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DOI
10.4233/uuid:bf57a478-fdd6-4c1e-afe6-921a02599781

Publication date
2024

Document Version
Final published version

Citation (APA)
Maheng, M. D. (2024). *Impact of land use and land cover changes on urban temperature, rainfall, and flooding: a case study of Jakarta*. [Dissertation (TU Delft), Delft University of Technology]. IHE Delft Institute for Water Education. https://doi.org/10.4233/uuid:bf57a478-fdd6-4c1e-afe6-921a02599781

Impact of land use and land cover changes on urban temperature, rainfall, and flooding

A case study of Jakarta

Muhammad Dikman Maheng

IMPACT OF LAND USE AND LAND COVER CHANGES ON URBAN TEMPERATURE, RAINFALL, AND FLOODING
A CASE STUDY OF JAKARTA

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DISSERTATION

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen,
chair of the Board for Doctorates
and
in fulfilment of the requirement of the Rector of IHE Delft
Institute for Water Education, Prof.dr. E.J. Moors,
to be defended in public on
Monday, 28 October 2024, at 12:30 hours

by

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This dissertation has been approved by the promotor and copromotors.

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This research was conducted under the auspices of the Graduate School for Socio-Economic and Natural Sciences of the Environment (SENSE)

Published by IHE Delft Institute for Water Education
www.un-ihe.org

ISBN 978-90-73445-66-6

In memory of my beloved late mother, Wa Ode Murni

“You have to go and make us proud, do not worry, I will be okay here”

Kendari, 13 February 2017

ACKNOWLEDGMENTS

Alhamdulillah, all praise and gratitude be to Allah. I believe that I have been given the strength, patience, and perseverance to complete this PhD study. I convey my prayers and greetings to the Prophet Muhammad (PBUH), his family, his companions, and muslims.

My sincere gratitude goes to my promotor, Professor Chris Zevenbergen, who encouraged me to take PhD when we met for the first time during his field visit for the MARE Asia project in 2014 in Kendari, Indonesia. Your guidance, motivational insight, and encouragement have played a vital role for my PhD research. Thank you very much for your warmth welcome to my family when they arrived in Schipol for the first time that we always remember.

I would like to extend my gratitude to my co-promotors, Assela Pathirana and Biswa Bhattacharya. Your insightful feedback, constructive criticism, challenges, and encouragement have been instrumental in improving the quality of my research as well as broadening my perspectives. Assela, thank you very much for your guidance and discussion which helped me to develop this topic from the very beginning, and your assistance with the UrbClim and the WRF setup, high-performance computing, and Python coding. Biswa, many thanks for your willingness to join the supervisory team, the inspirational, reflective talks and suggestions for improving this research. I also would like to thank Ishara Ducton, my MSc guidance student, for the insightful discussion during UrbClim simulation for Colombo.

My sincere appreciation also goes to the Government of Indonesia in particularly the Ministry of Research and Education, and the Ministry of Finance for providing scholarship through BUDI - LPDP (Indonesia Endowment Fund for Education). I could not have gone through the PhD research without its adequate financial support. I would like to express also my full gratitude to Universitas Muhammadiyah Kendari for giving me a chance to leave the university for pursuing my PhD.

Special thanks to Vito Belgium that provided the UrbClim model for my PhD research, which enabled me to simulate air temperature with a high resolution of hundred of meters. I wish to acknowledge BMKG Indonesia and my colleagues at the BMKG office Jakarta, pak Siswanto, who provided the meteorological data of Jakarta as well as fruitfull discussion about urban climate during my field visit at the BMKG office, as well as for the support during the publication process.

My special gratitude goes to my colleagues at the Flood Resilience Group (FRG) of IHE Delft: Berry, Mohan, William, Maria, Ha, Hieu, Polpat, Mya, who provided critical insight from different perspectives for my PhD research. Mohan, thank you for being my English advisor who was always available for helping me for the English correction. Hieu, thank you for the discussion, coffee, snacks, and lunch on every Thursday. To my PhD

colleagues, Aftab, Aklan, Gani, El Ghandour, Ruknul, Thaha, Mohaned, Nasser, and those cannot be mentioned here. Thank you very much for keep helping and inspiring each other throughout this PhD journey.

Thank you very much to the Indonesian students at IHE Delft and TU Delft, Keluarga Muslim Delft (KMD), and Indonesian families in Delft, Mas Agung and family, Mas Marwan and family, Pak Aries and family, Pak Luthfi and family, Mas Nasikun and family, Mas Sebrian and family, who always be my family during my time in Delft. Mas Sebrian, thank you very much for helping me in finalising the defense schedule at TUD. Indo-IHE 2009 batch, Yuli and Sony for your support and sharing during my PhD. Pak Suryadi for your reminder and encouragement. Pengurus Cabang Istimewa Muhammadiyah (PCIM) Belanda, bu Janie, thank you very much for giving me an opportunity to initiate the social media, and the online halaqoh for the Muhammadiyah community in the Netherlands. Euromoslem Amsterdam, thank you very much for your warmth welcome and accompanion on every Sunday at the Masjid At-Takwa, Amsterdam.

I am deeply thankful to my big family in Indonesia and Germany who keep supporting me throughout in Delft. My brothers and their family, who always support me with the best prayers and wishes.

Finally, I am indebted to my wife and my son. We started this journey when we had difficult times when our beloved parents had just passed away. Both of you are willing to join me in Delft, leaving your job, your school, friends, and big family. Your patience, understanding, and endless supports have been my greatest motivation and inspiration.

Alhamdulillah

SUMMARY

Increasing global population and domestic migration have a significant impact on global land-use and land-cover (LULC) changes. Global LULC changes in recent times led to a reduction in vegetation cover within all types of ecosystems, which are potentially linked to human activities. LULC changes are not only affecting the quantity of green spaces but also the pattern of green spaces, which are becoming more fragmented and scattered into smaller areas. Those changes would influence the hydrological cycle resulting in a decrease in urban ecosystem services leading to an increase in various natural hazards, for instance, high urban temperature and urban flooding. Ecosystem services are the varied benefits to humans from the natural environment and healthy ecosystems. In an urban area, ecosystem services include temperature regulation, carbon storage, water regulation, and recreation. An increase in urban temperature is mainly related to a decrease in evapotranspiration, while urban flooding is related to a decrease in infiltration, a decrease in flow resistance, and a reduction in rainfall interception. Furthermore, high urban temperatures and urban flooding might occur in two different time periods, but they can occur in the same area.

Green spaces are the key contributor to the urban vegetation cover and hence they have an important influence on the urban climate and the occurrence of urban flooding. In general, studies on the relationship between green spaces and urban temperature and urban flooding reveal a positive relationship between the area of green spaces and ecosystem services that mitigate those detriments. However, the total area of green spaces used in the ecosystem services calculation is perceived as a lumped area ignoring the spatial characteristic of green spaces, such as aggregation and connectivity, which may result in an over or an under estimation of ecosystem services. Furthermore, the temperature change analysis that is looking at different land-use transformation can give more detailed information indicating the main contributor to increased urban temperature. Increased temperature in urban areas compared to that in non-urban areas can modify atmospheric circulation and precipitation. Furthermore, increased urban temperature can trigger cloudbursts that are the short period of heavy rainfall, which can be a serious threat to urban infrastructure. Furthermore, high urban temperature and flooding that are happening in the same place at different times has not been given any special attention. Both hazards do occur and are expected to increase in frequency due to climate change and urbanization. Therefore, it is important to improve our understanding of the role of green spaces in urban temperature, rainfall and flooding. This requires a detailed assessment of the impact of LULC changes on the effective area of green spaces and the temperature changes at different land-use and land cover change classes.

The high rate of LULC changes is already observed in Jakarta, which is one of the most populated cities in Asia. Jakarta has been experiencing rapid urbanization and extensive

land transformation from green spaces into urban surfaces that are impermeable and largely devoid of vegetation. Both these factors have reduced the latent heat flux that is impacting the urban temperature which has increased in the last decades. At the same time, an increase in flooding in Jakarta has been observed in the recent years. Flooding in Jakarta is influenced by several factors including land subsidence, higher rainfall in the city and in the upstream area, hydrological impact of the reduction of urban green spaces, and inadequate capacity of urban drainage. Increased urban temperature and rainfall in Jakarta also indicate the potential of multi-hazard that should be considered in the future urban planning of the city.

The specific objective of this PhD research was to improve our understanding of the role that green spaces play in urban temperature, rainfall, and flooding. This research was conducted on Jakarta and was divided into four parts. The first part analysed the impact of urbanization and LULC change on landscape pattern and ecosystem services. A new method on the calculation of ecosystem services, termed the "Landscape Metric Area" (LMA), was proposed to determine the effective area of green spaces. The LMA used landscape metrics of aggregation, connectivity, and class area to calculate the effective area of green space of two land-use maps which were based on the Landsat 5 for 1995, and the Landsat 8 for 2014. Three ecosystem services which were carbon sequestration, temperature regulation, and runoff regulation were quantified.

In the second part the impact of urbanization and LULC change on urban temperature was numerically simulated. The impact was analysed by looking at the sensitivity of urban temperature to the green spaces using greening scenarios (increasing the area of green spaces) and urbanization scenarios (reducing the area of green spaces). For this purpose, a fast urban boundary layer climate model, UrbClim, was utilized. The urban temperature was simulated by using UrbClim with a spatial resolution of 250 m which was finer than the typical resolutions of mesoscale weather models such as the Weather Research and Forecasting (WRF) model. The temperature simulations in UrbClim were performed for different land-use scenarios using 20 years of reanalysis data as model boundary conditions. Use of the same forcing data provided insights into the impact of each of the Urban Heat Islands (UHI), the temperature difference between urban areas and non-urban areas, resulting only from the LULC change. For instance, the influence of global warming equally affected all numerical experiments.

The third part analysed the temperature changes over several land use change classes and identify the main contributor to increased urban temperature. The temperature change was analysed by looking into the way temperature had been changed over several LULC class changes. For instance, the temperature changes in an area which was transformed from green spaces to built-up areas or in an area where there were no LULC changes. The urban temperature was simulated with the same model setup used in part two.

The fourth part investigated the long-term impacts of urbanization and LULC change on daily temperature, daily rainfall patterns, and their potential relationship with urban flooding. A comprehensive analysis was conducted by using daily temperature, daily rainfall, and flooding events data. The comprehensive analysis was based on a 30-year study period from which the maximum daily temperature and the maximum daily rainfall were calculated. The maximum daily rainfall was then matched with the flooding events, collected from literature, scientific reports, and newspaper articles, to look into the relationship between the daily rainfall and flooding. The increasing trend of urban temperature and rainfall patterns were analysed by using the statistical analysis of the Mann-Kendall and the Pettitt's test.

The results of this PhD research showed that the spatial characteristics of green spaces in an urban area are correlated with variations in urban temperature and flooding. The LULC change does not only relate to an increase of built-up areas and decrease of green spaces, but also changes in the landscape pattern of green spaces. Hence, when calculating ecosystem services of green spaces, alongside the quantity, it is essential to take into account landscape pattern changes, which can offer a more realistic perspective compared to commonly used area-based approaches. Furthermore, studying urban temperature changes with UrbClim at a horizontal resolution of hundreds of meters, provided satisfactory results. The simulation results showed that there was an inverse relationship between the area of green spaces and urban temperature. Moreover, the temperature changes at different LULC change classes indicated that the land-use transformation from green spaces to built-up areas, such as trees to urban or grassland to urban, had the highest contribution to an increase of the urban temperature. On the other hand, land-use transformation from built-up areas to green spaces, for instance, from urban to grassland, can result in cooler urban temperature, which indicated the contribution of green spaces to influencing temperature. Finally, historical data analysis showed that there was an increasing trend in daily temperature, daily rainfall, and flooding in Jakarta. The increasing trends implicitly indicated an increase of the chance of the occurrence of high urban temperature and flooding in the same place at different times. In conclusion, a reduction in the overall area, connectivity, and aggregation of green spaces has a significant impact on the increase in urban temperature and flooding.

This PhD research contributes to the existing body of knowledge a better understanding of the impact of LULC quantity and pattern changes on urban temperature and flooding. This research suggests that LULC changes can greatly impact the ecosystem services. The Landscape Metric Area method provides a preliminary indication, suggesting a more realistic calculation of ecosystem services compared to commonly used area-based approaches, where green spaces are often perceived as a single aggregated area. The analysis of the temperature changes indicates that providing detailed information of the land use transformation, and their consequences on the temperature changes are important in urban climate studies. The land-use transformation-based temperature change analysis can be an improvement over many existing methods that do not look into details of the temperature change as a result of land-use transformation. Most previous studies in Jakarta have predominantly concentrated on flooding and rainfall intensity. This PhD study is one of the first ones to offer novel insights emphasizing the importance of paying greater attention to the occurrence of high urban temperature and flooding. The results of this study provide new and essential insights for further research to enhance flood resilience and climate adaptation, advocating a holistic approach required to mitigate the risks associated with these multi-hazards.

SAMENVATTING

Toenemende wereldbevolking en binnenlandse migratie hebben een significante invloed op wereldwijde veranderingen in landgebruik en landbedekking (LULC). Deze recente veranderingen in LULC hebben geleid tot een afname van vegetatiebedekking in verschillende droge en semi-droge ecosystemen, die mogelijk verband houden met menselijke activiteiten. Een LULC-verandering beïnvloedt niet alleen de hoeveelheid groene ruimtes, maar ook het patroon van groene ruimtes, die meer gefragmenteerd raken en samenkomen in kleinere gebieden. Deze veranderingen kunnen de hydrologische cyclus beïnvloeden, wat leidt tot een afname van stedelijke ecosysteemdiensten en verschillende risico's van natuurlijke oorspong, zoals hoge stedelijke temperaturen en stedelijke overstromingen. Ecosysteemdiensten leveren meerdere voordelen op voor mensen en natuur. In een stedelijk gebied kunnen ecosysteemdiensten onder meer temperatuurregulering, koolstofopslag, waterregulering en recreatie omvatten. Een toename van de stedelijke temperatuur hangt voornamelijk samen met een afname van de verdamping, terwijl stedelijke overstromingen samenhangen met een afname van infiltratie, een afname van stromingsweerstand en een afname van regeninterceptie. Bovendien kunnen hoge temperaturen en overstromingen in de stad zich in twee verschillende tijdsperioden voordoen, maar ze kunnen zich ook in hetzelfde gebied voordoen.

Groene ruimtes hebben een belangrijke invloed op het stedelijk klimaat en de frequentie van stedelijke overstromingen. Over het algemeen tonen studies over de relatie tussen groene ruimtes en stedelijke temperaturen en stedelijke overstromingen een positieve relatie tussen de oppervlakte van groene ruimtes en ecosysteemdiensten aan. De totale oppervlakte van groene ruimtes die wordt gebruikt in de berekening van ecosysteemdiensten wordt echter beschouwd als een samengevoegd gebied dat de ruimtelijke kenmerken van groene ruimtes, zoals aggregatie en connectiviteit, negeert, wat kan leiden tot een overschatting van de ecosysteemdiensten. Verder kan een analyse van temperatuurveranderingen die verschillende landgebruikstransformaties beschouwt, gedetailleerdere informatie opleveren over welke verandering wat bijdraagt aan de toename van de stedelijke temperatuur. Tegelijkertijd is nog weinig bekend over de gevolgen van het optreden van de combinatie van hoge stedelijke temperaturen en stedelijke overstromingen. Deze gecombineerde risico's worden verwacht in frequentie toe te nemen als gevolg van klimaatverandering en verstedelijking. Daarom is het belangrijk om ons begrip van de rol van groene ruimtes op het stedelijke klimaat en overstromingen te vergroten. Dit vereist een gedetailleerde beoordeling van de gevolgen van LULC-verandering op het effectieve oppervlak van groene ruimtes en de temperatuurveranderingen bij verschillende klassen van landgebruiksverandering.

De hoge snelheid van LULC-verandering wordt al waargenomen in Jakarta, één van de dichtbevolktste steden in Azië. Jakarta ondergaat een snelle verstedelijking en grootschalige transformatie van groene ruimtes naar verharde oppervlakken. Beide hebben invloed op de stedelijke temperatuur, die de afgelopen decennia is toegenomen. Tegelijkertijd is er meer recent een toename van stedelijke overstromingen in Jakarta waargenomen. Overstromingen in Jakarta worden beïnvloed door verschillende factoren, waaronder bodemdaling, hoge intensiteit van regenval in het stroomgebied, vermindering van stedelijke groene ruimtes, gebrek aan capaciteit van stedelijke drainage en toename van dagelijkse regenval. De toename van de stedelijke temperatuur en daar aan gerelateerde toename van de dagelijkse regenval in Jakarta vergroot ook de kans op het gecombibeerd optreden van deze twee. In de toekomstige stadsplanning van de stad zal hiermee meer rekening gehouden moeten worden.

Dit promotieonderzoek heeft tot doel onze kennis over de invloed die groene ruimtes hebben op het stedelijke klimaat en overstromingen te vergroten. Dit onderzoek wordt uitgevoerd in Jakarta en is verdeeld in vier delen. Het eerste deel analyseert de impact van verstedelijking en LULC-verandering op het landschapspatroon en ecosysteemdiensten. Een nieuwe methode voor de berekening van ecosysteemdiensten, de "Landscape Metric Area" (LMA), wordt voorgesteld om het effectieve oppervlak van groene ruimtes te bepalen. De LMA maakt gebruik van landschapsmetingen van aggregatie, connectiviteit en klasseoppervlakte om het effectieve oppervlak van groene ruimte te berekenen op basis van twee landgebruikskaarten, gebaseerd op Landsat 5 voor 1995 en Landsat 8 voor 2014. Drie ecosysteemdiensten, namelijk koolstofopslag, temperatuurregulering en afvoerregulering, worden gekwantificeerd.

In het tweede deel wordt de impact van verstedelijking en LULC-verandering op de stedelijke temperatuur gesimuleerd. De impact wordt geanalyseerd door te kijken naar de gevoeligheid van de stedelijke temperatuur voor groene ruimtes met behulp van vergroeningsscenario's (toenemende oppervlakte van groene ruimtes) en verstedelijkingsscenario's (verminderen van de oppervlakte van groene ruimtes). De stedelijke temperatuur wordt gesimuleerd met behulp van UrbClim met een ruimtelijke resolutie van 250 m, wat fijner is dan die van het WRF-model. De temperatuursimulaties in UrbClim zijn uitgevoerd voor 20 jaar reanalysegegevens als modelgrenscondities, waarbij alleen de landgebruiksgegevens zijn gewijzigd. Ook zijn deze gegevens gebruikt om inzicht te verkrijgen in de geïsoleerde impact van UHIs. Dit heeft bijvoorbeeld, geleid tot het inzicht dat de invloed van de wereldwijde opwarming alle numerieke experimenten op gelijke wijze heeft beinvloed.

Het derde deel analyseert de temperatuurveranderingen over verschillende klassen van landgebruiksverandering en identificeert de belangrijkste factoren die bijdragen aan een toename van de stedelijke temperatuur. De temperatuurverandering is geanalyseerd door gedetailleerd te kijken naar de temperatuurveranderingen over verschillende LULC-veranderingklassen, bijvoorbeeld de temperatuurveranderingen in een gebied dat is getransformeerd van een groene ruimte naar een bebouwd gebied, van een groene ruimte naar bebouwde gebieden, of in een gebied waar geen LULC-veranderingen zijn. De stedelijke temperatuur is gesimuleerd met UrbClim op een ruimtelijke resolutie van 250 m, volgens dezelfde modelopstelling die in het tweede deel is gebruikt.

Het vierde deel analyseert de veranderingen in de dagelijkse temperatuur- en dagelijkse regenvalpatronen en de potentiële relatie met stedelijke overstromingen. Een uitgebreide analyse is uitgevoerd met behulp van de dagelijkse temperatuur-, dagelijkse regenval- en overstromingsgegevens. De uitgebreide analyse gebruikt een periode van 30 jaar waarin de maximale dagelijkse temperatuur en de maximale dagelijkse regenval zijn berekend. De maximale dagelijkse regenval is vervolgens gekoppeld aan de overstromingsgebeurtenissen, verzameld uit kranten, onderzoek en rapporten, om de relatie tussen de dagelijkse regenval en overstromingen te onderzoeken. De toenemende trend van stedelijke temperatuur- en regenvalpatronen is geanalyseerd met behulp van een statistische analyse volgens de Mann-Kendall en de Pettitt-test.

De resultaten van dit promotieonderzoek tonen aan dat de ruimtelijke kenmerken van groene ruimtes in een stedelijk gebied gecorreleerd zijn met variaties in stedelijke temperatuur en overstromingen. LULC-verandering heeft niet alleen betrekking op een toename van de bebouwde gebieden en een afname van de groene ruimtes, maar ook op veranderingen in het landschapspatroon van groene ruimtes. Dit alles heeft invloed op de ecosysteemdiensten. Daarom is het bij het berekenen van ecosysteemdiensten essentieel om rekening te houden met veranderingen in het landschapspatroon, wat een realistischer perspectief kan bieden in vergelijking met veelgebruikte oppervlaktebenaderingen. Verder heeft de analyse van temperatuurveranderingen met UrbClim op een horizontale resolutie van honderd meter bevredigende resultaten opgeleverd. De simulatieresultaten tonen aan dat er een negatieve relatie is tussen de oppervlakte van groene ruimtes en stedelijke temperatuur. Bovendien geven de temperatuurveranderingen bij verschillende LULC-veranderingklassen aan dat de landgebruikstransformatie van groene ruimtes naar bebouwde gebieden, zoals bomen naar stedelijk of grasland naar stedelijk, de grootste bijdrage levert aan een toename van de stedelijke temperatuur. Aan de andere kant kan landgebruikstransformatie van bebouwde gebieden naar groene ruimtes, bijvoorbeeld van stedelijk naar grasland, leiden tot een koelere stedelijke temperatuur. Dit wijst op de bijdrage van groene ruimtes aan temperatuurregulering. Ten slotte laat de uitgebreide historische analyse zien dat er een toenemende trend is in dagelijkse temperatuur, dagelijkse regenval en overstromingen in Jakarta. De toenemende trends geven impliciet aan dat de kans op het optreden van gecombineerde effecten toeneemt. Geconcludeerd kan worden dat een afname van het algehele oppervlakte aan groene ruimte en de connectiviteit en aggregatie van groene ruimtes een significante invloed hebben op de verandering van de stedelijke temperatuur en frequetie van overstromingen. Deze nemen toe.

Deze studie draagt bij aan het bestaande kennisniveau en kan helpen om het effect van LULC-verandering op stedelijke klimaten en stedelijke overstromingen beter te begrijpen. De analyse van het landschapspatroon suggereert dat LULC-verandering de ecosysteemdiensten aanzienlijk kan beïnvloeden door veranderingen in het landschapspatroon. De LMA-methode biedt een meer realistische berekening van de ecosysteemdiensten in vergelijking met de veelgebruikte oppervlaktebenaderingen, waarbij groene ruimtes vaak worden gezien als een enkel samengevoegd gebied. De analyse van de temperatuurveranderingen geeft aan dat het verstrekken van gedetailleerde informatie over de transformatie van het landgebruik en de gevolgen daarvan voor de temperatuurveranderingen belangrijk is in stedelijke klimaatstudies. De op landgebruikstransformatie gebaseerde analyse van de temperatuurverandering kan een alternatief zijn voor veel bestaande methoden die niet gedetailleerd kijken naar de temperatuurverandering als gevolg van landgebruikstransformatie. De meeste eerdere studies in Jakarta hebben zich voornamelijk gericht op overstromingen en regenintensiteit. Dit promotieonderzoek is een van de eerste die nieuwe inzichten biedt en benadrukt het belang van gecombineerde risico's die verband houden met hoge stedelijke temperaturen en overstromingen. De resultaten van dit onderzoek bieden nieuwe en essentiële inzichten voor verder onderzoek om de veerkracht tegen overstromingen en klimaatadaptatie te verbeteren, en pleiten voor een holistische aanpak die nodig is om de risico's die gepaard gaan met deze gecombineerde gevaren te verkleinen.

CONTENTS

1

INTRODUCTION

1.1 BACKGROUND

The world population has increased in last decades triggering Land Use and Land Cover (LULC) changes that transform natural landscape into built-up environment. The transformation of LULC from natural green spaces into grey built-up environment influences the hydro-climatological process leading to increasing urban temperature, extreme rainfall events, higher surface runoff, and increased flooding in urban areas (Bao et al., 2016; Kubota et al., 2017; Pachauri & Reisinger, 2007; Zope et al., 2017). The land-use transformation mainly alters green spaces distribution and quantity. Green space is an couland community gardens (Nazombe & Nambazo, 2023; U.S. Green Building Council, 2024). Green space has an important role in mitigation and adapation of several natural hazards such as flooding, high temperature, landslides, and coastal erotion. The important role of green spaces in mitigation and adaptation of natural hazards is an integral component of ecosystem services.

1.2 URBAN ECOSYSTEM SERVICES

An ecosystem is a network of interactions between species and their environment through which people get benefits from ecosystems named ecosystem services categorized as provisioning services, regulating services, cultural services, and supporting services. The provisioning services are defined as the products obtained from ecosystem whereas the regulating services are benefits obtained from regulation of ecosystem processes. The cultural services are non-material benefits obtained from ecosystems and the supporting services that are services required for the production of all other ecosystem services (Vinet & Zhedanov, 2011).

Ecosystem services vary from one area to another depending on its location, as they are significantly influenced by the local environment and socio-economic characteristics (Gómez-Baggethun & Barton, 2013). In the case of the urban environment, a city can be seen as a single ecosystem where the interaction between human and its urban environment including natural green and blue areas are observed. Ecosystem services in urban areas are essential to improve air quality, noise reduction, to moderate high temperature, and water regulation (Bolund & Hunhammar, 1999). Green space is a part of urban ecosystems that increasingly play important roles to anticipate the impacts of climate change and urbanization mainly through the regulating services. Depietri et al. (2012) discussed policy aspects to maximize the regulating services of the ecosystem in buffering impacts of hydro-meteorological hazards such as heat waves and flooding in urban areas. The hydro-meteorological hazards can increase the vulnerability of the ecosystem and urban system. However, the ability of the ecosystem to minimize impacts of the hazards through regulating services are decreasing since urbanization tends to fragment the ecosystem. According to Burkhard et al. (2012), each ecosystem has the capacity to supply services based on its structures and processes which are related to (1) the natural conditions including hydrology, topography, biodiversity; and (2) anthropogenic activities in ecosystems. In the case of urban areas, the ecosystem services can be quantified by using several criteria and indicators, for example air purification, noise reduction, carbon storage, infiltration, evapotranspiration and recreational (Burkhard et al., 2012; Derkzen et al., 2015; Gkatsopoulos, 2017; Gómez-Baggethun & Barton, 2013; Tratalos et al., 2007).

1.3 Land atmosphere interaction

The Earth system is a complex system shaped by the interaction among land, atmosphere, ocean, and the life, occurring across diverse spatial and temporal scales. Key interfaces facilitating these interactions include the land-atmosphere, atmosphere-ocean, and land-ocean interfaces, each playing a crucial role in the global climate system and Earth's environmental processes. All these processes are influenced by human actions. The land-atmosphere interaction is particularly important to understand how the earth-atmosphere system reacts to the surface conditions like LULC changes. The energy and material (e.g. water) transfer between earth and atmosphere occurs in the atmospheric boundary layer (ABL). ABL is a dynamic active part of the Earth's atmosphere consisting of up to about 2 km from the earth surface, playing a vital role in the transfer of energy, matter, and momentum between the surface and the overlying atmosphere (Wallace & Hobbs, 2006). According to Hidalgo et al. (2008), the interaction between land and atmosphere is affected by four general physical characteristics of urban areas as follows: 1) usually low vegetation cover with high imperviousness of building materials and paved surfaces; 2) high thermal material absorbing more heat energy and releasing it within a few hours; 3) the urban canopies and urban canyon shape of streets; 4) anthropogenic activities. Even though located in a local scale, urban areas can influence atmospheric composition, water cycle components, and the carbon cycle and ecosystems. Hove et al. (2011) and Shepherd (2005) give a brief discussion how the climate system plays on the different spatial scales by dividing the urban environment into three different horizontal scales and related vertical scales, namely micro, meso and macro scales, in decreasing spatial resolution.

Microscale often deals with phenomena occurring over spatial scales of a few meters to around 1-2 kilometres. Therefore, this is the scale at which individual elements of the city such as buildings, roads, and trees, that play an important role in affecting urban climates at the local scale can be (sometimes explicitly, but often as high-resolution spatial patterns) meaningfully represented. The interaction between microscale and local scales exists within Urban Canopy Layer (UCL), which is the zone between the ground and below the top of the urban land structures such as trees and buildings. Urban Boundary Layer (UBL) is the layer of air above the urban canopy up to the height influenced by urban structures. UBL starts from the top of UCL and ranges 1 to 2 km from the surface above which the direct influence from urban landscape on the atmospheric dynamics is no longer significant.

1.4 Urban temperature

Due to urbanization, natural elements are replaced by materials with high thermal properties that are able to store more solar energy that can increase surrounding air temperature. In case of low vegetation cover and lack of water bodies in urban areas, solar energy is directly converted to sensible heat instead of latent heat by evapotranspiration and the photosynthesis process. This is the main contributor to the increase of urban temperature compared to its surrounding non-urban areas with high vegetation cover. The temperature difference between temperature in urban areas and in surrounding non-urban areas is known as Urban Heat Island (UHI) at which temperature in urban areas is higher than that in surrounding non-urban areas. Increasing temperature in urban areas is not only affected by reduced latent heat flux and radiative impact of high thermal admittance materials but also by the geometry of urban areas. For example, urban canopy/urban canyon geometry affect the destiny of the radiative energy.

The UHI can be divided into two types, namely Surface Urban Heat Island (SUHI) and Atmospheric Urban Heat Island (AUHI) (Hove et al., 2011; U.S. Environmental Protection Agency, 2008). The SUHI is the temperature difference between surface temperature of urban areas and rural or non-urban areas, while the AUHI refers to the air temperature difference in urban areas and rural or non-urban areas (Medina-Fernández et al., 2023). Both the SUHI and the AUHI are influenced by several factors including LULC, the weather condition, and the intensity of the sun.

Some studies have shown that SUHI and AUHI are interrelated. Kawashima et al. (2000) revealed that there was a strong correlation between the surface temperature and the air temperature indicated by their correlation coefficient varying from 0.87 to 0.92, which occurs due to the influence of the vegetation density. Schwarz et al. (2012) revealed that there was a positive relationship between the observed air temperature and the surface temperature based on their study in Leipzig, Germany. Anniballe et al., (2014) revealed that the surface temperature and the air temperature in Milan had a positive relationship during the daytime during the summer months.

Many studies have been devoted to investigating the UHI, which include both observational and modelling studies. The observational studies are generally conducted by comparing records from meteorological stations inside and outside of urban areas or using the instrumented car moving from the rural to the city centre or *vice versa*. Furthermore, the modelling studies is conducted by using atmospheric models that some of them can provide satisfying results (De Ridder et al., 2015; García-Díez et al., 2016). Furthermore, advanced computer technology along with high spatial resolution of satellite images have enabled an opportunity to investigate the UHI, particularly the SUHI (Voogt & Oke, 2003; Weng, 2009).

1.5 ATMOSPHERIC MODELS

The development of atmospheric models is based on the behavior of the complex systems of the Earth's atmosphere. The atmospheric models use some numerical schemes to solve the conservation relationship which are mass, momentum, heat, and conservation (and phase changes) of water using a non-hydrostatic 3-D set of equations (Arnbjerg-Nielsen et al., 2013; Pathirana et al., 2014). The conservation relationship can be numerically solved by using 3 Dimensional Navier-Stokes equation as follow:

Continuity equation:

$$\frac{\partial_u}{\partial_x} + \frac{\partial_v}{\partial_y} + \frac{\partial_w}{\partial_z} = 0 \tag{1.1}$$

The Navier-Stokes equation in x direction:

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + F_x \tag{1.2}$$

The Navier-Stokes equation in y direction:

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) + F_y \tag{1.3}$$

The Navier-Stokes equation in z direction:

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) + F_z \tag{1.4}$$

where:

u, v, w : the velocity in x, y, z directions

p : pressure

ρ : density

μ : viscosity

F_x, F_y, F_z : gravity or coriolis forces

The mathematical equations of the Navier-Stokes can be solved by using either analytical method or numerical method. The implementation of the Navier-Stokes equation in the atmospheric models requires numerical methods to solve non-linear and complex mathematical model for which computing load may be very high (Z. Zhang & Moore, 2015).

The advanced computational technology enables analysis of the climate system from global to regional and urban scale. Depending on its spatial and temporal scales, the climate models can be divided into global and regional climate models. At the global scale, modelling climate system is facilitated by Global Climate Models (GCMs) deployed for a large spatial scale. The Atmosphere-Ocean General Circulation Models (AOGCM) are the standard global climate model that is used to understand the interactions between atmosphere, ocean, land, and sea ice. There are a number of global climate models available which are participating in Coupled Model Intercomparison Project 3 (CMIP3) and CMIP5. The GCMs are usually operated using coarse resolutions, for example, 50 km or more, which can not cover detailed local features such as topographic features and land cover heterogenities.

To cover the local features, Regional Climate Models (RCMs) have been used to downscale the GCM outputs to finer resolutions. Many studies on downscaling global climate data to regional climate data have been carried out using RCMs, for instance the Weather Research and Forecasting Model (WRF). Qiu et al. (2017) used the WRF model to downscale the global climate data of precipitation and daily temperature from the ERA-Interim reanalysis data for Central Asia. Huong & Pathirana (2013) used the WRF model to downscale local rainfall patterns from the National Centres for Environmental Prediction (NCEP) Final (FNL) Operational Model Global Tropospheric Analyses for Can Tho, Vietnam. Tursilowati et al. (2012) applied the WRF model to monitor impacts of land use conversion on UHI in Jakarta, Indonesia, and compared the results with the climate data observation in the year 2002.

The above atmospheric models do a detailed representation of atmospheric dynamics and microphysics. The downside of that is that they are computationally quite heavy, particularly at high spatial resolutions of hundreds of metres required for urban studies. Hence, modelling urban climates at hundreds of metres spatial resolution requires high investment for computing infrastructure. UrbClim is a specialized atmospheric model designed to simulate the temperature and heat-stress fields at a city scale. UrbClim was developed by De Ridder et al. (2015) by using a land surface scheme that consists of simple urban physics, coupled to a 3-D atmospheric boundary layer module. However, UrbClim does not have a microphysics scheme to produce rainfall and uses simplified urban physics to achieve fast computational speeds.

The UrbClim's performance had been tested to simulate the local climate in several European cities, which show the ability of UrbClim to perform accurately as well as at a lower computational cost compared to the WRF. For example, García-Díez et al. (2016) simulated UHI phenomenon in Barcelona (Spain) using the UrbClim and the WRF. Lauwaet et al. (2015) coupled the UrbClim with eleven global climate models from CMIP5 to study future urban heat island in eight cities from three continents. UrbClim was also used to simulate the future urban temperature of New Delhi, India (Sharma et al., 2019).

The impact of LULC changes on urban temperature can be simulated using atmospheric models. The urban temperature simulation is generally carried out by using two or more land-use data from different years representing LULC changes. Furthermore, the land-use data is simulated with the same meteorological data as the model's boundary condition. By using that approach, it is expected that the influence of global climate change on temperature changes can be neglected. Some studies have been conducted by using that approach implemented in the WRF model. Zhan et al. (2013) analysed increased urban temperature as the impact of urbanization in the Beijing-Tianjin-Tangshan Metropolitan Area, China. In their study, two land use data for the year 2010 and 2030 were simulated with the same meteorological boundary condition from 2030 to 2040 in the WRF model with the spatial resolution of 1 kilometre. Kubota et al. (2017) simulated the impact of land use change from 2011 to 2030 in Hanoi. Two land use maps were prepared for the year 2010 and 2030 simulated with the summer condition of June 2010 in WRF with the spatial resolution of 1 km. Modelling the impact of LULC change on urban temperature using the WRF model has already given a significant contribution to understand the relation between decreased green spaces and increased urban temperature. Furthermore, modelling the impact of LULC change on urban temperature is a complex and challenging task, and it is still necessary to carry out in-depth research since there are some local features which cannot be adequately represented in the spatial model resolution of 1 kilometre.

1.6 Flooding in urban areas

The impact of LULC changes in urban areas is not limited to an increase in urban temperature but also extends to increased flooding due to hydrological impact of that change. Increased temperature in urban areas compared to non-urban areas can modify atmospheric circulation and precipitation (Siswanto et al., 2022). As a result, increased urban temperature can trigger extreme rainfall intensity which pose a threat to urban infrastructure. The relation of increased urban temperature and extreme rainfall will be further discussed in the next section. Loss of green spaces due to LULC change creates hydrological impacts on urban areas indicated by a decrease in infiltration, a decrease in flow resistance, and a reduction in rainfall interception leading to an increase in surface runoff (Bhattacharya et al., 2018). The impact of an increasing urban and built-up areas on infiltration and flooding has been discussed in a number of studies. In their study, Eshtawi et al. (2016) found a linear relationship between the expansion of urban areas and the subsequent increase in surface runoff within the Gaza strip. Notably, a 50% increase in urban areas led to an increase in surface runoff of about 13% to 27%. Skougaard Kaspersen et al. (2017) demonstrated the significant impact of urban development on flooding in urban areas between 1984 and 2014. Their study revealed that a 1% increase in impervious surfaces could lead to a 10% increase in runoff volume in four European cities of Odense, Vienna, Strasbourg and Nice. Furthermore, Ngo et al. (2022) studied the impacts of urbanization on flood extents in CanTho in the Mekong delta. Their study showed that urbanization made the CanTho city more vulnerable to flooding. They projected that the flood extents in the city would increase by 2050 (under RCP 4.5 and RCP 8.5). Meanwhile, Apollonio et al. (2016) showed a positive correlation between increased flooding areas and decreased vegetation covers between 1984 and 2011 in the Cervaro basin in Southern Italy.

1.7 URBANIZATION AND RAINFALL

Increased urban temperature can trigger and increase extreme rainfall intensity in urban areas. The way the increasing urban temperature influences extreme rainfall intensity in urban areas is a complex mechanism that is influenced by the urban environment (Kusaka et al., 2014; Shepherd, 2005), particularly through the land-atmosphere interaction in urban areas (Han et al., 2014; Hidalgo et al., 2008; Jin et al., 2015; Pathirana et al., 2014; Rozoff et al., 2003; Zhong et al., 2017). The land-atmosphere interaction, between the urban environment and the lower atmosphere, can impact local precipitation through one or combination of UHI, an increase in urban surface roughness, and concentration of Cloud Condensation Nuclei due to pollution (CCN) (Han et al., 2014). Rozoff et al. (2003) and Ashley et al. (2012) investigated land-use impacts on thunderstorm activity. They found that the UHI initiates deep and moist convection downwind of urban areas. Moreover, Zhong et al. (2017) revealed that the UHI affects air circulation through UHI-thermal perturbation of the boundary layer which enhances convective cloud formation. Meanwhile, convergence on the upwind side of urban areas is influenced by surface roughness, but the convergence is too small to initiate moist convection (Rozoff et al., 2003). During particular thermodynamic conditions, moist convection can be initiated by updraft cell downwind of the heat island (Baik et al., 2001). The presence of aerosols, particularly Cloud Condensation Nuclei (CCN), is an important factor in the precipitation-forming processes (Jin et al., 2005; Khain et al., 2005; Pathirana et al., 2007). Rosenfeld (2000) identified that increasing the concentration of CCN due to urban and industrial air pollution can suppress rain and snow. The concentration of CCN can nucleate many small cloud droplets that coalesce into raindrops. Andreae et al. (2004) investigated that reduced size of cloud droplet can delay the precipitation onset allowing intense updrafts that trigger more intense ice precipitation, hail and lightning. However, the aerosol might have low impacts for the change of urban rainfall amount particularly in summer months (Jin et al., 2005). Han et al. (2014) revealed a general mechanism of urban-induced precipitation. The urban heat island generates updrafts that initiate moist convection under favourable thermodynamic conditions followed by precipitation that is likely to increase during high air humidity.

1.8 PROBLEM STATEMENTS

Urban green spaces provide multi-functional benefits such as socio-economic, ecosystem services and climate adaptation (Bolund & Hunhammar, 1999; Emmanuel & Loconsole, 2015). However, urbanization triggers LULC changes that reduce green spaces which are transformed into built-up areas dedicated for public infrastructures, housing, new business area and public facilities (Haaland & van den Bosch, 2015). LULC changes are not only decreasing the quantity of green spaces but also changing the landscape characteristics of green spaces identified by changes in landscape matrices such as decreased aggregation. Furthermore, decrease in urban green spaces has influenced the hydro-climatological processes, and made cities and urban areas vulnerable to high temperature, increased daily rainfall, and urban flooding.

As a part of urban ecosystems, green spaces provide ecosystem services which include provisioning services, regulating services, supporting services and cultural services. The regulating services of ecosystem services include temperature regulation and runoff regulation. Some studies related to urban green spaces and ecosystem services have been conducted by considering several aspects such as population, economic condition, ecosystem services, public health, and urban heat island (Bolund & Hunhammar, 1999; Choumert & Salanié, 2008; Emmanuel & Loconsole, 2015; Kabisch & Haase, 2014; Richards et al., 2017; Wüstemann et al., 2017; J. Yang et al., 2017). Those studies are mainly based on the area of green spaces in an urban area, while a few of them consider a combination between composition and configuration, different land use transformation, as well as landscape characteristics of green spaces (Meerow & Newell, 2017; Neema & Ohgai, 2013). The ecosystem services analysis is mainly based on the area of green spaces which is often perceived as a lumped area, which may lead to under or over estimation of ecosystem services produced by green spaces. Hence, the process that green spaces affect urban ecosystem services needs to be evaluated by considering landscape characteristics that can be changed during urbanization. Furthermore, the influence of green spaces on urban temperature is mainly seen from the area of green spaces, without looking into the temperature change over different land use transformation processes which may help in identifying the main contributor of increased urban temperature.

The study of the impact of LULC changes on urban temperature using atmospheric models is generally conducted by using the WRF model (Huong & Pathirana, 2013;

Kubota et al., 2017). Generally, the urban temperature in the WRF model is simulated at the horizontal resolution of 1 kilometre, which may not cover some urban details, for example, city parks, small wetland areas and lakes. Hence, it is essential to have urban temperature simulations at finer horizontal resolution, for instance hundreds of meters, so that the effect of such urban details on urban temperature can be identified.

Furthermore, urban green space studies generally focus only on high temperature (Sodoudi et al., 2018), flooding (Eshtawi et al., 2016), the relation between high urban temperature and extreme rainfall (Siswanto et al., 2022), or extreme rainfall and urban flooding (Huong & Pathirana, 2013). Some studies show that increased temperature in urban areas could affect urban rainfall leading to flooding (Huong & Pathirana, 2013; Siswanto et al., 2022), which indicate the potential occurrence of combined or multi-hazard in an urban area. The potential occurrence of multi-hazard or combined hazards may increase in the future considering the on-going urbanization process and the global climate change that may exacerbate impacts of the hazards, while studies that investigate combined or multi-hazard in an urban area are still limited. Hence, it is important to have a good insight of combined or multi hazards in an urban area that can help in preparing climate change adaptation planning.

Considering the aforementioned problems, it is seen that it is essential to study the impact of LULC changes on urban temperature, rainfall, and flooding by looking into several aspects related to urban green spaces including landscape pattern changes, land-use transformation processes, and combined or multi-hazard potential in an urban area, which are not much covered in green space studies.

1.9 RESEARCH OBJECTIVES

The general objective of this research is to improve understanding of the impact of LULC changes on urban temperature, rainfall, and flooding. Furthermore, the specific objectives of this research have been formulated to:

1. analyse the impact of LULC changes on landscape pattern changes and ecosystem services affecting increased urban temperature and urban flooding (Chapter 2);
2. simulate the impact of LULC changes on urban temperature using an urban climate model at the horizontal resolution of hundreds of meters (Chapter 3);
3. analyse the temperature changes over several LULC change classes and identify the main contributor to increased urban temperature (Chapter 4);
4. analyse the changing pattern of daily temperature and daily rainfall, and the potential combined hazards of high urban temperature and flooding (Chapter 5).

1.10 RESEARCH QUESTIONS

Given the objectives, the related research questions can be formulated as follow:

1. How can ecosystem services of green spaces be affected by landscape pattern changes due to LULC changes?
2. How can an urban climate model be used for a better urban temperature simulation?
3. How can urban temperature be influenced by different land-use transformation processes in an urbanized area?
4. What are the long-term impacts of urbanization and LULC changes on urban temperature, and flooding?

1.11 STUDY AREA

This study was conducted in Jakarta, the capital of Indonesia, which has experienced rapid urbanization and the extensive land-use transformation from vegetative green spaces into impermeable urban surfaces (Nagasawa et al., 2015; Pravitasari, 2015; Ramdhoni & Rushayati, 2016; Rustiadi et al., 2002). The impacts of urban development in Indonesia, particularly on the local climate, are found to relate to urban temperature (Darmanto et al., 2019; Ramdhoni & Rushayati, 2016; Siswanto et al., 2016) and extreme rainfall leading to urban flooding (Siswanto et al., 2015; Supari et al., 2017). Urbanization in Jakarta is driven by several factors, including its strategic political and economic position as the capital city where important activities such as the functions of the national government, education, manufacturing and commerce are taking place (Firman, 2009). Jakarta has six municipalities, which are Central Jakarta (CJ), North Jakarta (NJ), West Jakarta (WJ), South Jakarta (SJ) and East Jakarta (EJ), as shown in Figure 1.1, and one regency, which is the Thousand Islands (not shown in the figure). This study focused on the municipalities that consist of 42 subdistricts, which were home of approximately 10 million people, with the population growth rate of 1.57% per year in 2018 (DESA, 2018). East Jakarta is the most populated area, whereas West Jakarta is the most densely populated area with a population density of 19,018 per km^2. Located on the northwest coast of Java, Jakarta's climate is a tropical monsoon climate according to the Köppen climate classification system and it has two seasons, which are the rainy season from October through May and the dry season from June to September. During the rainy season, the average monthly rainfall is 300 mm, while it is 43 mm in August during the dry season (BPS DKI Jakarta, 2016).

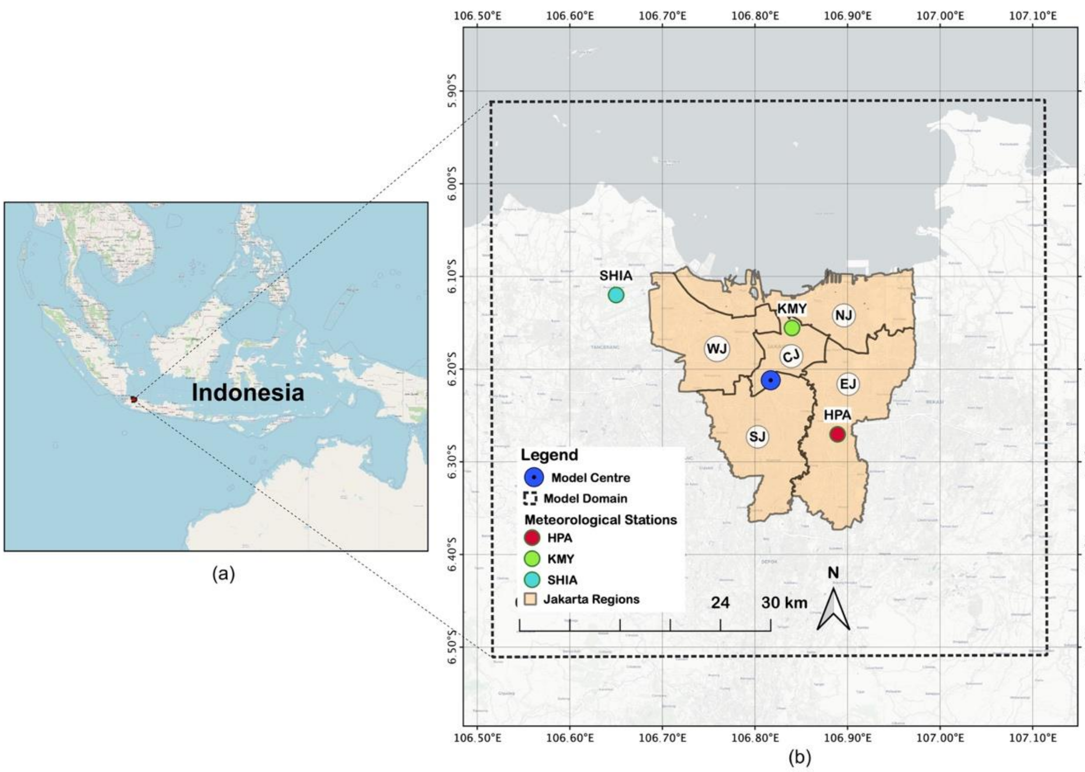


Figure 1.1. The location of study area in Indonesia, model domain, and meteorological stations in Jakarta.

1.12 Thesis outline

This thesis is arranged into six chapters summarized as follow:

Chapter 1 discusses the introduction to this research. It discusses the research background, a description of the study area, identification of problem statements, research objectives and questions considered in this study.

Chapter 2 investigates the impact of urbanization and LULC change on landscape pattern changes and ecosystem services afffecting increased urban temperature and urban flooding. This chapter proposes a new method using “Landscape Metrics Area (LMA)” to evaluate the ability of green spaces in providing ecosystem services, particularly carbon sequestration, temperature regulation, and runoff regulation. The method considered landscape pattern changes identified by using landscape metrics of class area (CA), connectivity (COHESION), land proportion (PLAND) and aggregation index (AI). The LULC map from this chapter was later used as the input data for urban temperature simulation in Chapter 4.

Chapter 3 simulates the impact of LULC change on urban temperature using an urban climate model at the horizontal resolution of hundreds of metres. The urban temperature change was analysed by looking at the sensitivity of urban temperature to the changes of the area of green spaces. The urban temperature was simulated by using an urban boundary layer climate model (UrbClim). UrbClim is a new urban climate model that has the model resolution up to 100 m, which is finer than other climate models such as WRF. The sensitivity of urban temperature to green spaces was simulated by modelling urban temperature of Colombo, Sri Lanka. Two general scenarios which were greening (increasing the area of green spaces) and urbanization (decreasing the area of green spaces) were implemented in the urban temperature modelling activities. All numerical experiments were performed for 20 years (1996 through 2015) of reanalysis data as model boundary conditions, changing only the land-use data for each experiment. The similar model setup was later used for urban temperature simulation of Jakarta in Chapter 4.

Chapter 4 investigates the temperature changes over several LULC change classes and identify the main contributor to increased urban temperature. The investigation was conducted by modelling urban temperature of Jakarta for the year 1995 and 2014 using UrbClim. The model setup was based on the model setup used in Chapter 3. This chapter used an alternative method that looked the temperature changes at different LULC change classes, instead of using general temperature change information. The temperature change analysis was conducted by looking into the temperature changes as the result of land use transformation at one particular area, for example the temperature changes in an area transformed from green spaces to built-up areas, and *viceversa*.

Chapter 5 identifies the changing pattern of daily temperature, daily rainfall, and the potential combined or multi-hazard of high urban temperature and flooding. The daily temperature and daily rainfall data were collected from the Meteorological, Climatological, and Geophysical Agency (BMKG) of Indonesia. The flooding history data was collected from various sources such as newspaper, technical or project reports, and scientific report. The meteorological data was used to identify the changing temperature and rainfall pattern over a 30-year period by looking into the annual maximum daily temperature and the annual maximum daily rainfall. The changing pattern of urban temperature and daily rainfall were analysed by using the Mann-Kendall and the Pettitt's test. The meteorological data analysis results were later matched with the flooding history to identify the implicit relation between increased urban temperature, daily rainfall, and flooding, as well as the potential combined or multi-hazard.

Chapter 6 presents the general conclusions of this research. It also outlines limitations associated with this study and provides suggestions for future research.

2

Impact of Landscape Pattern Changes on Urban Ecosystem Services

Urbanization is changing land use–land cover (LULC) transforming green spaces (GS) and bodies of water into built-up areas. LULC changes are affecting ecosystem services (ES) in urban areas, such as a decrease of the water retention capacity, the urban temperature regulation capacity, and the carbon sequestration. The relation between LULC changes and ES is still poorly examined and quantified using actual field data. In most ES studies, GS is often perceived as lumped areas instead of distributed areas, implicitly ignoring landscape patterns (LP), such as connectivity and aggregation. This chapter provides quantitative evidence of the influence of landscape pattern changes on a selection of urban ecosystem services in a megacity such as Jakarta, Indonesia. The impact of urbanization on the spatiotemporal changes of ES had been identified by considering connectivity and aggregation of GS. It was revealed that LP changes had significantly decreased carbon sequestration, temperature regulation, and runoff regulation by 10.4, 12.4, and 11.5%, respectively. This indicated that the impact of GS on ES was not only determined by its area, but also by its LP. Further detailed studies will be needed to validate these results.[1]

[1] Based on Maheng, Dikman, Assela Pathirana, and Chris Zevenbergen. 2021. "A Preliminary Study on the Impact of Landscape Pattern Changes Due to Urbanization: Case Study of Jakarta, Indonesia." *Land* 10 (2): 1–27. https://doi.org/10.3390/land10020218

2.1 Introduction

More than half of the World population will reside in urban areas by 2050 (United Nations, 2014). Increased population drives land use–land cover (LULC) change transforming green spaces as well as bodies of water into built-up areas resulting in decrease and loss of ecosystem services (ES) in urban areas (Dou & Kuang, 2020; Wu et al., 2019; Q. Xu et al., 2018; Ye et al., 2018). Ecosystem services are the varied benefits to humans from the natural environment and healthy ecosystems. They can be categorized as provisioning services, regulating services, cultural services, and supporting services (Alcamo et al., 2003). A city or an urban area can be seen as a single ecosystem where the urban population directly benefits from ecosystem services generated by urban ecosystems, such as green and blue infrastructure (Bolund & Hunhammar, 1999). Ecosystem services in urban areas include air quality improvement, noise reduction, controlling air temperature, carbon storage and sequestration, water regulation, and recreation (Bolund & Hunhammar, 1999; Burkhard et al., 2012; Derkzen et al., 2015; Gkatsopoulos, 2017; Gómez-Baggethun & Barton, 2013; Tratalos et al., 2007; Van Oudenhoven et al., 2012) and therefore enhance citizens well-being (Loures et al., 2007; Panagopoulos et al., 2016).

Many studies show that urbanization and LULC change are key anthropogenic drivers affecting urban ecosystem’s functions and services (Clerici et al., 2019; Depietri et al., 2012; Dupras et al., 2016; Fox et al., 2012; Gómez-Baggethun & Barton, 2013). Some examples of the impact of LULC change on ES due to urbanization are a decrease in the capacity to retain stormwater leading to urban flooding (Farrugia et al., 2013), and an increase in the land surface temperature (LST) (Marando et al., 2019) in cities. Yuan et al. (2018) showed that in Nanjing, China, there was a decrease in the provision and delivery of supply services, the supporting services, and the regulating services by 17, 0.9, and 4.3%, respectively, due to urbanization between 2000 and 2015. In Beijing, urban growth between 1985 and 2015 decreased carbon storage and water yield by 3.3 and 4%, respectively, while sediment export increased by 15.5% (Sun et al., 2018a). Another study from Atlanta Metropolitan area, US, showed that urban expansion between 1985 and 2012 reduced carbon storage by 23%, water purification capacity by 28%, and nitrogen and phosphorus by 49%, but increased sediment transport by 17% (Sun et al., 2018b). Jaligot et al. (2018) showed that the cultural services in Yaoundé, Cameroon, decreased by more than 90% due to urbanization between 2000 and 2018. LULC change from 1990 to 2017 in the West Bengal, India, resulted in some of the regulating services increasing while others decreased. Water regulation, water supply, and waste treatment increased by 57, 22, and 8%, respectively, while climate regulation and nutrient cycling decreased by 31.82 and 31.25%, respectively (Das & Das, 2019).

The relationship between urbanization, LULC change and ES has been studied from various perspectives. Panagopoulos et al. (2016) discussed the importance of urban ES and landscape planning to sustainable urban development. Das & Das (2019) investigated the impact of LULC change on ES by quantifying the total ecosystem service value (ESV) based on the area of the ecosystem, and a value coefficient (VC) (Costanza & D'Arge, 1997). The extension of built-up areas in West Bengal decreased agricultural and vegetation covers. As a result, the total ESV of landscape decreased by 24.30% from 1990 to 2017. Wang et al. (2019) investigated the impact of urbanization from 2000 to 2010 on multiple ES at hotspots and urban megaregion scale of Beijing–Tianjin–Hebei (BTH), the capital economic zone of China, by considering three components of urbanization: the built-up area proportion, the population density, and the gross domestic product (GDP) density. The ES in their study was calculated using the area of the ecosystem, for instance, the total food production was based on the area of cropland. It was revealed that providing services of food supply had an "inverse U" shape relation with the population and the GDP density, while urban expansion decreased regulating services. The impact of urbanization on ES was not only influenced by an increase in urban areas or a decrease in green spaces but also by landscape pattern changes, such as number of patches (NP), aggregation index (AI), and Clumpiness index (CLUMPY), as discussed by Asadolahi et al. (2018). The ecosystem services in their study were based on the area of ecosystems, including water bodies, agriculture, rangeland, forest and urban area. Moreover, the influence of landscape patterns to ES provision was analysed by comparing the landscape metric changes and ES. They saw that increasing food supply had a positive correlation with the good connectivity and connectedness of agricultural land. Haas et al. (2015) discussed the relationship between a decrease in ES with an increase in built-up areas and landscape pattern changes due to urbanization in the period from 1989 to 2001 in Stockholm and Shanghai. They observed that an increase in built-up areas along with landscape pattern changes, such as a decrease in connectivity, an increase in fragmentation, and more complex shapes of the natural landscape, had a negative impact on ES. The ES in their study was based on the area of ecosystems, such as wetland, water, forest, agriculture, urban green space, high-density building, and low-density building. Moreover, the relationship between ES and landscape pattern changes was discussed by comparing the changes of the landscape metrics and ES. For urban flood mitigation, Bai et al. (2018) conducted a field survey study in Luohe, China, which observed that inundated areas had a low proportion of green spaces and bare land. Moreover, landscape metrics analysis showed that the mean patch size of green spaces of flooded areas was smaller compared with that of roofs. Meanwhile, the connectivity of green spaces had no significant contribution to mitigating urban flooding. The importance of landscape patterns on surface runoff control was also observed by Zhang et al. (2015). They directly integrated large patch index (LPI) and aggregation index (AI) of green spaces with runoff coefficients to estimate runoff volume controlled in Beijing, China. It was found that increasing runoff was related to a decrease in green spaces, as well as increasing the fragmentation and disaggregation of green spaces. The landscape patterns can also exhibit a relation with an increase in LST in the Olympic Forest Park of Beijing, China, as investigated by using the Pearson correlation analysis (Amani-Beni et al., 2019). It was revealed that an increase in LST was related to increasing urbanization in the period 2000 to 2015. Moreover, there was a negative correlation between LST and the landscape metrics of large patch index (LPI) and aggregation index (AI) of green spaces.

A growing number of studies have investigated the impact of urbanization and LULC change on ES. These studies reveal that a decrease in green spaces affects ES, feeding the perception that there is a positive relationship between the surface area of green spaces and urban ecosystem functioning (Jaganmohan et al., 2016; Q. Xu et al., 2018). However, these studies generally ignore the impact of spatial heterogeneity of the land surfaces as they lump together the area of each land-use type. Only a few of them acknowledged the differences in landscape patterns but still did not consider landscape patterns in calculating the impact of green spaces. As a result, an area of green spaces, as shown in Figure 2.1, can still be perceived as a lumped area instead of a distributed area, where the green space units have different landscape patterns, such as connectivity, aggregation, mean patch size, and large patch index, which can affect ecosystem services (Mitchell et al., 2013, 2015).

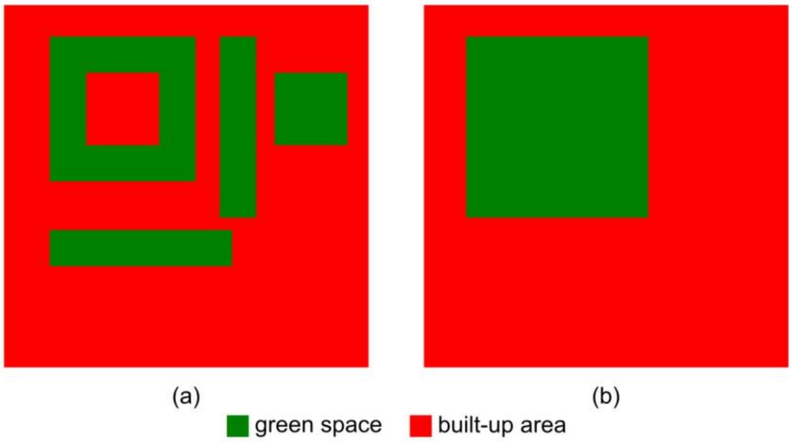


Figure 2.1. Schematic illustration of the loss of information due to lumping green spaces. (a) Real landscape pattern; (b) the lumped area used in many previous ecosystem services (ES) studies.

In many existing studies, the impact of urbanization and LULC change on ES is generally discussed using the lumped area of green spaces. Some studies have discussed the impact by comparing the ES changes and the changes of landscape patterns, which show that landscape patterns can affect ES. However, there is a lack of studies that directly examine the impact of landscape pattern changes of green spaces to ES calculation.

This study was aimed to identify the impact of landscape pattern changes on urban ecosystem services using two spatial configurations of green spaces, as shown in Figure 2.1. Firstly, the area of green spaces was assumed as a lumped area, as depicted in Figure 2.1(b). Secondly, the area of green spaces was assumed as a distributed area, as shown in Figure 2.1(a), which was represented by directly combining the area and landscape patterns defined by the aggregation and the connectivity of the green spaces and bodies of water. This study was designed to focus on the investigation of the landscape pattern changes and their influence on urban ES. It was expected that the results of this study can provide insight into the influence of landscape patterns on ES calculation. Moreover, the validation of the results was not a part of this study since there was a lack of field survey data for all municipalities in Jakarta. Hence, the validation would be considered as a part of further studies.

This study was divided into three main parts: (1) assessing the impact of urbanization on LULC changes; (2) analysing the impact of LULC changes on the landscape patterns; and (3) analysing the impact of the landscape pattern changes on ecosystem services.

2.2 MATERIAL AND METHODS

This study was carried out in Jakarta, Indonesia, and it was conducted in six steps. First, LULC maps for 1995 and 2014 were generated using Landsat images. The LULC classification used six LULC classes, which were urban, suburban, grassland, cropland, trees, and water (sea and surface water). Second, the results of LULC classification were imported into the FRAGSTATS, the spatial pattern analysis program, for landscape metric analysis. The analysis considered four landscape metrics and the relationship between them: Class Area (CA), Land Proportion (PLAND), Aggregation Index (AI) and connectivity (COHESION). The landscape metrics analysis was carried out for five municipalities of Jakarta. Third, the impact of urbanization on LULC change was analysed, which was based on the CA of LULC classes. Fourth, the impact of LULC change on the landscape patterns was analysed, which was based on PLAND, AI and COHESION. Fifth, ecosystem services were calculated using two methods: area-based estimation and landscape metric area (LMA). The area-based estimation followed commonly ecosystem services area calculation that uses only the area of green spaces, while the landscape metric area directly incorporated the landscape metric representing the spatial characteristic/configuration of green spaces to ecosystem services area calculation. Sixth, ecosystem services changes between 1995 and 2014 from two different methods were then analysed using ecosystem services index (ESI).

2.2.1 Data sources

The impact of urbanization on LULC change was analysed using land use–land cover maps of Jakarta for the year 1995 and 2014. The maps were prepared using Landsat images selected for the area of Jakarta and its surrounding. For the year 1995, the Landsat 5 TM L1TP from 24 August 1995 was used, while the Landsat 8 OLI TIRS L1TP obtained on 13 September 2014 was selected for the land use–land cover map of the year 2014. Both datasets had 30 m resolution. The land cover classification was based on the land cover classes used to investigate the relationship between green spaces and increasing urban temperature (De Ridder et al., 2004). We used the semiautomatic classification in QGIS (Leroux et al., 2018), a free and open-source geographic information system, to generate six land cover classes: urban, suburban, grassland, cropland, trees, and water. An urban area is an area where there is a dense mix of compact high-rise, compact midrise, or low-rise buildings, while a suburban area is an open arrangement of low-rise buildings with pervious land covers, such as grass, low plants, and scattered trees. A grassland area is defined as an area where the vegetation is dominated by grasses, and there are few or no other plants. A cropland area is an area mainly used for agricultural and farming purposes, where rice, corn, vegetables, and fruits are grown. An area of trees is an area where trees are dominant. Water represents both sea and surface water, such as rivers and lakes. Moreover, the LULC change analysis was based on the CA from five land cover classes: urban, trees, grassland, cropland, and bodies of water.

The boundary area of Jakarta and its municipalities was obtained online from the Geospatial Information Agency of Indonesia (BIG) database, https://tanahair.indonesia.go.id/portal-web (accessed on 24-09-2019).

2.2.2 Landscape metrics

Landscape metrics are quantified characteristics of the spatial pattern at different levels (i.e., patch level, class level and landscape-level) used to describe landscape structures and LULC change (Arowolo et al., 2018; Gökyer, 2013; Mugiraneza et al., 2019). Landscape structure can be used to describe the composition and configuration of green spaces (Mitchell et al., 2015). Composition refers to vegetation density and variety of land-cover types, and green spaces size (Leitao et al., 2006). On the other hand, configuration of UGS is related to spatial pattern as well as the layout of UGS including aggregation, shape, and cohesion of patches (Sodoudi et al., 2018). Information about landscape structures is essential to analyse ecosystem structures, functions and services (Daniels et al., 2018) and to evaluate their spatial effects at the patch–class–landscape level (Estoque & Murayama, 2013; McGarigal et al., 2014). Patch level metrics are important for defining individual patches and for characterizing the spatial context of the patches, which are used as the computational basis for other landscape metrics. At the class level, the metrics are calculated by integrating all patches from a given class. The class level calculation can be done by a simple aggregation of the area of patches to reflect the total area of a given class. Moreover, landscape-level metrics are the integration of all classes over the landscape (De Smith et al., 2007). This study used four landscape metrics to capture the spatial features which affect urban ecosystem processes: class area (CA), connectivity (COHESION), land proportion (PLAND), and aggregation index (AI). CA is a measure of landscape composition; specifically, to indicate how much of the landscape is comprised of a patch type. The class area is the primary component used in the ecosystem service quantification (Mugiraneza et al., 2019). The connectivity of a class is measured by the patch cohesion index (COHESION) that measures the physical connectedness of the corresponding patch type. Patch cohesion increases as the patch type become more clumped or aggregated in its distribution; hence, more physically connected (Kong et al., 2010). The decrease in patch connectivity in a landscape can be a negative sign for ecosystem services (Haas et al., 2015). The land proportion (PLAND) is the percentage of a landscape, which quantifies the proportional abundance of each patch type in the landscape, while the AI is used to understand the spatial aggregation of a patch in a landscape (Amani-Beni et al., 2019; He et al., 2000; Mugiraneza et al., 2019). The landscape metrics in this study were calculated using FRAGSTATS 4.2, the spatial pattern analysis program, which was developed by McGarigal and Cushman of University of Massachusetts in the United States of America (McGarigal et al., 2014).

The landscape metrics used in this study were selected based on the premise that there is a correlation between ES and the area, the aggregation, and the connectivity of ecosystem (Amani-Beni et al., 2019; Bao et al., 2016; Mugiraneza et al., 2019). In general, many ES studies focus on the relationship between ecosystem services and the area of green spaces revealing a positive correlation between the size of the green spaces and the weight of the ecosystem services provided (J. Chen & Goh, 2017; Estoque et al., 2017; X. Li et al., 2012). However, some studies showed that ecosystem services were also influenced by landscape patterns (Bai et al., 2018; X. Li et al., 2012; Ramesh et al., 2015; B. Zhang et al., 2015). In this study, ES was analysed by considering the "effective area" of green spaces and bodies of water by considering the influence of aggregation and connectivity on the area of green spaces and bodies of water. The landscape metric combinations for this study were selected based on the FRAGSTATS 4.2 guidelines and the existing research on landscape metric and ES. There are some indices that can be used to analyse the relationship between landscape metrics and ES, such as Number of Patch (NP), Patch Density (PD), Large Patch Index (LPI), patch cohesion index (COHESION), land proportion (PLAND), CONTAGION, and Aggregation Index (AI). Furthermore, the AI was selected because it can give more accurate results compared to that of other aggregation indices, such as CONTAGION (He et al., 2000), while the COHESION was selected for connectivity analysis because it can represent the connectivity of a corresponding patch type of a particular class (Haas et al., 2015; Kong et al., 2010). This resulted in the "Landscape Metric Area" (LMA) calculated by multiplying the metrics class area (CA), aggregation index (AI), and cohesion index (COHESION) for each land cover class, as follows:

$$LMA = CA \times AI \times COHESION \tag{2.1}$$

2.2.3 Urban ecosystem services

Many studies discussed ES in urban areas (Bolund & Hunhammar, 1999; Cortinovis & Geneletti, 2018; Derkzen et al., 2015; Haas et al., 2015; Mugiraneza et al., 2019; Vincent et al., 2017). Back in the 1990s, one of the pioneering urban ecosystem services studies considered six ecosystem services: air filtering, microclimate regulation, noise reduction, rainwater drainage, sewage treatment, and recreation (Bolund & Hunhammar, 1999). Derkzen et al. (2015) studied ecosystem services bundles in Rotterdam, the Netherlands, considering six ecosystem services: air purification, carbon storage, noise reduction, runoff regulation, cooling, and recreation. The importance of urban ecosystem services inspires local and national governments to incorporate ES in their urban planning process and documents (City of Sydney, 2017; Cortinovis & Geneletti, 2018; Oslo, 2011; Rotterdam, 2015). For example, the government of Indonesia requires a minimum of 30% open green spaces in each city and urban area (Arifin & Nakagoshi, 2011; Werner, 2014).

In this study, ES changes analysis was limited to carbon sequestration, temperature regulation, and runoff regulation, due to the limitation of the medium resolution satellite images to capture several urban details, such as street corridors and small city parks. Furthermore, in the ES selection increasing carbon emissions (Rusiawan et al., 2015; Surahman et al., 2016), and recent climate-related hazard events in Jakarta, such as urban flooding in 2013, 2014, 2015, and 2020, have also been considered (Siswanto et al., 2015; Wijayanti et al., 2017), as well as the potential increase in the urban temperature (Darmanto et al., 2019; Ramdhoni & Rushayati, 2016). The ES estimation adopted a weighting factor used in (Derkzen et al., 2015), where the green space with high-temperature regulation capacity was given a weight of 1.0, whereas 0.5 was given for low capacity. In this study, the weighting factor was implemented for all ES estimations for which the factor was given based on the importance of a particular green space to a particular ES. For example, grassland was given the weight of 0.5 for temperature regulation, but it was given 1.0 of the weight factors for runoff regulation.

2.2.4 Carbon sequestration

Green spaces have an important role in the carbon cycle, capturing CO_2 from the atmosphere during photosynthesis, and releasing it during respiration. In an urban area, carbon sequestration mainly takes place in green spaces (Churkina, 2011; Kuittinen et al., 2016; Nero et al., 2017). Each green space has a different carbon sequestration rate, and urban trees generally have a higher rate compared to that of other green spaces because of their higher leaf area index (LAI), which is the ratio of the area of trees' leaves per area of the land surface (Forman, 2013). For example, the urban forest of Punggol Forest in Singapore had the annual carbon sequestration rate of 1.6 ton/year/ha, where trees with high LAI such as *Delonix regia* and *Artocarpus heterophyllus* gave a significant contribution (J. Chen & Goh, 2017). Studies from Indonesian cities showed that trees had a carbon sequestration rate higher than that of other vegetation, including grass and herbaceous. For instance, the carbon sequestration of tree-covered areas in a part of Jakarta was 129.92 kg/ha/hour, much higher than 2.74 kg/ha/hour for grass areas (Azaria et al., 2018). Moreover, trees in the city of Singaraja on Bali Island had 112.751 tons/ha of carbon sequestration higher than 4.845 tons/ha of carbon sequestration of herbaceous (Oviantari et al., 2018).

In this study, carbon sequestration was based on the LMA of trees. The LMA of trees was given a weight of 1.0 considering its carbon sequestration, which is higher than that of other vegetation. Other types of green spaces were given a weight of 0, assuming no significant contribution to capturing carbon in the atmosphere.

2.2.5 Temperature regulation

Increasing LST and air temperature in urban areas can be influenced by several factors, including a decrease in green spaces and bodies of water. The contribution of green spaces to the control of urban temperatures can be achieved through ecosystem functions such as evapotranspiration, trees shading, and modifying air movement, while the greatest contributing factor to the cooling effect is shading and evapotranspiration (Oke et al., 2017). The effectivity of green spaces in providing the ecosystem functions is influenced by various factors, including the area and the spatial distribution of green spaces (Maheng et al., 2019), the configuration and the shape of green spaces (Bao et al., 2016; Sodoudi et al., 2018), and the connectivity of green spaces (Amani-Beni et al., 2019). Among green spaces, trees have high cooling potential through shading and evapotranspiration, while other short vegetative covers such as grass and crops might have a lower capacity (Amani-Beni et al., 2018; Derkzen et al., 2015). The temperature in urban areas can also be regulated through evaporation and heat absorption from bodies of water (Steeneveld et al., 2014). The cooling effect of bodies of water is influenced by the area of the bodies of water (Theeuwes et al., 2013), and the effect decreases with the increase in distance from the water body, which is similar to the cooling effect from green spaces (Y. C. Chen et al., 2014; Gunawardena et al., 2017).

Temperature regulation in this study was estimated using the combination of the LMA from trees, grassland, cropland, and bodies of water. The LMA of trees was given a weight of 1.0, while a weight of 0.5 was given for the LMA of grassland, cropland, and bodies of water.

2.2.6 Runoff regulation

Due to urbanization, cities and urban areas are more vulnerable to urban flooding. The increasing vulnerability is influenced by some factors such as a decrease in green spaces and bodies of water. As a result, many urban areas have an insufficient capacity for infiltration and interception, as well as an increase in the runoff coefficient. Urban flooding-related studies showed that the area of green spaces can be considered as one of the important factors that determine runoff regulation (A. Alves et al., 2020; B. Yang et al., 2019; B. Zhang et al., 2015). For instance, increasing tree-cover by nearly 11% in Beijing could increase the total runoff reduction volume by more than 30% (Yao et al., 2015). Moreover, the capacity of green spaces in controlling surface runoff is also influenced by several factors, including the interception of rainfall. Among many types of green spaces, trees can provide the high interception capacity, particularly in the short–moderate rainfall or in the earlier periods of precipitation, and it decreases in the longer duration or during high rainfall intensity (ASCE, 1996). A field experiment from the city of Uruaçu, Goiás, Brazil, showed that interception rate during short, low-intensity precipitation was about 40%, while the rate was about 3.6% in the high intensity and long duration rainfall (P. L. Alves et al., 2018). Besides interception, green spaces also provide runoff regulation through infiltration, which is influenced by numerous factors including rainfall intensity, green space types, soil characteristics, and green space coverage (Fox et al., 2012; Highfield, 2011; Te Chow et al., 1988; X. Yang et al., 2013). In addition, green spaces contribute to runoff coefficients by increasing flow resistance, which can be associated with its density (Shang et al., 2020). Furthermore, bodies of water like rivers, lakes, and wetlands also have the potential to control surface runoff through storage functions (A. Alves et al., 2020).

The estimation of runoff regulation service in this study considered the combination of the LMA from trees, cropland, grass, and bodies of water. All green spaces were given a weight of 1.0 based on the assumption that green spaces and bodies of water had a similar contribution to runoff regulation from one or the combination of infiltration, interception, flow resistance, and storage functions.

2.2.7 Ecosystem services index (ESI)

This study used ecosystem services index (ESI) to assess the ES changes. The ESI was based on the ES calculated using the combination of the LMA from green spaces and bodies of water. The ES calculation was divided into two steps. First, the ES was only based on the area of green spaces and bodies of water called area-based estimation. Second, the ES was based on the LMA Calculated using the following equation.

$$ES = aLMA_{tree} + bLMA_{grassland} + cLMA_{cropland} + dLMA_{water} \quad (2.2)$$

where a, b, c, and d were the weighting factors for each green space and bodies of water. The weighting factor was different for each green space in each ES estimation, as given in Table 2–1.

Table 2–1. The weighting factors. Modified from Derkzen et al. (2015).

Weighting factors	**Carbon sequestration**	**Temperature regulation**	**Runoff regulation**
a (trees)	1	1	1
b (grassland)	0	0.5	1
c (cropland)	0	0.5	1
d (water)	0	1	1

The ESI was then calculated by normalizing the ES values using the following formula:

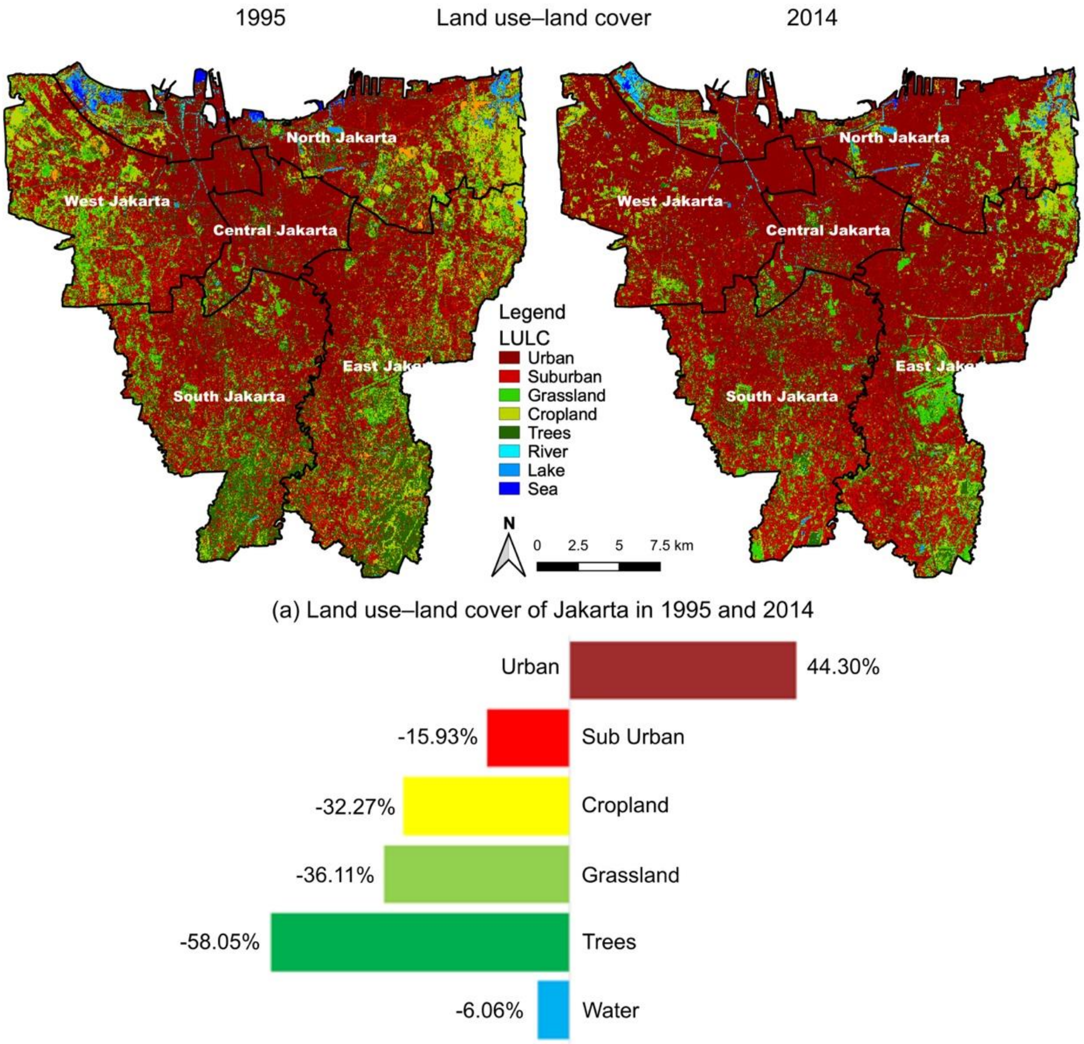
$$ESI_{ij} = \frac{ES_{ij} - ES_{min}}{ES_{max} - ES_{min}} \qquad (2.3)$$

where ESI_{ij} is the index of ES, i for the municipality j, ES_{ij} is the value from ES i for the municipality j, andES_{min} and ES_{max} are the minimum and the maximum value of ES i, respectively.

2.3 RESULTS

2.3.1 Land use–land cover (LULC) change analysis

The high rate of land transformation marked urbanization in Jakarta from 1995 to 2014, as shown in Figure 2.2. It shows that there had been a substantial change in the spatial distribution of green spaces due to increasing urban areas. The growing urban areas was about 44.3%, while the loss of trees was about 58.1%, followoed by the loos of grassland of about 36.1%, cropland of about 32.3%, suburbanareas of about 15.9%, and 6.1% of bodies of water (lakes and rivers).



(a) Land use–land cover of Jakarta in 1995 and 2014

(b) Land use–land cover transitions between 1995 and 2014

Figure 2.2. Land use–land cover changes from 1995 to 2014.

The LULC change in the study was analysed by focusing on the spatial extension of the urban areas and the decrease in vegetative cover and bodies of water from 1995 to 2014, as shown in Figure 2.3. In 1995, the spatial distribution of urban areas was concentrated in three municipalities, which were East Jakarta (65.3 km^2), followed by North Jakarta (63.9 km^2) and South Jakarta (58.5 km^2). On the other hand, the smallest urban area was about 35.4 km^2, which was observed in Central Jakarta. After 20 years, urban areas increased in all municipalities. The largest urban area in 2014 was about 97.8 km^2 in West Jakarta, which increased by about 93.7% from that in 1995. Meanwhile, urban areas in East Jakarta and North Jakarta increased by almost a half from that in 1995. On the other hand, the smallest urban area, by approximately 38.4 km^2, was identified in Central Jakarta, which increased by 8.2%.

The increase in built-up areas was also observed in suburban areas from 1995 to 2014, as shown in Figure 2.3. In 1995, the largest suburban area was detected in East Jakarta (36.4 km^2), followed by South Jakarta (31.6 km^2) and West Jakarta (26.9 km^2). Central Jakarta had the smallest suburban area by about 4.30 km^2. The spatial distribution of suburban areas in 2014 was a bit different from urban areas, which increased in all municipalities. The changes of suburban areas were marked by a decrease in West Jakarta (−64.0%), followed by North Jakarta (−51.0%) and Central Jakarta (−19.6%), but they increased in East Jakarta and South Jakarta. The largest suburban area of 38.37 km^2 was identified in East Jakarta, which increased by 5.3% from that in 1995. This increase, however, was lower than 17.7% in South Jakarta. On the other hand, the smallest suburban area of 3.4 km^2 was detected in Central Jakarta.

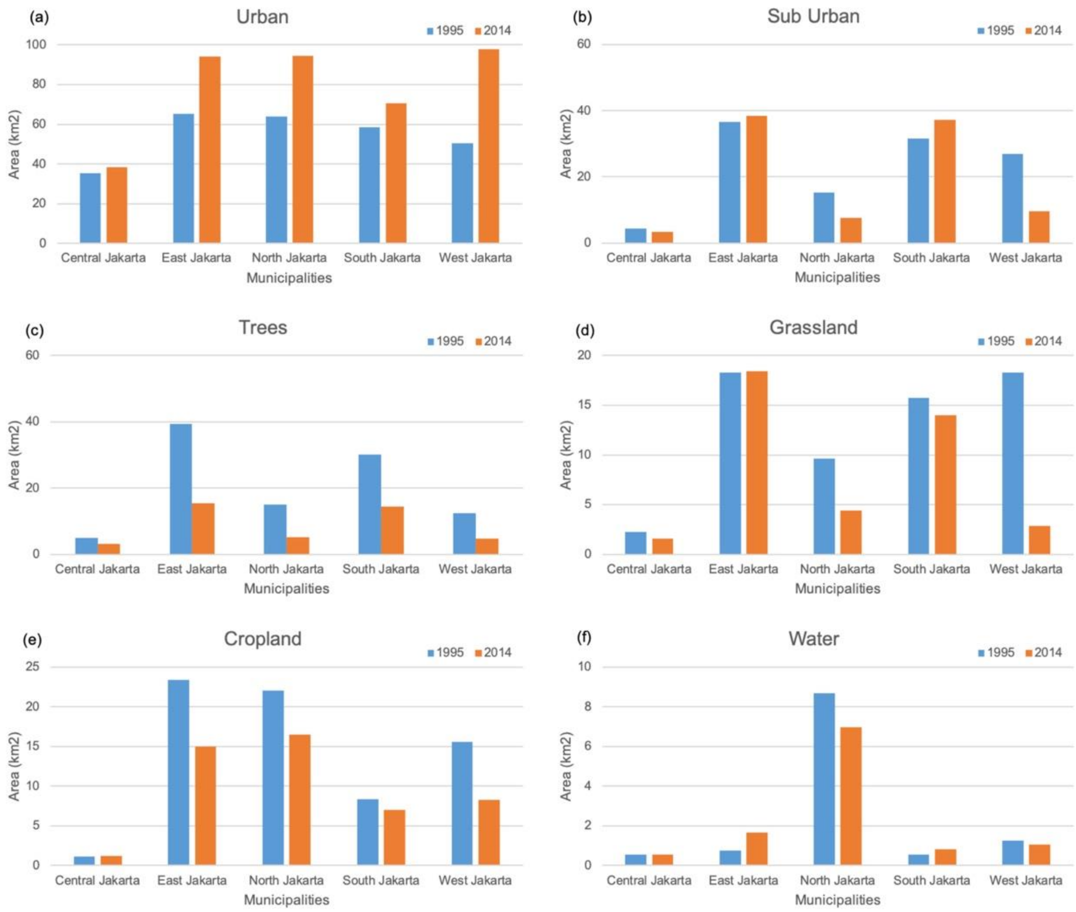


Figure 2.3. The area of land use–land cover of Jakarta in 1995 and 2014. (a) The area of urban class; (b) the area of suburban class; (c) the area of trees; (d) the area of grassland; (e) the area of cropland; (f) the area of bodies of water.

The dynamic changes of the built-up areas affected the area of green spaces, where trees were by far the most affected, followed by grassland and cropland, as shown in Figure

2.3 and Figure 2.4. In 1995, trees were mainly distributed in East Jakarta and South Jakarta, where the area of trees was more than two times of that in the other municipalities, such as in North Jakarta and West Jakarta. The largest area of trees (39.4 km^2) was observed in East Jakarta, while the smallest area of 5.0 km^2 was in Central Jakarta. In 2014, the area of trees decreased above the average in all municipalities except in South Jakarta and Central Jakarta. A significant decrease of 65.8% was observed in North Jakarta, followed by West Jakarta (−62.2%) and East Jakarta (−61.1%). However, the area of trees in that area was still higher than that in other municipalities. For instance, East Jakarta had the largest area of trees (15.4 km^2), which was higher than 14.5 km^2 in South Jakarta. On the other hand, the smallest area of trees (3.2 km^2) was detected in Central Jakarta.

Besides trees, areas of grassland were also impacted by an increase in the built-up areas, as depicted in Figure 2.3 and Figure 2.4. In 1995, the widespread occurrence of areas of grassland was mainly detected in East Jakarta, West Jakarta, and South Jakarta. The largest grassland area (18.3 km^2) was observed in East Jakarta, which was similar to that of West Jakarta. On the other hand, Central Jakarta had the smallest area of about 2.3 km^2. In 2014, the grassland area remained almost the same in East Jakarta, while a significant decrease of 84.5% was observed in West Jakarta, followed by North Jakarta (−54.5%). The smallest area of grassland was observed in Central Jakarta (1.6 km^2), followed by West Jakarta (2.8 km^2) and North Jakarta (4.4 km^2).

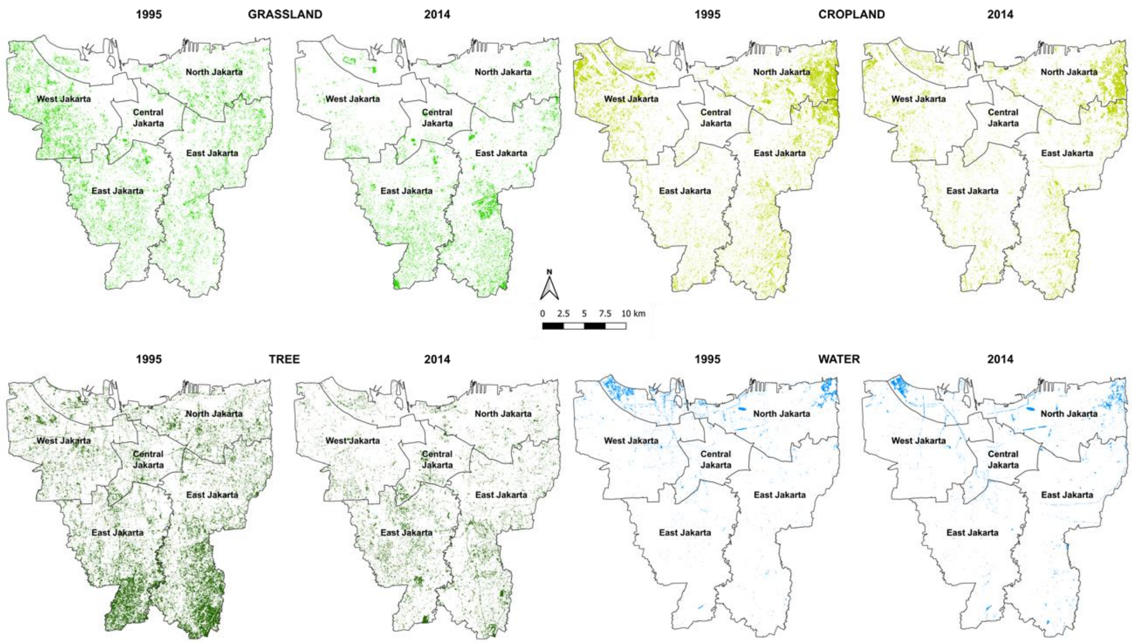


Figure 2.4. The spatial and temporal distribution of green spaces and bodies of water in 1995 and 2014.

A decrease in the area of green spaces was also found in the area of cropland during urbanization from the year 1995 to 2014, as shown in Figure 2.3 and Figure 2.4. The spatial distribution of cropland in 1995 was dominant in East Jakarta and North Jakarta, where the areas of cropland were 23.4 km^2 and 22.1 km^2, respectively. In 2014, there was a decrease in the area of cropland. The highest decrease was identified in West Jakarta, where the area of cropland decreased by 47.1%, followed by East Jakarta (−35.9%) and North Jakarta (−25.2%). Moreover, the spatial distribution of cropland in 2014 was similar to that in 1995, where the dominant distribution of cropland was observed in North Jakarta (16.5 km^2), followed by East Jakarta (14.9 km^2).

The existence of bodies of water between 1995 and 2014 was identified by a small decrease by −6.1%, as shown in Figure 2.3 and Figure 2.4. The spatial distribution of the bodies of water was mainly observed in North Jakarta, representing lakes, fishponds, and wetlands. As a result, North Jakarta had the largest area of bodies of water between 1995 and 2014, where small patches of bodies of water, including rivers, creeks, and small wetlands, were evenly distributed in all municipalities.

2.3.2 Landscape metrics analysis

The rapid urbanization in Jakarta not only changed the spatial distribution of green spaces but also altered the landscape patterns indicated by changes in the proportion, the aggregation, and the connectivity of green spaces, as well as of bodies of water. In 1995, landscape metrics analysis showed the highest proportion of trees at the municipality level of about 20% in East Jakarta and South Jakarta, while other municipalities had about 10% of trees in their area. Meanwhile, trees showed a dispersed distribution in Central Jakarta, North Jakarta, and West Jakarta, where the AI was lower than 50%. However, trees had good connectivity, as shown in Figure 2.5. It shows that trees had the COHESION higher than 60% in all municipalities, with the highest values being observed in South Jakarta.

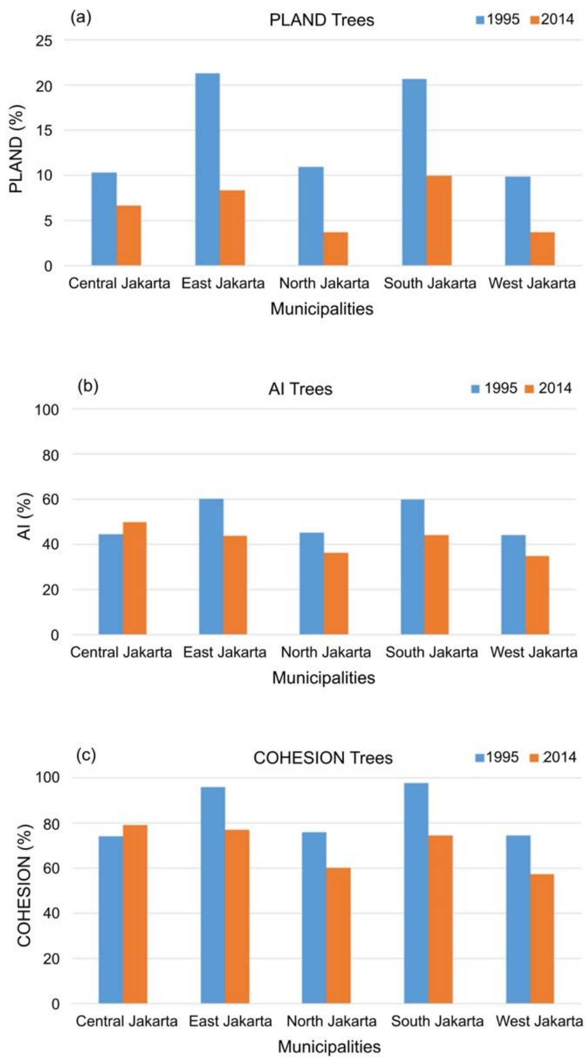


Figure 2.5. Landscape metrics of trees. (a) Land proportion (PLAND); (b) aggregation index (AI); (c) cohesion (COHESION).

In 2014, the proportion of trees decreased in all municipalities, where the highest decrease of 65.8% was observed in North Jakarta, followed by West Jakarta and East Jakarta, where the proportion decreased by 62.2 and 61.1%, respectively. Meanwhile, the highest trees proportion of 9.9% was identified in South Jakarta, followed by East Jakarta (8.3%) and Central Jakarta (6.6%), while a similar proportion was observed in West Jakarta and North Jakarta. The decrease in the proportion of trees was followed by a decrease in the aggregation and the connectivity of trees except in Central Jakarta. It was found that trees in Central Jakarta were more aggregated and connected in a small proportion. The aggregation and the connectivity of trees in Central Jakarta increased by 12.1 and 6.7%, respectively. In other municipalities, trees were more disaggregated, as indicated by a decrease in the AI values. For instance, the AI in East Jakarta and South Jakarta decreased by 27.4 and 26.3%, respectively. Furthermore, the connectivity of trees also decreased in East Jakarta and South Jakarta, where the connectivity decreased by 19.7 and 23.8%, respectively. However, the connectivity of trees was still high in all municipalities since the COHESION was higher than 50%.

Meanwhile, the dominant proportion of the urban areas also influenced the landscape patterns of the grassland, as shown in Figure 2.6. In 1995, the highest proportion of grassland was about 14.5% in West Jakarta, followed by South Jakarta (10.9%) and East Jakarta (9.9%). The proportion of grassland in West Jakarta was found higher than the proportion of trees in the same year, which showed a different green space pattern in a municipality. Meanwhile, the low AI percentage indicated that grassland had dispersed distribution in all municipalities. The connectivity of grassland in 1995 was almost similar in four municipalities where the connectivity varied from 71.4% to 72.4%. The highest connectivity of grassland was observed in West Jakarta, where COHESION was 84.9%.

In 2014, all municipalities saw a decrease in the proportion of grassland. The highest decrease was observed in West Jakarta, where the proportion decreased from 14.5% in 1995 to 2.2% in 2014. In addition, the location of the highest proportion shifted from West Jakarta to East Jakarta. The highest grassland proportion of 9.9% was identified in East Jakarta, which was slightly higher than 9.6% in South Jakarta. On the other hand, a similarly low proportion was observed in Central Jakarta, North Jakarta, and West Jakarta, where the proportion of grassland was 3.3, 3.2, and 2.2%, respectively. Furthermore, the area of grassland underwent a small amount of disaggregation in all municipalities except in East Jakarta, where the area of grassland was aggregated by 12.7%. The connectivity of grassland in 2014 was also affected by urbanization as it decreased in four municipalities, but it increased in East Jakarta. The highest decrease was 29.3%: this was observed in West Jakarta, where the connectivity reduced from 84.9% in 1995 to 60.0% in 2014. Moreover, a small decrease was found in Central Jakarta, South Jakarta, and North Jakarta, where the connectivity decreased by 5.9, 5.3, and 3.5%, respectively.

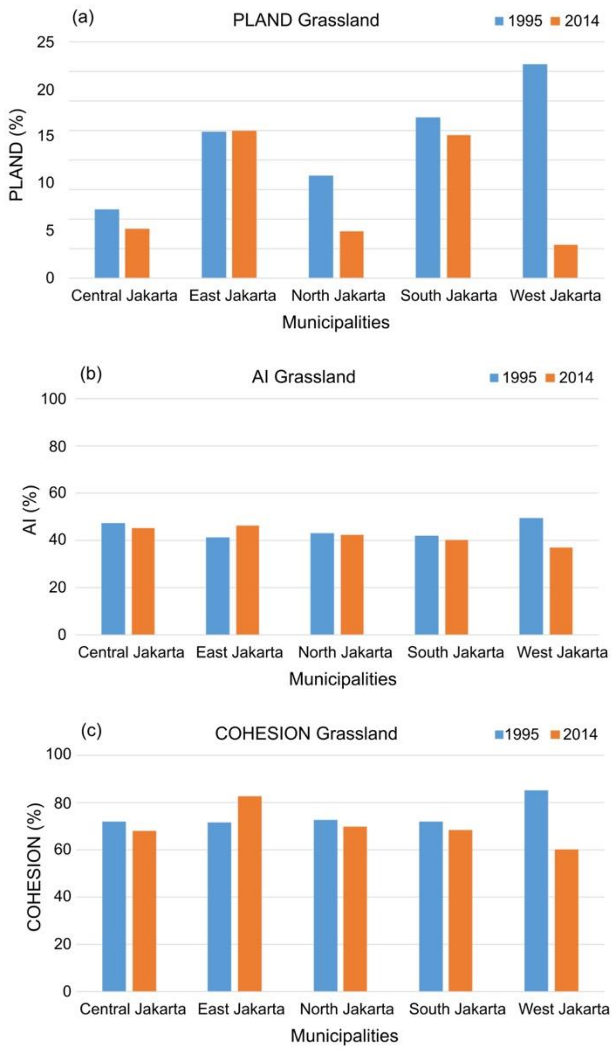


Figure 2.6. Landscape metrics of grassland. (a) Land proportion (PLAND); (b) aggregation index (AI); (c) cohesion (COHESION).

Moreover, the landscape patterns of cropland were also subject to dynamic changes due to urbanization, as shown in Figure 2.7. In 1995, the highest proportion of cropland was mainly observed in North Jakarta, East Jakarta, and West Jakarta. The highest cropland proportion of 15.9% was observed in North Jakarta, while the lowest cropland proportion of 2.3% was observed in Central Jakarta. Meanwhile, the cropland distribution in the four municipalities exhibited a scattered pattern, as indicated by the AI percentage. For instance, cropland in Central Jakarta, East Jakarta, and South Jakarta was below 50%. Moreover, the connectivity of crops was high in North Jakarta, West Jakarta, and East Jakarta, where the COHESION was 95.3, 87.9, and 84.6%, respectively.

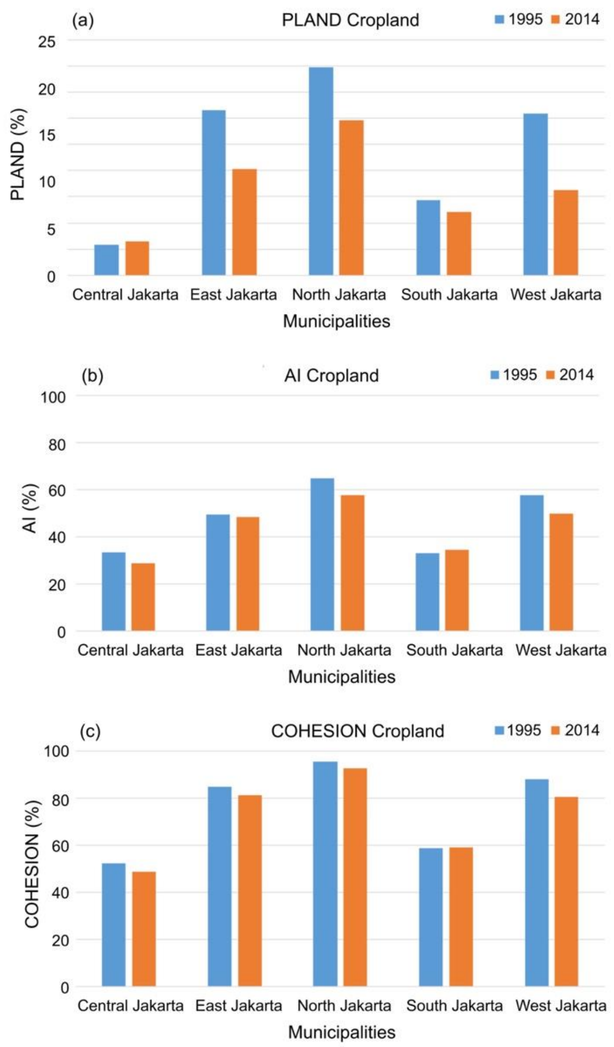


Figure 2.7. Landscape metrics of cropland. (a) Land proportion (PLAND); (b) aggregation index (AI); (c) cohesion (COHESION).

In 2014, the proportion of cropland decreased sharply. The highest decrease of 47.1% was identified in West Jakarta, followed by East Jakarta and North Jakarta, where cropland decreased by 35.9 and 25.2%, respectively. However, North Jakarta still had the highest cropland proportion of 11.9%, while the smallest cropland proportion of 2.6% was observed in Central Jakarta. The decrease in the proportion of cropland affected its aggregation in some municipalities in 2014. For instance, cropland in West Jakarta was disaggregated by 13.9%, followed by North Jakarta and Central Jakarta, where cropland was disaggregated by 11.3 and 13.8%, respectively. Furthermore, cropland had a small decrease in the connectivity, but the percentage was still high. For instance, the highest decrease of 8.4% was observed in West Jakarta, where the connectivity of crops was 87.9%.

In contrast with the landscape patterns of green spaces, urbanization did not have a significant impact on the landscape patterns of bodies of water, as depicted in Figure 2.8. The proportion of bodies of water in 2014 was similar to that in 1995. The dynamic changes of the landscape patterns of bodies of water were marked by a small increase in the proportion of bodies of water in East Jakarta and South Jakarta, while this proportion decreased in North Jakarta and West Jakarta. However, the aggregation and the connectivity of bodies of water increased in all municipalities in 2014, as shown in Figure 2.8.

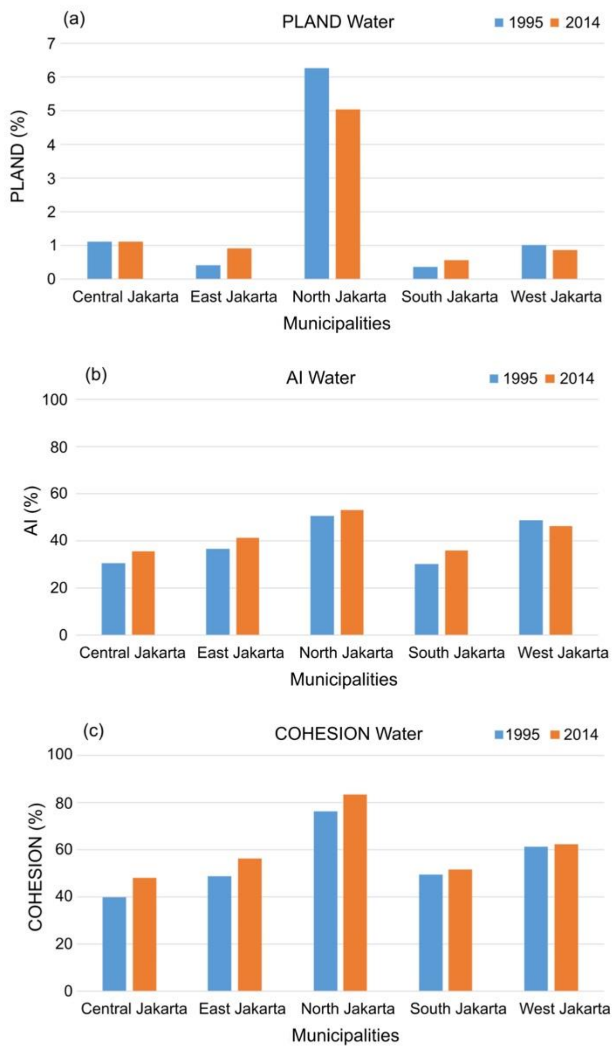


Figure 2.8. Landscape metrics of water. (a) Land proportion (PLAND); (b) aggregation index (AI); (c) cohesion (COHESION).

2.3.3 Spatial and temporal distribution of ES changes

The spatial and temporal distribution of ES changes were analysed using Equations (2.2) and (2.3). The results showed that the landscape pattern changes had a significant impact on the decrease in the carbon sequestration, temperature regulation, and runoff regulation.

The spatiotemporal changes of the carbon sequestration are given in Figure 2.9. The picture shows that the area-based estimation and the LMA-based estimation gave an almost similar pattern of the carbon sequestration, but the decrease rates were different. The area-based estimation that used a lumped area of trees gave a higher carbon sequestration capacity compared to that from the LMA-based estimation, which used an effective area. The area-based estimation showed that East Jakarta had the highest carbon sequestration in 2014, followed by South Jakarta, North Jakarta, West Jakarta, and Central Jakarta. The highest decrease in the carbon sequestration was identified in North Jakarta (−65.8%), followed by West Jakarta (−62.2%), East Jakarta (−61.1%), South Jakarta (−51.8%), and Central Jakarta (−35.5%). On the other hand, the landscape pattern changes in the LMA-based estimation gave a significant change in the carbon sequestration capacity. For instance, the LMA-based estimation suggested that North Jakarta had the highest decrease in the carbon sequestration (−78.4%), followed by East Jakarta (−77.3%), West Jakarta (−77.1%), South Jakarta (72.9%), and Central Jakarta (−22.8%). Furthermore, East Jakarta had the highest carbon sequestration in 2014, followed by South Jakarta, Central Jakarta, North Jakarta, and West Jakarta.

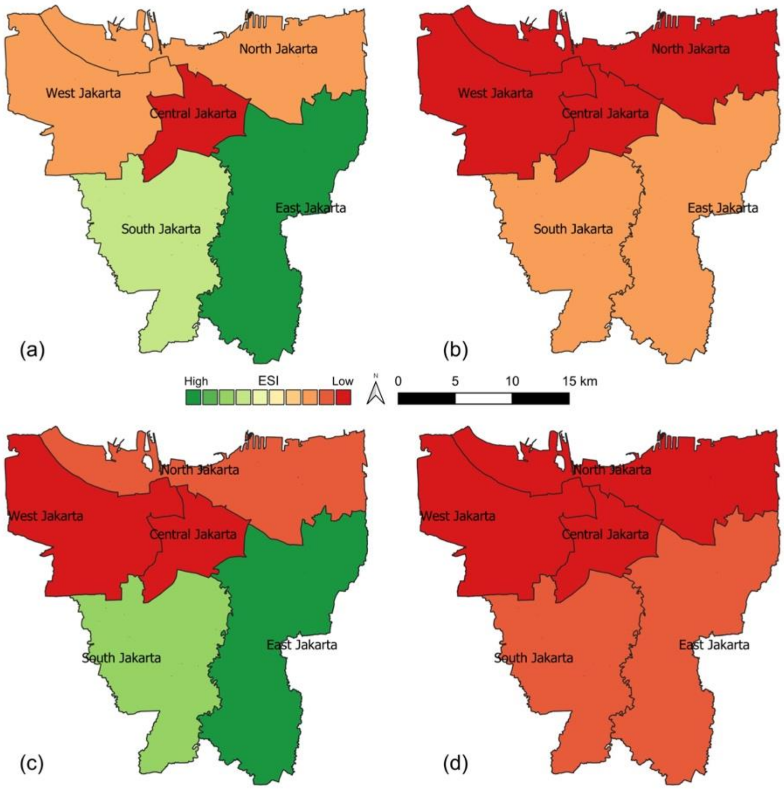


Figure 2.9. ESI for carbon sequestration in the year 1995 and 2014. (a) ESI in 1995 without LMA; (b) ESI in 2014 without LMA; (c) ESI in 1995 with LMA; and (d) ESI in 2014 with LMA.

The different spatial patterns of the temperature regulation indicated the influence of the landscape patterns of green spaces and bodies of water, as shown in Figure 2.10. It shows that the temperature regulation from the LMA-based estimation had a higher decrease rate compared to that from the area-based estimation. The impact of the landscape pattern changes on the temperature regulation was reflected in the LMA-based estimation that suggested the highest decrease rate in West Jakarta (−74.6%), followed by South Jakarta (−64.1%), East Jakarta (−61.1%), North Jakarta (−50.1%), and Central Jakarta (−23.7%). Moreover, the highest temperature regulation in 2014 was in East Jakarta, followed by North Jakarta, South Jakarta, West Jakarta, and Central Jakarta. On the other hand, the area-based estimation showed a similar spatial distribution of the temperature regulation, but the decrease rate was lower than that in the LMA-based estimation. For instance, the decrease rate of the temperature regulation with the area-based estimation in East Jakarta was −44.7% lower than that from the LMA-based estimation. This decreased pattern was also observed in all municipalities.

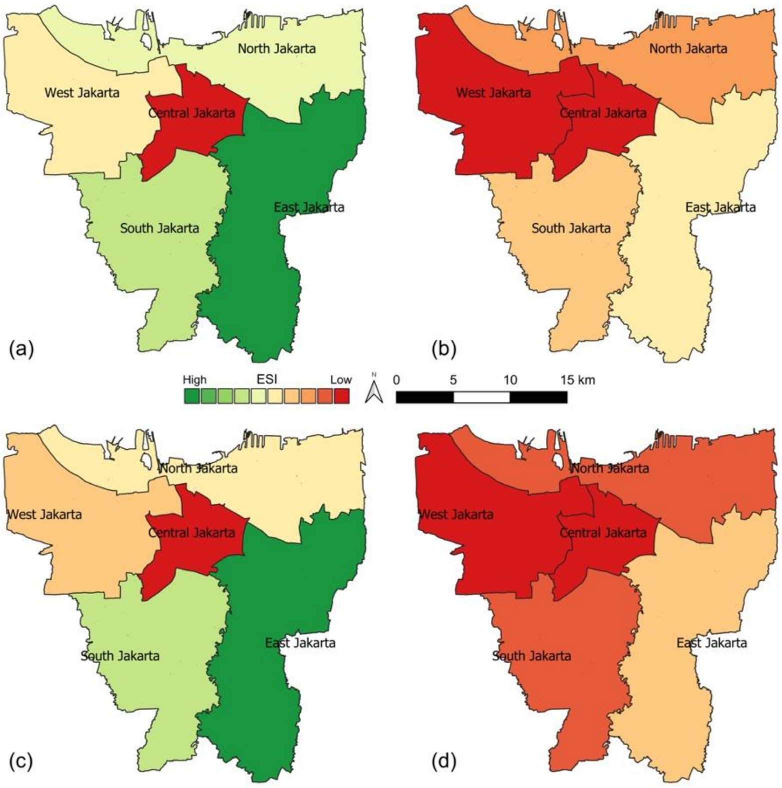


Figure 2.10. ESI for temperature regulation in the year 1995 and 2014. (a) ESI in 1995 without landscape metric area (LMA); (b) ESI in 2014 without LMA; (c) ESI in 1995 with LMA; and (d) ESI in 2014 with LMA.

Furthermore, the dynamic changes of the landscape patterns affected the spatial distribution of the runoff regulation, as shown in Figure 2.11. It shows that the area-based estimation indicated a decrease of the runoff regulation between 1995 and 2014 in all municipalities where the highest decrease was found in West Jakarta (−64.6%), followed by North Jakarta (−40.5%), East Jakarta (−38.4%), South Jakarta (−33.6%), and Central Jakarta (−25.8%). Meanwhile, East Jakarta had the highest runoff regulation in 2014, followed by South Jakarta and North Jakarta, while the lowest runoff regulation was in Central Jakarta. The LMA-based estimation, on the other hand, showed a higher decrease rate of the runoff regulation. By considering landscape metrics in the effective area of green spaces, the LMA-based estimation suggested that the highest decrease rate was in West Jakarta (−74.6%), followed by South Jakarta (−57.9%), East Jakarta (−51.8%), North Jakarta (−46.3%), and Central Jakarta (−25.0%). Furthermore, the highest runoff regulation was in East Jakarta, followed by North, South Jakarta, West Jakarta, and Central Jakarta.

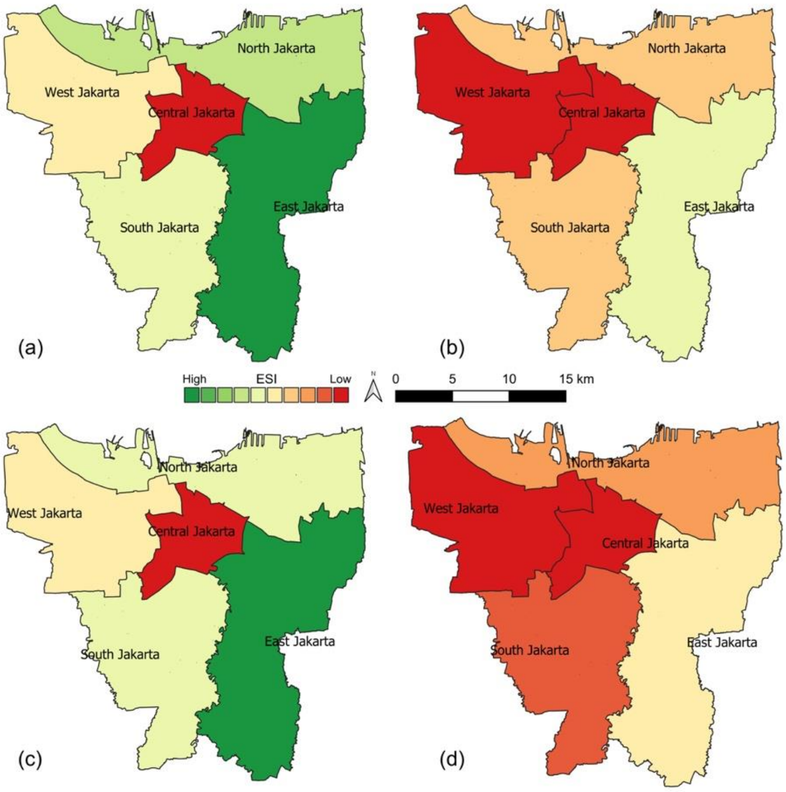


Figure 2.11. ESI for runoff regulation in the year 1995 and 2014. (a) ESI in 1995 without LMA; (b) ESI in 2014 without LMA; (c) ESI in 1995 with LMA; and (d) ESI in 2014 with LMA.

2.4 Discussion

2.4.1 Landscape pattern changes and ecosystem services

The LULC change analysis showed a considerable change in the spatial distribution and the landscape patterns of green spaces between 1995 and 2014, which in turn affected ecosystem services, as given by the LMA-based estimation. An increase in built-up areas results in a decrease in the size and the proportion of green spaces, as well as in the disaggregation and disconnection of green spaces. A change in the landscape patterns affects the capacity of green spaces to provide ecosystem services (Burkhard et al., 2012; Mugiraneza et al., 2019).

This study indicated that the decrease in the carbon sequestration between 1995 and 2014 was influenced by a decrease in the area of green spaces, as well as a decrease in the aggregation and the connectivity of trees. For instance, Central Jakarta was covered with about 3.2 km^2 of trees in 2014, which was smaller than the area of trees in North Jakarta (namely 5.2 km^2). However, the carbon sequestration capacity in Central Jakarta was higher than that in North Jakarta, which could be explained by differences in the landscape patterns. In Central Jakarta, the trees were more aggregated, as indicated by 49.6% of the AI index, while the AI of the trees in North Jakarta is 36.1%. Moreover, the trees in Central Jakarta were more connected, as seen from 78.9% of the COHESION, which was higher than 59.9% in North Jakarta. However, the influence of the connectivity and the aggregation of the trees was not always significant compared to its area. For instance, Central Jakarta had a smaller area and higher connectivity of trees, but carbon sequestration in that area was lower than that in East Jakarta, which had a higher area of trees. Furthermore, the aggregation of trees in East Jakarta was slightly lower than that in Central Jakarta and South Jakarta. The relationship between the carbon sequestration with the area and the landscape patterns of the green spaces was consistent with a previous study in Jakarta, which showed that a higher carbon sequestration rate was observed in the location of a large area of trees (Azaria et al., 2018). The essential influence of the area of trees in the carbon sequestration was also observed in a tropical city, such as Singapore (J. Chen & Goh, 2017) and in a city located at high latitudes, such as Espoo, Southern Finland (Kuittinen et al., 2016). Moreover, it is important to underline that the carbon sequestration discussed in this study and the examples from other cities were limited to a city or an urban scale. The urban carbon sequestration may not give a significant contribution to the global carbon sequestration process because the total carbon uptake from urban vegetation is smaller than carbon emissions in urban areas, as reported in some cities, including Mexico City and Singapore (Velasco et al., 2016), Beijing (Tang et al., 2016), and Cebu City, Philippines (Pansit, 2019).

The significant influence of the landscape patterns on ecosystem services was also observed when comparing the temperature regulation estimates based on the area and the landscape patterns of green spaces, and bodies of water. Between 1995 and 2014, temperature regulation was found to decrease in all municipalities where the contribution of green spaces was more significant than that of bodies of water, which had small areas and proportions as a result of the land cover classification. As a result, the bodies of water in this study only provided a small contribution to temperature regulation as well as to other ES. Moreover, temperature regulation was more influenced by the area of green spaces compared to the connectivity of green spaces. For instance, the lowest temperature regulation was identified in Central Jakarta and West Jakarta, where the area of green spaces was small in 2014, while the connectivity was high. On the other hand, the highest temperature regulation in 2014 was observed in East Jakarta, where the large area and the high connectivity of green spaces are observed. In addition, the proportion of green spaces in this municipality was relatively higher than that in other municipalities except for West Jakarta. A positive relationship between the increasing urban temperature and the dynamic changes of the landscape patterns were found in this study which was consistent with the spatial distribution of LST and air temperature in Jakarta discussed in Ramdhoni & Rushayati (2016). In their study, the high LST (higher than 30 °C) was distributed in all municipalities. At the same time, the high air temperature was identified in Central Jakarta, East Jakarta, and North Jakarta, mainly where the small and the fragmented green spaces were observed in our study. The relationship between LST and the landscape patterns of green spaces was also observed in three megacities in Southeast Asia: Jakarta, Bangkok, and Manila (Estoque et al., 2017). It revealed that Jakarta had the highest mean LST of the three cities considered. It was concluded that this high LST was caused by the relatively large, complex, and more aggregated impervious built-up areas of Jakarta. Furthermore, the impact of the decreasing aggregation and connectivity of green spaces was also identified in the urban centre of the Olympic Forest Park in Beijing, China. The observed increase in LST correlated with an increase in the green space fragmentation and a decrease in the green space connectivity (Amani-Beni et al., 2019).

Urbanization in Jakarta between 1995 and 2014 decreased runoff regulation in all municipalities, which could be related to a decrease in green spaces and bodies of water, and the landscape pattern changes. The changes in the runoff regulation were mainly influenced by the dynamic changes of the area and the landscape patterns of green spaces, while the influence of bodies of water was relatively small. The most significant decrease in runoff regulation was observed in West Jakarta, where there had been a high decrease in the area and the proportion of green spaces, which mean West Jakarta had the lowest runoff regulation. Furthermore, in all municipalities the connectivity of green spaces was relatively high while the proportion of green spaces was relatively low and more disaggregated, as shown by a decrease in the aggregation index. The low surface runoff regulation in North Jakarta and West Jakarta was consistent with the area inundated by the 2013 flood (Padawangi & Douglass, 2015). Moreover, the capacity of green spaces to control surface runoff can also be influenced by local physical characteristics such as the slope of the land. However, these characteristics were not addressed in this study. Increasing the area of green spaces for surface runoff control can be considered in the gentlest sloping area with the high topographic wetness index (TWI), while this is not an appropriate solution in an area with the steep slope and the low TWI (Kim & Park, 2016). The capacity of green spaces to minimize surface runoff was also associated with LPI and AI. In Beijing, for instance, a decrease of LPI and AI reduced the runoff reduction capacity from 23% in 2000 to 17% in 2010 (B. Zhang et al., 2015). The low connectivity and aggregation can be associated with a decrease in the capacity of green spaces to minimize surface runoff. A study from Texas, US, showed that large area, less fragmentation, and high connectivity of green spaces could play an important role in anticipating the mean annual peak runoff. On the other hand, urban development can increase the built-up land cover class, which has more edges, more complex shapes, and is more connected, which facilitates high runoff (Kim & Park, 2016).

2.4.2 Limitations of this study and future perspectives

The spatial analysis in this study used a medium satellite image resolution of 30 m from Landsat 5 and 8 to analyse three ecosystem services: carbon sequestration, temperature regulation, and runoff regulation. The Landsat products provide a cost-effective option for spatial analysis purposes, such as the LULC change analysis and the landscape metrics analysis. However, some specific urban details such as city parks, small wetland areas, and lakes, as well as street corridors, can not be captured properly. Meanwhile, this study's results have not yet been validated, which can limit the applicability of the proposed method. Even though it indicated a more realistic ES calculation, the proposed method can potentially bias the results due to different spatial scales used in this study and field survey data.

In future studies, the use of high spatial resolution satellite images for land use–land cover classification is recommended. This increases the spatial analysis quality, and it allows researchers to include more ecosystem services analysis, such as air purification from trees on street corridors or tourism and educational ecosystem services from the city and the neighbourhood parks. The proposed ES estimation can be further improved in the future by incorporating empirical values based on runoff coefficients derived from land cover classes. For validation purposes, future studies should consider methods which apply remote sensing techniques using a range of spatial resolutions combined with actual land management information to identify carbon sequestration rates, land surface temperatures, and flood-prone areas.

2.5 Conclusion

The present study showed that the landscape pattern changes in the period 1995–2014 had a significant impact on urban ES in Jakarta. The observed landscape pattern changes reduced the carbon sequestration, the temperature regulation and the runoff regulation with an average value of 66, 55 and 51%, respectively, during that period. The impact of the landscape pattern changes on a decrease of ES was higher compared to the area-based calculation in which the average decrease of the carbon sequestration was 55%, followed by the temperature regulation (44%) and the runoff regulation (41%). This indicates that the ability of green spaces to provide ES is strongly influenced by the spatial characteristics or the landscape patterns of green spaces.

From 1995 to 2014, it was observed that urbanization had not only reduced the number and total surface area of green spaces but also had changed its spatial characteristics. After 20 years, an increase in built-up areas had affected the spatial characteristics of green spaces marked by a scattered distribution, and a decrease in the aggregation and the connectivity of green spaces, making green spaces more fragmented. The average decrease in aggregation was about 8.7 and 9.6% for its connectivity, which could be associated with a decrease in urban ES. The reduced number and area of green spaces along with the landscape pattern changes and a decrease in urban ES indicate that there is a relationship between those factors, which need to be considered in the ES calculation.

This study proposed a new method for ES calculation that explicitly acknowledges the landscape patterns of green spaces resulting in the landscape metric area (LMA) of an urban area. The LMA reflects the area which is defined as green space that provides an effective contribution to ES. The spatial characteristics of green spaces are not static but change over time. This study shown that urbanization is a factor that impacts the separation and disaggregation as well as the disconnection of green spaces—and thus to a large extent the spatial distribution of green spaces. Ignoring the influence of the landscape patterns may result in an under or an overestimation of the ES of an urban area, as shown in this study.

The importance of the area of green spaces to ES provision has been discussed in many previous studies, which feed the general perception that there is a positive relationship between the area of green spaces and ES. The findings of our study contribute to the existing body of knowledge in this field and suggest that ES calculations should consider not only the area of green spaces but also the landscape patterns, which represent the spatial configuration of green spaces. By considering the landscape patterns in this study, the proposed method indicates a more realistic ES calculation compared to commonly area-based approaches in which green spaces can be perceived as a lumped area. This study is one of the first to provide quantified and convincing evidence of the influence of the landscape pattern changes on urban ecosystem services in a megacity such as Jakarta. We acknowledge that further detailed studies will be needed and that the present study will provide incentives and directions to initiate further research. It is recommended to further improve this new method by using land cover classification from a high satellite image resolution, considering more landscape metric combinations, incorporating empirical values such as runoff coefficients or albedo values based on LULC, using field survey data, or using model simulations to verify the ES calculation.

3

SENSITIVITY OF URBAN HEAT ISLAND TO URBAN GREEN SPACES

Urbanization continues to trigger massive land-use land-cover change that transforms natural green environments to impermeable paved surfaces. Fast-growing cities in Asia experience increased urban temperature indicating the development of urban heat island (UHI) because of decreased urban green space, particularly in recent decades. This chapter investigates the existence of UHI and the impact of green spaces to mitigate the impacts of UHI in Colombo, Sri Lanka, using UrbClim, an urban boundary layer climate model, that ran two classes of simulations, namely urbanization impact simulations and greening simulations. The urbanization impact simulation results showed that UHI spreaded spatially with the reduction of vegetation cover and increased the average UHI intensity. The greening simulations showed that increasing green spaces up to 30% in urban areas could decrease the average air temperature by 0.1 °C. On the other hand, converting entire green spaces into urban areas in suburban areas increased the average temperature from 27.75 °C to 27.78 °C in Colombo. This demonstrated the sensitivity of UHI to vegetation cover in both urban and suburban areas. These seemingly small changes were average grid values and might indicate much higher impacts at sub-grid levels.[2]

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[2] Based on Maheng, D., I. Ducton, D. Lauwaet, C. Zevenbergen, and A. Pathirana. 2019. "The Sensitivity of Urban Heat Island to Urban Green Space-A Model-Based Study of City of Colombo, Sri Lanka." *Atmosphere* 10 (3). https://doi.org/10.3390/atmos10030151

3.1 INTRODUCTION

Urban heat islands (UHI) are meteorological impacts of urbanization that cause the air temperature in urban areas to be higher compared to their surrounding non-urban areas. Increasing urban temperature due to urbanization has been observed and studied in cities around the world such as Atlanta (Fu & Weng, 2017), Dhaka (Ahmed, 2015), Ho Chi Minh City (Q.-V. Doan & Kusaka, 2016), Karachi (uz Zaman Chaudhry et al., 2015), Jakarta (Tokairin et al., 2010), Colombo (Vidanapathirana et al., 2017) and Tokyo (Matsumoto et al., 2017). UHI may adversely affect physical and mental health (Kasai et al., 2017; Steul et al., 2018; Z. Xu et al., 2018), as well as promote cardiovascular disease and chronic kidney disease (Watts et al., 2018). They also have significant effects on energy consumption for cooling of urban buildings (Hirano & Fujita, 2012; Kolokotroni et al., 2012). Urbanization is the main driver of UHI, as it leads to massive land-use land-cover (LULC) change, transforming natural urban landscapes from green into grey areas to accommodate housing and public infrastructure. Land transformation has influenced local hydro-climatological conditions, leading to increasing temperature, extreme rainfall events, and more flood events due to increased runoff (Bao et al., 2016; Huong & Pathirana, 2013; Lin et al., 2011; Pachauri & Reisinger, 2007; Pathirana et al., 2014; Zope et al., 2017). As cities grow due to urbanization, natural elements such as urban green spaces (UGS) are replaced by high thermal admittance materials which enable the storage of more solar energy, leading to an increase of the surrounding air temperature once it is re-emitted. In case of low vegetation and/or water body in urban areas, solar energy is directly converted into sensible heat instead of latent energy for evapotranspiration and chemical energy in photosynthesis (Hidalgo et al., 2008; Wallace & Hobbs, 2006). This increases the air temperature, resulting in higher urban temperatures during the evenings and nights compared to those in surrounding non-urban areas with high vegetation covers (U.S. Environmental Protection Agency, 2008). Increasing the air temperature in urban areas is also impacted by the geometry of urban areas. Whether urbanization has resulted from expansion or densification, it alters the urban geometry, which potentially impedes the release of longwave radiation or changes the wind direction and increases shortwave energy absorption due to the bouncing around of sunlight in the urban canopy. This condition might result in higher temperatures when the sky view factor (SVF), which is a measure of the openness of the sky to radiative transport, is low (Brown & Grimmond, 2001; Svensson, 2004). Furthermore, the variation of urban temperature can also be influenced by the interaction between urban temperature and air pollution in urban areas where aerosol particles can minimize the incoming shortwave radiation that changes the surface energy budget (H. Li, Meier, et al., 2018).

Green space is a very subjective concept and has many interpretations (Taylor & Hochuli, 2017). Presently, most cities in the world are greening their cities. For example, the city of Rotterdam in the Netherlands implements the greening concept in city planning and development (Rotterdam, 2015). Cities can reduce the heat island effect by using green spaces that provide shadings and open wind-flow paths, which can eliminate the accumulation of heat (Bolund & Hunhammar, 1999). This can be practically done by increasing the percentage of green spaces in urban areas. For example, cities can introduce some of interventions collectively known as sustainable drainage systems, which include green roofs, vegetated swales, and rain gardens (Charlesworth, 2010).

Many studies have looked at the relationship between the intensity of UHI and UGS regarding its composition and configuration (Bao et al., 2016; Forman, 1995; R. Sun & Chen, 2017; Tran et al., 2017; Zhou et al., 2011). Composition refers to vegetation density and variety of land-cover types, and green spaces size. Some studies show that the composition of UGS can be more significant to cooling effects, as opposed to its configuration. In Hanoi, Vietnam, the transformation of agricultural land into the impervious (built-up) surface due to urbanization and industrialization between 2003 and 2015 has increased the mean land-surface temperature (MLST). For example, the MLST in urban built-up areas was 43 °C in 2003 and increased to 46 °C in 2015. On the other hand, the MLST increase was lower in rural open land where vegetation cover was dominant and water bodies are present. In those areas, the MLST was 36 °C in 2003 and 38 °C in 2015, which showed how the vegetation and water contribute to lower surface temperature (Tran et al., 2017). Sun & Chen (2017) revealed that 108.86 km^2 of the green space in Beijing was lost, which increased LST between 1.6 °C and 2.2 °C, while 92.5 km^2 of the green spaces expansion had reduced the LST within the range of −1.1 °C to -0.67 °C. These results indicate that changing the levels of green space influence air temperature changes and generate various temperature patterns.

On the other hand, the configuration of UGS is related to spatial pattern as well as the layout of UGS including aggregation, shape, and cohesion of patches (Sodoudi et al., 2018). In a particular configuration, UHI intensity can be significantly increased or decreased by different spatial arrangements of UGS (Xiao et al., 2018). The configuration or spatial distribution of urban green spaces can influence the flow of energy or the energy exchange among different land-cover features. For example, distribution of green spaces comprising large tree canopies within a certain distance provides a large cooling effect, while green spaces with grass should be concentrated to maximize the cooling effect (Sodoudi et al., 2018). Hence, the configuration of green spaces should consider spatial distribution (concentrated or dispersed), the distance between each green space, and shape complexity. Even though there is no significant relationship between the degree of aggregation of green spaces and mean temperature, it has been found that in a particular space, dispersed configuration or evenly distributed UGS has led to a decrease of the mean temperature (Bao et al., 2016). Moreover, available UHI studies are intended to evaluate the impact of existing land-use change on increasing temperature (Connors et al., 2013; Kikon et al., 2016; Lian et al., 2017; Ramdhoni & Rushayati, 2016; Ranagalage et al., 2017; Senanayake et al., 2013). However, the research on mitigation of the existing UHI impacts, and in particular projections of increasing temperature due to urban growth and urban planning, are still limited (V. Q. Doan, 2018; Kleerekoper et al., 2012; Kubota et al., 2017; Kusaka et al., 2016; Lee et al., 2017; Neema & Ohgai, 2013; Pathirana et al., 2014; J. Wang et al., 2016; Y. Zhang et al., 2017).

UHI studies can be performed using several methods, including field observations, remote sensing (H. Li, Zhou, et al., 2018), and numerical modelling (Oke et al., 2017). Field observations are normally made by comparing records from meteorological stations inside and outside of the urban area or using mobile monitoring cars moving between rural fringe and the city centre (Hidalgo et al., 2008). In addition, advanced computer technology along with high spatial and temporal resolution of satellite imagery has been used to measure UHI in more detail (Voogt & Oke, 2003; Weng, 2009). The UHI phenomenon can also be studied by using numerical atmospheric simulation (climate) models (García-Díez et al., 2016; Lauwaet et al., 2018; Lazarova & Kusaka, 2018; H. Li et al., 2019; Skamarock et al., 2008; Trusilova et al., 2013). The latter approach provides a unique ability to study the response of various land-cover change scenarios on UHI.

In this chapter, we presented the results of a series of numerical experiments using the urban boundary layer climate model UrbClim (De Ridder et al., 2015) to understand the sensitivity of UHI to UGS in Colombo, Sri Lanka. This study started with the hypothesis that changes in the quantity and distribution of green spaces had significant impacts on the spatial and temporal temperature distribution in urban areas. Two groups of green space conditions that represented decreasing and increasing green spaces were simulated, and the results were compared with the reference year.

3.2 METHODOLOGY

3.2.1 Study Area

Colombo, the capital city of Sri Lanka, is one of the emerging cities in Asia. It has a total city area of 37 km^2 and has about 500000 inhabitants (Figure 3.1). The city of Colombo has seen a rapid increase in urbanization in recent decades. It adopted new development programs around a decade ago, triggered by the end of the civil war in the country. According to World Health Organisation (WHO), 9.5 m^2 of green area per capita is the minimum requirement for healthy living (Kuchelmeister, 1998).

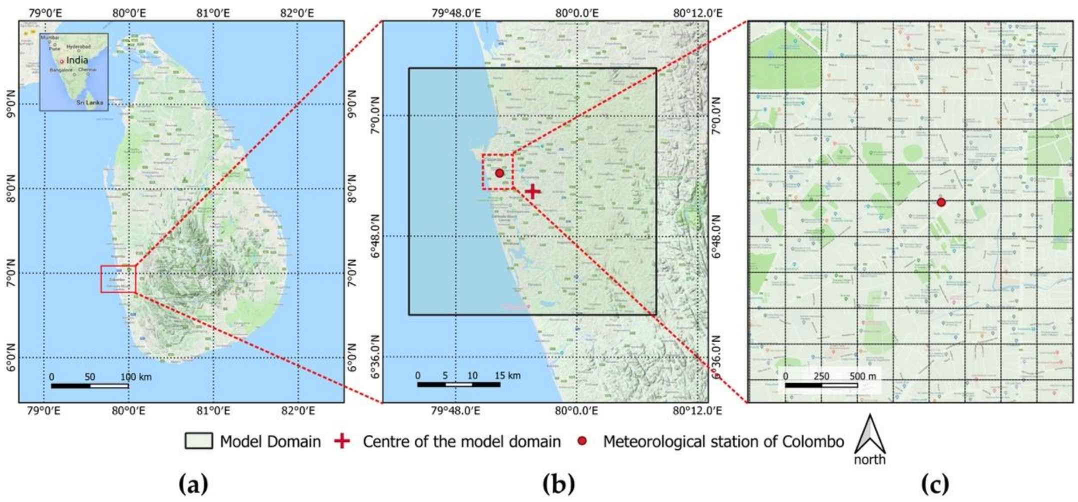

Figure 3.1. The location of the study. (a) Sri Lanka (Source: Google maps https://goo.gl/9WypnH); (b) model domain covered with 181x181 grid cells of 250 m 250 m size (grid cells are two dense to show on the figure); (c) The actual grid cells (250mx250 m) around the location of the meteorological station.

The rapid urban development in Colombo has altered the urban landscape by decreasing green spaces, resulting in an uneven spatial green spaces distribution resulting in 34 out of 55 administrative divisions not complying with the WHO standards for the city (Senanayake et al., 2013). Recent observational studies in Colombo reveal that the metropolitan area is experiencing a UHI as there is a significant urban–rural temperature difference, which has not been observed in recent decades (N. Perera, 2015; Ranagalage et al., 2017; Senanayake et al., 2013). However, it is a huge challenge to protect the existing green spaces in the metropolitan area of Colombo from human activities, which can influence the Colombo urban climate.

Colombo is situated in the tropical monsoon climate and experiences average maximum temperatures of about 31 °C from March to April. The south-western monsoon season that produces large quantities of rainfall is expected from May to September. Average minimum temperatures drop to 22 °C during the drier months of December to February.

3.2.2 Urban boundary layer climate model (UrbClim)

UrbClim is an urban boundary layer climate model developed by using a land-surface scheme that includes simplified urban physics, coupled with a 3-D atmospheric boundary layer module (De Ridder et al., 2015). The model is designed to simulate the temperature and heat-stress fields using high spatial resolution up to 100 metres. UrbClim comprises two main modules, namely surface module, and atmospheric module. In the land-surface scheme of UrbClim, an impermeable slab with proper values of emissivity, albedo, and aerodynamic and thermal roughness length is used to represent the urban terrain. The model also considers anthropogenic heat fluxes. The surface module simulates the relevant physical interactions between soil, vegetation and atmosphere following the scheme developed to investigate the interactions between the land-surface and regional atmospheric circulations and climate (De Ridder & Schayes, 1997). UrbClim model makes some major simplifications in the atmospheric model compared to a “standard” mesoscale model such as the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008), to achieve fast simulations.

The UrbClim performance has been validated by simulating UHI in Toulouse (France), Ghent (Belgium), Antwerp (Belgium), and Bilbao (Spain) (De Ridder et al., 2015). Moreover, UrbClim model performed at a good accuracy with the root mean square error (RMSE) values ranging from 1.6 °C to 1.9 °C when the model’s outputs were validated with data from 11 ground stations, and had lower computational costs compared to the WRF model when simulating the UHI in Barcelona (Spain) (García-Díez et al., 2016). UrbClim has been implemented to define a new method to assess the UHI in Amsterdam based on the UHI simulation over some cities in Europe (Lauwaet et al., 2018) and to investigate future UHIs in Delhi, India (Sharma et al., 2019).

3.2.3 Model Setup

Like many limited-area atmospheric models, UrbClim requires two types of data: the geographical data consisting of land cover and topography, and meteorological data which can be obtained from historical re-analyses or large-scale (e.g., global) models. Landsat satellite images for the years 1997 and 2015 were used as the basis for land-cover data. Both geographical (e.g., land use, topography) and meteorological data (initial and lateral boundary conditions) input data sets should have an identical model grid configuration. For this study, a 250 m spatial resolution as grid spacing for the model was selected. Given the grid spacing, the area of interests was covered by a model domain of 181 × 181 square grid that consisted of 32,761 grid cells with the centre point at 79.9268° E, 6.8745° N.

For the surface module, land-use data were prepared by using Landsat satellite images from the year 1997 and 2015 selected with the cloud cover less than 10% and daytime as the main selection criteria. Land-use classification was made by following the Local Climate Zone Classification (LCZC) framework developed by the World Urban Database and Access Portal Tools (WUDAPT) (Bechtel et al., 2015). In the LCZC framework, land-use land cover is classified by considering land definitions from the Local Climate Zone (LCZ) classification designed for urban climate studies. The LCZ framework is based on universal knowledge of built forms and land-cover types, and it is not based on local characteristics such as local topography and climatology of individual cities (Stewart & Oke, 2012). Originally, the LCZ framework consists of 17 standard classes divided into ten built types and seven land-cover types. The built type represents urban and non-urban forms identified by height and density of roughness features such as compact high-rise, compact mid-rise, compact low-rise or open low-rise as well as typical urban materials such as paved surface, and low plants or scattered trees in open areas. Moreover, the land-cover type is a classification of surface covers around the roughness which are influenced by various factors such as anthropogenic activities and weather patterns (Stewart & Oke, 2012). The first application of the LCZ framework for the city of Colombo had been made in a previous study (N. G. R. Perera & Emmanuel, 2018) in which a set of sub-classification was developed for the LCZ to adapt the local features, for instance, the compact low-rise zone has mid-rise sub-classification that combines the compact mid-rise and open mid-rise zone, which were some typical land-cover patterns in Colombo.

In this study, the LCZ classes were re-arranged to accommodate the 15 land-use classes of UrbClim by considering building density and arrangement, the permeability of areas, and building materials. For instance, three compact land uses from the LCZ were classified into urban land-use class in UrbClim. Having established the land-use classes, the LCZC classification tool in SAGA GIS (Ren et al., 2017) was used to generate two land-use maps from the Landsat satellite images to understand land-use change from 1997 to 2015 in Colombo. The SAGA GIS is a free open-source GIS application that provides some plugins for land classification purposes including the LCZC. In SAGA GIS, the LCZC needs training areas that can be prepared in Google Earth (GE). Before running the land classification, Landsat image was resampled from 30 m to 250 m by using the nearest neighbour method to meet the UrbClim spatial resolution. In addition, some corrections had been made related to the actual land use and land cover by conducting the field survey and referring to the city development information. Two land-use maps corresponding to 1997 and 2015 (Figure 3.2) were created, which were based on the UrbClim land-use classes. Other parameter values for the surface module such as albedo and emissivity were specified by following the standard values prepared by the UrbClim development team (De Ridder et al., 2015).

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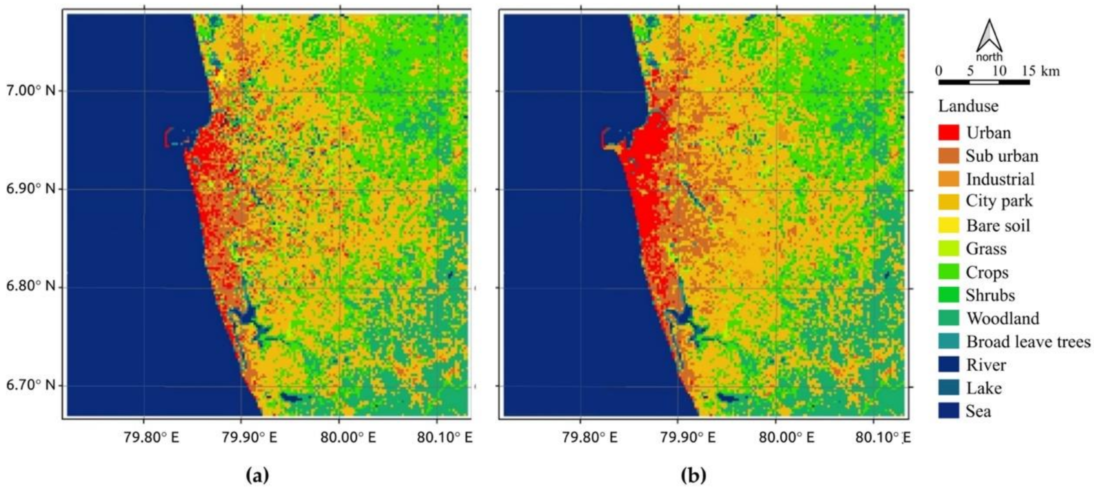

Figure 3.2. Land-cover map of (a) 1997; and (b) 2015.

The land-use map of 1997 was considered as the reference land use to calculate the relevant percentage changes by 2015 (see Table 3–1). Analysis of the land-use change showed that during the 19-year period, urban areas had been increased by approximately 51% while suburban areas had been decreased by 15%. It was evident that increased urbanization results in new industrial areas and that a lot of marshes and wetlands located around the city of Colombo had been lost. On the other hand, the proportion of open water bodies decreased by almost 9%, by reclaiming the small lakes located in the vicinity of these marshes/wetlands as urban areas.

Table 3–1. Land-use change of Colombo between 1997 and 2015

Land-Use Classes	**Land-Use Change (%)**
Urban	50.90
Suburban	−15.50
Industrial	32.39
City Park	2.01
Green Spaces (Grass, Crops, Shrubs, Woodland, Broadleaf Trees)	−8.94
Open Water (River, Sea, Lake)	−8.97

Initial and lateral boundary condition data for the atmospheric module were obtained from the ERA-Interim reanalysis of the European centre for medium-range weather forecasts (ECMWF) from 1996 to 2015 totally covering a period of 20 years. Such an extended period was needed to obtain statistically valid results. The reanalysis data was obtained by using temporal and spatial resolution parameters. The temporal resolution of data from the ERA-Interim is 3 h, while the spatial resolution is 0.75 × 0.75 degree. In this study, the observed air temperature was obtained from the only one weather station from the Department of Meteorological (DoM) located within the area of interest. The station had hourly observations of 2 m air temperature for 1997 and 2015.

3.2.4 Numerical simulations

All numerical experiments were performed for 20 years (1996 through 2015) of reanalysis data as model boundary conditions, changing only the land-use data for each experiment. Further use of the same forcing data would allow us to understand the isolated impact of UHI because impacts such as global warming had equally affected all numerical experiments. To investigate the sensitivity of the UHI to green spaces in the city of Colombo, this study was conducted by using two groups of numerical simulations, namely “urbanization impact simulations” and “greening simulations”. The urbanization-related simulations were conducted in two parts. The first urbanization impact simulation was performed to identify the existence of the UHI due to land-use change from 1997 to 2015, while the second simulation was intended to investigate the extension of the UHI by expanding urbanization to suburban areas. This was a realistic circumstance, as the city of Colombo was expanding over the time and most of the existing suburban areas are converted into urban areas. For instance, the built-up area in Colombo from 1997 to 2017 was expanded beyond the metropolitan area as indicated by an increase in the normalized difference built-up index (NDBI) of suburban areas (Ranagalage et al., 2017), which was seen to deliver an impact on the UHI in Colombo. Urban expansion was included by assuming a reduction of green spaces in suburban areas. In this study, the land use of 2015 was used as the baseline for the urban expansion simulation in which the green spaces in the suburbs were assumed to drop to 0%, which indicated a conversion of entire suburban areas into urban areas. The simulation was performed by providing 10% green spaces in suburban areas and comparing the results with the average temperature due to the actual land-use change in 2015. Following similar steps, the simulations were proceeded by providing 5% and 0% of green spaces in suburban areas.

The greening simulations in this study were assuming various urban greening such as parks, grass, and urban forest. Increasing green spaces were made by incrementally increasing the amount of green space in urban areas by 10%, 20%, and 30%. The maximum increment of 30% green spaces was a practical approach for a city in a developing country such as Sri Lanka. The greening simulations were started by increasing green cover in urban areas by 10% and comparing the result with the existing condition in 2015. The similar procedure was applied when green spaces increased by 20% and 30%.

The model's performance was evaluated by comparing 2 m air temperature from the model's output with observational data from a meteorological station. The difference between both data was investigated by using the RMSE, the mean absolute error (MAE), and the Pearson correlation coefficient, which had been generally used to evaluate the performance of climate models (Best & Grimmond, 2013; Chai & Draxler, 2014) including modelling the UHI in Barcelona (García-Díez et al., 2016).

3.3 RESULTS

3.3.1 Model validation

The statistical tests were made to evaluate the model's performance by comparing simulated values from the model and observed data from the meteorological station. The simulated values were extracted from a grid point situated about 100 m from the measurement station. This was the nearest grid point to the coordinate of the Colombo meteorological station located approximately at latitude 6.9047° N and longitude 79.8725° E where the air measurement device was positioned at 2 m above the grass. The nearest grid point was selected since the grid point values indicated the climate condition of the cell area of 250 × 250 m covering the location of the point measurement. The time series plots for the simulated and observed data is given in Figure 3.3 that shows 2 m air temperature values in January 1997 and 2015, respectively. It can be seen that the simulated air temperature was overestimated as confirmed by the RMSE value that was higher than 2 °C.

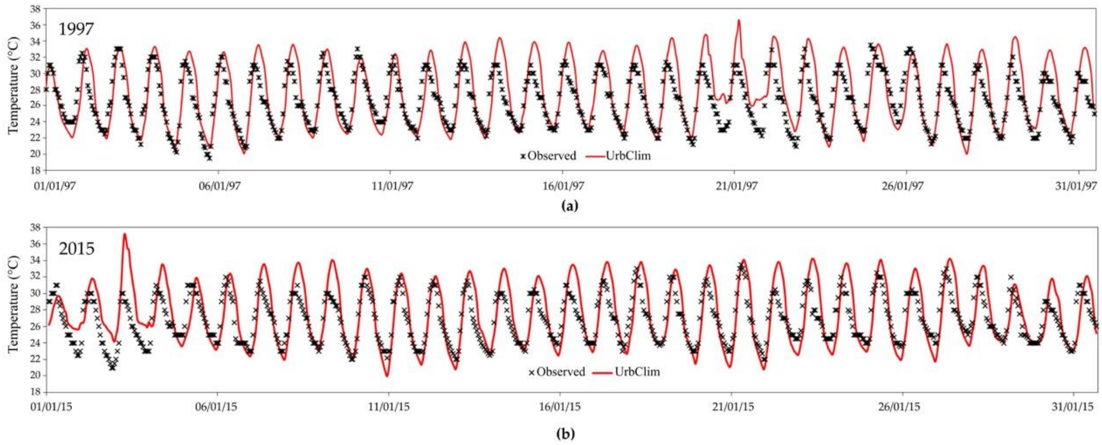

Figure 3.3. Simulated and observed daily time series 2 m air temperature of January (a) 1997; (b) 2015.

The overestimate in the simulation is observed at the daytime and earlier at the night-time as shown in Figure 3.4. UrbClim tended to overestimate temperatures after 13:00 with the highest value of 4.06 °C and 3.96 °C in 1997 and 2015, respectively. The figure clearly shows that the temperature at the grid point at the daytime was higher than at the point measurement. Furthermore, the temperature was well simulated by UrbClim at the night-time when the high intensity of UHIs was generally observed. The maximum bias values for the night-time temperature were 0.58 °C in 1997 and 0.79 °C in 2015.

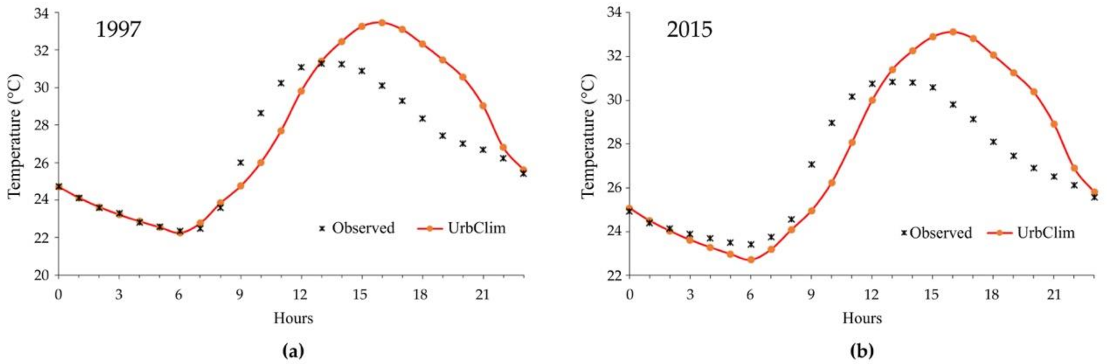

Figure 3.4. Mean diurnal variation of 2 m air temperature of January (a) 1997; (b) 2015.

The statistical test showed that the RMSE of the two data sets for 1997 and 2015 were 2.43 °C and 2.39 °C, respectively. In addition, the MAE test showed that the absolute error values for 1997 and 2015 were 1.86 °C and 1.89 °C, respectively. The MAE, which was less than 2 °C, is considered to be acceptable for 2 m temperature simulations (Emery et al., 2001). Furthermore, the Pearson correlation coefficient between simulated and observed data for 1997 and 2015 were 0.82 and 0.79, respectively as given in Figure 3.5. Since these values were within the range of 0.5 and +1, the correlation check is fairly acceptable compared to the similar test using more than one meteorological station from the UHI studies with UrbClim in Europe (De Ridder et al., 2015).

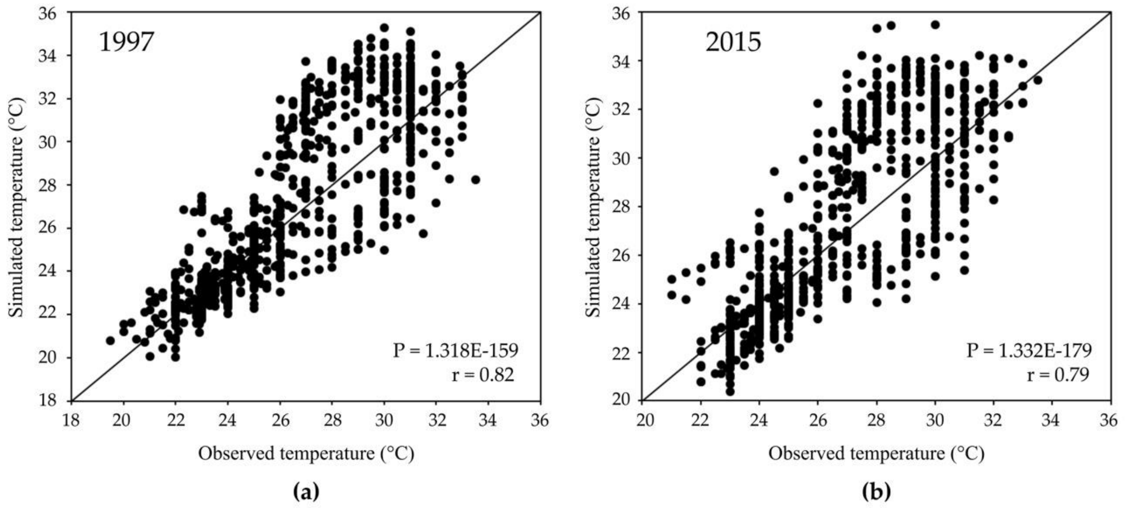

Figure 3.5. The Pearson correlation coefficient between simulated and observed 2 m air temperature in January (a) 1997; (b) 2015.

3.3.2 Impact of land-use change on UHI

The first simulation was conducted to investigate the contribution of the land-use change from 1997 to 2015 on increasing air temperature and development of UHI. At this step, 2 m air temperature variations were simulated in relation to the land-use change which showed that decreased green spaces from 1997 to 2015 resulted in increased temperatures (see Figure 3.6).

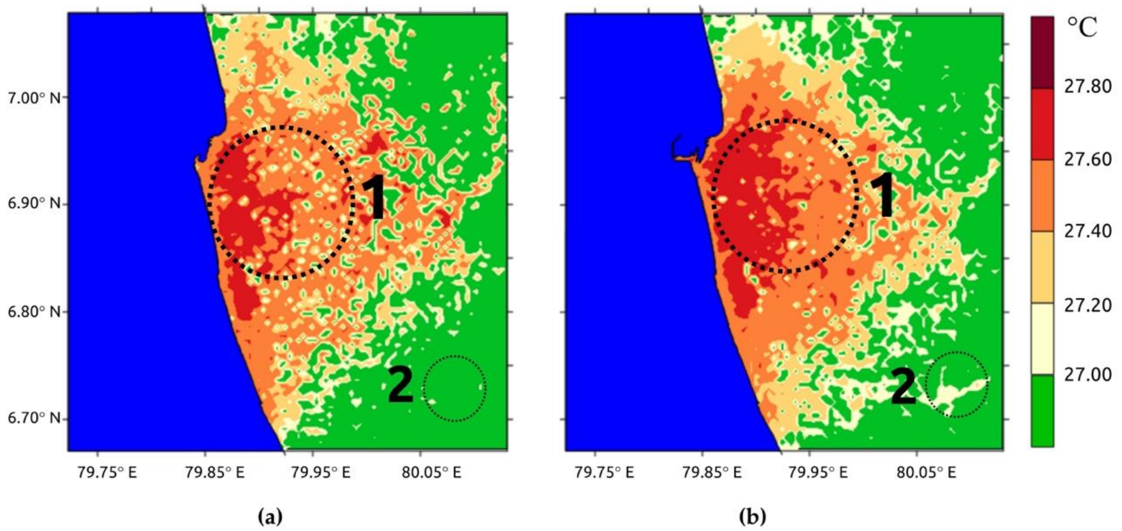

Figure 3.6. Spatial 2 m air temperature distribution in Colombo in (a) 1997; (b) 2015. Area 1: The urban land cover and Area 2: non-urban land cover was used for temperature comparisons.

The maximum temperature increment was found to be 0.8 °C with the average temperature increment within urban areas recorded to be 0.2 °C. Moreover, the total urban area (observed in location 1 in Figure 3.6) with the average temperature of 27.80 °C or above, increased from 114.81 km^2 in 1997 to 344 km^2 in 2015. A significant increase in temperature due to extended urbanization could be seen in the suburban areas indicated in location 2 from Figure 3.6. The average temperature increased sharply up to 27.20 °C in 2015. Furthermore, the results show an increase in the average UHI from 0.45 °C in 1997 to 0.80 °C in 2015. However, the temperature differences between urban and suburban areas in this study were less than found in the study (N. Perera, 2015) in which the temperature difference ranged from -0.90 °C to 4.40 °C.

3.3.3 Greening simulations

The green scenarios for urban areas (scenario 1–3) were developed by increasing the green spaces of parks by 10%, 20%, and 30%, as shown in Figure 3.7. The spatial distribution of increasing green spaces was considering the spatial temperature distribution due to land-use change from 1997 to 2015. This was made by increasing green spaces in the area where the temperature ranged between 26 °C and 27 °C, which were based on the spatial temperature distribution in 2015.

The greening simulations showed that increasing green spaces decreased average temperatures as well as UHI. In general, the highest intensity of UHI is observed at the night-time particularly during clear sky and calm wind (U.S. Environmental Protection Agency, 2008). In this study, it was observed that increasing green spaces reduced the average daily temperature in urban areas from 27.75 °C to 27.67 °C and decreased the average nighttime UHI from 1.41 °C to 1.25 °C. The average nighttime UHI in this study was based on the temperature from 18:00 to 06:00, while the average day time was based on the temperature from 06:00 to 18:00.

Moreover, increasing green spaces also influenced the spatial distribution of urban temperature. It was observed that there was a decrease in the area affected by high temperature (greater than 27.0 °C) as indicated in location 1 in Figure 3.7.

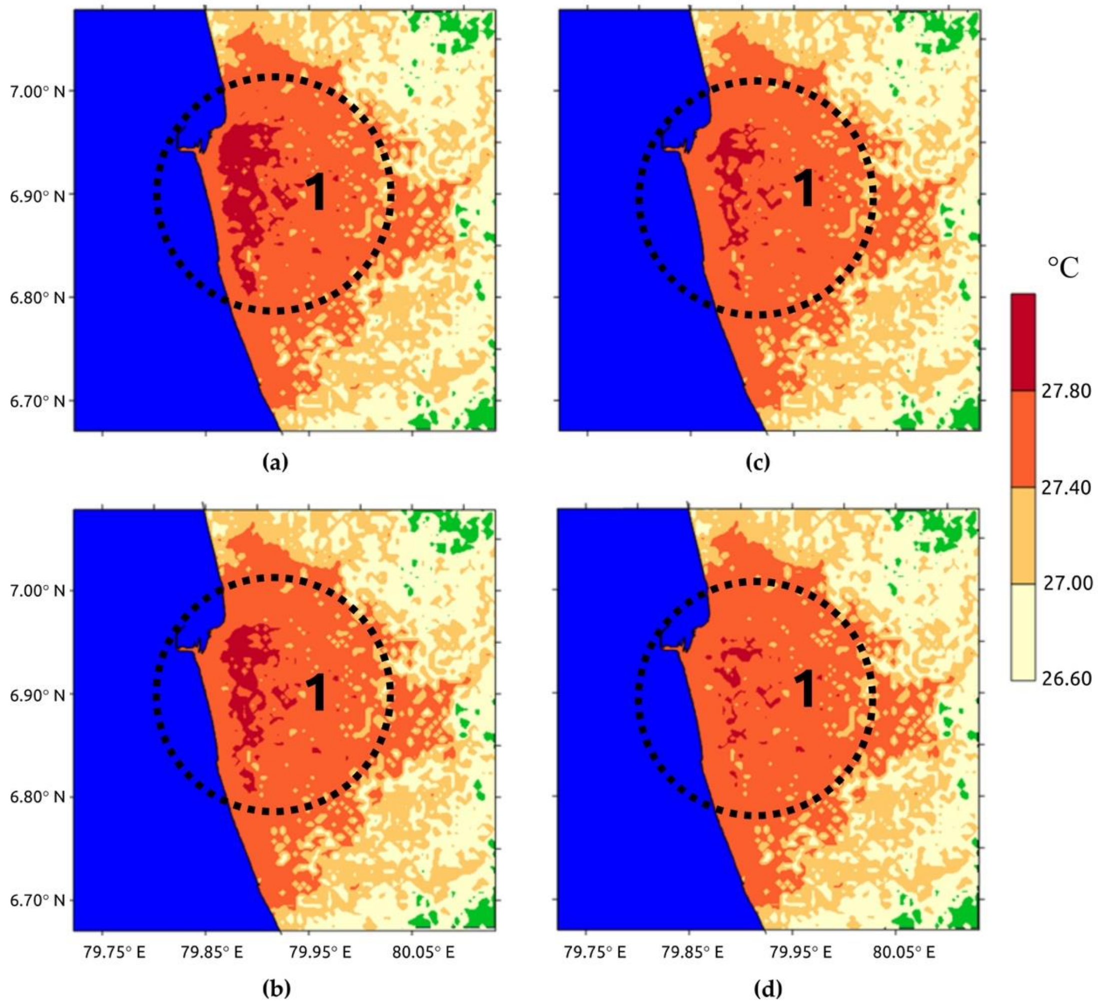

Figure 3.7. (a) Average temperature distribution due to land-use change in 2015; (b) Average temperature distribution with 10% greening; (c) 20% greening; (d) 30% greening.

It shows that the extent of the UHI effects could be reduced by 17.62 km^2 (26%), 31.25 km^2 (47%) and 43.31 km^2 (64%) when simulating scenarios 1, 2, and 3, respectively. The summary of model's outputs from scenarios 1, 2, and 3 are provided in Table 3–2.

Table 3–2. Model's output for greening scenarios

Simulation	Average Temperature in Urban Areas (°C)	Average Daytime UHI (°C)	Average Nighttime UHI (°C)	The Area Experience More than 27.8 ˚C as Avg. Temperature (km^2)	Area Reduction (km^2)
Existing situation	27.75	0.26	1.41	67.12	
Scenario 1	27.72	0.25	1.33	49.50	17.62
Scenario 2	27.70	0.24	1.28	35.87	31.25
Scenario 3	27.67	0.22	1.25	23.81	43.31

3.3.4 Urban expansion simulations

The second simulation of the impact of urbanization was done by assuming that there was urban expansion towards suburban areas. This was made by decreasing the green spaces by 10%, 5%, 0%, in scenario 4, scenario 5, and scenario 6, respectively, as shown in Figure 3.8. The UrbClim's output showed that decreasing green spaces in suburban areas had an impact on increasing temperature and UHI in Colombo. The simulation results of the average temperature distribution from the existing situation, scenarios 4, 5, and 6 are mapped and shown in Figure 3.8. It shows that the average daily temperature in urban areas increased from 27.75 °C to 27.78 °C. As the UHI intensity is higher in the nighttime, it was observed that urban expansion increased the average nighttime UHI intensity from 1.41 °C to 1.44 °C when the vegetation cover in the suburban region was reduced.

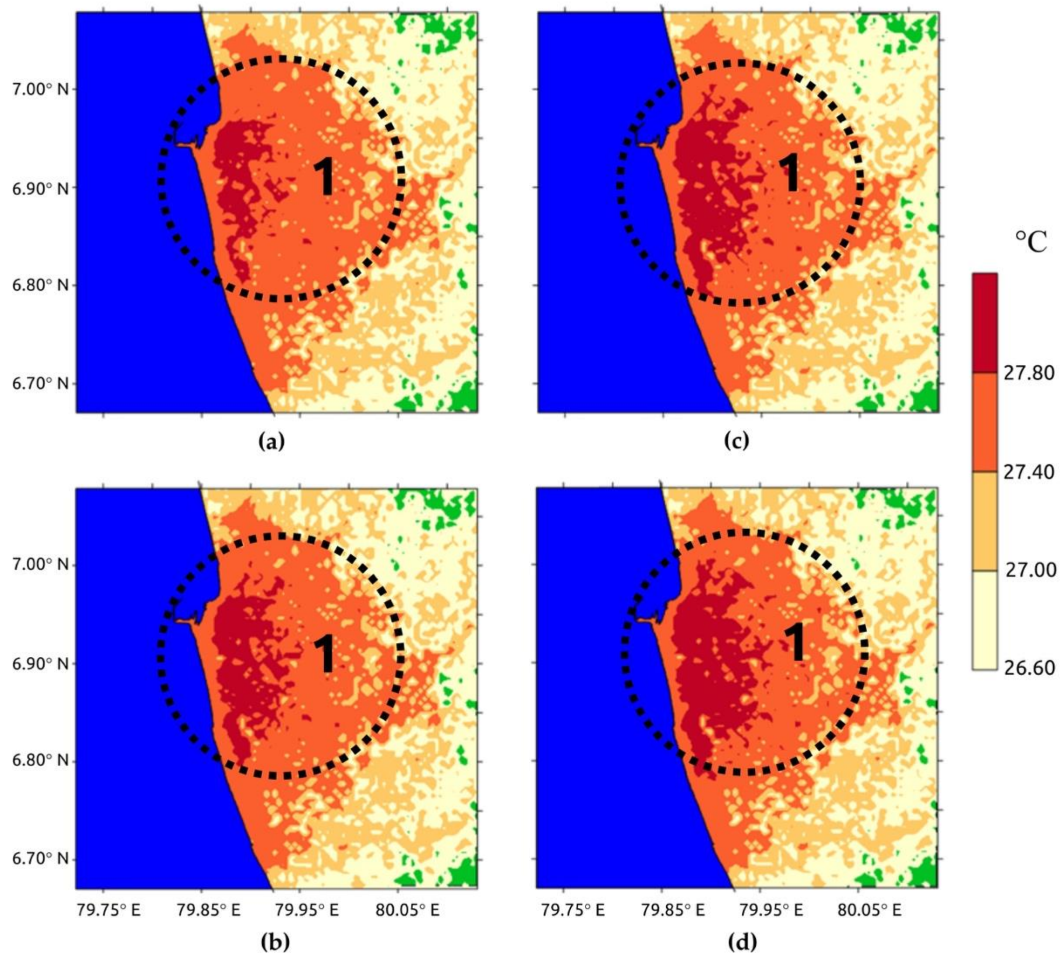

Figure 3.8. (a) Average temperature distribution due to land-use change in 2015; (b) Providing only 10% greening; (c) Providing by 5%; (d) No green spaces.

Moreover, an increase in areas affected by high UHI intensity was observed. The areas experiencing average high temperature increased by 35.63 km^2 (53%), 52.01 km^2 (77%), and 75.19 km^2 (112%) when UrbClim simulated air temperatures using scenario 4, 5, and 6, respectively. The summary of model's outputs for urban expansion simulations are given in Table 3–3.

Table 3–3. Model's outputs for urban expansion scenarios.

Simulation	Average Temperature in Urban Areas (°C)	Average Daytime UHI (°C)	Average Nighttime UHI (°C)	The Area with Avg. Temperature more than 27.8 °C (km²)	Increased Areas (km²)
Existing situation	27.75	0.26	1.41	67.12	
Scenario 4	27.76	0.22	1.42	102.75	35.63
Scenario 5	27.77	0.22	1.42	119.13	52.01
Scenario 6	27.78	0.22	1.44	142.31	75.19

3.4 Discussion

The simulation results showed that changes in the quantity and distribution of UGS in Colombo affected the spatial and temporal temperature distribution. Between 1997 and 2015, urban areas in Colombo increased by 51%. As a result, the average UHI intensity increased from 0.45 °C in 1997 to 0.80 °C in 2015. The main factor contributing to increasing urban temperature is that the decreased green space resulted in a low evapotranspiration rate while most of the solar energy is converted to sensible heat (Oke, 1982; Oke et al., 2017). This condition can be observed in Colombo particularly in impervious areas where green space coverage was low and at the same time surface materials with high thermal admittance such as concrete, asphalt, or black roof were dominant (Ranagalage et al., 2017). Those materials can accumulate heat more intensely leading to the formation of the UHI. Moreover, a decrease of the water bodies, as well as low soil moisture can also contribute to more sensible heat since less water is available for evapotranspiration (Gunawardena et al., 2017).

Another factor that should be considered in increasing the average temperature in Colombo is the low SVF (Vidanapathirana et al., 2017). The SVF has an inverse relation to shading effects at which the low SVF indicates a less shading effect available and vice versa. The low SVF contributed to the increased urban temperature of Colombo particularly in urban areas where the compact mid-rise and high-rise zones increased between 2010 and 2017 (N. G. R. Perera & Emmanuel, 2018).

The average temperature was reduced in the greening scenarios as demonstrated by simulating the regeneration of the vegetation cover of 1997 in 2015, which was done by providing up to 30% of green spaces coverage in urban areas. The model indicated that increasing the quantity of green spaces decreased the average, particularly within the area where built-up and impervious areas were re-converted to green spaces. These changes reduced the average temperature possibly through one or a combination of ecosystem services provided by green spaces such as intercepting solar radiation, evapotranspiration, and modifying air movement (Derkzen et al., 2015). The sensitivity of UHI to UGS from the greening simulations also showed that an appropriate quantity and distribution of green spaces can provide cooling effects to lower the air temperature (Bao et al., 2016) through evapotranspiration (Gkatsopoulos, 2017), which could be explained by the fact that approximately 1000 MJ was consumed by a single tree for heat energy in the transpiration process (Bolund & Hunhammar, 1999). The decreased temperature in urban areas can influence temperature differences between urban and suburban areas that lead to prevent UHI formation.

Moreover, the urbanization extension increased the average temperature as well as the extent of the affected areas. Extension of the built-up areas was represented by reducing the amount of available green spaces to 0% in suburban areas. From the simulations, it was shown that the expansion of urbanization towards the suburban areas had caused more regions to be affected by increased temperature (higher than 27 °C), although increasing the average temperature was small (0.03 °C). Increasing the average temperature as the impacts of future urban expansion have been investigated in some Asian cities, for example in Ho Chi Minh City (V. Q. Doan, 2018), where the impact of urbanization on increasing temperature could be approximately 20-30% of global warming. Future urbanization might not significantly increase the urban temperature as well as the intensity of UHI but it might extend the UHI (H. Li et al., 2017). The increased average temperature was mainly a result of the decreasing green spaces and reduced or loss of the water body as discussed above. However, there is a situation in the real world where the increased temperature can also be influenced by the energy exchange between adjacent areas. The exchange can happen through advection of sensible heat from urban to suburban areas (Oke, 1988). For instance, increased air temperature about 1 K between 1970 and 2000 in the Old City, a built-up historical area in Jakarta, was influenced by high temperature from adjacent areas where new urban development took place (Tokairin et al., 2010).

Different size and spatial distribution of the green spaces showed influence on the average temperature. The simulation results showed that the variation in spatial temperature distribution was consistent with findings from previous UHI studies in Colombo which showed temperature differences between urban and suburban areas (N. Perera, 2015; Ranagalage et al., 2017; Senanayake et al., 2013; Vidanapathirana et al., 2017). Moreover, the simulated temperature in UrbClim is the average temperature that is calculated based on grid values. In reality, the value should be considered only as an indication of high temperatures from specific places such as a car park, which influences ambient temperature in the immediate surrounding. Such sub-grid scale effects are not captured by the current model with 250 m grids. However, the indication from UrbClim simulation is useful to understand UHIs particularly when a UHI study is started by having limited information about urban detail such as urban canopy geometry.

Furthermore, the average UHI intensity in this study, which were 0.26 °C in the daytime and 1.41 °C in the nighttime, seem to be lower than that in another Asian city such as Delhi where the average urban–rural temperature differences could be more than 4 °C (Sharma et al., 2019). The lower UHI intensity in Colombo was related to the regional climate characteristics. Located in the tropical monsoon climate, Colombo receives the amount of rainfall over the year with total annual precipitation about 2500 mm. The influence of precipitation to the UHI intensification was also observed in Rennes, France, where the average UHI intensity at the daytime and the nighttime were 0.5 °C and 2 °C, respectively (Amorim & Dubreuil, 2017).

However, it was noticed that UrbClim model tended to overestimate air temperature values particularly when the results for January 1997 and 2015 were compared against the observed air temperature. The bias between the simulated and the observed temperature was related to the nature of data since the correlation test was made by comparing the point source observation data with the spatially averaged grid values from the model. The bias was also influenced by the difference in land-use classes. The land use of the grid point in UrbClim was classified as the urban class while the point measurement was located within a small grassy patch of about 50 m x 50 m size, which was not large enough to influence the land cover of the model grid. Located in the urban land-use classes in the simulation, the temperature at the grid point during the daytime was higher than at the point measurement and it was decreased slowly until the evening. Both these observations, namely, the higher peak and slower drop in temperature in the urban areas compared to green (e.g., grass) areas is expected. Urban areas absorb higher amount of thermal energy during the daytime and is slowly released in the evening (Oke et al., 2017). This overestimate results from UrbClim were also observed in the UHI study for the city of Ghent (Belgium) and Bilbao (Spain) with the correlation coefficient between simulated and observed data were recorded as 0.95 and 0.90, respectively (De Ridder et al., 2015). This therefore can be considered as a consistent issue with the UrbClim model.

Compared to some similar cases one of the obvious limitations of the present study is the fact that the availability of only one weather station within the study area. This is largely an unavoidable issue not only in this case study but many potential future studies in data-poor environments, unless data is augmented by techniques such as low-cost citizen observatories (Gharesifard et al., 2017).

3.5 CONCLUSION

In this study, we investigated the influence of green spaces on the spatial and temporal distribution of urban temperature as well as UHI. The investigation was made by changing the size and distribution of green spaces using two sets of simulation named “urbanization impact simulations” and “greening simulations”. These simulations were conducted using UrbClim, an urban boundary layer climate model, with a spatial resolution of 250 meters and two different land-use maps from 1997 and 2015, which were generated from Landsat images by using the LCZ framework.

It was observed that urbanization altered urban landscape from green to grey environments, affecting the spatial temperature distribution. Two urbanization impact simulations showed that the decreasing green spaces both in urban and suburban areas increased the average temperature as well as extended areas affected by high temperature. On the other hand, the greening simulations showed that the increasing size of green spaces decreased average air temperature and it can minimize the spread of high temperature. Moreover, increasing urban temperature and UHI can be influenced by other aspects such as the SVF and urban morphology, which were not considered in this study.

It should be noted that while this study used a relatively finer resolution of 250 m (in comparison to typical mesoscale atmospheric simulation studies), still the temperature values produced by the model were grid-average values that ignored a lot of sub-grid-scale heterogeneity. Therefore, the seemingly moderate increases in temperature reported at grid-average scale should only be considered as a symptom of (much higher) sub-grid-scale temperature variations. Actual temperature hotspots may demonstrate temperature increases often much larger than the grid-average value. Further studies, ideally in conjunction with field observations, should be done to establish such sub-grid-scale temperature relationships.

The numerical urban climate simulations with UrbClim using the variations of green space sizes and distribution showed that the spatial and temporal distribution of urban temperature is sensitive to the size and distribution of green spaces. It can be seen from the variations in temperature differences between urban and suburban areas where green spaces are modified. Moreover, a numerical experiment that combines various scenarios including land-use change, mitigation, and adaptation (greening scenarios), and urban expansion, is still necessary while UHI studies combine those scenarios are limited. Hence, it is relevant to establish the relationship between green spaces, urban planning, and UHIs, and ascertain the sensitivity of the UHI effect to the presence of green spaces.

4

IMPACT OF LAND USE AND LAND COVER CHANGES ON AIR TEMPERATURE IN JAKARTA

Urbanization is one of the important drivers of increasing local temperatures. As cities and urban areas evolve, extensive land use and land cover (LULC) changes alter the physical properties of surface materials. This modification results in reduced evapotranspiration rates, ultimately contributing to higher surface and air temperature. This chapter investigates the impact of urbanization on urban temperature in Jakarta. Urban temperature was simulated for a 20-year period (1995-2014) by the urban boundary layer climate model UrbClim, using LULC data for both 1995 and 2014. Temperature changes were analysed by assessing the temperature anomaly across different LULC change classes divided into four main classes namely no built-up changes (BB), no green spaces changes (GG), built-up to green spaces (BG), and green spaces to built-up (GB). This study revealed that the conversion of green spaces to built-up areas (GB) had the most significant impact on the increase in air temperature. This was indicated by the average temperature anomaly of GB of about 0.25 °C followed by GG, BB, and BG with the average temperature anomaly of about 0.19 °C, 0.18 °C, 0.06 °C, respectively. The different temperature anomalies of the LULC change classes indicated that green spaces have an important role in maintaining local climate. Hence, it is important for local government to effectively manage the composition, the quantity, as well as the distribution of green spaces within a city. By looking at temperature anomalies of LULC change classes, this chapter provides an alternative approach to many existing methods that provide general information about temperature changes, without specifically analyzing the effects of LULC transformation.[3]

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[3] Impact of land use and land cover changes on air temperature in Jakarta: Insights from an Urban Boundary Layer Climate Model. *Under Review*

4.1 INTRODUCTION

Urbanization is one of the key factors driving urban temperatures to increase. As cities and urban areas expand and regenerate over time, they experience significant land-use land cover (LULC) change due to urban development and densification. Urbanization and LULC changes influence the landscape pattern of urban areas often resulting in a decrease in aggregation and connectivity of green spaces, along with an increase in built-up areas and their aggregation (Haas et al., 2015; Maheng et al., 2021). As a result, green spaces are becoming more fragmented and clustered into smaller areas. In contrast, built-up areas become more connected and lumped into larger continua such as commercial business districts, industrial areas, and dense residential areas, impacting urban ecosystem services (Depietri et al., 2012; Y. Zhang et al., 2018). The spatial extent and pattern of clustered built-up areas and green spaces in urban areas influence the surface energy balance, which in turn affects urban temperature (Das Majumdar & Biswas, 2016; Guo et al., 2020; Kumari et al., 2019; J. Song et al., 2014; C. Wang et al., 2019). Nowadays, many cities are experiencing periods of elevated temperatures which become more intensive during the summertime leading to public health-related problems (De Troeyer et al., 2020; Kasai et al., 2017; Sharma et al., 2019; Steul et al., 2018), increase energy usage for cooling buildings (Kolokotroni et al., 2012), and trigger the generation of extreme rainfall events (Pathirana et al., 2014; Tsiringakis et al., 2017).

Numerous observational and modelling studies have been recently conducted to investigate the relationship between LULC change and urban temperature (Maheng et al., 2019; Rizvi et al., 2020; Sharma et al., 2019; Srikanth & Swain, 2022). Most of the studies suggest that the removal of vegetation which reduces transpiration rates of urban surface resulting in a decrease of latent heat leading to an increase of the urban temperature. Other factors associated with increasing urban temperature are the widespread use of high thermal admittance materials, such as concrete and asphalt in urban constructions, changes in urban morphology, and an increase in anthropogenic heat. An increase in the built-up and impervious surface has increased sensible heat (De Ridder et al., 2015; Derkzen et al., 2015; Q.-V. Doan & Kusaka, 2016), particularly in areas where the vegetation cover is replaced by intensive use of grey materials, impervious surface, and high thermal admittance materials (Maheng et al., 2019; Ranagalage et al., 2017). Urban morphology can also contribute to an increase in the urban temperature, particularly where the configuration of high-rise buildings hampers wind movement (Kleerekoper et al., 2012; Oke, 1987; Rajagopalan et al., 2014). Furthermore, the increasing urban population puts physical stress on the urban environment, by increasing anthropogenic heat (AH) fluxes from fossil fuel vehicles, buildings, and human metabolism (Lazarova & Kusaka, 2018).

Many recent studies have investigated the impact of LULC change within a certain period on the air temperature of an urban area based on mean temperature changes (Darmanto et al., 2019; Kubota et al., 2017; Sharma et al., 2019). Those studies, however, do not provide insight into the extent the changes in land-use influence the urban temperature and temperature variations associated with different LULC change classes. For instance, temperature changes in green spaces within urban areas that undergo transformation into built-up areas may be higher compared to those urban areas that experience no land-use transformation (Arshad et al., 2022; Nayak & Mandal, 2019). A temperature increase is expected in areas that were previously green spaces, primarily due to a reduction in latent heat and evapotranspiration, as well as alterations in radiative responses stemming from changes in the thermophysical properties of surface materials (De Ridder et al., 2015; Forman, 2013; Hamilton et al., 2014; Oke et al., 2017). This urban climate information is essential for urban planners, designers and local governments to foster sustainable urban development in cities without adversely affecting the comfort and well-being of the inhabitants.

In recent years, urban air temperature studies have been supported by a number of different numerical atmospheric models (Darmanto et al., 2019; De Ridder et al., 2015; Hürzeler et al., 2022; Michau et al., 2023; X. Zhang et al., 2017). Climate models offer several advantages for urban climate studies as they provide projections of future urban climate conditions (Oke et al., 2017). UrbClim is one of the climate models suitable for urban temperature studies (García-Díez et al., 2016). This model is an urban boundary layer climate model designed for urban temperature simulation in the spatial resolution range of hundred meters. It has been developed by De Ridder et al. (2015) using a land surface scheme that is based upon a simplification of urban physics coupled with a 3-D atmospheric boundary layer module. The land surface scheme of UrbClim follows energy exchange between soil-vegetation-atmosphere which takes into account urban surface physics. The urban surface in UrbClim is represented as a rough impermeable slab that has values for the albedo, emissivity, thermal conductivity and volumetric capacity. UrbClim has a finer spatial resolution compared to that of the WRF model, which is the current state-of-the-art Mesoscale model. This model is generally used to simulate local climate conditions at a spatial resolution of 1 kilometre. WRF can simulate both urban temperature and urban rainfall (Pathirana et al., 2014), while UrbClim is limited to urban temperature. The ability of UrbClim to simulate urban temperature has been demonstrated in some previous UHI studies, for example, in the studies of Toulouse, Ghent, Antwerp and Bilbao (De Ridder et al., 2015), Athens (Kourtidis et al., 2015), and Barcelona (García-Díez et al., 2016), as well as Asian cities such as Colombo (Maheng et al., 2019) and New Delhi (Sharma et al., 2019).

An increase in the urban temperature due to LULC change is mainly influenced by a decrease in the green spaces and an increase of the built-up areas. The land-use transformation from natural green spaces to built-up areas can change the surface energy balance in an urban area, which decreases latent heat and increases sensible heat (Rios &

Ramamurthy, 2022; Wiegels et al., 2021). Important mechanisms of green spaces to control urban temperature are evapotranspiration and tree shading (Oke et al., 2017). In the evapotranspiration process, green spaces absorb solar radiation which is converted into latent heat which in turn converts water from liquid to water vapor. Latent heat ends up in water vapor, which does not raise the air temperature (Forman, 2013). On the other hand, built-up areas are likely to increase the air temperature. Built-up areas are generally dominated by man-made impervious materials which increase solar radiation absorption. The absorbed energy from solar radiation is converted into sensible heat that is slowly released into the atmosphere causing an increase in air temperature (Oke, 1987). This is the reason why an area becomes warmer after being transformed from a green into a built-up area. The aggregated effect of a gradual and dispersed transformation of green spaces into built-up areas across a city may cause an increase in UHI intensities. Conversely, the LULC change from built-up areas to green spaces can reduce the upward flux of sensible heat and increase latent heat (Roth et al., 2017). Green city policies aiming to increase green and water surface areas in a particular area of a city can influence the air temperature not only at a local scale but also in a larger area (Wiegels et al., 2021).

This study investigated the impact of urbanization on the spatiotemporal changes of urban air temperature by looking at the temperature anomaly across LULC change classes. LULC changes were categorized into four main classes: no built-up changes (BB), no green spaces changes (GG), built-up to green spaces (BG), and green spaces to built-up (GB). The impact of the LULC changes on the urban temperature was analyzed using land-use data from 1995 and 2014, sourced from the study conducted by Maheng et al. (2021) (Figure 4.2**)**. Maheng et al. (2021) used the Landsat 5 TM L1TP from August 24, 1995, with a spatial resolution of 30 m for the year 1995, and Landsat 8 OLI TIRS L1TP with a spatial resolution of 30 m from September 13, 2014, for the year 2014. The data showed that there was a significant LULC change in Jakarta between 1995 and 2014, in particular with respect to the natural green spaces which had been converted into impervious built-up areas. The surface area of the urban areas increased by 44% whilst the surface area of the green spaces showed a significant decrease particularly for the tree-covered areas of the green spaces which showed the highest decrease of 58%. Furthermore, the urban air temperature was simulated by using the boundary climate model UrbClim. Two input data were used comprising LULC data of 1995 and 2014 with the boundary climate data from the European Centre for Medium-Range Weather Forecasting (ECMWF) (ECMWF, 2017). Finally, the temperature anomalies were analysed by extracting the temperature difference at each LULC change class.

4.2 METHODOLOGY

This study was divided into two parts. The first part focused on the atmospheric modelling activities, involving the simulation of urban air temperature for the years 1995 and 2014.

This period was chosen due to the availability of Landsat data with cloud cover less than 15%. The second part concerned the temperature anomaly analysis which was aimde to investigate the temperature changes across different LULC change classes.

4.2.1 Atmospheric modelling

An urban boundary layer climate model (UrbClim)

Urban air temperature in Jakarta was simulated with the UrbClim model, using a model domain of 265 x 265 grid cells with a grid resolution of 250 m (Figure 4.1). The number of vertical layers was 17 of which the first layer was 10 m above the displacement height which decreased upward to 250 m at the model top at a height of 3 km (De Ridder et al., 2015). The centre of the model domain was at 106.817°E and -6.212°S, which is located in Jakarta’s downtown, as depicted in Figure 4.1. Two LULC input data for 1995 and 2014 were simulated with the boundary climate input data from ECMWF for the years 1995 to 2014. The ERA-Interim data has a temporal resolution of 3h and a spatial resolution of ~80 km x 80 km, covering 60 vertical layers is situated with the top situated at 0.1 hPa (Dee et al., 2011). The model was initially simulated for a 20-year period (1995-2014) using land cover data from 1995. Subsequently, the same period was simulated again, but with the 1995 land cover data replaced by the data from 2014. The only difference between the two simulations was the landcover data, which made it possible to attribute any differences like temperature anomalies between the two simulations to landcover. This allowed the separation of the impact of land-use change on the urban temperature keeping all other factors (e.g. non-stationarity of large-scale forcing) constant by using the exact same atmospheric forcing data for the two model runs. Hence, the “urban temperature of 2014” in this study was the mean temperature of the 20-year period from 1995 to 2014 using the 2014 LULC, and the “urban temperature of 1995” was the mean temperature of the 20-year period from 1995 to 2014 using the 1995 LULC map.

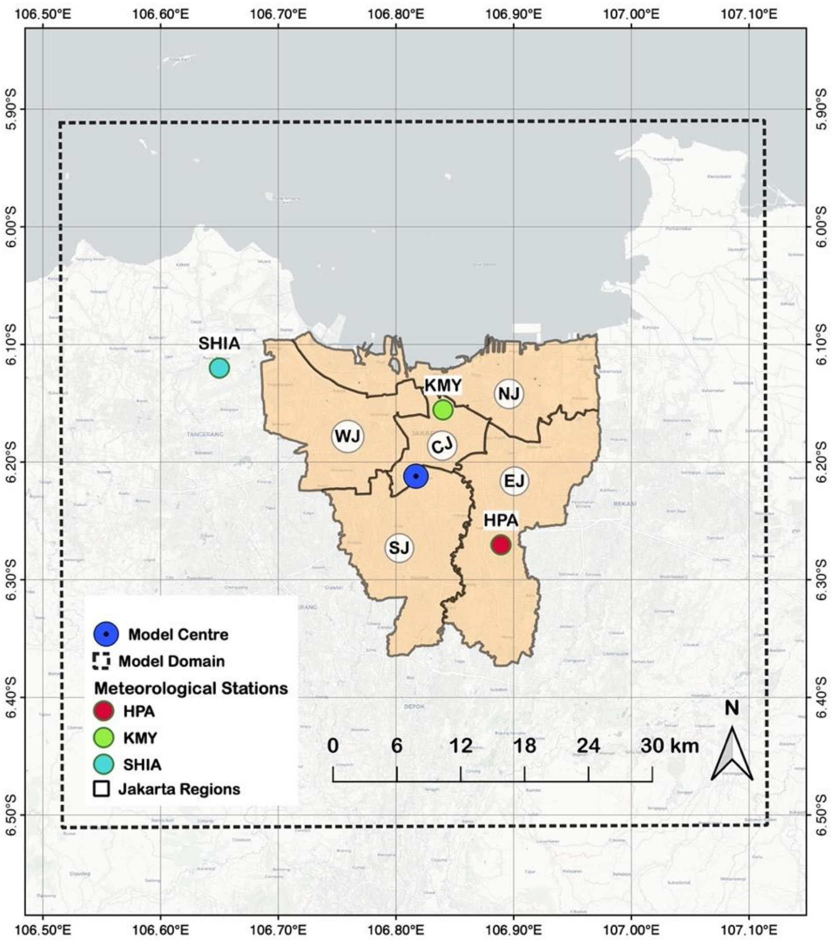


Figure 4.1. Model domain and model centre of UrbClim, as well as the location of meteorological stations in Jakarta.

The model outputs were validated with the recorded air temperature at three meteorological stations, namely Soekarno Hatta International Airport (SHIA), Halim Perdanakusumah Airport (HPA) and BMKG office (KMY), as depicted in Figure 4.1. The model performance was statistically tested using root mean square error (RMSE) and mean absolute error (MAE), similar to previous UrbClim studies (De Ridder et al., 2015; García-Díez et al., 2016; Maheng et al., 2019).

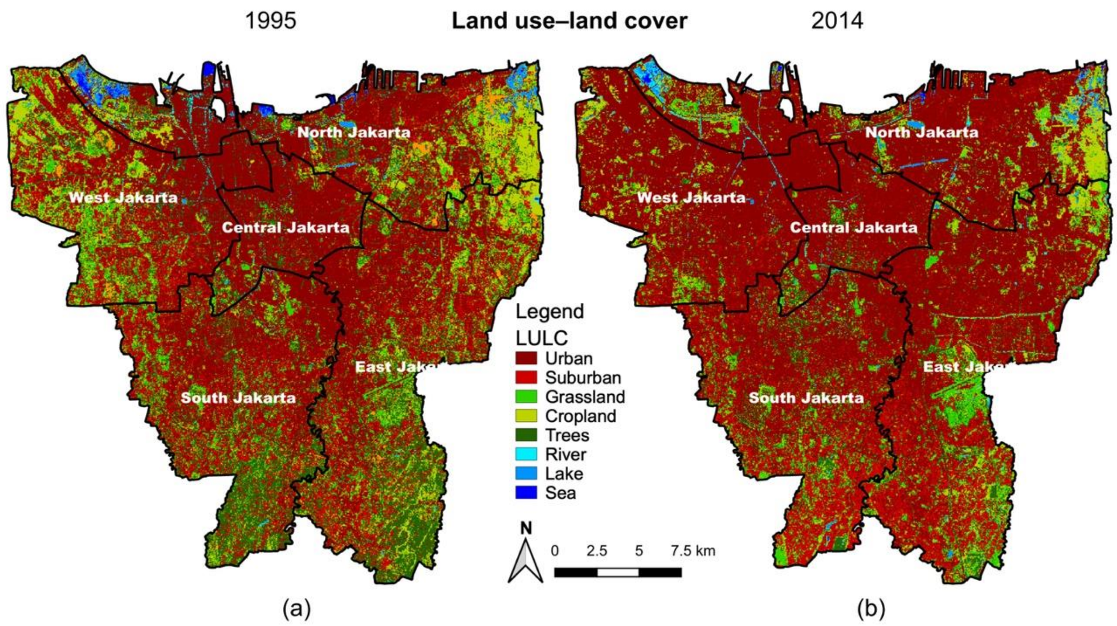


Figure 4.2. LULC of Jakarta in (a) 1995 based on Landsat 5 TM; (b) 2014 based on Landsat 8 OLI TRS (Maheng et al., 2021).

Land use land cover (LULC)

Landsat-based LULC data were obtained from Maheng et al. (2021). Satellite images were utilized to classify the land cover into eight categories: urban, sub-urban, barren land, grassland, cropland, shrubs, trees and water. These classes are the land-cover input standard of surface data for UrbClim, as illustrated in Figure 4.2 (De Ridder et al., 2015).

Air temperature simulations

Air temperature of 1995 and 2014 were simulated using two land-use maps in UrbClim simulations in which only the land-use input data was changed. UrbClim's outputs were validated using data from the BMKG stations and the GHCN database, which included three meteorological stations: Soekarno-Hatta International Airport (SHIA), Halim Perdanakusumah Airport (HPA) and the BMKG office (KMY). The BMKG data was used to validate the outputs from UrbClim's simulations using the land-use map of 2014, while the GHCN data was used for the UrbClim's simulations using the land-use map of 1995. The validation test was conducted by comparing the mean air temperature of a corresponding cell located nearby the three corresponding stations. The mean air temperature of 1995 was the output of the UrbClim simulation using the land-use map of 1995. Furthermore, the same setup was applied for the mean air temperature of 2014.

Meteorological data

This study used two meteorological products used as an input and for model validation. The first was the ERA-Interim from ECMWF (ECMWF, 2017) which was used as an input for the initial and lateral boundary conditions of UrbClim (forcing data). The ECMWF data was also used in the previous UrbClim studies (Maheng et al., 2019; Sharma et al., 2019). The ECMWF data has a spatial resolution of ~80 x 80 km for the model domain of 66 x 66 km covering the main area of Jakarta and surrounding areas such as Depok, Tangerang, Bogor, Bekasi and Karawang. The second meteorological data comprised the observed data used to validate the model's output. The observed data was collected from the Agency for Meteorology, Climatology and Geophysics of Republic of Indonesia (BMKG) and the Global Historical Climatology Network (GHCN). The BMKG data was used to validate the model's output of the urban temperature of 2014, while the GHCN data was used for the urban temperature 1995 simulation. The GHCN data was used since there was no data of 1995 available for the BMKG data at the time this study was conducted.

4.2.2 Temperature anomaly analysis

The analysis of the impact of urbanization on urban air temperature were carried out in two steps. First, the urban air temperature change was analysed by calculating the mean air temperature of LULC map of 1995 and 2014. Second, the temperature anomaly was calculated for each LULC change classes, for instance built-up class in 2014 that used to be green spaces in 1995.

The impact of urbanization and LULC change on the urban air temperature change was analysed by calculating the temperature anomaly. The temperature anomaly is the difference between the temperature of a certain year, and a reference value which was in the present study the average temperature over the period of observation (1995 to 2014) (Liang et al., 2022). The temperature anomaly was chosen because it results in a normalization of the data in order to derive at a more accurate temperature pattern, and temperature evolution characteristics (Chelani & Rao, 2013; Pyrgou et al., 2019). In this study, the temperature anomaly was calculated based on the mean air temperature of 1995 and 2014. The temperature anomaly was calculated following the equation below.

$$\Delta T_{2014i} = T_{2014i} - \bar{T}_{1995,2014i} \qquad (4.1)$$

where T_{2014i} was the mean air temperature of cell i of the 2014 LULC, and $\bar{T}_{1995,2014i}$ was the mean air temperature of cell i of the 1995 LULC and the 2014 LULC. The mean air temperature of 1995 and 2014 was used as the reference value. The temperature anomaly was then calculated by subtracting the 2014 mean air temperature from the reference value. A positive anomaly indicated that the average temperature in 2014 was warmer than in 1995, while a negative anomaly indicated that the average temperature in 2014 was cooler than in 1995.

The impact of urbanization and LULC change on the urban temperature was analysed by calculating the temperature anomaly of each LULC change class, for instance, the temperature anomaly in green spaces to built-up areas. The LULC change analysis was done by comparing the LULC map of 1995 and 2014 using the land-use change analysis of the SCP plugin in QGIS (Congedo, 2021). QGIS is an Open-Source Geographic Information System (GIS) that supports vector, raster, several database formats, and spatial analysis functions. QGIS can be used across several operating systems including Linux, Windows, and Mac OSX (QGIS, 2021). This comparison provided detailed information of the spatial changes associated with the transformation of one class to another, for instance, where cropland areas were transformed into urban areas and *vice versa*. The LULC change classes were divided into main classes and sub-classes. The LULC change main classes were divided into four classes: no built-up changes (BB), no green spaces changes (GG), green spaces to built-up (GB), and built-up to green spaces (BG), as given in Table 4–1. The LULC change sub-classes were divided into 25 sub-classes, as given in Table 4–2. The temperature anomaly was extracted for each LULC change sub-class to assess the temperature changes of the different LULC change sub-classes.

Table 4–1. LULC change main classes.

No.	Codes	Types
1	BB	No built-up change
2	GG	No green spaces changes
3	GB	Green spaces to built-up
4	BG	Built-up to green spaces

Table 4–2. LULC change sub-class.

No.	Codes	Types	No.	Codes	Types	No.	Codes	Types
1	U-U	urban to urban	11	Gr-U	grassland to urban	21	T-U	trees to urban
2	U-S	urban to suburban	12	Gr-S	grassland to suburban	22	T-S	trees to suburban

3	U-Gr	urban to grassland	13	Gr-Gr	grassland to grassland	23	T-G	trees to grassland
4	U-C	urban to cropland	14	Gr-C	grassland to cropland	24	T-C	trees to cropland
5	U-T	urban to trees	15	Gr-T	grassland to trees	25	T-T	trees to trees
6	S-U	suburban to urban	16	C-U	cropland to urban			
7	S-S	suburban to suburban	17	C-S	cropland to suburban			
8	S-G	suburban to grassland	18	C-Gr	cropland to grassland			
9	S-C	suburban to cropland	19	C-C	cropland to cropland			
10	S-T	suburban to trees	20	C-T	cropland to trees			

4.3 RESULTS

4.3.1 Model validation

UrbClim was able to simulate air temperature in 1995 and 2014, as shown from the statistical test outputs (see Table 4–3).

The validation test indicated that the mean air temperature for land-use 1995 and 2014 had small errors, which are deemed acceptable for 2 m air temperature simulations (Emery et al., 2001). This indicated that UrbClim was able to reproduce the urban air temperature of Jakarta in 1995 and 2014 using land-use map 1995 and 2014, respectively. Moreover, the statistical results showed that the mean air temperature simulation of land-use 1995 had smaller errors compared to that of 2014. The MAE test gave better results compared to that of the RMSE. Moreover, the validation test was conducted in January as the representation of rainy season, while July was the representation of dry season. The validation results are provided in Table 4–3.

Table 4–3. Model's validation results.

Year	Month	Statistical method	Station		
			KMY	SHIA	HPA
2014 (BMKG data)	January	RMSE (°C)	2.17	1.75	1.53
		MAE (°C)	1.76	1.42	0.84
		R^2	0.3	0.48	0.19
	July	RMSE (°C)	1.42	3.14	1.22
		MAE (°C)	0.77	2.71	0.54
		R^2	0.99	0.55	0.61
1995 (GHCN data)	January	RMSE (°C)	0.68	1.15	1.34
		MAE (°C)	0.25	0.80	0.75
		R^2	0.49	0.60	0.22
	July	RMSE (°C)	NA	2.51	1.46
		MAE (°C)	NA	1.86	0.72
		R^2	NA	0.79	0.62

4.3.2 Spatiotemporal changes of air temperature

The LULC change between 1995 and 2014 was marked by an increase in built-up areas and a decrease in green spaces, as given in Figure 4.3. An increase in built-up areas was observed in all municipalities where the highest increase rate was observed in West

Jakarta (39%), followed by East Jakarta (30%), North Jakarta (28%), and South Jakarta (20%). A small increase rate of 5% was identified in Central Jakarta where the built-up areas was already existed in 1995 as the downtown of Jakarta. The expansion of built-up areas had a notable impact on the availability of green spaces in Jakarta. It was an evident that green spaces experienced a decline across all municipalities, correlating with an increase in the air temperature, as illustrated in Figure 4.3 (c), (d), and (e).

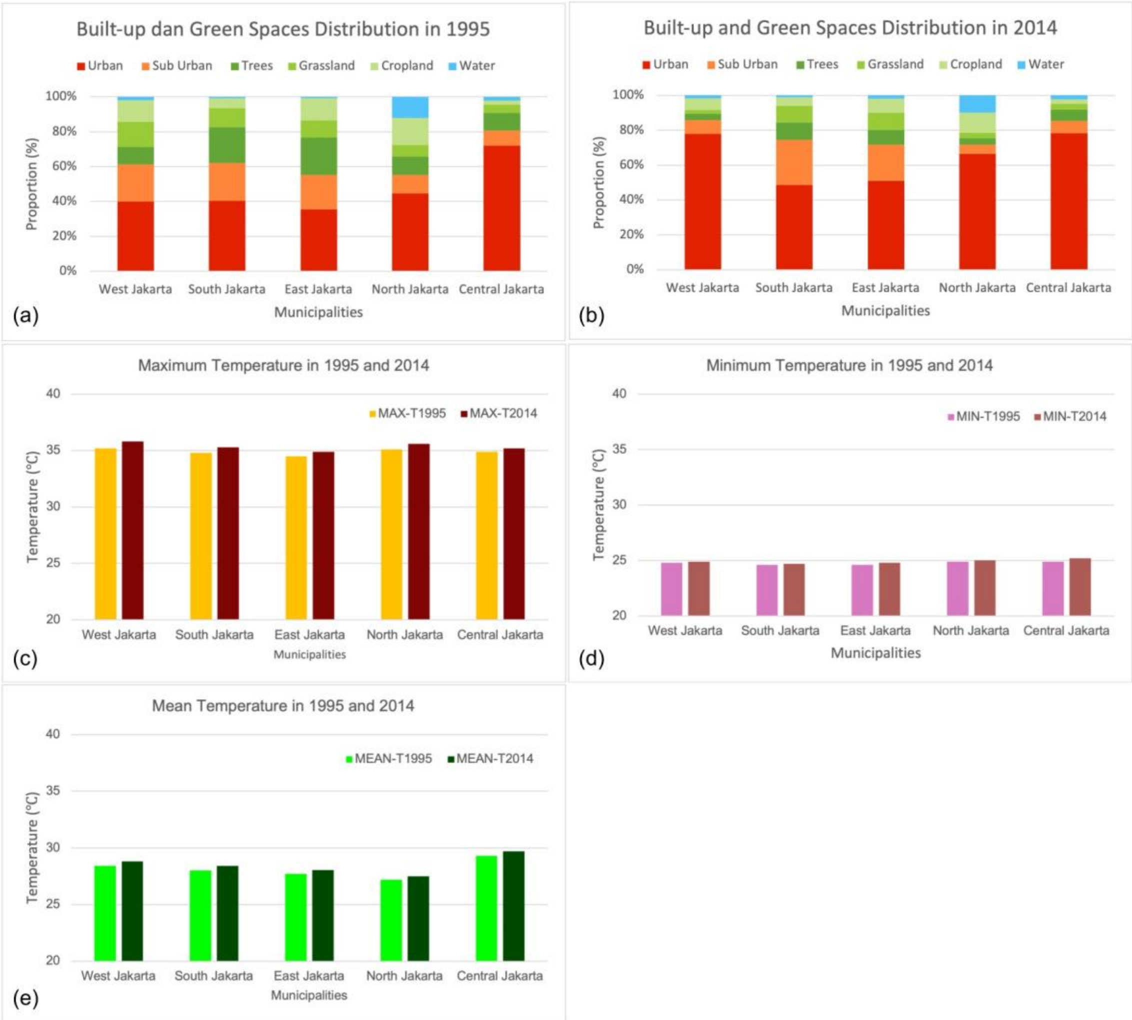


Figure 4.3. The proportion of built-up and green spaces, and variations of air temperature of 1995 LULC and 2014 LULC. (a) and (b) show changes and an increase in the proportion of built-up areas compared to green space; (c), (d), and (e) show increasing maximum temperature, respectively.

The expansion of built-up areas and reduction in green spaces impacted the air temperature, changing its spatial distribution between 1995 and 2014, as illustrated in Figure 4.4. This figure demonstrates an increase in mean air temperature during the same period, with the spatial distribution predominantly extending towards West Jakarta. In

1995, the mean air temperature was higher than 28 °C in West Jakarta (with mean value of 28.4 °C), Central Jakarta (with mean value of 29.3 °C), and South Jakarta (with mean value of 28.0 °C), while East Jakarta and North Jakarta showed the mean air temperature of 27.7 °C and 27.2 °C, respectively. Compared to 1995, the mean air temperature in 2014 showed an increase in all municipalities; the increase was mostly observed in West Jakarta and Central Jakarta that had mean air temperature 28.8 °C (an increase of 0.4 °C compared to 1995) and 29.7 °C (an increase of 0.4 °C compared to 1995), respectively. Other municipalities also experienced an increase in mean air temperature; however, their spatial extension was not as significant as observed in West Jakarta, Central Jakarta, and North Jakarta.

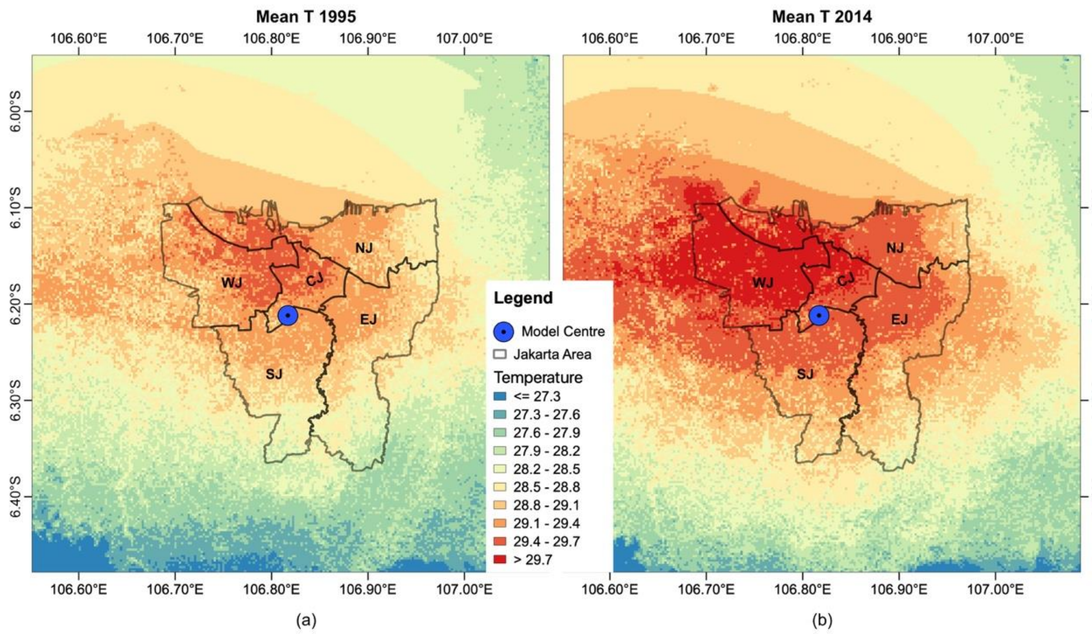


Figure 4.4. Spatiotemporal changes of mean air temperature field of (a) 1995 LULC; (b) 2014 LULC.

4.3.3 Temperature changes in different LULC change classes

LULC change classes had an important role in the air temperature variations, as shown in Figure 4.5. The temperature anomaly in areas where green spaces were transformed into built-up areas (GB) was higher than that in the other LULC change classes, as shown in Figure 4.5(b). The highest temperature anomaly (of about 0.5 °C) was mainly detected in the new built-up areas of Jakarta, particularly in West Jakarta, South Jakarta, and East Jakarta, where the LULC change was dominated by the GB class. Moreover, no changes in LULC classes, such as built-up to built-up (BB), were observed mainly in Jakarta's downtown and scattered in other municipalities, which had the temperature anomaly up to about 0.15 °C.

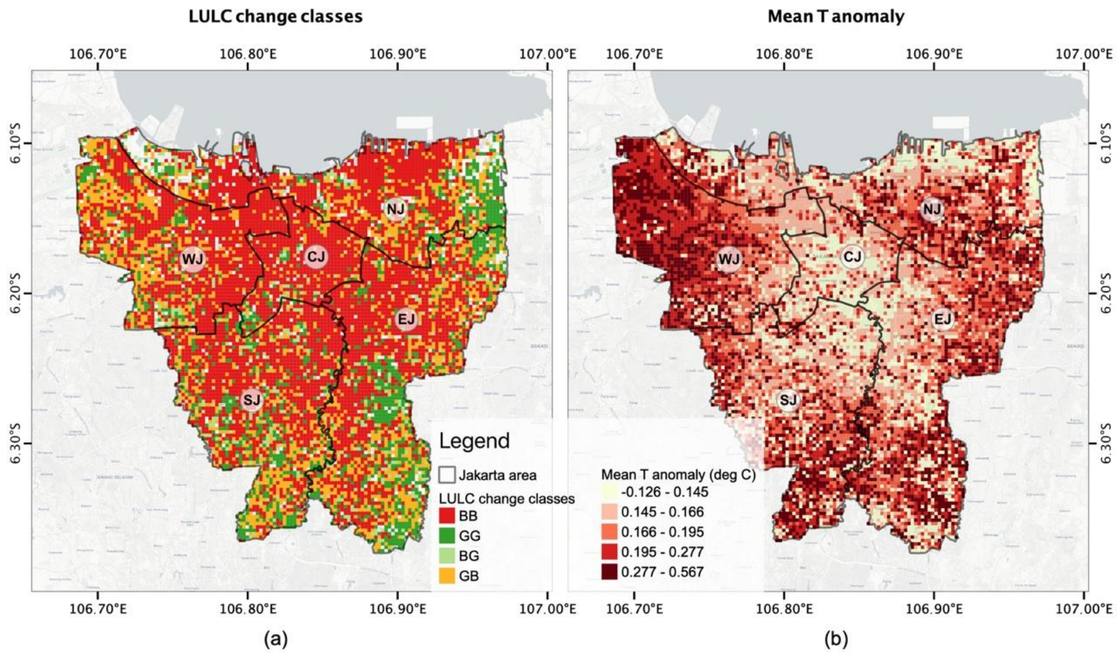
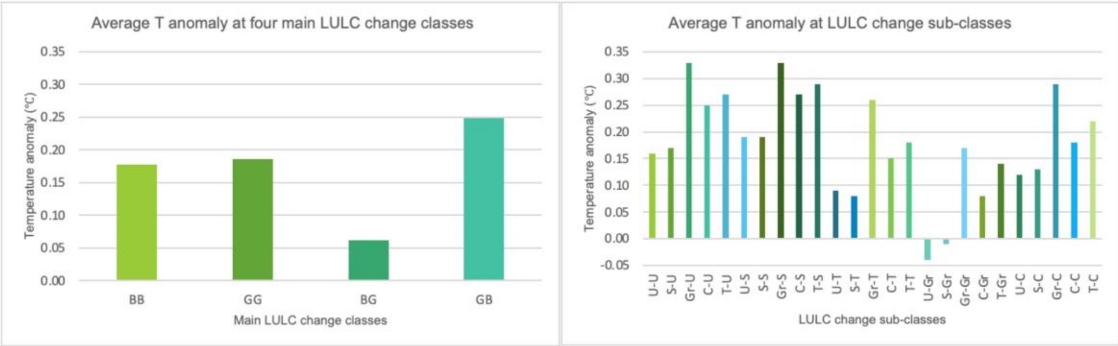


Figure 4.5. LULC change classes and the average mean air temperature anomaly.

Moreover, the temperature anomaly in the GB sub-class exhibited an average value higher than that in the BG sub-class, as shown in Figure 4.6(b). For instance, the mean air temperature anomaly of the Gr-U sub-class (grassland to urban) and the Gr-S sub-class (grassland to suburban) had an average value of about 0.33 °C, followed by the T-S sub-class (trees to suburban), where the average value was about 0.29 °C. In contrast, the U-Gr sub-class (urban to grassland) had the lowest average air temperature anomaly of about -0.04 °C.

Lower average values were also observed in the BG sub-classes (built-up areas to green spaces), such as urban areas to trees (0.09 °C), suburban areas to trees (0.08 °C), urban areas to cropland (0.11 °C), and suburban areas to cropland (0.12 °C). Additionally, temperature changes in built-up class transitions of the U-U, U-S, S-U, and S-S sub-classes ranged from 0.16 °C to 0.19 °C. Furthermore, the average air temperature anomaly in all no LULC change classes was approximately 0.17 °C. Statistical significance test revealed a statistically significant difference (p-value < 0.01) between BG-GG, BG-BB, GB-GG, and GB-BB.



(a) (b)

Figure 4.6. Average T anomaly in (a) main LULC change classes; and (b) LULC change sub-classes.

4.4 Discussion

The LULC changes in Jakarta significantly influenced the spatiotemporal distribution and changes in urban air temperature. This study linked temperature changes to LULC change classes, categorized into four main classes: no built-up changes (BB), no green spaces changes (GG), built-up to green spaces (BG), and green spaces to built-up (GB), each with 25 sub-classes, as given in Table 4–2. A notable rise in air temperature was predominantly observed in areas where green spaces were converted into built-up areas.

In this study, it was observed that the LULC transition from green spaces to built-up areas had a significant impact on an increase in air temperature. In areas where green spaces were transformed into built-up areas such as trees to urban/sub-urban, cropland to urban/sub-urban, and grassland to urban/sub-urban, it was found that the temperature anomaly was higher than that of other classes. An increase of air temperature in those LULC transformation classes can be associated with a decrease in latent heat and an increase in sensible heat due to a decrease in green spaces. Decreasing green spaces makes urban areas absorb more solar energy that results in higher temperature compared to that in non-urban areas. The increasing air temperature in the LULC transformed from green spaces to built-up areas in this study was also observed in other Asian cities, such as in Dhaka in Bangladesh (Imran et al., 2021), or in Lahore in Pakistan (Arshad et al., 2022).

The spatial distribution of an increased temperature was noted in areas dominated by built-up infrastructure. Notably, in West Jakarta, significant urbanization impact were observed between 1995 and 2014, with this urban area experiencing a 39% increase in built-up areas and a coresponding rise in mean air temperature of about 0.4 °C. This observed temperature increase aligned with findings from previous studies on air temperature in Jakarta (Ramdhoni & Rushayati, 2016; Siswanto et al., 2016). Ramdhoni & Rushayati (2016) discovered that the reduction in green spaces in Jakarta led to an increase in mean air temperature, rising from 24 °C and 30 °C in 2001 to 27 °C and 30 °C in 2014. Moreover, Siswanto et al. (2016) observed an increase in the annual mean air temperature of about 1.6 ºC per century in the observed period from 1866 to 2012 in Jakarta, which was associated with urbanization. The increasing temperature was higher than the observed global mean temperature rise of 0.85 °C in the period from 1880 to 2012 (IPCC, 2013). The phenomenon of increasing air temperature due to urbanization was also observed in some other cities, such as Beijing (J. Wang et al., 2016), Berlin (H. Li et al., 2019), Delhi (Sharma et al., 2019), Ho Chi Minh (Q.-V. Doan & Kusaka, 2016), Tokyo (Matsumoto et al., 2017), and American cities of different climate zones (C. Wang et al., 2019). The observed trend of an increasing temperature is predicted to persist in the future in Jakarta (Darmanto et al., 2019).

The observed air temperature anomaly in between 1995 and 2014 stressed the essential role of green spaces in reducing high air temperature in Jakarta and hence the impact of urbanization on the urban temperature characteristics. The important role of green spaces is generally associated with their ecosystem functions such as evapotranspiration, tree shading and air movement modification (Oke et al., 2017). The influence on the composition and configuration of green spaces is acknowledged but less understood (Bao et al., 2016). In this study it was demonstrated that green spaces could reduce high temperatures indicated from the comparison of the mean temperature anomaly in the BG class with that of other classes. The observed lower value indicated that an increase of the temperature was mitigated by the existence of green spaces.

4.5 CONCLUSION

This study investigated the impact of urbanization on the spatiotemporal distribution of changes in the air temperature in Jakarta between 1995 and 2014. It was found that the LULC change had altered the spatial distribution of air temperature and increased the air temperature. Moreover, the mean temperature anomaly in areas transformed from green spaces to built-up areas was higher than in other LULC change transformations like in grassland to urban.

The LULC change resulted in a significant impact on the variations and the spatial distribution of mean air temperature in Jakarta between 1995 and 2014. The expansion of built-up areas contributed to the rise in air temperature, attributed to a reduction in evapotranspiration resulting from decreased green spaces. Significant increases in air temperature were observed in areas that were transformed from green spaces into built-up areas. These transformations were mainly observed in newly built-up areas of Jakarta. However, a decreased temperature was observed in areas which were transformed from built-up areas into green spaces. This indicates that an increasing air temperature can be mitigated by greening solutions in which built-up areas are transformed into green spaces.

The ability of green spaces to provide such a climate regulation is influenced by several factors, including the proportion and the distribution of green spaces, as shown in this study. Hence, urban planning and urban land-use management have to play an important role to safeguard that there is an appropriate quantity, composition and distribution of green spaces in urban (re)development programs to control a further increase of the urban air temperature.

In this study, the increase in urban air temperature was simulated using UrbClim, and the results were validated using data from meteorological stations and the GHCN dataset. Utilizing two different datasets helped overcome the challenge of missing data, particularly the absence of hourly temperature data from the meteorological station in Jakarta for 1995, which was essential for model validation. While hourly temperature data was available for 2014, it was not accessible for 1995 during the study period. The temperature variations at each LULC change sub-class from the model outputs were validated using a point measurement located at the meteorological stations. This might create bias results since the model outputs were the gridded data representing a temperature condition over an area of 250 m in this study. For further research, it is recommended to provide similar data generated from consistent raw data acquisition and pre-processing.

The method proposed in this study enables to analyse the detailed impact of urbanization on urban temperature. It offers comprehensive information on land use and land cover (LULC) changes and their implications for temperature variations, a crucial aspect in urban climate studies. The method also highlights that internal changes within the urban environment, such as LULC change, can play a significant role in urban climates alongside the impact of global climate change. Furthermore, the method can serve as an alternative to many existing approaches that offer general information about temperature changes within a specific timeframe, but do not provide detailed insights into temperature changes resulting from LULC transformation.

This study can be further improved by considering the temperature change based on the change of leaf area index (LAI) or the change of albedo values. Furthermore, in-situ temperature monitoring over a certain period at a particular LULC class can provide more accurate temperature information, which is important in model validation.

5

CHANGING URBAN TEMPERATURE AND DAILY RAINFALL PATTERNS IN JAKARTA

Increasing global population and in-country migration have a significant impact on global Land Use Land Cover (LULC) change, which reduces green spaces and increases built-up areas altering the near-surface radiation and energy budgets, as well as the hydrological cycle over an urban area. The LULC changes can lead to a combination of hazards such as increasing urban temperatures and intensified rainfall, ultimately resulting in increased flooding. This chapter aims to discuss the changing pattern in urban temperature, daily rainfall and flooding in Jakarta. The daily urban temperature and daily rainfall were based on a 30-year data from three meteorological stations of Jakarta in the period 1987 and 2017. The changing trend was analysed by using the Mann-Kendall and the Pettitt's test. The relation between daily rainfall and flooding was analysed by using a 30-year flooding data collected from several sources including the international disaster database, research and newspaper. The results showed that there was an increasing trend of the daily temperature and the daily rainfall in Jakarta. The annual maximum daily temperature showed an increasing trend started in 2001 at the KMY station, and in 1996 at the SHIA station. In general, the highest annual maximum daily temperature between 1987 and 2017 was about 37 °C, while the lowest annual maximum daily temperature of about 33 °C. Moreover, the maximum daily rainfall started increasing since 2001. The increase of the maximum daily rainfall was observed mainly in January and February, which coincided with the flood events recorded in these months in Jakarta. This indicates that Jakarta is not only vulnerable to high urban temperature but also to flooding.[4]

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[4] Based on Maheng, D., Bhattacharya, B., Zevenbergen, C., & Pathirana, A. (2024). Changing Urban Temperature and Rainfall Patterns in Jakarta: A Comprehensive Historical Analysis. In *Sustainability* (Vol. 16, Issue 1). https://doi.org/10.3390/su16010350

5.1 INTRODUCTION

The world has been seeing an increase in the global population in recent decades. In 2017, the world population reached 7.3 billion, which would increase to 8.5 billion by 2030, and 11.2 billion in 2100 (DESA, 2018). Moreover, people living in urban areas was 54% higher than that in rural areas in 2014, and it is projected to be 66% in 2050 (UNDESA, 2018).

Increasing global population and in-country migration have a significant impact on global Land Use Land Cover (LULC) change (MacDicken, 2015; X.-P. Song et al., 2018; Winkler et al., 2021). According to Winkler et al. (2021), approximately 32% of the Earth's surface experienced LULC changes between 1960 and 2019. Moreover, global LULC dynamics during the period from 1982 to 2016 led to a reduction in vegetation cover within various arid and semi-arid ecosystems, potentially linked to human activities (X.-P. Song et al., 2018). An increase in built-up areas globally between 2000 and 2020 was about 50%, where Asia had about 60% of the total built-up areas gain mainly affected by urban expansion in China and India (Potapov et al., 2022). Anticipating the future, global projections indicate a growth in urban areas by a factor of 1.8 to 5.9., which would mainly occur in Africa and Asia by 2100 (Gao & O’Neill, 2020).

The land-use transition reduces green spaces and increases built-up areas which change the near-surface radiation and energy budgets over an urban area. Consequently, there is a decrease in latent heat and an increase in sensible heat leading to an increase in urban temperature. Green spaces have an important role to control urban temperature through evapotranspiration, trees shading, or air movement modification (Oke et al., 2017). Green spaces absorb solar radiation that is converted to latent heat used as the energy source to convert water from liquid form to gaseous form in the evapotranspiration process. Latent heat mainly ends up in water vapor, which does not raise the surrounding air temperature (Forman, 2013). Moreover, urban materials mainly have a good thermal admittance capacity that allow solar radiation absorption and release it as sensible heat which causes increasing air temperature (Oke, 1987). An increase in urban temperature due to LULC change has been observed in many cities such as Atlanta (Fu & Weng, 2017), Dhaka (Ahmed, 2015), Ho Chi Minh (Q.-V. Doan & Kusaka, 2016), Jakarta (Tokairin et al., 2010), Colombo (Maheng et al., 2019) and Tokyo (Matsumoto et al., 2017). During summertime, an increasing urban temperature is becoming more intensive that leads to health-related problems (De Troeyer et al., 2020; Kasai et al., 2017; Sharma et al., 2019; Steul et al., 2018; uz Zaman Chaudhry et al., 2015).

Furthermore, increasing urban temperature due to LULC change can influence urban rainfall. Urban-induced rainfall is a complex process, intricately influenced by the urban environment (Kusaka et al., 2014; Lin et al., 2011; Shepherd, 2005; Umer et al., 2023). Temperature changes in urban areas are related to urbanization and global warming, which can affect local precipitation (McCarthy et al., 2010). The impact of urbanization on urban rainfall has been studied by analysing the land-atmosphere interactions in urban areas (Han et al., 2014; Hidalgo et al., 2008; Jin et al., 2015; Rozoff et al., 2003; Zhong et al., 2017). These interactions are mainly influenced by an increase in sensible heat fluxes and surface roughness of an urban area (Q.-V. Doan et al., 2021; Huff & Vogel, 1978; L. Marelle et al., 2020). Due to LULC change, natural surfaces and green spaces of urban areas are replaced by man-made artificial surfaces that absorb more solar energy. The latter is released as sensible heat. This process affects atmospheric circulations and the formation and distribution of extreme rainfall (Lei et al., 2023). Many studies have been dedicated to investigating this interaction. Q.-V. Doan et al. (2021) highlighted the strong urban effect on local rainfall in Singapore where urban areas contributed to the total rainfall during late afternoons and evening for about 20-30%. Marelle et al. (2020) showed that an increasing upward movement of warm air and moisture convergence to an increasing sensible heat could be an important driver of increasing rainfall due to urbanisation. Umer et al. (2023) showed that changes in an urban landscape dominated by urban and built-up areas increased extreme rainfall intensity resulting in flash floods in the city of Kampala, Uganda. Future urbanization and Land Use and LULC changes are projected to sustain the increase in urban rainfall, as observed in Can Tho, Vietnam (Pathirana et al., 2014), as well as in cities like Paris and Shanghai (B. M. S. L. Marelle & Myhre, 2021), along with numerous other urban centers worldwide.

Moreover, decreasing green spaces and increasing built-up areas can make an urban area more susceptible to flooding. Loss of green spaces due to LULC change can alter the hydrology of an urban area causing a decrease in infiltration, a decrease in flow resistance, or a reduction in rainfall interception leading to an increase in surface runoff (Fletcher et al., 2013; Shang et al., 2020; Yao et al., 2015). Decreasing green spaces are associated with a loss of permeable surfaces of soils. Because of surface soil removal, cultivated land tends to have a low infiltration capacity since it is compacted with decreased pore space (Bergeson et al., 2022). The impact of an increasing urban and built-up areas on infiltration and flooding has been discussed in a number of studies. In their study, Eshtawi et al. (2016) found a linear relationship between the expansion of urban areas and the subsequent increase in surface runoff within the Gaza strip. Notably, a 50% increase in urban areas led to an increase in surface runoff of 13% to 27%. Kaspersen et al. (2017) demonstrated the significant impact of urban development on flooding in urban areas between 1984 and 2014. Their study revealed that a 1% increase in impervious surfaces could lead to a 10% increase in runoff volume in four European cities of Odense, Vienna, Strasbourg and Nice. Furthermore, Ngo et al. (2022) studied the impacts of urbanization on flood extents in CanTho in the Mekong delta. Their study showed that urbanization made the CanTho city more vulnerable to flooding. They projected that the flood extents in the city would increase by 2050 (under RCP 4.5 and RCP 8.5). Meanwhile, Apollonio et al. (2016) showed a positive correlation between increased flooding areas and decreased vegetation covers between 1984 and 2011 in the Cervaro basin in Southern Italy.

Decreasing green spaces due to LULC change in Jakarta in the last decades have been observed in several studies (Carolita et al., 2002; Maheng et al., 2021; Pravitasari, 2015; Rustiadi et al., 2002). Rustiadi et al. (2002) studied the LULC change of Jakarta and its surrounding areas Bogor, Tangerang, and Bekasi, between 1972 and 2001. They showed an increase of the built-up areas by about 51% in Jakarta, which was higher than that in the surrounding areas. Carolita et al. (2002) revealed that built-up areas in Jabotabek increased by about 12% between 1992 and 2001, while agricultural land decreased by about 6%. Ramdhoni & Rushayati (2016) highlighted a decrease in green spaces in Jakarta by about 12% between 2001 and 2014. Maheng et al. (2021) studied LULC change in Jakarta between 1995 and 2014. They revealed that the spatial-temporal distribution of land use and land cover (LULC) change in Jakarta was characterized by extensive urban development. The increasing built-up areas had a significant impact on the green spaces, which decreased by about 50%.

The impact of LULC change on increasing urban temperature in Jakarta has been studied by (Darmanto et al., 2019; Ramdhoni & Rushayati, 2016; Siswanto et al., 2016; Sobri, 2009; Tokairin et al., 2010). Tokairin et al. (2010) revealed an increase in urban temperature in the old Jakarta area due to urban development. Sobri (2009) highlighted that a decrease of urban green space in Jakarta and its metropolitan area could be associated with an increase in air temperature between 0.4 °C and 1.8 °C. Ramdhoni & Rushayati (2016) revealed an increase in land surface temperature (LST) of about 30 °C between 2001 and 2014, and an increase in air temperature from average 24°C and 30°C in 2001 to 27°C and 30°C in 2014. Siswanto et al. (2016) studied historical meteorological data from a 134-year daily record of Jakarta, which indicated that urbanization in Jakarta area contributed to an increase in the daily mean temperature in the last 100 years by almost 2 °C. The maximum temperature increased sharply with almost 2.12 °C in 100 year, which is higher than the rise in global land surface temperature. A recent study from Maheng et al. (2023) revealed that an increase of built-up areas resulting from urbanization between 1995 and 2014 had changed the spatial distribution of the urban temperature in Jakarta. The temperature increase was about 0.5 °C. They also highlighted that the temperature anomaly in the LULC change from green spaces to built-up areas was higher compared to that of changes in other LULC classes. Increasing urban temperature in Jakarta was associated with extreme rainfall intensity (Nuryanto et al., 2018; Siswanto et al., 2022; Tsiringakis et al., 2017). Tsiringakis et al. (2017) found that the flooding of February 2015 could be associated with increased in precipitation due to increased urban temperature because of urbanization. The increased urban temperature contributed to increased precipitation by 12%. During the dry season, the rainfall intensity is influenced by surface temperature (Siswanto et al., 2016), which tends to increase due to increased urbanisation (Supari et al., 2017). Nuryanto et al. (2018) have revealed that LULC change contributes to an increase of 0.2 °C of the urban temperature and 6% of the urban rainfall. Both changes were associated with the flood event in Jakarta of January 17, 2014.

The aforementioned studies indicate that as built-up areas increase and green spaces decrease, it can lead to combined or multi-hazard, including rising urban temperatures and intensified rainfall, ultimately resulting in more flooding (Q.-V. Doan et al., 2021; Nuryanto et al., 2018; Pathirana et al., 2014; Siswanto et al., 2016, 2022; Tsiringakis et al., 2017). Some studies have been devoted to discussing these relationships in Jakarta with a predominant focus on flooding events post-2013. However, there were some flooding in Jakarta before 2013, which were categorized as major floods, but insufficient information is available about the interrelation between urban temperature, extreme rainfall and flooding. Hence, this study was aimed to identify and to discuss the changing pattern of urban temperature, daily rainfall and flooding, as well as potential combined or multi-hazard in Jakarta in the period 1987 and 2017.

5.2 Data source

This study was based on 30-year data of air temperature, daily rainfall and flooding in Jakarta. The meteorological data of rainfall and temperature was made available on a daily resolution by the Indonesian Meteorological organisation BMKG through their online portal (https://dataonline.bmkg.go.id, Table 5–1) (BMKG, 2022). The rainfall and temperature data were provided by the meteorological stations and comprised collected data for the period between 1987 and 2017. The historical flooding data was collected from various sources, including newspapers, research papers, reports and the international disaster database (CEDR, 2022).

The daily rainfall and the daily air temperature data were from three meteorological stations of the Meteorological, Climatological, and Geophysical Agency (BMKG) of Indonesia. The meteorological stations are located in Jakarta (HPA and KMY) and at the Soekarno-Hatta international airport (SHIA) at the outskirt of Jakarta, as depicted in Figure 1.1.

Table 5–1. Data sources

Meteorological Stations	Data	Time period	Source
KMY	daily temperature, daily rainfall	1987 to 2017	https://dataonline.bmkg.go.id
SHIA	daily temperature, daily rainfall	1987 to 2017	https://dataonline.bmkg.go.id
HPA	daily temperature, daily rainfall	1987 to 2017	https://dataonline.bmkg.go.id

5.3 METHODOLOGY

The causal relationship between urban form and climate change impacts is described by urban density, LULC, urban materials, high urban temperature, urban rainfall and urban flooding. Urban density can be referred to the density of people or to the number of buildings in an urban area. Furthermore, materials in an urban area can be asphalt, concrete or metal. The relationship between the climate change impact and urban form indicates that urban forms can have direct impacts at urban scale resulting in high urban temperature/urban heat island and urban flooding. The impacts may further be exacerbated by urban, regional and global climate change.

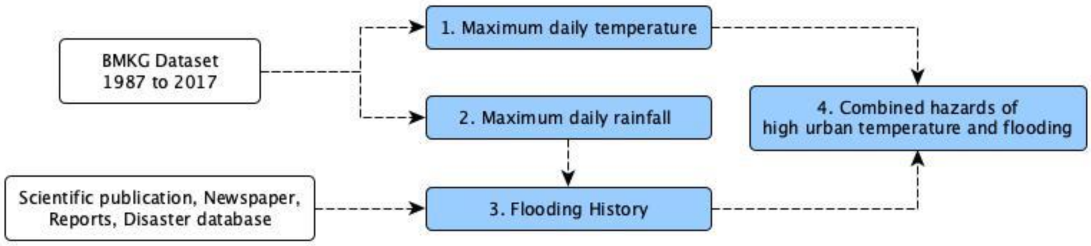

Figure 5.1. Research framework.

This study was conducted in four steps as shown in Figure 5.1. Firstly, air temperature data of Jakarta was collected from three meteorological stations of BMKG for the period 1987 and 2017. The maximum daily temperature was used for the air temperature analysis since the data available for the minimum and the average daily temperature were incomplete. The air temperature dataset was used to extract annual maximum daily temperature to see the general trend of maximum daily temperature over a 30-year period. The temperature trend was analysed by using the statistical analysis of the Mann-Kendall, and the Pettitt's test to identify the change point. Those two statistical tests are non-parametric tests that have been widely used to identify the trend and the change point of historical climate and hydrological data (Arvind et al., 2017; Y. Li et al., 2005; Marani & Ignaccolo, 2015; Towler et al., 2020). Furthermore, the monthly maximum daily temperature was prepared to understand the maximum daily temperature trend over a year. The monthly analysis divided the temperature dataset into three periods, namely the 1st period (1987 and 1996), the 2nd period (1997 and 2006), and the 3rd period (2007 and 2017).

Secondly, the daily rainfall analysis was based on the annual maximum daily rainfall in Jakarta between 1987 and 2017. The annual maximum daily rainfall was used to calculate the rainfall amount from one-day to three-day rainfall. The maximum daily rainfall was the average values of maximum daily rainfall from three stations, which was calculated by using the Thiessen polygon method (Te Chow et al., 1988). The statistical test was also conducted to analyse the trend and the change point of the maximum daily rainfall in Jakarta. Furthermore, the rainfall amount was classified into four classes, namely low, medium, high and very high. The classification was based on the statistical approach to identify rainfall extreme following some previous studies on the rainfall analysis (Arvind et al., 2017; Y. Li et al., 2005; Marani & Ignaccolo, 2015; Towler et al., 2020). The statistical approach was used to calculate the mean values and the standard deviation of the rainfall dataset. The first class was the low class which was defined by the range of the rainfall amount between its mean value and mean plus one standard deviation. The second class was the medium class where the rainfall amount was between its mean plus one standard deviation and mean plus two standard deviations. The third class was the high class where the rainfall amount was between its mean plus two standard deviation and mean plus three standard deviations. The fourth class was the very high class where the rainfall amount was higher than its mean plus three standard deviations. Furthermore, extreme rainfall was defined as the rainfall amount associated with the major flooding or severe flooding in Jakarta. The rainfall classification used in this study is given in Table 5–2.

Table 5–2. Rainfall classification used in this study. μ and σ denote average and standard deviation of maximum daily rainfall respectively whereas p denotes the daily maximum rainfall on a given day.

Proposed rainfall classification in Jakarta	**Daily rainfall amount**
Low	$p < (\mu + \sigma)$
Medium	$(\mu + \sigma) < p < (\mu + 2\sigma)$

High	$(\mu + 2\sigma) < p < (\mu + 3\sigma)$
Very high (extreme)	$p > (\mu + 3\sigma)$

Thirdly, flooding history in Jakarta from 1987 to 2017 was documented from various sources, such as newspaper, reports, websites and scientific publications. The historical flooding was used to identify flooding between 1987 and 2013, which helped to indicate the rainfall threshold of flooding in Jakarta.

Fourthly, a combined or multi-hazard possibility of high urban temperature and flooding was analysed. This section was looking into the result of urban temperature analysis and flooding history documentation. By looking at the two outputs, it is possible to identify combined or multi-hazard in Jakarta.

5.4 RESULTS

5.4.1 Maximum daily temperature

Between 1987 and 2017, air temperature in Jakarta exhibited an increasing trend, as depicted in Figure 5.2. The figure shows that three meteorological stations recorded an increasing trend of annual maximum daily temperature. The highest annual maximum daily temperature was about 37 °C recorded at all stations, while the SHIA station recorded the lowest annual maximum daily temperature of about 33 °C. Figure 5.2(a) shows the changing temperature trend line at the HPA station with the significant *p*-value (of Pettitt's test) < 0.05. At the HPA station, the lowest annual maximum daily temperature of about 34 °C was recorded in 1992, while the highest annual maximum daily temperature of about 37 °C was observed in 2009. The Pettitt's test result showed that the significant value of the Pettitt's test for the HPA station was greater than 0.05, indicating that there was not a change in the temperature data. As a result, the HPA station probably did not have the changing point. The temperature change trend line of the KMY station is shown in Figure 5.2(b). Figure 5.2(b) shows that the lowest annual maximum daily temperature at the KMY station was almost similar to that at the HPA station, but it was observed in 2001 for the KMY station. The highest annual maximum daily temperature at the KMY station was about 37 °C observed in 2014. The temperature trend line of the KMY station had the significant *p*-value < 0.05. The annual maximum daily temperature started increasing at the KMY station in 2001 as indicated by the changing point as the result of the Pettitt's test with the significant *p*-value < 0.05. Figure 5.2(c) shows the temperature change trend line of the SHIA station. It is shown that the annual maximum daily temperature of the SHIA station started increasing in 1996 as indicated by the changing point of the Pettitt's test with the significant *p*-value < 0.05. Furthermore, the lowest annual maximum daily temperature at the SHIA station was about 33 °C observed in 1995, while the highest temperature was a bit higher than 37 °C observed in 1999.

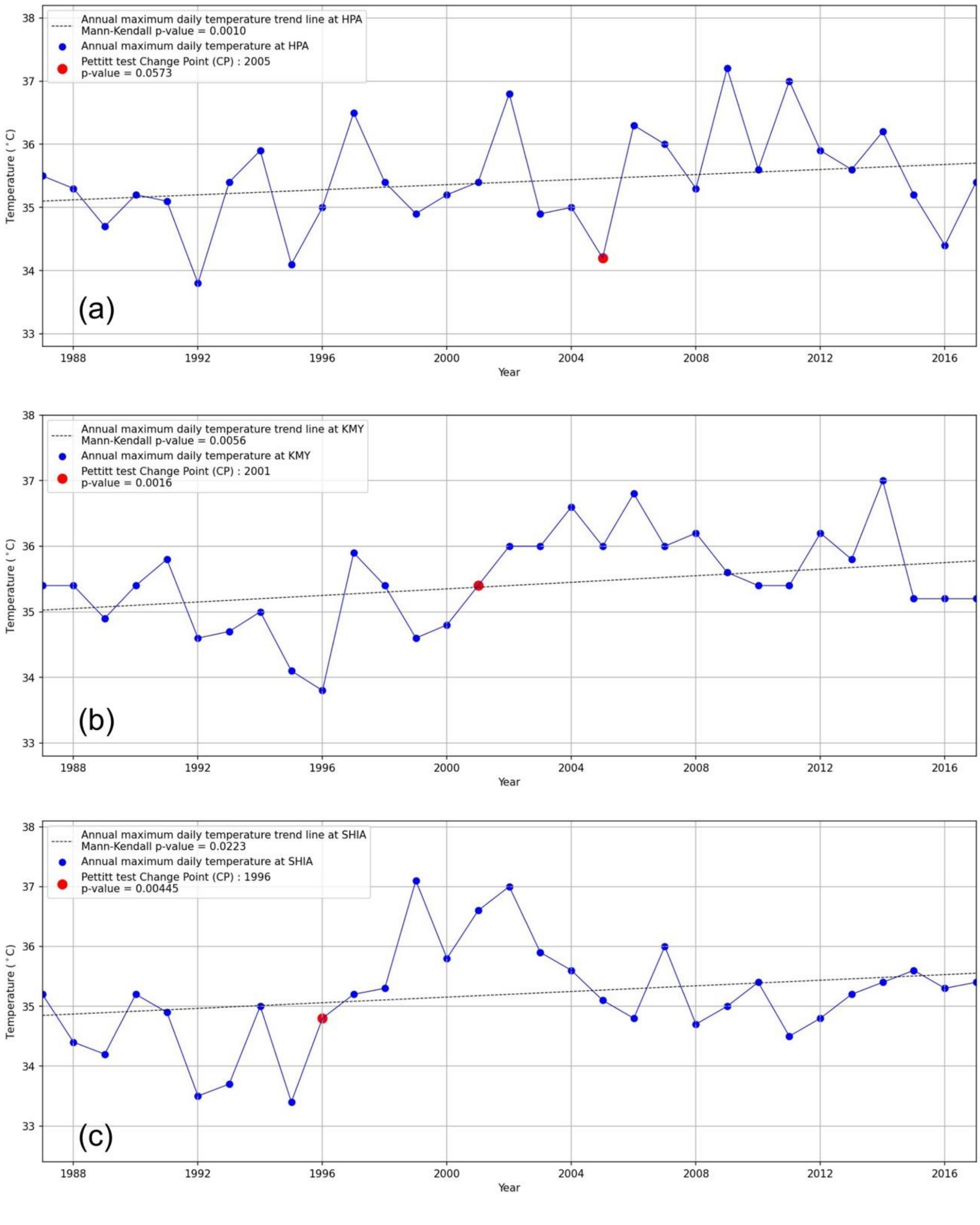

Figure 5.2. The annual maximum daily temperature change trend and the changing point at the meteorological stations. (a) the HPA station; (b) the KMY station; (c) the SHIA station.

The increasing trend of maximum daily temperature was also observed in the monthly maximum daily temperature, as given in Figure 5.3(a), Figure 5.3(b), and Figure 5.3(c). The monthly maximum daily temperature data was divided into three periods: from 1987 to 1996 (1st period), from 1997 to 2006 (2nd period), and from 2007 to 2017 (3rd period).

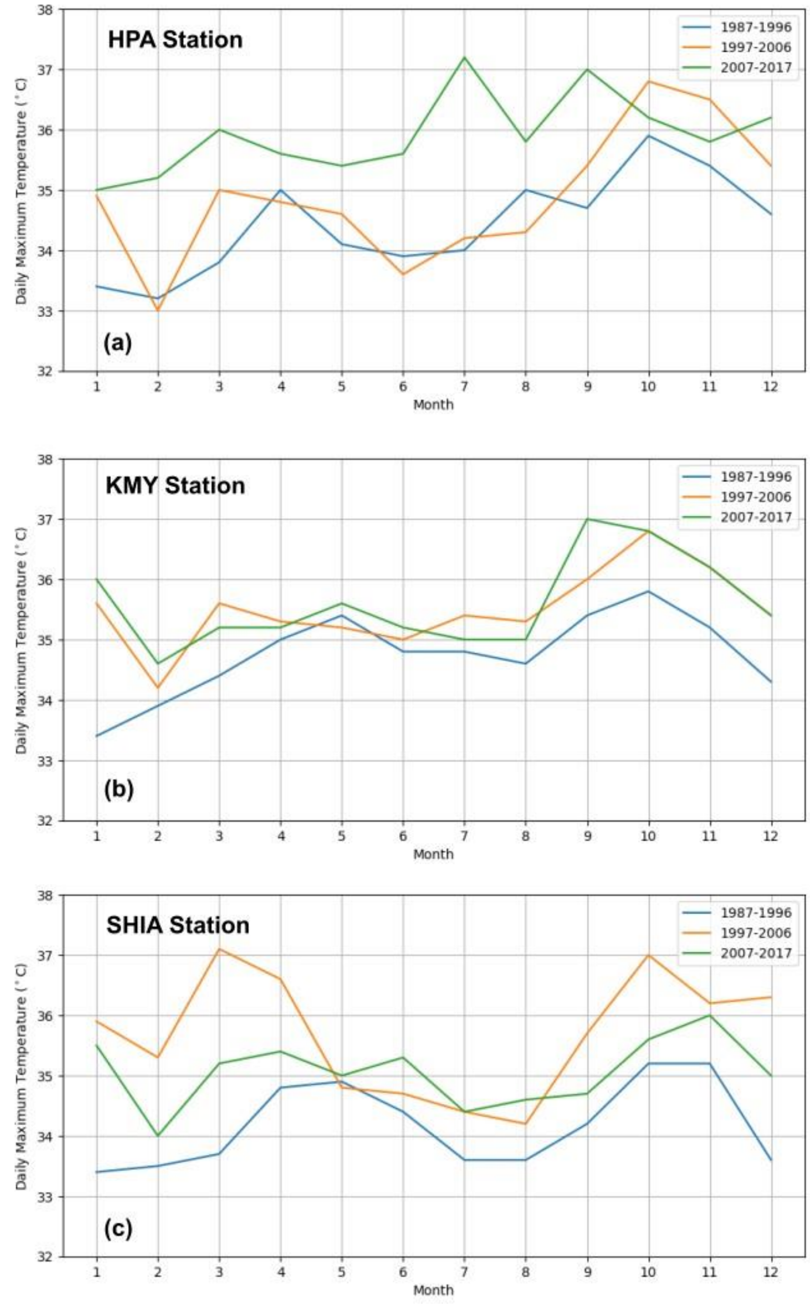

Figure 5.3. Maximum daily temperature between 1987 and 2017 in Jakarta. (a) Monthly maximum daily temperature at the KMY station; (b) Monthly maximum daily temperature at the HPA station; (c) Monthly maximum daily temperature at the SHIA station.

Figure 5.3(a) shows a consistent increase of the monthly maximum daily temperature at the HPA station over 30 years spanning the three periods. At the HPA station, the lowest maximum daily temperature increased from about 33 °C in the 2^{nd} period to about 35 °C in the 3^{rd} period. The highest maximum daily temperature increased from about 35 °C in the 1^{st} period to about 37 °C in the 3^{rd} period. The maximum daily temperature at the HPA station had an increasing trend starting from February to October in the 1^{st} period and the 2^{nd} period, while the highest maximum daily temperature of the 3^{rd} period was observed in July. The maximum daily temperature in the 1^{st} period started increasing from about 33 °C in February to about 35 °C in October. In the 2^{nd} period, the maximum daily temperature increased from 33 °C in February to about 36 °C in October. The 3^{rd} period showed a significant increase of maximum daily temperature. The maximum daily temperature increased from about 35 °C to about 37 °C in July.

The increasing trend of maximum daily temperature at the KMY station is given in Figure 5.3(b). The lowest maximum daily temperature increased from about 33 °C in the 1^{st} period to about 34 °C in the 3^{rd} period. Moreover, the highest maximum daily temperature also increased from about 35 °C in the 1^{st} period to about 37 °C in the 3^{rd} period. Furthermore, it was observed that the maximum daily temperature increased gradually from February to October in the 1^{st} period and the 2^{nd} period, while it increased from February to September in the 3^{rd} period. In the 1^{st} period, the maximum daily temperature increased from 33 °C in February to almost 36 °C in October when the rainy season normally begins. In the 2^{nd} period, the maximum daily temperature increased from about 34 °C in February to almost 37 °C in October. In the 3^{rd} period, the maximum daily temperature had a similar pattern with two other periods, but the highest maximum daily temperature was observed at 37 °C in September.

The maximum daily temperature pattern at the SHIA station is given in Figure 5.3(c). Compared to two other stations, the SHIA station showed an increase in the maximum daily temperature from the 1^{st} period to the 2^{nd} period. At the SHIA station, the lowest maximum daily temperature increased from about 33 °C in the 1^{st} period to about 35 °C in the 2^{nd} period. The highest maximum daily temperature increased from about 35 °C in the 1^{st} period to about 37 °C in the 2^{nd} period. Furthermore, the maximum daily temperature in the 1^{st} period showed an increasing trend started from about 33 °C in February to about 35 °C in October. In the 2^{nd} period, the maximum daily temperature had a high variation. The maximum daily temperature started increasing from about 35 °C in February to the highest value of about 37 °C in March. Afterwards, the trend decreased gradually to reach the lowest maximum daily temperature of about 34 °C in August. The 3^{rd} period showed a lower maximum daily temperature compared to that in the 2^{nd} period. The lowest maximum daily temperature in the 3^{rd} period was about 34 °C in February, while the highest temperature was about 36 °C observed in November.

5.4.2 Maximum daily rainfall

The statistical test results from the Mann-Kendall test showed that there was an increase in daily rainfall and daily accumulated rainfall in Jakarta between 1987 and 2017, as depicted in Figure 5.4, with the significant p-value < 0.05. The increasing trend of accumulated daily rainfall was observed for daily rainfall (Figure 5.4(a)), two-day rainfall (Figure 5.4(b)), and three-day rainfall (Figure 5.4(c)). Furthermore, the accumulated daily rainfall started increasing in 2001 as indicated by the change point of the Pettitt's test with the significant *p*-value < 0.05.

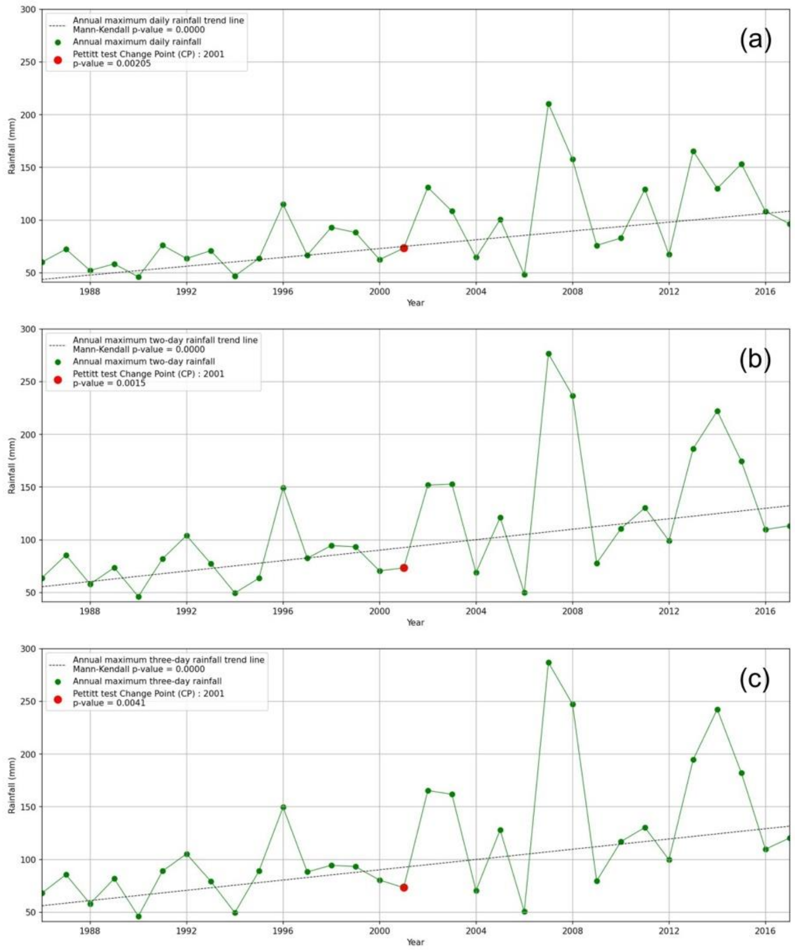

Figure 5.4. The daily accumulated rainfall and the changing point in Jakarta. (a) daily rainfall; (b) two-day rainfall; (c) three-day rainfall.

The increase of the maximum daily rainfall was observed mainly in January and February, which coincided with the flood events recorded in these months in Jakarta, as given in Table 5–3.

Table 5–3. The daily accumulated rainfall of flood events based on BMKG data in Table 5–1.

Dates	**Accumulated rainfall (mm)**		
	One-day	**Two-days**	**Three-days**
9-Feb-1996	114.9	149.5	149.7
25-Feb-1998	93.2	94.5	94.5
1-Feb-2002	131.1	151.9	165.4
29-Dec-2003	108.5	152.9	161.8
18-Jan-2005	100.6	121.3	128.2
1-Feb-2007	210.5	276.6	286.9
1-Feb-2008	157.7	236.8	247.3
28-Feb-2011	129.3	130.4	130.4
17-Jan-2013	165.6	186.5	194.7
17-Jan-2014	130.0	222.1	242.4
10-Feb-2015	153.3	174.5	182.2
21-Apr-2016	108.4	109.8	109.8

Figure 5.5 shows the annual maximum daily rainfall in Jakarta. It shows that at one-day, the flooding could be associated when the maximum daily rainfall was above the mean value of about 92 mm. Figure 5.5 shows that the flooding identified in 1996, 1998, 2002, 2003, 2005, 2011, 2014 and 2016, could be associated with the low class of the rainfall. Furthermore, the medium class of the rainfall was identified in 2008, 2013, and 2015. The maximum daily rainfall in 2007 was classified into the very high class since it was above 200 mm.

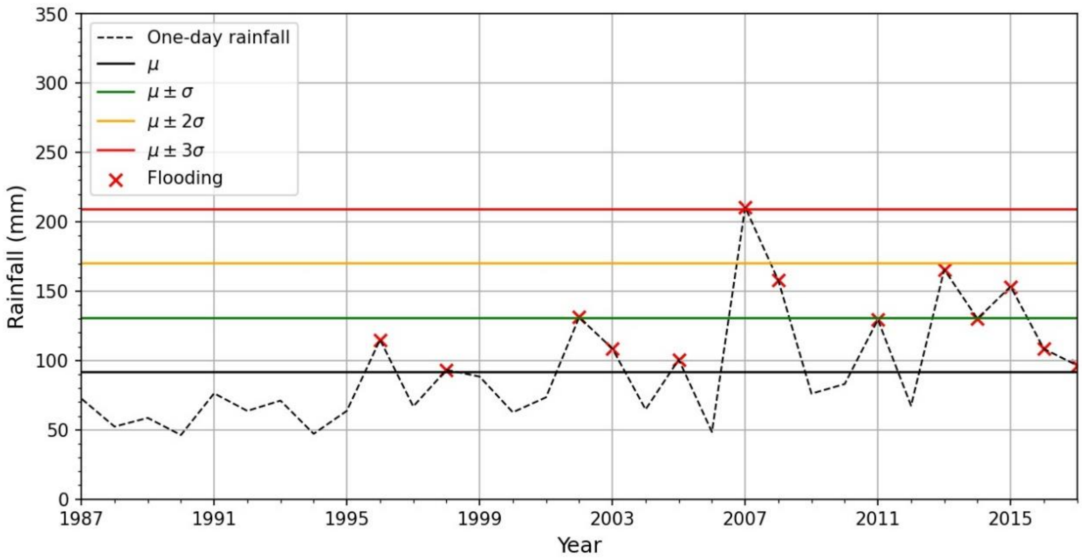

Figure 5.5. Annual maximum daily rainfall in Jakarta between 1987 and 2017. The maximum daily rainfall which resulted flooding are presented with a red cross. Here μ and σ denote the standard deviation and the mean value of the annual maximum daily rainfall (Pm) time series during 1987-2017 for Jakarta, respectively.

The annual maximum two-day rainfall is depicted in Figure 5.6. It can be seen that there was a slight change in the rainfall classification compared to that of the daily maximum rainfall, particularly in 1998 and 2016. The maximum two-day rainfall in 1998 and 2016 were below its mean value of 110 mm. The maximum two-day rainfall that could be associated with the flooding was observed in 1996, 2002, 2003, 2005, 2007, 2008, 2011, 2013, 2014, and 2015. The low-class rainfall was identified in 1996, 2002, 2003, 2005, and 2011. The medium class was observed in 2013, 2014, and 2015, while the high class was identified in 2007 and 2008. At two-day rainfall, there was no rainfall classified into the very high class.

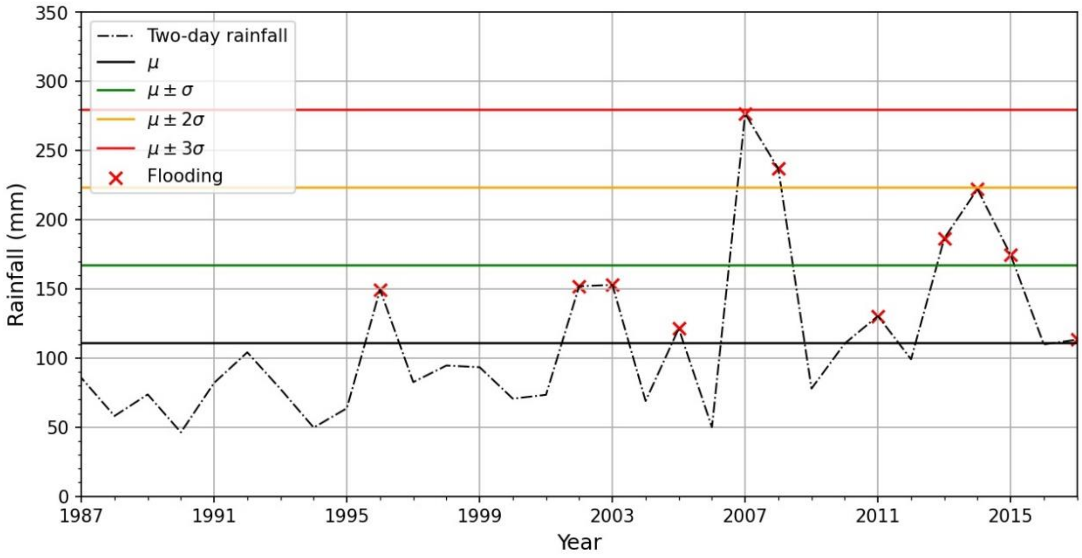

Figure 5.6. Annual maximum two-day rainfall in Jakarta between 1987 and 2017. Here μ and σ denote the standard deviation and the mean value of the annual maximum two-day rainfall (Pm) time series during 1987-2017 for Jakarta, respectively.

The annual maximum three-day rainfall is depicted in Figure 5.7. The figure indicates that the maximum three-day rainfall associated with flooding has appeared in 1996, 2002, 2003, 2005, 2007, 2008, 2010, 2011, 2013, 2014 and 2015. The low-class rainfall was identified in 1996, 2002, 2003, 2005, 2010 and 2011. Moreover, the maximum three-day rainfall of 2011 at 72-hour was higher than that at 24-hour. The medium class was observed in 2013 and 2015. Furthermore, the maximum three-day rainfall in 2007, 2008 and 2014 were classified into the high class.

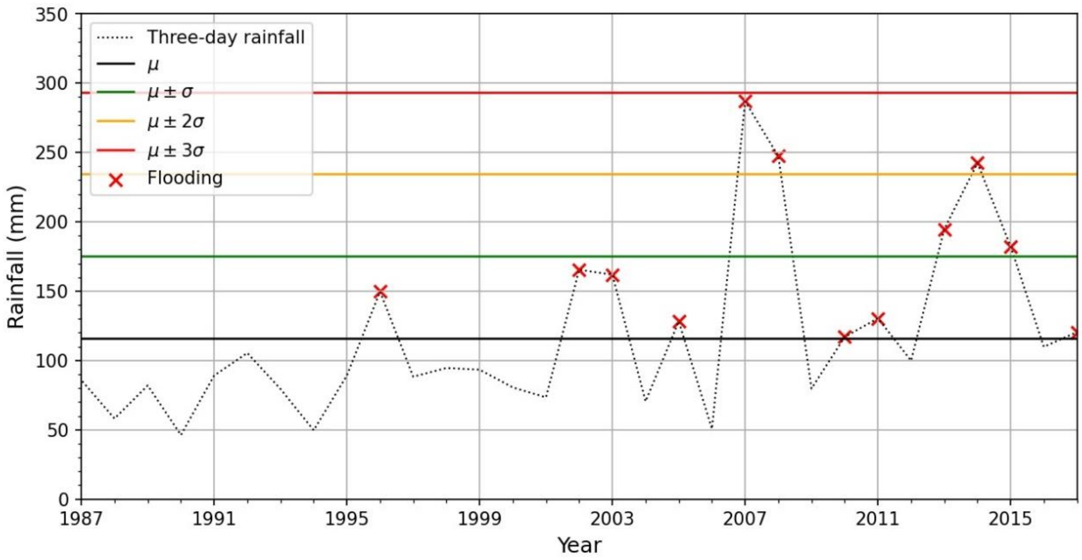

Figure 5.7. Annual maximum three-day rainfall in Jakarta between 1987 and 2017. μ and σ denote the standard deviation and the mean value of the annual maximum three-day rainfall (Pm) time series during 1987-2017 for Jakarta, respectively.

According to the daily rainfall analyses above, it can be seen that Jakarta was inundated once the daily rainfall amount was more than 92 mm. Figure 5.5 shows that the maximum daily rainfall above this threshold value was observed in 1996, 1998, 2002, 2003, 2005, 2007, 2008, 2011, 2013, 2014, 2015, and 2016. Furthermore, severe flooding was observed when there was extreme rainfall higher than 150 mm.

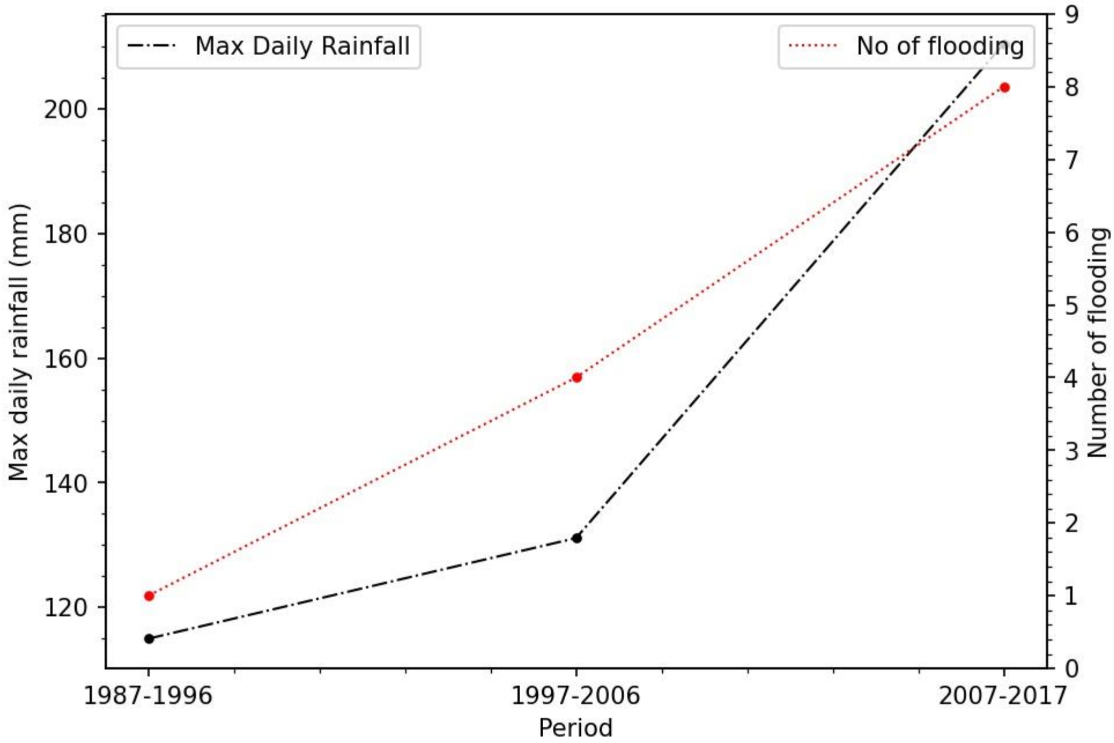

Figure 5.8. Maximum daily rainfall and number of flooding at several observation periods.

An increase in number of flooding between 1987 and 2017 in Jakarta had the relationship with an increase in daily rainfall, as depicted in Figure 5.8. The number of flooding between 1987 and 1996 was one event when the maximum daily rainfall was about 114 mm. The number increased to four events between 1997 and 2006 when the maximum daily rainfall was about 131 mm. Afterwards, the number of flooding between 2007 and 2017 also increased to eight events when the maximum daily rainfall was about 210 mm observed in 2007.

5.4.3 Flooding history in Jakarta

Jakarta has a long history of flooding. Noorduyn & Verstappen (1972) revealed that the first flooding in Jakarta was documented in the Prasasti Tugu from the 5th century.

Table 5–4. Years of flooding, the impacts and information sources

Dates	Number of affected people	Number of deaths	Remarks	Flooding information sources
09 Feb 1996*	~30000	20	Major flooding	(CEDR, 2022; Ndoen et al., 2013)
1998	NA	NA		NA
01 Feb 2002*	~ 400000	~ 33	Major flooding	(CEDR, 2022; Ndoen et al., 2013; ReliefWeb, 2002)
29 Dec2003	NA	NA		(CEDR, 2022)
2005	NA	NA		(detiknews, 2005)
01 Feb 2007*	~ 400000	~ 57	Major flooding	(Guardian, 2007; JBA, 2014; Ndoen et al., 2013; ReliefWeb, 2007)
01 Feb 2008*	~ 80000	NA	Major flooding	(Aldrian, 2008; detiknews, 2008)
2011	NA	NA		NA
17 Jan 2013*	~ 250000	~ 20	Major flooding	(JBA, 2014; Nuryanto et al., 2019; ReliefWeb, 2013)

Dates	Number of affected people	Number of deaths	Remarks	Flooding information sources
17 Jan 2014*	~ 130000	~ 20	Major flooding	(CEDR, 2022; JBA, 2014; Nuryanto et al., 2018; Siswanto et al., 2015)
10 Feb 2015	NA	NA		(CEDR, 2022; ReliefWeb, 2015; Siswanto et al., 2017)

Over the last three decades, spanning from 1987 to 2017, Jakarta experienced numerous floods, which have been documented in research papers, reports and newspapers, as shown in Table 5–4. Among them, major floods were observed in 1996, 2002, 2007, 2008, 2013 and 2014. This study did not have access to direct damage data for the floods that occurred between 1987 and 2017. Hence, the severity of the floods was based on the affected number of people and number of deaths. In the decade between 1990 and 2000, Jakarta experienced a significant flood in 1996, resulting in the loss of 20 lives and affecting 30,000 people (CEDR, 2022; Ndoen et al., 2013). From 2001 to 2010, at least three major floods were recorded. One of them was in 2002 when the number of affected people reached more than 400000 and 22 people died (CEDR, 2022; Ndoen et al., 2013; ReliefWeb, 2002). Diposaptono et al. (2004) highlighted that the 2002 flood was one of the most severe floods in Jakarta. However, the flood in 2007 had a more significant impact as the number of casualties was higher (JBA, 2014; Ndoen et al., 2013; ReliefWeb, 2007). The inundated areas of flooding in 2007 were available in (Cobián Álvarez & Resosudarmo, 2019). Flooding in 2008 did not cause a significant impact since the number of affected people was smaller than that of other flooding. Between 2011 and 2017, two major flooding were recorded. In 2013, the flooding affected 25000 people (JBA, 2014; ReliefWeb, 2013). Moreover, flooding in 2014 had a relatively small impact compared to that of previous flooding as the number of affected people was decreasing. However, the 2014 flooding still caused damages to the city though the flood was not comparable to that in 2007 and 2013 (JBA, 2014).

5.5 DISCUSSION

5.5.1 Increasing maximum daily temperature and maximum daily rainfall

From 1987 to 2017, Jakarta experienced an upward trend in both maximum daily temperature and maximum daily rainfall, which had been linked to the rising frequency of flooding in recent years. In general, the increasing maximum daily temperature was observed in three stations of BMKG. The monthly maximum daily temperature showed an increase in February to September, October or November, when the maximum daily temperature reached the highest temperature. The daily rainfall was associated with flooding observed mainly during the rainy season, particularly in January and February.

An increase in the maximum daily temperature was observed in Jakarta. At the HPA station, the increasing maximum daily temperature was observed, but there was no clear evidence when the temperature started increasing at the station. On the other hand, two other stations, the KMY and the SHIA stations, showed that the maximum daily temperature started increasing in 2001 and 1996, respectively. In general, the maximum daily temperature in Jakarta started to increase at the end of the rainy season in February and March and reached the highest temperature in September and October at the KMY and the HPA station, respectively. After this period, the maximum daily temperature decreased gradually until February of the coming year at all the stations. The highest maximum daily temperature was about 37 °C, while the lowest one was about 33 °C. At the KMY and the HPA station, the first and the second period showed that the maximum daily temperature started to increase from February to reach the highest temperature in October. In the third period, the maximum daily temperature shifted from October to September. However, the SHIA station showed a different maximum daily temperature pattern compared to that of other stations. The increasing urban temperature in Jakarta can be related to the observed LULC change, which shows an increase of the proportion of built-up areas and a decrease of the green spaces in Jakarta (Carolita et al., 2002; Maheng et al., 2021; Ramdhoni & Rushayati, 2016; Sobri, 2009). In the last decades, the increasing built-up area in Jakarta is associated with an increasing urban temperature. The increasing urban temperature in this study was consistent with earlier findings on the impact of LULC change on urban temperature in Jakarta (Darmanto et al., 2019; Maheng et al., 2024; Ramdhoni & Rushayati, 2016; Tokairin et al., 2010).

Increasing maximum daily rainfall observed during the rainy season could be associated with the occurrence of major floods in Jakarta. The maximum daily rainfall started increasing in 2001 after which Jakarta experienced major flooding in 2002. In general, the daily rainfall analysis results revealed that inundations in Jakarta occurred when the daily rainfall amount was about 92 mm. In addition, flooding was more severe when the daily rainfall or the accumulated daily rainfall amount was above 150 mm. These results were consistent with previous studies which suggested that major flood events were recorded in 1996, 2002, 2007, 2008, 2013, 2014 and 2015, as a result of accumulated rainfall over two to three days (Aldrian, 2008; JBA, 2014; Media Jaya, 2020; Siswanto et al., 2015). In this study, it was observed that the rainfall amount in those years (1996, 2002, 2007, 2008, 2013, 2014, and 2015) was about 150 mm. For instance, the two-day rainfall in 1996, which caused flooding was about 150 mm. In 2002, the two-day and three-day rainfall were about 152 mm and about 165 mm, respectively. The major flood in 2003 could be related to the two-day and the three-day rainfall of about 153 mm and 162 mm, respectively. The major flood in 2007 was the worst flood event in Jakarta when the rainfall amount was about 211 mm. Furthermore, the two-day and the three-day rainfall in 2007 were about 277 mm and 287 mm, respectively. In 2008, the one-day, two-day, and three-day rainfall were about 158, 237 and 247 mm, respectively. The one-day rainfall in 2013 could be related to the flooding in Jakarta since the rainfall amount was about 165 mm over 24 hours.

5.5.2 Increasing number of flooding

This study showed that the increasing maximum daily rainfall could be associated with increased flooding. From 1987 to 2017, it was observed that an increase in flooding in Jakarta began after the year 2001, while the maximum daily rainfall increased gradually since 2001. The increasing number of flooding in Jakarta could be associated with the high rate of LULC that decreased the area of green spaces and increased the area of built-up area (Carolita et al., 2002; Maheng et al., 2021; Nagasawa et al., 2015; Ramdhoni & Rushayati, 2016), as well as changed the landscape pattern (Maheng et al., 2021). The decrease in green spaces and the change in landscape pattern can result in an insufficient capacity for infiltration and interception which can lead to an increase in surface runoff (Kim & Park, 2016; B. Zhang et al., 2015). The increasing daily rainfall intensity along with the decrease in green spaces had given the significant impact of flooding in Jakarta as the number of major flooding was observed in 1996, 2002, 2007, 2008, 2013 and 2014. Furthermore, increased flooding in Jakarta from 1987 to 2017 could also be influenced by several other factors, such as land subsidence, particularly in Northern part of Jakarta (Hasibuan et al., 2023; Takagi et al., 2021), an inadequate drainage system in Jakarta (Wicaksono et al., 2021) and fluvial flooding (Budiyono et al., 2016; Wijayanti et al., 2017). These are typical problems in many cities in the Global South where flooding is likely to increase due to an increase in both hazards frequency and intensity and vulnerability (Zevenbergen et al., 2017).

In this study, the results indicated that there was an implicit relationship between the increasing urban temperature during the rainy season and its potential association with rising maximum daily rainfall amounts. The increasing urban temperature can affect rainfall intensity through the complex process of land-atmosphere interaction influenced by LULC changes and urbanization. The results showed consistency with previous research on the relationship between increasing urban temperature and extreme rainfall intensity in Jakarta (Siswanto et al., 2022). Siswanto et al. (2022) observed an increase of the urban temperature with an increase of the atmospheric moisture content increased extreme rainfall intensity in Jakarta between 1900 and 2010. It is noted here that extreme rainfall intensity in Jakarta is also influenced by several other factors, such as the Asian monsoon system, The Madden Julian Oscillation (MJO), and El Niño–Southern Oscillation (ENSO) (Aldrian, 2008; Siswanto et al., 2015, 2022; Supari et al., 2018), which were not taken into account in this study.

5.5.3 Multi-hazard of high urban temperature and flooding

The analysis of urban temperature and daily rainfall in this study showed that both hazards, high urban temperature and flooding, were implicitly interrelated. The daily air temperature time series indicated that the air temperature in Jakarta had increased in the 30-year study period. The highest maximum daily temperature had increased from about 33 °C to 37 °C. These high temperatures can have an impact on human health, particularly when the air temperature is higher than 35 °C, which is the temperature threshold for human health (Roca-barcelo et al., 2021). Therefore, maintaining the air temperature below 35 °C is vital to prevent hyperthermia (Sherwood & Huber, 2010).

People in some areas of Jakarta have been already impacted by high urban temperatures and flooding. For an area affected by both hazards, people would be experiencing high urban temperature during the dry season, particularly those who are living in the built-up environment. On the other hand, they can be exposed to flooding during the rainy season. The combined or multi-hazard possibility of high urban temperature and flooding are also observed in some other cities, such as in Bangkok (Majidi et al., 2019).

5.5.4 Limitations of this study and future perspectives

This study used a methodology that considered recorded data from meteorological stations along with historical flooding data from various sources. The meteorological data is publicly available at the daily resolution. The non-availability of meteo data at sub-daily scale was seen as a limitation; availability of such data may provide further insight in connecting increased urban temperature, increased rainfall to increased flooding (Siswanto et al., 2022; Young et al., 2021).

In future studies, the use of hourly temperature and rainfall data, if available, are recommended. This will allow to have a more detailed analysis of the relationship between local warming and changing rainfall intensity. Furthermore, maps of flooding before 2013 could be produced with the help of flood modelling. However, flood modelling requires thorough data preparation, including the provision of an appropriate layout of drainage systems. To address health-related risks, acquiring patient data in Jakarta becomes crucial. This information will reveal the number of people affected by high urban temperatures and their respective residential areas. With this data, it becomes feasible to identify areas impacted by the combined hazards of high urban temperatures and flooding.

5.6 Conclusion

This study discussed the changing pattern of daily urban temperature, daily rainfall, and flooding in Jakarta from 1987 to 2017. This study showed that there was a changing pattern indicated by an increase in maximum daily temperature, that coincided with an increase in daily rainfall and flooding. The daily temperature increased at all stations, but they did not start at the same time. Furthermore, the increase of daily rainfall started in 2001. Afterward, the number of flooding event increased in Jakarta. This study revealed Jakarta’s vulnerability not only to rising urban temperatures but also to the consequent heightened risk of increased flooding.

The increase of urban temperature in Jakarta could be attributed to the reduction of green spaces. Over the past few decades, the city experienced significant losses in its green spaces due to urbanization, urban development and industrialization. These changes led to a decrease in the latent heat provided by green spaces and an increase in sensible heat. Consequently, Jakarta witnessed elevated maximum daily temperatures, posing potential impacts on human health. The increased urban temperature along with the specific regional atmospheric conditions of Jakarta could be related to an increase in rainfall intensity.

In this study, an increase in flooding was associated with an increase in daily rainfall in Jakarta. Some of these floods were categorized as major floods. Since 2001, an increase in daily rainfall along with an increase in flooding was observed in Jakarta. These hazards became more frequent since 2002. Flooding in Jakarta was primarily caused by extreme rainfall accumulated over one-day, two-day and three-day periods crossing rainfall thresholds. The rainfall analysis highlighted in this study indicated that Jakarta was inundated when the maximum daily rainfall surpassed the mean value of annual maximum daily rainfall. In addition, the occurrence of flooding in Jakarta was also influenced by other factors, such as land subsidence and inadequate drainage systems, which are not covered in this study.

This study indicated that Jakarta is vulnerable to the high urban temperature and flooding. Elevated urban temperatures, revealing an increasing trend since 1987, were observed during the dry season. At the same time, the flooding history showed an increase in flooding in Jakarta. The two hazards occurred in two different time periods, but they could occur in the same area. This observation stressed the importance of integrated urban water management solutions such as water sensitive urban design, climate sensitive urban design, and nature-based solutions to be considered in sustainable urban development and planning for enhancing flood resilience, while providing ecosystem services and other benefits. Hence, these approaches aim to minimize water-related risks and maximize benefits of interventions. They foster the preservation and/or the introduction of green spaces in cities to simultaneously address floods and high temperatures.

For Jakarta, this study was one of the first study to analyse the relationship between the combined or multi-hazard of high urban temperature and flooding. While previous studies in Jakarta had predominantly concentrated on flooding and rainfall intensity, this study offered novel insights by examining the possibility of the simultaneous occurrence of these hazards. The results of this study provided new and essential insights for further studies to enhance flood resilience and climate adaptation, advocating a holistic approach required to tackle these combined or multi-hazard.

6

CONCLUSIONS

Urbanization coupled with LULC change have a significant impact on reducing green spaces and expanding built-up areas. LULC change was not only affecting the total area of green spaces but also their landscape pattern. As a result, there was a decrease in ecosystem services provided by green spaces such as temperature regulation and runoff regulation. One important impact of a decrease of green spaces is an increase in urban temperatures. The results from this study showed that an increasing urban temperature is not only influenced by the total area of green spaces but also by the landscape pattern and the type of green spaces. Land-use tranformation in LULC change processes plays an important role in temperature changes. Futhermore, a decrease in green spaces is affecting surface runoff which tends to increase due to the low permeability of built-up areas. The increasing surface runoff might result in flooding. Over the long term, urbanization and LULC change can change the pattern of the daily temperature and daily rainfall of a city as indicated by the observed increasing trend and a change point in the time series data from 1987 to 2017. Increasing trend of daily rainfall intensity increase vulnerability of a city to flooding.

6.1 Conclusions

6.1.1 Urbanization and LULC changes in Jakarta

Jakarta has experienced rapid urbanization and the extensive transformation of vegetative green spaces into impermeable urban surfaces. Urbanization in Jakarta has given a significant impact on LULC change. It was found that there has been a substantial change in the spatial distribution of green spaces due to increasing urban areas. During the study period the urban areas increased by about 44%, while other areas including the areas of trees, grassland, cropland, suburban and water (lakes and rivers) decreased by about 58%, 36%, 32%, 15%, and 6%, respectively.

6.1.2 The influence of urbanization and LULC changes on landscape pattern and ecosystem services

The rapid urbanization in Jakarta not only changed the spatial distribution of green spaces but also altered the landscape patterns indicated by changes in the proportion, the aggregation, and the connectivity of green spaces, as well as of bodies of water. An increase in built-up areas resulted in a decrease in the size and the proportion of green spaces, as well as in the disaggregation and disconnection of green spaces. A change in the landscape patterns affected the capacity of green spaces to provide ecosystem services.

The increase in built-up areas during a 20-year period affected the spatial characteristics of green spaces marked by a scattered distribution and a decrease in the aggregation and the connectivity of green spaces, making green spaces more fragmented. On average, there was an 8.7% decrease in aggregation and a 9.6% decrease in connectivity, which correlates with an average decline in carbon sequestration (55%), temperature regulation (44%), and runoff regulation (41%). The reduced number and area of green spaces along with the landscape pattern changes and a decrease in urban ecosystem services has indicated that there is a relationship between those factors, which needs to be considered in the ecosystem service calculation.

The observed landscape pattern changes reduced the carbon sequestration, the temperature regulation, and the runoff regulation with an average value of 66, 55 and 51%, respectively, during the period of study. This indicates that the ability of green spaces to provide ecosystem services is strongly influenced by the spatial characteristics or the landscape patterns of green spaces.

6.1.3 A better urban temperature simulation using an urban climate model, UrbClim

The simulation of urban temperature at the horizontal resolution of hundreds of metres in this study was made possible by the urban boundary layer climate model, UrbClim.

UrbClim was used to simulate the urban temperature of Colombo, Sri Lanka. The urban temperature was simulated by using two input data which were land-use data of the year 1997 and 2015 with the horizontal resolution of 250 m and the meteorological boundary conditions from the ERA-interim reanalysis data covering the period of 1997 to 2015. In addition, two LULC change scenarios, namely urbanization scenarios (decreasing the area of green spaces) and greening scenarios (increasing the area of green spaces) were simulated. Having the horizontal resolution of 250 m, the urban temperature simulation in UrbClim was able to cover some urban details such as city parks. The statistical tests, RMSE and MAE, were carried out to evaluate the model's performance by comparing simulated values from the model and observed data from the meteorological station. The RMSE test indicated that UrbClim overestimated the urban temperature by about 2 °C. Furthermore, the MAE test showed that the absolute error values was less than 2 °C which is acceptable for 2 m temperature simulations. Meanwhile, the Pearson correlation coefficient between simulated and observed data of Colombo were within the range of 0.5 and +1 indicating strong correlation.

Furthermore, the sensitivity of urban temperature to green spaces was observed in UrbClim simulation. The urbanization scenarios showed that the decreasing area of green spaces resulted an increase in air temperature by about 0.03 °C. On the other hand, the greening scenarios indicated that the increasing area of green spaces decreased temperature by about 0.08 °C. The small temperature change should only be considered as a symptom of higher temperature variations since the UrbClim's output is the grid-average values that ignore a lot of sub-grid-scale heterogeneity.

6.1.4 The impact of different land-use transformation processes on urban temperature

This study showed that the different land-use tranformation processes can have a different impact on the variations and the spatial distribution of the mean air temperature. An increase in built-up areas had a significant impact on increased air temperature which could be associated with a decrease in evapotranspiration as a consequence of a decrease in green spaces. A significant increase in air temperature was observed in areas which had been transformed from green spaces into built-up areas, for example, from areas dominated by trees into urban areas where the average increase in temperature was about 0.27 °C. The main contributor to increased urban temperature was the land-use transformation from green spaces to built-up areas where the average temperature change was about 0.25 °C. On the other hand, decreased temperature was observed in areas which had been transformed from built-up areas to green spaces, for instance, from urban areas to grassland where the average temperature change was about -0.04 °C. This indicated that an increase in air temperature can be mitigated by greening solutions in which built-up areas are transformed into green spaces. The ability of green spaces to provide such a climate regulation is influenced by several factors, including the proportion and the distribution of green spaces. Hence, urban planning and urban land-use management have to play an important role to safeguard that there is an appropriate quantity, composition, and distribution of green spaces in urban (re)development programs to control a further increase of the urban air temperature.

6.1.5 The long-term impacts of urbanization and LULC changes on urban temperature, and flooding

A decrease in green spaces and an increase in built-up areas due to urbanization and LULC change had influenced urban climates and hydrological cycle of an urban area. Consequently, there was an increase in the maximum daily temperature and flooding events. LULC change in Jakarta contributed on the changing pattern of urban temperature. The urban temperature in Jakarta started increasing in 1996 as observed at the SHIA station, and in 2001 at the KMY station. An increase in urban temperature was in line with an increase in daily rainfall, which could be associated with some major floods between 1995 and 2013. The daily rainfall started increasing in 2001 after which a number of floods in Jakarta was observed and flooding became more frequent since 2002. Flooding in Jakarta was primarily caused by extreme rainfall accumulated over one-day, two-day, and three-day period higher than rainfall thresholds required to initiate flooding. The rainfall analysis in this study indicated that Jakarta was inundated when the maximum daily rainfall surpassed the mean value of annual maximum daily rainfall.

Over a 30-year period Jakarta had seen an increase in urban temperature and flooding. This indicates that Jakarta may have combined hazards of increased urban temperature and flooding. Both hazards may occur simultaneously or at different times in the same area. Given the ongoing urbanization and global climate change trends, Jakarta will likely face compounded threats from multiple hazards in the future.

6.2 RECOMMENDATIONS FOR FURTHER RESEARCH

6.2.1 LULC changes, landscape pattern and ecosystem service analysis

The spatial analysis in this study used a satellite image of medium resolution of 30 m from Landsat 5 and 8 to analyse LULC change and ecosystem services. However, some important urban details which provide ecosystem services such as city parks, small wetland areas, and lakes, as well as street corridors, could not be captured properly. In future studies, the use of high spatial resolution satellite images for land use–land cover classification is recommended. This increases the spatial analysis quality, and it allows researchers to include more ecosystem services analysis. The proposed Ecosystem

Services estimation can be further improved in the future by incorporating empirical values, for example, runoff coefficients derived from land cover classes. For validation purposes, future studies should consider methods which apply remote sensing techniques using a range of spatial resolutions combined with actual land management information.

6.2.2 An urban temperature simulation at UrbClim

The urban temperature simulation in UrbClim was using a relatively finer horizontal resolution of 250 m (in comparison to typical mesoscale atmospheric simulation studies). Still temperature values produced by the model were grid-average values that ignored numerous sub-grid-scale heterogeneities. Therefore, the seemingly moderate increases in temperature reported at grid-average scale should be considered as an indication of much greater sub-grid-scale temperature variations. Actual temperature hotspots may demonstrate temperature increases often much larger than the grid-average value. Further studies, ideally in conjunction with field observations, should be done to establish such sub-grid-scale temperature relationships.

6.2.3 Land-use transformation's impact on urban temperature

The modelling outputs from UrbClim was validated by using two different data sources, which are meteorological station data and the GHCN dataset. The temperature variations at each LULC change sub-class from the model outputs were validated using a point measurement located at the meteorological stations. This may create biased results since the model outputs are the averaged grid data representing a temperature condition over an area of 250 m which is the spatial resolution of UrbClim. For further research, it is recommended to provide similar data generated from consistent raw data acquisition and pre-processing. This study can be further improved by considering the temperature changes based on the change of leaf area index (LAI), or the change of albedo values. Furthermore, in-situ temperature monitoring over a certain period at a particular LULC change class can provide more accurate temperature information. Meanwhile, the further impact of increased urban temperature on extreme rainfall can be an interesting research topic which can bring insight on the ways land-use transformation can affect not only urban temperature but also extreme rainfall leading to urban flooding. However, UrbClim is limited to urban temperature simulations, so the use of another model such as WRF to simulate urban temperature and rainfall can be useful for assessing the impact of land-use transformation on urban temperature and extreme rainfall.

6.2.4 LULC changes' impact on urban temperature, extreme rainfall, and flooding

This study used a methodology that considered recorded data from meteorological stations along with historical flooding data from various sources. The meteorological data are publicly available on a daily resolution. The lack of meteorological data at a sub-daily scale is seen as a limitation; such data may provide further insight into the relationship between increased rainfall and increased flooding. In future studies, the use of hourly temperature and rainfall data, if available, is recommended. This will allow for a more detailed analysis of the relationship between local warming and changing rainfall intensity. Furthermore, maps of flooding before 2013 can be produced with the help of flood modelling. However, flood modelling requires thorough data preparation, including the provision of an appropriate layout of the drainage systems. To address health-related risks, acquiring patient data in Jakarta becomes crucial. This information will reveal the number of people affected by high urban temperatures and their respective residential areas. With these data, it will become feasible to identify areas impacted by the combined hazards of high urban temperatures and flooding.

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List of Acronyms

ECMWF	European Centre for Medium-Range Weather Forecasting
GIS	Geographical Information System
UrbClim	Urban boundary layer climate model
QGIS	Quantum Geographical Information System

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About the Author

Muhammad Dikman Maheng was born in Kendari, Southeast Sulawesi, Indonesia. He has a bachelor's degree in civil engineering from Universitas Islam Indonesia in 2002. He has been working as a lecturer since 2005 at Universitas Muhammadiyah Kendari which is one of universities of the biggest Islamic organization in Indonesia, Muhammadiyah.

In 2009, he pursued his MSc at UNESCO-IHE, Institute for Water Education, Delft, the Netherlands, financially supported by StuNED, and graduated in 2011 with the specialization in Integrated Urban Engineering. After obtaining the MSc degree, he returned to Kendari, Indonesia, and was involved in several water and sanitation related projects and activities. He was appointed as an engineering facilitator for the sanitation acceleration program from 2012 to 2013, a civil engineer for water and sanitation infrastructure evaluation program from 2014 to 2015, a member of water and sanitation working group of Kendari city in 2015, and as a post research master student for the MARE Asian Development Bank (ADB) green city action planning (GCAP) project in Indonesia from 2014 to 2016. The latter project was to support three medium-sized cities in Indonesia (Batam, Kendari, Malang) in preparing the green city action planning (GCAP) that included how to provide the minimum green spaces in cities and urban areas. The green city project had inspired his PhD research which focuses on the relationship between green spaces, ecosystem services, and urban climates.

He started his PhD in February 2017 at the Flood Resilience Group (FRG) of IHE Delft and the Faculty of Civil Engineering and Geosciences, Delft University of Technology with a PhD topic related to land use and land cover changes, urban climates and urban flooding. In his PhD research, he worked extensively with the boundary layer climate model (UrbClim) for urban air temperature simulations, and some rainfall-landuse interaction experiments using the WRF model. In addition, he was also using various spatial analysis applications such as QGIS, Fragstat, and GeoDa, as well as programming languange of Python and R. He is also interested in Linux operating system with which he made some contribution to some PhD research and projects during his PhD.

Journals publications for the doctoral research

Maheng D, Pathirana A, Bhattacharya B, Zevenbergen C, Lauwaet D, Siswanto S, Sugondo A. Impact of Land Use Land Cover Changes on Urban Temperature in Jakarta: Insights from An Urban Boundary Layer Climate Model. Under review

Maheng D, Bhattacharya B, Zevenbergen C, Pathirana A. Changing Urban Temperature and Rainfall Patterns in Jakarta: A Comprehensive Historical Analysis. *Sustainability*. 2024; 16(1):350. https://doi.org/10.3390/su16010350

Maheng D, Pathirana A, Zevenbergen C. A Preliminary Study on the Impact of Landscape Pattern Changes Due to Urbanization: Case Study of Jakarta, Indonesia. *Land*. 2021; 10(2):218. https://doi.org/10.3390/land10020218

Maheng D, Ducton I, Lauwaet D, Zevenbergen C, Pathirana A. The Sensitivity of Urban Heat Island to Urban Green Space—A Model-Based Study of City of Colombo, Sri Lanka. *Atmosphere*. 2019; 10(3):151. https://doi.org/10.3390/atmos10030151

Other publications

H Ngo, R Ranasinghe, C Zevenbergen, E Kirezci, **D Maheng**, M Radhakhrisnan, A Pathirana. An efficient modeling approach for probabilistic assessments of present-day and future fluvial flooding. Frontiers in Climate, 2022. https://doi.org/10.3389/fclim.2022.798618

Balogun, A. L., Marks, D., Sharma, R., Shekhar, H., Balmes, C., **Maheng, D**., … & Salehi, P. (2019). Assessing the potentials of digitalization as a tool for climate change adaptation and sustainable development in urban centres. Sustainable Cities and Society, 101888. https://doi.org/10.1016/j.scs.2019.101888

Conference proceedings

Dikman Maheng, Assela Pathirana, Chris Zevenbergen. Identifying The Impact of Urbanization on Urban Ecosystem Services in Jakarta. IWA Water and Development Congress & Exhibition 2019. 1-5 December 2019, Colombo, Sri Lanka. Poster Presentation.

Ishara Ducton, **Dikman Maheng**, Chris Zevenbergen, Assela Pathirana. Greening Cities Mitigates Urban Heat Islands – A Model-based Investigation City of Colombo, Sri Lanka. IWA Water and Development Congress & Exhibition 2019. 1-5 December 2019, Colombo, Sri Lanka. Poster Presentation.

D. Maheng, A. Pathirana, I. Ducton, H. Chen, C. Zevenbergen. Impact of urbanization on urban heat island in Asian cities: A comparative atmospheric modelling approach of four cities. International Conference Urban Transitions 2018, 25-27 November 2018, Sitges, Barcelona, Spain. Oral Presentation.

Dikman Maheng, Wisya Aulia Prayudi, Assela Pathirana, Chris Zevenbergen. The current state of Green Space: from policy and implementation to mitigate water-related impacts due to climate change. International Conference Water Science for Impact, October 16-18, 2018, Wageningen University of Research, the Netherlands. Poster Presentation.

D. Maheng, A. Pathirana, I. Duction, H. Chen, C. Zevenbergen. Impact of urbanization on urban heat island in Asian cities: A comparative atmospheric modelling approach of four cities. Urban Transitions 2018 International Conference. November 25-27, 2018, Sitges, Barcelona, Spain. Oral Presentation.

Dikman Maheng, Assela Pathirana, Chris Zevenbergen. Urban green space allocation based on urban climates for climate mitigation and adaptation: what and where? 2018 Summer Academy on World Risk and Adaptation Futures – Urbanization, September 24-28, 2018, UNU-EHS, Bonn, Germany. Oral Presentation

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The Netherlands research school for the
Socio-Economic and Natural Sciences of the Environment
(SENSE) declares that

Muhammad Dikman Maheng

born on 27 June 1977 in Kendari, Indonesia

has successfully fulfilled all requirements of the
educational PhD programme of SENSE.

Delft, 28 October 2024

Chair of the SENSE board

Prof. dr. Martin Wassen

The SENSE Director

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The SENSE Research School has been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW)

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The SENSE Research School declares that **Muhammad Dikman Maheng** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a work load of 45.1 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2019)
- Research in context activity: 'Organising the Urban Drainage System Design Workshop' (2018)

Selection of Other PhD and Advanced MSc Courses

- Water Sensitive Cities, IHE Delft (2017)
- Creative and Critical Thinking, TU Delft (2018)
- Problem-Solving & Decision-Making in Research, TU Delft (2018)
- Urban Drainage System Design Workshop, IHE Delft (2018)
- Summer Academy 'World Risk and Adaptation Futures – Urbanization', UNU-EHS (2018)
- Bucharest Urban Climate Summer School, University of Bucharest (2019)
- Advanced Problem-Solving and Decision-Making, TU Delft (2019)
- Foundations of Teaching, Learning and Assessment, TU Delft (2019)
- Geostatistics for Water Management and Environmental Sciences, IHE Delft (2019)

Management and Didactic Skills Training

- Teaching on 'Urban Water Infrastructure as a tool to manage urban heat' in Water Sensitive Cities MSc Module 11, IHE Delft (2018-2019)

Oral Presentations

- *Urban green space allocation based on urban climates for climate mitigation and adaptation: what and where?*, 2018 Summer Academy on World Risk and Adaptation Futures – Urbanization, 24-28 September 2018, UNU-EHS, Bonn, Germany
- *Impact of urbanization on urban heat island in Asian cities: A comparative atmospheric modelling approach of four cities*, Urban Transitions 2018 on 'Integrating Urban and Transport Planning, Environment and Health for Healthier Urban Living', 25-27 November 2018, Sitges, Barcelona, Spain

SENSE coordinator PhD education

Dr. ir. Peter Vermeulen

IHE DELFT
Institute for Water Education
under the auspices of UNESCO

TU Delft
Delft University of Technology

The increasing global population and economic development have a significant impact on global land use and land cover (LULC) changes. LULC changes are affecting the quantity of green spaces and their patterns. Both influence urban ecosystem services (ES). The higher temperatures in urban areas compared to that in non-urban areas, modify atmospheric circulation and precipitation, triggering extreme rainfall leading to urban flooding. Those hazards happening in the same place at different times have not been given any special attention as many existing studies are mainly focusing on the quantity of green spaces. They have not paid special attention to different LULC transformation processes, and combined hazard events such as high urban temperatures and urban flooding.

The reduction in Urban ES is evident from changes in the hydrological cycle in the form of an increase of the urban temperature and frequency and extent of urban flooding. This research aims to improve our understanding of the role of green spaces in urban temperature, rainfall, and flooding. It considers the pattern of green spaces, models LULC changes influenced on daily urban temperature, daily rainfall patterns and their potential relationship with urban flooding. The results derived from the city of Jakarta provide new and essential insights for further research to enhance flood resilience and climate adaptation, advocating a holistic approach required to mitigate the risks associated with these multi-hazards.

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