IMPACT OF LAND USE LAND COVER CHANGE ON RUNOFF AND WATER QUALITY OF AN INCREASINGLY URBANIZED TROPICAL WATERSHED IN JAVA, INDONESIA

by

IKE SARI ASTUTI

(Under the Direction of Deepak R Mishra)

ABSTRACT

Increasing water resource problems such as accelerated sedimentation, drying-up springs, and downstream eutrophication were reported in Indonesian water bodies, especially in Java. The growing pressures on watershed due to land use land cover change (LULC) was perceived as the cause of watershed degradation. Information about the nature of LULC change and drivers was poorly understood, how LULC plays a role in generating runoff was unknown, and what factors governing the variability of water quality (TSS and Chl-a) in water ecosystems like reservoirs is unavailable. This study aims at improving the understanding on relationship between LULC change (1995-2015), drivers, impacts on runoff and water quality. Upper Brantas was chosen as the study state, representing a typical urbanized tropical watershed in developing countries. Varying methods were used covering remote sensing, GIS and SWAT modelling. Findings revealed the direct and indirect causes of LULC change with agricultural expansion, population growth, infrastructure, accessibility, economic, social and cultural factors jointly affected the LULC change. Major LULC change trajectories were forest to dryland agriculture, dryland-agriculture to rice-field, and rice-field/dryland agriculture to settlement. Urban areas became the land use type exhibits the fastest growth, being doubled in a 21-year period. Forest conversion, farm loss, and rapid uncontrollable settlement development appear to be the challenges for land use planning. SWAT-based assessment results showed that the LULC change over the past 21 years led to subtle increase in surface runoff, water yield, and decrease in ground water. Among these, surface runoff was the most affected variable with relative increase of 8%. Forest conversion both to settlement or dryland agriculture generated greater impact in generating runoff, followed by dryland agriculture conversion to urban. Long-term TSS and Chl-a assessment showed that TSS in all reservoirs was closely associated with rainfall and discharge. This amplifies the needs for runoff management from existing land use practices. On the other hand, the Chl-a variability appeared to be influenced both by internal and external conditions of each reservoir as well as the corresponding draining watershed. The findings suggest the watershed management cannot be generalized due to large variability in land use and watershed physical conditions.

INDEX WORDS: Land Use Land Cover Change; SWAT; Runoff; Water Quality; Reservoirs, Tropical Watershed; Indonesia

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DEDICATION

I dedicate my work to my parents who inspired me for bravely embracing the life and pursuing knowledge to the highest limit. May Allah SWT grant you a blessed life here and the hereafter in His *jannah*.

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Term	Abbreviation
ANNs	Artificial Neural Networks
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
BPDAS	*Balai Pengelolaan Daerah Aliran Sungai*
BPS	*Badan Pusat Statistik*
CHLA	Chlorphyll-a
DAS	*Daerah Aliran Sungai*
DEM	Digital Elevation Model
ET	Evapotranspiration
ETM	Enhanced Thematic Mapper
FAO	Food and Agriculture Organization
FRSE	Evergreen Forest
FRST	Dryland Forest
GDP	Gross Domestic Product
GIS	Geographic Information System
GLCF	Global Land Cover Facility
GLP	Global Land Program
GSSHA	Gridded Surface Subsurface Hydrologic Analysis
GWQ	Groundwater flow
HRU	Hydrologic Response Units
HSPF	*Hydrological* Simulation Program - FORTRAN
IDFP	Industrial Dryland Forest
ISODATA	Iterative Self-Organizing Data Analysis Technique
ISRIC	International Soil Reference and Information Centre
LAKIP	*Laporan Akuntabilitas Kinerja Instansi Pemerintah*
LaSRC	Landsat Surface Reflectance Code
LATQ	Lateral Flow
LEDAPS	Landsat Ecosystem Disturbance Adaptive Processing System
LOOCV	Leave One Out Cross Validation
LULC	Land Use/Land Cover
MADL	Mixed Dryland Agriculture
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MERIS	MEdium Resolution Imaging Spectrometer
MODIS	Moderate-resolution imaging spectroradiometer
NDCI	Normalized Difference Chlorophyll-Index
NDSSI	Normalized Difference Suspended Sediment Index

NIR	Near Infra-Red
NRSME	Normalized RMSE
NSE	Nash–Sutcliffe model efficiency
NSMI	Normalized Suspended Mineral Index
OACs	Optically Active Constituents
OBIA	Object Based Image Analysis
OLI	Operational Land Imager
PBIAS	Percent BIAS
PCA	Principal Component Analysis
PJT	*Perum Jasa Tirta*
PLTN	Plantation
RBI	Richard Barker Index
RCFL	Rice field
RGCI	Red-Green Chlorophyll Index
RICE	Rice field
RMSE	Root Mean Squared Error
RNGB	Rangeland Bushland
RNGE	Rangeland grassland
SeaWiFS	Sea-Viewing Wide Field-of-View Sensor
SLBL	Shurbland/Bushland
STBU	Settlement/Built Up
SUFI	Sequential Uncertainty Fitting
SUGC	Sugarcane
SURQ	Surface Runoff
SVGL	Savanna/grassland
SWAT	Soil and Water Assessment Tool
SWAT-CUP	SWAT-Calibration Uncertainty Program
SWIR	Short Wave Infra-Red
TM	Thematic Mapper
TSS	Total Suspended Solids
URHD	Urban Residential High Density
URMD	Urban Residential Medium Density
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WATR	Water
WS	*Wilayah Sungai*
WYLD	Water Yield

CHAPTER 1

INTRODUCTION

1.1 Background

Land use/land cover (LULC) change has long been considered as a factor affecting global environment (Turner et al., 1993 and Lambin et al., 2001). Numerous studies over the past decade have highlighted the role of LULC change on various aspects of environment such as hydrological response (Ghaffari et al., 2010), climate change (Xu et al., 2016), biodiversity (de Castro et al., 2016), food security (Rutten et al., 2014), energy conservation (Preston and Kim, 2016), and water quality (Giri and Qiu, 2016). LULC change represents human influence on natural landscapes manifested in different processes such as agricultural expansion, deforestation and urbanization. In the last few decades, rapid LULC change world-wide induced by a growing population has imposed continuing pressure on variety of ecosystems.

Among the studied impacts of LULC change, hydrological responses and associated factors such as water quality have been part of widely investigated themes due to increasing concerns about water resources. However, despite numerous studies, interrelationship between LULC change and water resources remains poorly understood. This is partly because of the complexities in LULC change process and the associated hydrological process. It is understood that LULC change vary across geographic regions and the drivers are often dependent on the ecological, socio-economic and historic-political context (Lambin et al., 2003). Such drivers invariably interplay with each other making it difficult to assess the relative importance of each driver. Studies have shown that LULC change occurs at differing scales and drivers of LULC change vary greatly among places (Gonzales, 2001; Prishchepov et al., 2012; Davies et al., 2014). Changes in land use in the watershed alter the hydrological response and may produce negative impact such as increased runoff and erosion, and exacerbate the susceptibility to droughts and floods (David et al., 1997; Paul and Meyer, 2001; Santangelo et al., 2011; and De Vries et al., 2012). Studies have shown wide variations in hydrological response due to variations in watershed characteristics (Bruijneel, 2004; Hundecha and Bárdossy, 2004; Wagner et al., 2013; and Beck et al., 2013). On the other hand, unlike hydrological functions, it's the visible status of natural resources which define the goals, issues and challenges that are addressed by watershed managements (Kerr, 2007). This implies that studies on land use change of a particular watershed bear their own importance.

Until the 1990s, South East Asia was the region with the highest LULC change rate (Lambin et al., 2003). Indonesia, the world's fourth most populated country, was no exception. Rapid and sporadic LULC change have been observed in Indonesia at a broad scale, especially during the period of significant economic growth from 1975 to 1996 (Firman, 2002). The island of Java is the most densely populated territory with around 60% of Indonesia's 250 million people and population density of more than 900 people/km^2. For decades, Java has witnessed constant pressure on land resources and quickly experienced transition from a largely rural to a largely urbanized environment (Verburg et al., 1999; and Handayani, 2013). In recent years, reliance on water resources has been heavier due to increased water use and degrading watershed conditions (Pawitan and Haryani, 2011). Around 458 watersheds in Indonesia have been declared under critical condition calling for improvement in watershed management (Fulazzaky, 2014). Freshwater ecosystems in Java have been subjected to natural and anthropogenic stressors and developmental pressure (Heathwaite, 2010). For example, the Upper Brantas watershed in

East Java has particularly attracted scrutiny due to increasing reports of environmental problems such as sedimentation (Adi, et al., 2009), eutrophication (Sulastri et al., 2004) and discharge of pollutants (Fulazaky, 2009). With rapid population growth, these environmental issues in Upper Brantas are expected to be more severe in near future.

1.2 Research Questions and Objectives

Considering vital use of inland water resources, proper watershed management is required. To support effective watershed management, a thorough understanding of the relationship between LULC change in Java and associated hydrological response is required. Unfortunately, there have been limited studies investigating LULC change in Java. Currently, there is no published literature that looks at how land use within watersheds have changed during the last few decades, and what are the potential direct and non-direct drivers for such change. Further, there has been a gap of information about how land use affect hydrological responses and water quality in watersheds of Java, Indonesia.

The overall objective of this research is to improve the understanding about the relationship between LULC change and hydrological response in Upper Brantas watershed, Java, Indonesia. The hydrological response analysis is particularly focused on surface runoff which is the main driver of sediment and nutrients affecting the water quality. This research is comprised on three studies. Each study has addressed a particular research component including LULC change, hydrologic response, and water quality.

The first study was intended to provide insights on LULC change in Upper Brantas. The objectives of this study were (1) understanding how LULC has changed in Upper Brantas Sub-Basin during 1995 - 2015, (2) identifying potential drivers of the observed LULC change, (3) identifying/illustrating the current condition of watershed functions based on hydrologic and water quality conditions, and deriving implications of existing LULC change drivers on water resources.

The second study was to investigate how land use might affect the hydrological response using Soil and Water Assessment Tool (SWAT) hydrologic modeling. Specifically, the study was aimed at (1) setting up and validating a SWAT model for Upper Brantas river basin, (2) simulating the impact of LULC change over the past two decades (1995 – 2015) on the hydrological response of the catchment with a focus on surface runoff, (3) investigating the effect on runoff generation resulting from gradual conversion of a particular LULC type to settlement or dryland agriculture.

The third study was aimed at understating the cumulative impact of LULC change and altered hydrologic response on two important water quality parameters, Total Suspended Solid (TSS) and Chlorophyll-a (Chl-a). They are part of the most frequently used water quality standards and strongly linked to hydrologic processes such as sedimentation and eutrophication. Iinland water ecosystems such as lakes and reservoirs serve as a sentinel to the changing environment such LULC and climate change. Sutami reservoir in Upper Brantas has been reported to undergo periodic intense sedimentation and eutrophication. Understanding how TSS and Chl-a in Upper Brantas have varied over the past two decades will generate novel information about the potential governing factors. Specifically, the study (1) investigated the accuracy of remote-sensing based TSS and Chl-a bio-optical models on three reservoirs namely Sutami, Lahor and Selorejo, (2) applied the best bio-optical model to Landsat images to evaluate the long-term variations of TSS and Chl-a, (3) assessed the interaction between TSS and Chl-a and identified governing environmental factors controlling these water parameters. The main focus of this study was the Sutami reservoir, however, the results were compared to two other reservoirs, Selorejo and Lahor, with different watershed characteristics including morphometry, geology, topography and land uses configuration.

Despite numerous studies about LULC change and hydrological response as well as water quality worldwide, such studies are rare in Indonesia. Comprehensive reports investigating the nature and drivers of LULC as well as consequences on hydrology and water quality have not been available yet for East Java. Given a growing importance of Malang as one of major rapid developing region, water-related ecological issues will likely continue to escalate. The impacts may no longer narrow to ecological loss but also expand to social and economic issues such as public health and energy generation. The study can enrich information needed to better understand the ecological and anthropogenic factors governing the landscape. For other regions, which have not yet developed such as regions outside Java, this study may exemplify lessons learned from urbanization impacts from an Indonesian perspective. In a broader context, the study provides deeper insights for land use planning targeting sustainability. Ecological and anthropogenic variability should gain a higher consideration in support of implementation of the recently enacted integrated watershed management in Indonesia.

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CHAPTER 2

LITERATURE REVIEW

Land Use and Land Cover (LULC) represents a broad aspect signifying the interaction between natural and human influence on the Earth's surface. LULC change has been perceived as a factor that can produce multiple impacts, ranging from water resource to food security. Specific to water resources, impacts of LULC change have been linked to varying entities such as groundwater, stream water, surface runoff, evapotranspiration, as well as sediment and nutrient yields. Given a broad range of area, there have been numerous methods developed to investigate LULC change and its impact. Advancement in science and technologies have refined the understanding about LULC and diversified methodologies. This chapter is designed to provide a framework outlining brief information related to LULC change assessment and its relationship to water resources. More specifically, this chapter provides information about what constitutes Land Use/Land Cover (LULC), how studies assess LULC change, how LULC change may affect water resources, and methods employed to quantify impacts of LULC change on water resources.

2.1 Land Use Land Cover (LULC) Change

Land use and land cover are often misunderstood as two identical or interchangeable entities. However, there are significant differences between these terms. Land cover is a representation of bio-physical attributes of the earth's terrestrial surface and immediate sub-surface including biota, soil, topography, and built-up structures, while land use is the objectives for which attributes of land cover have been modified (Lambin et al. 2006). In terms of changes, land cover change can be divided into two components, land cover conversion and cover modification. While the first deals with the replacement of one type of land cover with another, the latter represents changes to land cover's characteristics without a full change in the land cover itself (Verburg et al., 2006). Land cover change can alter biotic diversity, actual and potential primary productivity, soil quality, runoff quality, sediment transportation and a host of other attributes that are associated with the terrestrial landscape (Steffens et al., 2004).

Land cover change is caused by a number of factors which are labeled as drivers. Drivers of land cover change pertain to anything that directly or indirectly influence a change in the natural characteristic of land cover. The causes or drivers of land cover change have been classified into direct causes and indirect causes (Lambin et al., 2001). Direct causes, also called proximate causes, can be attributed to anthropogenic activities that directly modify the land cover such as agriculture or settlement, while indirect causes compensate the underlying drivers that trigger the proximate causes such as demography and policies (Lambin et al., 2001). Underlying causes of land cover change does not occur in isolation but exhibit a complex interaction among these different levels of scales (Mather, 2006). Underlying causes of land cover change include social, political, economic, demographic, technological, cultural, institutional, and biophysical factors (McNeill et al., 1994; Li et al., 2006). Land use change may occur gradually, or even more abruptly due to specific events such as natural hazards or change in political forces (Kariyeva and van Leeuwen, 2012).

2.2 Assessment of LULC Change

There are many ways to obtain information on LULC. These can include ground survey, the use of GPS, air photo, and satellite images through remote sensing. LULC changed studies became routine with the launch of LANDSAT providing a global coverage of the earth surface in 1972. Since then, the LULC mapping techniques have advanced significantly. Methods used to extract LULC information are broadly divided into unsupervised classification techniques (Dhodhi et al., 1999; Bruzzone and Prieto, 2001), and supervised techniques (Ji and Jensen, 1996; Jensen, 2005). The unsupervised technique can be applied without any prior knowledge about the study area and involve clustering with various algorithms such as chain method, Iterative Self-Organizing Data Analysis Technique (ISODATA) iterations, and cluster busting (Jensen 2007). The supervised method requires a deep knowledge of the study area, field data, and development of a training dataset involving pixels extracted from the image representing every LULC class (Jensen 2007). Quite frequently a hybrid method is used which is basically a blend of the two methods.

Recent advanced LULC techniques include sub-pixel classification methods such as fuzzy-set classifiers (Shalan et al., 2003; Fauvel et al., 2006); object oriented image segmentation (Hay et al., 2005); decision tree/expert system classifiers (Kahya et al., 2010); neural network classifiers (Liu et al., 2004), and linear spectral mixture analysis (Mayes et al., 2015). Object-Based Image Analysis (OBIA) approach offers new ways of classification by developing segments instead of pixels as the unit of analysis, and combining spectral, textural, and spatial attributes of segments for building supervised classifiers or rules-based classifiers (EXELIS 2012, Lyons et al. 2012). Monitoring changes over time requires consistency among maps both in terms of real world representation and statistical performance of the maps. Often, studies employing remote sensing approach for land use mapping use different sensors in order to produce a longer temporal coverage. To examine the LULC change using remote sensing, the images have to be acquired at different dates (Singh, 1989). There have been several methods developed for assessing LULC change. These include the ‘from-to’ quantitative change (Lu et al., 2004), image differencing (Song et al., 2001); image ratioing (Prakash and Gupta, 1998), and principal component analysis (Ye et al., 2016). Lu et al., (2004) suggested the use of post-classification comparison for a detailed ‘from-to’ detection.

In mapping LULC, two properties of satellite images namely spatial and temporal resolution should be considered. Images with high temporal resolution are able to capture highly dynamic changes, but often poor in spatial resolution, which makes them unable to reveal high spatial variability of land cover (Jensen, 2007). Medium spatial resolution Landsat data have been used by studies to map LULC changes with differing periods ranging from 2 years, 5 years (Tran et al., 2017), 10 years (Thakkar et al., 2010) 15 years (Sanhouse-Garcia et al., 2016), and 40 years (Qasim et al., 2013).

2.3 LULC Change and Water Resources

The concept of water resources is multidimensional. It is not limited only to its physical measure (hydrological and hydrogeological), the ‘flows and stocks’, but encompasses other more qualitative, environmental and socio-economic dimensions (FAO, 2003). Often it narrowly refers to water quantity and quality. United States Department of Agriculture (USDA) defines water quality as, " the physical, chemical, and biological composition of water as related to its intended use for such purposes as drinking, recreation, irrigation, and fisheries". Ren et al., (2003) outlines that surface water quality is not only determined by the presence of pollutants but also by the pattern and amount of runoff. Runoff is the major process delivering nonpoint source pollutants into water bodies. Runoff is often regarded as water quantity in hydrology representing water movement on the Earth's surface. An understanding on the quantity (runoff) and quality of surface runoff is fundamental for better managing water resources (Gray, 2008).

Relationship between LULC and water resource is complicated due to natural variability of watersheds, difficulties in controlling LULC change, limitedly available controlled catchment-based experiments, and challenge in generalizing results from previous studies to other systems (deFries and Eshelman, 2004). LULC change modify the surface cover that eventually disrupts the hydrological response. Studies shown that changes in vegetation cover and density cause alteration in catchment hydrology processes such as interception, evapotranspiration, percolation, runoff and groundwater recharge (Hörmann et al., 2005; and Schilling et al., 2008). General reported impacts of deforestation and urbanization have been documented such as reduced and flashier flows, increased susceptibility to landslide and floods, reduced water quality and worsened sedimentation, stormwater runoff, nutrients and pollutants (David et al., 1997; Corbett et al., 1997; Verbist et al., 2005; and Salvadore et al., 2015). Yet, some findings present inconsistent results suggesting natural variability (Bruijnzeel, 2004; and Gyamfi et al., 2016). With all these concerns, it is therefore critical to understand how a watershed evolves because of the LULC dynamics.

2.4 Hydrological Modeling for Water Resources

There have been a number of methods developed to assess water resources. Hydrologic models examine water distribution patterns and constituents. In general, watershed hydrologic models can be classified based on the approaches used for the modelling. These can include the nature of algorithms, (either empirical, conceptual or physically-based), model input and parameters specification (deterministic or stochastic), and spatial representation (lumped or distributed) (Melone et al., 2005). Empirical models involve statistical fits between the explanatory variables and the variable of interest. Example of these are regression techniques (Yürekli et al., 2005; and Wang et al., 2014). More advanced techniques employ Artificial Neural Networks (ANNs) (Kang et al., 2015). Watershed-scale models can be further categorized on a spatial basis as lumped, semi-distributed, or distributed models. In lumped models, a watershed is considered as a single unit for the analysis or computation. In these models, the variables or parameters are averaged. On the contrary, semi-distributed and distributed models consider the spatial variability of the hydrological processes, inputs, and watershed properties (Liu et al., 2008; Daniel et al., 2011). The physically-based models were developed based on the understanding of the physical processes associated with the hydrological processes that occurs within a catchment (Grayson et al., 1992). Examples of widely applied physically based models include GSSHA (Downer and Odgen, 2004), HSPF (Xie et al., 2013)], and SWAT (Arnold et al., 1993; and Gassman et al., 2007).

2.5 Soil and Water Assessment Tool (SWAT)

SWAT is one of widely used physically based models that operates at daily level and was designed to simulate the impact of management on water, sediment and chemicals from agriculture (Arnold et al., 1993; and Gassman et al., 2007). In SWAT, the watershed is divided into multiple sub basins, which are then further subdivided into Hydrologic Response Units (HRUs). Each HRU is a designated area having unique combination of land use, soil characteristics and slope. Outputs for the model namely evapotranspiration, soil water storage, and water yield (surface runoff plus subsurface flow. SWAT incorporates the CN method and non-spatial HRU, which supports adaptation for any watershed under varying hydrologic conditions (Gassman et al., 2007). Despite having been designed for the U.S condition, studies have shown favorable results from many countries with differing site condition across watersheds (Ghaffari et al., 2010; Wagner et al., 2013; Gyamfi et al., 2016; and Seyoum et al., 2016). SWAT supports varying applications ranging from simulating LULC change impacts, climate change, best management practices for chemicals, irrigation and bacteria management, and sediment and nutrient loading on different watersheds (Milewski et al., 2014; Francesconi et al., 2016; and Lamba et al., 2016).

2.6 Remote Sensing of Water Quality

Remote sensing instrument measures electromagnetic radiation reflected/emitted by the earth’s surface, and for water bodies, the signal captured and measured by the remote sensor often referred to as water-leaving radiance i.e., upwelling radiance arising from the water surface (Kirk 1996). Thus, remote sensing based water quality models are derived using the relationship between water quality parameters and water-leaving radiance (Lindell et al., 1999). The ability of remote sensing techniques to estimate the targeted bio-physical constituents in water is highly reliant on the algorithms or models. Researchers in water remote sensing, despite of no well-defined terms and explicit agreements, have classified water remote sensing modeling approaches into three broad categories, namely empirical, semi-analytical, and quasi analytical (Sathyendranath, 2000). Empirical models are simple to develop but often limited to local application, while the other two are more complicated models yet offer greater transferability. A chlorophyll-a (Chl-a) model derived from a ratio of Landsat top of atmosphere reflectance at bands centered at 835 and 660 nm is an example of an empirical model (Tebbs et al., 2013). Reviews show that empirical approaches cannot produce multi-temporal estimation, nor allow retrospective assessment on water quality, and thus remote sensing models should be developed form a method that is independent of *in situ* measurements, and semi or quasi analytical approaches are considered reliable to produce multi-temporal algorithms. (Dekker et al., 2002). Semi-analytical and quasi analytical models extend the empirical approach by utilizing physical characteristic of water including the use of water optical properties (Gitelson et al., 2008; Mishra et al. 2013; Mishra et al. 2014; Ogashawara et al., 2017).

Despite of widespread modeling efforts, remote estimation of water constituents remains challenging due to their optical complexity. High uncertainty is still observed from several developed algorithms due to various issues such as inaccurate atmospheric correction, difficulties of parameterization and spectral slope derivation, limited satellite band choices (Mishra and Mishra, 2012). For example, semi-analytical Chl-a models, developed for clear waters, such as blue-green algorithms often fail or perform poorly when applied to turbid waters, or if successful, the models produce relatively high errors in areas with low Chl-a concentrations (Gons et al. 2008). Similarly, for retrieving Total Suspended Solids (TSS) concentration, various approaches have been used, ranging from empirical to semi-analytical models. Yet, the reflectance sensitivity at a given band differs significantly with TSS distributions in various types of waters ranging from open ocean to turbid waters, and thus, it is difficult to build a generalized model for all water types (Mao et al., 2012).

The launch of MODIS, SeaWiFS, and MERIS with their superior spectral and radiometric properties to resolve water optical complexity has triggered the advancement of water remote sensing research. Yet, due to the poor spatial resolution, these sensors have been considered less suitable for studying inland waters where the spatial variability of constituents can be high in relatively smaller areas (Gerace and Schott, 2009). Most of the remote sensing studies on water quality are geographically restricted to oceanic and coastal waters in northern hemisphere and very few studies focused on tropical inland waters (Campbell et al., 2011). In the context of Indonesia, small numbers of studies on water remote sensing conducted in Indonesia have focused solely on the coastal or sea waters and none on the inland water systems. For example, estimation of TSS and Chl-a was carried out in coastal waters near Kalimantan using ocean color inversion model by Budhiman et al., (2012). However, this model was developed for coastal waters and its application in tropical inland waters in Indonesia is untested. The lack of models suitable for tropical inland water impedes its application in long term monitoring efforts.

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CHAPTER 3

DRIVERS AND IMPLICATIONS OF MULTI-DECADAL LAND USE LAND COVER CHANGE ON THE FUNCTION OF INDONESIAN WATERSHEDS[1]

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ABSTRACT

Land use and land cover (LULC) change has long been the focus of research studies because of its local and regional impact. Changes of LULC are of particular importance for the sustainability of watershed functions. Thus, a thorough understanding of the drivers of LULC is required. In this study, an object based image analysis (OBIA) method with hierarchical rules (80% accuracy) has been applied to analyze the changes in LULC in Upper Brantas river basin complex, East Java, Indonesia The study covers the Upper-Brantas, Lahor and Konto watersheds for the period from 1995 to 2015. A land use change framework from Lambin (2002) was adopted, to identify both potential direct and non-direct causes. Published data, literature review, reports and news articles were further used to deepen the understanding on the causes/drivers of the LULC. Findings show that this basin complex represents a typical tropical watershed where agricultural and urban areas dominates the landscape. The three sub-catchments are undergoing increasing urbanization. Post-change detection results show that in the last 20 years, settlement has been the most rapid land use with more than 100% change from its extent in 1995. Expansion of agriculture were limited mostly to steeper zones and was compensated by the loss of forest. Rapid urbanization and agricultural expansions were the primary drivers of LULC change in the watershed. While deforestation was found to have been low (15% loss), the challenge now is how to deal with rapid and sporadic urbanization and agricultural development. Compared to other agricultural land uses, rice fields experienced the smallest changes for the last two decades. This relatively stable land use might be associated with government's subsidy and irrigated land protection law. Evidence from field data shows the worsening conditions from increasing discharge of water, elevated suspended sediment concentration, and flood events over the past two decades. Implementation of political, administrative and fiscal decentralization since 2004, which were intended to give greater autonomy and powers to local governments, has so far not proven effective in dealing with degrading watershed conditions. Similarly, the implementation of integrated watershed-based water resource management has been relatively recent and thus far has not shown any improvement in the condition of the watershed.

Keywords: land use change, direct and non-direct drivers, watershed conditions, local autonomy, water quality, Upper Brantas, Indonesia

3.1 Introduction

Land use/land cover (LULC) change has long been considered as a factor affecting global environment (Turner et al., 1993 and Lambin et al., 2001). LULC change studies highlight the role of LULC change to various aspects of environment such as climate change (Xu et al., 2016), biodiversity (de Castro et al., 2016), food security (Rutten et al., 2014), energy (Preston and Kim, 2016), and water quality (Giri and Qiu, 2016). A number of global efforts have also been made to better address problems associated with land use change impacts such as Global Land Program (GLP), and Global Land Cover Facility (GLCF). For countries in the tropical zone, land use change has become a bigger concern due to the region's role in the global environment. Tropical forests are known for their essential roles in climate regulation, ecosystem services and socio-economic benefits (Miura et al., 2015). With about half of the world's forests spread in the tropical belt, massive forest loss caused by agricultural expansion and urbanization world-wide have exerted serious threats to biodiversity hotspots, green-house gas emission, carbon storage and water supply (Hansen et al., 2013). The difficulty of handling these issues is further exacerbated by limited capacities for land use/land cover inventory and monitoring by countries in this region (Romijin et al., 2015).

It is understood that LULC changes vary across places and the drivers are often dependent on the ecological, socio-economic and historic-political context (Lambin et al., 2003). Geist and Lambin (2002) addressed the importance of each of these drivers to land use change and framed them into a generic framework that can be used to understand the land use change process. Such drivers invariably interplay with each other making it difficult to assess the relative importance of each driver. A number of studies have highlighted the role of access, institutional and political change in shaping the landscapes (Prishchepov et al., 2012; Belay et al., 2014; Chávez et al., 2014; and Su et al., 2016). For example, after the collapse of the former Soviet Union, a loss of state driven policy led to the introduction of free market, withdrawal of government support, and land reforms that affected many sectors. These changes led to the development of land tenure insecurity, and eventually triggered the abandonment of agricultural lands at differing rates, depending on how the transition process took place (Prishchepov et al., 2012). Changes in policies can also have implications for various unrelated processes that eventually affect water resources (Peng et al, 2011 and Davies et al., 2014). Biazin and Sterk (2013) showed how uncertainty caused by intermittent droughts together with migration and increased access to land, made woodland pastoral systems vulnerable to land use change leading to mixed agriculture and conversion to cultivation lands. Abiotic characteristics of environment such as soil, terrain and climate affect each other and influence the extent to which land can be exploited naturally (Geist, 2006). Changes in rainfall intensity was shown to trigger changes in soil properties which led to shifts in drylands in West African Sahel (Gonzales, 2001).

The current methods of watershed management came out of these large concerns related to land use change and the increasingly pressing problems with water resources. (Wang X, 2001; Biggs et al., 2010; and Hooper BP, 2011. From an ecological perspective, a watershed can be thought as a collection of land use units with varying physical sizes, each of which is defined by its ownership or control and use(s) of the land unit (Gregersen et al., 2007, Geist and Chabbra, 2006). In watershed scale, land use is one of the governing factors that influences the hydrological condition. Changes in land use in the watershed alter the hydrological response and may produce negative impacts such as erosion, drought, and flood (Rogger et al., 2012). A direct impact of urbanization, for example, is the loss of vegetation cover, which then accelerates run-off and elevates sediments and nutrients carried by stream flow (Paul and Meyer, 2001).

Studies show that watershed conditions are affected by the land use configurations within the watershed (Corbett et al., 1997; Brabec et al., 2002; and DeFries and Eshleman, 2004). Forested watersheds exhibit differing characteristics from urbanized watersheds. Watershed functions have been frequently related to the presence of forested areas with reduced peak flows, greater dry season flows, landslide prevention, improved water quality and reduced sedimentation of reservoirs and waterways (Verbist et al., 2005). On the other hand, urbanized and agricultural watersheds are often associated with increased storm water run-off, nutrients and pollutants (David et al., 1997; Corbett et al., 1997; Carey et al., 2013 and Salvadore et al., 2015). Given all these concerns, it is therefore critical to understand how a watershed evolves because of the LULC dynamics. Considering the potential damaging impacts of land use within a watershed on water resources, an understanding of land use change and its driving forces is needed to better portray the dynamics within the watershed. This will lead to better understanding of possible future condition of watersheds. Unfortunately, watersheds' characteristics are diverse and even site-specific. This is particularly true for hydrological processes since wide variation in hydrological responses has been reported among different watersheds (Bruijneel, 2004). On the other hand, unlike hydrological functions, it's the visible status of natural resources which define the goals, issues and challenges that are addressed by watershed managements (Kerr, 2007). This implies that studies of land use change on a particular watershed bear their own importance.

Until the 1990s, South East Asia was the region with the highest LULC change rate (Lambin et al., 2003). Indonesia, the world's fourth most populated country, was no exception. The island of Java with around 60% of the total 250 million is home to the largest population of Indonesia, and has a density of more than 900 people/km^2. For decades, Java has witnessed constant pressures on land resources and quickly experienced transition from a largely rural to a largely urbanized environment (Verburg et al., 1999 and Handayani, 2013). Several studies highlighted the consequences of increasing urbanization on Java, such as increasing farm loss (Partoyo and Shrestha, 2013), water pollution (Djuangsih, 1993), increased sedimentation and flood events (Valentin et al., 2008 and Romandi et al, 2016). For the last two decades, major events have contributed to socio—economic and political dynamics in Indonesia. Global economic crisis in 1997-1998 hit Indonesia, causing disruption in various aspects of livelihood. Employment declined along with currency power, export-imports, manufacturing and industry and construction / transportation (Sunderlin et al., 2000, Tambunan et al., 2010). The worsening crisis finally led to the fall of the long-term ruling regime in May 1998, which eventually accelerated the government decentralization through the enactment of the Local Autonomy Act in 2001 (Silver et al., 2001). Studies in other islands, such as Kalimantan and Sumatra, showed that the changing economic and political settings triggered the massive changes in land use through increased deforestation and development of oil-palm plantations, particularly in Sumatra (Sunderlin et al., 2001 and Tsujino et al., 2016).

The *Wilayah Sungai* (WS), or "River Region" Brantas is a delineated river basin management area in Indonesia that holds strategic economic and ecological importance. The WS represents a section of the river basin that covers multiple watersheds (called *Daerah Aliran Sungai*, DAS) and falls under a management concept known as "one river basin one management" (Kementrian PU, 2011 and Bappenas, 2012). Being the longest stretch in the river network of East Java and harboring 60% of the province's population, WS Brantas meets 73% of the total water demand of the province. It also generates around 63% of electricity that is consumed by the province, and plays a critical role in water conservation, water resource utilization and as water hazards controller (Adi, S et al., 2009 and Kementrian PU, 2011). WS

Brantas river management encompasses three river sub-basin management areas; Lower, Middle and Upper Brantas river basins. The Upper Brantas has particularly attracted scrutiny due to increasing reports of environmental problems such as sedimentation (Adi, et al., 2009), eutrophication (Sulastri et al., 2004) and discharge of pollutants (Fulazaky, 2009). Even though impacts from land use change is well recognized, studies on land use change in Java is limited. Currently, there is no published literature that looks at how land use within watersheds have changed during the last few decades, and what are the potential direct and non-direct drivers for such change. However, with increasing reports on watershed degradation and water pollution, such study will be essential in gaining a better understanding on how the landscape evolves and on how the changing landscape can be associated with watershed degradation. WS Brantas represents a typical watershed in Java that has been continually subject to rapid development and population growth. While greater attention has been paid to land use change outside Java (Sumatra, Kalimantan and Papua) – where tropical forest is the prevailing land cover and where development is less intense than in Java – a study on an unceasingly urbanizing watershed will provide a better understanding on how land use drivers play a role in changing the environment. The study focuses on Upper Brantas Sub-basin as a case study aimed at (1) understanding how LULC has changed in Upper Brantas Sub-Basin, (2) looking at potential drivers that might contribute to the LULC changes, (3) identifying/illustrating the current condition of watershed functions based on hydrologic and water quality conditions, and deriving implications of existing LULC change drivers on water quality. This is the first of its kind study which examined 2-years of LULC change in these watersheds and how natural and anthropogenic drivers such as infrastructure, government policies and watershed physical condition might have played a role in changing the landscape.

3.2 Materials and Methods

3.2.1 Study Area

The Brantas river basin area is one of the most important watershed in Java island. It meanders around 320 km in the central part of East Java Province, passing through 19 cities and municipalities with an area of approx.11,050 km^2. This river basin encompasses Upper, Middle and Lower Brantas Sub-Basins. Three sub-river basins, or catchments, called *Daerah Aliran Sungai* (DAS) cover the Upper Brantas Sub-Basin: The Konto DAS, DAS Lahor and DAS Brantas Hulu (Figure 3.1). The DAS (or catchments)' have a total drainage area of 2,358 km^2, or about 25% of the total Brantas River Basin area. These catchments harbor multi-purpose reservoirs built for electricity generation, water supply, irrigation, flood control, water conservation and recreation. The catchment complex is also surrounded by mountainous regions: Mt. Kawi, Mt. Arjuno, Mt. Kelud, and Mt. Bromo-Semeru, whose topography creates elevation variations within the catchments. Volcanic materials produced from eruption of Mt. Kelud, Bromo and Semeru often lead to volcanic debris flows and sediment deposition in the rivers and reservoirs. Brantas Hulu sub-river basin exhibits a tropical monsoon climate with a dry season lasting from May to October and a rainy season from November to April. Due to topographic influence, the Upper Brantas region has a large variation in precipitation with an average of 2000 mm/year and the highest is around 3000 – 4000 mm/year in Mt. Kelud region. Administratively, Upper Brantas accommodate two cities (Batu and Malang) and one municipality (*Kabupaten* Malang – *Kab*. Malang), with Malang being the second largest city after Surabaya, the capital of the province. Among several LULC change studies, none exclusively investigated the LULC change in Upper Brantas. However, as similar to other parts in Java, Upper Brantas has experienced rapid development. Increased population often resulted in the increasing demand of settlement. Favorable weather, increasing business centers and attraction, concentrated education places and close proximity to the capital have also attracted the people outside Malang. All these might contribute to anthropogenic modifications to the watershed.

3.2.2 Land Use / Land Cover (LULC) Change Mapping

To carry out land use / land cover mapping, remote sensing-based land use/land cover classification was selected, following an existing land use classification scheme (Table 1). Atmospherically corrected Landsat surface reflectance images from 1995 to 2015 were acquired from USGS Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS). Due to very frequent cloud cover and tropical atmospheric disturbances such as haze and sun glint, it was challenging to obtain a cloud free good quality image for such a large area. Screening from available datasets resulted in cloud free images for the years 1995, 2001 and 2015. Landsat 5/TM Path/Row 66/118 were downloaded for mapping LULC in August 1995 and August 2001, while Landsat 8/OLI (July 2015) was used for LULC mapping in 2015. Medium spatial resolution Landsat data have been used by studies to map LULC changes with differing periods ranging from 2 years, 5 years (Tran et al., 2017), 10 years (Thakkar et al., 2010) 15 years (Sanhouse-Garcia et al., 2016), and 40 years (Qasim et al., 2013). In this study, a time interval of 20 years for LULC change analysis was used not only because of the availability of good quality cloud free images, but also because of the opportunity to find out if there are certain land use types that change faster than others.

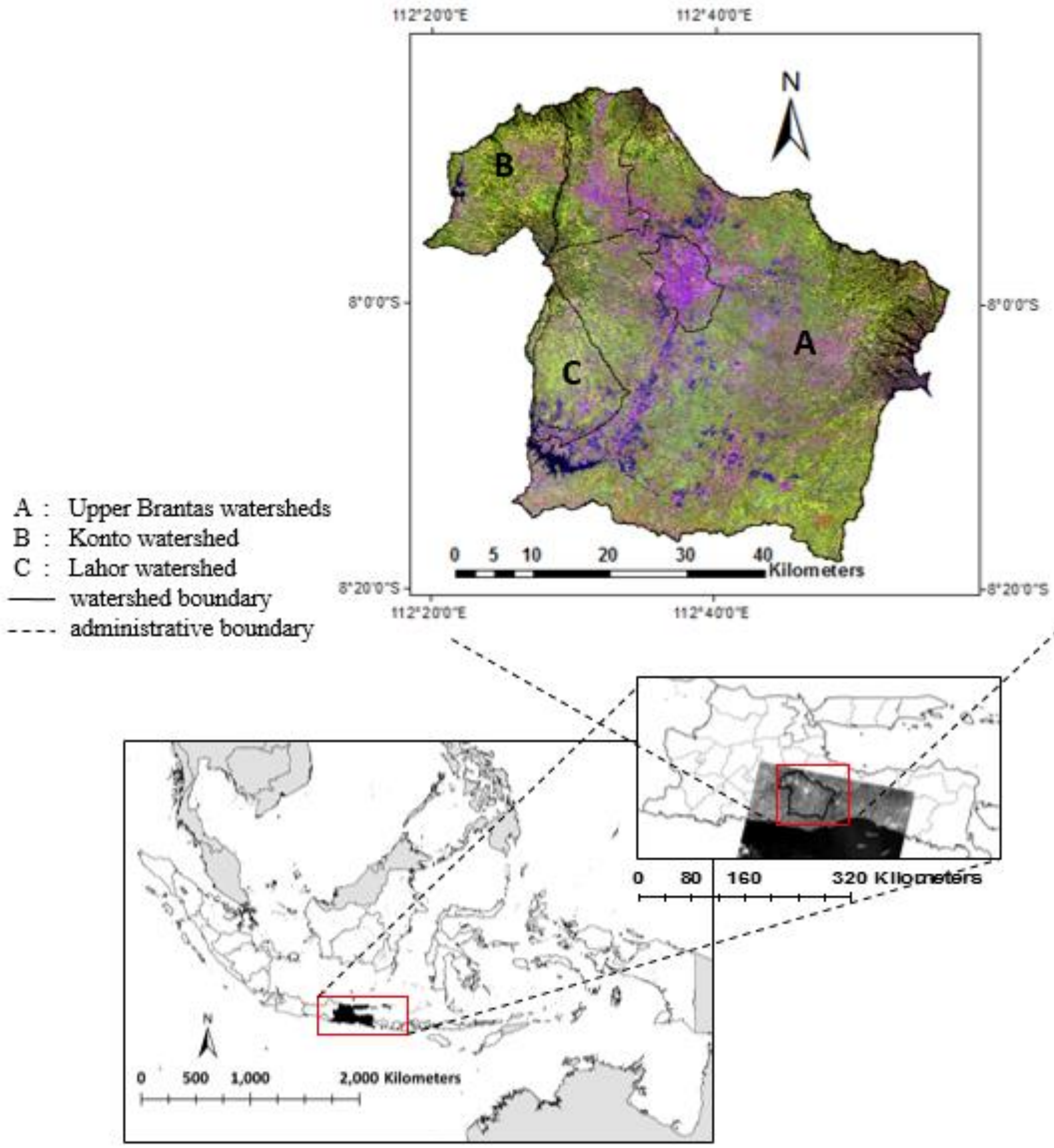


Figure 3.1. Upper Brantas sub-river basin area covering DAS Upper Brantas (A), Konto (B) and Lahor (C) in 5-4-3 L8/OLI's band composite (Path/ row 118/66, June 16th, 2015)

An Object Based Image Analysis (OBIA) in Ecognition/Developer environment with hierarchical rulesets approach was selected because of several reasons including (1) OBIA can better reduce salt-pepper effect than pixel-based approach (Blaschke, 2010), and (2) hierarchical rulesets can integrate spectral and spatial features of an object, which is useful for mapping objects with similar spectral response but having differing spatial features such as shapes, lengths, and width (Myint et al., 2011). The LULC classification scheme was adopted from the Ministry of Forestry (MoF), Republic of Indonesia (2010). This classification has been applied to Landsat images for mapping forest change in Riau/Sumatra (Margono et al., 2016). Details of LULC schemes is presented in Table 1.

Table 3.1. LULC classification scheme and definition

No	LULC class	Definition	Code
1	Dryland Forest	Forest in the lowlands, hills, and mountains	FRST
2	Shrubland/Bushland	Natural vegetation with multiple stems and canopies, revegetated areas from dryland forest	SLBL
3	Savannah/Grassland	Natural non forest vegetation, grassland with few trees	SVGL
4	Industrial Forest Plantation	Large scale tree planted agriculture (In Upper Brantas is mixed pines, acacia, *jati, sengon)*	IDFP
5	Plantation	Large scale crop areas, (In Upper Brantas this is usually sugarcane or elephant/Napier grass)	PLTN
6	Dryland agriculture	All types of agricultural areas on dryland, mixed between cropland, and garden, usually corn, soy, peanuts, cassava	DLAG
7	Mixed Dryland Agriculture	Dryland agricultural areas mixed with shrub, bushes, and mostly trees, usually crops like corn, soy, peanut, cassava, mixed with bamboo, coconut, cloves, *sengon*, *jati*	MDAG
8	Rice field	Paddy field / rice field on wetland, including rain fed paddy field and irrigated paddy field	RCFL
9	Built-up areas	All non-vegetated areas including roads, urban, rural settlement and natural openings	STBU
10	Water	All aquatic environment including sea, rivers, lakes, reservoirs	WATR

Prior to LULC mapping, images were screened based on cloud cover, haze, sun glint and potential systematic noise appearances. Topographic Normalization following Teillet et al., (1982) was applied to reduce erroneous reflectance values due to the effect of terrain-induced shadow. A set of rules was applied by incorporating a number of features such as single band reflectance, band ratio, indices such as NDVI, NBR2 and Sand (USGS, 2016), Slope, Digital Elevation Model (DEM) from ASTER-DEM, and Principal Component Analysis (PCA) images. These parameters were selected because they showed better visual discrimination for land use types. One challenging condition was that there is high variability within the same LULC classes in Java/Indonesia and relatively small in size leading to patchy and scattered land uses. For example, Mixed-Dryland Agriculture accommodates all kinds of plant species that comprises agricultural plants (annual and perennial) and shrubs/bushes regardless of species. Slope and DEM were used as part of rules since these two factors control the operational limits of farming activities in Java and in other regions (Prasetyo et al., 2009 and Gilani et al., 2015). PCA images were incorporated as visual assessment revealed better discrimination for some land use classes. Due to time and resource constraints, only 270 ground-truth points were acquired in Metro sub-catchment in 2015. This catchment was selected due to its representation in all LULC classes. Google Earth was used for accuracy assessment for the rest of study area in 2015 by using 1-km density with systematic sampling (932 points). For 1995 image, three historic air photos with 1: 25,000 scale from local Army Service were used to assess the accuracy of the LULC maps. Unfortunately, only 50 points were extracted due to poor photo quality.

The complete LULC mapping workflow is presented in Figure 3.2. In this workflow, Landsat atmospherically corrected images were first checked for quality. Visual assessment was used to seek good quality images which are clod free, haze free, and sensor-induced systematic error free. Further, topographic correction was implemented to remove the influence of topography on object reflectance. The study area covers a complex terrain from steep mountain ranges to flat valleys. Areas that are under sun shadow will have different reflectance from the non-shadow areas. This causes erroneous errors in land use mapping, and topographic normalization helps in reducing the errors by normalizing the reflectance with sun angle. Seven bands (Blue, Green, Red, NIR, SWIR1 and SWIR2) of Landsat images were used as part of input in OBIA along with PCA images, slope and DEM. PCA was performed on 7-band Landsat data and the first three components accounted for 97.57% of the variability in the study area.   OBIA rulesets were created hierarchically using a range of objects starting from the largest classes (Water, Land and Vegetation) to the more detailed classes. The rulesets implemented in OBIA is presented in Figure 3.3. The threshold values applied for building the ruleset were obtained from visual check and trial and errors on a series of samples of objects. Results of classification were exported to shapefiles. Accuracy assessment was carried out by comparing the resulted land use classes from OBIA with classes derived from ground checking, historic air photos and Google Earth.

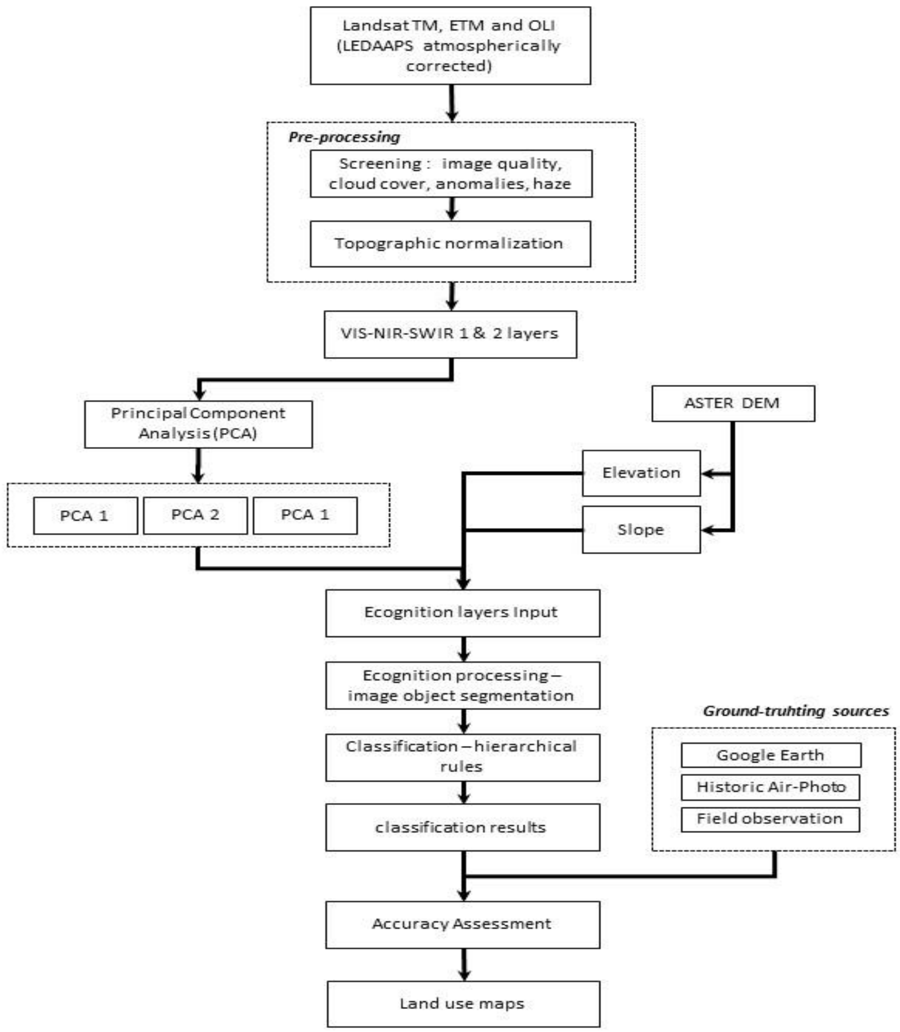


Figure 3.2. The OBIA hierarchical LULC mapping workflow using Landsat 7/ ETM (1995) and Landsat 8/OLI (2015), DEM and PCA images.

A. LULC Changes and Potential Drivers

Post-classification change detection was carried out using ArcGIS for investigating the extent and distribution of LULC change in the last 20 years (1995-2015). In this case, only the 1995 and 2015 images were used for change analysis. A 20-year interval was selected because (1) there have been previous studies which considered 20 - 40-year period of land use change using Landsat images (Qasim et al., 2013; Narumalani et al. 2004; and Brink et al, 2014), (2) to capture the effect of policy change in 2004 when Indonesia started to implement Law of Autonomy which gave bigger authorities to local government for managing their regions. LULC analysis spanning over twenty years and 10 years after the implementation of the law, might provide sufficient time window to capture the impact of policy implementation. Some land uses may change more gradually and need a longer time period to capture the changes. The 20-year time window was considered to examine both proximate and underlying drivers of land use change.

Land use is a representation of the users' goals for utilizing their land resources whose decisions are affected by contexts of socio-economy, biophysical environments, as well as culture with which land uses are associated, which can be diverse both spatially and temporally (Lambin et al., 2003). To better understand the potential drivers of LULC change, we should consider factors affecting the decision making of land users. A generic framework of LULC change drivers from Geist and Lambin (2002) was chosen for analyzing potential drivers of land use change in Uppper Brantas between 1995 and 2015 (Figure 3.4), which illustrated proximate (direct) and underlying (non-direct) causes. Socio-economic data such as populations, roads, gross domestic product, employment, were collected from Indonesia National Statistical Agency (*Badan Pusat Statistik*, BPS). Biophysical data such as hydrologic data, climate and rainfall were obtained from Indonesia's National Meteorological Center. Policy documents were obtained from published literatures and Malang Regional Planning Agency. Descriptive analysis was implemented to a series of relevant policy and government documents, which is a common method applied by some land use change studies (Verbist et al., 2005, Peng et al., 2011, and Sahide et al., 2015) to gain an understanding of the context of society and environment.

3.2.3 Assessment on Watershed Conditions

One of goals of this study was to provide a brief analysis of the current condition of watershed. Several studies did report the indications of degrading conditions of Brantas River Basin. Widianto et al (2001) reported qualitative observation from local people about increasing loss of sprints in upper areas, and reduced discharge in rainy seasons. Decreasing storage capacity of Sutami reservoir built within the watershed has reduced almost half, from 100% in 1972 when it was opened to 57% in 2003, while the reservoir was expected to function for 100 years (PJT, 2005). Apart from these studies, there has been no long-term assessment on watershed condition in Upper Branntas. Unfortunately, rivers in Upper Brantas are limitedly gauged and measurements of water quality parameters are not available. Studies showed the associated conditions related to an urbanizing watershed such as increasing runoff coefficient, flashier flows, increased sediment and nutrient loads, as well as increased floods/land slide probability (Shuster et al., 2005; DeGasperi et al., 2009; and Santaangelo et al., 2011). Physical watershed condition was assessed using limitedly available data gathered from local agencies. A flashiness hydrograph index was calculated following Baker et al., (2004) from the collected streamflow data. Water quality parameter such as Total Suspended Sediment (TSS) collected from monthly observation at three reservoirs together with qualitative data of floods/landslide occurrences were used to help gaining insights about watershed condition.

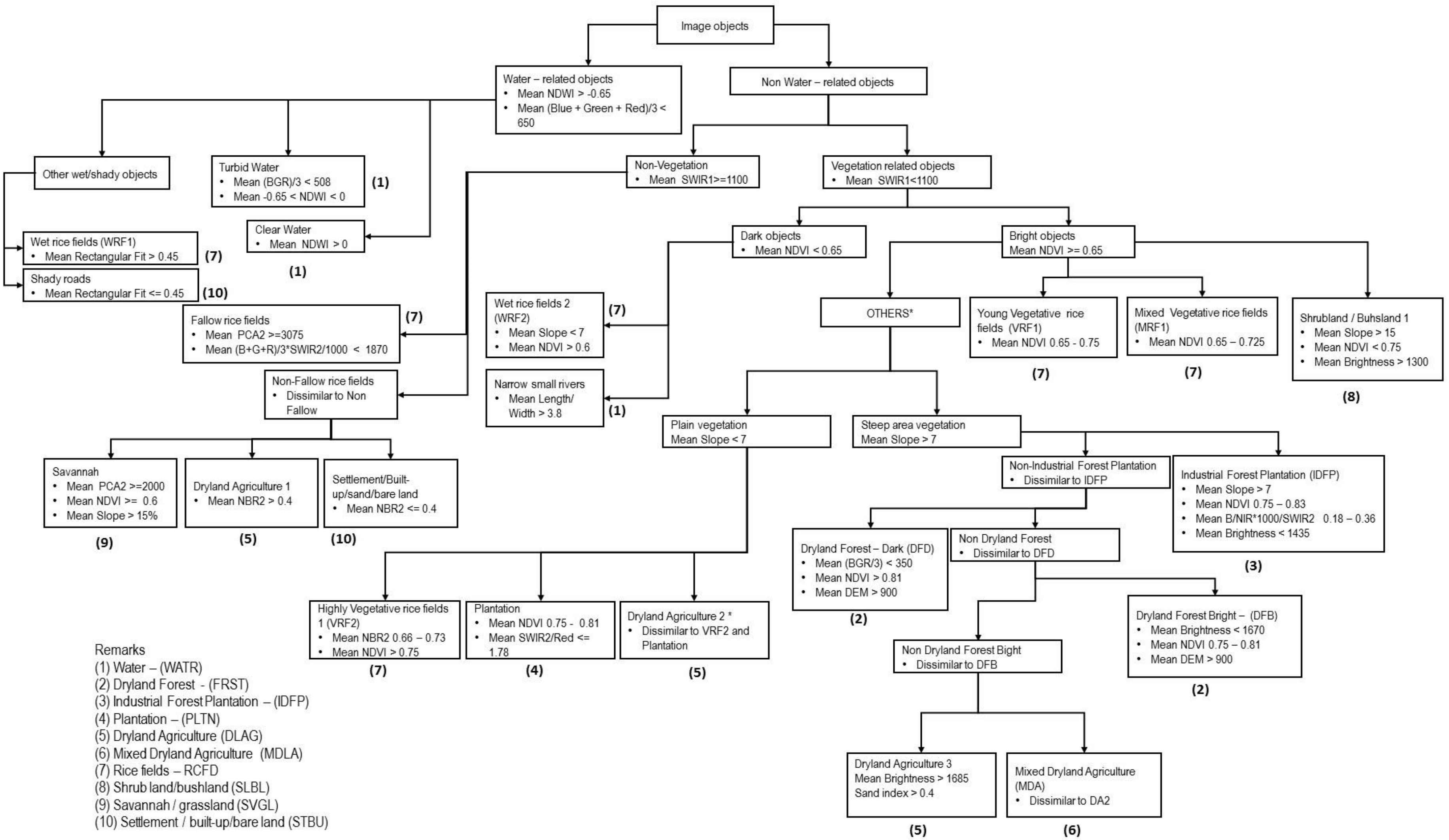


Figure 3.3. Hierarchical ruleset applied in OBIA LULC mapping for Landsat 7/ETM and Landsat 8/OLI for Upper Brantas by combining DEM, Slope, Surface Reflectance, and Reflectance Indices

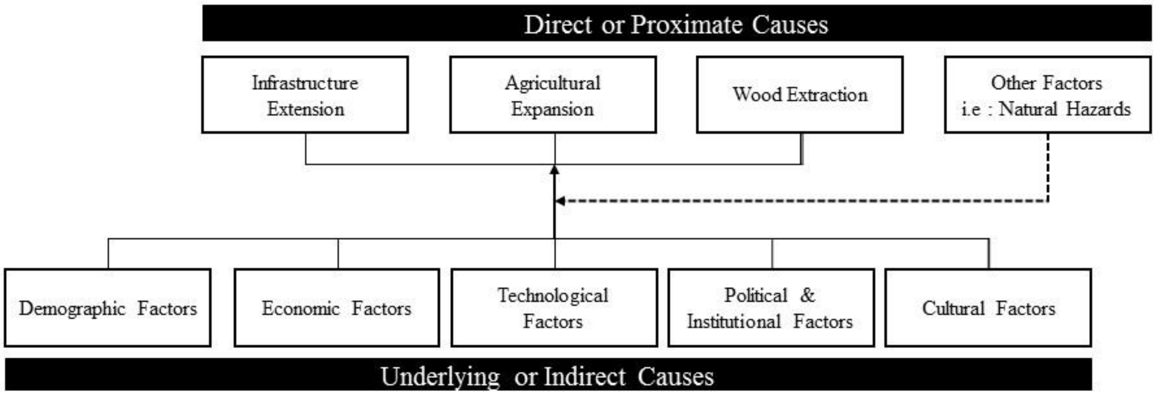


Figure 3.4. A generic framework of five board groups of the underlying drivers that underpin the direct drivers of land use change especially tropical deforestation (modified from Geist and Lambin, 2002)

3.3 Results and Discussion

3.3.1 Land Use/Land Cover Change (1995 – 2015)

Observation of field condition during ground checking and visual assessment using Google Earth-based analysis showed a large variability for Dryland Agriculture (DLAG) and Mixed-Dryland Agriculture (MDAG) classes. In addition, accuracy results showed that these two classes contributed the biggest source of uncertainty in both omission and commission errors. Due to this condition, these two classes were merged into one named Mixed and Dryland Agriculture (MADL). Accuracy assessment result revealed an overall accuracy of 84.16% (Kappa 79.10%), (Appendix 1).

The LULC maps in 1995, 2001 and 2015 show that the terrain might play a role in controlling the distribution and pattern of land uses in Upper Brantas. Dryland forests are mainly found in high elevation, circling the mountains. Forests in Java are mostly concentrated on the highland or mountain regions because lowland forests had been converted to agriculture because of massive agricultural expansion in 1960's (Lavigne and Gunnell, 2006) (Figure 3.5A and 3.5B). Similar to dryland forest, Industrial forest plantations were found in the lower altitudes, confined to the outer ring of dryland forest. Industrial forest plantations were established not only for timber production but also for buffer zones, supporting dryland forest conservation. Shrub land/bushlands were mainly found on mountain peak zones, as a result of forest encroachment and naturally less vegetated zones nearing the summits. In Upper Brantas, slope remains one of limiting factors in land use practices. Lowland areas with flat slopes (0 – 7%) are dominated with terrain-limited land use practices such as rice field, plantation, and settlement/built-up areas. Mixed and dryland agricultural land uses were scattered between lowland and highland.

Based on post-classification change detection results, land uses in Upper Brantas sub-river basin exhibited differing change rates average. Some LULC classes remain relatively stable, while some others witnessed considerably major changes. For example, forests regarded as the most threatened land use, decreased from around 450 km^2 in 1995 to around 384 km^2 i.e., approximately 13% from its original extent in 1995. Together with industrial forest plantations, forested areas cover roughly about 17.66% of the watershed LULC in 2015, while agricultural land uses covering rice fields, plantations and mixed and dryland agriculture remain the prevailing land use types, accounting for almost 900 km^2 or 65% of the total area. Among agricultural land use classes, Mixed and dryland agriculture (MADL) became the dominant farming practice (38%), followed by rice field about 18%. Settlement almost doubled from 1995, representing about 15% of the total watershed area. Settlement/build-up has become the land use class experiencing the highest change rate, with an average 5% increase per year. Compared to 1995, almost all land uses decreased except for settlement and industrial forest plantations. The decrease in forest area was mostly associated with the conversion to agriculture (MADL) and forest logging that led to the development of shrub lands/bush lands (Table 2). As expected, the growth of urban areas was compensated through the loss of agricultural land uses.

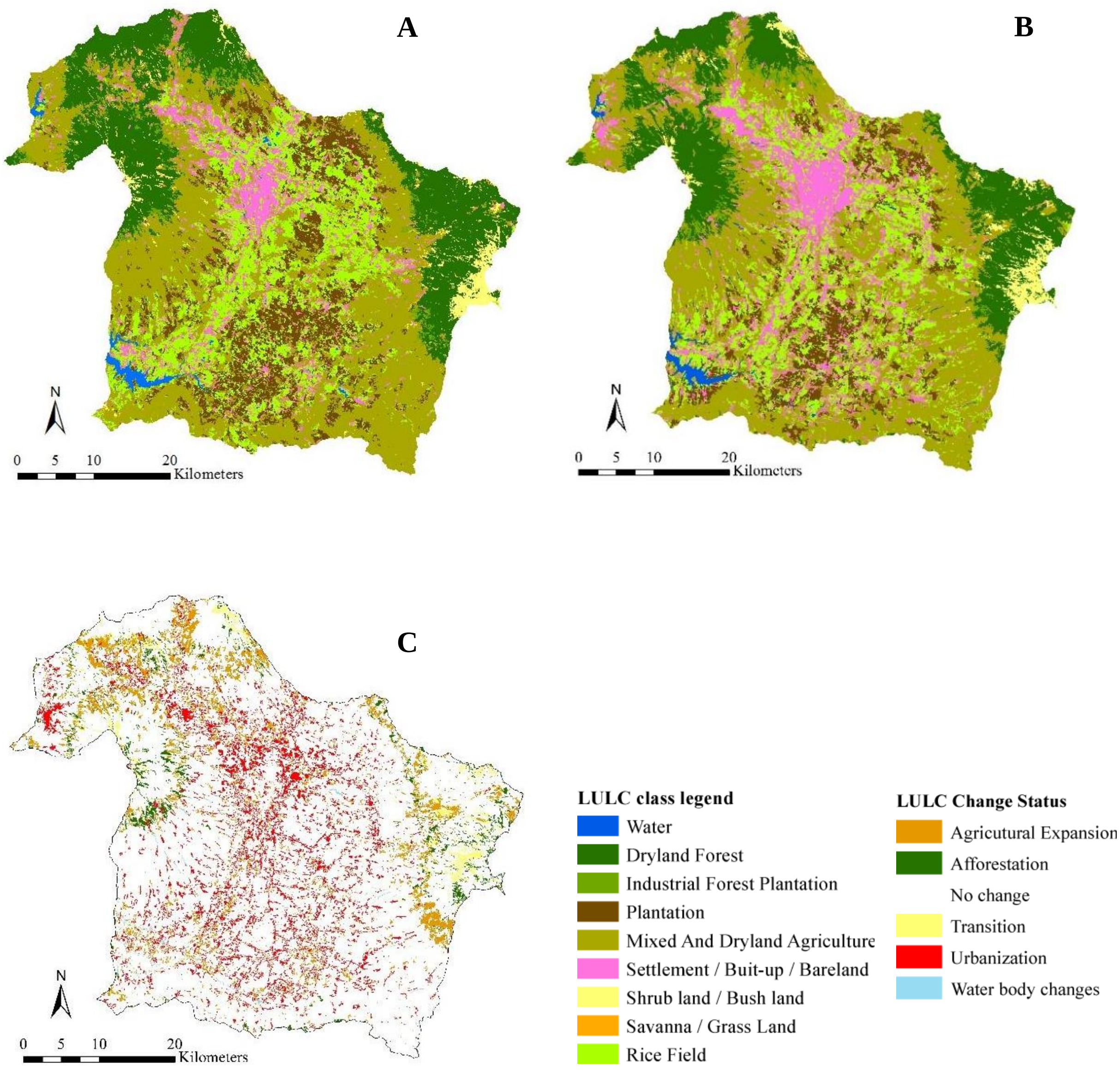


Figure 3.5. Land use/land cover map of Upper Brantas in 1995 (A), in 2015 (B), and (C) Status of land use conversion based on the changes of land uses from 1995 to 2015.

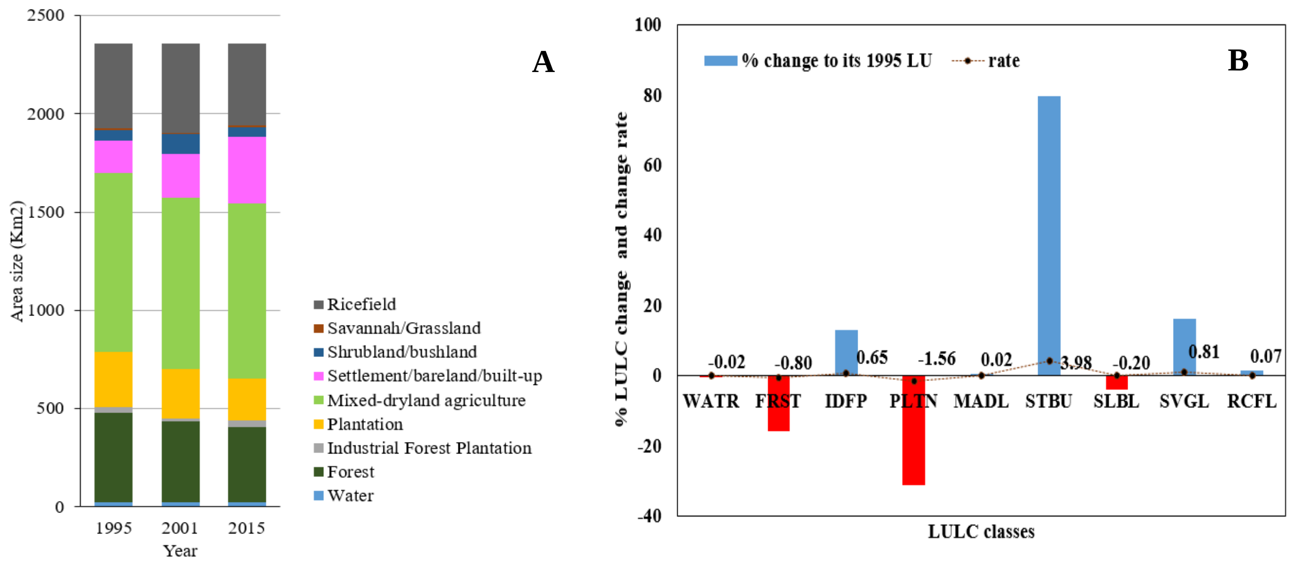


Figure 3.6. (A) LULC Changes in Size (km^2) for Period 1995, 2001, and 2015, (B) Percentage of LULC Change and Change Rate for Period 1995 – 2015.

Table 3.2. Land Use/Land Cover Post-Classification Change Detection Matrix 1995-2015

		To 2015 (km^2)								
		WATR	FRST	IDFP	PLTN	MADL	STBU	SLBL	SVGL	RCFL
From 1995 (km^2)	WATR		0	0	0	1	1	0	0	4
	FRST	0		12	0	75	3	26	2	0
	IDFP	0	9		0	4	0	0	0	0
	PLTN	0	0	0		85	28	0	0	62
	MADL	2	12	3	46		90	1	1	124
	STBU	0	0	0	5	28		0	0	9
	SLBL	0	21	1	0	5	0		2	0
	SVGL	0	2	0	0	3	0	1		0
	RCFL	3	0	0	57	74	90	0	0	

**) WATR: Water, FRST: Dryland Forest, IDFP: Industrial Forest Plantation, PLTN: Plantation, MADL: Mixed and Dryland Agriculture, STBU: Settlement/Built-up/Bare land, SLBL: Shrub land/bushland, SVGL: Savanna/Grassland, RCFL: Rice field*

Regrouping similar land use types into broad categories for comparison between 1995 and 2015 allowed for the identification of the pattern of agricultural extension, urbanization, and afforestation. For this, plantation, rice field, and mixed-dryland agriculture classes were grouped as “agriculture”, dryland forest and industrial forest planation were grouped as “forest”, shrub lands and savanna/grassland were grouped as "transition" land uses (Appendix 2). All previous changes from other LULC classes to agricultural classes were considered as agricultural expansion. All changes leading to the growth or settlement were regarded as urbanization. While changes from non-forest to forest were classified as afforestation, all changes to shrub land and grassland were grouped as "transition". Figure 3.5C shows the distribution of these categories. Forest conversion leading to agricultural expansion and transition land uses were largely concentrated on the most outer or lower ring of forest, while logged areas that developed into shrub land were mainly concentrated around the upper ring of forests. Lower rings are less steep and closer to road network, making this area more accessible. The development of urban areas appeared to follow accessibility and proximity to existing urban areas. Figure 3.7 visualizes the several major types of LULC change trajectories in the study area.

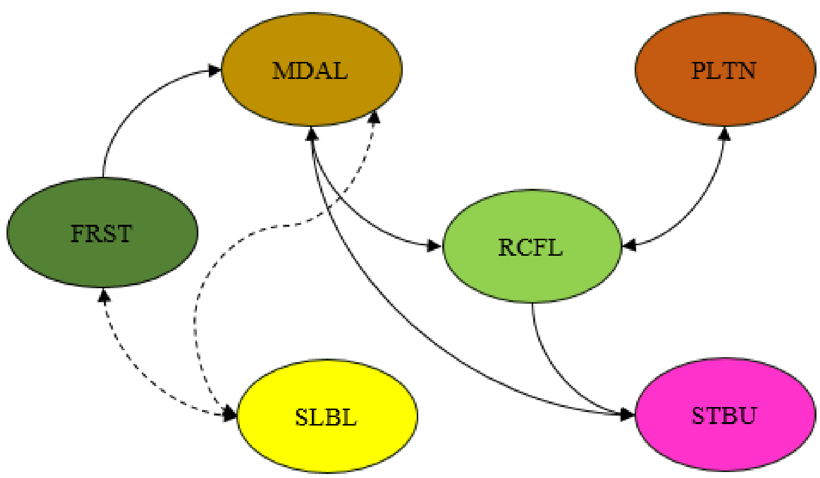


Figure 3.7. Several major types of LULC change trajectories in the study area (FRST: Everegreen dryland forest, MDAL: mixed-dryland agriculture, RCFL: rice-field, PLTN: plantation, SLBL: shrubland/bushland, STBU: settlement/built-up).

Drivers of LULC Changes – Proximate and Underlying Causes

The framework of LULC drivers by Geist and Lambin (2002) perceives a change in LULC as a synergic interaction among several factors. Therefore, the land use change process should not be seen solely from a single factor. Studies show that the proximate and underlying drivers vary among places and drivers do not necessarily exist for all places. For example, an extreme hazard may not exist in a certain region for a certain period, or, a region might be stable politically but diverse culturally. The changes in land uses in Upper Brantas river basin for the last 20 years also represent the interactions of these drivers.

Proximate Causes

Direct causes or proximate drivers of land use change are factors explaining how human activities might affect the appearance of the land cover and ecological processes. In varying degrees, these factors can include infrastructure development, wood extraction, agricultural expansion, environmental or biophysical drivers, and abrupt physical and social events such as earthquakes or wars (Turnet etal., 1990; and Geist and Lambin, 2002).

1. Wood extraction and agricultural expansion

Wood extraction and agricultural expansion represent two activities that directly alter physical land cover configuration in a particular region. While the first represents wood harvesting for fuelwood, the later represents forest/wetland openings for new farming land. Between 1995 – 2015, forest cover steadily declined, accounting for 17.67% in 2001, and 16.30% of total area in 2015. The relatively sharper decrease in 1995 – 2001 period might be attributed to increased illegal logging that increased in 1997/1998 (Nugroho and Darwiati, 2016). All forest areas are clustered in the mountain region since lowland forest had lost even in early 1900's (Lavigne and Gunnell, 2006). Wood extraction can be considered negligible. In

Indonesia, wood extraction signifies the use of wood for domestic fuel, and this is commonly associated with upland areas where electricity has not reached the sites yet. Upper Brantas is a relatively developed watershed where most of people have replaced wood with gases and electricity, and thus wood extraction might not be significant. However, despite the negligible wood extraction, forest poaching activities can still be found in Upper Brantas basin. In most cases, forest encroachment can cover a wide range of activities from minor ones like bamboo shoot theft and leaves theft for forages to major ones like illegal logging; however, the illegal logging in Bromo-Semeru, eastern part of Upper Brantas were getting smaller due to forest guard and improved awareness from community (Nugroho and Darwiati, 2016). To sum up, while traditional wood extraction may no longer exist, wood loss due to illegal cuts still impose threats that may alter forested areas in Upper Brantas.

Agricultural sector has long been the backbone of local and national economy of Indonesia, including in Java. The development of agriculture was marked by nation-wide agricultural expansion from 1960s to 1980s for supporting self-sufficiency programs (Kasryno et al, 2004, and Nurvianto, 2014). Since 1970's, expansion was no longer the main agricultural development approach in East Java (Kasryno et al., 2004 and Nurvianto, 2014). This means that official or government-supported forest/land clearing for creating new agricultural lands ceased. In Upper Brantas River Basin, most of the forest loss in the last two decades was due to conversion to mixed-and dryland agriculture, accounting for 5% for the whole area.

2. Infrastructure development and accessibility

Accessibility has been recognized as a factor influencing land use through the development of road networks, which eventually induces deforestation and agricultural expansion (Cropper et al., 2001; Pfaff et al., 2007; Wyman and Stein et al., 2010). Infrastructure and accessibility are also interlinked with population. Improved infrastructure and accessibility can possibly be attributed to the strategic role of Malang as a center of education and tourism in East Java. Three big state universities, and tens of private ones, have harbored thousands of students from across the country have increased the number of native inhabitants of Malang. Solely from the education sector, there has been considerable development of urban areas for student accommodation. The pleasant weather and sceneries in Malang and Batu City have triggered substantial development of housing for tourism industries. Travel Bisnis (2016) reported that these two sectors have stimulated the establishment of settlement, boarding houses, hotels, restaurants, companies and offices. For the last two decades, local government has been trying to improve accessibility. In that regard, efforts to provide roads are constantly undertaken in order to deliver better access for increased population in Kab. Malang (the largest region) (Figure 7A). Massive infrastructure improvement was evident in Upper Brantas. Hotels, restaurants, markets, and housing become more available in Upper Brantas. Data from Malang region statistics agency (2016) showed that the number of accommodations such as hotels and lodgings doubled in 7-year period, from 2,109 properties in 2009 to 4,798 in 2016. These new accommodation sites were compensated through the loss of other land uses mainly agriculture. Participatory study conducted by World Agroforestry Center involving stakeholders in Batu city recognized the loss of agricultural lands for hotel provisions (Widianto et al., 2001). It can be safely argued that rapid infrastructure and accessibility provision triggered by both population and economic activities proliferate the increase of urban areas in Upper Brantas.

3. Ecological condition

Bio-physical drivers of a watershed such as climatic, geologic, edaphic and hydrologic condition define the natural capacity for land uses (Lambin et al., 2002). Climatically, Upper

Brantas River Basin is benefited from favorable weather for agriculture. Abundant rainfall, humid and warm temperature, and relatively stable solar radiation, provide suitable growing conditions. In normal condition, farming activities can be carried out throughout the year in Upper Brantas. Between 1995 and 2015, extreme weather events can be considered to be limited. Almost no extreme long weather events occurred, except for the 1997 El Nino induced drought, and the 1998 La Nina floods. These events might have contributed to the loss of agricultural land uses between 1995 and 2001, not only for forested lands but also for agricultural lands.

Upper Brantas River Basin is an area with influence of volcanoes. Seven mountains circles the Upper Brantas River Basin (Mt. Semeru, Mt. Bromo, Mt. Kelud, Mt. Arjuno, Mt. Welirang, and Mt. Kawi). Six out of the seven volcanoes are active, only Kawi is not active. Before 1995, there had been many recorded eruptions from these mountains in differing extents. Between 1995 – 2015, eruptions occurred from Mt. Bromo and Mt. Kelud. Mt. Bromo erupted massively in 2010, while Mt. Kelud erupted in 2007 and recently erupted in February 2014. It has been reported that the eruption damaged agricultural land uses due to volcanic materials; however, all these eruptions mainly spread to north-west of Kelud (De Bélizal et al., 2012) and East of Bromo (Bachri et al., 2015), and these regions are outside Upper Brantas River Basin, and therefore, impacts of these hazards to land use changes in Upper Brantas during 1995-2015 were considered insignificant. Geist and Lambin (2002) noted that such natural hazards may play a role in causing abrupt land use / land cover change. However, volcanic Java environment is gifted with high resiliency that led to no drastic change of land uses due to this hazard (Lavigne and Gunnell, 2006). The fertile volcanic soils and warm humid weather can regrow loss vegetation rapidly after large – scale eruption impacts.

Farming activities require suitable growing factors such as soils, topography, and favorable climate. Conversion from rice field to other land uses occurred with the conversion trajectory mostly to plantation (sugar cane), mixed-dryland agriculture or settlement. On the other hand, conversion to rice field was also mostly from plantation and dryland agriculture. All these land uses are terrain-limited and require similar bio-physical growing factors. Most rice field areas are associated with flat slopes, accessibility to water and fine soils such as *Epiaquepts* where water table is relatively low and in gently sloping position, making it physically suitable for water-demanding practices such as rice farming. Conversion from rice to sugar cane and vice versa might be attributed to the changes in farmer's economic capability. Growing rice is economically more expensive and physically more laborious. When facing economic hardship, farmers can change farming practice such as rice to sugar cane. A further study is required to investigate this factor i.e., livelihood level in detail. In other parts, soils in the study area are dominated by *Andosols* developed from volcanic materials. Soils in this ordo are broadly categorized as medium that support moderate quality for agricultural production (Schiefer et al., 2015). With this condition, most of the conversion from one agricultural land use type to another, except for rice field and sugar cane which require flat topography, would be made possible without extreme modification.

Underlying Causes

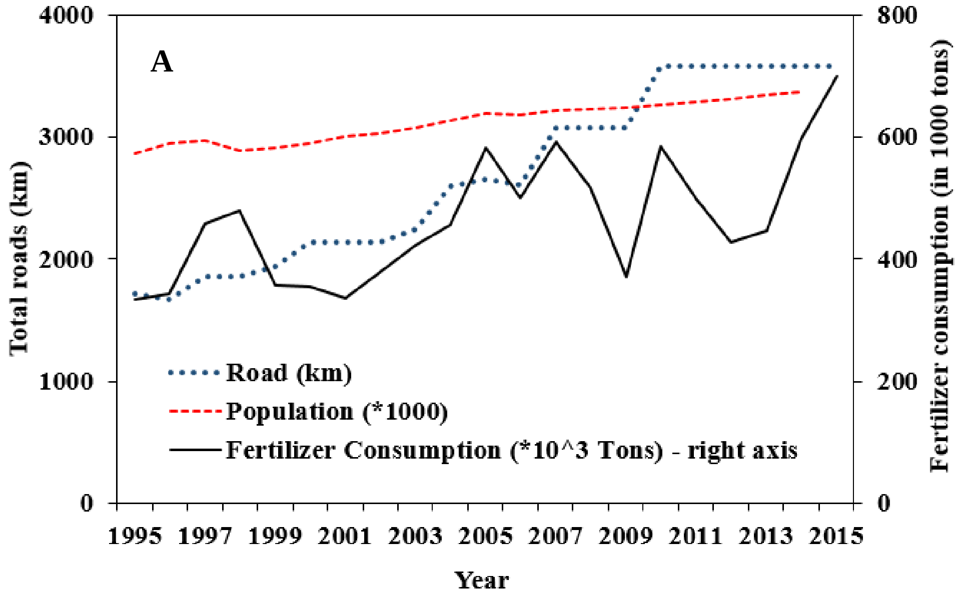
Underlying land use drivers are defined as the essential processes in society that trigger direct causes and can operate in varying level, which can broadly cover demographic, economic, technological, political and social institutions (Geist and Lambin, 2002). In Asia, socio-cultural institutional and policy factors in combination became the biggest cause along with technology and demography (Geist and Lambin, 2002). In this section, we outline how these factors may have driven the land use change in Upper Brantas River Basin.

1. Demographic factor

Population is one important demographic factor that contributes to land use changes. Increased population bring various consequences such as higher housing demand, higher labor availability but also higher employment and logistic demand. Between 1995 and 2015, population in Malang Regency (Kab. Malang) increased from around 3 to 3.6 million. Similar to this region, increase of population has also been experienced in Malang City (from around 730 K to more than 850 K). Population pressure has been one of the significant factors for expansion of settlement areas (Meyer and Turner, 1992; Liu et al., 2006; and Sen et al., 2009). Upper Brantas observes varying degree of population density. In Malang City, the population density average is about 2,373 people/km^2 while in Malang municipality (the largest part), the population density now is 821 people/km^2. With a projected population growth of 0.8% per year (Pemkab Malang, 2011), increase in urban areas will not be negligible. Analysis of land use map and road networks revealed that new urban areas are mainly located on relatively flat terrain and in closer proximity to existing urban areas (based on post-classification change detection) and in vicinity of road networks. This urban expansion might have contributed to the shift in agricultural land uses. Rice and other annual crops were mostly concentrated on lower parts of the watershed, but 2015 land use map shows the establishment of these land uses were not only found in flat areas but also in steeper zones and less accessible areas. It appears that development of new urban areas may trigger land use competition with agricultural land uses, and higher demand of settlement might force the openings of settlement in these areas.

2. Economic factor

Despite increasing urbanization, the agricultural sector remains dominant in the watershed. Data in 2006 – 2010 showed that around 40% of total labor pool worked in agricultural sector; however, from year to year, the proportion was gradually smaller (Pemkab Malang, 2011). Agriculture remains the top contributor to the labor pool with the largest livelihood group, followed by trading and finance sectors contributing 20% and 14% respectively. The significance of agriculture was also represented by the share of Gross Domestic Product (GDP) from this sector (Figure 3.8B). From 1995 to 2015, despite the decrease in size, agricultural land uses' GDP continued to rise. Improved technology, accessibility and elevated fertilizer consumption, might have contributed to the increase of GDP in Agricultural sector. However, compared to other sectors such as manufacturing industries that produces similar share of GDP, agriculture sector occupied a bigger portion of the labor pool. In other words, increasing share of GDP from non-agriculture (industry and trade) indicated bigger values or profit in these sectors and might have attracted people to convert their agricultural land for industry/trade. This might also have contributed to the increase in urban areas. Compared to other agricultural and forest land uses, rice field showed the lowest change rate, only 0.17 during the last two decades. Rice is a strategic commodity that government puts in significant efforts for its steady availability. Long-term rice subsidy has been given by the government to reduce the financial burdens on rice farmers in meeting their farming cost and this might have contributed to the relatively higher stability of rice field (Panuju et al., 2013).



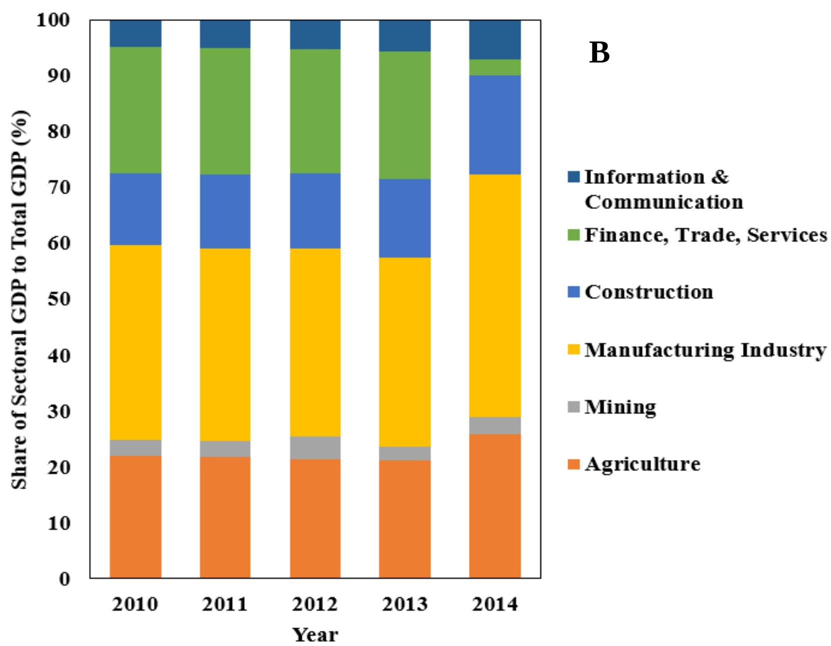


Figure 3.8(A). Long-term data for total roads, number of population (in thousand) in Kab. Malang and nation-wide fertilizer consumption (right-axis, in thousand tons), and (B) Share of Gross Domestic Product (GDP) of each sector in Kab. Malang for 2010-2014. Source: Central Bureau of Statistics (*Badan Pusat Statistik, BPS*) and Indonesian Fertilizer Producers Association for fertilizer data.

Studies showed that higher prices of non-agricultural commodity attracted the land owners to convert their land (Firman, 2002; Fan et al., 2007). In Upper Brantas River Basin, conversion from agricultural land use to urban is evident at urban fringe areas. Before the economic crisis in 1997 – 1998, Indonesia enjoyed the benefits from the boom where certain sectors grew promisingly, stimulating investment and demand-driven settlement development (Firman, 2002). Massive economic crisis hitting Asian countries in 1997 - 1998 led to a wide range of impacts, hitting financial sectors, causing reduced employment, reduced export-import, and currency depreciation. During the crisis years, most economic sectors (industries, transportation, restaurants, communications, housings) plunged into a negative growth except for the agricultural sector due to its low dependency on imported components (Tambunan, 2010). The hardship in livelihood triggered the fall of long ruling government regime *Orde Baru* (New-Era) in May 1998. Political instability induced riots or chaos nationwide and eventually sparked the notion for local autonomy. At the community level, the freedom movement against the government was expressed through exploitation of natural resources such as illegal logging, which had been reported to occur nation-wide (Lavigne and Gunnell, 2006). Similar condition occurred in East Java, Indonesia. Lack of income due to jobs closing and increasing prices might have triggered people to commit to find any measures for income generation including illegal logging. Forest areas are areas that are not secured. They are far from cities and less accessible, creating favorable condition for poaching. This condition suggests that economic and political condition, especially in 1997-1998 affected the LULC change in the watershed.

Indonesia was able to recover from the crisis, and economy grew gradually since 2000 (Firman, 2002). Data from local statistics agency (BPS) Malang showed that for the period 2004 – 2013, housing price index increased gradually, despite being at lowest rate compared to agricultural products (crops and grains) (data not shown). This might indicate the increase demand of housing. In the last decade, development of tourism in Batu and Malang was promising. Combined with increasingly urbanized life style and globalization, it triggered investment on goods and services as well as infrastructure improvement, which in turn led to the rapid increase of urban areas.

3. Technological factors

Introduction or adoption of new technologies from a particular sector might contribute to the development of a certain land use type through the provision of better access or use of resources (Lambin et al., 2002). With regards to this, examining the impact of agricultural technology development in Upper Brantas is worth noting. Long before 1995, irrigation systems in Java had been already constructed, which was the legacy of the Dutch colonization (Panuju et al., 2013) and results from new agricultural establishment in 1970's (Nurvianto, 2014). The use of technology and high agricultural inputs (fertilizers, pesticides) demarcated the shift from expansion to intensification. Data on application of agricultural technologies is limited, however; national data of fertilizers use (Figure 3.8A) showed that fertilizer applications tend to increase. Discussion with an agricultural service officer and land users during the field work in 2014 also noted that almost all farmers have already adopted complete agricultural inputs such as fertilizers, pesticides, certified seeds, and growth stimulators. In some cases, over use of agricultural inputs were observed, especially for those perceiving higher outputs from increasing inputs. Awareness of environmental issues started to develop among farmers in Upper Brantas, and higher profit generated from organic products stimulated organic farming for the last five years stimulated the local agricultural service to set a target of 25% growth in organic farming by 2017 (Malang Times, 2017). Relatively constant share of agriculture's GDP to total GDP in the last five years implies that agricultural sector developed higher efficiency in productivity, and this might be possibly caused by improved farming technologies.

4. Institutional factors

Institutional factors represent political, economic and social settings that might affect the decision making of individuals, which eventually cause changes in land use, and these factors are often activated at the national level that permeates to various aspects at the regional or local level (Lambin et al., 2002). The institutional factors usually involve government policies that can support or hinder the development of particular land uses. Since gaining its independence in 1945, Indonesia had undergone a series of events that could play a role in shaping Indonesia's landscape. Politically, the change of ruling regime is often associated with the changes in policies, regulations and governmental arrangement.

In a regional context, the land use change in Upper Brantas cannot be separated from the past and recent policies that affected community systems, which might affect the transformation of the watershed's landscape. Figure 3.9 represents the major policies in Indonesia / East Java that might be relevant to the land use changes observed in the watershed. In early 1970s when log export was introduced, forestry-based farming system were gaining support. Higher profit induced the establishment of industrial plantation and strongly triggered large forest clearance. The Old Basic Agrarian Law (UU 5/1960) replacing Dutch legacy recognized private land ownership and *adat* (customary laws). Under Basic Forestry Law (UU 5/1967), concession was issued for timber production that led to massive commercial logging, improper forestry practices, increased forest disturbances, and forest conflicts due failure to recognize *adat* land for forests (Rossabi, 1998 and Guritno and Murao, 1999). In early 1970s, under the new regime, Indonesia targeted agricultural intensification for rice self-sufficiency. Under Presidential Instruction

(*Inpres*) 4/1973, massive efforts were made available to support rice field development. Especially for Brantas River Basin as a whole, early 1970s was the first phase of the River Basin development. The launch of Water Law (UU 11/1974) emphasized the conservation and utilization of water for public welfare. Despite its recognition for conservation, in this period, the watershed-based planning was not yet recognized. Until 1994, infrastructure development within the Upper Brantas was mainly for supporting water supply for irrigation, drinking water and electricity generation. Creation of dams and reservoirs in 1970s, and improvement of infrastructure in 1980s were mainly for supporting the rice field irrigation and flood control (Ramu, 2004). In these periods, with increasing population, Java island as a whole observed a growing urbanization and agricultural expansion (Verburg et al., 1999).

The launch of log ban in 1985 was intended to increase the added value of wood products which was expected to give positive effects such as the openings of employment in wood industries, yet, the practices triggered more illegal cutting (Guritno and Murao, 1999). In the meantime, increasing environmental problems within Upper Brantas watershed such as sedimentations have been reported to appear. Agricultural practices on steep slopes, flood occurrences due to lowering capacity and increased urban, and occasional volcanic eruption contributed to increasing sedimentation in Upper Brantas (Ramu, 2004, and PJT, 2015)

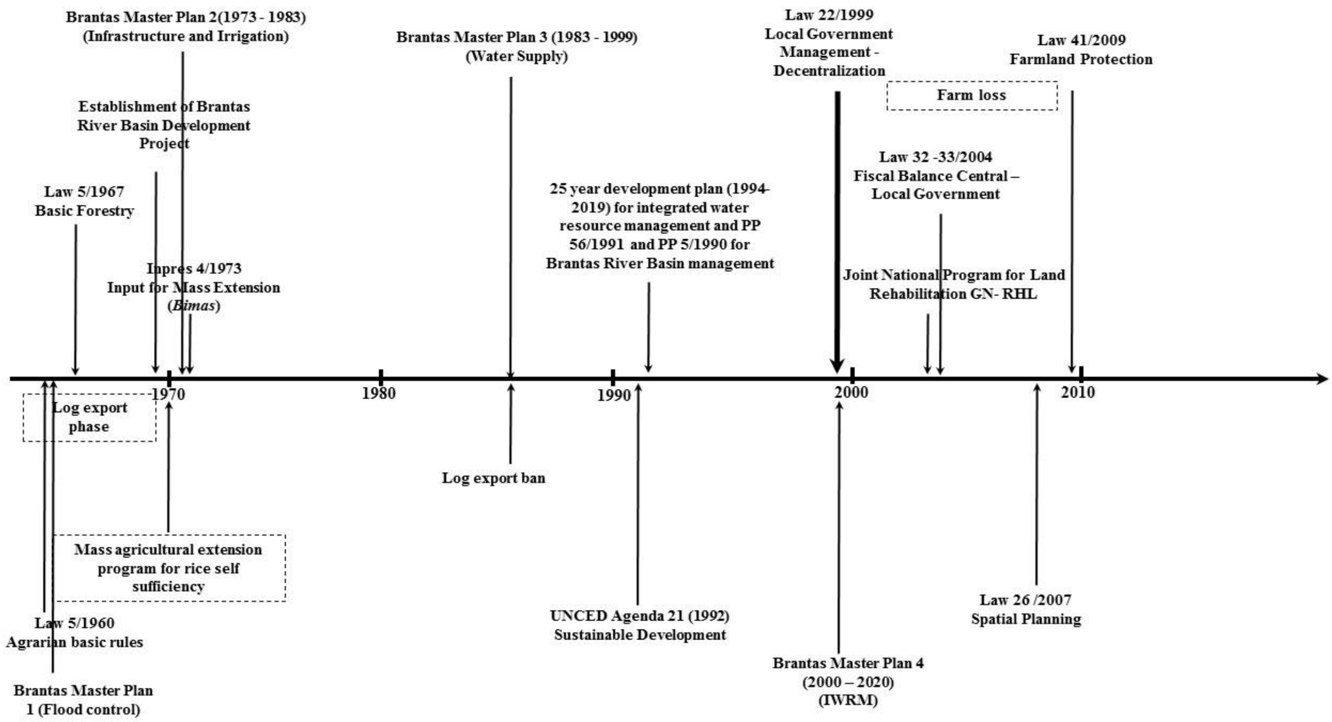


Figure 3.9. Major national and regional policies were established to East Java / Upper Brantas River Basin area

The notion of sustainable development brought by the non-binding Agenda 21 in Rio de Janeiro 1992 shaped the Indonesia's policies afterwards. In 1994, with the establishment of Perum Jasa Tirta - (State-owned company) mandated to manage the Brantas River Basin under Government Regulation (*Peraturan Pemerintah*, PP 56/1990) - the 25-year development plan for Brantas River Basin was established. This demarcated for the first time, the idea of integrated water resource management, which then was made official through the issuance of Brantas Master Plan 4. Possibly, the most influential policy that might have shaped the landscape was the issuance of Law 22/1999. With this law, Indonesia started to implement a much larger extent of decentralization. Previously, with three tier government: national, state and local government, most policies and their implementation in the forms of development activities were centralized.

With this new law, that was then detailed in Law 32-32/2004, local government was given a larger autonomy for most areas including forestry, agriculture, industry and spatial planning.

With the new development paradigm and greater authorities, it was expected that local government would have better access and greater efforts for better managing the region. In practice, the enactment of new decentralization policies triggered the local government to carry out any measures based on their own interpretation, including to exploit natural resources, and to generate higher revenues through the taxes from new industries and housing sectors (Firman, 2010). Accessibility and infrastructure have been the major interest of most local government to maximize the benefit for their region. In the meantime, land and housing policies after 1999 were unclear and contradictory to the 1999 Law of Local Autonomy (Firman, 2004). The housing sector behavior in Indonesia is complex and heterogeneous due to varying land permit system and housing development systems (Mokkonen, 2013). One important thing to note that informal settlement (self-built housing) is part of major urban areas in Indonesia, and this type of settlement is not much affected by regulation for housing developers (Monkonnen, 2013). Lack of clear and consistent housing policies, greater interest of local government for accessibility and infrastructure improvement after the local autonomy implementation, and concerns for boosting industry and tourism development appeared to be major trigger for increasing urban areas in Upper Brantas.

Before the fall of the New Era (*Orde Baru*) in 1998, most of natural forest was mainly governed under the central government's jurisdictions. The Decentralization Law 22 enacted in 1999 was considered to be more harmful for forest conservation. The decentralization notion was perceived to give local government greater access to exploit forested lands by issuing more concessions for wood industries and eventually induced larger illegal logging (Siregar et al., 2007, Tsujino et al., 2016). In 1999, the central government launched National Action for Forest and Land Rehabilitation and provided loans to attract communities to plant trees. However, this action seemed to be rarely successful (Siregar et al., 2007). It was reported that critical land in Malang Regency has decreased and Government targeted to completely rehabilitate all critical lands by 2013 (Antara, 2012). Yet, statistics of critical land sizes in Malang itself shows an inconsistent data due to differing data sources that make it difficult to derive solid information. However, the fact that rate of forest loss in last decade from change detection result implied that efforts to recover the degraded forest might work to a certain extent.

One evident problem in Upper Brantas is the loss of rice-fields. To protect massive farmland loss, Law 41/2009 about farmland protection was enacted. The objective is to provide stricter regulations for converting land, especially irrigated land, to non-agricultural land uses. Yet, communities escaped the law by drying up the land so that it can no longer be classified as irrigated land, and thus can be converted to non-agricultural uses, mostly settlement (Malang Times, 2016). Cool climate, good accessibility, beautiful landscapes appears to support housing sector's fast growth in Malang and Batu. Significant land price increase has been observed for these regions, with an estimate of 50% increase every year (Warta Malang, 2014), and this could possibly attract the land owners for converting them. With regards to rice field, incentives given for rice farmers might have not been sufficient to resist more conversion.

Despite the spirit of autonomy, Law 27/2007 of Spatial Planning recognized hierarchical approach in spatial planning system in Indonesia. This new spatial planning law replaced the 1992 law with a recognition in rapid urbanization and re-emphasizes the need of maintaining 30% of urban areas for open spaces (Rukmana, 2015). However, it is also known that spatial planning in Indonesia is not equipped with instruments for controlling land use allocation. In other words, even if local government have adopted the same notion in their local spatial planning, the real land use practices often violate the proposed land use plans. For example, the presence of both small and large settlement complex along the river banks or springs is common in Malang region. Informal housing was the source of this issue and resulted in uncontrollable urban growth. Increased violation against local spatial planning has been observed from year to year due to lack of law enforcement (Walhi, 2013 and Malang Times, 2016). Apart from the policy establishment, issues conflicting policies, poor law enforcement, weak coordination among government bodies, limited financial capability, and poor instruments for policy implementation have long been identified as constraints for urban/ land and water management (Widianto et al., 2001; Firman, 2004; Mokkonen, 2013; and Fulazakky, 2016). With this condition, it appears to be challenging to expect land use change in Indonesia to be well regulated.

5. Cultural factors

Cultural factors define how cultural instruments such as land tenures, customs, tradition, beliefs and values might affect the behavior of land users. Culturally, Indonesia is a diverse country, where languages, traditions, customs, land tenures, beliefs and perceptions vary among places. All these factors together might influence the operating systems that finally affect the land owner as the land use decision makers. The dynamics of agricultural land uses in Upper Brantas cannot be separated from the cultural or social context of Javanese farmers. In Indonesia, mostly in Java, the average size of land ownership is very small (less than 1 ha per person) and the land is often inherited from previous generation family members, causing land size to get smaller (Hamzah et al., 2014, Susilowati, 2015). In this case, a piece of land that was formerly utilized for agriculture by the father/family leader can be converted to other land uses when there is disagreement among beneficiaries on how the legacy (land) is supposed to be used. Decisions on how to utilize a land might also be affected by other non-market forces such as needs of instant huge cash for important events, unsecured land tenure, lack of manpower interested in farming activities, high land taxes, and when these issues are encountered, land owners tend to sell the land (Susiolowati, 2015). With regards to national laws on land status, Indonesia recognizes state's lands, private lands, customary lands, and recognizes differing rights of land and water either to use, to exploit, to lease, to collect forest products, or to use water and air space (Loffler, 1996). Varying land tenure types exist in differing agricultural land uses from fully land owner and grower, land grower but renter, tree-order, tree-leased, tree-sharecropped, to full contract (Suryanata, 1994; and Susilowati, 2015). Farming practices in eastern part of Upper Brantas (Gubuk Klakah) showed these land tenure variations and decision on plant types to be grown is not always made by land user but also by land owner who does not necessarily represent the interest of land user (Suryanata, 1994). For sugar cane plantations, farmers can develop a planting contract with sugar cane factories for a certain period. When the contract ends, farmers can decide to renew or stop and change the land use to other agricultural types, including rain-fed rice, which needs a much lower input. However, this observation was merely based on visual analysis and brief talk with farmers and agricultural officer during ground checking. While data of farmers growing sugar cane is not available, this conclusion needs further study for verification or detailed explanation. All these imply that agricultural land use changes in Upper Brantas is a complex process where agricultural land uses are not always market-driven.

Besides physical land suitability influences, cultural belief might contribute to the reason why no massive agricultural land use decrease occurred in the last two decades. People living in

Java's volcanic slopes developed adherences to their living including their farming practices. Local perceptions about volcanic hazards, bound to place of origins, improved hazards knowledge and adaptive capacity have contributed to develop the resiliency of the human-environment system in volcanic slopes of Bromo, the eastern part of the watershed (Bachri et al., 2015). In this case, natural hazards might have contributed to short-term or abrupt land cover changes due to materials coverage on lands or plants but once the land recovered, people might preserve the same land uses. However, it is predicted that in the future the adherence of people to their origin and current livelihood will be weakened. Increasing influence of global life style and improved education level have been recognized as one factor reducing the interest of younger generation in farming activities (Hendri, 2013). More and more youngsters with better education prefer to leave villages and look for jobs in the city. With this likely tendency, loss of agricultural areas for supporting urban development might become more evident in the future.

3.3.2 Land use changes and watershed functions

It is understood that LULC change affects hydrological processes in the watershed. In general, forests play an important role in watershed functions by reducing peak flow, sedimentation, and landslide or flood occurrences. Loss of forest leads to degrading functions signaled by increased fluctuations of river discharge in dry and wet season or flashier flows, increasing occurrences of flood events, and decreasing reservoir capacity due to elevated sedimentation (Verbist et al., 2005; Adi et al., 2013). Detrimental impacts of human activities have been reported such as urbanization causing the increased runoff and water pollution, and agricultural activities bringing sediment and nutrient (Randhir, 2003). Together with increased urban areas, agricultural soil tillage might reduce soil capability to infiltrate rainfall, and eventually leads to excessive and increased runoff with associated sediment and nutrient.

For the last two decades, forested areas reduced continuously from 485 km^2 to 416 km^2. This loss was compensated dominantly for mixed-dryland agriculture and shrubland/bushland. Mixed-dryland agriculture in Upper Brantas is mainly located on steep slopes, with more than 44% are located on slopes higher than 15%. In the last five years, the occurrences of floods and landslides have increased almost double without observed positive trend of rainfall (BNPB, 2016) (data not shown). This suggests that Upper Brantas watershed condition might have been degrading, experiencing reduced slope stability. The removal of densely vegetated areas having steep slopes might affect the slope stability. Conversion from forest to mixed-dryland agriculture and development of urban settlement on steeper slopes could increase the pressure on land. Thompson and Turk (1997) noted that increasing human activities may destabilize a slope to cause mass wasting. In the last two decades, urbanization has increased from 167 km^2 to 335 km^2. This doubled extent might provide substantial impact to the watershed. Meanwhile, agricultural farming practices such as maize, cassava and potatoes are proven to have higher amount of erosion in upland volcanic slopes in Java (Babier, 1990). Application of high input agriculture has also worsened the watershed condition causing massive non-point source pollution (Widianto et al., 2001). The presence of river-side housing and surrounding settlements exacerbated the non-point source pollution. With expected growth of population around 3%, river pollution issues could be more severe. Without proper future watershed management, erosion and sedimentation may likely worsen, not only because of current farming practices in volcanic slopes but also the potential loss of physical resilience in Upper Brantas. Tree-less mountain areas will have lowered ability to reduce damaging impacts of eruptions and might induce a larger sediment inputs to rivers and reservoirs. The yearly TSS data collected in three reservoirs showed that there was no significant positive TSS trend (Figure 3.10A). Yet, the slight positive gradients should be considered as a potential risk for the future. Similarly, annual RB-Index showing the degree of hydrograph flashiness collected from three small rivers and one reservoir did not indicate significant increase (Figure 3.10 B). Despite incomplete data in many years, the increase of the RB-Index in some years should be regarded as sign of the urbanizing watersheds. The data might not be able to provide a clear state of the watershed, which is the limitation of this study. Yet, these should be considered for future watershed management.

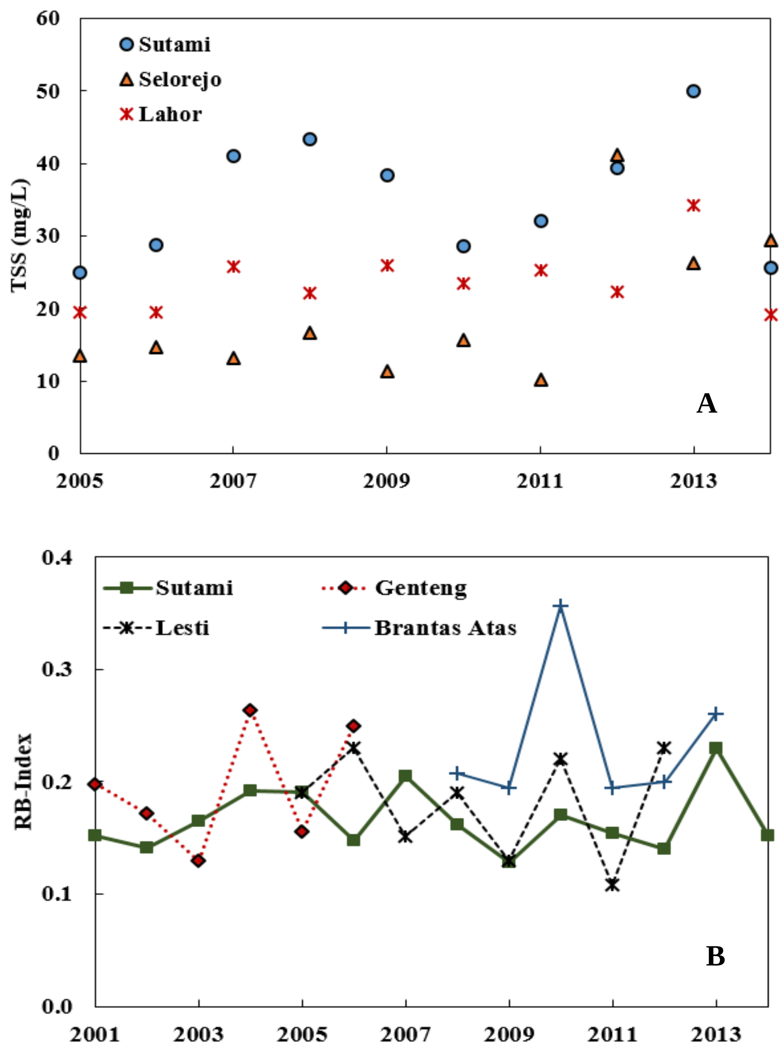


Figure 3.10. Annual average of TSS concentrations sampled in three reservoirs within the watershed (A), the RB-Index calculated from daily streamflow in four stations (B). Source: Perum Jasa Tirta and Local Water Service (Dinas Perairan)

The likely implications of LULC change to watershed functions might depend not only on the degree of LULC change within the watershed, but also how watershed management has been being administered. One evident challenge in managing the Upper Brantas river basin is the trans-boundary issue. Upper Brantas lies within three administrative boundaries: two cities and one municipality. While the authorities for local government have been increased, ideas for joint watershed management programs are limited. Watershed related programs have not yet been considered as important or urgent. For the last five years, the allocation for watershed-based management programs by local government of Malang city is very limited, accounting for less than 10% of the total budget for development programs (data not shown, source: calculated based on LAKIP Kota Malang 2012, 2013 and 2015). Ideas of integrated water resource management that have been adopted for watershed management plan for Brantas river basin requires a good understanding, agreed responsibility and well shared responsibility among stakeholders in transforming the values into practices. With many differing stakeholders involved, a well-mapped matrix plan for all stakeholders will help determine priorities and ensure integration. Unfortunately, at this point, it appears that what have been done is still inadequate. Fulazzaky (2014) noted eleven elements of integrated water resource implementation for the future in Indonesia, with division for both river basin authorities and cities/municipalities authorities. However, the challenges lie not only within a local authority but also among authorities, especially for a multi-cities watershed like Upper Brantas. Within a local government level, conflicting interest or priorities exacerbated the complexity in managing Upper Brantas. For example, Batu city that harbors the most upper streams and is supposed to consider protection for recharge areas, has now experienced a massive urban development for boosting local economy without considering the effects for the downstream (Widianto et al., 2001). While each city pursues the same interest for development, challenges become greater with upstream – downstream impacts. With all this complexity, issues related with water resource and land use will remain a challenge.

3.4 Conclusion

Upper Brantas has undergone considerable land use / land cover changes for the last twenty years from 1995 to 2015. Within this period, the total forest cover has been reduced from around 20% to 16% of the total area, accounting for a net loss of 69 km^2 forested areas. In addition to, total agricultural land uses comprising mixed-dryland agriculture, rice-field and plantation, have also decreased from 69% to 65%. Yet, since it becomes the dominant LULC class, this 4% reduction might produce considerable impact to the watershed. Compared to other agricultural land uses such as plantation and dry-land agriculture, rice field has experienced the smallest decrease in the last 20 years. Settlement has been the land use class with the most rapid development. In 20 years, urban land use has doubled in growth from only 7% to 15% of the total watershed area. Most of forest conversion was for agricultural land uses. This finding confirmed the previous findings that agricultural expansion is the first phase of deforestation, which then leads to development of urban areas.

All elements of proximate and underlying driving forces of land uses as framed by Geist and Lambin (2002) are interrelated and exist in varying degrees. Similar to most typical developing countries, improved accessibility such as roads and infrastructure triggered forest and agricultural conversion to urban areas. While wood extraction and natural hazard factors can be considered as little, agricultural and infrastructure expansion can be major drivers of LULC change in the study area. In the last 20 years, it can be said that Upper Brantas has been a fast growing region with urban areas. In terms of the underlying driving factors, the five drivers namely demographic factors, economic, technology, political/institutional and socio-cultural factors contributed to shape the landscapes in a more diffuse way and it is difficult to isolate the relative importance of each driver. Interaction among these drivers as well as the relative importance of each driver are challenging to quantify and became the limitation of this study. Further research is needed to quantify these factors and to identify how they are interconnected and can be quantified.

With regards to political and institutional drivers, the collapse of long time ruling regime occurred in 1998 can be regarded as the breaking point that drove the enactment of a larger extent of decentralization law in 1999. The establishment of varying policies afterwards represented greater authorities for local governments in managing their territories. Unfortunately, in practice, current evidences show that existing policies may not be sufficient to direct the land use changes. Continuing deforestation, despite its slower rates, uncontrollable urban areas and farming loss might imply that more is needed than just land-uses related polices.

Concerns about the implications of land use on water resource has been acknowledged. The Integrated Water Resource Management approach has recently been adopted and integrated in different policies since 1994. However, the condition of watershed for the last 20 years has continued to degrade. Increasing flood and landslide events, and run-off indicated that the changes of land use turned to be harmful for water resources. Current agricultural practices, physical vulnerable conditions of the watershed, rapid and uncontrolled urbanization could be the continuing contributors of water resource degradation. Upper Brantas is a watershed that is culturally rich, socially diverse, politically/institutionally complex, and physically prone to disturbances due to its terrain and climatic condition. This study showed that Upper Brantas represents a typical tropical watershed in the developing countries where poor regulations, limited political institutions and complex social institutions can often add complexity in managing the ecological issues. With these complexities, more studies are needed to better understand the watershed and derive sound long run solutions. While land use changes and the underlying processes are challenging to quantify, this study can serve as a baseline to provide initial information and indicative drivers and implications for water resources in Upper Brantas.

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Appendix 3.1. Accuracy Assessment of Land Use/Land Cover Mapping (9 classes)

		Estimated LULC class									
		WATR	FRST	IDFP	PLTN	MADL	STBU	SLBL	SVGL	RCFL	Total
Observed LULC class	WATR	7	0	0	0	0	0	0	0	0	7
	FRST	0	163	3	0	3	0	1	0	0	161
	IDFP	0	10	18	0	5	0	0	0	0	28
	PLTN	0	0	1	43	7	0	0	0	4	50
	MADL	1	16	0	12	338	9	1	0	16	386
	STBU	0	0	0	1	4	135	0	0	10	144
	SLBL	0	10	0	0	15	0	27	1	0	40
	SVGL	0	0	0	0	0	0	0	6	0	6
	RCFL	0	0	0	10	8	8	0	0	92	110
Total		8	199	22	66	380	152	29	7	122	932

(Overall accuracy 84,16%, Kappa: 79,30%, Producer Accuracy 81,50% and User Accuracy 87,50%)

1. WATR Water
2. FRST Forest
3. IDFP Industrial Forest Plantation
4. PLTN Plantation
5. MADL Mixed and dryland agriculture
6. STBU Settlement/bare land/built-up
7. SLBL Shrub land/bushland
8. SVGL Savannah/Grassland
9. RCFL Rice field

CHAPTER 4

IMPACT OF LAND USE/LAND COVER CHANGE ON SURFACE RUNOFF IN AN INCREASINGLY URBANIZED TROPICAL WATERSHED[1]

[1]Ike Sari Astuti, Kamalakanta Sahoo, Adam Milewski, Deepak Mishra. To be submitted to *Journal of Hydrology: Regional Studies*

ABSTRACT

Land Use Land Cover (LULC) change within a watershed can produce potentially large impacts on hydrological systems or water resources. Upper Brantas watershed in East Java, Indonesia is a tropical watershed experiencing rapid LULC change, a phenomenon typical to developing countries such as Indonesia. A growing population has exacerbated the ongoing pressures of accelerated sedimentation due to deforestation, drying-up of springs, and frequent downstream eutrophication. A 21-year LULC change analysis between 1995 and 2015 suggests that the basin is subject to increased urbanization and continuing forest loss for agricultural development. Yet, the impact of LULC change on runoff as main driver for sediment and nutrient was unknown. This study investigated how LULC change in the Upper Brantas affected the hydrological processes especially surface runoff using the Soil and Water Assessment Tool (SWAT). Monthly streamflow calibration (2003 – 2008) resulted in a well-established model with an R^2 of 0.94 and NSE of 0.94, with a R^2 of 0.91 and NSE of 0.91 for validation (2009 – 2013). The calibrated model was used to simulate the effects of LULC change between 1995 and 2015 on surface runoff. During 1995-2015 the Upper Brantas watershed had an increase of settlement (7% of total area), with concurrent increase of dryland agriculture (3%), decrease in forest (3%), rice field (3%) and sugarcane plantation (4%). Changes in these LULC types resulted in moderate changes in long-term average runoff (+8%), water yield (+0.28%), groundwater (-1.8%), and evapotranspiration (-1.15%). Quantitative assessment revealed that changes in runoff were mostly associated with changes in forest, dryland agriculture and settlement. Gradual LULC simulation with four varying LULC trajectories showed a linear

relationship between the amount of removal of each LULC and runoff generation. With increasing urbanization, industry and agricultural intensification, increased runoff impacts will be more critical for water bodies due to associated nutrients and sediments. This study provides baseline information on how LULC change impact the surface runoff. Future work is needed to quantify how the changes in runoff affect sediment and nutrient yields that contribute to downstream sedimentation and eutrophication.

Key words: SWAT, Land Use/Land Cover Change, Urbanization, Surface Runoff, Brantas Watershed, Indonesia.

4.1 Introduction

Changes in Land Use Land Cover due to anthropogenic drivers are often associated with alteration in various natural support systems such as water resources, both quantity and quality (Giri and Qiu, 2016), biodiversity (de Castro et al., 2016), food security (Rutten et al., 2014), and energy supply (Preston and Kim, 2016). From a hydrological perspective, LULC change within a watershed has been recognized as a critical factor influencing runoff generation (Chang, 2007), and in some studies, LULC change has been suggested to have a stronger impact than climate change on runoff (Vörösmarty et al., 2000 and Li et al., 2012). In tropical regions, the impact of LULC changes and climate on streamflow can be stronger due to greater energy inputs and faster anthropogenic changes.

South East Asian countries have been experiencing the fastest LULC change over the last few decades (Lambin et al., 2003). For example, the loss of tropical forest in Indonesia has been very high, the second fastest after Brazil (Hansen et al., 2009). Indonesia’s major source of water resources rely on approximately 5,590 rivers, 521 lakes, and 100 reservoirs, with surface areas of lakes and reservoirs vary from 1.9 km^2 to 1,130 km^2 (Lehmusluoto et al., 1995 and World Water Council 2003). The increased water use and degrading watershed conditions have intensified overall stress on already diminishing water resources (Pawitan and Haryani, 2011). Around 458 watersheds in Indonesia have been declared under critical condition calling for improvement in watershed management (Fulazzaky, 2014).

To support effective watershed management, a thorough understanding of the hydrological processes occurring in the watershed is important. Numerous studies on land use change impact on hydrological parameters such as runoff mechanism have been carried out at different sites (Ghaffari et al., 2010; Wagner et al., 2013; and Eshtawi et al., 2016). Yet, a well-generalized quantitative mechanism of how LULC change affects the hydrological processes remains poorly understood (Hundecha and Bárdossy, 2004). In addition, some studies have shown contradictory findings and lack of consistency, especially in large catchments (> km^2) where influences from sub-basins can mask out the impacts of LULC change in the whole watershed (Li et al., 2012; Wagner et al., 2013; and Beck et al., 2013). The lack of understanding has mainly been attributed to the heterogeneity of watershed characteristics, land use pattern and configuration, threshold behavior in hydrological processes, and inference of climate, which are difficult to quantify (Sullivan et al., 2004; Zehe and Sivapalan, 2009; and Wang, 2014). Therefore, a similar study from a particular watershed bears some merits in enhancing our understanding about the impact of LULC change on the ecosystem.

Assessing the LULC change impact on hydrological processes has been carried out for decades. The methods range from using pair catchment experiments to hydrological modelling. Paired catchment studies mostly carried out in the past are often impractical due to long time window, but they are simpler and produce more rapid results to be fit into local decision making process (Ghaffari et al., 2010; and Ochoa-Tocachi et al., 2016). Nowadays, modelling approaches have been more frequently used to replace paired catchment approaches. In hydrological modelling, Soil Water Assessment Tool (SWAT) has been increasingly used to assess the impacts of land use change on hydrological processes and hydrologically influenced ecosystem services (Neitsch and Arnold, 1999; Gassman et al., 2007; Douglas-Mankin et al., 2010; and Francesconi et al., 2016). Despite numerous studies worldwide, there has been limited SWAT based hydrological studies carried out in Indonesia (Othman Faridah and Solichin, 2008; Rahayuningtyas et al., 2014; Barkey et al., 2017; and Marhaento et al., 2017). There has been no study to investigate impacts of land use change on surface runoff generation in Upper Brantas River basin in East Java.

For decades, Java Island is home to around 60% of the country's population. It has experienced increasing pressures on land resources, and quickly exhibited a transition from a mainly rural to a largely urbanized environment (Verburg et al., 1999 and Handayani, 2013). Several studies highlighted the impacts of increasing urbanization on Java, such as increasing farm loss (Partoyo and Shrestha, 2013), water pollution (Djuangsih, 1993), accelerated sedimentation and flood events (Valentin et al., 2008 and Romandi et al, 2016). Since hydrology serves as the main driver governing sediment and nutrients, knowing the hydrological response especially the runoff generation in Javanese watersheds is of importance. This study is aimed at (1) setting up and validating a SWAT model for Upper Brantas river basin, (2) simulating the impacts of LULC change over the past two decades (1995 – 2015) on the hydrological response of catchment with a focus on surface runoff, (3) investigating the relationship between runoff and gradual removal of a particular LULC type for settlement or dryland agriculture.

4.2 Materials and Methods

4.2.1 Study Area

The study site is the Upper Brantas watershed located in East Java, Indonesia. Upper Brantas watershed is part of the *Wilayah Sungai* (WS) Brantas. *Wilayah Sungai*, or "River Region" Brantas is a delineated river basin management area in Indonesia that holds strategic economic and ecological importance. The WS river basin covers multiple watersheds (called *Daerah Aliran Sungai,* DAS) and is managed under a concept known as "one river basin one management" (Kementrian PU, 2011 and Bappenas, 2012). Having the longest river network of East Java and harboring 60% of the province's population, WS Brantas provides 73% of the total water demand of the province. It also produces around 63% of electricity that is consumed by the province, and plays a critical role in water conservation, water resource utilization and as water hazards controller (Adi, S et al., 2009 and Kementrian PU, 2011).WS Brantas river management encompasses three river sub-basin management areas; Lower, Middle and Upper Brantas river basins. Over the years, the Upper Brantas has attracted scrutiny due to increasing reports of environmental problems such as sedimentation (Adi, et al., 2009), reservoir eutrophication (Sulastri et al., 2004) and discharge of pollutants (Fulazaky, 2009). Upper Brantas watershed is surrounded by mountains creating a circularly-shaped drainage area of almost 2,000 km^2. The elevation ranges from 223m to 3673m above sea level, with average slope from 0% to greater than 45% percent. Assigned as Am under Koppen climate classification, Upper Brantas experiences abundant rainfall with a mean total annual rainfall of 2063 mm from 1991 – 2015. Similar to other monsoon influenced regions, Upper Brantas exhibits distinct rainfall distribution with intense precipitation during wet season, October – March (Wet Season), peaking in

December-January, and low precipitation during April – September (Dry Season). The watershed experiences slight variation of temperature, ranging from 19°C to 30°C.

4.2.2 SWAT Model

SWAT was used to assess the impact of LULC change on water resources, mainly runoff generation. SWAT model is a continuous, semi-distributed, physically based model developed by U.S Department of Agriculture – Agricultural Research Service (USDA – ARS). It is a watershed-based hydrological model developed to predict the impact of land management practices on water, sediment and chemicals from agriculture within a watershed (Neitsch et al., 2011). It has been widely applied to study hydrological responses and pollutant loads at varying spatial and temporal scales with adequate accuracy to make it useful for simulating watershed condition worldwide (Gassman et al., 2007; Milewski et al., 2009; Becker et al., 2012; Milewski et al., 2014; and Francesconi et al., 2016). This study focuses mainly on surface runoff component of the model. SWAT applies physical algorithm to estimate the runoff using biophysical data such as precipitation, soil properties, topography, land use and land cover, and SCS curve number equation (Abbaspour, 2007).

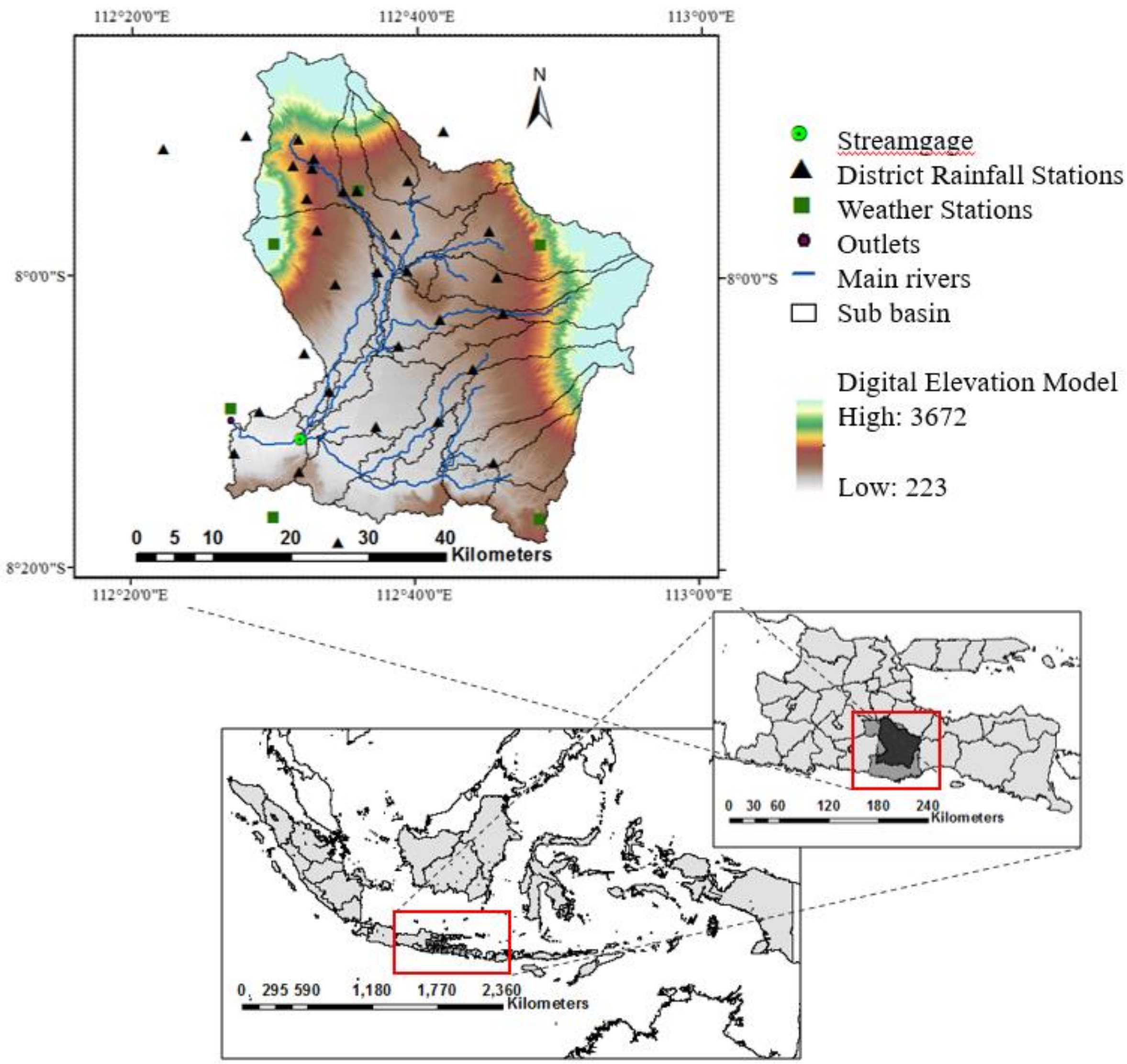

Figure 4.1. Map of Indonesia, East Java and Upper Brantas watershed with corresponding elevation and gaging stations

In SWAT, the watershed is divided into multiple sub-watershed and hydrologic response units (HRUs). Each HRU is a designated area having unique combination of land use, soil characteristics and slope. It uses a water balance principle to simulate the hydrological process within a watershed and all flow parameters are routed to a sub-basin level, and eventually to a basin level as described in Neitsch et al (2011) as:

$$SW_t = SW_{t-1} + \sum_{i=1}^{t}(R_i - Q_i - ET_i - P_i - QR_i) \quad (1)$$

Where SW_t (mm) is the final soil water content, SW_{t-1}(mm) is the initial soil water content at day, i is the time (days), R_i is the amount of precipitation on day i (mm), Q_i (mm) is the amount of surface runoff on day i, ET_i (mm) is the evapotranspiration amount on day i, P_i (mm) is the amount of water percolating through the soil profile on day I, and Q_i (mm) is the amount of return flow on day i. Despite increasing urbanization, rural areas are dominant land cover types in watersheds of Java, and therefore, influence from artificial drainage network can be considered minimum.

4.2.3 Input Data

SWAT input data included topography, climate, land use and land cover, and soil. Topography data was obtained from a-30m ASTER Digital Elevation Model (ASTER GDEM V2, obtained from USGS (2017). The land use maps were obtained from a previous study consisting of land use for 1995 and 2015, and derived from an Object Based Image Analysis classification technique using Landsat images (Astuti et al., 2017). The land use classification scheme adopted the Indonesia's Ministry of Forestry was reclassified to meet the nomenclature used in SWAT soil database namely AGRL, FRSE, RICE, SUGC, URMD, RNGB, RNGE and WATR. URMD (Urban Residential Medium Density) was selected instead of URHD or URLD with an assumption that settlement areas in Java, Indonesia are not heavily covered with impervious surface. URMD class is assumed to have around 38% of impervious surface in the settlement areas (Neitsch et al., 2011) and that percentage is relatively applicable to most urban areas in Java. Slope classes from the Guideline of Land Rehabilitation from Indonesia's Ministry of Forestry (1987) were adopted for deriving the HRU unit. The land use maps for the site were produced with an overall accuracy of 85 (Kappa 81%).

Table 4.1. SWAT Data Input and Sources

Data Type	Source	Remarks
Land Use Map	Previous study (in preparation, 2017), Derived from LANDSAT	30m
Streamflow	Perum Jasa Tirta, Malang	Daily
Soil	Harmonized World Soil Database (FAO, ISRIC)	
DEM	ASTER GDEM V2 (USGS)	30m
Slope classes	Indonesia’s Ministry of Forestry	
Rainfall	• Weather Agency (BMKG Malang) • Water Service Agency, Malang	Daily
Relative humidity, Solar radiation and Wind	• Weather Agency (BMKG Malang) • National Centers for Environmental Prediction Climate Forecast System Reanalysis (http://globalweather.tamu.edu/)	Daily

4.2.4 Model Evaluation

SWAT model was calibrated and validated on a monthly time step using discharge from Sutami gage station as represented in Figure 1. A systematic approach to calibration, sensitivity analysis, and validation was carried out to improve the validity of the model. The sensitivity analysis ranked the highly sensitive parameters which produced the largest response in model outputs. This is to help identifying important parameters as well as adjustment to value range of each parameter. The initial parameters were selected based on watershed characteristics and based on previously published studies (Van Griensven et al., 2006; Ghaffari et al., 2010; and Seyoum et al., 2015). Because of the variability of input data, model design, and parameters, the model requires uncertainty analysis. SWAT model was calibrated (2000-2008) and validated (2009-2013) at monthly time step considering 3 years of warm-up.

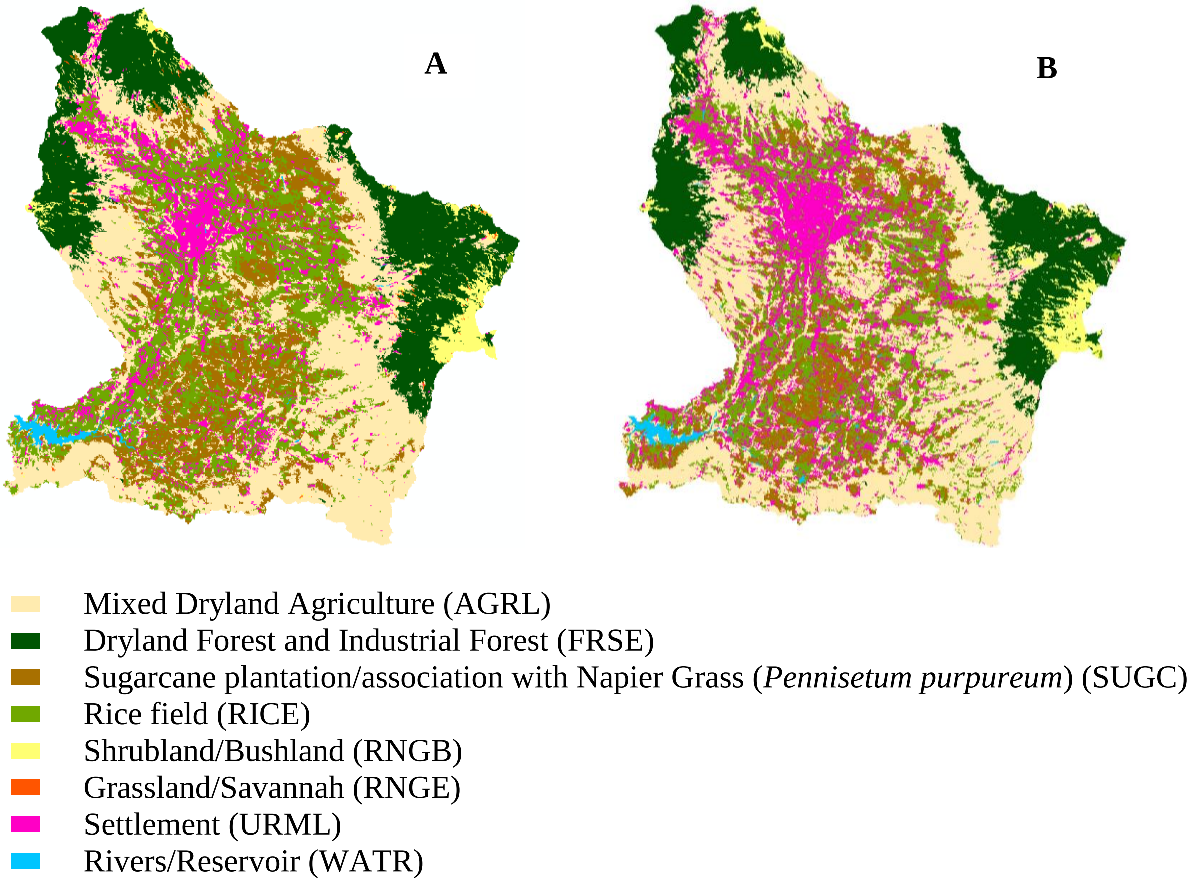

Figure 4.2. Land Use Land Cover (LULC) in Upper Brantas Watershed for 1995 (A) and 2015 (B)

The SWAT-Calibration Uncertainty Program (SWAT-CUP) was used to perform calibration, validation and sensitivity analysis using the routine called Sequential Uncertainty Fitting version 2 (SUFI-2) (Abbaspour, 2013). SUFI-2 is a semi-automated inverse model that accounts for sources of uncertainty. Several statistical measures were developed and are used to quantify the degree of uncertainty by the P-factor (percentage of the simulated values fall within the 95% probability band), r-factor (the width of the 95% probability band). Ideally, a value of 1 for P-factor and 0 for r-factor indicate that the simulated data perfectly match with the observed data (Abbaspour, 2013). The relative sensitivity of each parameter is measured by t-test and p-values. The higher the absolute value of t-test, the more sensitive the parameter. The p-denotes the statistical significance of each parameter sensitivity result. In each iteration, SWAT-CUP updates the parameter ranges and produces suggested ranges so that the model converges to the best simulation based on the objective function set in the model. The iterations are stopped till the sensitivity results showed all parameters consistently sensitive. Overall, the model performance is assessed using R^2, NSE, and PBIAS. Coefficient of determination (R^2) measures the proportional variation in the simulated variable explained by the measured variable and indicates the linear relationship between the estimated and measured variables. Nash-Sutcliffe Efficiency (NSE) determines the relative magnitude of the residual variance compared to the observed data (Nash and Sutcliffe, 1970). It ranges from - ∞ to 1 with 1 representing a perfect agreement between the simulated and measured values. Percent BIAS (PBIAS) measures the percentage of the over estimation or underestimation of the simulated variables.

$$R^2 = [\frac{\sum_{i=1}^{n}(O_i - S_i)(S_i - \bar{S})}{(\sum_{i=1}^{n}(O_i - \bar{O})^2)^{0.5}(\sum_{i=1}^{n}(O_i - \bar{O})^2)^{0.5}}]^2 \quad (2)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (3)$$

$$PBIAS = \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n} O_i} \quad (4)$$

Where Oi is the observed value, Si is the simulated value, $\bar{O}$ and $\bar{S}$ is the mean of the observed and simulated values, n is the number of observations.

4.2.5 Main Parameters and Model Performance

For initial iteration, 27 parameters were included in SWAT-CUP analysis. he iterations were run four times before reaching the last six constantly sensitive parameters. For subsequent iterations, the range of each input parameter was narrowed, and new parameters suggested were applied to next iteration, while keeping the value within the allowed range. Table 2 summarizes the 12 most sensitive parameters with six of which are statistically significant (absolute t-stat values ≥ 2 and p-value ≤ 0.05). Most of these parameters are related to soil and groundwater characteristics, which are similar to the findings from the study of Rahayuningtyas et al (2014) in Lesti catchment, East Java.

Table 4.2. List of 12 parameters that produced the 12 highest relative sensitivity

Parameter	Description	Default range	Fitted value	t-stat	p-value
v__GW_DELAY.gw	Groundwater delay time (d)	0 - 500	203.13	19.38	0.000
v__LAT_TTIME.hru	Lateral flow travel time	0 - 180	4.89	-15.16	0.000
r__SOL_K.sol	Saturated hydraulic conductivity	-0.9 - 1	-0.54	4.43	0.000
v__CH_K2.rte	Effective hydraulic conductivity in main channel	-0.01 - 500	21.57	2.85	0.005
v__GWQMN.gw	Threshold depth of water in the shallow aquifer	0 - 5000	649.65	2.57	0.010
v__GW_REVAP.gw	Groundwater revap coefficient	0.02 - 0.2	0.10	2.57	0.011
r__SOL_BD.sol	Moist bulk density	0.9 - 2.5	0.32	1.57	0.118
v__ALPHA_BNK.rte	Baseflow alpha factor for bank storage	0 - 1	0.72	1.12	0.263
r__CN2.mgt	SCS runoff curve number	68 - 89	-0.14	0.93	0.355
v__CH_W2.rte	Average width of main channel	0 - 1000	549.57	0.78	0.435
v__SURLAG.bsn	Surface runoff lag time	0.05 - 24	0.86	-0.62	0.534
v__CH_D.rte	Average depth of main channel	0 - 30	13.52	0.55	0.583

The calibration and validation results showed that the identified optimal parameters for the model are reasonable. he statistical fits produced for streamflow monthly time step according to Moriasi et al (2007), were “very good”, indicating that the SWAT model set up was reliable for further application.

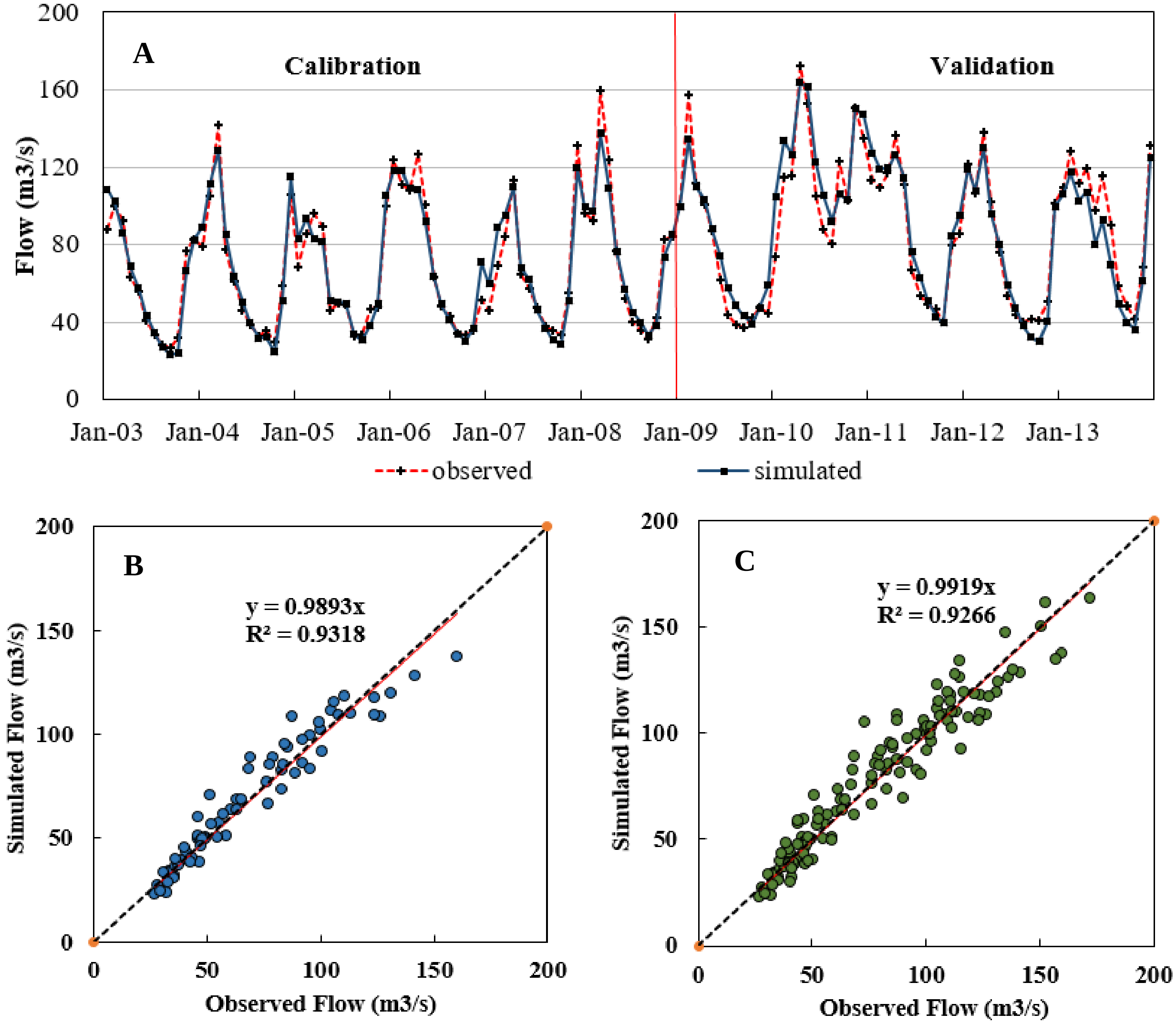

Figure 4.3. Plot of observed and simulated flow during calibration and validation periods (A), 1:1 graph of observed and simulated flow for calibration (B) and validation (C)

Table 4.3. SWAT Model Performance for Calibration and Validation

Simulation	Value of statistical fits			
	R^2	NSE	p-factor	PBIAS (%)
Calibration (January 2003 - December 2008)	0.94	0.94	0.85	-0.1
Validation (January 2009 - December 2013)	0.91	0.91	0.75	1.4

The high R and NSE in the calibration and validation simulation suggest that the calibrated model can describe the variability of streamflow within the basin. Hence, we can confidently assume that the calibrated model with the optimized parameters can be further applied to assess the impacts of LULC change in Upper Brantas on hydrological responses.

4.2.6 Model Implementation

To simulate the impact of LULC change over the past two decades on hydrological responses, first the SWAT model was calibrated and validated for the selected periods. This “fix-changing” or “delta” method (Ghaffari et al., 2007; Wagner et al., 2013; and Wang et al., 2014) was implemented by running the model using 1995 LULC first. In this approach, all the changes to hydrological variables were assumed to be the results of different land use inputs. The validated model was then applied to the 2015 LULC while keeping other parameters such as climate, soil and topography constant. The climate during 2000 – 2013 was assumed to be “no-change”. A Mann-Kendall (MK) trend test was carried out to rainfall as the principal driver in hydrologic processes. The MK test was used to detect the presence of a rainfall trend, testing whether the rainfall trends show significant variability. The null hypothesis for the MK test is no trend in the data, which was tested at a significance level of 0.05. This test is often used in hydrological applications (Liu et al., 2009; and Pingale et al., 2014). Test result showed that the Thiessen weighted rainfall within the study area did not have any trend over the last 20 years as shown in Figure 4.

4.2.7 Influence of LULC Change on Hydrological Processes.

Numerous SWAT studies have employed differing methods to quantify the impacts of LULC change on hydrological variables. Most studies have applied simple comparison of the variables of interest between different years (Mekonnen et al., 2009; Ghaffari et al., 2010; Khoi and Suetsugi, 2014; and Sajikumar and Remya, 2016). Others have applied statistical analysis using either correlation or regression between hydrological parameters and LULC (Wagner et al., 2011; Wang et al., 2014; Gyamfi et al., 2016).

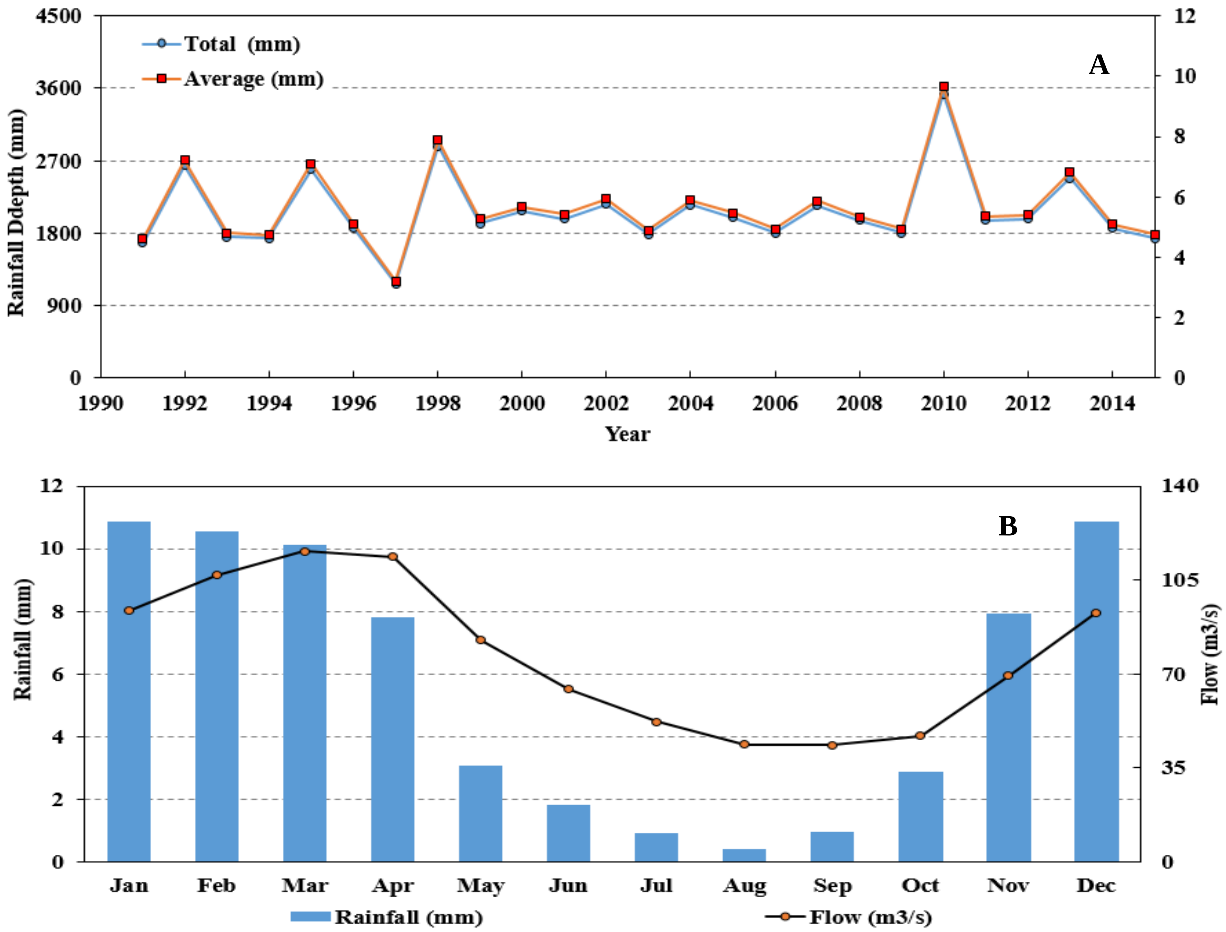

Figure 4.4. Rainfall trend over 25 years (1990 – 2015) (A) and mean monthly rainfall and discharge data for the period 1998 – 2014 in Upper Brantas (B).

To get a deeper insight about changes to a particular hydrological variable as a result of changes to a particular land use class, some studies have applied gradual land use change by running SWAT model on one land use map and performing gradual simulation using specific scenario (Ghaffari et al., 2010; Eshtawi et al., 2016). This study adopted a combined method to assess the LULC change impact on a hydrological variable. Comparative analysis was performed to provide an overview of changes in surface runoff due to LULC change in 1995 and 2015. Correlation was used to identify the relative importance of each major land cover types. Lastly, a gradual change scenario (0% to 100%) on LULC 1995 was applied to examine the relative impact of urbanization and agricultural expansion on surface runoff. For these, the scenario was applied to the selected sub-basin having considerable extents in agriculture, forest, and urban areas.

4.3 Results and Discussion

4.3.1 LULC Change over 20 Years in Upper Brantas.

Comparison between LULC 1995 and LULC 2015 revealed that the Upper Brantas watershed has undergone observable LULC changes. In the last 20 years, there has been a reduction in forested areas, plantation and rice fields ranging from 2% - 4% of the total watershed size. On the other hand, mixed-dryland agricultural areas within Upper Brantas increased 63 km^2, adding 3% of the total area. Over the past two decades, the changes in each LULC class were relatively small, ranging from 0.06% to 6.83% of the total basin area. Larger changes involved changes in dryland agriculture and urban development. Approximately, 9% and 14% of Mixed Dryland Agriculture in 1995 was converted to rice fields and urban areas respectively in 2015. Despite a small reduction of forest land (3% of total watershed), around 20% of forest in 1995 was replaced by Mixed Dryland Agriculture, and 6% of which was turned into shrubland and bushland due to logging. One relatively larger shift in the landscape was the reduction of rice fields. Around 26% of the rice fields in 1995 were converted to settlement in 2015. Settlement became the LULC class that experienced the biggest shift with an increase of around 136 km^2 by 2015 (Table 4). This represents an 80% change from its urban size in 1995, accounting for 6% of the total catchment area.

From post-classification change detection, it was found that forest reduction was mainly caused by conversion to mixed-dryland agriculture. Meanwhile, urban development was compensated mainly through the conversion of rice fields and mixed-dryland agriculture. The loss of rice fields has become an increasing concern due to its significant role as the staple food source for Indonesians. From 1995 to 2015, population in Malang city and Malang municipality increased from 2,869,596 to 4,556,648 (BPS Malang, 2015). This increase accounted for almost 60% increase in two decades with an average change rate of 2.78% per year. Considering the rapid economic development within the watershed for the last few decades, it is expected that urban areas will remain the land use experiencing the fastest growth in future.

Table 4.4. LULC Change over the Past 20 years (1995 – 2015) in Upper Brantas Watershed

LULC	1995	2015	Change (km2)	% Change of 1995	% Change of Total Area
Mixed Dryland Agriculture	696.36	759.21	62.85	9.03	3.15
Dryland Forest and Plantation Forest	373.75	310.91	-62.84	-16.81	-3.15
Sugarcane Plantation	264.61	175.80	-88.81	-33.56	-4.45
Rice field	417.42	373.15	-44.28	-10.61	-2.22
Shrubland/Bushland	54.43	53.28	-1.15	-2.12	-0.06
Grassland/Savannah	3.38	0.19	-3.19	-94.33	-0.16
Settlement	171.29	307.47	136.17	79.50	6.83
Water	13.50	14.74	1.25	9.25	0.06
TOTAL (km^2)	1994.75	1994.75			

4.3.2 Changes in Overall Water Balance due to LULC Change

Two 21-yr model runs were carried out using the LULC 1995 and LULC 2015. The resulting simulation using two land use revealed changes in all water components. Compared to LULC 1995, the average annual basin value of surface runoff in LULC 2015 increased from 460 mm to 496 mm, an 8% increase. In contrast, the evaporation decreased from 481 mm to 476 mm.

Overall, changes in LULC for two decades was resulted in the slight increase in water yield, from 1628 mm to 1633 mm, followed by decrease in annual groundwater average depth from 893 to 877 mm. One limitation in SWAT is that SWAT does not rigorously estimate the groundwater process (Rostamian et al., 2008). Thus, groundwater-related estimates should be considered indicative. The increase in water yield can mainly be attributed to increase in surface runoff. This was also caused by the decrease in groundwater due to less water percolating down.

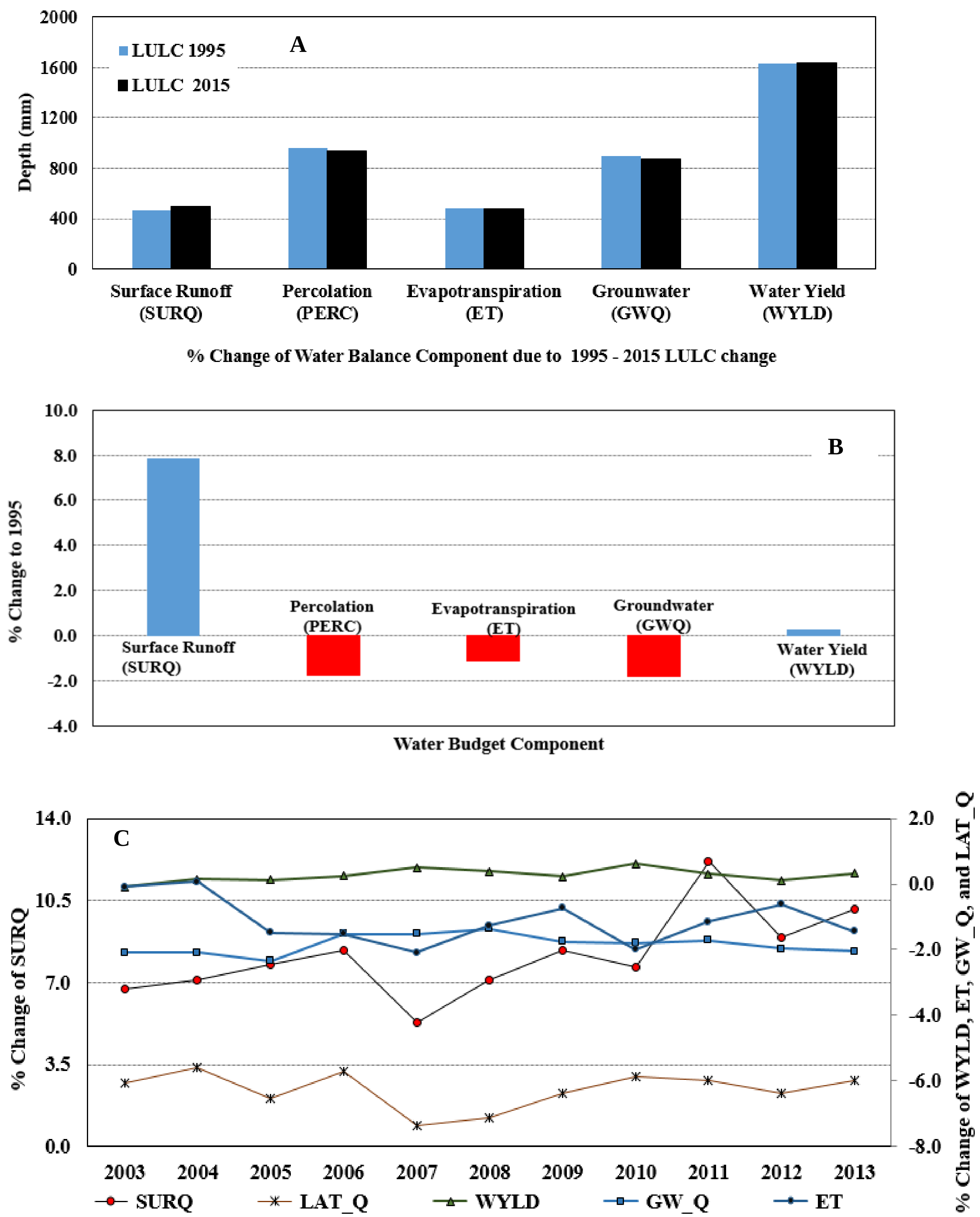

Figure 4.5. Changes of water balance (average annual values) in % from its original LULC 1995 (A) and in Depth (mm) (B) and long-term annual average of changes of water balance components (C)

The changes for annual average of surface runoff, evapotranspiration groundwater and water yield were relatively small, less than 40 mm. Compared to others, changes in surface runoff was most evident, the change magnitude was around 5% from the average runoff due to LULC 1995. This observation was also reflected in annual trends. For 11-year simulation, changes in surface runoff from LULC 1995 to LULC 2015 were more pronounced than changes in other components. The Mann-Kendall test performed to the yearly simulation from 2003 to 2013 showed a significant probability of an increasing trend in the surface runoff changes.

At sub-basin level, 25 of 27 sub-basins experienced an increase in annual average runoff, with changes varying from -4% to 50%. Differing conditions were observed in water yield, groundwater and evapotranspiration. In these components, variability of changes was higher, creating a cancelling-out effect to the whole watershed. Variability of surface runoff changes among sub-basins suggests variations of changes in each LULC class at sub-basin level. At this level, alteration to Mixed Dryland Agriculture varied from -17% to 29% of the sub-basin area size, while modification to urban areas ranged from 0.6% to 20%. The cancelling-out effect observed in this study has been reported by many prior studies (Ghaffari et al., 2010; Wagner et al., 2013; and Eshtawi et al., 2016).

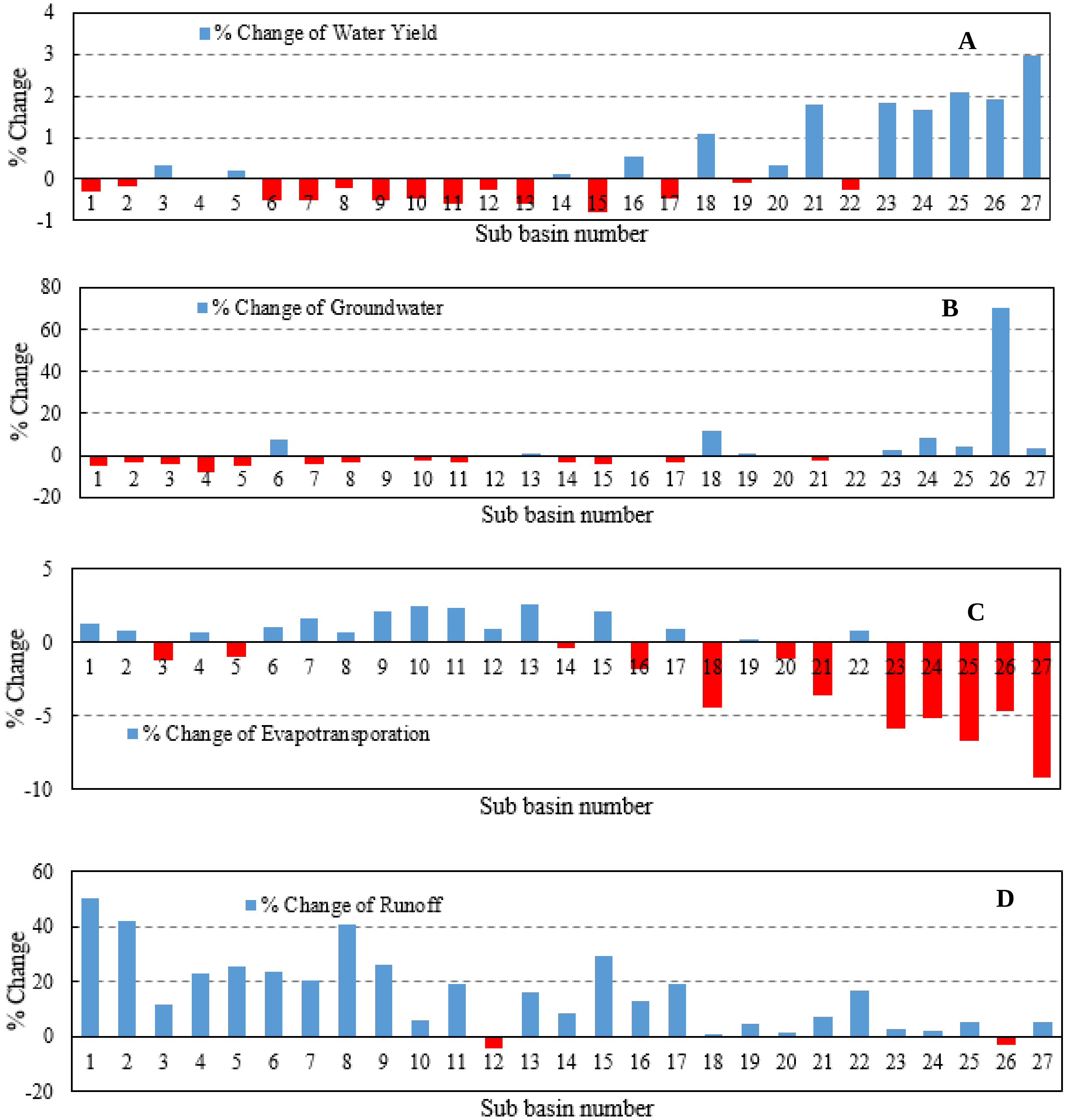

Figure 4.6. Changes at sub-basin level for water yield (A), groundwater (B), evapotranspiration (C) and surface runoff (D)

4.3.3 Relative Impact of Land Use Change on Surface Runoff

The 21-year LULC change in Upper Brantas has caused increase in surface runoff at varying degrees at sub-basin level. This implies that each land use might have a different relative sensitivity to runoff generation and other hydrologic components. In order to relate the land use change to water budget component, the relationship of changes of each water budget component to changes of each land use in each sub-basin was computed using the non-parametric Spearman rho-correlation (Hughes et al., 2012; and Zemke, 2016).

Table 4.5. Correlation for changes in four major LULC types and hydrologic components between 1995 and 2015*

	ET	SURQ	GW	WYLD	LATQ	FLOW	ARGL	FRSE	RICE	SUGC	URML
ET											
SURQ	**0.56**										
GW	-0.48	-0.45									
WYLD	**-0.97**	0.30	0.34								
LATQ	0.48	-0.25	**-0.60**	-0.23							
FLOW	**-0.78**	0.01	0.22	**0.61**	0.02						
ARGL	0.22	**0.63**	**-0.57**	-0.11	0.23	0.13					
FRSE	0.19	**-0.70**	0.19	-0.17	0.03	0.39	**-0.59**				
RICE	-0.28	-0.37	0.44	0.25	-0.36	0.12	**-0.28**	-0.17			
SUGC	-0.06	-0.45	0.46	0.04	-0.07	-0.08	-0.56	0.05	-0.07		
URML	0.34	**0.53**	**-0.60**	**-0.55**	0.43	-0.48	0.26	-0.06	**-0.58**	-0.23	

**) ET: Evapotranspiration, SURQ: Surface Runoff; WYLD: Water Yield; LATQ: Lateral Flow; GW: Groundwater flow, FLOW: Streamflow, AGRL: Mixed-Dryland Agriculture, FRSE: Dryland Forest, RICE: Rice field, SUGC: Sugar cane/Napier grass association plantation. URML: Settlement. Bold numbers are for $p < 0.05$*

As indicated in post-classification change detection matrix, some of the major changes in LULC in 21 years involved forest (FRSE) conversion to dryland agriculture, loss of rice field (RICE) and mixed dryland agriculture (AGRL) to settlement development (URMD). These major LULC trajectories were confirmed with relatively high negative correlation (Table 5). Correlation between changes in runoff and changes in LULC types suggest that runoff generation was associated mainly with the increase in dryland agriculture and settlement, and reduction in forest area. Relationship between changes in runoff and these three LULC types (AGRL, FRSE, and URMD) can be seen in Figure 4.7. The changes to FRSE accounted for 52% ($R^2 = 0.52$) of runoff variations, as opposed to AGRL and URMD which showed an R^2 of 0.35 and 0.11 respectively. All three LULC types' impact on runoff were significant ($p < 0.1$ at level 90% for URMD and $p < 0.$ for FRSE and AGRL). Since there were several LULC types in each sub-basin with varying degrees of change, the change in runoff might be a resultant impact of changes in these LULC types. Thus, it is difficult to discern the relative impact of a particular LULC type. The magnitude of increase in runoff can be resulted from increase in AGRL, URML or FRSE together in a particular sub-basin.

To better understand the impact of changes in runoff just from changes of one single LULC type to another single LULC type, a series of gradual simulations were run. SWAT was run using the 1995 LULC map and a gradual/incremental change (0% to 100%) was used in the selected sub-basin (sub-basin 6). This sub-basin was selected because it represents one of major sub-basins with four major LULC types so that simulation using differing LULC trajectory can be made possible.

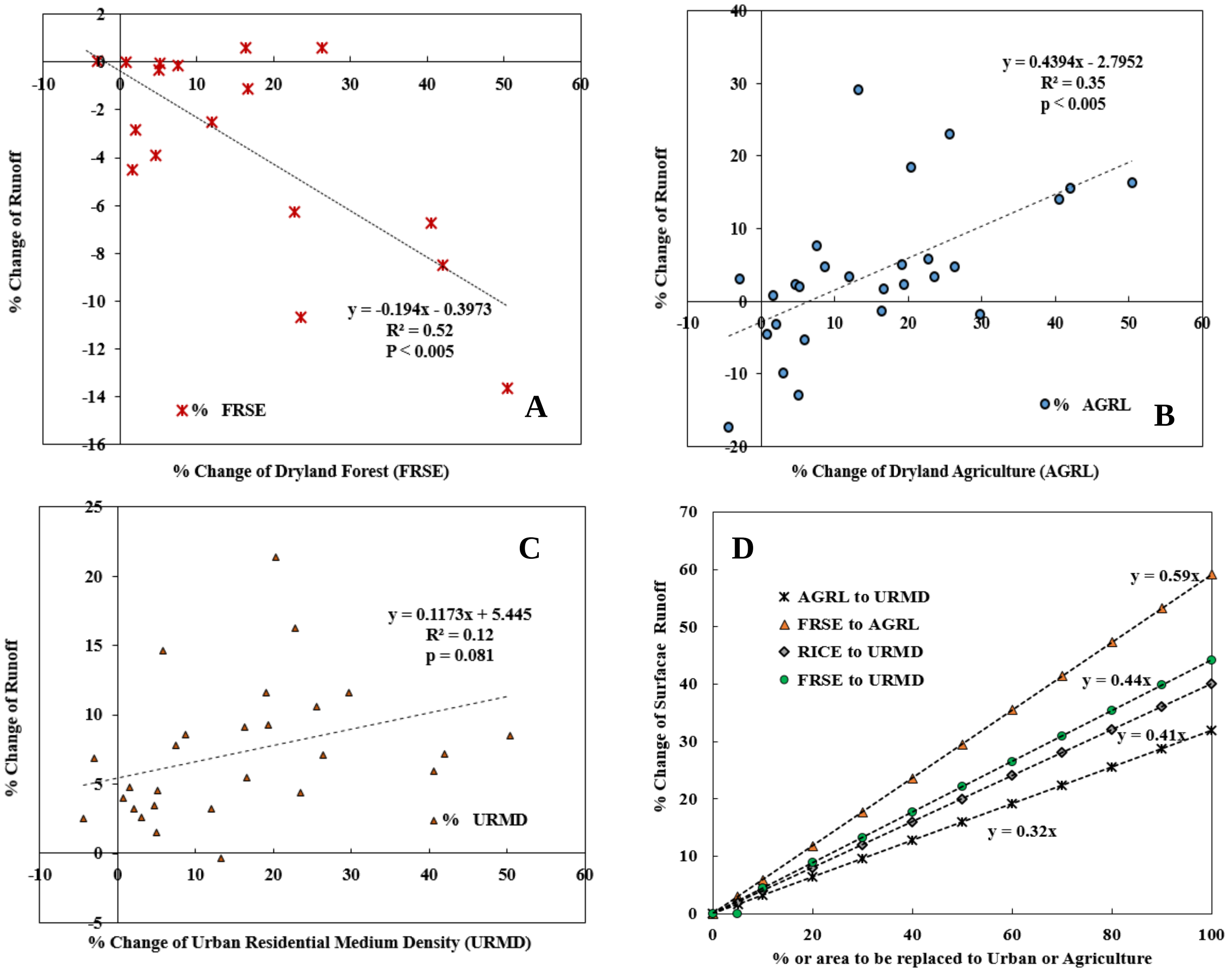

Figure 4.7. Relative impact of a particular LULC change on runoff (A, B, C) and impact of gradual LULC Change from four different LULC trajectories (D)

A linear relationship between runoff and forest/farm loss and urban development was observed in all types of simulations. This linear relationship was similar to the simulation of urban sprawl in Gaza (Eshtawi et al., 2016). However, a different result was showed from a study by Ghaffari et al (2010) who found a non-linear relationship for runoff change after a 70% removal of rangeland. Different gradients for different LULC change paths demonstrate the sensitivity of each LULC type removal to runoff generation. The result confirmed that forest conversion to other LULC types (to AGRL or to URMD) has a pronounced effect on surface runoff (Figure 7B).

Simulating a 21-year LULC change in Upper Brantas watershed revealed the changes in hydrological processes occurred at basin and sub-basin levels. At the whole basin level, the 21-years of changes in LULC resulted in slight increase in long term annual average runoff and water yield, and decrease in evapotranspiration and groundwater. The overall magnitudes of changes at basin or catchment level were relatively small. However, at sub-basin level, the percentage of changes of these elements were more diverse. Variation among sub-basins was noticeable, especially for water yield and evapotranspiration. Apparently, the sub-basins compensated each other so that the long-term changes at watershed level were less evident. Wilk and Hughes (2002) highlighted the influence of LULC change on hydrological responses can be masked by complexity in a large catchment. One can argue that in 21 years, the changes in LULC with the biggest change of only 7% of the total area might not be significant enough to create a distinct change in the long term annual average. Yet, the cancelling-out effect was also found in other studies with more pronounced LULC changes such as higher than 10% of the total watershed (Wagner et al., 2013; Gyamfi et al., 206; and Marhaento et al., 2017). It is also important to note that the sub-basin areas in Upper Brantas delineated by SWAT vary greatly from 300 to 24,000 hectares. In addition, Upper Brantas is a catchment with large variation in topography and LULC types. AGRL class represents a generic dryland agriculture in East Java, which can vary in terms of plant types. A farm land classified as mixed-dryland can have a composition of crops, fruits, vegetables and shrubs or bushes, or even hard trees such as coconuts and mangoes, whose density and species diversity can vary from one land to another. The variation in magnitudes of changes in four hydrological components supports the study from

Bruijnzeel (2004) that variability in topography, soil types, and geological settings can all play a role in affecting the water balance. FAO (2002) recommended smaller basins (< 1000 km^2) for more accurately discerning the impact of various bio-physical factors in the watershed.

Despite the relatively small change in long-term average, surface runoff change was found to be the most prevailing than others. Quantitative analysis showed that changes in runoff can mainly be attributed to the loss of forest and increase in mixed-dryland agriculture and settlement. Sub-basin level analysis revealed that more distinct runoff increases was observed mostly in sub-basins located either in north-east upper parts where forest encroachment and agricultural expansion occurred, or in middle part where urbanization is more concentrated. Another factor that can possibly contribute to this is the role of lithology. Groundwater contribution to the stream flow has been dominant in Brantas Watershed (ratio of GWQ/P and LATQ/P around 40% and 20%). The geological formations in these sub-basins are mixed between impervious and permeable rocks that control the water movement to the groundwater. In addition, the relatively dense dominating parallel – dendritic river patterns in the watershed support close association of rainfall-runoff, which suggest that excessive rainfall can barely be absorbed. While most sub-basins exhibited runoff increase, sub-basins 12 and 26 were the only ones experiencing slightly reduced runoff. LULC change in these sub-basins showed noticeable reduction in mixed dryland agriculture and smallest forest loss that might have contributed to lessen the runoff magnitudes. However, considering sub-basin 12 is only 139 hectares in area, being the smallest sub-basin, the pronounced change in groundwater might not be a representative hydrological process.

Results from gradual LULC change simulations using four different LULC change trajectories confirmed that forest conversion to mixed-dryland agriculture is most detrimental, followed by forest to settlement, rice to settlement, and mixed-dryland agriculture to settlement. The gradient of runoff changes from forest to dryland agriculture is steeper than from forest to urban, suggesting that increase in agriculture might have caused higher runoff than increase in settlement. The plausible explanation for this is that the combined effect of topography and LULC characteristics. For instance, around 43% of total AGRL areas were located on steep terrains with slope between 25 – 45%, while settlement areas were mainly distributed on gentler slopes (below 15%). With intense rainfall and mild temperature at higher elevation, mixed-dryland agricultural types in upper part of the basin are dominated by vegetable farming. The land management practices for growing vegetables in this region involve traditional terracing against the contour lines that allows water running down the slope directly for better aeration, a favorable condition for vegetable plots. This condition can amplify the runoff generation within the landscape. On the other hand, settlement on gentler slopes, except in the city, is relatively sparse and the presences of trees with denser canopy might allow higher amount of water to be retained from soil and thus produces smaller runoff.

The changes in LULC in Upper Brantas for the last 20 years highlights the importance of future watershed management. With apparent impact of surface runoff increases due to urbanization and forest conversion to agriculture, proper management for mitigating the impact of LULC is of importance. Despite relatively small changes in runoff generation due to the 21-year LULC change, the findings suggest that increasing urbanization and forest conversion to dryland agriculture in Upper Brantas can impose serious threats in the long run. This will be more complicated with the on-going rapid economic development within the watershed. Threats from increasing point-source pollutions as a result of increasing industries can exacerbate the watershed condition. Findings from several studies suggested that increasing runoff lead to increasing sediments and nutrients brought across the landscape through the runoff. Polakov et al (2010) found the non-linear increase in sediment yield with increase in runoff events semi-arid watersheds in Ariona; while Michaelides et al (2012) found linear increase in nutrient yield associated with the runoff. Elevated nutrients runoff has been regarded to increase risks of eutrophication in the receiving water bodies (Smith et al., 1999). Sutami reservoir within Upper Brantas watershed has been reported to undergo increasing occurrence of eutrophication. Considering this, challenges are how to establish agricultural land use practices that reduce the surface runoff, strengthen forest protection to reduce encroachment for agricultural expansion, and to establish settlement that accommodates more green spaces for runoff reduction in the watershed.

4.4 Conclusion

Upper Brantas represents a typical tropical watershed undergoing LULC change. As similar to those in most developing countries, the LULC change is expected to be more severe due to increasing globalization, leading to forest conversion for agriculture, and eventually farm loss for urban development. While lack of regulations and poor watershed management practice have remained frequent issues, the LULC change can impose more serious threats for the watershed condition, especially at regions where data is very limited.

This study showed that the SWAT model using generally available data can be used to simulate the LULC impacts on hydrological responses in data-scarce regions. The land use change in Upper Brantas for the last 21 years was relatively similar to those in typical developing countries in southeast Asia, where LULC changes mainly involve forest loss to compensate for the agricultural expansion and increasing urbanization. Over the past two decades, the overall changes in LULC in Upper Brantas was relatively small but urban / settlement experienced the largest growth, accounting for an increase around 7% of the total watershed, followed by increase in dryland agriculture and forest loss, denoting 3% - 5% of total area. Simulation using two differing land use maps revealed slight changes in the long-term average of water balance components, leading to increased runoff and water yield, and decreased groundwater and evapotranspiration. Among these components, surface runoff became the component with most pronounced increase, denoting to 8% change in long-term average runoff depth, while others variables were less noticeable. The effect of land use change at sub-basin level was more pronounced, showing high variability in hydrological variable changes. Compared to other LULC types, surface runoff was found to be associated with conversion of forest to dryland agriculture and rice field and dryland agriculture to urban areas/settlement. Spatially, sub-basins with significant runoff increase was mostly restricted to sub-basins experiencing higher loss in forest and urban expansion. The simulation results suggest the importance of watershed management for a sustainable use. Impact of increased runoff and water yield would be more evident with continuing urbanization, especially in upper part of watershed. Considering the ability of SWAT model for simulating the hydrological responses in Upper Brantas watershed, extended applications of similar study for investigating LULC impacts on water quality will help dealing with a concern for sustainable use of the watershed.

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CHAPTER 5

ASSESSMENT OF LONG-TERM WATER QUALITY VARIABILITY AT THREE TROPICAL RESERVOIRS IN INDONESIA[1]

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ABSTRACT

Remote sensing-based assessment on long-term variability of optically active constituents such as sediment and algae help provide information for knowing the dynamics of ecological condition in inland fresh water, especially when traditional monitoring is limited or unavailable. The study presented a Landsat-based assessment for understanding TSS and Chl-a in three reservoirs: Sutami, Lahor, and Selorejo, East Java - Indonesia. Green band was identified to be a selected explanatory variable for estimating TSS in Selorejo, while NSMI ratio (Green + Red – Blue)/(Green + Red + Blue) worked best in capturing TSS variability in Sutami-Lahor. The TSS models' performance was acceptable with an R^2 of 0.83 (NRSME 11.92%) for Selorejo and R^2 of 0. 77 for Sutami-Lahor (NRSME 16.40%). The Chl-a model selected for Selorejo was single Blue band model for Selorejo (R^2 0.75, NRSME 17.14%), and NIR – Red/NIR + Red ratio model for Sutami-Lahor (R^2 0.71, NRMSE 15.56%). Long term analysis showed differing relationship between TSS and Chl-a. The TSS co-varied with Chl-a in Selorejo, while TSS negatively affected Chl-a in Sutami-Lahor. In all reservoirs, TSS pattern is seasonal with rainfall and inflow jointly increased TSS during wet season (October – March), and lowered during dry season (April – September). In contrast, Chl-a seasonal pattern showed a possible influence of localized condition in each reservoir. The presence of extensive hyacinth in Selorejo and massive cage fish farming in Sutami-Lahor appeared to affect algal proliferation differently. Higher Chl-a in Sutami-Lahor during dry season might have been a resultant impact of reduced turbidity, stable temperature and water level, lower wind in early dry season. Comparison on reservoir's characteristics showed that both ecological factors from external environment such as climate and hydrological as well as watershed properties, and internal condition such as the

presence of cage fish farming and water hyacinth may interplay in determining the degree of eutrophication and sedimentation in each reservoir.

Key words: Landsat, TSS, Chl-a, tropical reservoirs, eutrophication, sediment, Upper Brantas, Sutami, Lahor, Selorejo, Indonesia

5.1 Introduction

Inland waters covering various ecosystems such as lakes, rivers, reservoirs, marshes, swamps, floodplains, small streams, ponds, and caves are an important part of the hydrologic cycle that provides a range of services including fresh water provision, food production, energy supply, and global climate regulation (Price, 1999; Hasan et al., 2005 and Likens, 2009). Lakes and reservoirs provide important information on patterns and mechanisms of terrestrial and aquatic response to climate condition (Williamson et al., 2009). With development of human activities, the uses of inland waters have become more diverse, extending from solely for water supply to recreational and educational uses. Therefore, for ensuring sustainable use, ecological management of inland water bodies is needed (Price 1999).

To support ecological management, a good understanding on how lakes and reservoirs respond to their connected terrestrial environments is of importance. Unfortunately, there have been a lack of information needed to comprehend the roles of reservoirs and their response to global changes (Matthews, 2014). Among water quality parameters, Total Suspended Solid (TSS) and Chlorophyll-a (Chl-a) concentrations in reservoirs are two most widely used indicators and frequently studied due to their significance in inland water ecosystems. TSS affects the water's turbidity and has a deleterious effect on light propagation through the water column limiting the primary production (Shen et al., 2010), besides, it plays an essential role in transporting nutrients and contaminants in the water (Wu et al., 2013). TSS has been widely used to investigate various environmental impacts such as accelerated erosion (Bakr et al., 2012), increased sedimentation (Kaba et al., 2014) and water pollution (Nasrabadi et al., 2016). Similarly, Chl-a is a widely used environmental indicator of phytoplankton abundance, which serves as an important part in aquatic food web, and a simple measure of ecosystem's trophic state (Han and Rundquist, 1997; Sass et al., 2007; and Boyer et al., 2009).

Studies on spatio-temporal assessment of TSS and Chl-in reservoirs and reservoirs provide insight on (a) the environmental factors controlling these parameters (Wang et al., 2010), (b) reveal interaction between TSS and Chl-a (Mishra and Mishra, 2010 and Zheng et al, 2015), (c) infer possible anthropogenic influences (Huang et al., 2014), (d) predict ecological changes and consequences of those changes (Dall'olmo et al., 2005) and (e) help outlining the best sampling strategy for reservoir monitoring and assessment (Wang and Weng, 2013). Unfortunately, despite being considered relatively synonymous, reservoirs and reservoirs are diverse in terms of climate, geology, and morphology that lead to differences in reservoir governing processes such as mixing, stratification, and internal loading (Thornton, 1984). These factors may affect the differences in characteristics of long term TSS and Chl-a variability. For example, some reservoirs may show Chl-a peaking in summer, while others show peak in winter months (Feng et al., 2015, Breunig et al., 2016). Some reservoirs may show close Chl-a–rainfall association, while others are influenced by non-point source (Morrison et al., 2006). Some reservoirs may show shorter lag between sediment plume (TSS) and algal bloom (Chl-a), while others have longer lag time (Mishra and Mishra, 2010; Feng et al., 2015; and Kumar et al., 2016). The water quality variability within a reservoir could be closely tied to it watershed and the above studies infer that such site specific study merits its own importance.

Assessment of lakes or reservoirs' water quality parameters such as TSS and Chl-a is expensive, time consuming and laborious. Remote sensing technologies have been applied as additional tool for helping reservoir monitoring and providing insight on spatial and temporal information of water quality due to their synoptic, systematic and periodic data collection (Baban, 1999 and Hadjimistis et al., 2010). TSS and Chl-a mapping using remote sensing have gained considerable success, especially in oceanic waters. As opposed to ocean water, inland water is optically more complex where the optically active constituents (OACs) originate from differing sources in addition to phytoplankton such as by a composite of dissolved organic matter from terrestrial inputs, dead particulate organic matter, and inorganic particulate matter. Thus modeling of water quality in inland water remains a challenge (Mishra and Mishra, 2010; Gholizadeh et al., 2016). TSS and Chl-a have been modelled using various approaches, ranging from empirical by using single band with linear, polynomial and exponential models (Miller and McKee, 2004; Shie et al., 2015 and Kumar et al.,2016), semi-empirical such as band ratios (Moses et al., 2009; Le et al., 2009; Yang et al., 2011; and Mishra and Mishra, 2012) and quasi analytical models (Gokul et al., 2014; and Watanabe et al., 2016). Yet, despite these varied models, currently there is no unified or generic TSS and Chl-a model that is applicable world-wide.

Monitoring TSS and Chl-a in water bodies is of importance to ensure sustainable use of the inland water resources. Indonesia's major source of inland water relies on approximately 5,590 rivers, 521 reservoirs, and 100 lakes, with varying surface area from 1.9 km^2 to 1,130 km^2 (Lehmusluoto et al., 1995 and World Water Council, 2003). Most of these reservoirs and reservoirs are used for multiple purposes such as irrigation, water supply, recreation, energy generation and flood control. Unfortunately, water quality data for reservoirs and reservoirs are very limited. Traditional and expensive laboratory-based water quality data are not frequently acquired and not publicly available. In addition, remote sensing technologies based studies are highly sporadic. While most of remote sensing-based water quality models were developed outside the tropical belt (Dörnhöfer and Oppelt, 2016), there have been very limited studies on water quality modeling for Indonesia's aquatic systems. The published and peer reviewed studies were mostly confined to coastal and estuarine systems in Kalimantan (Ambarwulan et al., 2011 and Budhiman et al., 2012).

Considering the increasing reports of eutrophication and sedimentation in Indonesia's reservoirs and reservoirs, an intense remote sensing based spatial mapping effort for more efficient water quality monitoring is required. For example, Sutami is one of Indonesia's reservoirs that has been subject to eutrophication and sedimentation (Ramu, 2004). Unfortunately, despite the perceived issues, there have been no studies investigating the spatio-temporal trends of TSS and Chl-a, the two water quality parameters associated with eutrophication and sedimentation. This study is aimed at (1) investigating of the accuracy of remote-sensing based TSS and Chl-a bio-optical models for the selected reservoirs namely Sutami, Lahor and Selorejo, (2) applying the selected models on Landsat images to evaluate the long term variations of TSS and Chl-a, (3) assessing the interaction of TSS and Chl-a and identifying potential governing environmental factors controlling these parameters. The main focus of this study is the Sutami reservoir. To gain deeper understanding, results were compared to two other reservoirs, Selorejo and Lahor, which have different watershed characteristics.

5.2 Materials and Methods

5.2.1 Study Area

Sutami, Lahor, and Selorejo are three tropical reservoirs built in 1972 and located within Brantas river system under Brantas River Basin in East Java, Indonesia. Sutami reservoir, lies in Daerah Aliran Sungai (DAS) or catchment Upper Brantas, while Selorejo and Lahor reside in DAS Konto and DAS Lahor respectively (Figure 5.1). All three reservoirs are located between -7.74 Latitude / 112.22 Longitude and -8.29 Latitude / 112.95 Longitude. The three reservoirs are under administrative boundaries of Malang municipality (Kabupaten Malang), East Java, Indonesia. All these reservoirs represent multi-purposes reservoirs, with uses vary from energy generation, water supply, fisheries and recreation.

Climatically, the three reservoirs are located in humid tropical regions with relative humidity over 90% and temperature between 23 and 26 degrees Celsius. Monthly precipitation ranges from 0.4 to 10.29 mm in Sutami and Lahor, and 0.42 to 15.26 mm in Selorejo. The study sites reside in a tropical region where seasons are classified as wet or rainy season (October to March) and dry season (April to September). The surface area of Sutami and Lahor are separated around 1 km, but both are connected by a man-made underground channel in the lower part of Sutami. Agricultural land uses in vicinity of Sutami are rice fields and sugar cane in the north part, and dry-land agriculture (crops and trees: maize, soya, oaks, banana, bamboo, coconut) in the southern part. In Selorejo, the eastern part is dominated with urban areas, and crops in western part. Similar to Selorejo and Sutami, the vicinity of Lahor reservoir is mainly crops. Table 1 summarizes the reservoir properties and their tied catchments.

Soil types might affect the characteristics of the drained materials brought by runoff across the landscape can impact the water quality in the receving water bodies. Edaphically, soils in DAS Upper Brantas and DAS Lahor are dominated by Distrudepts and Epiaquepts developed from Basaltic materials. In DAS Konto, several types of soils exist, making a compsite of Hapludans, Hapludults, and Dystrudepts. DAS Konto is circled by mointain complex: Kelud, Arjuno-Welirang with geologic formation dominated by andesit, lava, breccia and tuff, creating volcanic landforms rich with organic materials (basesd on GIS analysis on geologic and soil map of the study area). The reservoir has been impacted by volcanic eruptions from the surrounding mountains, however the impact is dependent on the extent and direction of eruptions. Immense rainfall, eroding landuse, and steep slopes triggered the frequent occuruence of landslide and floods in highland Javanese catchments (Mulia, 2013; Utami, 2014; and Lukas, 2014)

5.2.2 Field and Hydro-climatic Data

Weather parameters such as monthly rainfall and temperature are collected from local weather station. Monthly inflow data for each reservoir were obtained from Perum Jasa Tirta, the state company responsible for managing the reservoirs. The GIS boundary layers for each catchment were obtained from National Agency for Watershed Management – BPDAS. To capture the intra and interannual variability of TSS and Chl-a in the three reservoirs, several fieldtrips were carried out in both dry and wet sesons at the following dates: 19 August 2014, 4 September 2014, 19 September 2014, 7 January 2015, 14 Augsut 2015, 3 September 2015, 2 May 2016, and 17 June 2016. The dates of sampling were designed to be within $\pm$ 1 day of the Landsat 8/OLI overpass datas. In each field trip, water samples were collected from surface area (0 – 50 cm) for TSS and Chl-a analysis. All samples were collected between 8 am and 14 pm local time. 2 liters of water was collected from each site using Niskin bottle for both TSS and Chl-a analayis. The TSS concentration was determined in the laboratory using gravimetric method. For each sample, 500 ml of water was collected. A pre-weighted dry filter of 45 µm of porosity and 47 mm of diameter was used to filter each water sample. The TSS concentration was obtained based on the differences before and after the drying the sample at 500°C. The Chl-a content (in µg/L or mg/m3) was measured using spectrophotometry. Chl-a pigment was extracted using 90% acetone at 4◦C for overnight under dark conditions. The optical density (OD) of the extracted pigment was measured at three wavelengths (645, 665, and 750 nm).

Tabel 5.1. Comparison of catchment and reservoir properties of Sutami, Selorejo and Lahor

Catchment properties for each reservoir*

	Brantas (Sutami)	Lahor (Lahor)	Konto (Selorejo)
Area (km^2)	1996	165	237
Perimeter (km)	242	58	80
A/P	8.26	2.82	2.94

* Data calculated using ArcGIS. Names in bracket are names of reservoirs

Reservoir properties

	Sutami	Lahor	Selorejo
Mean Depth (m)	20	11	15.48
Depth max (m)	50	30	32
Size (km^2)	15	2.6	4
Volume storage estimate (km^3)	0.34	0.037	0.062
Schindler's ratio*	44	70	65
Development index	1.20	1.50	1.88
Resident Time	-	-	-
Elevation (m)	210	210	620
Mixing type	Oligomictic	Oligomictic	Oligomictic

Source: Lehmusluoto et al (1997)

* calculated after Stefanidis and Papastergiadou (2012)

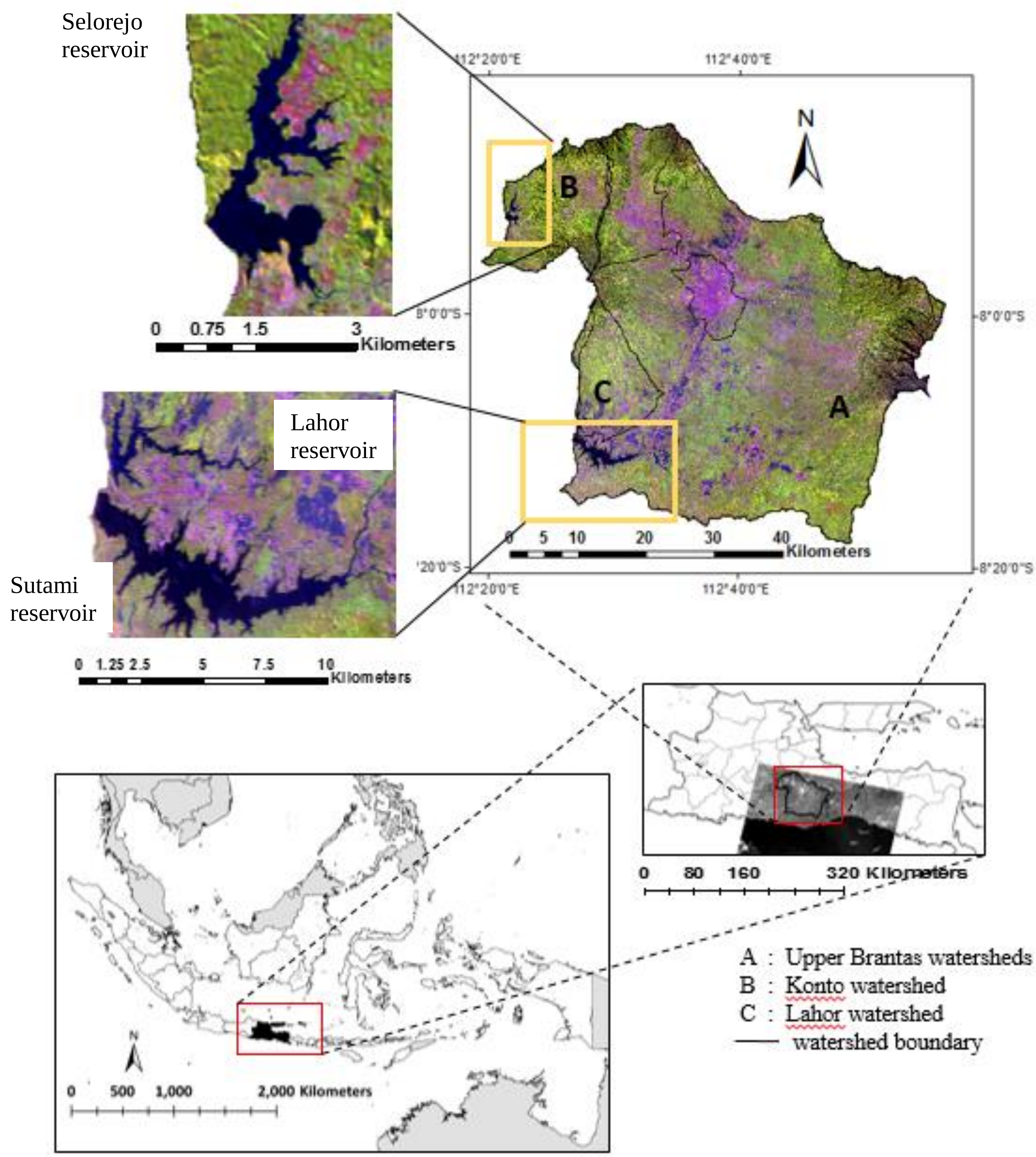

Figure 5.1. Location of Sutami, Selorejo and Lahor reservoirs within DAS Upper Brantas (A), Konto (B) and Lahor (C) and appearance of current Landsat 8/OLI (Path/row 118/66, False color 5-4-3 composite, August 2015), and relative position of watersheds in East Java Province, Indonesia.

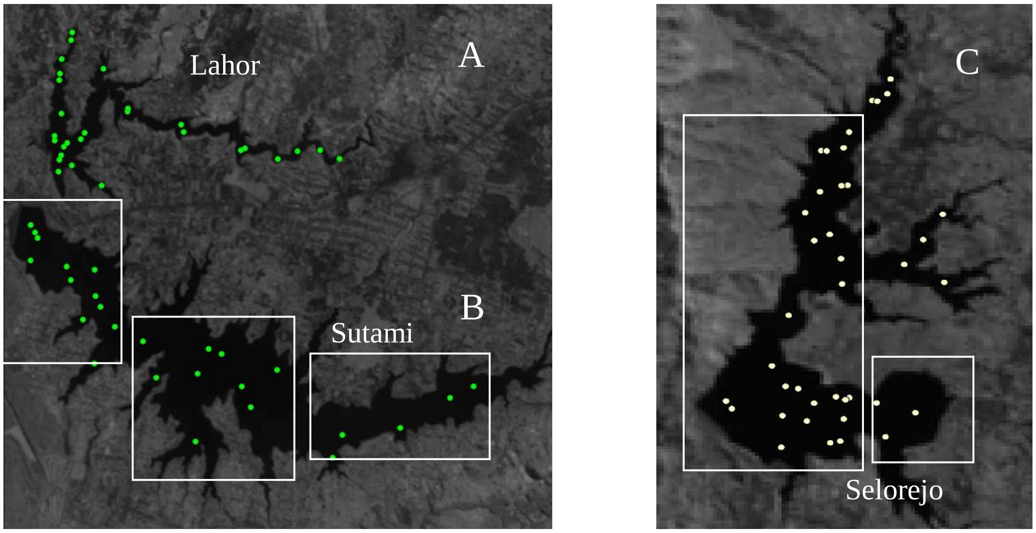

Figure 5.2. Locations and distributions of TSS and Chl-a sampling sites from each reservoir: Lahor (A), Sutami (B) and Selorejo (C). White boxes represent arbitrary boundaries of reservoir sections: lower, middle, upper for Sutami, and lower – upper for Selorejo (from left to right)

5.2.3 Landsat 8/OLI Image Processing

To derive TSS and Chl-a estimates, the Landsat 8/OLI - Landsat Surface Reflectance Higher Level- Data Products generated from Landsat Ecosystem Disturbance Adaptive Processing Systems (LEDAPS) and Landsat Surface Reflectance Code (LaSRC) (USGS, 2015) were used, which are available on request basis from https://espa.cr.usgs.gov/. The images downloaded have already been atmospherically corrected using Landsat Surface Reflectance Code (LaSRC) for Landsat 8/OLI and 6S algorithm for Landsat 7/ETM images. Despite being considered provisional, these already atmospherically corrected images were used based on consideration that atmospheric correction requires many atmospheric parameters such as optical thickness, air pressure and water vapor information, which are not readily available for the study sites. In addition, simple atmospheric correction method such as Dark Object Subtraction was not possible to be implemented due to absence of clear cloud/haze free dark pure water body in the study site. A recent study supported the choice of using LaASRC products showing that LSR reflectance had a good agreement with in-situ simulated Landsat bands and produced the smallest RMSE and BIAS for estimating water quality parameters (Bernanrdo et al., 2017). Despite this promising finding, it is acknowledged that the use of provisional surface reflectance might contribute to the error of the water quality models. In order to obtain corresponding Landsat reflectance values from each sample site, the locations of important landmarks in local base maps were used to geo-locate the position of the site in Landsat 8/OLI images. The surface reflectance representing the site was derived by averaging 3x3 pixels in visible, NIR and SWIR-1/2 layers.

5.2.4 Modeling Approach and Long-Term Data Extraction

The empirical modeling approach exploiting the statistical relationship between surface reflectance and TSS or Chl-a was used because of the lack of inherent optical properties data (absorption and backscattering) from the study sites. In addition, the simplicity of empirical approach ensures a wider applicability. Several existing TSS and Chl-a empirical models world-wide covering a wide range of concentrations were tested, but none of the models were able to provide satisfactory results based on correlation analysis (R^2) (Appendix 1 lists the performance of the TSS and Chl-a models tested in this study). This condition led to the approach of tweaking the best performing models to make them applicable for the three study sites. To figure out the potential explanatory variables, TSS and Chl-a values were correlated with various empirical indices derived from single band (band 2 to 6 in Landsat 8). All possible band ratio combinations from these bands including various published indices such as RGCI (red-green chlorophyll index), NDSSI (Normalized Difference Suspended Sediment Index), NSMI (Normalized Suspended Mineral Index), and NDCI (Normalized Difference Chlorophyll-Index) were tested and compared. Variables with highest correlation values were selected for modeling. Best fitting approach was used to select the type of model whether linear, polynomial, power or exponential. Final models were selected based on their performance parameters such as R^2, RMSE, MAPE and MAE (Zheng et al., 2015, Mishra and Mishra, 2012). The Leave One Out Cross Validation (LOOCV) was also carried out to assess the TSS and Chl-a model performance (Martin et al., 2008; Wang et al., 2010; and Feng et al., 2014).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(x_{est,i} - x_{meas,i}\right)^2}{n}} \quad (1)$$

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{\mathrm{xmax} -_{meas} - \mathrm{xmin}_{meas}} \times 100 \quad (2)$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} \left| \left(x_{est,i} - x_{meas,i}\right) \right| \quad (3)$$

$$\mathrm{MAPE} = \frac{1}{n}\sum_{i=1}^{n} \left| \left(x_{est,i} - x_{meas,i}\right)/x_{meas,i} \right| \quad (4)$$

where n is the number of samples, $x_{est,i}$ and $x_{meas,i}$ are related to the estimated and measured values, respectively.

After the final TSS and Chl-a models were obtained, they were applied on Landsat 7/ETM+ and 8/OLI images spanning from 1999 to 2015. The reason for selecting this time window is that even though Landsat images started to be consistently available for Indonesia from 1995, the hydro-climatic data were available only from 1999. Conducting long-term assessment requires the consistency among sensors because of differing band sensitivity and radiometric resolution. Studies on Landsat 7 and Landsat 8 cross sensor calibration in different places show differing results for slope and intercepts in band by band regression techniques indicating the importance of environmental variables (Teillet et al., 2006 and Roy et al., 2015). These differences based on geographic location also imply that the atmospheric condition differ from one site to another. Thus, local cross-sensor calibration was applied by selecting good quality images from Landsat 7/ETM and Landsat 8/OLI (both path/row 118/66) for which the overpass mismatch is at the most less than equal to 7 days. Good quality images represent images with free of clouds and haze, and have for the targets and having quality index of 9 according to Landsat classification. Four pairs of Landsat 7/ETM and Landsat 8/OLI were used for cross sensor calibration (19 April/27 April 2000, 5 June/13 June 2014, 21 April/29 April 2015, 16 June/24 June 2015). To obtain band by band relationship between Landsat 7 and Landsat 8, a total of 1350 urban pixels were selected. This analysis was limited to urban pixels as urban feature reflectance values are relatively stable and consistent over time compared to water and vegetation which can change considerably within a week due to changes in vegetation growth phase or water constituent composition.

To obtain spatio-temporal trend of TSS and Chl-a concentration, images that are free from clouds, haze, glints and observable systematic errors were selected. Several site locations (28 for Sutami, 10 for Lahor and 14 for Selorejo) were also selected from each reservoir using point extraction technique to avoid possible mixed pixels. Aquaculture fish cages heavily occupy parts of Sutami and Lahor reservoir, while floating macrophytes (hyacinth) can be found in parts of Selorejo (Appendix 2). In addition, reservoir areas affected by the n-line striping error in Landsat 7 were also avoided. For Sutami, the 28 points were based on three regions: 8 points for upper, and 10 points for middle and lower. While for Selorejo, the 14 points were assigned into two regions: 4 points in upper / river mouth, and 10 points for lower part. This division followed the arbitrary division of Perum Jasa Tirta monthly monitoring scheme (personal communication). Landsat surface reflectance values were derived by averaging 3x3 pixels surrounding each point. Cross calibration regressions were applied to pixels extracted from Landsat 7 images. The selected TSS and Chl-a models were applied to the surface reflectance values extracted for each point. To obtain long term TSS and Chl-a variability, monthly aggregation was carried out. Median values were used to represent the variability since it is more resistant to outliers. Use of Landsat data 16-day revisit period could be considered as a potential limitation of this study because of the lack of frequent observation data. The study sites are subject to frequent cloud and haze regardless of the seasons. In many cases, only one scene or even no data were found due to cloud or haze coverage. This monthly observation is similar to a study which used one image per month for studying TSS variations in Poyang Reservoir, China (Cui et al., 2013)

Table 5.2. Statistics of TSS and Chl-a samples collected from each reservoir during fieldtrips

	TSS (mg/L)						
	n	Mean	Min	Max	Median	Stdev	CV
Selorejo	38	61	4	226	29.15	62.43	1.02
Sutami - Lahor	55	53	3	258	21.45	65.69	1.25

	Chl-a(mg/m^3)						
	n	Mean	Min	Max	Median	Stdev	CV
Selorejo	37	38.75	5.83	96.09	25.78	26.51	0.68
Sutami - Lahor	47	25.23	1.61	58.05	26.65	15.15	0.66

5.3 Result and Discussion

5.3.1 TSS and Chl-a Modeling

A number of existing TSS and Chl-a models obtained from published literature were tested using samples combined from all reservoirs. Despite the similarity in TSS and Chl-a concentration and ecosystem types, the models performance was not satisfactory (see Appendix

2). These finding implied that the variability in reservoirs' characteristics affect the composition of OACs and therefore, site-specific models may be more appropriate compared to a universal model. Correlation between TSS or Chl-a and several explanatory variables using data combined for three reservoirs did not show any potential predictors for either constituent. Considering the differences in their geological or edaphic characteristics, as well as topographic and surrounding land uses, the samples were divided for model calibration and validation. Samples from Selorejo were separated, whereas, samples from Sutami and Lahor were used together. Relationship between TSS and Chl-a in these two groups verified the differing optical conditions of these reservoirs (Figure 5.3).

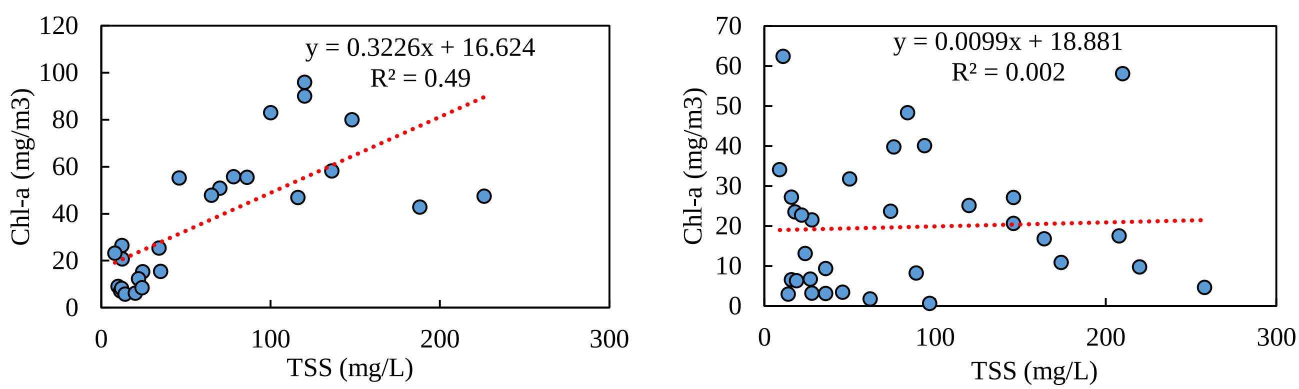

Figure 5.3. TSS and Chl-a relationship in Selorejo (A) and combined Sutami and Lahor (B).

Both TSS models show that exponential model outperformed the other models (linear, power and logarithmic) (Figure 5.4). Both models produced considerably good validation with less than 20% NRMSE (Table 3). The relatively high RMSE of TSS model for Sutami-Lahor was mainly caused by larger errors from samples with TSS higher than 150 mg/L. Further RMSE breakdown showed that for sites with TSS concentration below 150 mg/L (47 samples out of 55), the magnitude of RMSE decreased significantly to only 15.76 mg/L (data not shown).

Despite having considerably good R^2, limitations were observed for both models. Both models exhibit better sensitivity of green band and NSMI index to TSS concentration variations below 150 mg/L for Selorejo and below 100 mg/L for Sutami-Lahor. Above these ranges, the models show sign of saturation. Saturation is frequently observed for exponential and logarithmic models either at lower or higher limits. Several studies have shown similar saturation at high turbidity levels causing larger errors in those conditions (Dekker et al., 2001; Cui et al., 2013; Wu et al., 2013; and Kumar et al., 2015).

Similar to the TSS models, there is no unified Chl-a predictor that can be applied for all reservoirs. Separating into two groups: Selorejo and Sutami-Lahor, different Chl-a models were produced. For Selorejo, blue band showed highest correlation to Chl-a variations, with exponential model outperforming linear model. The exponential model was selected for further application due to its higher R^2, lower RMSE and NRSME. In other studies, blue band is mostly used as a predictor for Chl-a in oceanic waters and for low Chl-a range, however; there have also been studies where blue band was used to estimate Chl-a in inland reservoirs (Ritchie et al., 1990).

The L_NDCI index for Sutami-Lahor confirms the importance of NIR and Red band for Chl-a estimation in turbid waters. Several previous studies applied these two bands by exploiting variants of few indices for mapping Chl-a such as the 2B model with NIR_705/red_665 ratio (Gitelson et al., 2010), NDCI (NIR_705 – Red_665)/(NIR_705 + Red_665) (Mishra et al., 2016), and (Red_665 – NIR_705) (Yacobi et al., 2011). These studies used the 705 nm band in NIR region. The 865 nm was used because of the lack of a 705 nm band in Landsat. For Sutami-Lahor, even though a polynomial model represents better performance (higher R^2 and slightly lower RMSE and NRMSE), the linear model was selected to avoid saturation effect often experienced by a non-linear model. Linear model produced larger errors for Chl-a concentration higher than 70 mg/m3, increasing uncertainty in Chl-a prediction beyond that limit which corresponded to L_NDCI value of 0.1 or higher. The model might be less reliable to capture events where Chl-a concentrations are extremely high. However, considering the occurrence of high Chl-a concentration higher than 70 mg/m3 is relatively episodic in nature, the model remained to be considered for the study.

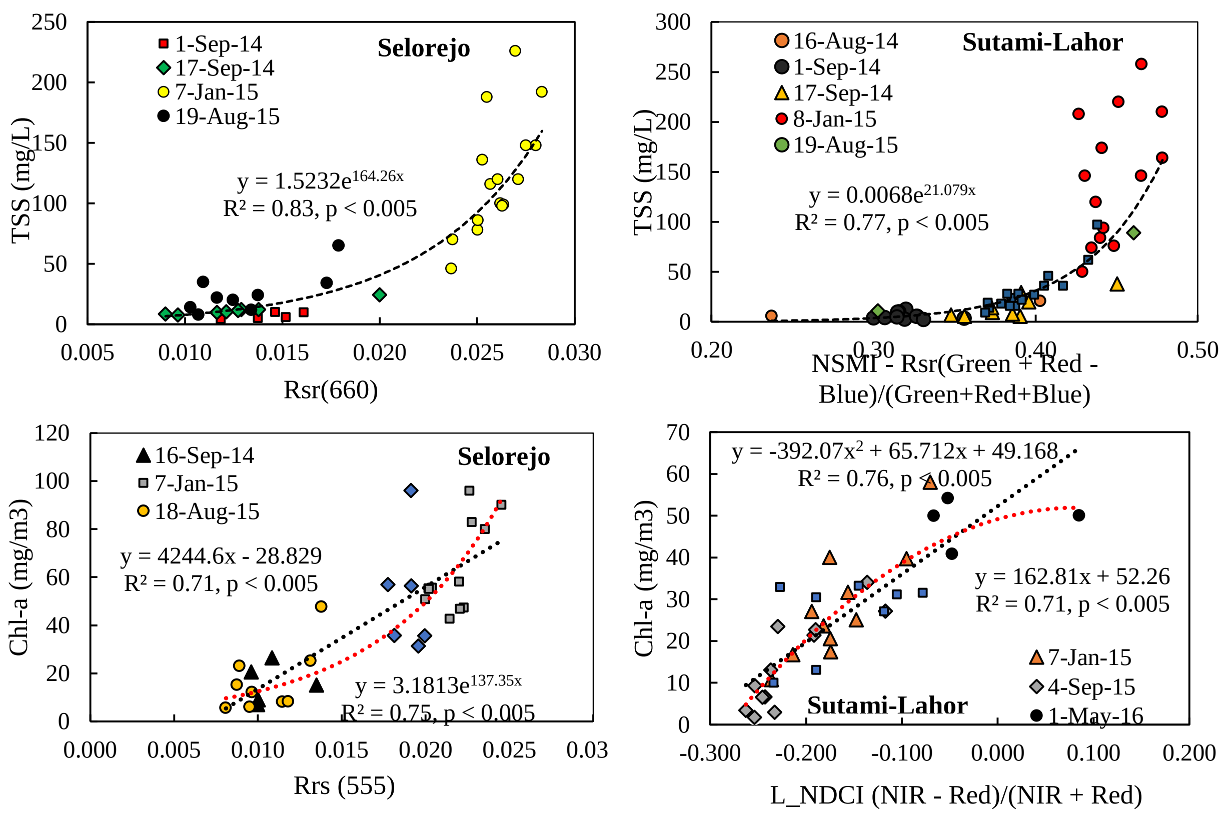

Figure 5.4. TSS and Rrs(660) relationship in Selorejo (A) and TSS – NSMI index relationship in Sutami – Lahor Reservoirs (B). Dates indicate dates when the samples were collected. Chl-a and Rrs(555) relationship in Selorejo (C) and Chl-a– L_NDCI index relationship in Sutami – Lahor Reservoirs (D). L_NDCI stands for Landsat-based NDCI. Dates indicate the dates when the samples were collected

Table 5.3. TSS and Chl-a model performance in Selorejo and Sutami-Lahor Reservoirs

Chlorophyll-a						
Site	**Model**	**R^2**	**RMSE (mg/m^3)**	**NRMSE (%)**	**MAE (mg/m^3)**	**MAPE (%)**
Selorejo	Chl-a= 4244.6*Blue - 28.829	0.71	15.48	17.16	12.12	42.91
	Chl-a= $3.1811e^{137.35*Blue}$	0.75	15.47	17.14	11.28	38.39
Sutami-Lahor	Chl-a= 162.81*RCGI + 52.26	0.71	8.76	15.56	7.02	58.29
	Chl-a= $-392.07*L\_NDCI^2 + 65.712*L\_NDCI + 49.168$	0.76	7.95	14.14	6.19	43.48

Total Suspended Sediment						
Site	**Model**	**R^2**	**RMSE (mg/L)**	**NRMSE (%)**	**MAE (mg/L)**	**MAPE (%)**
Selorejo	TSS = $1.5232e^{164.26*Green}$	0.83	26.43	11.92	15.86	39.78
Sutami-Lahor	TSS = $0.0068e^{21.079*NSMI}$	0.77	41.91	16.40	21.56	55.36

Since 2006, monthly monitoring has been conducted for three reservoirs by collecting water samples for TSS measurements. Comparison between the measured TSS collected by Perum Jasa Tirta and median TSS values estimated from the model is presented in Figure 5.5. Despite the temporal lag of 1 – 4 days between TSS monitoring dates and TSS satellite dates, the measured TSS values were in the range of estimated TSS values of each reservoir. One thing to note that the monthly monitoring is carried out on an arbitrary basis in each segment without fixed locations or stations or any information about coordinates where the samples were collected.

5.3.2 Seasonal and Inter-annual TSS and Chl-a Variability

The models were applied to Landsat 8 data for Sutami reservoir to monitor its water quality in 2014. 2014 was selected mainly because of the availability of clear images and field data. Figure 5.6 shows the spatio-temporal distribution of TSS and Chl-a concentrations in Sutami. TSS and Chl-a varied seasonally across the reservoir and the variability within the sections (upper, middle and lower) were higher during wet months. As expected, in wet months the TSS concentrations were higher than in dry months. Conversely, Chl-a concentrations were relatively higher in dry months. In 2014, TSS concentration was high in February, March and

November, while Chl-a was higher in April, May, and October. Multi peaks of Chl-a in a year indicated favorable condition for phytoplankton growth at several times during the year. This might be attributed to the differing monthly pattern of discharge, rainfall, and temperature. Several prior studies have reported similar muti-peaks such as in Passo Real and Pampula, the tropical reservoirs in Brazil (Figueredo and Giani, 2001 and Breunig et al., 2016).

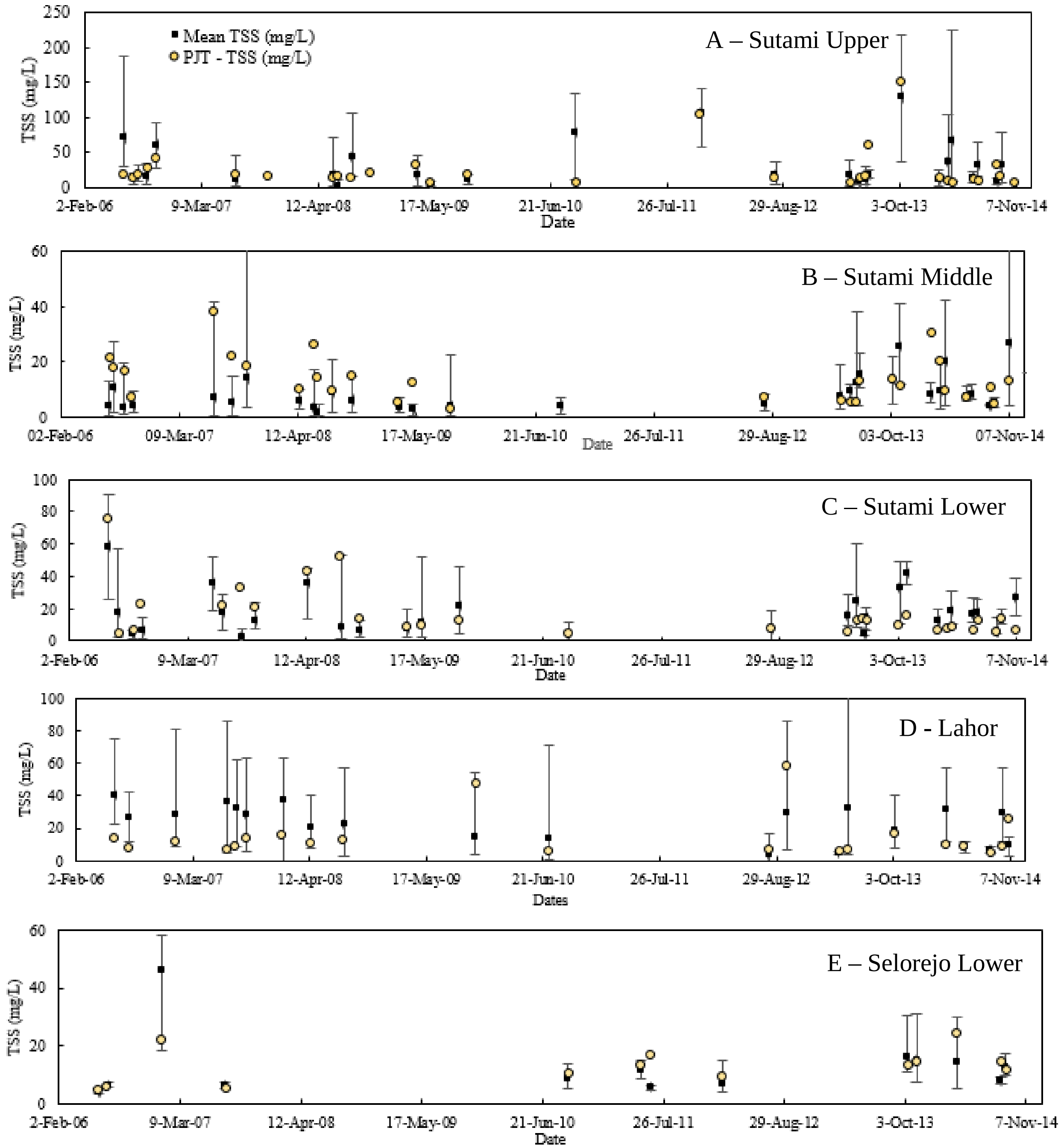

Figure 5.5. Comparison between median satellite-derived TSS and measured TSS from Sutami-upper(A) Sutami-middle(B), Sutami-lower(C), Lahor (D), and Selorejo Lower (E). Bars represent min – max values.

Analysis of median TSS and Chl-a versus monthly rainfall and inflow showed that higher TSS values in all reservoirs were associated with higher precipitation and inflow during wet months (Figures 5.7 and 5.8). Larger variability was observed mostly during wet months (December – February). All three reservoirs exhibited similar range of TSS both in dry and rainy seasons. In wet months the TSS ranges in upper segment of Sutami were much higher than in middle and lower parts, ranging from 20 mg/L to more than 100 mg/L. The Sutami middle was relatively less turbid than the lower part in dry months, with TSS ranging from 10 mg/L to 20 mg/L. Similar to Sutami, TSS concentrations in upper Selorejo close to the main river mouth were higher than the main or lower part, especially in wet months.

As opposed to TSS, Chl-a magnitudes in Selorejo were relatively smaller than in Sutami and Lahor. In this reservoir, Chl-a estimates ranged from below 10 mg/m^3 to around 40 mg/m^3. On the other hand, Sutami's and Lahor's median monthly Chl-a ranged from 25 to 80 mg/m^3. In these two reservoirs, Chl-a concentrations in dry months were generally higher than in wet months. The variability of TSS and Chl-a within reservoirs was relatively large (> 0.2) and exhibited seasonal trends. Compared to TSS, the CV of Chl-a values were lower. During wet months, the coefficient of variations (CV) usually were higher than dry months. Higher TSS variability was probably associated with seasonal physical factors where rainfall and discharge are more prevailing to sediment movement, causing turbulent conditions.

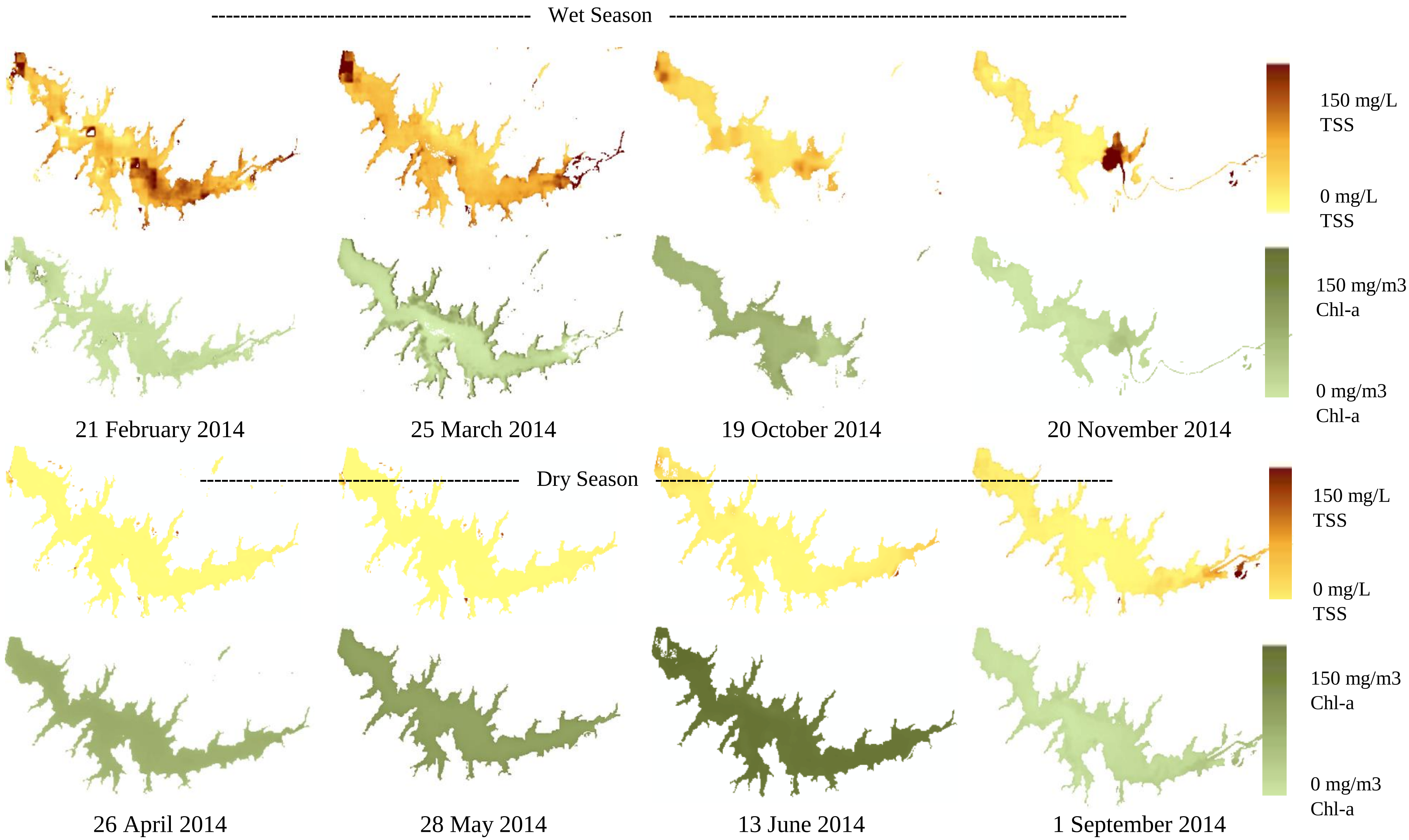

Figure 5.6. Spatio-temporal distribution of TSS and Chl-a concentrations in Sutami reservoir during 2014. Images with heavy could cover were excluded.

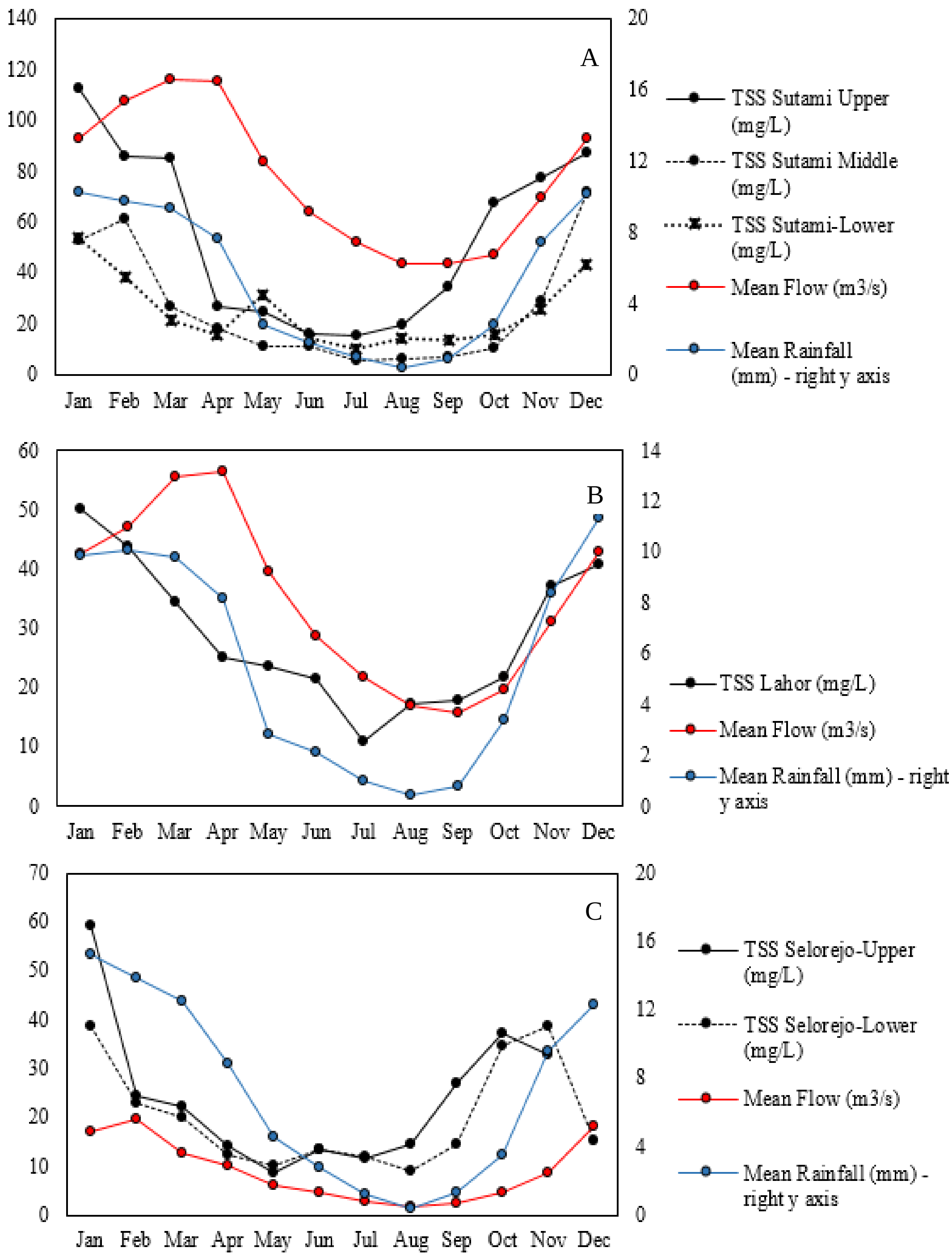

Figure 5.7. Patterns of monthly median TSS from 2000 to 2014 in Sutami- (A), Lahor (B), Selorejo (C).

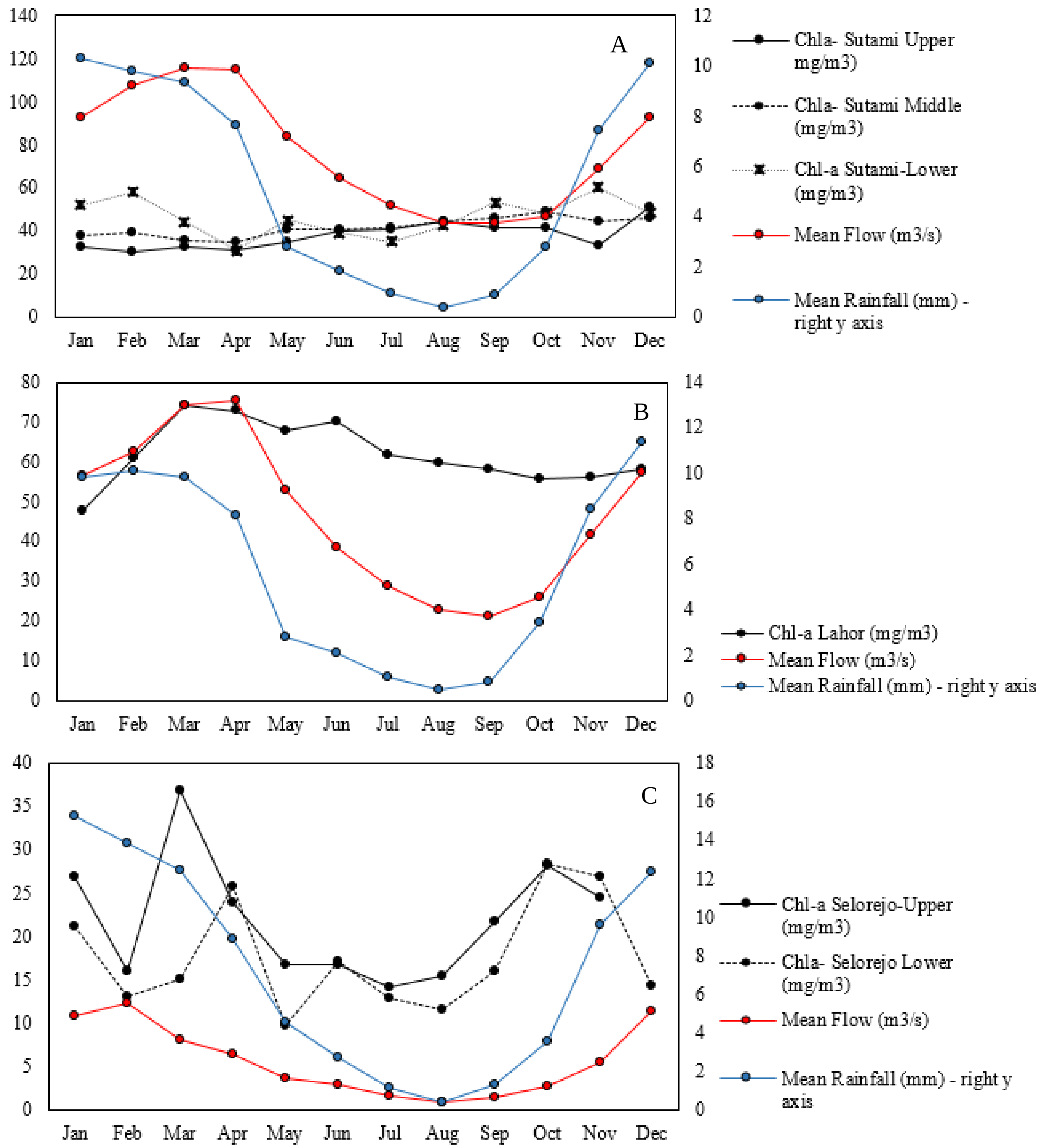

Figure 5.8. Patterns of monthly median Chl-a from 2000 to 2014 in Sutami- (A), Lahor (B), Selorejo (C).

Inter-annual Landsat-based TSS and Chl-a dynamics in three reservoirs were presented in Figures 5.9 and 5.10. In general, there were no strong positive or negative trends observed in TSS and Chl-a yearly variability. In addition, there were Mt. Kelud eruptions in 2012 and 2014 that caused elevated sedimentation to Selorejo reservoir. In 2010 and 2013, the rainfall was relatively higher, which led to the increased inflow. A major drawback in assessing the inter-annual TSS and Chl-a variability was the lack of number of usable Landsat images. Unfortunately, persistent presence of heavy cloud cover and haze seriously limited the satellite data availability, which might not have represented the general condition or the spatio-temporal variability of TSS and Chl-a observed in the reservoirs during these years. The lack of data was evident for years 2005, 2008, 2010, 2011 and 2012. Distribution of images in wet months mainly in December and January was lower than in dry months. However, this study improved our understanding of water quality variability in tropical reservoirs, especially in Indonesia, where data availability is very limited.

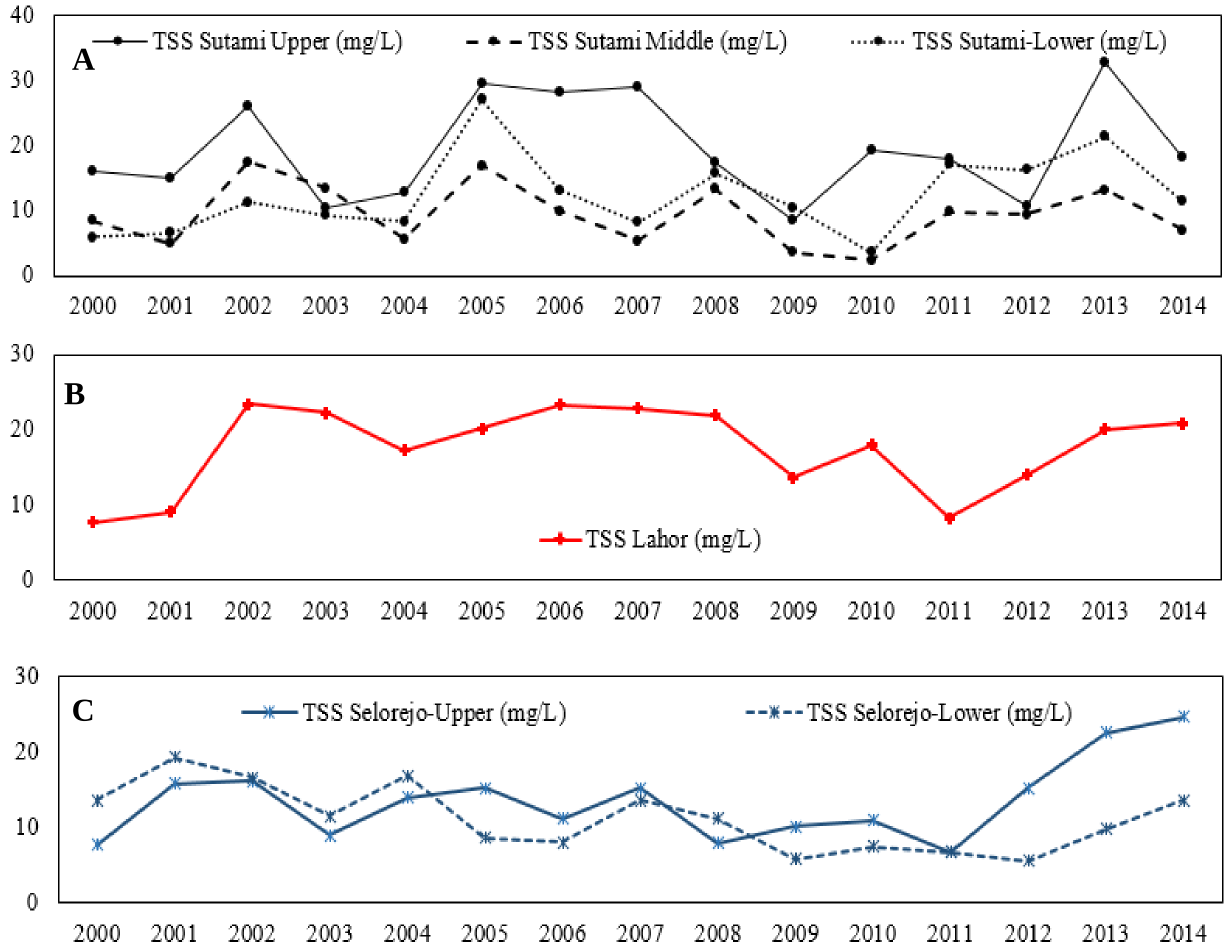

Figure 5.9. Inter annual median TSS variability from 2000 to 2014 in Sutami (A), Lahor (B) and Selorejo (C).

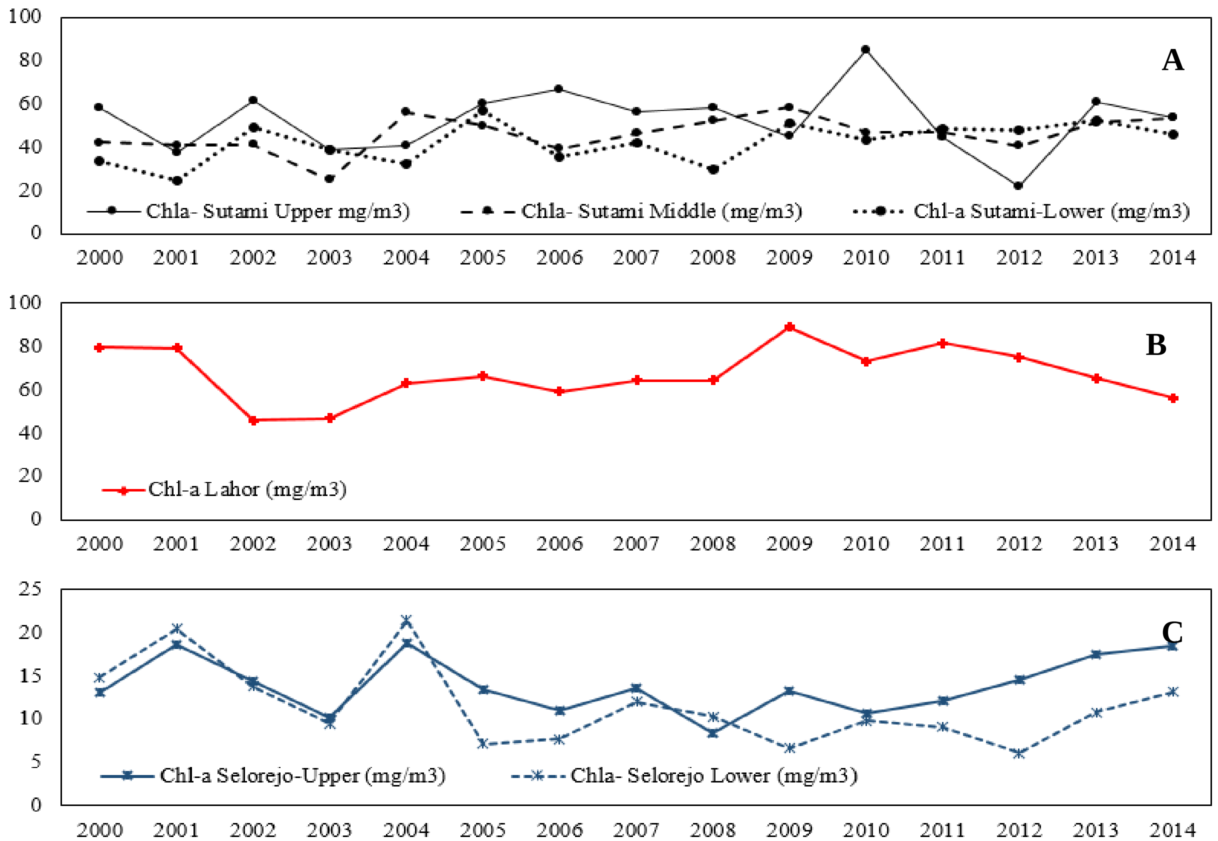

Figure 5.10. Inter annual median Chl-a variability from 2000 to 2014 in Sutami (A), Lahor (B) and Selorejo (C).

5.3.3 Factors Controlling Variability of TSS and Chl-a

Numerous studies have investigated the possible governing natural and anthropogenic factors of TSS and Chl-a variations in aquatic systems in general such as rainfall, discharge, light availability, wind, depth, temperature, dredging, land uses and associated non-point source contribution. In practice, these factors operate differently at different scales for different water bodies. In some water bodies, rainfall and discharge are more influential in regulating the TSS and Chl-a variations (Kumar et al., 2015), and in other environments, mixing and wind play a bigger role (Wu et al., 2015), high temperature drives persistent high Chl-a (Te and Gin, 2011 and Paerl and Otten, 2013), and anthropogenic factors such as nutrient runoff can also serve as the dominant driving force (Morrison et al., 2006 and Feng et al., 2012). Similar to many other tropical reservoirs, long term monthly TSS analysis for the three reservoirs showed a close association with rainfall and inflow. Elevated TSS concentrations were mostly observed during wet months and dropped considerably during dry months. Numerous studies have reported the combined role of rainfall and discharge in raising TSS in varying ecosystems such as in rivers and reservoirs (Feng et al., 2015, Zheng et al., 2015), in reservoirs (Breunig et al, 2016), and in coastal zones and estuaries (Kumar et al., 2015). Correlation between monthly median TSS and rainfall showed positive gradients for all parts of the reservoirs with R^2 ranging from 0.26 to 0.80 (data not shown). Slightly lower R^2 values (0.18 – 0.40) were observed from median monthly TSS – inflow data analysis. Weaker correlation between TSS and inflow compared to TSS and rainfall in all reservoirs implies that the inflow data may not represent the total volume of water draining into these systems. The inflow data was collected from the only available gauged tributary in each reservoir. These reservoirs especially Sutami and Selorejo have multi inlets contributing substantially to the total volume of water draining into these systems.

The upper part of Sutami is consistently more turbid than lower and middle throughout the year. This can be attributed to the closer proximity to the major river mouth where the sediment enters the reservoir. In addition, Sutami-upper is much shallower than middle and lower parts with depth varying from 3m to 10m, making this zone more susceptible to re-suspension of bottom sediment. The upper part is also subject to periodic shrinking of the surface area. The lowered depth caused by shrinking might amplify the influence of rainfall and inflow in governing TSS concentration variations in Sutami. Seasonal shrinking is also common in Lahor and Selorejo, even though the extent is less evident compared to Sutami. The upper part of Sutami usually starts shrinking in September and reaches its highest extent in November. Remote-sensing based assessment of surface area variations showed that at the highest extent of shrinking, the loss of surface area can reach up to 40% (data not shown). The lag between peak rainfall and inflow to peak surface area is about 4 – 6 months. While rainfall usually peaks in December-January and inflow peaks in February-March, the surface area peaks in May-June.

Despite being the smallest reservoir with the smallest catchment area, Lahor exhibited relatively similar turbidity to Sutami. Lahor catchment is an A-shape catchment where most of areas are steep. Almost 40% of the catchment is areas with slope higher than 15%, and most part of reservoir perimeter is surrounded by steep lands, with agriculture as the dominant land uses (Figure 5.11E). Urban and agriculture areas contribute toward the fluctuations of inorganic nutrients levels and high yield of sediments (Tong and Chen 2002; Tu, 2013; and Robinson et al. 2014). While forest is restricted to upper cone of the mountain in the watershed, agricultural land uses and settlement in the steep zones might be accelerating the erosion process and delivering sediment faster to the reservoir. Lahor is also relatively shallower than Sutami and Selorejo, making it less resistant to water mixing and sediment re-suspension. All these factors can jointly drive high sedimentation in Lahor reservoir.

In general, Chl-a in Sutami and Lahor are generally higher than in Selorejo. There could be several factors contributing to the more eutrophic condition in Sutami and Lahor. First, large numbers of fish farming cages exist in most part of these reservoirs and have been considered to be over capacity. Cage farming aquaculture systems in these two water bodies have been in existence since 1980's and the extent of cages distribution is growing at an alarming rate (Radar Malang, 2016 and Dinas Kelautan dan Perikanan DKP Jawa Timur, 2017). Several studies highlighted the negative impact of the fish farming cages in reservoirs and reservoirs. Floating caged fish farming utilize daily inputs of fish feed throughout the years. Highly nutrient laden residuals produced from the uneaten fish food and fish' faces are released into water, which then can be oxidized into soluble and consumable substances for phytoplankton (Jia et al., 2015). Tropical reservoirs and reservoirs are known as lentic environments with thermal stability, and therefore influx from high nutrient loads produced from fish farming most likely creating a favorable condition for the increased phytoplankton growth (Venturoti et al., 2015).

Current fish farming practices in reservoirs in Java show that these activities might play a role in internal nutrient loading and contribute to elevated nutrients in the water column. In Lahor reservoir, which is assumed to be in similar state as Sutami, the current farming practices contribute 3 – 8 kg fish food every day per cage containing approximately 25,000 fish (Apridayanti, 2008). A study in Sermo reservoir, Central Java, Indonesia reported that around 0.3 kg daily solid waste was produced from 1 kg of fish cultivated in cages, and 25% of this amount present in the water column and releases approximately 0.3 – 0.8 g/day of ammonium in total, 0.13 – 0.21 g/day nitrate, and 0.07 – 0.17 g/day of total phosphor (Rustadi, 2009). With this magnitude of nutrient loading, higher Chl-a concentrations in Sutami and Lahor can be ascribed to the presence of massive farming cages. Studies reported that high Chl-a concentrations were typically observed in reservoirs with cage fish farming systems (Guo and Li, 2003; Venturoti et al., 2015). For example, consistently high Chl-a concentration from January to December ranging from 75 to 300 mg/m^3 was observed in Reservoir Niusanhu, China which supported a massive amount of floating cage fish farming (Guo and Li, 2003).

Another factor that might contribute to the elevating Chl-a in Sutami and Lahor is the watershed characteristics. It is known that watershed size might not directly influence the nutrients transport but it may alter the magnitude of land use impact by modifying the spatial extent of land use that contributes to nutrient and sediment transport (Fraterrigo and Downing, 2008). Stefanidis and Paspaterigidaou (2012) found that reservoirs with higher Schindler's ratio and development index are more trophic than others. Schindler ratio defines the intensity of catchment area impact on the water body (Kolada et al., 2005). For smaller catchments, the surrounding land uses will be more influential in affecting the water quality. Lahor's land uses may play a role in amplifying the degree of eutrophication in the reservoir. For the last 20 years, agriculture has been greatly dominating the watershed and occupies the riparian zones of the reservoir. With steeper slopes dominating the riparian zones, sediment and nutrients originate from upper region will be released more intensely to the reservoir.

Overall, the long term Chl-a and TSS median values in Selorejo are relatively lower than in Sutami-Lahor. There are several possible reasons for this. First, land uses configuration in Konto catchment for Selorejo reservoir are dominated by forested areas. In the last two decades, forest has been the largest land use type in this watershed (Figure 5.11C and 5.11F). Forest-based farming practices in East Java use lower inputs of fertilizers and pesticides than agriculture-based farming practices. In addition, forest cover impedes erosion thus reduces the magnitude of runoff contributing to sediment and nutrient transport. With this land use configuration, Konto watershed delivers relatively less sediment and nutrient; and accordingly, experiences a lesser extent of sedimentation and eutrophication.

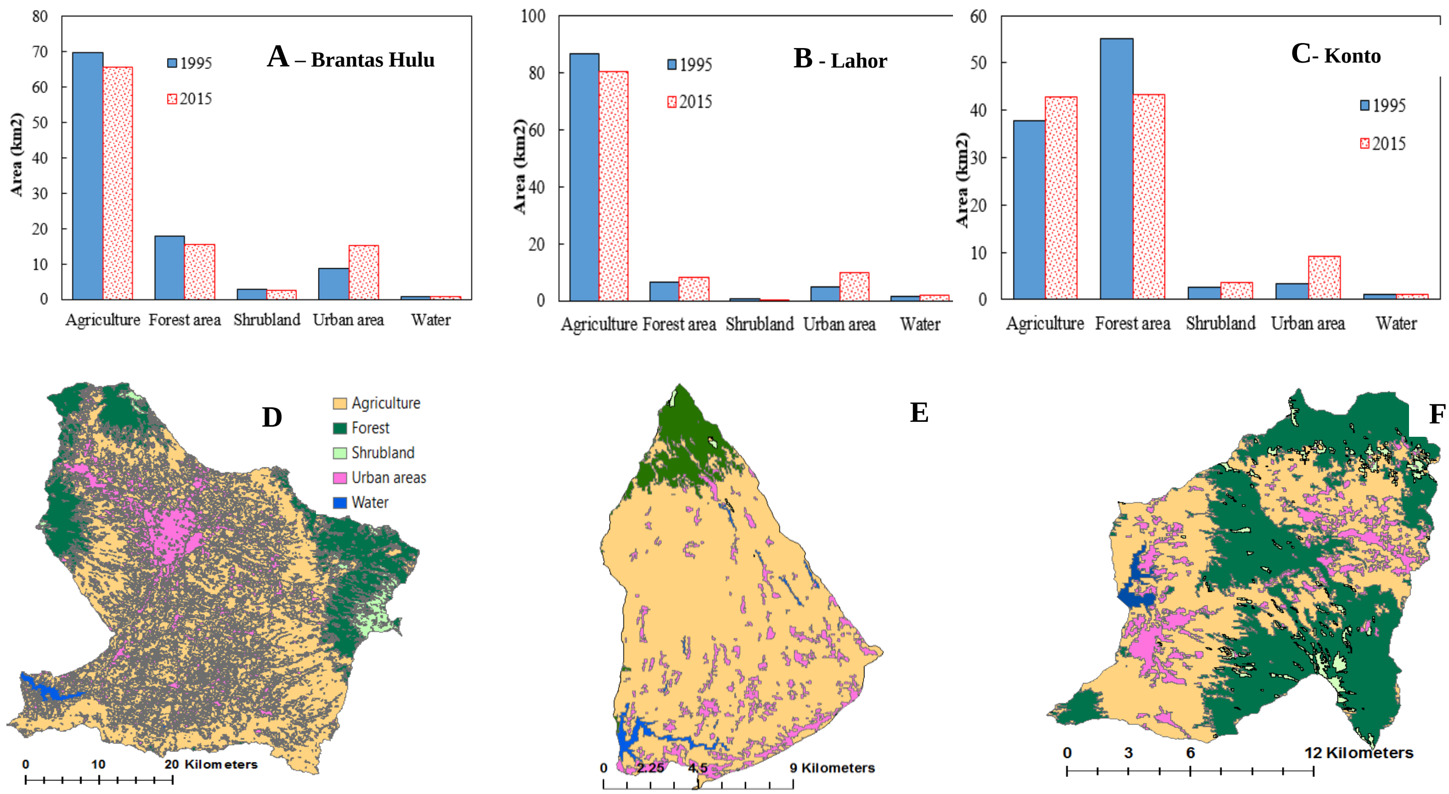

Figure 5.11. Land use change from 1995 to 2015 in Brantas Hulu (Sutami) (A), Lahor (Lahor) (B), Konto (Selorejo) (C) catchments. Distribution of land uses in 2015 in three catchments: Brantas Hulu (Sutami) (D), Lahor (Lahor) (E), Konto (Selorejo) (F). Names in bracket are names of reservoirs. Data source: Astuti et al., (in preparation, 2017).

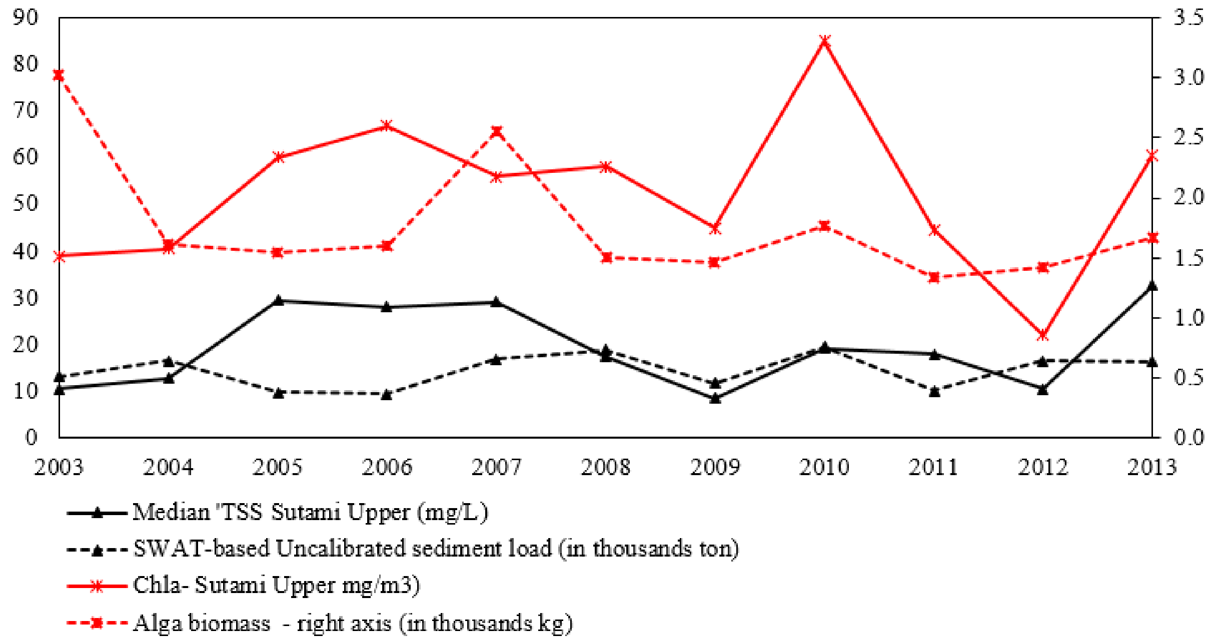

Figure 5.12. Uncalibrated SWAT-based median sediment (in thousand tons) and algal biomass transported into streams (in thousand kg), and estimated TSS and Chl-a in Sutami Upper.

Comparison of annual TSS and Chl-a with the annual SWAT-based sediment and algal biomass loading to the stream showed a weak relationship, even though in some years, similar increases and decreases were observed. This could be due to few potential limitations observed in this study. First, the sediment and algal loading from SWAT were considered indicative as they were not calibrated. In addition, the SWAT-based values were resulted from the model where point-source pollution and information of land use management practice were not modeled due to data unavailability. Second, the TSS and Chl-a variability in these years may not be representative due to the lack of usable images in some years especially in 2005, 2006, 2011 and 2012. Given these limitations, the relative impacts of each land use type to sediment and nutrient concentration have not been quantified. This may lead to few questions for further research which are; to what extent the forest cover should be maintained in a watershed to reduce sedimentation and eutrophication in a reservoir? and how to identify the best land use configuration that can accommodate forest, agriculture and urban areas without producing detrimental effects on water bodies?

Unlike temperate and sub-tropical reservoirs, tropical reservoirs and reservoirs exhibit higher stability in temperature and oscillation of total radiation throughout the year (Tailing, 1987), however; seasonal changes in precipitation can alter water characteristics, which eventually affect phytoplankton dynamics (Figueredo and Giani, 2001). Studies also show that light is a crucial factor in modulating phytoplankton growth. The median monthly Chl-a variations in Sutami and Lahor showed slightly elevated concentrations in drier months (April – September). In this period, the rainfall and runoff reduce significantly, which results in lower sediment loading. During these months, the water level increases and peaks between May and June for Sutami, which may be caused by the lag-effect and reservoir operation. With reduced runoff and higher water level, water clarity increases which in turn facilitate higher rate of photosynthesis and proliferation of phytoplankton growth. Despite the lack of data on residence time, inflow during dry season reduces greatly, implying a higher residence time. Similar studies have shown that high Chl-a is also associated with higher residence time (Soares et al., 2012 and Wang et al., 2013). During this period, the deposited riverine inputs from previous higher discharge can be sequestered by phytoplankton (Paerl and Otten, 2013).

Drier months appear to provide favorable condition for phytoplankton development in Sutami and Lahor. These reservoirs are located at lower elevation (210m). Compared to Selorejo (620m), the air temperature is Sutami-Lahor is slightly higher. Throughout the year, fluctuation of median monthly temperature is minimal, ranging only from 24.29°C to 25.74°C.

In Selorejo, median monthly temperature ranges between 22.68 to 24.07°C. Some phytoplankton taxa maintain ability to grow optimally in high temperatures. A study from Kranji, a tropical reservoir in Singapore reported that high temperatures in a reservoir from the equatorial belt can preserve continuous high level of Cyanobacteria, or Chl-a concentrations with levels higher than 50 mg/m3 (Te and Gin, 2011). Median monthly Chl-a estimates in Sutami-Lahor showed that multi peaks of Chl-a can develop mostly during dry months (April – September). These peaks could be observed in May, June or September. This fluctuation might be a result of interaction among different factors that operate seasonally. For example, both rainfall and discharge elevate in wet season, but the peaks of each do not occur in the same period. Rainfall peaks in December or January, while inflow peaks in February-March. For temperature and wind, the temperature peaks (slight peak) in October – November, while wind peaks in July – August. However, anthropogenic factors might also drive episodic eutrophication. Local news reported instances of high loads of industry waste released by factories in Upper Brantas, which were then suspected to be the cause of severe eutrophication in Sutami (Liputan 6, 2004; and Tempo, 2016). It highlights the challenge in managing point-source pollution in regions where pollution or waste monitoring scheme is limited.

Algal abundance analysis carried out from water samples in September 2014 showed that Cyanophyta highly dominated phytoplankton species in Sutami and Lahor, 40 – 90% of the total cell count, while Chlorophyta and Cyanophyta showed similar abundance (30 – 80%) in Selorejo (data not shown). It is worth noting that seasonal phytoplankton changes are acknowledged and the samples collected from one single date may not be representative. However, the available data can provide a snapshot of differing phytoplankton compositions in these reservoirs. A laboratory based study showed that phytoplankton types show great variations in time-lags as a response to nutrient pulses, from 0 to 72 hours (Coyos, 1986), while a MODIS-based study in Reservoir Pontchartrain showed a lag of around 42 days between peak of TSS and Chl-a (Mishra and Mishra, 2010). The available median monthly TSS and Chl-a variations are not able to capture daily or weekly changes of these parameters, and therefore it is difficult to conclude the onset and end of Chl-a and TSS peak periods and how they interact on a daily basis. Differing dominant phytoplankton types and composition in Selorejo and Sutami/Lahor implies differing lag response of phytoplankton to nutrient pulse, rainfall, temperature and water level. Co-varying TSS and Chl-a in Selorejo might imply that the phytoplankton has a shorter lag response time to nutrient in this reservoir than in Sutami/Lahor.

In general, slightly opposite relationship between TSS and Chl-a was observed in both Sutami and Lahor. Inverse relationship between these two water quality parameters are common and were reported by many studies (Zheng et al., 2015; Breunig et al., 2016; and Kumar et al., 2016). In Sutami – Lahor, this might be attributed to the longer lag between rainfall peak (January – February), discharge peak (April), and water level peak (May -June). Conversely, TSS and Chl-a exhibits concurrent patterns in Selorejo, which has also been reported at other sites such as in an Indian Lagoon before a hurricane landfall (Kumar et al., 2016) and Poyang Reservoir, China (Feng et al, 2015). In situ TSS and Chl-a data show a considerably positive correlation in Selorejo. This can suggest that sediment in Selorejo is mostly organic in composition, either originating from algal decomposition or from the organic materials contained in the soil. No supporting data are available, however; the geologic setting and edaphic materials show association of soils with high organic content.

Another possible explanation of differing TSS - Chl-a relationship is the level of nutrients carried by sediment particles. A related study on effect of turbidity on algal growth showed that

Chl-a in Fox River escalated with the increase of TSS, while the opposite condition was observed in Illinois River (Wang, 1974). This study concluded that increased Chl-a due to increased TSS in Fox River was because the sediment was far less polluted with heavy nutrients and thus did not create a limiting factor for phytoplankton growth. Similar to that study, it is possible that the heavy pollutant concentration in Selorejo was less than in Sutami-Lahor although there is no data to test this hypothesis. The presence of cage farming in Sutami-Lahor was suspected to amplify the nutrient levels. Additionally, heavy pollutant may have contributed to the worsening reservoir condition. Local news often reported the violation by factories for releasing untreated waste in a significant amount to Brantas watershed (Liputan 6, 2004; Tempo, 2006; and Radar Malang, 2016). One difference between Selorejo and Sutami-Lahor is the presence of water hyacinth (*Eichhornia crassipes*). In Selorejo, *E. crassipes* grows continuously throughout the year and becomes more severe between June – August. Elevated Chl-a is often related to increased nutrients providing more food resources for algal growth. However, water hyacinth is a tropical plant that is capable of assimilating nutrients, metal ions, and organic pollutants (Malik 2007; and Nesterenko-Malkovskaya et al., 2012; and Zhent et al., 2016). Because of this ability, water hyacinth is used as a bio-control to remove excess nutrient in places like Reservoir Daichi (Wang et al., 2012). Because it is such an effective nutrient consumer, it might serve as a barrier for algal growth. Massive floating mat developed due to intense hyacinth growth causes significantly reduced light availability for photosynthesis and thus curtails the development of algae (Gichuki et al., 2012). Hyacinth was also found in Sutami-Lahor but the extent was far less substantial than in Selorejo. There are several possible reasons why hyacinth distribution in Sutami-Lahor is negligible. First, reservoir morphometry plays a role in affecting hyacinth distribution. Sutami is a deeper reservoir than Selorejo. *E.*

crassipes's roots require a stable anchorage for a steady growth (Ngari et al., 2009). With a deeper substrate in Sutami, the chance of hyacinth to grow optimally is smaller. Unfortunately, the presence of hyacinth and fish cage farming couldn't be mapped using remote sensing due to their scattered distribution and coarse spatial resolution of LANDSAT images.

A study in Greece concluded that reservoirs with higher development of volume index (DVI) showed a greater extent of macrophyte distribution. DVI basically defines the ratio between mean and maximum depth, indicating the shape of the bottom (Béné et al., 2009). In the Greece's study, it was found that reservoirs with higher DVI generally exhibit gently littoral slopes, which are favorable for hyacinth growth (Stefanidis and Papasterigiadou, 2012). Compared to other reservoirs, the DVI of Selorejo is the highest, suggesting a more favorable setting for hyacinth development. Second, hyacinth preferred a medium that is rich in organic bottom (Ngari et al., 2009). Geologic and edaphic settings of Selorejo might support the development of organic soils and thus it is likely that the sediment deposited in Selorejo reservoir and original bottom materials are also richer in organic substances. Despite the likely positive impacts of hyacinth presence, studies also reported the negative from its uncontrollable growth such as clogged shipping lanes, reduced drinking water quality and diseases vector medium (Güereña et al., 2015). Currently, hyacinth grows naturally without any human-induced modification such as removal or harvesting. Considering the potential negative impact of overgrown hyacinth, thoughtful consideration based on scientific assessment should be made to determine to what extent the hyacinth should be naturally permitted to grow.

Differing TSS and Chl-a variations in these three reservoirs highlight the variability of natural and anthropogenic drives in Indonesian reservoirs. This is also supported by variability in watershed characteristics. Findings from this study show that eutrophication and sedimentation can be highly site specific. Influence of internal factors such as cage farming, macrophyte growth, reservoir operation and internal natural reservoir conditions interfere with the influence of external natural and anthropogenic factors such as deforestation, urban development, variations in temperature and precipitation. Efforts in reducing sedimentation and eutrophication should also consider these natural and anthropogenic factors and how they affect the sediment and nutrient level in these reservoirs. Considering the economic importance of cage fish farming, the efforts for managing nutrients might be more complicated. Finding a trade-off between economic and ecologic goals is of importance, and thus further research is needed to investigate to what extent the cage farming might affect eutrophication in the reservoir. Similar questions apply to land uses in the watershed. Findings from this study support the previous studies which showed agricultural dominated watersheds' close positive association with sedimentation and eutrophication, and negative association with forest cover. However, what land use configuration that can best accommodate both economic and ecologic objectives is still highly unknown. There is still much research needed for filling the gap.

5.4 Conclusion

Existing TSS and Chl-a models world-wide did not provide satisfactory results, indicating the highly variable site-specific nature which might limit the models applicability. Recalibrated models for TSS and Chl-a produced better results for Sutami-Lahor and Selorejo when applied separately, implying considerable differences in ecological and optical characteristics between these waterbodies. Both TSS exponential models have limitations in capturing very high level turbidity due to saturation effect. However, long-term TSS and Chl-a analysis together with other biophysical factors such as rainfall, inflow, wind and temperature showed that the models was helpful in providing insights about TSS-Chl-a interaction in the reservoirs.

Spatio-temporal variability of TSS and Chl-a in Sutami, Lahor and Selorejo represents differing interactions among natural and anthropogenic factors, with upper segment of reservoirs are more turbid. This section is also more dynamic due to seasonal shrinking of surface area. While response of TSS to rainfall, discharge and temperature are similar in all reservoirs, the Chl-a patterns showed differing response between Sutami-Lahor and Selorejo. In Selorejo, Chl-a increased with increased turbidity indicating the differing role of TSS as a nutrient source than as light inhibitor. The presence of hyacinth in Selorejo was assumed to help remove heavy nutrients and pollutant trapped in sediment, making eutrophication less severe than in Sutami-Lahor. In these reservoirs, high non-point sources from surrounding watersheds together with massive distribution of cage fish farming amplified the nutrients availability for supporting persistent eutrophication. The amount of nutrients originated from cage farming or runoff is still unknown. Similarly, the amount of nutrients and pollutants removed by hyacinth to help lessen the eutrophication is also unknown. All these findings merit future research for a more comprehensive understanding of the dynamics of ecological and anthropogenic states in the reservoirs and their watersheds. The study, despite its limitations due to limited unequal coverage of data, frequency of in situ data, and uncertainty in atmospheric correction and cross calibration, is considered valuable to enrich one's understanding about the influence of external and internal forcing in controlling the water quality in tropical reservoirs, especially in the watersheds of developing countries such as Indonesia. The study provided an insight that variations in ecologic and anthropogenic conditions between reservoirs and watersheds should not be overlooked. Reservoir management should consider variability of the ecological and anthropogenic conditions in the draining watershed. Future research would include model refinement, improved atmospheric correction procedures, and spatio-temporally dense monitoring scheme which in combination will enhance the opportunity of harnessing remote sensing technologies for monitoring the degradation of inland waters in Indonesia.

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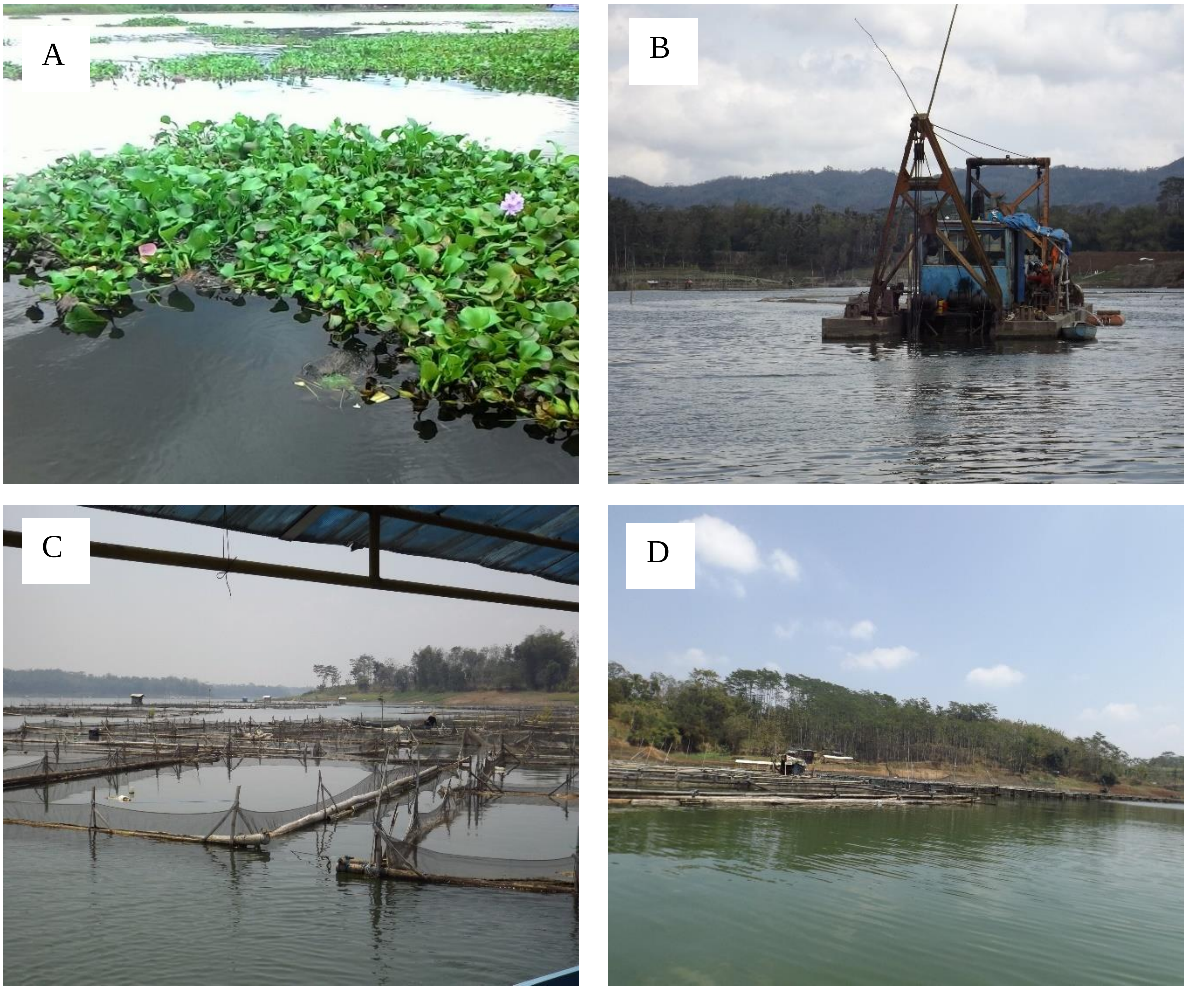
Appendix 5.1. Performance of existing TSS and Chl-a models tested using combined datasets from three reservoirs

No	TSS Model	Source	R^2	No	Chl-a Model	Source	R^2
1.	0.00522* Exp(1002*(R645 – R858))	Hu et al., 2004	0.01	1.	Ln(chl) = - 43.54 + 15.97*(Ln(R645))	Dekker and Peters, 1993	0.26
2.	Exp (2.15*R_{645}/R_{555}) *0.95	Bi et al., 2009	0.18	2.	((R485+R555)/R855)-R485*100 + 5) ^-5.05	Cox et al., 1998	0.31
3.	-0.0907 * Log(R_{645})/Log(R_{555}) ^2 + 0.2636* Log(R_{645})/Log(R_{555}) + 1.5436	Chen et al., 2009	0.01	3.	OC4 model; Chl = $10^{a0 + a1*R + a2*R2 + a3*R3)}$ + a4	O'Reilly et al., 2000	0.25
4.	10^((Log10(R_{645})/Log(R_{555})) - 0.8288)/0.4339	Chen et al., 2011	0.08	4.	61.324*(R705/R855) - 37.94	Gilerson et al., 2010**	0.25
5.	0.0567 Exp (7.0174 * R_{654}/R_{469})	Lathrop, 1991	0.29	5.	14.039 + (86.115*(705-665)/(705 + 665)) + 194.325*(705-665)/(705 + 665)^2)	Mishra and Mihsra, 2012	0.25
6.	0.5901 Exp $^{(R555 + R654)/2*24.092)}$	Dekker et al., 2002	0.23	6.	14.039 + 86.115 * L_NDCI + 194.325 * (L_NDCI)2; L_NDCI = 3.4374 * L_FAI + 0.212	Hu, 2009	0.28
7.	1.1246 Exp $^{11.502*R858/R555}$	Doxaran et al., 2003	0.14	7.	29.41 - 31.77*C2	Wang et al., 2010	0.27
8.	7167 * Rrs645 - 42	Qian and Rossiter, 2008	0.29	8.	11.18*R485 - 8.96*R555 - 3.28	Giardino et al., 2001	0.01
9.	-1.91+ 1140.25*Rrs645	Miller and Mckee, 2004	0.29	9.	Ln(chl) = 0.52*ln(R485)-0.79ln(R555)	Brivio et al., 2001	0.01
10.	1.063*Exp(27.859*R645)	Cui et al., 2013	0.31	10.	Log(chl) = -9.5126 + 12.8315 *(LogR485/LogR645)	Han and Jordan, 2005	0.01
11.	0.0567Exp $^{7.0174 * R645/R469}$	Fan, 2014	0.24	11.	116.98*(R855/R655) - 29.709	Duan et al., 2007	0.25
12.	556.98* R858/R469 – 30.272	He et al., 2013	0.15	12.	48.396+1142.22*R555 - 147.624*R645	Wang et al., 2006	0.28
13.	8.602 – 1805.26* R858 + 900713.14*R858^2	Kong et al., 2015	0.25	13.	Ln(chl) = 5.001*(R665/R485) -1.855	Torbick et al., 2008	0.01
14.	1149.1$(R645/R858)^2$ - 1918.6(R645/R858) + 802.26	Liu et al., 2006	0.15	14.	Ln(chl)=1.974(ln(R645) + 11.556	Allan et al., 2011	0.23
15.	235.09*((R858/R555) ^ 1.247)	Song et al., 2014	0.12	15.	0.0937*(1/R665 – 1/R485) *1/R855 + 5.4003	Sing et al., 2014	0.29
16.	-29.707* ((R_{469} – R_{645})/(R_{469}+ R_{645})) + 41.86*((R_{469} – R_{645})/(R_{469}+ R_{645}))^3 + 11.358	Zhang et al., 2010	0.38	16.	(-115.95*R855) + (19.31*R655) + 4.56	Yip et al., 2015	0.32
17.	0.8476*Exp$^{24.242*R645}$	Chu et al., 2009	0.31	17.	-323.81 *(R855/R665^2* (1179.7*v-120.87))	Watanabe et al., 2015	0.01
18.	1.8*Exp(19.11*(R645+R858))	Hudson et al., 2013	0.28	18.	-2.61 + 0.57*(R655/R485) *2	Nazeer et al., 2015	0.05
19.	13181*R645^2 – 1408.6*R645 + 44.15	Kumar et al., 2015	0.19	19.	Log(chl)=125121((logR645/LogR858) + 1.5) ^-13.8	Huang et al., 2011	0.01
20.	9.65*Exp(58.81*R645)	Shi et al., 2015	0.31	20.	CI ≈ Rrs555 – 0:5(Rrs443 + Rrs670)	Hu et al., 2012	0.25

**) modified bands – using available Landsat bands in the same band region

Appendix 5.2. Pictures of reservoirs condition in Selorejo (A), dredging in Sutami upper (B), fish cage farming in Sutami-middle part (B) fish cage farming in Lahor (D).



CHAPTER 6

CONCLUSION

Increasing problems in water resources such as accelerated sedimentation, drying-up springs, and downstream eutrophication have been reported in Indonesian reservoirs, especially in Java. Increasing pressure on watershed due to land use land cover (LULC) change has been considered as the cause of the degrading watershed condition. Studies from other regions have shown that LULC play a role in altering hydrological response including surface runoff. Close association between sediment and nutrients delivered to water bodies suggest the need of runoff management. On the other hand, large variability of natural and anthropogenic factors from different sites suggests that the relationship between LULC change and water resources is site-specific. To support a sound watershed management, a good understanding about LULC change, its drivers and its likely impact on runoff is required. Unfortunately, these kinds of information and studies have been lacking in Java and Indonesia as a whole. This study aims at improving our understanding of the relationship between LULC change, hydrological response, runoff generation and water quality (TSS and Chl-a) in Java by using Upper Brantas as a case study. Three separate studies were carried out with specific objectives.

The first study investigated how LULC have changed in the last two decades and what were the likely drivers as well as implication for water resources. Findings from the first study revealed that mixed-dry land agriculture remained the prevailing land use type in Upper Brantas. Most LULC types showed a slight decrease except for settlement or urban areas. Compared to the original extent in 1995, forest has reduced about 4%. Similarly, a 4% reduction of agricultural land uses that comprise mixed-dryland agriculture, rice field, and plantation was observed. The loss of forest and agricultural land appeared to compensate for the development of urban areas. In 21 years, this particular land use type has almost doubled in size. The major LULC change pathways or trajectories were forest to mixed-dryland agriculture, dryland-agriculture to rice-field or planation, and rice-field to urban. These findings confirmed the results of previous studies that agricultural expansion is the first phase of deforestation, which then leads to development of urban areas. Similar to most typical developing countries, improved accessibility such as roads and infrastructure triggered forest and agricultural conversion to urban areas. Current agricultural practices, physical vulnerable conditions of the watershed, rapid and uncontrolled urbanization could be the continuing contributors of water resources degradation. The demographic, economic, technologic, political/institutional and socio-cultural factors contributed to shape the landscapes in a more diffuse way. Recent enactment of regional autonomy intended for better local management has not been proven sufficient. Lack of supporting policy instruments, conflicting policies, complex social and cultural institution, and lack of watershed oriented management budget jointly became the challenges in managing water resources issues.

Considering runoff as the major factor in controlling sediment and nutrient yield, the second study examined the impact of LULC change oh hydrological response with surface runoff as the main focus. In this study, a subset of Upper Brantas was used as the area for examining the LULC change impact. Similar to the whole Upper Brantas, this subset region experienced a significant increase in settlement and slight decrease in forest and agricultural land uses. The changes in long-term average of runoff, water yield, ground water and evapotranspiration were subtle with magnitudes less than 40 mm. Among these hydrological variables, runoff became the most affected variable having the largest relative change. Changes in these LULC types resulted in moderate changes in long-term average runoff (+8%), water yield (+0.28%), groundwater (-1.8%), and evapotranspiration (-1.15%). Further assessment revealed that changes in runoff were mostly associated with changes in forest, dryland agriculture and settlement. To examine the relative impact of LULC change on runoff, gradual LULC change simulation with four major LULC change trajectories were carried out. Results showed a linear relationship between the amount of removal of each LULC change trajectory and runoff generation. Conversion of forest to agriculture and urban imposed a greater increase in runoff than conversion of dryland agriculture or rice field to urban.

With increasing urbanization, industry and agricultural intensification, impact of increased runoff will be more critical for water bodies due to associated nutrients and sediments. Upper Brantas has been subject to increased sedimentation and eutrophication. TSS and Chl-a were considered part of the most important water quality parameters, being proxies for sedimentation and eutrophication assessments. The third study assessed the factors governing TSS and Chl-a in reservoirs, examined the interaction between the two variables. Three reservoirs namely Sutami, Selorejo and Lahor were used as study sites for gaining deeper insights about TSS and Chl-a variability as well as watershed characteristics. Remote-sensing based modeling was used as the approach for estimating spatio-temporal TSS and Chl-a variability.

Results from the third study showed that in all reservoirs, TSS co-varies with rainfall and river discharge. This confirms the role of runoff as the main modulator of sediment found in many studies. In contrast, Chl-a seasonal pattern showed a possible influence of localized condition in each reservoir. While TSS and Chl-a generally co-vary in Selorejo, inverse relationship was observed in Sutami and Lahor. Higher Chl-a in Sutami-Lahor during dry season might have been been resulting from reduced turbidity, stable temperature and water level, lower wind in early dry season. Differing TSS – Chl-a interaction revealed a likely role from internal reservoir condition, watershed characteristics and point-source pollution. The presence of extensive hyacinth in Selorejo and massive cage fish farming in Sutami-Lahor appeared to affect algal proliferation differently. Hyacinth known for ability to absorb nutrients in the water column might be lessening the eutrophication in Selorejo. In contrast, frequent eutrophication in Sutami-Lahor could be attributed to massive fish farming cages in these reservoirs combined with potential non-point source pollutants within the watershed. Comparison between reservoir's characteristics showed that both ecological factors from external environment such as climate and hydrological as well as watershed properties, and internal conditions of reservoirs may interplay in determining the degree of eutrophication and sedimentation in each reservoir.

Overall, the three studies were considered helpful to provide baseline information on relationship between LULC change and water resources in Java, Indonesia. Findings show that issues in LULC change in Java mainly involves forest loss to agricultural expansion and farm loss to settlement development. Increased runoff associated with these conversions appeared to be the most evident impact. Varying interaction between TSS and Chl-a in three reservoirs suggest that sediment and nutrient relationship in water bodies might not simply be related to external ecological and anthropogenic factors. The findings from the third study also suggested that efforts for sedimentation and eutrophication management cannot be generalized. Given varying watershed conditions, water resource management should be based at watershed level, which has been recently adopted. Considering this, challenges for future management are how to deal with rapid uncontrollable settlement development, agricultural land use practices that reduce surface runoff, forest protection to reduce encroachment of agricultural expansion, point-source management, and settlement that accommodates more green spaces for runoff reduction in the watershed.

Substantial new information about the watershed was generated by this study. However, there has also been considerable information, which remains unknown or poorly understood. Despite the useful findings, limitations are acknowledged in this study. The LULC mapping approach was capable of providing generic land use information. Nonetheless, large variability in particular classes such as mixed-dryland agriculture and dryland-forest was observed. A more detailed LULC mapping that allows species discrimination will be extremely useful for providing in-depth change analysis. The data used in the first study were derived mainly from publicly available resources. This led to difficulties in obtaining detailed depiction of LULC change and in isolating and quantifying every single change drivers and change trajectories. Further studies are required for in-depth analysis and to produce deeper information especially about the relative importance of LULC drivers covering direct and indirect drivers. Second, findings from the second study were proven helpful for showing the full potential of SWAT as a modeling option for developing countries with data scarcity for future studies. In the second study, the modeling was carried out solely by calibrating and validating the streamflow due to unavailability of water quality and land management practices data. Acquisition of water quality and land management practices data would allow comprehensive SWAT-based studies for investigating the sediment and nutrient yield in future. This would provide a more reliable framework for dealing with sedimentation and eutrophication issues.

Remote sensing has been proven to be a potential tool for water quality assessment including TSS and Chl-a. Yet, for a more robust application, remote sensing based water quality models should be refined and tested for its spatio-temporal stability. The second study highlights the importance of routine and proper water quality data collection for long-term ecological studies. Improvement can include but not limited to additional samples covering more wet and dry seasons, the use of semi-analytical and quasi-analytical approaches, as well as investigation involving the potential use of cloud-penetrating images such as LiDAR and RADAR images. This would be helpful in providing more complete data for cloud prone tropical regions like Indonesia. At the same time, a robust remote sensing modeling will support a more accurate spatio-temporal analysis. Given the fact that TSS and Chl-a variability are related to both intrinsic and extrinsic factors of reservoirs, the second study relied on visual and qualitative assessment of reservoir and watershed characteristics. This was helpful for gaining insight about the dynamics of TSS and Chl-a within reservoirs. However, the study was not able to quantify the relative contribution of internal sediment and nutrient loadings that can possibly mask the influence of external ecological and anthropogenic factors. Integration with lake/reservoir system modeling in future would allow better understanding of the complexity of TSS and Chl-a dynamics within water bodies.