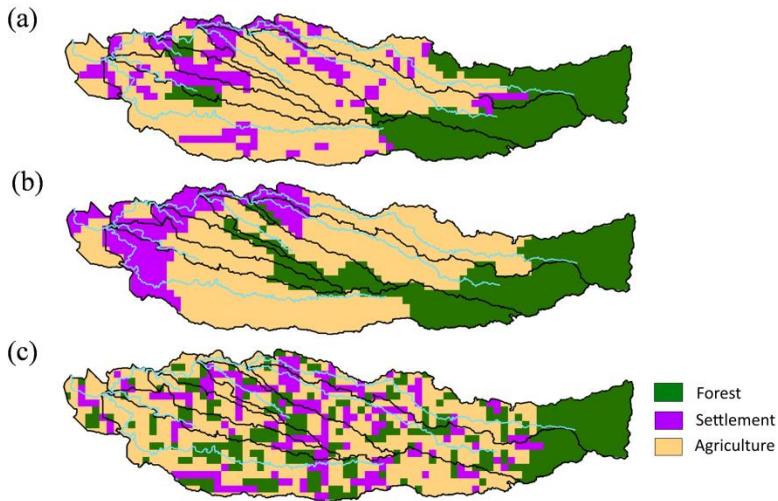


Figure 5.6. Land use distribution of the baseline scenario (i.e. land use planning) (a), the clustered scenario (b), and the scattered scenario (c). The land use scenarios represent different cohesion values while the percentages of the different land use types are fixed.

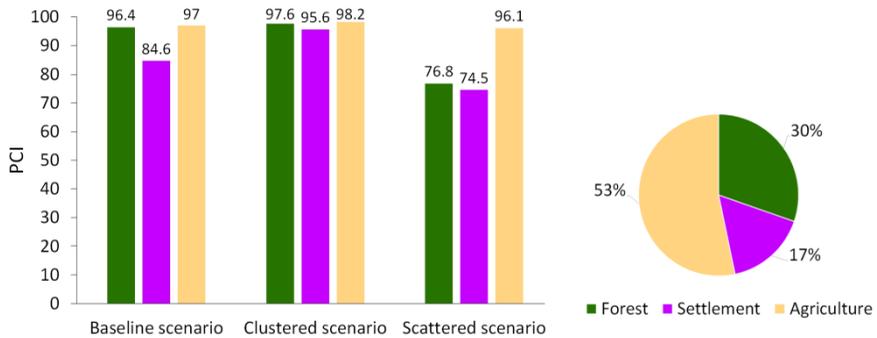


Figure 5.7. Patch cohesion index (PCI) of each land use type for different land use scenarios with each the same percentages of the different land use types.

At catchment scale, the results of the simulations show that the clustered and scattered scenarios reduce the long-term average of Q_s/Q . In comparison to the baseline scenario, the long-term average of Q_s/Q reduced from 0.37 to 0.35 under the clustered land use scenario and from 0.37 to 0.36 under the scattered land use scenario. The long-term average of Q_{dry}/Q_{wet} increased under the clustered land use scenario and reduced under the scattered scenario. Figure 5.8 shows that simulations using different land use scenarios may result in different hydrological responses. However, the changes in the long-term average of Q_s/Q and Q_{dry}/Q_{wet} at catchment scale under different scenarios were relatively small (i.e. ranged from -0.02 to +0.01).

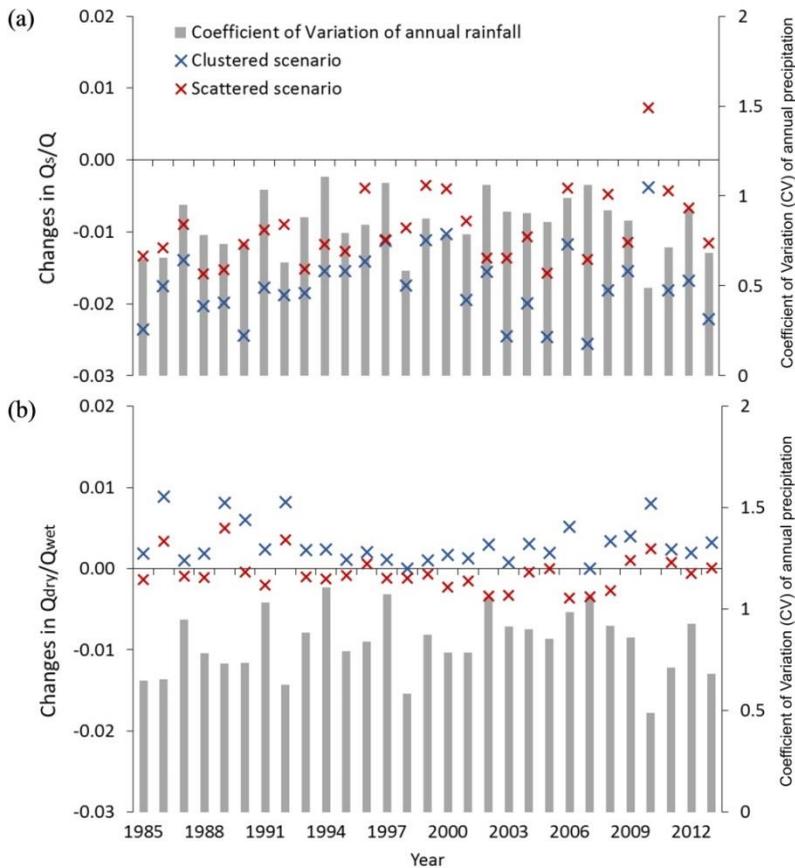


Figure 5.8 (a) Changes in the ratio of surface runoff to total runoff (Q_s/Q) and (b) the ratio of streamflow in the dry season to streamflow in the wet season (Q_{dry}/Q_{wet}) under different scenarios relative to the baseline scenario, including coefficient of variation of annual precipitation for the period 1985-2013.

Clear effects of changes in the patch connectivity on the streamflow characteristics can be observed at the sub-catchment level, in particular for changes in PCI_s . As can be seen in Figure 5.9, Q_s/Q has increased up to +0.1 following an increase in PCI_s up to +0.9 under the clustered land use scenario, whereas Q_s/Q has decreased up to -0.18 following a decrease in PCI_s up to -2.4 under the scattered land use scenario. Conversely, Q_{dry}/Q_{wet} has increased up to +0.02 following a decrease in the PCI_s up to -2.4 under the scattered scenario, while less clear impacts on Q_{dry}/Q_{wet} under the clustered land use scenario can be observed. While the effects of changes in PCI_s on the streamflow characteristics are discernible, there is no clear relation between PCI_f and the streamflow characteristics.

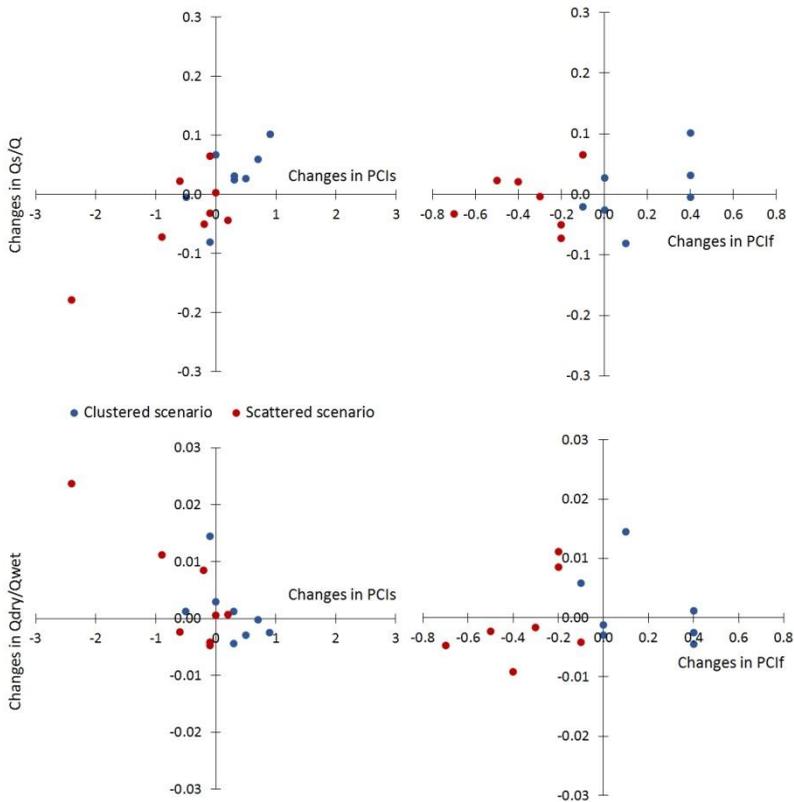


Figure 5.9. Relationship between changes in the patch cohesion index for settlement (PCI_s) and forest (PCI_f) and changes in streamflow characteristics relative to the baseline scenario.

5.5. Discussion

The study shows that changes in the streamflow characteristics of the study catchment can be attributed to both changes in the percentages of the different land use types and changes in the physical connectivity between patches of similar land use types. A decrease of vegetation and an increase of impervious areas were likely the cause of substantial changes in the streamflow generation. A consistent decline of forest area in the catchment due to conversion into settlement area has decreased the infiltration rate resulting in reduced groundwater recharge and water storage in the soil. As a result, a larger volume of precipitation was transformed into surface runoff. With less water infiltrated and stored into the soil, an increased fraction of flow becoming surface runoff and a less balanced water distribution between the wet and dry seasons can be expected. These findings regarding the relationship between changes in the percentages of different land use types and changes in the streamflow characteristics confirm those in earlier studies (e.g. Bruijnzeel, 1989; 2004; Brown et al., 2005; Wagner et al., 2013; Remondi et al., 2013; Gumindoga et al., 2014b; Marhaento et al. 2017a; 2017b).

When the percentages of different land use types are fixed but the physical connectivity of patches is changed, changes in streamflow characteristics occur at both catchment and sub-catchment level. However, changes at catchment level are very small, where different patch cohesion indices from different land use scenarios hardly affect the streamflow characteristics. A clearer relationship between streamflow characteristics and patch connectivity can be observed at sub-catchment scale, where Q_s/Q is positively correlated and Q_{dry}/Q_{wet} is negatively correlated with the patch connectivity of settlements. Apparently, the opposite impacts of changes in the patch connectivity at sub-catchment level compensate each other at catchment level. It was expected that the clustered forest area in the upstream part would reduce Q_s/Q and increase Q_{dry}/Q_{wet} while the clustered settlement area in the downstream part would increase Q_s/Q and decrease Q_{dry}/Q_{wet} . With different directions of changes in streamflow characteristics between upstream and downstream areas within the catchment, long-term changes of those variables at catchment level canceled each other out. This is similar to the findings from Wilk and Hughes (2002) and Wagner et al. (2013) who argue that the net hydrological result at catchment level can mask the impacts of land use changes on hydrological processes at sub-catchment scale.

The impacts of changes in the patch connectivity of settlement on streamflow characteristics are more pronounced than the impacts of changes in the patch connectivity of forest. This study agrees with Mejía & Moglen (2009), Wagner et al. (2013) and Su et al. (2014) who argue that urban imperviousness patterns

within catchments can play an important role in determining changes in streamflow characteristics, particularly because of changes in the fraction of flow becoming surface runoff. When the settlement area is clustered, peak flows will increase without much affecting the flow volume compared to scattered settlement (Corbett et al., 1997). When the urban development is located in the downstream area near the catchment outlet (as simulated in this study under the clustered scenario), more concentrated impacts can be expected compared to settlement scattered over the catchment (Su et al., 2014; Wheater & Evans, 2009).

It was simulated that the percentages of different land use types strongly affect the runoff generation of the study catchment, while the patch connectivity for a certain land use type may affect surface runoff and the seasonal balance of flows by accelerating or decelerating runoff responses. However, it should be noted that the spatial heterogeneity of hydrological response over catchments is scale-dependent, where the landscape metrics may change with changing scale (McGarigal & Marks, 1995; McGarigal et al., 2012) as well as dominant hydrological processes (Blöschl et al., 2007; Zhang et al., 2013). This study uses a semi-distributed SWAT model that simulates hydrological processes in each Hydrological Response Unit (HRU) within sub-catchments. Thus, the water balance simulation will be at a HRU, which is a combination of land use type, soil type and slope class. With the coarse scale of land use scenarios used in this study, spatial detail of changes in the land use patterns might be lost. As shown in Figure 5.9, both land use scenarios provide relatively small changes in the patch connectivity at sub-catchment scale. Although the results show relatively clear signals for changes in the streamflow characteristics due to changes in the patch connectivity, a more discernible signal can be expected if the land use change scenarios were developed at a finer scale. SWAT model is able to simulate streamflow only at the sub-catchment level so that the spatial flow variation between HRUs within a sub-catchment is not taken into account. With this model limitation, changes in hydrological processes due to changes in land use patterns cannot be presented at a smaller scale than at sub-catchment scale. To further investigate the impacts of different land use metrics on streamflow characteristics, the use of a fully-distributed model, e.g. the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model (Zhang et al., 2013) can be considered.

Although the effects of climate variability are isolated in the simulations by forcing the model with the same meteorological input for different land use inputs, the contribution of climate variability to changes in streamflow characteristics cannot be neglected. As can be seen in Figure 5.8, the hydrological response to different land use scenarios varies across years, likely

due to precipitation variability. Marhaento et al. (2017c) found for the same study area that changes in the precipitation variability may have large impacts on the water availability of the study catchment.

Findings of this study offer an opportunity to include hydrological impact considerations in developing land use plans. For the study catchment, the existing land use planning has been projected to reduce the mean annual streamflow and surface runoff, and increase the mean annual base flow and evapotranspiration (Marhaento et al., 2017c). By altering the spatial patterns of the land use plan, e.g. by scattering settlement area in the downstream area and clustering forest area in the upstream area, surface runoff can be reduced and a more balanced distribution of streamflow between the dry and wet season can be achieved. Since land use planning always occurs at different scales (e.g. national level, provincial level and district level), multi-scale analysis of the impacts of land use patterns on streamflow characteristics is recommended.

5.6. Conclusions

This study has assessed the effects of changes in land use patterns on streamflow characteristics in the Samin catchment and found that changes in the ratio of surface runoff to streamflow (Q_s/Q) and the ratio of dry-season to wet-season streamflow (Q_{dry}/Q_{wet}) are significantly affected by the percentage of forest and settlement (PL_f and PL_s) and the patch cohesion index of forest and settlement (PCI_f and PCI_s). Simulations with the SWAT model indicate that a decrease of PL_f and PCI_f and an increase of PL_s and PCI_s cause an increase of Q_s/Q and a decrease of Q_{dry}/Q_{wet} . Independently, changes in PCI may affect the streamflow characteristics, where clear relationships were found at the sub-catchment level. When simulating the impact of two hypothetical land use scenarios, a clustered scenario and a scattered scenario, it was found that an increase in PCI_s with PL_s maintained may result in an increase of Q_s/Q and a decrease of Q_{dry}/Q_{wet} , and vice versa, while changes in PCI_f with PL_f maintained have less impact on streamflow characteristics. The findings show that, particularly for settlements, altering the spatial configuration can be an effective measure to achieve a more balanced distribution of streamflow between the dry and wet season.

Chapter 6

Conclusions

6.1. Overview of the main findings

Analysis of streamflow time series for the period 1990-2013 for the Samin catchment show that annual streamflow has increased by an average of 12.1 mm/year. Chapter 2 shows that the contributions of changes in land use and climate to this change in streamflow were estimated to be about 72% and 28%, respectively. This result has been corroborated by land use change analysis and statistical trend analysis for the mean annual streamflow, precipitation and potential evapotranspiration. These analyses show that an increase in the annual streamflow during 1990-2013 was in line with a decrease in forest area from 48.7% to 16.9%, an increase in agriculture area from 39.2% to 45.4% and an increase in settlement area from 9.8% to 34.3%, while changes in climate variables (i.e. precipitation and potential evapotranspiration) are minor. In addition, land use change has affected other water balance components, such as actual evapotranspiration and the fractions of precipitation that become surface runoff, lateral flow and base flow.

In Chapter 3, the Soil and Water Assessment Tool (SWAT) was used to simulate hydrological processes in the study catchment. It was found that, at the catchment level, land use changes have resulted in an increase of the ratio of streamflow to precipitation from 35.7% to 44.6%, a decrease in the ratio of evapotranspiration to precipitation from 60% to 54.8%, an increase in the ratio of surface runoff to streamflow from 26.6% to 37.5% and a decrease in the ratio of base flow to streamflow from 40% to 31.1%. At the sub-catchment level, the impacts of land use changes on the water balance were diverse, depending on the extent of changes in forest and settlement areas. It was observed that positive and negative changes in the water balance components at sub-catchment level have counterbalanced each other, resulting in relatively small long-term changes of those variables at catchment level. Although it was found that changes in the hydrological processes can be mainly attributed to land use change rather than climate change, the contribution of climate change to changes in hydrological processes cannot be neglected.

In Chapter 4, the future climate variability (2030-2050) of the study catchment was assessed based on the output of a bias-corrected Regional Climate Model and the outputs of six Global Climate Models to include climate model uncertainty. Under two climate change scenarios namely Representative Concentration Pathway (RCP) 4.5 and 8.5, it was projected that climate change

may significantly affect water availability in particular if the changes in the mean annual precipitation are larger than 10%. The impacts of future climate conditions on water availability can be larger when combined with the future land use distributions under the business-as-usual scenario. It was observed that the combination of the RCP 4.5 climate scenario and the business-as-usual land use scenario may result in changes in mean annual streamflow and surface runoff ranging from -7% to +64% and from +21% to +102%, respectively, which is about 40% and 60% more than when land use change is acting alone. In this chapter, the effectiveness of governmental land use planning were also estimated. It was projected that under the RCP 4.5 climate scenario, land use planning reduces the mean annual surface runoff up to 30% and increases the mean annual base flow up to 8%. The effectiveness of applied land use planning to mitigate future water-related risks can be improved if the spatial land use distribution is optimized.

In Chapter 5, the effects of land use patterns on streamflow characteristics were assessed. It was found that two land use pattern characteristics, namely the percentage of different land use types and the physical connectivity between patches of similar land use types within the catchment, are dominant drivers for changes in the streamflow characteristics. While effects of changes in the percentages of different land use types on streamflow characteristics are expected (based on the results of Chapter 2, 3 and 4), it is interesting to know how changes in the physical connectivity between patches of similar land use types may affect streamflow characteristics as well. Based on the SWAT model simulations, using two hypothetical land use scenarios as inputs, a clustered scenario and a scattered scenario, an increase in the settlement connectivity can result in an increase in the ratio of surface runoff to streamflow and a decrease in the ratio of streamflow in the dry season to streamflow in the wet season, and vice versa, while changes in the forest connectivity have less impacts on streamflow characteristics. Findings of this study further suggest that land use management can be an important component of water management in the study catchment.

6.2. Limitations and future outlook

To achieve the research objective, this study uses various datasets such as spatial data (e.g. satellite images, elevation data, soil data, administrative maps) and non-spatial data (e.g. hydro-meteorological data) acquired from governmental and non-governmental agencies. In addition, this study employs a hydrological model and outputs from land use change and climate models to assess past and future impacts of land use change and climate change on

hydrological processes. The data and models used can be a source of uncertainty. For the data, it is a challenge to obtain long-term and reliable hydro-meteorological data for the study catchment. This is typically for South-East Asian countries including Indonesia where meteorological gauge networks generally include a limited number of stations which, commonly, are not well distributed over catchments (Douglas, 1999). In addition, for the study catchment most of the hydro-meteorological data were manually operated resulting in potential recording errors. For these reasons, data checks for errors and data corrections using well-established methodologies as shown in this study (Chapter 2) can be useful to construct more reliable datasets. As input for the SWAT model, this study used a soil map from FAO et al. (2012) with a coarse resolution. This global soil map was used because of limited information on soil characteristics in the local soil map available in the study catchment. Because of this soil generalization, several details important for hydrological processes for different soil conditions (e.g. surface runoff from different combinations of soils and slopes) might be obscured. For the models used in this study (Chapters 3, 4 and 5), sources of uncertainty can be present due to model choice and structure (e.g. model assumptions, equations, parameterization), data inputs (e.g. lack of relevant spatial and temporal variability of data on precipitation, soils, land uses and topography) and assumptions used to predict and project future conditions (e.g. population, climatic forcing). In addition, for future simulations it was assumed that land use change is independent of climate change so that mutual interactions between land use change and climate change due to local atmospheric feedbacks of land surface processes are not taken into account. Nevertheless, future changes in land use and climate are hard to predict since these changes are controlled by many policy-related, economic, and environmental factors which were not fully considered in this study. Considering all these uncertainties, accumulation of errors can be substantial affecting the results. Consequently, conclusions drawn in this study should be interpreted taking into account the uncertainty in the results (e.g. relatively large uncertainties in changes in the simulated water balance components as a result of land use change as can be seen in Chapter 4).

For future research, four main points are suggested for consideration. First, it is essential to use a reliable hydro-meteorological dataset. As mentioned earlier, the data-based approach applied in Chapter 2 heavily relies on the quality of hydro-meteorological data in particular for the streamflow data. Applying data corrections to the streamflow data (as conducted in Chapter 2) will affect the attribution results and the uncertainties can be considerable. In addition, the meteorological data obtained from the field gauges were the main input for the SWAT model (Chapter 3, 4 and 5), so that the spatial and temporal distribution of the meteorological gauges may affect the simulation results (see Cho et al.,

2009). Calibrating a model using observed, erroneous streamflow data will lead to misinterpretations of the overall water balance (see Montanari & Baldassarre, 2013; Van den Tillaart et al., 2013). For these reasons, it is expected that this study can provide more convincing results if hydro-meteorological datasets are available for a long time period (at least 30 years) and extracted from reliable and well distributed gauges over the study catchment. Second, it is suggested to use a soil map with a higher resolution as input for the hydrological model. This study used a global soil map with a coarse resolution as input for the SWAT model rather than a local soil map available for the study catchment. The global soil map was selected because it provides information on the soil characteristics required by the model (e.g. soil texture, soil depth, soil permeability, etc.). In order to use the local soil map as input for the SWAT model, field measurements including laboratory experiments can be conducted to provide information on the soil characteristics of the local soil map. The third point is related to the robustness of the hydrological model (i.e. SWAT model). Although this study has shown the ability of the SWAT model to achieve the research objective, improvements on model structures can be considered for future research. It should be noted that the SWAT model is able to simulate streamflow only at the sub-catchment level (i.e. it is a semi-distributed model) and neglects the spatial flow variation between Hydrological Response Units (HRUs) within a sub-catchment. Consequently, this limits the impact assessment of different land use configurations on water availability within a given sub-catchment (Chapter 5). For this reason, the use of a fully-distributed model e.g. SWATgrid, a grid-based version of the SWAT model developed by Rathjens & Oppelt (2012), can be considered for future research. In addition, the model robustness can be potentially improved by the use of additional variables besides streamflow (e.g. actual evapotranspiration) in model calibration and validation. Remote sensing products such as MODIS data can be used for this purpose to generate spatially and temporally distributed actual evapotranspiration (see Rientjes et al., 2013). Finally, it should be mentioned that this study uses only one single catchment. For this reason, more research in different catchments with various hydrological and climatic conditions is needed to test the general applicability of the methods and reliability of the results.

6.3. Contribution to scientific advancement

This study provides insight in the impacts of land use change and climate change on water availability in the study catchment for past and future conditions. In addition, this thesis contributes to the advancement of the field of hydrology in four ways. First, a more thorough understanding of the methods available to attribute changes in hydrological processes of a tropical catchment

to land use change and climate change was gained. The methods used in this thesis to separate the impacts of land use change and climate change on hydrological processes (in Chapters 2 and 3) were applied for the first time in a tropical region. Moreover, the methods used for the attribution analysis were extended, thus advancing the methods. Second, this thesis offers an assessment of the effectiveness of land use planning to mitigate future risks associated with land use change and climate change (in Chapters 4 and 5). The methods and results of the thesis provide practical guidelines which can bridge the gap between land use planning and water resource management. As a result, this study can be useful for supporting the authorities to design appropriate land use management measures to achieve water sustainability and to improve water management. Third, this thesis shows the extents and directions of land use change and climate change impacts on water availability in a tropical catchment. Although this research is conducted in a single catchment (i.e. Samin catchment, Java, Indonesia), it is thought to represent problems characteristic for the hydrology in tropical regions having similar climate and land use conditions. Fourth, while most of the research focuses on the impacts of different land use types on water resources, this thesis successfully assessed the impacts of different land use configurations on the water availability as well (Chapter 5). For tropical regions, this assessment is one of the first studies investigating the relations between land use patterns and water resources. Ultimately, I would like to encourage and motivate colleagues in the same field to carry out more research in this very interesting yet challenging topic.

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About the author



Hero Marhaento was born in Yogyakarta, Indonesia on April 5th, 1982. He finished his elementary school in SD Tarakanita in 1994, junior high school in SMPN 5 Pawitikra in 1997 and senior high school in SMAN 3 Padmanaba in 2000. Afterward, he continued his studies in Forest Management at Universitas Gadjah Mada (UGM), Indonesia. In 2005 he obtained his BSc degree *cum laude* with a final project on the topic of “land suitability analysis for forest rehabilitation using remote sensing and GIS”. In 2007 he obtained his MSc degree in Environmental Studies focusing in Geo-Information for Disaster Management from the joint-program between UGM and International Institute for Geo-Information Science and Earth Observation (ITC), The Netherlands. For his final MSc project, he worked on the topic of “landslide hazard analysis using heuristic-statistic method in combination with multi-temporal landslide data”.

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List of publications

Papers in peer-reviewed journal

- Marhaento, H., Booij, M. J., Rientjes, T. H. M., & Hoekstra, A. Y. (2017). Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model. *Hydrological Processes*, 31(11), 2029-2040. DOI: 10.1002/hyp.11167
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- Marhaento, H., Booij, M. J., & Hoekstra, A. Y. Hydrological response to future land use change and climate change in a tropical catchment. *Submitted*
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Conferences

- Marhaento, H., Booij, M. J., & Hoekstra, A. Y. (2015). *Quantifying the contribution of land use and climate change to stream flow alteration in tropical catchments*. Presented at European Geosciences Union (EGU) General Assembly 2015, 12-17 April, Vienna Austria, Vienna, Austria.
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- Marhaento, H., Booij, M. J., Rientjes, T.H.M., & Hoekstra, A. Y. *Simulation of land use configuration impacts on stream flow characteristics of a tropical catchment*. European Geosciences Union (EGU) General Assembly 2018, 8-13 April, Vienna Austria, Vienna, Austria. *Submitted*
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Land use and climate changes are key factors determining changes in hydrological processes in catchments. For tropical countries like Indonesia, the effects of changes in land use and climate have been projected to cause a food crisis and eventually increase the degree of poverty in the future. In order to mitigate future water-related risks, knowledge on the extent and directions of land use change and climate change impacts on water availability is essential.

This book provides insight in the impacts of land use and climate changes on water availability in the Samin catchment in Indonesia for past and future conditions.

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