Geospatial Indicators for Community Resilience Assessment to Floods

(水害に対するコミュニティレジリエンス評価のための地理空間指標)

Charithmali Chethika ABENAYAKE

Geospatial Indicators for Community Resilience Assessment to Floods

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By

Charithmali Chethika ABENAYAKE

Honours Degree of Bachelor of Science in Town & Country Planning,
University of Moratuwa, Sri Lanka, 2008.
Master in Planning (Environmental Planning),
CEPT University, India, 2011.

Supervised by

Professor Yoshiki MIKAMI

Examination committee:
Prof. Yoshiki MIKAMI (Principal Supervisor)
Prof. Satoru OHTSUKA (Co-Supervisor)
Assoc. Prof. Yoko MATSUDA (Co-Supervisor)
Prof. Yuji HIRAO
Assoc. Prof. Kyoko OBA

Information Science and Control Engineering, Graduate School of Engineering
Nagaoka University of Technology
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Abbreviations

AHP - Analytic Hierarchy Process

CMR - Colombo Metropolitan Region

CRA - Community Resilience Assessment

CRI - Community Resilience Index

DS - Divisional Secretariat (Division)

DRM - Disaster Risk Management

DRR - Disaster Risk Riduction

FDD - Frequency of Disaster Declaration

FEMA - Federal Emergency Management Administration (of the United States)

FES - Flood resilience-supportive Ecosystem Service delivery

GIS - Geographic Information System

ISO - International Organization of Standardization

RCI - Resilience Capacity Index

RIMA - Resilience Index Measurement and Analysis

UNISDR - United Nations International Strategy for Disaster Risk Reduction

WLCM - Weighted Linear Combination Method

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Abstract

Disaster risk management, which is operationalized through reducing vulnerability and exposure, and strengthening the capacity to cope, is the precursor to Community Resilience Assessment (CRA). Assessing resilience of the inherently complex socio-ecological systems entrenches an absolute challenge to the domain of decision-making science. In response, resilience assessment tools have approached inductively by establishing a set of indicators as surrogates for resilience. Geospatial indicators have been widely acknowledged in decision-making in building resilience; however, not yet incorporated fully into assessment methodologies. Hence, this study attempts to propose a set of geospatial indicators for community resilience assessment to floods, particularly in regional scale decision-making applications.

First, the study conceptualized flood as a natural process, which is an integral function of mutually interacting, interdependent, and interrelated elements of socio-ecological systems. Hence, the proposed indicators are principally focused on the roles of the natural flood defence mechanisms, and the growth of built-up area. Most of the recent catastrophic floods have been triggered by anthropogenic forcing, primarily due to weakened resilience capacities of systems, i.e., absorptive capacity, recovery capacity, and transformative capacity. Secondly, the study formulated a set of 30 geospatial indicators to assess community resilience against floods. Thirdly, the study developed system performance-based outcome variables to measure resilience capacities. Fourthly, the formulated indicators were externally verified by using community evacuation, and recovery data for the flood occurred on May 2016 at Colombo, Sri Lanka.

Initial findings of the study revealed 14 geospatial indicators that show significant associations ($p < 0.05$) to the resilience-evidenced by three capacities. Based on further analysis, the study selected eight geospatial indicators as independent variables and modelled the community resilience for the given case study area. Modelling results were statistically significant (adjusted r-squared = 0.863 at sig. F change = 0.000) to recommend geospatial indicators as powerful predictors of community resilience.

As one of the key contributions to improve resilience assessment practice, this study has developed a composite environmental indicator representing flood resilience-supportive ecosystem services. Further, this is the first study that has verified geospatial indicators referring to three resilience capacities. Furthermore, the proposed analytical definition can

measure community resilience as a dynamically evolving process instead of an aggregation of properties. The set of proxy measures that estimate resilience by system performance throughout each resilience state operationalizes this definition. The developed proxy measures are proposed to be utilized in estimating resilience-evidenced, where such independent resilience proxies are extremely required for the current practice.

In the urbanizing world that flood damages grow exponentially, geospatial indicators can provide proactive insights for building resilience. Hence, geospatial indicators can strongly be recommended in community resilience assessment tools. Further studies on assessing the validity and adequacy of indicators can make the assessment process more scientific and comprehensive, leading towards a rational decision-making practice. Overall, incorporating theoretically-sound, non-ambiguous, statistically-verified geospatial indicators into CRA tools can direct the risk management decisions towards empowering communities to perform better during floods while ensuring the sustenance of earth’s life support systems.

Chapter – 1
Introduction

1.1. Background

1.1.1. The need for assessing community resilience to floods

Every year, thousands of people around the world struggle to confront natural hazards. The first decade of the 21st century was subjected to 3,496 hydro-meteorological disasters which is nearly five times as of the 743 catastrophes reported in the 1970s (WMO, 2013). "Disasters were about 5.5 times more expensive by 2010 than they were in the 1970s, and most of that was because of the rising losses due to floods" (ibid). Flood[1] is a hydro-meteorological disaster that has accounted for 47% of all weather-related disasters (1995–2015) affecting 2.3 billion people in the world during the decade (UNISDR, 2016). Flood often inundates clusters of human settlements, making it is a community crisis that calls for attention at local and regional geographies. As a global response, "making cities and human settlements inclusive, safe, resilient and sustainable" has become a goal of the Sendai Framework for Disaster Risk Reduction 2015-2030 and the adopted New Urban Agenda 2030 (UN, 2016). This global commitment emphasizes mainstreaming 'resilience building' into urban development and disaster risk reduction programs. Directing these initiatives to empower the most affected and the least resilient communities is a sustainable development challenge.

1.1.2. Indicators to assess Community Resilience

Community Resilience Assessment (CRA) is a policy and planning tool that facilitates decision-making on empowering community resiliency. CRA is a supportive tool to identify disaster risk, and to implement productive risk-reduction steps by building the resilience capacities to "prepare for, respond to, recover from, and more successfully adapt" (Cutter, 2016). As a type of CRA methods, the composite indicator is popular among policy makers because it is easier to comprehend to the general public (Cimellaro, 2016, p. 63). Composite

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[1] Flood is "an overflow or inundation that comes from a river or other body of water and causes or threatens damage" (USGS, 2015). Flood damages may include "loss of life, injury, disease and other negative effects on human, physical, mental and social well-being, together with damage to property, destruction of assets, loss of services, social and economic disruption and environmental degradation" (UNISDR, 2009).

indicators integrate multiple dimensions of resilience such as social, economic, environmental, and infrastructure (Cutter, 2016). Overall, very few indicators are available to capture the environmental dimension (Cutter, et al., 2008a); (Ostadtaghizadeh, et al., 2015). The limitedly available environmental indicators also largely focus on the effectiveness of environmental governance that assesses the status of environmental protection and conservation rather the functions of environmental systems. Hence, the current resilience indicators are not adequate enough to explain some important aspects such as the role that bio-physical environment performs in reinforcing community's resilience to natural disasters and the growth of built-up areas that weakens community resilience. The primary reason behind ignoring such important aspects is the popular notion that conceptualizing the community resilience as a process merely driven by socio-economic factors. Social and economic factors indeed play a vital role but measuring resilience without addressing the bio-physical factors makes the assessment process incomplete. Resilience indicators with a comprehensive coverage of multidimensional factors are crucial because the nature of indicators that employs in the assessment process determines the nature of the decisions on building resilience for the future development. In such context, this study attempts to formulate a set of indicators that able to capture the influence of biophysical environment on community resilience. This study is focused on geospatial indicators, which can represent biophysical features of geographic locations and able to point the resilience effects distinctly within socio-ecological systems.

1.2. Objectives

The main objective of this study is to develop a set of geospatial indicators for assessing community resilience capacities of socio-ecological systems to floods, particularly in regional scale decision-making applications.

The set of sub-objectives are as follows.

1. To review the capability of existing indicators in assessing community resilience capacities of socio-ecological systems to floods, particularly in the context of Sri Lanka.
2. To develop a composite environmental indicator that measures the fragility of flood resilience-supportive Ecosystem Services.

3. To formulate a system performance-based proxy measure for externally verifying community resilience concerning the empirical evidence on community responses to floods
4. To verify the adequacy of geospatial indicators in assessing the community resilience to floods in the context of Sri Lanka.

The expected output is a set of validated geospatial indicators which can compositely explain all types of resilience capacities and can capture the effects of biophysical environment on community resilience to floods.

The proposed set of geospatial indicators makes CRAs effective in decision-making. Hence, this study will constructively contribute to guiding future development towards more sustainable directions making communities resilient to floods.

1.3. Research Methodology based on System-Safety Risk Analysis

The domain of CRA lacks internationally standardized assessment methodology. Nevertheless, United Nations International Strategy for Disaster Risk Reduction's (UNISDR) Strategic Framework 2016-2021, which has been accredited by the United Nations general assembly, has recognized strengthening community resilience as its' principle disaster risk management approach (UNISDR, 2016a). Therefore, this study sought for an internationally recognized risk assessment methodology where the proposed resilience assessment indicators could be placed meaningfully. UNISDR is currently working on standardizing a disaster risk assessment methodology under the Sendai Framework for Disaster Risk Reduction (ibid, p.8). International Organization of Standardization (ISO) has developed two related standards on risk assessment: ISO 31000 Risk Management (ISO, 2009), and ISO/IEC Guide 51: 2014 (E), which is the umbrella standards for ISO 12100: 2010 (E) Safety of machinery (ISO/IEC, 2014). ISO/IEC Guide 51: 2014 (E) assesses any safety aspect related to people, property or the environment, or to a combination of these. ISO 31000 assesses the risks of management and operational tasks of an organization. Regarding flood risk assessment, which refers to a socio-ecological system, neither ISO/IEC Guide 51: 2014 (E) nor ISO 31000 is directly applicable. However, considering the fact that, these standards assess the risk at systemic level, particularly 'ISO/IEC Guide 51: 2014 (E) is applicable to the combination of people, property and environment', the general risk assessment principles presented in these standards could be utilized in the context of flood risk. In order to frame the proposed community resilience indicators, this study attempts to utilize the risk assessment principles of ISO/IEC Guide 51: 2014 (E) and ISO 12100: 2010 (E) Safety of machinery in line with the UNISDR Terminology.

1.3.1. Elements of Risk model

It is necessary to make the specific terminology in system safety and Disaster Risk Management (DRM) domains comparable when drawing them together for flood resilience assessment. As the first step, the working definitions for disaster and hazard are presented in Table 1-1 along with the reviewed terminology from respective domains.

Table 1-1: Working definition for hazard and disaster

Term	**Domain of system safety**	**Domain of DRM**	**Working definition**
Hazard	“Potential source of harm” (ISO, 2010, p.1.)	“A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation”. (UNISDR, 2017, p. 19)	Hazard: Occurrence of flood that may cause damages to socio-ecological system
Disaster		“A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts”. (ibid., p.13.)	Disaster: A serious disruption of the functioning of a community at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity.
hazardous event	“Event that can cause harm” (ibid., p.1.)	“The manifestation of a hazard in a particular place during a particular period of time”. (ibid., p.20.) Annotation: Severe hazardous events can lead to a disaster as a result of the combination of hazard occurrence and other risk factors.	

The term risk has been defined in the domain of system safety, as “combination of the *probability of occurrence of harm* and the *severity of that harm*” (ISO/IEC, 2014, p. 2) whereas in the domain of DRM as “the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of *hazard, exposure, vulnerability* and *capacity*” (UNISDR, 2017). Table 1-2 compares the respective elements of risk terms with reference to the details of machine safety standards and UNISDR terminology.

Table 1-2: Elements of risk in the domains of system safety and DRM

Element	Domain of System Safety	Domain of DRM	Justification
Severity of Harm	“Severity of harm is injury or damage to the health of people, or damage to property or the environment” (ISO,2010 p.17.)		System safety domain assesses the extent and the severity of possible damage. The concept of vulnerability in DRM domain assesses the conditions that increase the susceptibility to be damaged. Further, vulnerability assessments carried in DRM domain include damage function. Hence, severity of harm can be considered as a corresponding term to vulnerability as explained in the DRM domain
Vulnerability		“The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards[2]” (UNISDR, 2017, p. 24)	
Exposure	Annotation: Exposure of a person to a hazard [in hazard zone[3]]. (ibid, p.18.)	“The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas. Annotation: Measures of exposure can include the number of people or types of assets in an area” (ibid., p.18.).	In both domains, the elements-at-risk[4] considers as the people, properties and environmntal features in hazard-prone area.
The occurrence of hazardous event	Annotation: The probability of the occurrence of a hazardous event can be estimated by statistical data on accident history (ibid)	The probability of occurrence of a flood is estimated by ‘return period’, which is computed by frequency analysis of historical data. (ibid., p.18.)	System safety and DRM assess the probability of the occurrence of hazardous events.

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[2] Disaster impact is the total effect, including negative effects (e.g., economic losses) and positive effects (e.g., economic gains), of a hazardous event or a disaster. The term includes economic, human and environmental impacts, and may include death, injuries, disease and other negative effects on human physical, mental and social well-being (UN, 2016a, p.13).

[3] any space within and/or around machinery in which a person can be exposed to a hazard (ISO, 2010, p.3)

[4] Exposure is the total value of elements at-risk (WMO, 2017)

Element	**Domain of System Safety**	**Domain of DRM**	**Justification**
The possibility of limiting and avoiding the harm	Annotation: The possibility of avoiding or limiting the harm can be estimated by - the skill levels of persons who can be exposed to the hazard(s) - any awareness of risk (e.g. information for use, warning signs) - the human ability of avoiding or limiting harm (e.g. reflex, agility, possibility of escape) - practical experience and knowledge (ibid., p.18.)		The term 'possibility of avoiding or limiting the harm' does not directly use in DRM domain. Rather, DRM domain assumes if there is a capacity, then there is possibility of limiting and avoiding the harm. When estimating these two elements, human abilities such as skills, knowledge, agility, reflex, and awareness have been considered in both domains. Therefore, the possibility of limiting and avoiding the harm has been considered as a corresponding term to the capacity as explained in DRM domain.
Capacity		"The combination of all the strengths, attributes and resources available within an organization, community or society to manage and reduce disaster risk by strengthening resilience Annotation: Capacity can be estimated by - infrastructure - institutions - human knowledge and skills collective attributes (e.g. social relationships, leadership and management" (ibid., p.12.)	

Figure 1-1 depicts the elements of risk as presented in the domain of system safety.

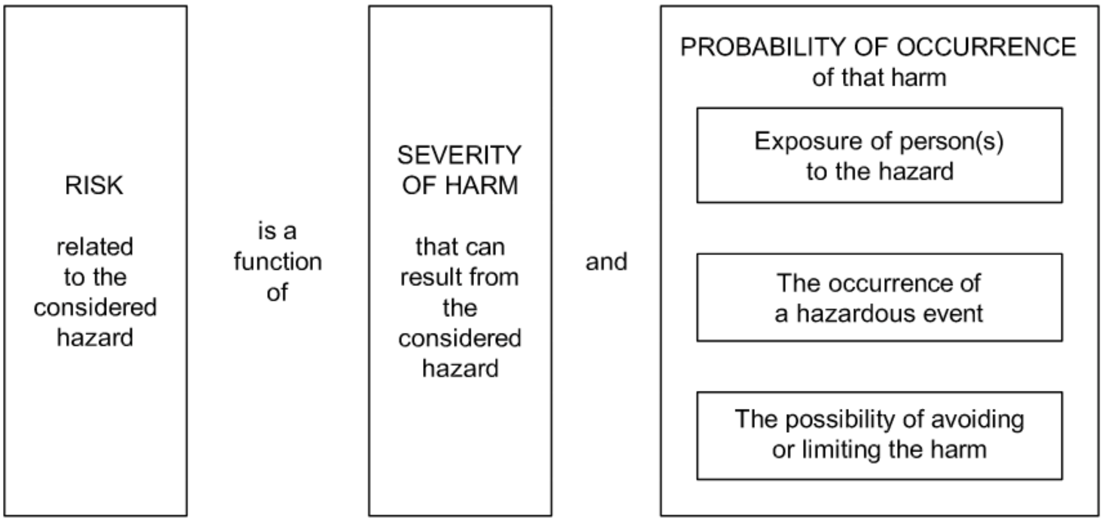

Figure 1-1: Elements of risk model in the domain of system safety
Source: (ISO/IEC, 2014, p. 3)

Per the comparison presented in Table 1-2, the elements at risk in the domain of DRM can be illustrated as follows (Figure 1-2).

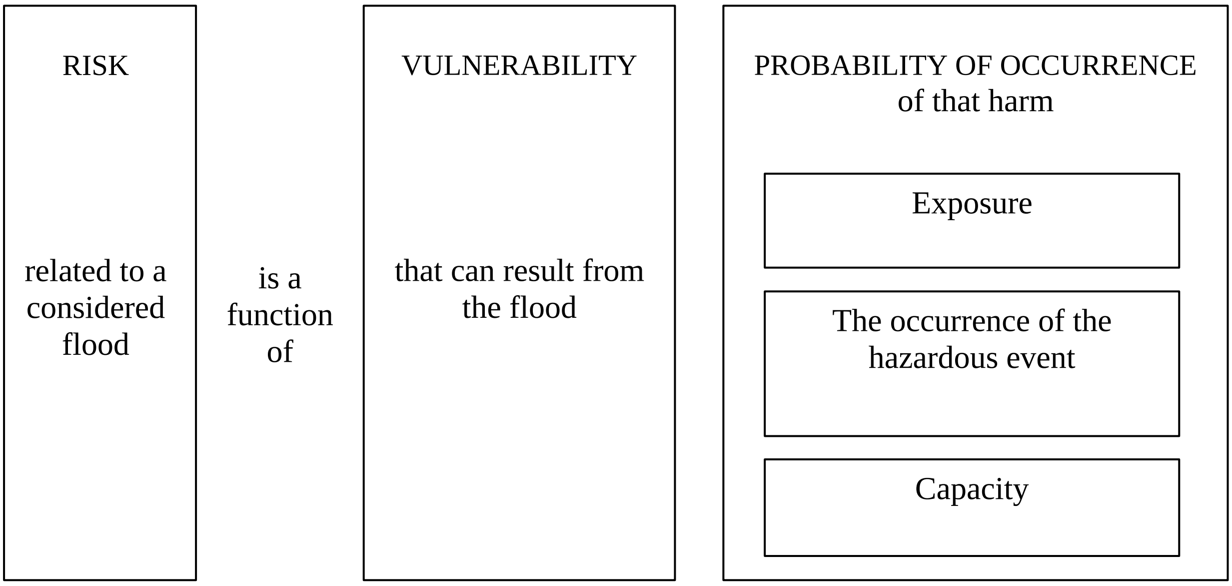

Figure 1-2: Elements of risk model in DRM

1.3.2. Risk and Resilience in the domain of DRM

The concept of risk in the domain of DRM can be algebraically expressed as follows.

$$Risk = f(V.H.E.C) \tag{1.1}$$

Where,
V = vulnerability
H = the probability of occurrence of the hazardous event (i.e. return period of flood)
E = exposure
C = capacity (to cope)

Building resilience has been well recognized as a risk management approach (UNISDR, 2016a). Operationalizing risk management requires addressing each element of risk. Nevertheless, in the context of floods, there is an exception to the occurrence of a hazardous event. In the domain of system safety, the occurrence of a hazardous event can be of technical or human origin (ISO, 2010) whereas in the context flooding, a natural occurrence. Hence, flood risk management is focused only on the vulnerability, exposure, and capacity. Correspondingly, building flood resilience is also focused only on the ability to manage flood risk by reducing vulnerability, reducing exposure and strengthening the capacity to cope.

Community resilience is a process that drives the capacities of a given system (OECD, 2009). Systems perform four types of resilience actions as plan, absorb, recover, and adapt (Larkin, et al., 2015); (NAS, 2012); (Linkov, et al., 2014); (Sharifin & Yamagata, 2016). These four actions are corresponding to the definition of community resilience provided by the National Academy of Sciences, USA. Accordingly, community resilience is "the ability of people to prepare and *plan* for, *absorb, recover* from, and more successfully *adapt* to adverse events" (NAS, 2012). Four types resilience action operationalize the resilience capacities: absorption capacity, recovery capacity, and transformative capacity. Strengthening each resilience capacity supports to manage the corresponding elements of the risk.

1.3.3. Risk reduction process in the domains of system safety and DRM

In ISO/IEC Guide 51: 2014 (E) the risk reduction process commences with a risk assessment. Once the risk is estimated by risk analysis, then the risk evaluation takes place to judge whether risk is tolerable. If the risk is intolerable, then risk reduction measures are implemented. Then, the risk assessment process is repeated for the improved (i.e., risk-reduced) system.

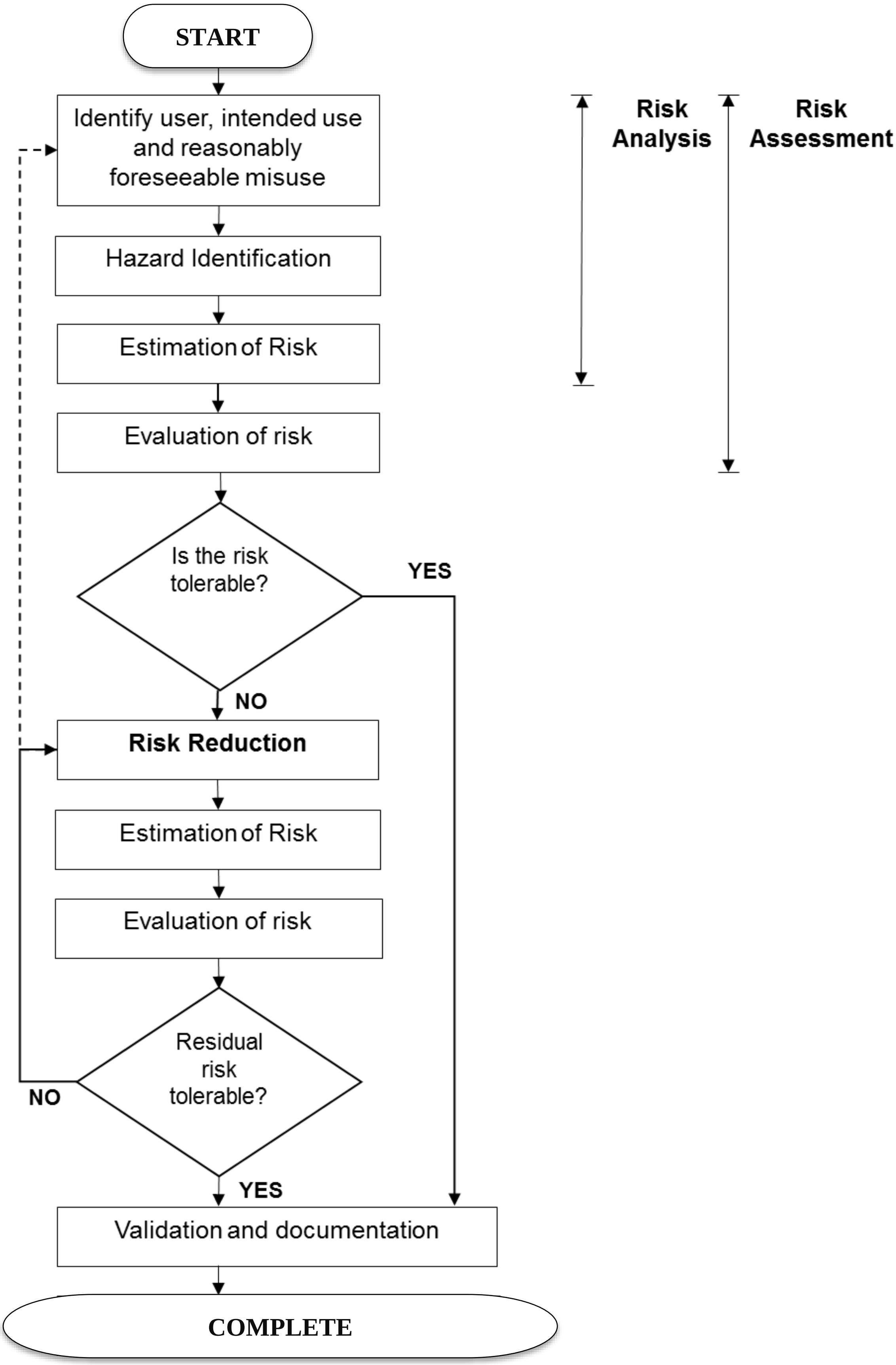

Figure 1-3: Schematic representation of the risk reduction process as per ISO/IEC Guide 51: 2014 (E)

If the residual risk is tolerable, then the given socio-technical system is certified for real-world operation. If not, the limits of the system should be specified again and looped back to the risk analysis (Figure 1-3).

‘United nations plan of action on disaster risk reduction for resilience’ defines risk assessment “as a methodology to estimate the nature and extent of risk by analysing potential hazards and evaluating existing conditions of vulnerability and capacities that together could potentially harm exposed people, property, services, livelihoods and the environment on which they depend” (UN, 2013, p. 13). Hence, in the DRM domain also risk management processes commences with risk estimation, followed by risk evaluation and risk management strategies.

However, there are two fundamental differences between the processes of two systems.

- First, in system safety, if the estimated risk is tolerable, the process completes after the risk evaluation. This is primarily done if the estimated risk level is on a par with the standards/ legal requirements per the current state of the art. Whereas in DRM domain, the objective is to continuously improve the system performance by reducing risk. Hence, always the process targets a better level than the estimated level.
- Secondly, in machine safety, all risk reduction actions steps are physically implemented and tested before putting into operation. Whereas, in DRM domain, risk management actions are usually tests through modelled scenarios or pilot projects before implement physically. Therefore, risk management actions have relatively prominent level of uncertainty during the implementation. In related to natural hazards, this uncertainty is further triggered by the inability to control the occurrence of hazard. Hence, disaster risk management actions need to be continuously monitored, reflect upon failures and best practices, and revise as a continuous process. Accordingly, whenever a set of risk reduction actions are implemented, the process is repeatedly followed based on monitoring the feedbacks of the system. This facilitates the system to be improved, metaphorically as an upward spiral.

Considering the above points, the adopted risk management process from system safety to DRM is illustrated in Figure 1-4.

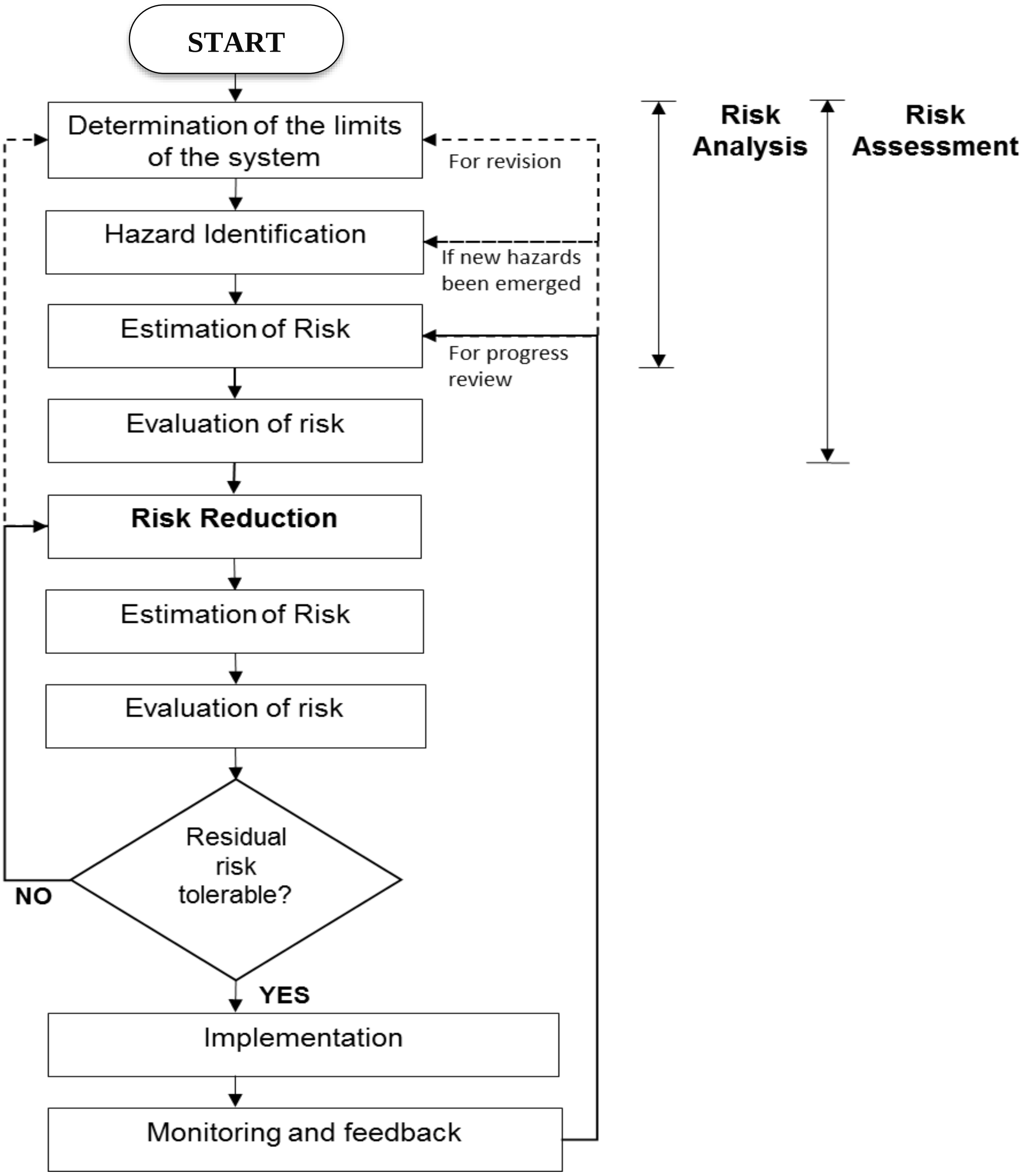

Figure 1-4: Schematic representation of the adopted risk reduction process to DRM

Per the comparability of the elements of risk and applicability of three-step risk reduction method (Annexure A), the risk reduction principles presented in ISO 12100: 2010 (E) and its umbrella standard ISO/IEC Guide 51: 2014 (E) were opted as the base of in developing the proposed resilience indicators for resilience assessment.

1.3.4. Risk Assessment and Resilience Assessment

Resilience assessment is a step of the continuous process of building resilience which is aimed at estimating and evaluating resilience. Resilience vision -followed by goals and objectives- is the initial step of building resilience. Stakeholder mapping, delineating boundaries, determining resilience needs do take part in the visioning and scenario building. Resilience assessment creates an information base estimating the baseline resilience status of the society. A finding of the resilience assessment enables decision-makers to evaluate the gap between the baseline status and vision; and to formulate strategies, prepare plans and implement them to meet the vision. Once implemented, the vision should be revisited in further plans based on the reflections of monitoring and feedbacks (Figure 1-5).

Figure 1-5: Resilience Building Process
Source: (Europe Aid, 2013)

ISO/IEC Guide 51: 2014 (E), “risk assessment is the overall process comprising a risk analysis and a risk evaluation” (ISO/IEC, 2010, p. 2). In this study, the proposed geospatial indicators are utilized for estimating community resilience. Risk estimation is “defining likely severity of harm and probability of its occurrence” and is part of risk analysis (ISO, 2010, p.3). In other words, risk estimation defines the elements of risk. Hence, resilience estimation can be termed as defining system’s ability to reduce the elements of risk. Accordingly, the proposed geospatial indicators are proxies to determine the ability of socio-ecological systems to reduce exposure, vulnerability, and to increase the capacity to cope for floods.

1.4. Framework of the study

This study aimed to develop a set of geospatial indicators for assessing community resilience capacities of socio-ecological systems to floods. The proposed approach to achieve this objective can be summarized into five steps (Figure 1.6).

As described above, at first, this study developed a methodology for the proposed resilience assessment based on system safety risk assessment. Secondly, the study reviews the capability of existing indicators in assessing community resilience capacities of socio-ecological systems to floods, particularly in the context of Sri Lanka. Thirdly, on the basis of the findings of the preliminary review, the theoretical framework of the study is built elaborating the analytical definition of community resilience and deriving the principles to design geospatial indicators. Fourthly, the study formulates a set of 30 geospatial indicators for assessing community resilience to floods by means of (a) reviewing the literature on related research domains (b) modifying the extracted indicators wherever appropriate, and (c) introducing a composite environmental indicator. Fifthly, the study develops an evaluation scheme to measure the outcomes of community resilience based on empirical evidence. Lastly, the study applies the formulated geosptial inidcators for selected localities in Colombo, Sri Lanka and verifies with reference to the empirical evidence pertaining to a given flood event occurred in Colombo. In order to measure the evidenced resilience during the flood event, the study plots the affected population data into system performance curves by locality.

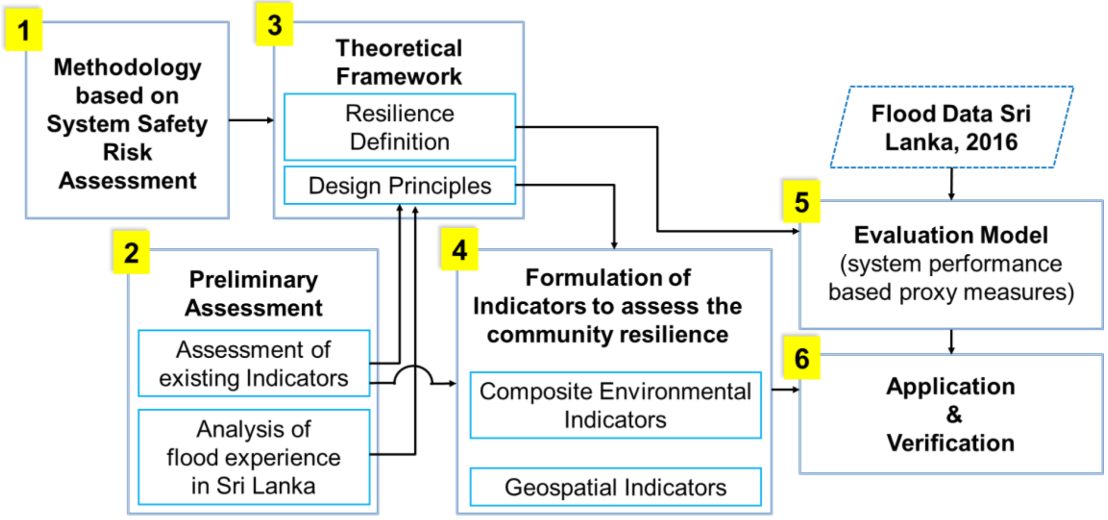

Figure 1-6: framework of the study

The study statistically tests the association of geospatial indicators with each of the evidenced-resilience capacities. Statistically verified geospatial indicators are aggregated into a composite indicator to model and geo-visualize community resilience levels in the case study area.

The study utilizes a Geographic Information System (GIS)-based application to compute geospatial indicators using publicly available spatial analysis tools. Weighted linear combination method and geographically weighted regression analysis are employed to aggregate composite indicators. The study is predominantly based on secondary data sources obtained from several national databases. Most of the data were obtained in digital format (i.e. GIS shapefiles), and some paper maps were georeferenced and digitized for processing. A limited amount of primary data was also collected at some points of the study. Analytic Hierarchy Process (AHP) method was employed in assigning the utility scores of land use which is a step followed in developing environmental composite indicator. 10 Sri Lankan professionals participated in this decision-making process. Further, secondary data related to the number of people overnight stayed in welfare centers was initially obtained from the published disaster situation reports but missing for some days. Disaster management officers of 20 DS divisions were interviewed to get those missing data. The details of methods and materials are described in each chapter.

1.5. Chapter Summary

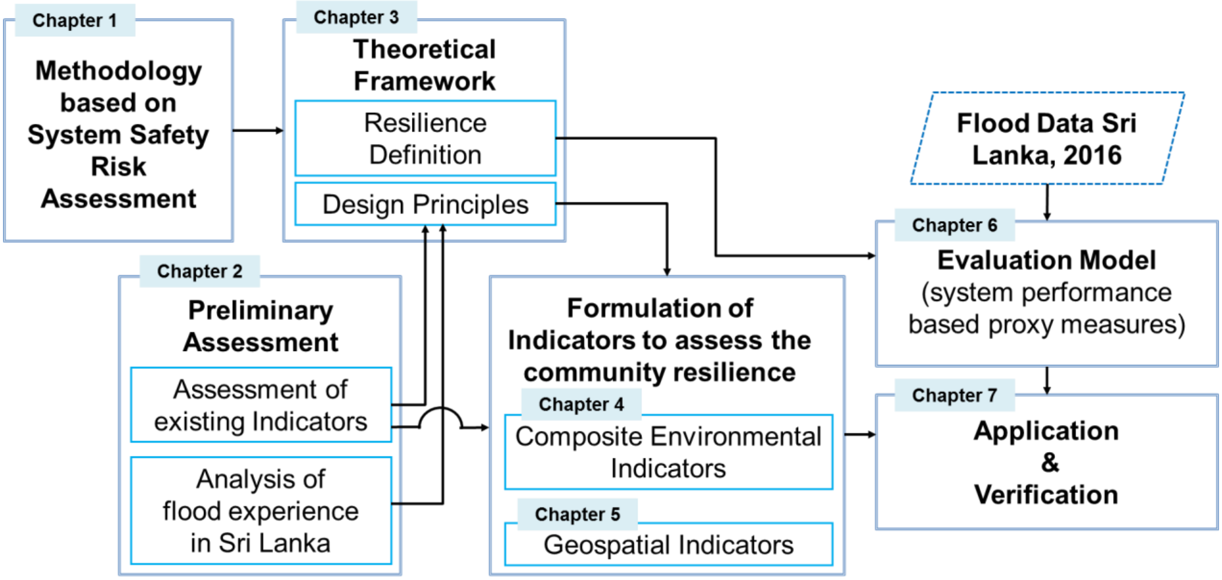

Figure 1-7: Chapter Summary

Following this introduction, **chapter two** brings the finding of the preliminary review of the existing CRA tools and CRA practice and flood experience in the Sri Lankan context. The first part reviews existing CRA tools and discusses the adequacy of indicators in addressing the effects of biophysical environment on resilience. The second part is focused on the present resilience assessment practice of Sri Lanka and applicability of CRA tools in local context.

chapter three presents the theoretical framework of the study. CRA requires resilience to be defined with measurable elements. More comprehensive the definition, more profound the assessment. Further, the proposed geospatial indicators have to be based on principles that capture the effects of biophysical environment on resilience. The theoretical framework elaborates the definition of resilience and design principles of resilience indicators.

Chapter four introduces the proposed composite environmental indicator to assess community resilience. The process of formulating the composite environmental indicator elaborates how the relationship between community resilience and ecosystem services is conceptualized, how the indicators are identified, and how the proposed composite indicator is computed with a case application in Colombo, Sri Lanka.

Chapter five provides the details of the draft set of geospatial indicators. This includes how the indicators were formulated, how to compute each and what data is required for computation. The proposed indicators are aimed to cater to the needs of Sri Lanka and other developing countries where typical data-constraint situations exist. In order to overcome such constraints, some alternative data options have also been discussed here.

Chapter six proposes an independent set of proxy measures to verify the proposed geospatial indicators externally. The proposed proxy measures are measured based on the system responses to real-world flood situation which plots on system performance curves. Further, these measures capable of assessing three resilience capacities corresponding to the life-cycle stages of community responses as portrays on system performance curve.

Chapter seven v the proposed set of geospatial indicators based on the flood event occurred in Colombo, Sri Lanka on May 2016. Downstream of the Kelani river basin is taken as the case study area that consists of 23 localities (N=23). The verification is twofold as first, test the association between resilience-evidenced and each geospatial indicator, and secondly, model the resilience by combining the verified geospatial indicators into a composite index.

Chapter eight summarizes the findings of the study, discusses the applicability of the proposed geospatial indicators, and presents community resilience map highlighting the key contribution of this study to reduce flood risk by building community resilience.

Chapter – 2

Preliminary assessment of existing CRA tools

2.1. Introduction

This chapter presents the finding of the preliminary review on the existing CRA tools and CRA practice in the Sri Lankan context. Following the sub-objective and the section on methods and material, rest of the chapter contains two parts. The first part reviews existing CRA tools and discusses the adequacy of indicators in addressing the effects of biophysical environment on resilience. the second part is focused on the present resilience assessment practice of Sri Lanka and applicability of CRA tools in local context. In order to assess the applicability of three selected CRA tools, the study computes the resilience levels for selected 40 localities in Sri Lanka, which are affected by climate-related disasters including floods. All data have obtained from secondary sources. The internal consistency of the resilience levels computed by three CRA tools will be statistically tested to assess the power of existing indexes to meaningfully direct the disaster resilience initiatives in the context of Sri Lanka.

2.2. Sub-objective

This preliminary assessment attempts to review the capability of existing indicators in assessing community resilience capacities of socio-ecological systems to floods, particularly in the context of Sri Lanka. Findings of this assessment guide the process of formulating the proposed geospatial indicators which is the overarching aim of this research study.

2.3. Materials and methods

2.3.1. Selection of CRA tools

The study has identified 33 CRA tools that are practiced by government, bilateral, private or non-governmental organization. This set includes toolkits, guidebooks, reports, manuals, checklists, and scorecards. Among, them the 19 CRA tools that either flood-specific or related to floods were selected for this review (Table 2-1).

Table 2-1: Selected CRA tools for the review

ID	CRA tool	Developer	Spatial/study unit	Conceptual base	Approach
1	A Coastal Community Resilience Evaluation Tool (NJOCM, 2011)	New Jersey Office of Coastal Management	City	Capacities	Bottom up
2	ASPIRE (World Bank, 2015) The Atlas of Social Protection: Indicators of Resilience and Equity	The World Bank Group	Country	Foundational	Top down
3	BRIC (Cutter SL, 2010) Baseline Indicators for Disaster Resilient Communities	Federal Emergency Management Agency (FEMA)	USA Counties	Characteristics	Top down
4	CART (Pfefferbaum, et al., 2011)Communities Advancing Resilience Toolkit	Terrorism and Disaster Center, Oklahoma City	City, Neighborhood	Capacities	Bottom up
5	Coastal Resilience Index (Sempier, et al., 2010)	Sea Grant Consortium	Neighborhood	Capacities	Bottom up
6	Community Resilience Index (Herreria, et al., 2008)	Australian Government Bureau of Rural Sciences	Regional, local	Capacities	Top down
7	Community Resilient System (CARRI, 2013) Coastal Resilience Index (Sempier, et al., 2010)	Community Resilience System Initiative (CRSI), United States Department of Homeland Security	Cities	Capacities	Bottom up
8	Community Capital approach (Zurich Insurance, 2014)	Zurich Flood Resilience Alliance	Organizational, neighborhood	Capacities	Bottom up
9	Characteristics of a disaster-resilient community: a guidance note (Twigg, 2007)	DFID (Department for International Development, UK)	Country	Characteristics	Bottom up
10	Flood Resilience Checklist (EPA, 2014)	EPA (Environmental Protection Agency)	Household, City	Capacity	Bottom up
11	Framework for Community Resilience, (IFRC, 2004)	IFRC (International Federation of Red Cross and Red Crescent Societies)	Countries, region, city	Capacity	Bottom up
12	Household resilience (Alinovi, et al., 2010)	FAO (Food and Agricultural Organization)	Neighborhood	Characteristics	Bottom up
13	Oxfam GB (Hughes & Bushell, 2013)	Oxfam GB	Country	Capacity	Bottom up
14	PEOPLES (Renschler et al. 2010)	NIST (National Institute of Standards and Technology)	City	Capacity	Top down

ID	CRA tool	Developer	Spatial/study unit	Conceptual base	Approach
15	Regional Capacity Index (The University of California , 2014)	Buffalo Regional Institute, USA	USA metro areas, Regions	Characteristics	Top down
16	Rockefeller 100 resilient cities (ARUP & Rockefeller, 2014)	Rockefeller Foundation	Cities	Capacity	Bottom up
17	Resilience Index Measurement and Analysis Model (RIMA) (FAO, 2013)	Food & agricultural organization	regions	Capacities	Top down
18	Toolkit for Measuring Community Disaster Resilience (IHA, 2014)	International Humanitarian Agency (Ireland)	City	Capacity	Bottom up
19	USAID Resilience (USAID 2013)	USAID	Countries	Capacity	Bottom up

Source: Author prepared by literature survey

2.3.1.1.Selection of CRA tools for case application in Sri Lanka

Three CRA tools are supposed to be selected for the next level of review. The selection criteria are considering the (a) agreement in the definition of disaster resilience, (b) ability to assess the resilience with secondary data, and (c) being a validated practical tool with a manual.

(a) Agreement in the definition of disaster resilience: Among many definitions on resilience, UNISDR defines disaster resilience as "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions" [UNISDR, 2007]. Disaster resilience has been defined in several ways; however, two common reflections that were considered in the screening for this study were the *ability to bounce back* after a shock and the *capacity to adapt* to a changing environment.

(b) Ability to assess the resilience with secondary data: "assessment becomes highly operational when data required are readily available from quantitative secondary and reliable sources" (Herreria, et al., 2008, p. 15). "The specific combination of measures chosen tends to be based on available data" (Mitchell & Harris, 2012, p. 3). This was considered to be essential in making decisions on national and regional scales and overcoming difficulties in collecting a large set of primary data for localities within widespread geographic boundaries. However, resilience assessment is a tool mostly applicable for pre-disaster planning, and "public involvement is already proclaimed as a key principle of pre-disaster recovery planning" (Tajima, et al., 2014, p. 8). Full dependency on readily available secondary data may afford a possibility of ignoring this important principle of public involvement.

(c) Availability of practical validated tools with a manual: The approach requires going beyond the theoretical frameworks to reach decision makers. Specially, it needs to be incorporated with a comprehensive set of supportive materials on how to compute, compare, prioritise and evaluate decisions.

Three selected CRA tools are (i) the Community Resilience Index (CRI) developed by Australian Government Bureau of Rural Sciences to assess the dependence on water for agriculture and social resilience (Table 2-2.), (ii) the Resilience Capacity Index (RCI) developed by the MacArthur Foundation Research Network on Building Resilient Regions with assistance from the State University of New York (Table 2-3), and (iii) the Resilience Index Measurement and Analysis (RIMA) model developed by the Food & Agricultural Organization (Table 2-4).

Table 2-2: Selected Indicators for CRI

Criteria	Indicator**	Modified Indicator
Social Vitality	Change of in/out migrations of population	1. Percentage of people live in the DS since birth
		2. Percentage of people in-migrated during last 5 years compared to previous 5 years*
	Changes in the percentage of working age population	3. Changes of the Labour force participation of working age population (age 15-60) during last three years (2010-2013)
	Percentage of labour force participants with post school qualifications	Data not available
	Access to safe drinking water	4. Access to safe drinking water
Social Stress*	Percentage of households earn less than SLR: 2500 per month	5. Poverty Head Count Index
	Percentage of households with at least 1 adult unemployed	6. Unemployment rate
	Changes of percentage of households in the housing stress/ live in rented houses/ live in poor quality houses	7. Percentage of households without a house
		8. Percentage of households live in a house with non-permanent roof materials
		9. Percentage of households live in a house with non-permanent wall materials
		10. Percentage of households live in a house with non-permanent floor materials
		11. Percentage of people live in an owner-occupied house
Social Inclusion	Percentage of women employed in occupations above labourers and clerical service	12. Labour force participation of females
		13. The share of women in employment in the non-agricultural sector
	Percentage of persons in 15-24 years age group attending in fulltime or part time education	14. Percentage of persons in 18-25 years age group attending in full-time or part-time education (only government institutions)
	Change in the mature age unemployed persons	15. Change in the unemployment rate 2010 to 2013

*Inverse values were taken for computation
Source: ** (Herreria, et al., 2008)

Table 2-3: Selected Indicators for RCI

Criteria	Indicators**	Modified
Income Equality	Gini coefficient for income inequality	1. Gini coefficient for income inequality*
Economic Diversity	Degree to which a metropolitan economy differs from the national economy by the proportion of its jobs in goods-producing, service-producing, and government sectors	2. Degree to which a local economy differs from the national economy by the proportion of its jobs in service, industrial and agricultural sectors
Regional Affordability	Percentage of households in the metropolitan area spending less than 35 percent of their income on housing	3. Percentage of households in the local area spending less than 35 percent of their income on housing*
Business environment	High level of small businesses, high levels of business churn (starts and stops), residential high-speed Internet connections, change in the number of broadband holding companies, and ample venture capital	4. Number of small & medium business, access to electricity, banking density, road accessibility
Educational Attainment	Percentage of the population age 25+ with a bachelor's degree or higher divided by the percentage of the population age 25+ without a high school diploma or GED	5. Literacy rate; and percentage of population age 18+ with a bachelor's degree or higher divided by the percentage of the population age 18+ without high school (G.C.E. Advanced Level)
Without disabled	Population that report no sensory, mobility, self-care or cognitive disabilities.	6. Prevalence of chronic illnesses and disabilities*
Out of Poverty	percentage of the population with income in the past 12 months above the federally defined poverty line	7. Poverty Head Count Index*
Health Insured	Population that report having health insurance coverage, including both public and private insurers.	8. Access to health service
Civic Infrastructure	The density of civic organizations	9. Distribution of primary school, public transport, market, health centre
Metropolitan stability	Annual average percentage over a five-year period of a metropolitan area population that lived within the same metropolitan area a year prior.	10. Annual average percentage over a five-year period of a local area population that lived within the same district a year prior.
Home Ownership	Number of owner-occupied housing units as a percentage of total occupied housing units	11. Number of owner-occupied housing units as a percentage of total occupied housing units
Voter Participation	Number of voters participating in the 2008 general election as a percentage of population age 18 and over	12. Number of voters participating in the 2008 general election as a percentage of population age above 18

*Inverse values were taken for computation

Source: ** (The University of California , 2014)

Table 2-4: Selected Indicators for RIMA

Criteria	**Indicator****	**Modified Indicator**
Productive Assets	Percentage of people live in own house	1. Percentage of people live in an owner occupied house
	Percentage of families own a vehicle	2. Percentage of families own a vehicle
	Ownership of agricultural assets	Data not available
	Nutrient score	3. Percentage of population above 2030 Kcal level of dietary energy consumption
Access to basic services	Access to safe drinking water	4. Access to safe drinking water
	Access to electricity	5. Access to electricity
	Access to sanitation	6. Access to sanitation
	Distance to primary school, public transport, market and health centre	7. Distance to primary school, public transport, market and health centre
Social safety nests	Duration of residence	8. Percentage of people live in the DS division since birth
	Access to credit	9. Bank density
Adaptive capacity	Number of sources of income	10. Average monthly income
	Employment as a percentage of labour force	11. Employment as a percentage of labour force
	Level of education of people above age 30	12. Data not available
	Literacy rate	13. Literacy rate
Sensitivity*	Number of climate-related disasters occurred previously	14. Number of evacuated, dead, affected and relocated people during climate-related disasters occurred in last 50 years
	Number of crop disasters occurred previously	15. Data not available

*Inverse values were taken for computation
Source: ** (Frankenburger & Nelson, 2013)

2.3.2. Comparability of selected CRA tools

"Many indices of resilience and vulnerability have been developed in disciplines like the humanities, environmental science, ecology, and information technology. In general, these measures employ different definitions of resilience and vulnerability and are constructed using dissimilar constituents (indicators or variables) and utilised for different purposes – and as a result they ultimately measure different things" (Prior & Hagmann, 2012, p. 6). Nevertheless, in circumstances where a specific, localised tool is not available, users must choose one from the existing alternative CRA tools developed in extra-local contexts. To discover how such choices are made, ten disaster management professionals who are working in Sri Lanka were interviewed through a telephonic, semi-structured questionnaire. According to their responses, in most of the cases, professionals do not make choices; rather, donor/partner agencies suggest the resilience assessment tool to be employed. However, on the occasions when professionals make choices, the selection is based on certain criteria. The lists of criteria that have been mentioned by the interviewees are of two types, including the criteria that represent the know-how and preference of the user and the criteria that are related to the characteristics of the assessment tool. When selecting three tools, the comparability was assessed by four criteria that are related to the characteristics of the assessment tools and have been commonly stated by interviewees. The four criteria are the purpose, focus, intended user and spatial scale of the assessment tool.

The purpose of the CRI, RCI and RIMA are to "develop methodological tools for understanding and measuring social resilience" (Herreria, et al., 2008, p. iv); "identifying and measure people's conditions …best for responding to and recovering from a disturbance" (The University of California , 2014) and "develop an analytical framework and guidelines for food and nutrition security resilience measurement of households" ((FAO), 2015, p. 2). Although there are certain differences, all three indices are aimed at assessing the disaster resilience of the community.

The literature survey conducted for selecting the three assessment tools considered the community resilience to climate-related disasters to be the theoretical foundation but also accounted for the ones that reflect the long-term negative consequences of climate change, such as water scarcity and food insecurity. RCI directly focuses on people recovering from a stress as in the case of a natural disaster (The University of California , 2014), whereas the two other indices are focused on the broader impacts of climate-related disasters. CRI assesses the "Susceptibility of …communities to changes in water use and access" (Herreria, et al., 2008, p. iv), and RIMA assesses the "resilience to food security shocks such as droughts" ((FAO), 2015, p. 2). This wide spectrum of impacts anticipated due to climate change leads decision makers to choose a range of tools, which consists of a different set of constituents that measure different states of resilience in a given locality. Nevertheless, being more specific in focus could lead the impacts of climate-related disasters to be narrowly defined.

Furthermore, the study searched for CRA tools that have been developed with the purpose of guiding policy formulators and planners who are involved in the decision-making process of climate change adaptation. Furthermore, the study aims practically at a broader spatial scale; therefore, it is focused on the tools that are applicable at both the regional and local levels.

The selected indices are not perfectly similar, but in terms of purpose and focus, intended user and spatial scale are versatile enough to be alternatively chosen by decision makers as extra-local tools to assess community resilience to climatic disasters at the local level for the initiatives to build resilience of Sri Lankan communities. Due to the differences in constituents, it is natural to have inconsistencies among the resilience levels derived from the three tools; however, considering that these tools can be alternative choices of decision makers to perform similar types of tasks, the inconsistencies are expected to be as minimal as possible. The results of the study were aimed at investigating whether the consistency/concordance is reasonable enough to continue the practice or whether the practice should be revisited.

2.3.3. Selection of study areas

"The regions of East and South Asia and the Pacific Islands are among the most hazard-prone areas in the world. Because of this, during the last century, most of the human casualties of 'naturally triggered' disasters have taken place in this region" (Haque, 2010, p. 478). Sri Lanka, being an island country, is highly vulnerable to the negative consequences of hydro-meteorological disasters (Figure 2-1). In response the disaster risk, there is a strong need for urban communities to cope and adapt (Ranjan & Abenayake, 2014, p. 94).

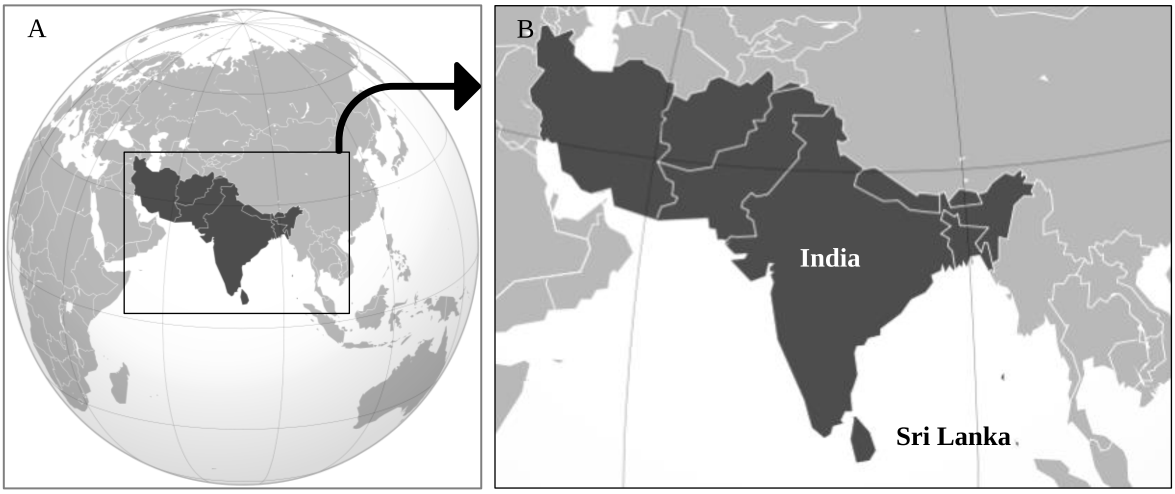

Figure 2-1: Location of Sri Lanka

Image B depicts the location of Sri Lanka as an island in the Indian Ocean. It is an enlarged version of image 'A', which highlights the South Asian countries in the global context

With reference to the Sri Lankan case study, the study has considered 12 districts that were identified for future urban expansions under the National Physical Development Plan. These

12 districts consist of 165 DS divisions[5], which represent 60% of the total land expanse of the country.

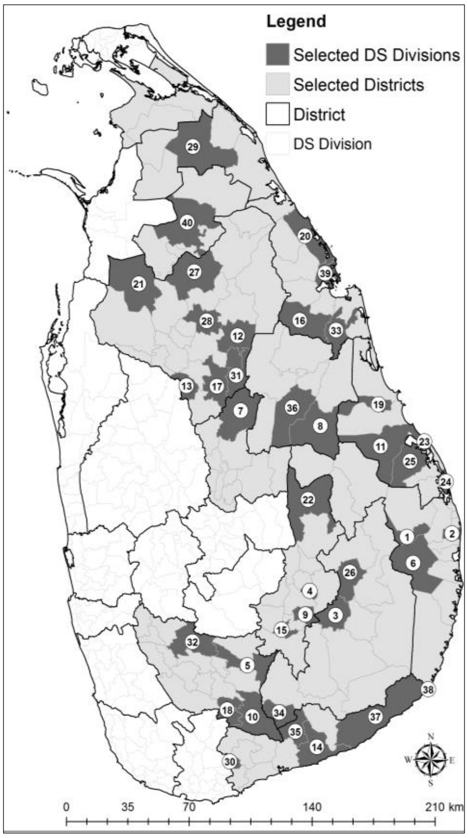

Figure 2-2: The selected 40 localities from 12 districts are highlighted in dark-grey colour and coded with an identification number.

Note: Names of the 40 localities (D.S. Divisions) are given in Table 3-7, corresponding to the identification number.

Selection of 40 samples out of the considered 165 DS Divisions was based on the magnitude of the disaster damage. Disaster damage was considered a function of four factors, including the number of victims, number of affected people, number of people evacuated and number of people relocated in each DS division. As per the 'Disaster Information Management System in Sri Lanka', the term '*victims*' refers to the number of people who either died or were injured due to the disaster, and the term '*affected people*' refers to the total residential population within the disaster-prone area (Disaster Management Centre, 2014). Forty years of disaster records (i.e., 1,402 records for the period of 1974 to 2014) of each DS division were obtained from the website of the Disaster Management Centre of Sri Lanka, as per the updates by December 2014. There were 12 types of natural disasters, as mentioned in the National Disaster Management Act No. 13 of 2005, Sri Lanka, and 9 of them are climate-related as follows: rain-induced landslides, subsidence, earth slips, floods, droughts, cyclones, high winds, hail, storm surges, and tornados. The data were fed into a GIS software, which generated an overlaid layer of aggregated disaster damages by a weighted overlay technique, giving equal weight for all indicators. The results were categorised into four classes of equal class-size. Then, the cohort of 40 DS divisions was selected as the sample (Figure 2-1). This is a criteria-based random sample that consists of DS divisions, having secondary data adequate

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[5] The Divisional Secretariat (DS) division is a local level spatially defined administrative unit in Sri Lanka. There are 225 DS divisions in the country within 25 districts.

enough to compute resilience. Furthermore, it contains 10 DS divisions from each class, ensuring that the sample represents different degrees of damage from climate-related disasters.

2.3.4. Methods to Compute Resilience values and assess consistency

The method of computing the resilience level is different from one index to another. Accordingly, in the CRI, the score of each indicator is converted to a score between 0 and 1 by dividing each DS division's score by the highest value for all DS divisions. The average of each dimension was given an equal weight, and the average of all dimensions was considered to be the resilience level (Herreria, et al., 2008, p. 17).

In the RIMA, "in the first stage, an index for each component is estimated separately using an iterated principal factor analysis over a set of observed variables. In the second stage, the resilience index [resilience level] is derived using a factor analysis on the interacting components estimated in the first stage in which the resilience index is a weighted sum of the factors generated using Bartlett's scoring method, and the weights are the proportions of variance explained by each factor (Alinovi *et al*. 2010)" (Frankenburger & Nelson, 2013, p. 17). In the RCI, "to accommodate different indicator scales and metrics, indicator values are reported as Z-scores, which quantify how many standard deviations—in a positive or negative direction—a region's performance on an indicator deviates from the all metropolitan [DS Division] average. The RCI [resilience level] for any metropolitan region [DS Division] is the simple average of its Z-scores for each of the underlying RCI indicators" (The University of California , 2014).

Resilience levels were computed according to the original methods specified in each tool, without any modifications. In referring to the RIMA, there are a range of techniques "that can be employed for this purpose [at the second step], such as principal component analysis. Multiple indicators multiple causes, factor analysis and structural equation models" (FAO, 2013, p. 7). This study employed factor analysis, which has been employed in many of the initial case studies of RIMA. In all of the above-mentioned indices, a higher resilience level indicates the better abilities of communities who live within a given locality to cope with climate-related disasters.

The internal consistency of the consolidated resilience index was statistically tested in order to assess the power of existing indexes' to meaningfully direct the disaster resilience initiatives in the context of Sri Lanka. When selecting the statistical measures, the correlation coefficient was chosen first, as it can indicate the strength of the relatedness of the variables. Pair-wise comparison between indices expresses how strongly the resilience levels of one index can be related to the resilience levels of another index. In the computation, Spearmen's co-efficient of correlation was employed to describe pair-wise relationships considering the differences in the scales. However, the correlation coefficient describes only the strength and significance of the association; therefore, this cannot be solely considered in explaining the overall consistency. Hence, the internal consistency reliability level and intra-class reliability level were computed, assessing the overall consistency among resilience levels derived from the three CRA tools.

2.3.5. Data acquisition

The data pertaining to the selected indicators were based on various sources as follows: the Population and Housing Census 2011 and the Provisional Census 2014, the MDG (Millennium Development Goals) indicators of Sri Lanka 2014, the Poverty Indicators 2012/2013, the Sri Lanka Labour Force Survey 2013, and the District Statistical Hand books 2014 published by the Department of Census and Statistics, the Central Bank annual report 2014 published by the Central Bank of Sri Lanka, the District Topological Maps (1:10000 scale) published by the Survey Department of Sri Lanka and the General Election Results 2010 published by the Election Department of Sri Lanka.

2.4. Findings of the Preliminary review

2.4.1. Environmental indicators in existing CRAs

The study surveyed 33 CRA tools that consist of 2716 indicators in order to examine the capability of existing community resilience indicators in addressing 'the impact of the growth of built-up areas and consequent disturbances to natural flood defence mechanisms.' In overall, there are very limited measurable indicators that have acknowledged the role of natural environment in reinforcing community resilience. Those limited indicators in existing CRA tools could be summarized into three types.

The first approach refers the extent that community is endowed with the flood defence mechanisms. The second approach incorporates the attributes that indicate the degree of disturbances being made to the natural flood defence mechanisms. The Third approach focuses institutional, legal and policy measures that have been taken to avoid or minimize the disruptions to the flood defence mechanisms. Table 2-5 provides a summary of the review.

The third approach is the most conspicuous one in existing CRA tools and includes the performances of protection and conservation mechanisms. The Flood Resilience Checklist (EPA, 2014) and some proposed tools (TNC, 2015); (UNISDR, 2013); (NIST, 2015) elaborates a set of such performance indicators with great detail on the effectiveness and the resourcefulness in the processes of implementation. However, these indicators primarily assess the status of governance mechanisms and not the status of community resilience. Availability of institutions, legal provisions, plans and actions projects to control unplanned development and to promote environmental conservation contributes to reducing the effect of anthropogenic forcing that intensifies floods. However, such indicators are not versatile enough to assess the degree of damages caused to natural flood defence mechanisms, and to benchmark the ecosystem functionalities based on tolerance thresholds. Therefore, the next levels of analysis of this study only focus on first and second approaches.

Table 2-5: Approaches towards the environmental indicators in existing CRA tools

ID	**CRA tool**	**Approach 1**	**Approach 2**	**Approach 3**
1	A Coastal Community Resilience Evaluation Tool (NJOCM, 2011)	-	-	√
2	ASPIRE (World Bank, 2015) The Atlas of Social Protection: Indicators of Resilience and Equity	-	-	-
3	BRIC (Cutter SL, 2010) Baseline Indicators for Disaster Resilient Communities	√	√	√
4	CART (Pfefferbaum, et al., 2011)Communities Advancing Resilience Toolkit	-	-	-
5	Coastal Resilience Index (Sempier, et al., 2010)	-	-	√
6	Community Resilience Index (Herreria, et al., 2008)	-	-	-
7	Community Resilient System (CARRI, 2013)	-	-	√
8	Community Capital approach (Zurich Insurance, 2014)	√	-	√
9	Characteristics of a disaster-resilient community: a guidance note (Twigg, 2007)	-	-	√
10	Flood Resilience Checklist (EPA, 2014)	-	-	√
11	Framework for Community Resilience, (IFRC, 2004)	-	√	√
12	Household resilience (Alinovi, et al., 2010)	-	-	-
13	Oxfam GB (Hughes & Bushell, 2013)	-	√	√
14	PEOPLES (Renschler et al. 2010)	√	-	-
15	Regional Capacity Index (The University of California , 2014)	-	-	-
16	Rockefeller 100 resilient cities (ARUP & Rockefeller, 2014)	-	-	-
17	Resilience Index Measurement Analysis (RIMA)	-	-	-

ID	CRA tool	Approach 1	Approach 2	Approach 3
18	Toolkit for Measuring Community Disaster Resilience (IHA, 2014)	-	-	√
19	USAID Resilience (USAID 2013)	-	-	√

Source: Author prepared by literature-based assessment

Table 2-6 Summarizes the resilience indicators belongs to first and second approaches.

Table 2-6: Environmental Indicators in existing CRA tools

Approach	Indicators	Source
1	Percent land area that does not contain erodible soil	(Cutter SL, 2010)
	Percent forested land cover	(Cutter SL, 2010)
	Percent green space	(Cutter SL, 2010)
	Natural resource base that sustains livelihoods	(Zurich Insurance, 2014)
	Environmental quality (Water, Air, Soil, Biodiversity, and Biomass	(Renschler et al. 2010)
2	Percent soil erosion/Extent soil erosion	(Hughes & Bushell, 2013); (Cutter SL, 2010)
	Percent wetland loss	(Cutter SL, 2010)
	Percent urban area	(Cutter SL, 2010)
	Reduction in environment degradation as a result of inappropriate land use, shelter construction, and projects	(IFRC, 2004)

In conclusion, it is clear that among the reviewed 2716 indicators only 10 were directly related to the explaining environmental and development challenges of floods.

2.4.1.1. Influence of Environmental indicators in assessing the community resilience to floods in Sri Lankan context

Flood is the most frequent natural disaster in Sri Lanka and every year thousands of people affected by floods all over the country. The mega-scale spatial development projects and rapid urbanization has severely damaged the natural flood defence mechanism in the country. Primary forest cover of Sri Lanka has dwindled from 72% (1900) to 8.3% (2005) over the last century (Kariyawasam & Rajapakse, 2014). In CMR, 42% of wetlands have been reclaimed within the period from 1954 to 2014.

Urban settlements are burgeoning and in many of the urban-declared areas. Figure 2-3 depicts the recent increase of built-up area in Sri Lankan cities from 2000-2012.

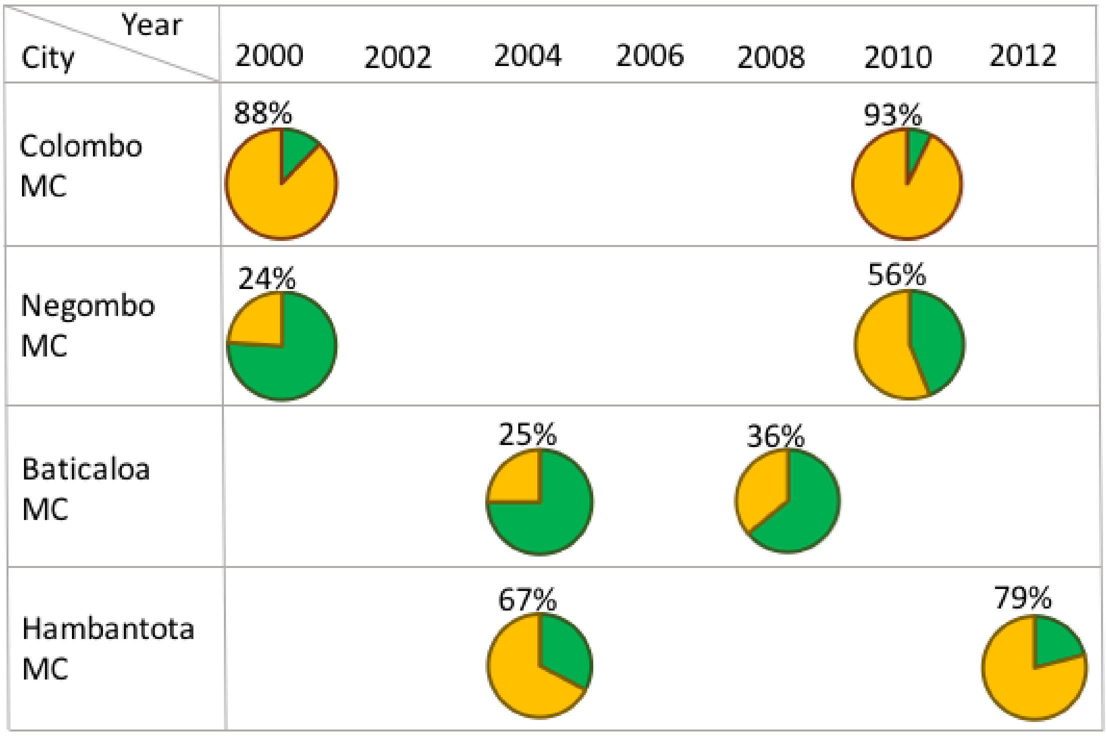

Figure 2-3: Increase of Built-up areas in Sri Lankan cities
Key: Built-up area in yellow and open spaces in Green colour
Source: Author prepared based on Land use maps obtained from Survey Department, Sri Lanka

Accordingly, in average 2% of open spaces in municipal councils (MC) convert into built-up areas every year. Legal plot coverage in MCs is higher as 80% permitting dense impervious growth. Therefore, geospatial environmental indicators are highly relevant and applicable to Sri Lanka.

2.4.2. Applicability of existing CRA tools in Sri Lankan context

Resilience values computed for 40 localities by 3 CRA tools are given below (Table 2-7).

Table 2-7: Resilience indices computed by three selected CRA tools

ID	DS Division	CRI	RCI	RIMA	ID	DS Division	CRI	RCI	RIMA
1	Ampara	1.40	0.42	18836	21	Medawachchiya	0.29	0.08	18911
2	Attalachena	2.39	0.14	15860	22	Mihintale	-0.50	0.34	22947
3	Badulla	1.47	-0.36	16484	23	Nachchaduwa	0.47	0.15	20219
4	Bandarawela	-0.22	-0.15	18741	24	Nainativu	3.53	0.18	19831

ID	DS Division	CRI	RCI	RIMA	ID	DS Division	CRI	RCI	RIMA
5	Damana	0.64	0.42	18509	25	Nochchiyagama	0.07	0.04	20856
6	Dehiattakandiya	3.11	0.13	16846	26	Nuwaragam palatha central	1.49	0.10	19225
7	Ella	1.62	-0.42	14411	27	Nuwaragam palatha east	-3.81	-0.70	10277
8	Galenbindunuwewa	-1.20	-0.48	1451	28	Padawiya	1.33	0.02	17190
9	Galnewa	0.69	-0.56	6850	29	Padiyatalawa	2.49	-0.05	21111
10	Haldummulla	-0.43	-0.21	26988	30	Palagala	3.40	0.31	19788
11	Horowupothana	1.69	-0.05	9774	31	Palugaswewa	2.94	0.41	23145
12	Ipalogama	0.61	-0.56	-418	32	Potuvil	2.21	0.16	24808
13	Kahatagasdigiliya	-2.43	-0.61	-218	33	Rajanganaya	1.56	0.43	24910
14	Kalmunai	2.76	-0.03	19059	34	Rambewa	2.13	0.41	5998
15	Karativu	2.80	0.06	23068	35	Sammanturai	1.01	0.01	19822
16	Kebitigollewa	0.67	0.09	19628	36	Talawa	0.42	0.49	23243
17	Kekirawa	0.36	0.06	24824	37	Thambuththegama	2.04	0.54	20912
18	Lahugala	1.67	-0.06	21240	38	Thirukkovil	1.34	0.09	22943
19	Maha-oya	2.47	0.09	14143	39	Tirappane	1.36	-0.49	19078
20	Mahawilachchiya	-0.12	-0.41	16664	40	Uhana	0.85	-0.06	22438

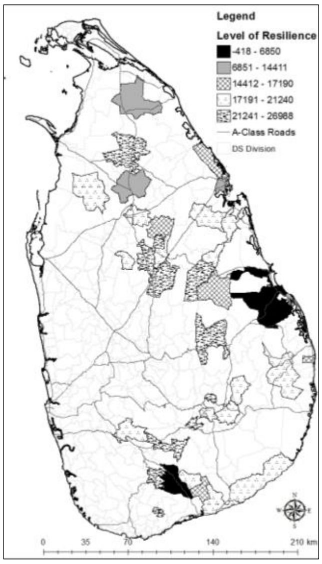

Figure 2-4: Spatial depiction of the resilient levels derived from the CRI

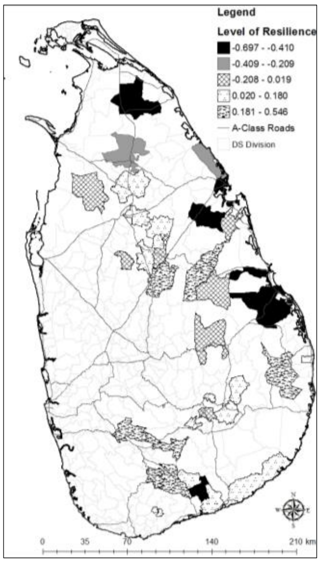

Figure 2-5: Spatial depiction of the resilient levels derived from the RIMA

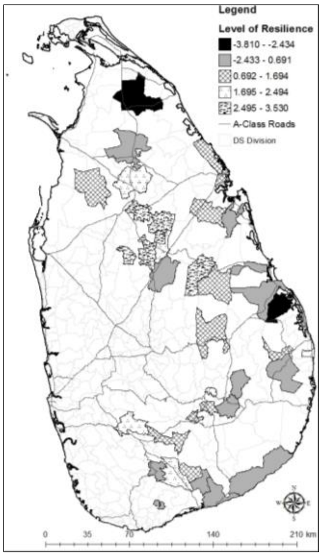

Figure 2-6: Spatial depiction of the resilient levels derived from the RCI

Resilience values computed for 40 localities by 3 CRA tools were arranged in ascending order and classified into five classes of equal class size. The results are depicted in the maps given in Figures 2-4, 2-5 and 2-6.

2.4.2.1.Pair-wise comparison of the relationships of CRI, RCI and RIMA

Pair-wise comparisons among the CRI, RCI and RIMA indices were conducted by employing Spearmen's coefficient of correlation, and the results are illustrated in scatterplots given in Figures 2-7, 2-8 and 2-9, respectively.

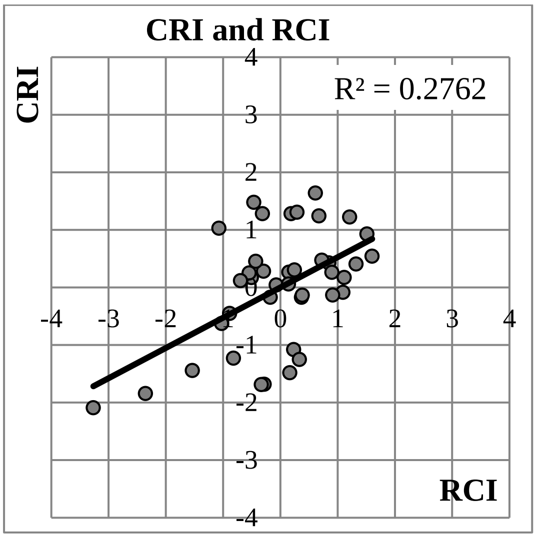

Figure 2-7: Scatterplots of the Spearmen's r computed for CRI and RCI

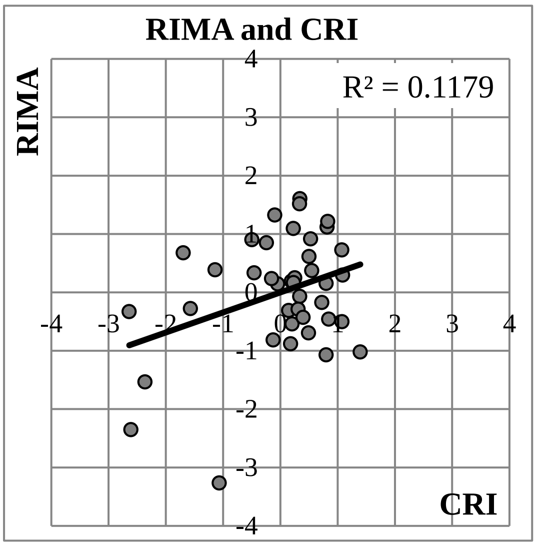

Figure 2-8: Scatterplots of the Spearmen's r computed for RIMA and CRI

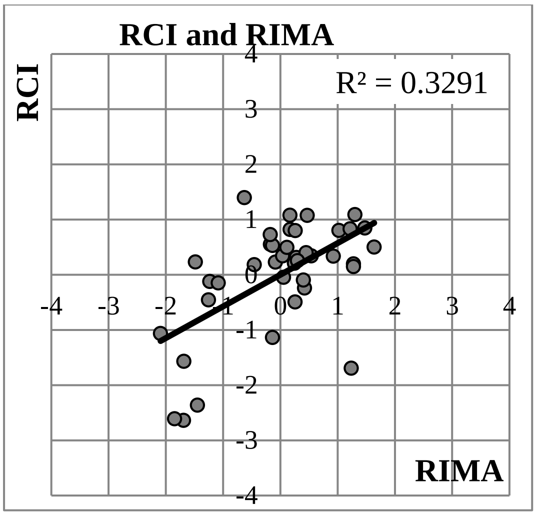

Figure 2-9: Scatterplots of the Spearmen's r computed for RCI and RIMA

Pair-wise comparison of the three indices revealed positive relationships with weak to moderate strength such as r = 0.526, $p < 0.01$ ($R^2 = 0.276$) between CRI and RCI; r = 0.344, $p < 0.05$ ($R^2 = 0.118$) between CRI and RIMA; r = 0.574, $p < 0.01$ ($R^2 = 0.329$) between RCI and RIMA. The relationships of CRI-RCI and RCI-RIMA were neither strong nor weak enough to decide the consistency or concordance among indices, but the relationship of CRI-RIMA was clearly weak. This indicates that there are variations among the resilience levels by indices, which may cause inconsistencies in the decision-making process.

2.4.2.2. Reliability analysis of the relationships of CRI, RCI and RIMA

In computation of internal consistency reliability, all 40 DS divisions were taken as valid cases, and the Cronbach's alpha based on standardised resilient levels of the three indices was recorded as 0.735. This score indicates fair agreement among the resilient levels computed by the three indices, but the item total statistics, which represent 'the Cronbach's Alpha if one index is not included in the calculation', are not favourable to this conclusion (Table 2-8).

Table 2-8: Item total statistics of Cronbach's Alpha

Index	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Z_CRI	.0000	3.147	.490	.279	.729
Z_RCI	.0000	2.687	.671	.451	.511
Z_RIMA	.0001	3.051	.525	.332	.689

Accordingly, the removal of any one of the indices would result in a lower Cronbach's alpha. Cronbach's alpha, if CRI is deleted (0.729), then decreases very slightly; however, if RCI or

RIMA is deleted, Cronbach's alpha decreases to a considerable degree, significantly affecting the reliability.

The Intraclass Correlation Coefficient (ICC) further assesses the consistency between indices, that is, how well the resilience levels correlate, rather than assessing the absolute agreement between them – to what extent their scores are identical (Table 2-9).

The single measure ICC was revealed to be 0.481, which can be inferred as 48.1% of the variance in the mean is reliable, to utilise just one index. Accordingly, there is a possibility of missing the 51.9% of values generated by the two other indices when we utilise one randomly selected index out of three.

Overall, the results could not establish strong agreement on the consistency among the resilient levels derived from the three CRA tools. Therefore, that tends to lead real-world decision-making process into many contradictory outcomes. To elaborate that point further, a hypothetical sample exercise was conducted, as explained in the section below.

Table 2-9: Interclass Correlation Coefficient

	Intra class Correlation	**95% Confidence Interval**		**F Test with True Value 0**		**F Test with True Value 0[b]**	
		Lower Bound	**Upper Bound**	**Value**	**df1**	**df2**	**Sig**
Single Measures	.481[a]	.292	.656	3.779	39	78	.000
Average Measures	.735[c]	.553	.851	3.779	39	78	.000

Note:
Two-way mixed effects model where people effects are random and measures effects are fixed
The estimator is the same, whether the interaction effect is present or not
Type C interclass correlation coefficients using a consistency definition. The between-measure variance is excluded from the denominator variance
This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise

2.4.2.3. Use of CRAs in decision-making to build community resilience

CRAs are practically employed at several steps in the decision-making process, including identifying the investment priorities, diagnosing the root-causes of weak resilience and reviewing the progress of implemented actions. This discussion has selected one such step in prioritising investment options. "Building resilience relies on making investment decisions that prioritise spending for activities offering alternatives that perform well under different scenarios” (The World Bank, 2012, p. 8). In a circumstance where resources are limited, the decision makers tend to invest in the localities where such investments are needed the most. Prioritising involves certain criteria and techniques; however, this discussion considered only the computed resilience values as the criterion, and ranking was statically computed organising ungrouped data. In this exercise, the 5 most resilient DS Divisions and the 5 least resilient DS division, as per each index, have been summarised in Table 2-10 and Table 2-11, respectively.

If a decision maker intends to identify the 5 least resilient DS Divisions and prioritise them in the investment process, then ideally, he should derive 5 common options from the three tools, although this provides 10 options. Furthermore, no DS division can be selected under the collective agreement of the three tools.

Table 2-10: The least resilient DS Divisions (rank: 40th - 35th)

RIMA		**RCI**		**CRI**	
Ipalogama	-418	Nuwaragam Palatha east	-0.70	Nuwaragam Palatha East	-3.81
Kahatagasdigiliya	-218	Kahatagasdigiliya	-0.61	Kahatagasdigiliya	-2.43
Galenbindunuwewa	1451	Ipalogama	-0.56	Galenbindunuwewa	-1.20
Rambewa	5998	Galnewa	-0.56	Mihintale	-0.50
Galnewa	6850	Tirappane	-0.49	Haldummulla	-0.43

Table 2-11: The most resilient DS Divisions (rank: 1st - 5th)

RIMA		**RCI**		**CRI**	
Haldummulla	26988	Thambuththegama	0.5460	Nainativu	3.53
Rajanganaya	24910	Talawa	0.4924	Palagala	3.40
Kekirawa	24824	Rajanganaya	0.4349	Dehiattakandiya	3.11
Potuvil	24808	Ampara	0.4265	Palugaswewa	2.94
Talawa	23243	Damana	0.4262	Karativu	2.80

A similar type of situation occurs even when identifying the 5 most resilient DS divisions. Two options are common between RIMA and RCI whereas all other 11 options are completely different from one another. The most critical point is that some DS Divisions that have been considered one of the most resilient as per one CRA tool have been recorded as one of the least resilient by another CRA tool. For instance, ‘*Haldummulla*’ is among the least resilient options as per CRI but is among the most resilient options as per RIMA. Hence, this clearly shows how significantly decisions can vary when the resilience levels computed by different indices are not consistent enough.

The three assessment tools have different constituents; therefore, they may not produce identical results. However, as these three tools could be considered by practitioners as alternative choices in conducting community resilience assessment to climate-related disasters, a reasonable consistency/concordance was anticipated. The results could not reveal community resilience levels of sufficient consistency/concordance as expected. A significant variation of decisions in terms of assessment tools was clearly shown in the decision-making exercise. On that basis, the resilience levels computed by existing CRA tools can be concluded as difficult to meaningfully interpret in the context of Sri Lanka.

2.5. Conclusion

This preliminary study reviewed 19 CRA tools that are practiced by government organizations, multilateral organizations, and non-governmental organizations. Among the examined 2716 indicators only ten could directly explain the effects of environmental mechanism and the growth of built-up areas on floods. Therefore, during the assignment of formulating geospatial indicators, it is recommended to develop a composite environmental indicator to assess the resilience of socio-ecological systems to flood.

Regarding the current practice of employing extra-local CRA tools to assess community resilience with no or minimal attempts on localising, then findings explained how the randomly selected extra-local CRA tools could produce different values. Hence, it is indispensable to validate any of the proposed CRA indicators with reference to empirical evidence obtained from Sri Lankan case studies before putting into practice.

Chapter – 3
Theoretical framework

3.1. Introduction

This chapter presents the theoretical framework of the study. CRA requires resilience to be defined with measurable elements. More comprehensive the definition, more profound the assessment. Further, the proposed geospatial indicators have to be based on principles that capture the effects of biophysical environment on resilience. Hence, the theoretical framework elaborates the definition of resilience and design principles of resilience indicators as follows.

3.2. Analytical definition of Community resilience: a literature-based derivation

3.2.1. Properties of resilience

As explained in the domain of resilience engineering, resilience is characterized by four properties: robustness, rapidity, redundancy, and Resourcefulness.

> **Robustness**: Robustness is the ability to withstand a given extreme event and still deliver a service, often measured by the residual functionality level after the occurrence of the event.
>
> **Rapidity:** Rapidity is the speed with which a structure recovers from such an event to reach a high functionality level.
>
> **Redundancy:** Redundancy is the extent to which elements and components of the investigated system are substitutable.
>
> **Resourcefulness**: Resourcefulness is the capacity to make the appropriate budget available, identify problems, establish priorities, and mobilize resources after an extreme event.

Robustness and rapidity are sometimes called the ‘goals’ of resilience, while redundancy and resourcefulness are the ‘means’ to achieve resilience. (Yodo & Wang, 2016).

3.2.2. States of resilience

Systems are subjected to disturbances including temporary events of shocks as well as gradual perturbations. A resilient system possesses the capability of maintaining its functions despites the shocks and perturbations. This capability have been theoretically illustrated by using system performance curve (Yodo & Wang, 2016); (Linkov, et al., 2014); (Vugrin, et al., 2011) or alternatively as system restorative curves (Shinozuka, et al., 2004) and system response curve

(Mens, et al., 2011) that typically plots system behaviour to a given disturbance as a function of time. With reference to these curves, behavior of resilient systems has generally been conceptualized into four states. It should be noted that, resilience is not a static property rather it is a continuous process. Therefore, even within a given upper and lower limits of the state, the resilience is dynamic.

Mens, et al’s works on the robustness of flood risk analysis describes four states of the system response curve as: resistance threshold, the severity of the response or amplitude, the proportionality of the response or graduality, and the point of regime shift (Mens, et al., 2011). Yodo and Wang referring to the complex engineering systems explained the four states as: “reliable state, vulnerable sate, restoration state, and the new state. To describe a resilient system over time, these four states mentioned before will continue to happen repetitively over time” (Yodo & Wang, 2016). Linkov, et al, with reference to the military network-centric operation study, has defined these four states as four life-cycle stages of a resilient system as: plan, absorb, recover and adapt stages (Linkov, et al., 2014). In this research, the four states of the resilience have been termed as persistence state, absorption state, recovery state and adaptation state. These states can be illustrated utilizing a system performance curve typically with characteristics as shown in figure 3-1.

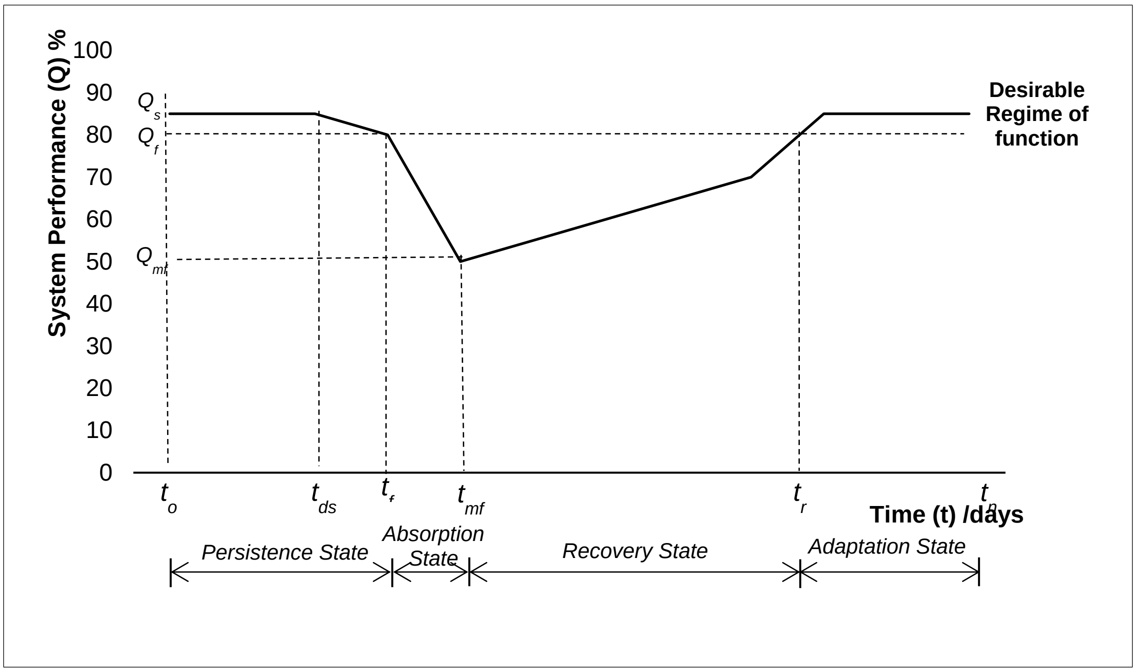

Figure 3-1: States of Resilience

The curve plots system performance as a function of time in days. The reduction in performance from initial state to any point indicates the system response to the onset of flood hazard. The curve represents four hypothetical scenarios and lets scenario-2 to be elaborated first. Scenario-2 graphically illustrates the fluctuations of system performance (Q) that has been disrupted by a flood event occurred at time t_0. Accordingly, the system persists disruptions till time t_{ds}. When the magnitude of the flood exceeds the absorption capacity, the system degrades and crosses the desirable regime of function at time t_{fs}. At the point time t_{mf} , the system records the maximum failure (Q_{mf}) and starts to restore. At time t_r the system reaches the desirable regime of function and continue to adapt transforming towards a better performance of resilience. The system performance curve explains how a system absorbs the shock and subsequently recover to a desirable regime of function and so forth. The following section provides the details of four resilience states.

3.2.2.1.Persistence state

"The baseline state in the system is denoted as the reliable state, in which the system operates under normal conditions without any failure observed. Despite normal deteriorations or performance degradation, the reliability of the system performance is maintained at a constant level in general" (Yodo & Wang, 2016). After the onset of a given hazard, the duration that system is able maintain either the baseline state or a desirable regime of function is termed as the persistent state. The duration that a system survives at persistence state is depend on its robustness. In community systems against the flood risks, this property can be considered as equal to the flood protection level (Vugrin, et al., 2011). The proactive initiatives to build resilience including forecasting trajectories, planning and preparations could greatly influence the time that system can persist (Yodo & Wang, 2016).

3.2.2.2. Absorption state

Flood events at higher magnitude could trigger system damage such that the system performance is significantly compromised. As a result, the system performance level may decrease following a major flood. In scenario-2, system performance function starts degrading from time t_{ds} until the restoration takes place at time t_{mf}. Tolerance is an important attribute that explains "how a system behaves near the boundary- whether the system gracefully degrades as stress pressure increase or collapse quickly when pressure exceeds the capacity" (Hollanagel, et al., 2006). How deeply and how steeply the system has moved away from its initial performance indicates the severity of the flood. Absorption state of the system performance curve depicts the partial loss of system's desirable performance level as well as the degree that systems absorbs the shocks and minimizes the damage.

3.2.2.3.Recovery State

The recovery state is when the system gradually regains its functionality with the implementation of recovery actions. System performance either quickly bounced off or eventually increases over time depends on the rapidity function of the system. In scenario-2, at point t_r, the system attains the desirable regime of function and recovery is considered complete. “The more time that has passed after a disaster, the more difficult it is to identify specific activities of recovery, which makes it difficult to define when the recovery process has stopped” (Wang & Blackmore, 2009).

3.2.2.4.Adaptation state

System performance function gradually reaches an equilibrium operating state, after successfully completing the restoration process (Yodo & Wang, 2016). Depending on the redundancy, resourcefulness, and the damage magnitudes, system performance in the adaptation state could be different to the system performance had in the baseline state. “Similar concept with a repairable system, where after repair the system performance may end up in either one of these possible scenarios: as good as old (same), better than old (higher), or worse than old (lower)” systems can equilibrate at different levels (Martorell, et al., 2014). Emergent systems can dynamically evolve over time to a higher order system behavior as a result of learning and experience (Hiple, et al., 2009). Equilibrating at a level lower to the desirable regime of function “implies that the response to a disturbance may be too large to recover from. In ecology, this is called a regime shift. After a regime shift, the given response curve is not valid anymore” (Mens, et al., 2011).

3.2.3. Capacities of Resilience

Four states of the recovery are corresponding to the four resilience actions. The capacities required to perform these actions can be formed into three types: absorptive capacity, recovery ability, and transformative ability. In resilience engineering, these capacities are explained as “building resistance, adaptability and the ability to recover quickly in the face of adverse events” (Linkov, et al., 2014). The following sections presents the details of resilience capacities.

3.2.3.1.Absorptive capacity

“Absorptive capacity is the degree to which a system can automatically absorb the impacts of system perturbations and minimize consequences with little effort. The absorptive capacity is an endogenous feature of the system” (Vugrin, et al., 2011). In resilience engineering, this property has been defined as the buffering capacity[6].

3.2.3.2.Recovery Capacity

Recovery ability is “often characterized by the rapidity of return to normal or improved operations and system reliability. This capacity should be assessed against a defined set of requirements derived from a desirable level of service or control” (Francis & Bekera, 2014). Recovery capacity makes systems able to recover the system misfortunes to its original operating state, given adequate resources and time to re-organize (Yodo & Wang, 2016).

3.2.3.3. Transformative Capacity

The transformative ability of a system is characterized by anticipation and adaptation. With the dint of anticipation, systems can persist the shocks and resist degradation. “The size or kinds of disruptions the system can absorb or adapt to without a fundamental breakdown in performance or in the system’s structure” (Hollanagel, et al., 2006). In engineering systems, this capacity is “attained through the practice of adverse event mitigation” (Francis & Bekera, 2014). In socio-ecological systems, the capacity can be further endowed through anticipation and preparation as well.

“Adaptive capacity is the ability of a system to adjust to undesirable situations by undergoing some changes…A system's adaptive capacity is enhanced by its ability to anticipate disruptive events, recognize unanticipated events, re-organize after the occurrence of an adverse event, and general preparedness for adverse events” (Francis & Bekera, 2014). Experiences of disaster shocks and responses are deposited in community systems as social learning and facilitate long-term adaptation. Effective adaptation leads systems to anticipate trajectories, plans and be prepared to imminent hazards.

3.2.4. Definition of resilience

The disaster literature provides a range of definitions of ‘community resilience’ despite the lack of agreement. A comprehensive literature review made by Community and Regional Resilience

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[6] “The size or kinds of disruptions the system can absorb or adapt to without a fundamental breakdown in performance or in system’s structure” (Hollanagel, et al., 2006)

Institute have summarized twenty-five different definitions of ‘community resilience’ that has been utilized in the disaster literature over the past three decades (CARRI, 2013). After reviewing those definitions, as well as the concept of resilience, this study developed the working definition based on resilience capacities.

The concept of community resiliency has primarily been used to understand the capacities to tackle the impacts, shocks, and stresses of disasters (Tanner, et al., 2015). Therefore, enhancing community resilience capacities can reduce the magnitude of disasters leading towards safe and sustainable societies. CRA as a decision-making tool facilitates the baseline status of community resilience, setting targets to improve, formulate plans and implement actions to build community resilience. Therefore, efficient CRA tools should consist of indicators that measure resilience capacities. In some CRA tools, resilience has been conceptualized as the general well-being of the society whereas some tools as the specific capacities required to respond to hazards. Many of those capacity-based CRA tools have only emphasized the peoples’ capacities driven by socio-economic processes. This study conceptualizes ‘community resilience’ as not merely a product of socio-economic determinants rather a process of complex interaction between socio-economic and biophysical constituents of the socio-ecological systems. Therefore, resilience assessments should be able to explicate the effects of natural and anthropogenic biophysical environmental processes on determining resilience capacities.

Accordingly, in this study ‘community resilience to floods’ has been defined as the ability of a socio-ecological system to persist the disturbances; absorb the shocks, restore into a desirable regime of function; and strengthen the capacity to adapt and anticipate trajectories of floods. As indicates in figure 3-1, absorbing shocks is corresponding to absorption capacity. Restore into a desirable regime of the function is corresponding to recovery capacity. Strengthening capacity to adapt and anticipate future trajectories and be prepared to persist flood risk are corresponding to the transformative capacity.

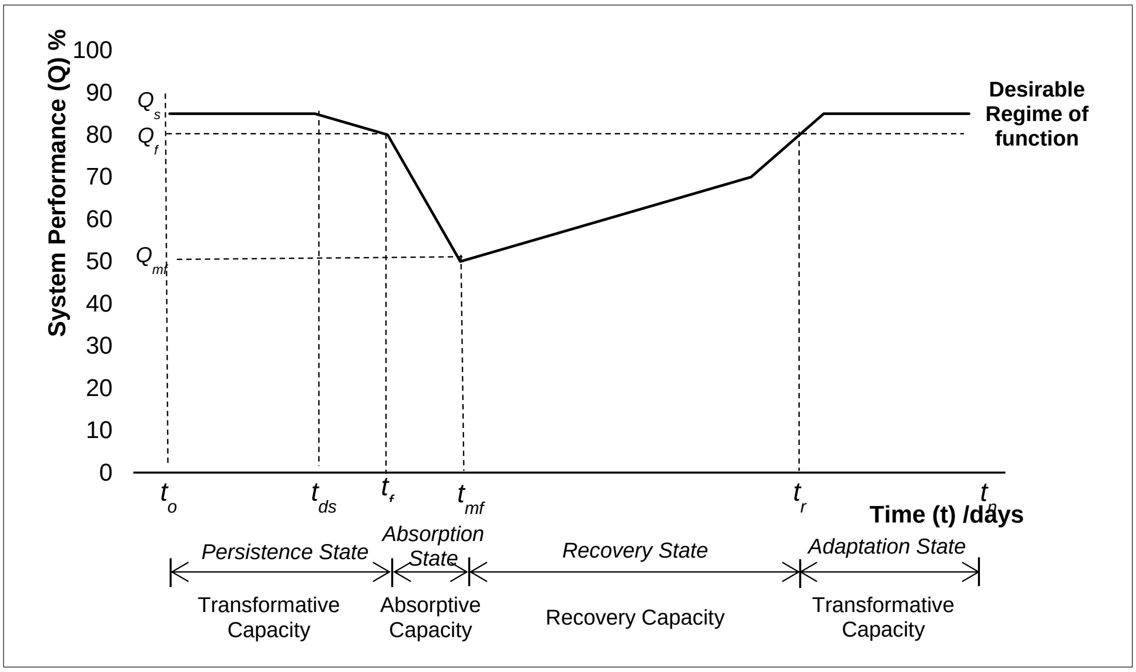


Figure 3-2: Capacities of Resilience

$$CR_j = f(A_j.R_j.T_j) \tag{2.1}$$

As indicated in formula 2.1, the resilience (CR) of a given community (j) can be algebraically expressed as a function of absorptive capacity (A), recovery capacity (R), and transformative capacity (T).

3.3. Derivation of design principles of the proposed geospatial indicators

3.3.1. Flooding as a natural process

Water has been asserted as *‘the driving force of all nature*’ (Da Vinci, 1888). Grounding from the biological survival of living beings, water performs a vital role in evolving human civilizations through agriculture, industrialization, and urbanization. 70% of the earth is covered by water yet, only 2.5% is available as fresh water sources seemly for human consumption (Shiklomanov, 1993). As classically illustrated in biogeochemical cycles, water transforms into several forms through hydraulic states. Precipitation is the prime function of depositing the freshwater on the earth. The natural supply system of water bodies transports precipitated water across the land surface by streams, rivers; and accumulates fresh water by ponds and lakes before discharges into the oceans. Water bodies are shaped by the geomorphological features of the earth surface and moved by gravitation flow. Water bodies provide various economic goods to human societies including water supply for drinking, irrigation and industrial purposes and hydropower generation.

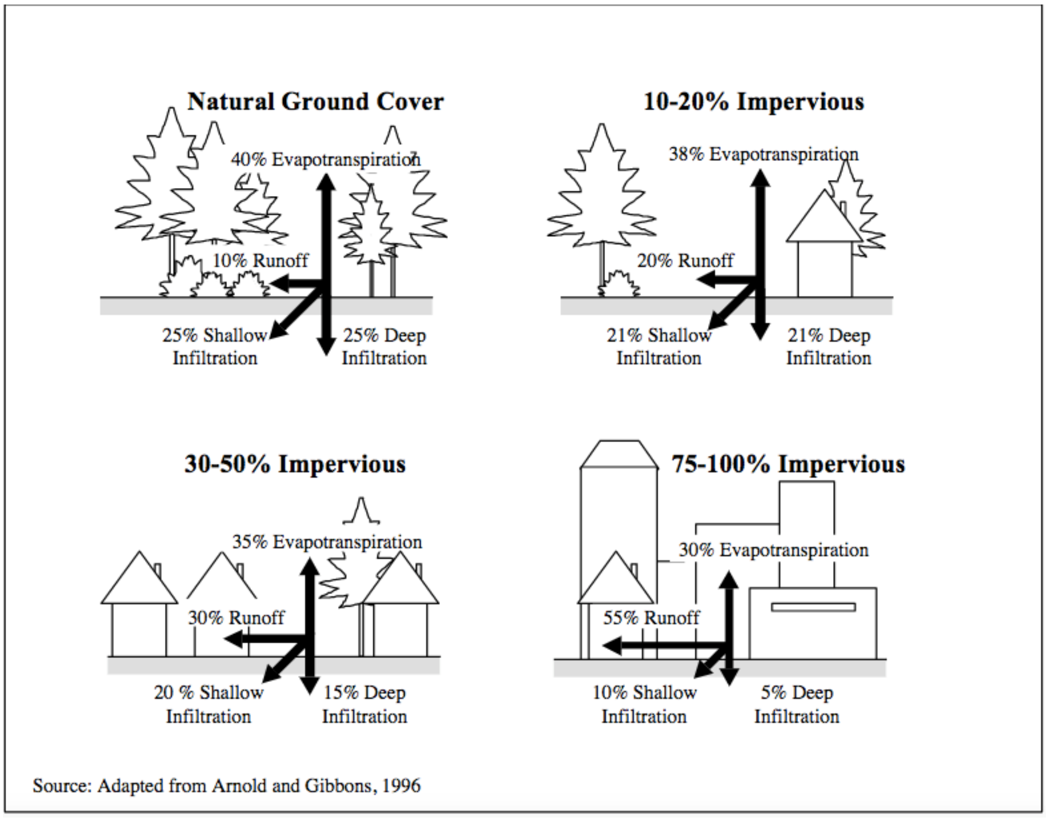
The occurrence of precipitation varies across the year primarily due to the seasonality effects of the planet's climate. During rainy seasons, earth surface receives relatively large volumes of water and water bodies overflows into flood plains. Floodplains are productive ecosystems, which mostly covered by wetlands that retain and detain water during the excess supply. Over a period of time, floodplains have become one of the most fertile lands on the earth making provisions for agriculture, fisheries, and livestock. The occurrence of precipitation furthermore varies over the years due to the long-term recurrence effect of climate cycles. Time-series analysis of precipitation illustrates the natural variations of intensity and magnitude of rainfall events. The onset of high-intensity precipitation events increases the surface levels of water bodies and inundates the land areas beyond primary floodplains. Frequency analysis of precipitation shows a cyclic pattern in the onset of extreme precipitation events typically at return periods of 100-years, 50-years, 25-years and 10-years triggering flood hazards. Usually, precipitation incidents at high return periods (i.e. low probability) inundate larger extents of areas and often turn flood hazards into disasters.

Even at extreme precipitation events, natural flood defence mechanisms perform a vital role to reduce the exposure, particularly the expanse of inundation and the flood height. Following the precipitation, surface runoff – 'part of the runoff that travels over the soil surface to the nearest stream channel' (USGS, 2015)- increases the surface level (i.e., gage height) of water bodies. When the surface level is higher, water bodies overflows into adjacent areas. In a forested ecosystem, surface runoff is little as 10% of precipitation due to the useful functions of evaporation and infiltration (EPA, 2000). Further, once overflow, wetlands can quickly absorb excess water and gradually release by the water retention and detention functions. Water holding capacity of a wetland is four times higher than a river (Shiklomanov, 1993). Therefore, wetlands including swarms, mangrove, wet grasslands also are functional ecosystem services that regulate flooding.

3.3.2. Impact of the growth of built-up areas on natural flood defence mechanisms

Built-up area is an anthropogenic formation over natural land cover, which has been rapidly growing with the urbanization. The unprecedented urban development over the last century has absurdly weakened the natural flood defence mechanisms, primarily with three main interferences.

First, built-up areas cover the land with impermeable surfaces such as roads, buildings, pavements that affect the infiltration and surface runoff (Figure 3-3).



Source: Adapted from Arnold and Gibbons, 1996

Figure 3-3: Effects of Imperviousness on Runoff and Infiltration

Source: EPA, 2000

A typical city with over three-fourth of impervious surfaces discharges 50% of the precipitation to water bodies which is five times higher than the discharge of a natural surface. Secondly, unplanned urban development has reclaimed wetlands reducing the water retention and detention functions in flood plains. The global extent of natural wetlands declined by 30% between 1970 and 2008 (UNEP, 2015). Thirdly, deforestation in upstream of drainage basins triggers soil erosion increasing the sedimentation yield at downstream. Sediment deposits in river beds and on floodplains reduce the water retention capacity of fluvial ecosystems permitting more water to overflow. Overall, the growth of built-up areas causes the cities in downstream to expose to floods six to eight-fold higher than it would have been under the natural land cover.

The impact of built-up area on flooding is not limited to increasing exposure by perturbing the natural flood defence mechanisms. As mentioned above, the magnitude of flood disasters is not determined only by the exposure, but also vulnerability (and capacity) within the inundated area. Hence, unless inundation areas consist of many elements-at-risk, such as population concentrations and physical structures (buildings and infrastructure), floods cannot be turned into high-risk events. The growth of built-up areas, especially along rivers and within floodplains, accumulates housing, economic activities, and infrastructure that are subjected to substantial damages if inundated. Once inundated, such massive damages cause significant economic losses and a long time to recover.

The nature of resilience assessing indicators influences the nature of the decision takes to build resilience which guides future community development process. Accordingly, this study assumes that if resilience indicators can well capture the roles of the natural environment in defending and the built-up areas in intensifying the floods, then future development can be guided towards more sustainable directions making communities resilient to floods. Widely used socio-economic indicators lack the capability to capture the process of the biophysical environment. Therefore, this study proposes geospatial indicators, which represent terrestrial features of geographic locations- can distinctly point the resilience effects within socio-ecological systems.

In order account this effect, the study proposes two design principles for formulating the proposed geospatial indicators are as follows.

1. The extensive growth of built-up areas intensifies flood damages
2. Natural flood defence mechanisms reinforce community resilience to floods.

3.4. Conclusion

This chapter has presented the working definition of community resilience which can be utilized for quantifying resilience. Accordingly, ‘community resilience to floods’ has been defined as the ability of a socio-ecological system to persist the disturbances; absorb the shocks, restore into a desirable regime of function; and strengthen the capacity to adapt and anticipate trajectories of floods. Hence, the resilience of a given community can be expressed as a function of absorptive capacity (A), Recovery capacity (R), and Transformative Capacity (T). This definition integrates the dynamic states of resilience into an organized process. This definition emphasizes the dynamic states of resilience as an emerging process. Such emphasis is essential to be made in assessing resilience because system responses are not linear. For instance, systems which were poor in absorbing shocks might emerge better with adaptation through learning and experience. Hence, the proposed capacity-based definition can measure resilience not merely as an aggregation of properties rather as a dynamically evolving process.

Decision-makers such as urban engineers, spatial planners and policy makers who mean to facilitate systems prior to a disaster are looking for proactive CRAs. Further, the decision-making process cannot completely rely on the risk-evidenced because in some cases the expected risk can be far higher. Therefore, disaster risk reduction measures have to be based on long-term predictions, which anticipate a range of possibilities and uncertainties. In this context, measuring the community resilience to disasters at a given futuristic state becomes hypothetical and assumption-based.

This study conceptualized flood as a natural phenomenon, which is an integral function of mutually interacting, interrelated and interdependent elements of socio-ecological systems. Most of the recent catastrophic floods can be considered as triggered by anthropogenic forcing as a result of weakened resilience capacities of systems. In order to capture this phenomenon in CRA, the study proposes two design principles for formulating the proposed geospatial indicators.

1. The extensive growth of built-up areas intensifies flood damages
2. Natural flood defence mechanisms reinforce community resilience to floods

Thus, the proposed geospatial indicators intend to capture the roles of the natural environment in defending and the growth of built-up area in intensifying the floods.

Chapter – 4

Composite environmental indicator to assess community resilience

4.1. Introduction

This chapter explains the process of formulating the composite environmental indicator. Following this introduction and the brief of approach given in the sub-section threes, the rest of this paper has been structured into two sections. The section four elaborates how the relationship between community resilience and ESs was conceptualized and how the indicators were identified on the basis of the conceptualized relationship. The section five demonstrates how to compute the proposed composite indicator with a case application in Colombo, Sri Lanka.

4.2. Background of the Composite Indicator

Biophysical environment performs a vital role in reinforcing community's resilience to natural disasters. Hence, many of the CRA tool have acknowledged the importance of environmental indicators. The early works of Susan et al. and later attempts of many scholars (Cutter, et al., 2008a); (Cutter, et al., 2008b); (Keating, et al., 2014); (Kotzee & Reyers, 2016) have suggested a few environmental indicators. Nevertheless, in practice, environmental indicators have intentionally excluded from many of the regional-scale resilience assessments, primarily, "due to the data inconsistency and relevancy when developing proxies for ecological systems resilience for large and diverse study areas" (Cutter, et al., 2008a). Despite the challenges and limitations, authors have repeatedly emphasized the necessity of incorporating environmental indicators into CRA tools and to develop a model for prioritization and to measure them (Ostadtaghizadeh, et al., 2015). In the given context, this study aimed to develop a composite environmental indicator to assess community resilience to disasters.

Several alternative approaches could have been adopted to develop environmental indicators for assessing community resilience. This study has opted for an ecosystem services-based approach that integrates the multiple dimensions of socio-ecological systems. Among several disasters that threaten community resilience, this study focuses on floods. In order to explain the role of Ecosystem Services (ESs) in strengthening community resilience, the study could have either be aimed alternatively at how fragile the service delivery or how efficient the service delivery. The study opted for the first because this geospatial composite indicator is intended to facilitate the policy and planning decisions, by distinctively pointing the locations where initiatives to build community resilience should be directed. Hence, when the indicator pinpoints the locations where ESs are mostly fragile, the remedial measures could be directed to such locations. Prioritized treatments given to the most fragile locations can effectively increase the efficiency of ESs and enhance the community resilience within the entire region.

4.3. Sub-objective

The specific objective of this study is to develop a composite environmental indicator that measures the fragility of flood resilience-supportive Ecosystem Services.

4.4. Methods and materials

This study attempts to formulate a composite indicator with a set of proxy indicators that measures the fragility of ESs at the regional scale, especially for floods. Accordingly, the composite indicator aggregates a set of proxy indicators that shows how fragile the ESs in a given region. Identification of the set of proxy indicators was based on a conceptualized relationship between ESs and community disaster resilience. Each proxy indicator is measured by one or several environmental parameters. Ecological parameters corresponding to each indicator were mapped as per a cross-disciplinary literature survey related to the existing indicators in the domains of flood resilience and ESs. The conceptualized relationships between ESs and community resilience to floods; ESs and environmental parameters along with the hierarchical linkages have been illustrated in two schematic diagrams. The selection of environmental parameters was criteria-based. The process of applying the composite indicator has been demonstrated by a case study from Colombo, Sri Lanka. The application has employed Weighted Linear Combination Method (WLCM) to compute the composite indicator on a Geographic Information System (GIS)-based platform. The section 4 of this paper provides further details on the methods and materials utilized in the application.

4.4.1. Introduction to the Case Study; Colombo, Sri Lanka

“Sri Lanka being an island nation with a developing economy is highly vulnerable to the adverse consequences of hydro-meteorological disasters” (Ranjan & Abenayake, 2014). Flood is the most severe type of natural hazard in Sri Lanka regarding the frequency of occurrence and the number of people affected. A torrential rain occurred in May 2016 affected nearly a half million Sri Lankan people where 50% of them were resided in the Colombo Metropolitan Region (CMR). Colombo is “surrounded by a vast and interconnected system of natural wetlands that provides a valuable flood control service. The rapid and partly ad hoc urbanization in the past 15-25 years has caused a steady degradation of the wetlands that severely threatens the ecosystem services” (Hettiarachchi, et al., 2014). Hence, the downstream of the drainage basin of the Kelani River, which flows via the core of Colombo was selected for this application (Figure 4-1). The study area consists of 20 DS divisions (i.e., local administrative units) within the CMR as depicted in the interactive plot map. The extent of the study area is 1250 km^2 and the population is 3.5 million that is 18% of the total population of Sri Lanka.

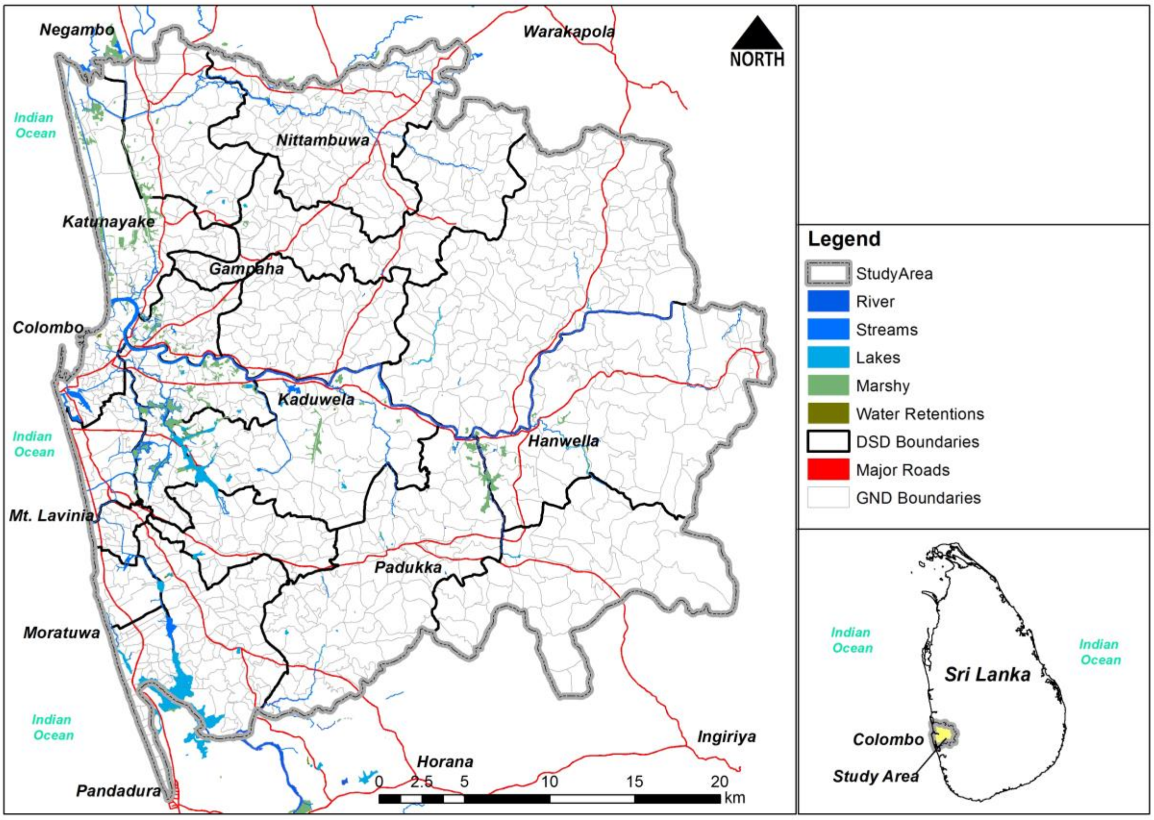


Figure 4-1: Downstream of the drainage basin of the Kelani River

4.5. Developing the composite indicator

4.5.1. Conceptualizing the ecological role in enhancing community resilience to floods

In the domain of environmental economics, 'all the benefits people obtain from ecosystems' have been defined as ecosystem services (CARRI, 2013; MA, 2005). Therefore, in this study, 'the natural reinforcements provided to the community that improves their resilience to floods' have been termed as 'Flood resilience-supportive Ecosystem Service delivery' (FES). Theoretically, the FES is a 'bundle of ESs' that includes, but is not limited to, strengthening community resilience to floods. Further, the bundle is spatially coincident and temporally synchronized. For the purpose of the study, this bundle of ESs has been synthesised conceptually into three regulating services; namely, flood regulation, climate regulation, and nutrient recycling. (MA, 2005; MA, 2005). Figure 4-2, presents the conceptualization that illustrates how a reliable flow of FES enhances the community's resilience to floods. The relationships in the socio-ecological systems are complex and non-parametric; however, this conceptual diagram attempts to simplify those relationships by focusing only on the primary linkages.

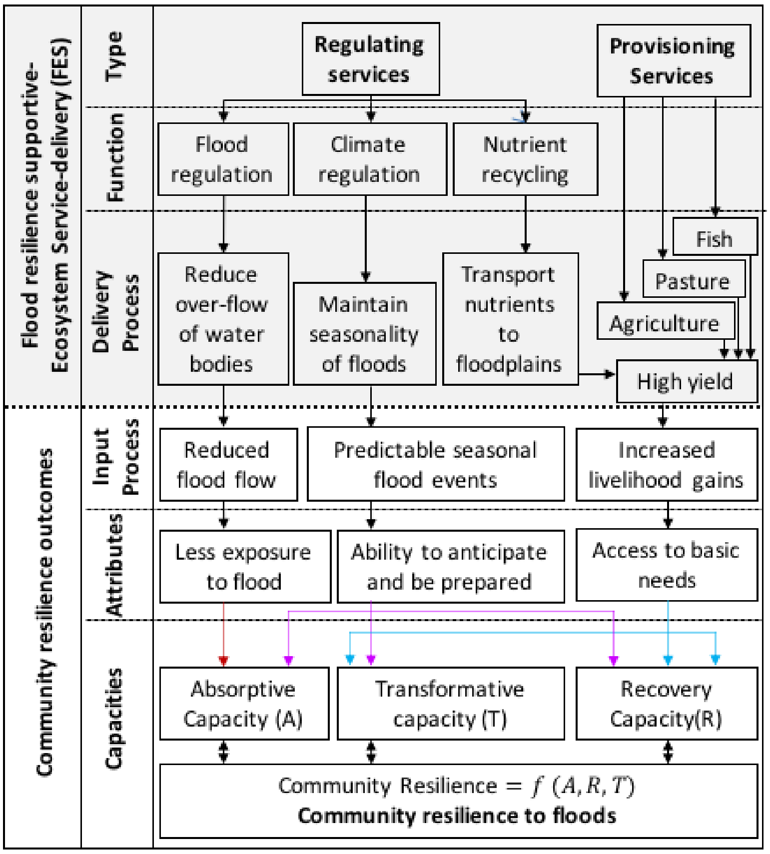


Figure 4-2: The synergy between ESs and Community resilience. This diagram shows how the FES process reinforces community's resilience to floods

Resilience in socio-ecological systems depends on the feedbacks between ecological and human communities" (NRC, 2013). Any disturbances to the ecosystem homeostasis either from a natural or an anthropogenic force may severely affect the service reliability.

Hydrological imbalances are able to increase the magnitude and frequency of floods to the extents that exceed the adaptive range of the socio-ecological system. Moreover, the disturbed patterns of climate regulation cause unprecedented extreme weather events with high risk and uncertainty. Due to the Imbalances of homeostasis, ESs may even turn into 'diseconomies' as in the case of crop damages and fatal injuries to livestock. Impacts of such disturbances could be further aggravated with the human interferences that increase the pollution levels of water bodies. Therefore, assessing the community resilience demands an overview of how fragile the FES processes concerning the cumulative damages been made to the homeostasis of the socio-ecological system.

4.5.2. Indicator mapping for the FES composite indicator

Though there are plenty of environmental valuation methods available to estimate ESs, measuring how likely a socio-ecological system to cross the tolerance threshold and to reach the equilibrium at a desirable regime of function is yet to have consensus on practical means. "However, for specific systems, it may be possible to define a set of metrics that measure key conditions, or processes link to system dynamics that can predict the resilience of the system and the return of provision of ecosystem services" (NRC, 2013). Accordingly, this study attempted to develop a composite indicator to assess the FES processes inferring the system feedbacks from the given conceptual framework (Figure 4-2). The 'objective function' of the proposed FES composite indicator is to 'lower the fragility of the FES processes in a given region'. Therefore, a set of several different indicators is needed to determine how fragile the FES processes in a particular baseline condition and how the feedback relationships affect this service delivery process.

Preliminary assessment of this study reviewed the existing environmental indicators as summarized in Table 4-1.

Table 4-1: The importance of the selected indicators (I) to the FES processes

I	The relevance for the FES processes
S	Infiltration capacity, soil erosion rate, and water retention-detention capacities are key soil hydraulic properties determining the inherent ability of soil to regulate floods and reinforce nutrient recycling (Stürck, et al., 2014, p. 200).
	Ecological parameters to measure infiltration capacity and water holding capacity consists of a range of sub-attributes such as soil texture, soil humidity, percentage silt, percentage clay, soil depth, soil moisture, soil particle density, coefficient of permeability and soil organic matter (Stürck, et al., 2014, p. 200; Acreman & Holden, 2013);
K	Surface runoff affects infiltration, soil erosion, nutrients load, and sediment yield of a drainage basin. Topography is important because the surface runoff varies according to the slope (Acreman & Holden, 2013, p. 783).
P	“The onset, duration, and magnitude of a flood hazard are highly dependent on precipitation intensity, duration and extent, constituting for different flood types (i.e., rainy-fluvial floods, flash floods, snowmelt-fluvial floods (Barredo, 2007); (Nedkov & Burkhard, 2012); (Stürck, et al., 2014, p. 200).
	Rainfall intensity increases the soil erosion rate triggered by the surface run-off (Stürck, et al., 2014, p. 200).
	Local climate variations affect community’s ability to anticipate the floods and to be prepared. Therefore, the predictability of precipitation onset, withdrawal and intensity could be considered to be an attribute of climate regulation services provided to the socio-ecological system (MA, 2005, p. 9).
L	“Land cover, land use and land management (hereafter referred to as land use) account for different levels of flood regulation supply by amplifying or moderating river peak flow through surface runoff modulations (Fohrer, et al., 2001)” (Stürck, et al., 2014).
	Land use specific variations of; evapotranspiration rates, Interception rate, vegetation–soil interactions and modifications of the surface roughness are the main drivers of surface runoff (Stürck, et al., 2014).
	Further, the nutrient recycling process could also be affected by the land use specific variations of waste generation potential and waste assimilative capacities affects the nutrient loads and fluctuation of chemical concentrations (of flood water).

This initial set of indicators was further expanded through reviewing the related literature in the domain of ESs indicators. With the support of the ESs literature, the FES processes figured in the first schematic diagram (Figure 4-2) could be further expanded by incorporating the correspond attributes and environmental parameters into the ESs delivery process. Figure 4-3 depicts those attributes and ecological parameters with the hierarchical links.

Key considerations in choosing the most appropriate indicators were applicability at the regional scale, the ability to visualize geospatially, and the ability to interpret to a broader segment of stakeholder. The ability to interpret to stakeholders is crucial in implementation because community resilience initiatives ought to be localized through participatory approaches, acknowledging the context-specific nature of socio-economic and biophysical environments (Abenayake, et al., 2016). “Many academic publications have put forward models that require complex and sophisticated mathematical modelling and calculation of community resilience, which could not be easily used by community members to measure and understand their degree of disaster resilience" (Arbon, et al., 2016).

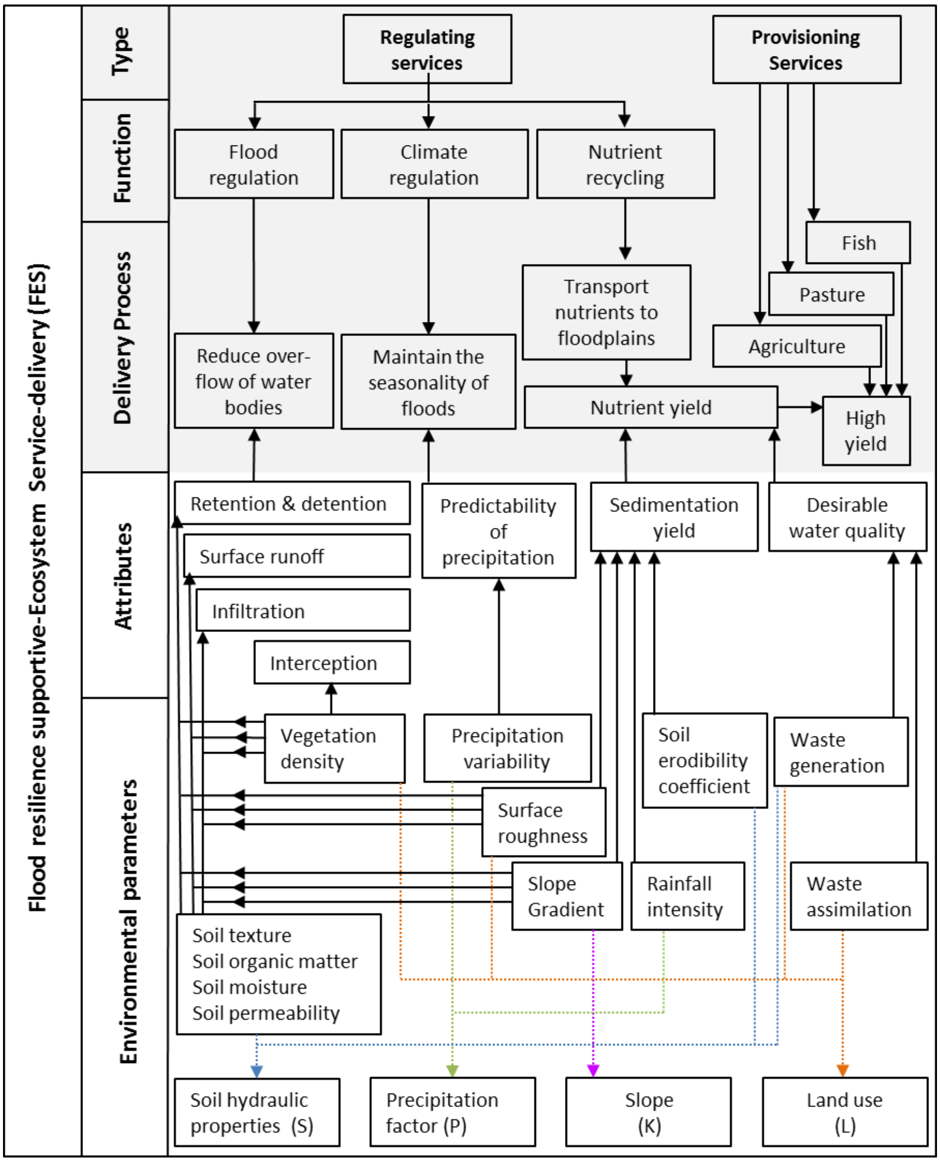


Figure 4-3: The attributes and corresponding environmental parameters of the FES process.
Note: This diagram shows how the four-selected ecological parameters have been derived from the bundle of ESs and how the parameters are inter-connected to the attributes

Accordingly, four indicators that primarily drives the FES process were selected as proxies of the composite indicator. The selected four indicators are soil hydraulic properties (S), slope (K), land use (L) and precipitation factor (P). Table 4-2 summarizes the role of these parameters in strengthening the FES process.

Table 4-2: Parameters of FES-composite indicator

Indicator	Ecological Parameters
Soil hydraulic properties	Soil texture
	Soil Moisture
	Soil organic matter
	Coefficient of permeability
Slope	Slope gradient
Precipitation factor	Rainfall intensity
	Predictability of precipitation
Land use-specific variations	Vegetation Density
	Surface roughness of land cover by surface materials and percentage built-up
	Waste assimilative capacity of the ecosystems
	Quantity and toxicity of waste (solid waste and waste water) generation potential by land use

4.6. Application of the FES composite indicator

The study employed WLCM in demonstrating the proposed FES composite indicator. WLCM was preferable because it is a popular multiple-criteria decision analysis tool that is highly compatible to work in GIS (Malczewski, 2000). According to the WLCM as described by Malczewski, the computation was made in five steps including (a) selection of a set of environmental indicators determining the FES process (b) define the boundaries of alternative spatial units in the case study region, (c) preparation of thematic maps for indicators, (d) weighting indicators, and (e) combine the weighted indicator maps to derive the composite indicator map. The subsections from 4.6.1 to 4.6.5 provide the step-wise details.

4.6.1. Selection of Environmental Indicators and parameters

The slope (K), soil hydraulic properties (S), precipitation factor (P) and land use (L) are the four environmental indicators. The ecological parameters utilised to measure them have been listed in Table 4-3.

4.6.2. Defining the boundaries of alternative spatial units

This application is aimed at computing the FES values for alternative spatial units within the study region and ranks them. In GIS environment, the environmental data in raster format, could be resampled into a Cartesian grid or any specific spatial unit such as sub-drainage basins, administrative boundaries or functional boundaries. The decision on the size of the spatial unit should be decided considering the required degree of accuracy for the interpretation and the spatial resolution of the input data. In assessing how fragile the ESs, the smaller the spatial unit is, the better the degree of detail. In this application, the study region was re-sampled into a raster grid where each cell is 750m by 750m in size.

4.6.3. Preparation of thematic maps for indicators

The geospatial data required for each indicator was collected from the secondary sources, primarily from the GIS databases of the Sri Lankan government. Table 4-3 contains the information on acquiring the geospatial data for each indicator.

Table 4-3: Data acquisition by Indicators (I)

I	Environmental Parameters	Geospatial Data	Scale	Source#
S	Soil texture, soil organic matter, and coefficient of permeability according to the soil type-based generic variations	Soil map, 2007	1: 10000	A
	Soil moisture by the distance to water bodies	Water bodies map, 2014	1: 5000	C
K	Slope gradient	Contour map, 2012	5m interval	B
P	Average annual rainfall	Rainfall Isohyets, 2007	1: 10000	A
L	Vegetation density Surface roughness of land cover Waste assimilative capacity of ecosystems Quantity and toxicity of waste generation potential by land use	Land use map,2014	1: 5000	C

Source#: A - National Atlas, Survey Department of Sri Lanka; B - Tsunami hazard map database, Coast Conservation, and Resource Management Department, Sri Lanka; C- Urban Transport System Development Project, Japan International Cooperation Agency, Japan

Each indicator was expressed as a scale of 1 (the least fragile) to 9 (the most fragile) indicating the different levels of the fragility of FES processes. In this computation process, the selected environmental parameters of slope and precipitation factor could directly measure with the available data but not the other two. Utility scores of rainfall and slope have been normalized by feature scaling, where the lower value of score 1 is the lowest value of the drainage basin, and the upper value of score 9 is the highest value of the drainage basin.

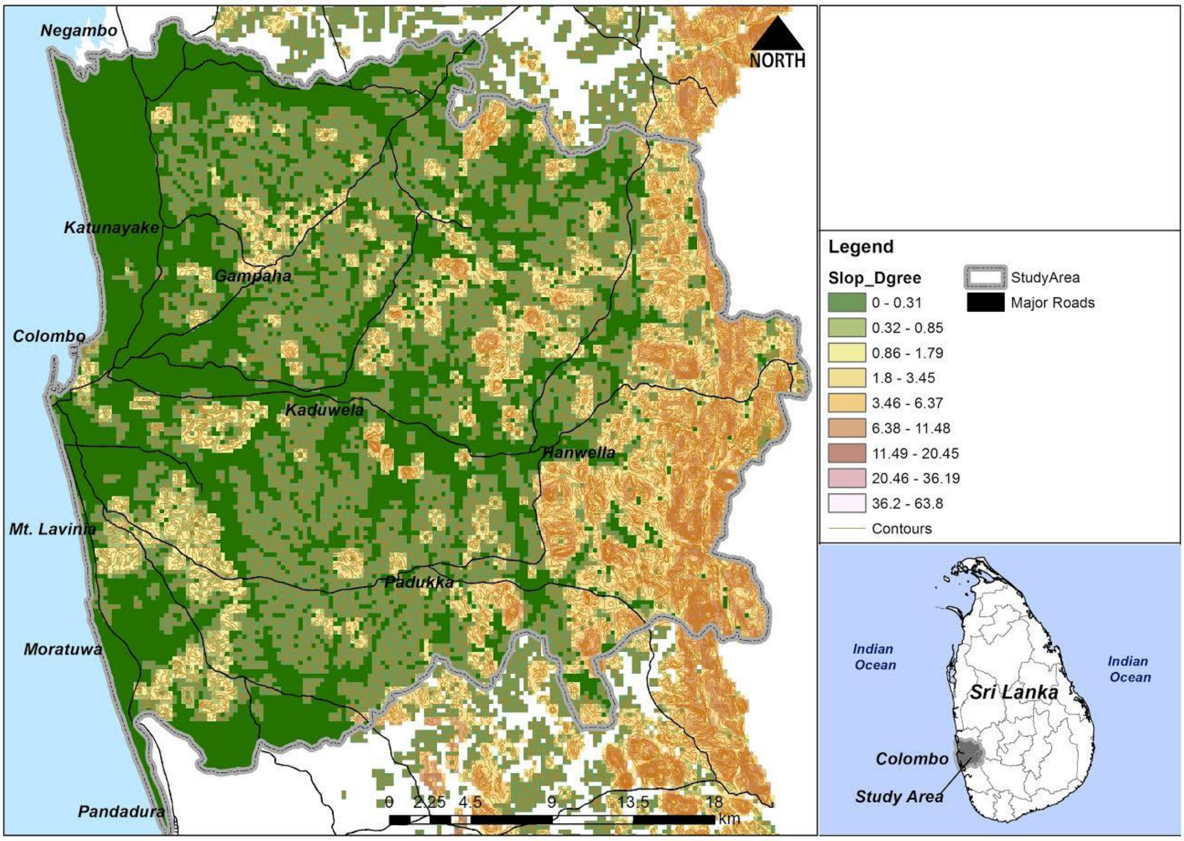


Figure 4-4: Slope map of Study area

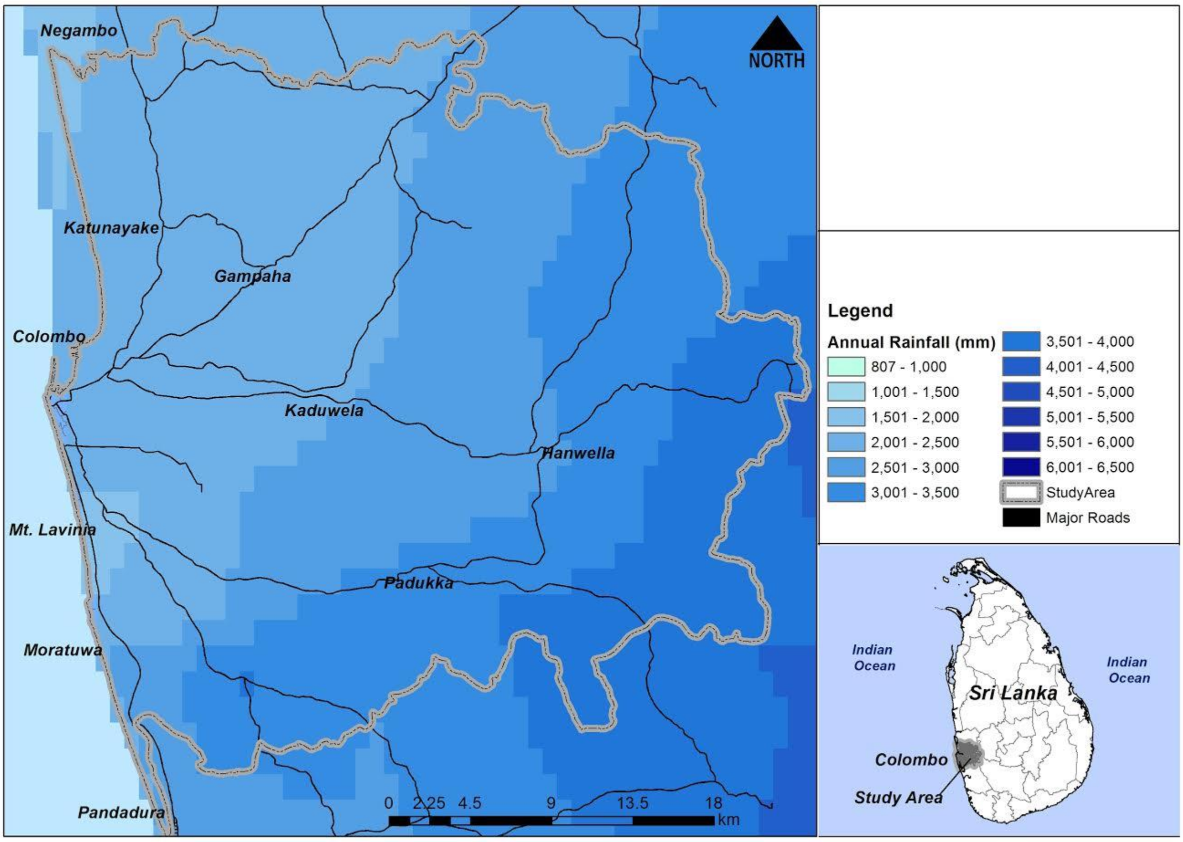


Figure 4-5: Rainfall map of study area

The following sections (4.6.3.1. and 4.6.3.2) describe the methods and materials employed in assigning and normalizing utility scores for soil hydraulic properties and land use.

4.6.3.1.Scoring Soil hydraulic properties

In GIS environment, having a set of point-based soil data with a large sample size and the laboratory-tested values provide the optimum accuracy of soil hydraulic properties. Nevertheless, due to the cost-constraints in performing such tests on drainage-basin scale, this study opted to score the soil hydrologic properties based on the generic soil characteristics of Sri Lanka (Formulae 4.1 to formulae 4.4).

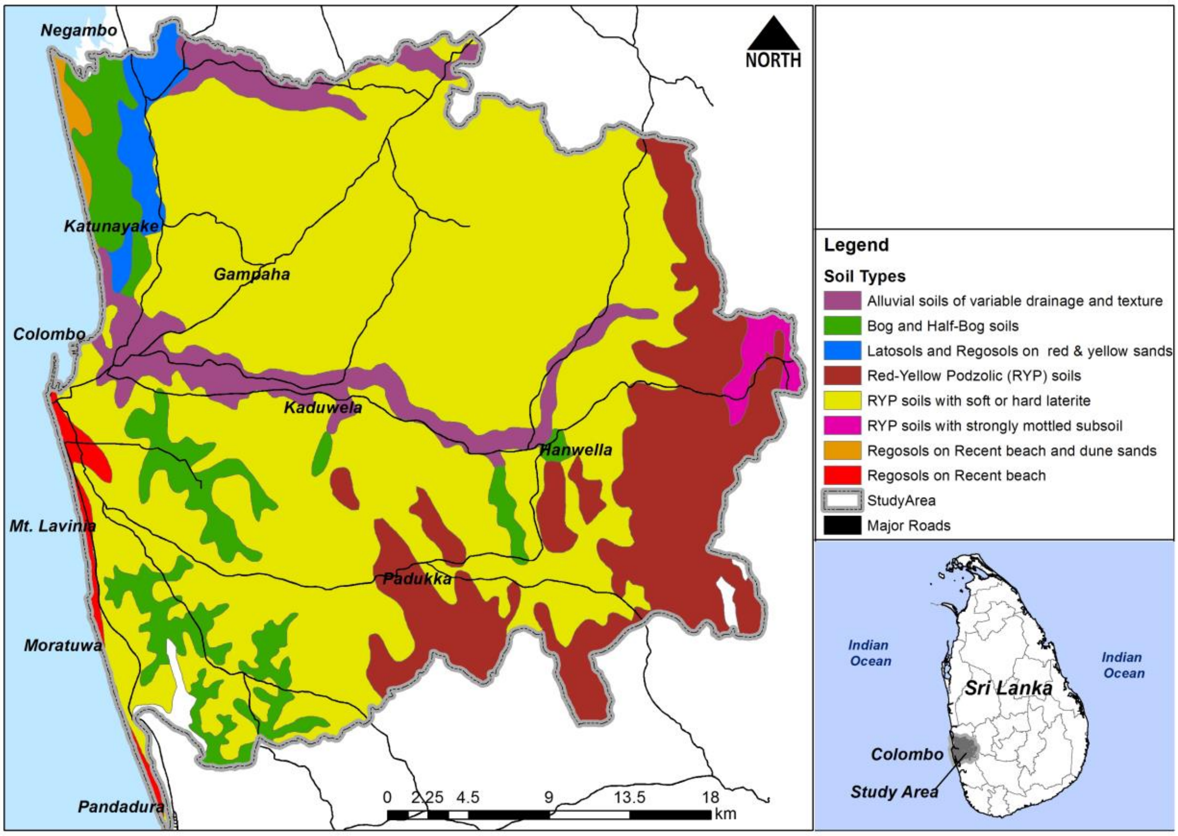


Figure 4-4: Soil map of the study area

Generic soil hydrologic properties (four properties, i.e., texture, percent clay, percent organic matter, and permeability) of Sri Lankan soil types were obtained from a secondary source and given in Table 4-4. Table 4-5 provides further details of the heuristic scores range from 1-9 that has been assigned to each soil property. The utility scores by each soil type were calculated as the average of the assigned heuristic scores of the four-selected soil hydraulic properties (refer Table 4-6).

Table 4-4: The utility scores assigned for soils in the study region

Soil class	Texture	% Clay	% Organic matter	Permeability	Soil hydraulic properties	
	(a)	(b)	(c)	(d)	(a+b+c +d) /n	Utility score
Red-Yellow Podzolic soils; steeply dissected, hilly and rolling terrain	9	7.5	5.5	8	7.50	9
Red-Yellow Podzolic soils with soft or hard laterite; rolling and undulating terrain	8	7.5	5.5	8	7.25	9
Red-Yellow Podzolic soils with strongly mottled subsoil & Low Humic Gley soils; rolling and undulating terrain	8	7	5.5	7	6.88	8
Bog and Half-Bog soils; flat terrain	7	3	9	5	6.00	5
Regosols on Recent beach sands; flat terrain	3	4	8.5	1	4.13	1
Regosols on Recent beach and dune sands; flat terrain	6	4	7.5	2	4.88	3
Latosols and Regosols on old red and yellow sands; flat terrain	6	7.5	8	5	6.63	7
Alluvial soils	8	7.5	6.5	8	7.50	9

Source - Prepared by author based on Table 4-5 and Table 4-6

Table 4-5: Soil hydrologic properties in the study region

Soil classification of the study area	Texture	% Clay	% Organic matter	Permeability
Red-Yellow Podzolic soils; steeply dissected, hilly and rolling terrain	Clay	0.3-0.4	4%	somewhat slow to very slow
Red-Yellow Podzolic soils with soft or hard laterite; rolling and undulating terrain	heavy clay with gravel	0.3-0.4	4%	somewhat slow to very slow
Red-Yellow Podzolic soils with strongly mottled subsoil & Low Humic Gley soils; rolling and undulating terrain	heavy clay with sand	0.25-0.4	4%	somewhat slow
Bog and Half-Bog soils; flat terrain	moderately clay	0.05-0.2	25%-30%	moderate
Regosols on Recent beach sands; flat terrain	sandy loam	0.15-0.2	1%	rapid
Regosols on Recent beach and dune sands; flat terrain	moderately fine silty sand	0.15-0.2	2%	somewhat fast to rapid
Latosols and Regosols on old red and yellow sands; flat terrain	sandy with fine clay	0.3-0.4	1-2%	moderate
Alluvial	sandy clay	0.3-0.4	3%	somewhat slow to very slow

Source: The national soil survey published in Soil of Ceylon, Moormann, F.R and Panabokke, C.R., 1961

Table 4-6: Utility scores assigned for soil hydrologic properties

Score (1-9 scale)	Texture	% Clay	% Organic matter	Permeability
1	sand, gravel	0-0.05	>10%	Very rapid
2	mostly sandy	0.05-0.1	8-10%	
3	loamy sandy and sandy loam	0.1-0.15	6%-8%	Somewhat fast
4	silty sand	0.15-0.2	5%-6%	
5	loam, moderately loam	0.2-0.25	4%-5%	Moderate
6	moderately fine sand with clay	0.25-0.3	3%-4%	
7	moderately clay	0.3-0.35	2%-3%	Somewhat slow
8	heavily clay with gravel, heavy clay with gravel, heavy clay with sand	0.35-0.4	1%-2%	
9	silty clay, clay	0.4-0.45	>1%	Very slow

Source: Prepared by author based on Soil of Ceylon, Moormann, F.R and Panabokke, C.R., 1961
Notes:
The desirability criteria of the assessment
Desirability criteria of the assessment was defined as higher the water retention and soil organic matter, better the resilience. Lower the surface runoff and soil erodability better the resilience. i.e., To minimize the fragility of FES processes by;

1- increasing the infiltration and the Interception rate;
2- reducing the soil erosion and increasing the permeability;
3- biologically assimilating the pollutants in water bodies
4- balancing the nutrient loads of water bodies through maintaining desirable quality of water (in the case of Colombo, reducing the mixing solid waste into surface runoff and waste water discharges into water bodies).

Assignment of the utility scores can be algebraically expressed as follows.

Soil hydrologic properties (S) of the jth cell is,

$$S_j = f(D_j . C_j) \tag{4.1}$$

Where, *'D,'* is the distance to water bodies and *'C'* is the soil classification-based generic variations of soil hydraulic properties.

Distance to water bodies (D) of the jth cell is,

$$D_j = 1/d_j \tag{4.2}$$

Where, '*d*,' is the Euclidean distance from a given water body.

Soil classification-based generic variations of soil hydraulic properties '*C'* of the jth cell is,

$$C_j = \sum_{i=1}^{n} (K_{ij}) / n \tag{4.3}$$

Where, K (i=1,2,3,…,n), is the utility value of the set of soil hydraulic properties (i.e., Soil texture, % clay, Soil Permeability, and soil organic matter).

Utility value of the 'K_i' soil hydraulic property for the jth cell is,

$$K_{ij} = \sum_{i=1}^{n} (k_{ij}\, a_j)/n \qquad (4.4.)$$

Where, 'k' (i=1,2,3,…,9), is the utility scores of the soil types present by K_i soil hydraulic property in the jth cell (given in the Table 4-6) and 'a_j' is the extent (in square meters) of the jth cell covered by the given soil type by K_i soil hydraulic property.

4.6.3.2. Scoring Land Use

The utility scores of land use were based on the experts' opinion. The experts' opinion could have been obtained through a range of alternative methods as per the context of the study. This application employed Analytic Hierarchy Process (AHP) where the specific details of this method are described elsewhere (Saaty, 2008). AHP was selected due to its increasing applicability in the domain of policy formulation and planning. Pairwise Comparison Matrices (PCMs) of 14 different types of land use were calculated by considering the four environmental parameters as the criteria. The four parameters were the density of land cover, the surface roughness of land cover, the waste assimilative capacity of the ecosystem, and the quantity and toxicity of waste generation potential of land use. 10 Sri Lankan professionals participated in this decision-making process. The opinion obtained from the local experts is the most appropriate because the given environmental parameters are highly depending on the local context. For instance, the decisions on the fragility of waste assimilation process, and desirability of water quality for fish and crop yields are completely depend on the baseline condition and the thresholds of ecosystems. Therefore, the assessors ought to have a sound expertise of the scientific knowledge as well as a clear awareness of the local environmental conditions. The selection of participants was stratified-random and the three criteria considered were (i) having experiences in any environmental planning and policy assignments conducted in CMR area; (ii) having experiences on implementing AHP method; and (iii) to include at least two experts from each related field i.e., the field of urban engineering, spatial planning, disaster management and natural resources management. In order to maintain the clarity of evaluation, a sub-objective for each of the criteria was developed, on the overall objective of the assessment, and was clearly mentioned to all participants (refer the notes of Table 4-6).

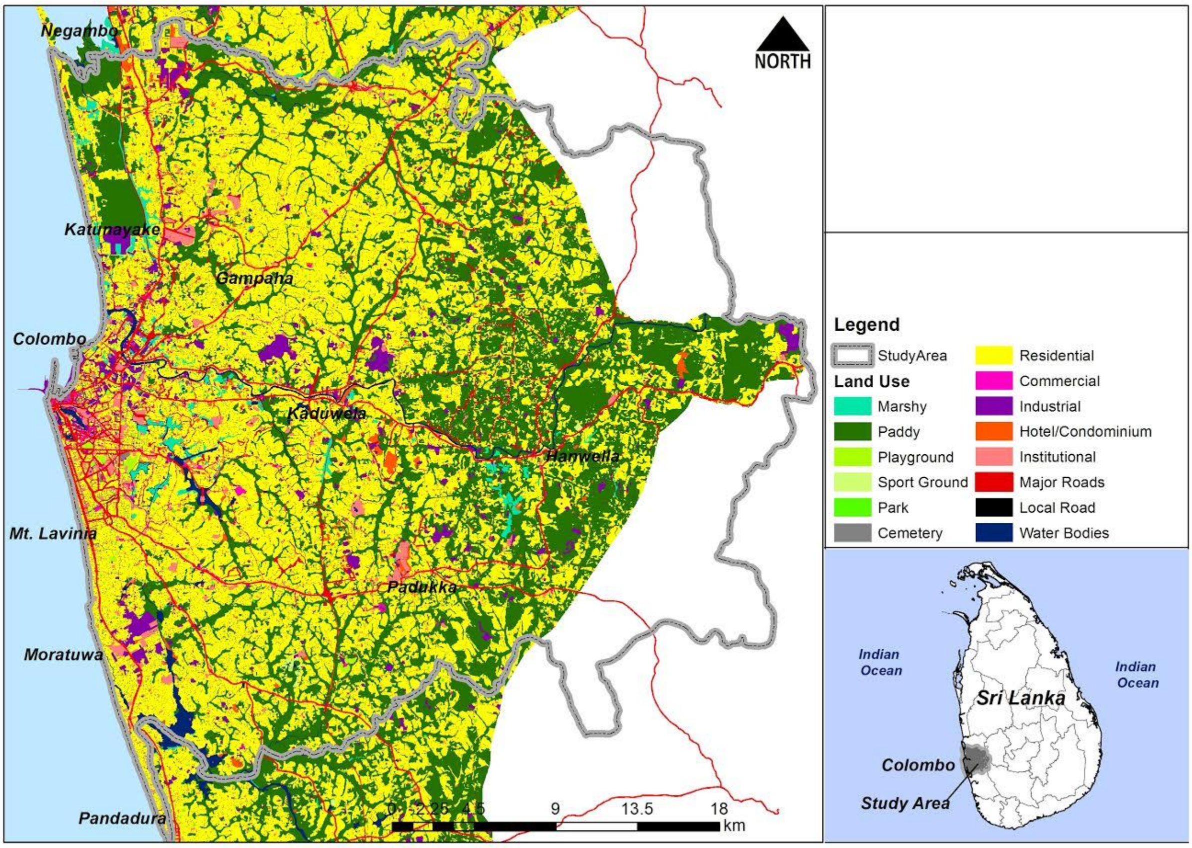


Figure 4-5: Land use map of the study area

Pairwise comparison values were instructed to be given on the scale from 1-9 for PCM elements where 1 refers to the similar level of importance and 9 refers to the least level of relative importance of the particular land use in achieving the given sub-objective. The participants were given a programmable spreadsheet to enter values such the consistency could be checked while performing the pair-wise comparison. Consistency Index of PCMs was maintained to less than 10 as the minimum acceptance level while instructed to obtain a value closer to zero. The aggregated Utility score of each land use type that has been obtained by AHP comparisons is given in Table 4-7.

4.6.4. Weighting Indicators

The weight could be assigned considering several properties including the relative importance of the indicator for the objective of the study, cumulative variance of the values within the study area, and accuracy and reliability of the data. This study was aimed at identifying the most fragile locations in order direct the initiatives for building resilience to such locations. Therefore, the relative importance was given to the manageable environmental indicators, primarily, the land use. Accordingly, heuristic weights were assigned as 0.4:0.2:0.2:0.2 for land use, Soil hydraulic properties, precipitation factor and slope respectively.

Table 4-7: Utility scores of land use types in 1-9 scale

	Average of cumulative normalized scores				**Scores derived from AHP (a+b+c)-d) /n**	**Utility score by type of land use**
Land Use	**Vegetation density (a)** [#1]	**surface roughness of land cover (b)** [#2]	**Waste assimilative capacity of ecosystem (c)** [#3]	**Waste generation potential by land use(d)** [#4]		
Marsh/mangrove	0.263	0.228	0.306	0.159	0.638	1
Abandoned paddy	0.231	0.219	0.278	0.159	0.569	2
Playground	0.042	0.072	0.053	0.087	0.08	8
Sports Ground	0.031	0.054	0.045	0.051	0.079	8
Park	0.191	0.168	0.041	0.072	0.328	5
Cemetery	0.098	0.046	0.045	0.047	0.142	7
Residential	0.052	0.045	0.045	0.028	0.114	8
Commercial	0.033	0.025	0.046	0.032	0.072	9
Industrial	0.049	0.045	0.045	0.018	0.121	8
Hotel/Condominium	0.125	0.079	0.041	0.024	0.221	6
Institutional	0.064	0.055	0.044	0.021	0.142	7
Major Road A, B, C	0.027	0.026	0.043	0.097	-0.001	9
Local Road D, E	0.027	0.03	0.043	0.053	0.047	9
Water bodies	0.036	0.214	0.252	0.089	0.413	4

Notes:

[#] Sub Objectives of the assessment, i.e., To minimize the fragility of FES processes by 1- increasing the infiltration and the Interception rate; 2- reducing the soil erosion and increasing the permeability; 3- biologically assimilating the pollutants in water bodies 4- balancing the nutrient loads of water bodies through maintaining desirable quality of water (in case of Colombo, reducing the mixing solid waste into surface runoff and waste water discharges into water bodies)

4.6.5. Preparation of the aggregated map

The aggregated map of the FES composite indicator has been derived as the weighted sum of the four-selected indicators. Accordingly, the fragility of FES processes of the j^th spatial unit could be stated as formula 4.5.

$$FES_j = \sum_{i=1}^{n} X_{ij} W_i \qquad (4.5)$$

Subjected to,

$$\sum_{i=1}^{n} W_i = 1 \; and \; 0 \le W_i \le 1$$

Where,‘X_i’ is the utility score of proxy indicators on a 1-9 point Likert scale and ‘W_i’ is the assigned weight of ‘X_i’.

The aggregated map produced for the study region is given in figure 4-8.

4.7. Results

4.7.1. FES values of the study area

According to WLCM, spatial units have been assessed based on the given set of indicators, and the aggregated value of each unit indicates how fragile the particular spatial unit. As the indicators were scaled between 1 and 9, the best possible performance, i.e. the lowest fragility of the FES processes, the value 1, and the worst possible performance, i.e. the highest fragility of the FES processes, the value 9. Hence, value 1 could be considered as the goal, and the distance from 1 indicates the level of fragility of FES.

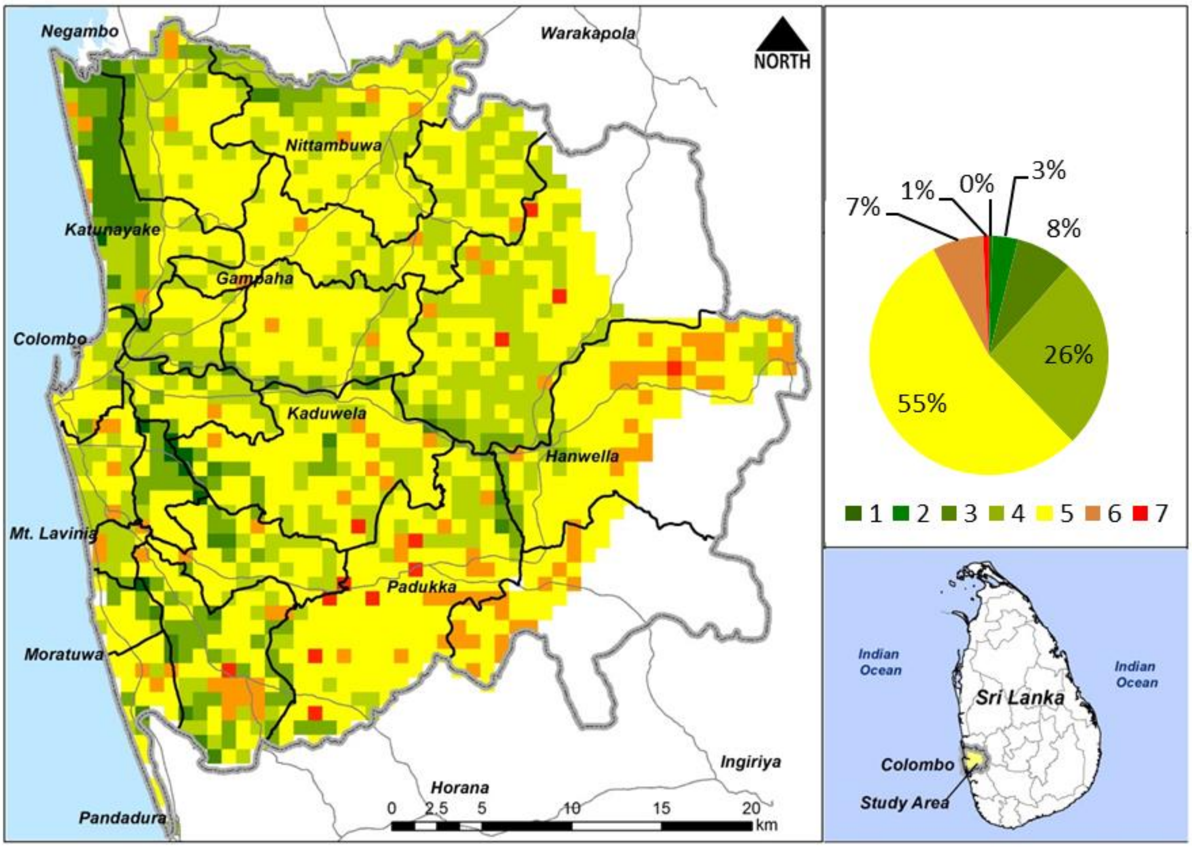


Figure 4-6: The spatial variations of the FES composite indicator within the case study area

The results depict geospatial variations of the FES within the case study region. This map is an intermediate output as an indicator proposed to be incorporated into community resilience assessment. Once developed into a composite index, the output can be utilized to rank the wards, villages or other administrative units in term of resilience. Nevertheless, it is possible to meaningfully imply the basic conclusions from this intermediate output. First, the eastern and south-eastern borders of the study area, which is highly concentrated with orange and red colour-coded cells ((i.e., >5 in the 1-9 scale), is needed the high priority attention of the initiatives for building resilience. These high priority clusters shall be the foremost concern of the immediate environmental conservation action plans. Secondly, the absence of values from 8-9 as well as having only 10% of the locations (i.e., cells) scored a fragility level above 5 reveals that the critical locations, which requires urgent attention are sizable. However, nearly half of the region is subjected to a moderate level of fragility (i.e., score 5 in 1-9 scale, coded in yellow) and these locations are densely concentrated in central northern, western parts of the region. The long-term environmental management strategies shall account this emerging threat proactively.

4.7.2. The relationship between Community Resilience and FES

As per the synergy between FESs and Community resilience illustrated in figure 4-2., FES process enhances the absorptive capacity, recovery ability and transformative ability of socio-ecological systems making community more resilient to floods. Amongst, the contribution to absorptive capacity is more coherent because each of the ES in the bundle is explicitly strengthening the absorptive capacity. Therefore, this study admitted absorptive capacity as versatile enough to test the applicability of FES composite indicator in assessing the community resilience. However, the absorptive capacity cannot be measured directly and requires an independent set of proxy surrogates. Considering the data availability, the study selected two proxy surrogates: frequency of disaster declaration (FDD) (Bakkensen, et al., 2016). FDD was measured as the Number of times a given locality was included in flood declaration reports as a percentage of the total number of flood declaration reports issued within the study area from 1970 to 2016. 51 flood events have been declared within this period including annual floods. Table 4-8 indicates the number of times each DS division has been affected for 51 flood events.

Table 4-8: Number of declared flood events by DS division

DS division	Number of declared flood events (1970-2015)	Average FES value
Colombo	30	3.06
Kolonnawa	47	3.06
Thimbirigasyaya	9	2.72
Wattala	13	3.70
Kelaniya	20	2.61
Kaduwela	48	3.11
Sri Jayawardanapura Kotte	31	3.46
Seethawaka	50	6.00
Biyagama	7	2.46
Homagama	22	3.31
Ratmalana	21	3.08
Mahara	11	2.68
Katana	48	4.02
Maharagama	18	2.75
Negombo	30	3.63
Dompe	33	4.08
Padukka	50	5.00
Kesbewa	32	3.75
Gampaha	15	2.56
Attanagalla	26	3.26
Moratuwa	20	3.26
Ja-Ela	34	2.99
Dehiwala	1	2.39

In environmental systems, the cause and effect may not have a perfect linear spatial relationship, primarily because a cause occurred at one location does not necessarily affect the same location. However, many of the selected environmental parameters are logically plausible to have the effects within the immediate surroundings. Hence, it is theoretically valid to expect some significant correlation between the FES composite indicator and FDD.

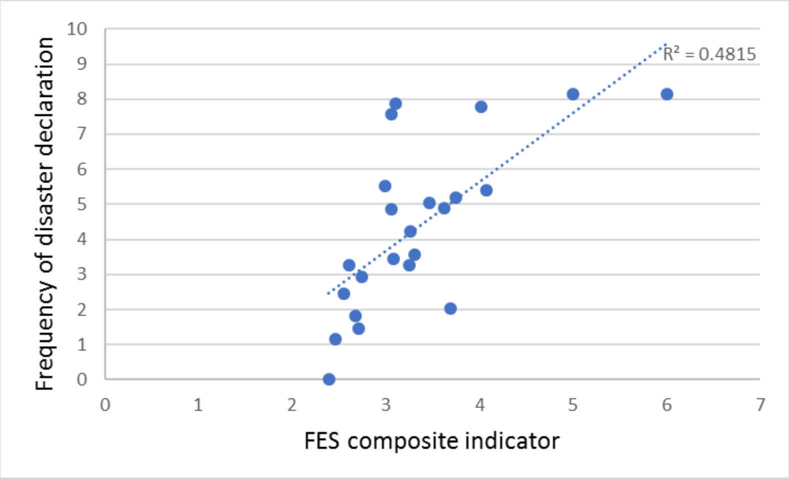


Figure 4-7: Scatter grams showing a positive correlation of FDD with FES composite indicator

In testing the relationship, Spearmen’s coefficient of correlation was employed considering the differences in the scales. As indicated in the scattergrams (Figure 4-9), FES showed a significant correlation with FDD ($r=0.6939$, $p<0.01$).

The result revealed the capability of FES composite indicator to explain the key determinants of the community resilience. Hence, the composite indicator can be recommended for incorporating into the extant CRA tools.

4.8. Conclusion

This paper attempts to improve the quality of existing CRA tools by suggesting a set of geospatial, environmental indicators, particularly applicable on a regional scale. For that purpose, the FES composite indicator was developed with a set of proxy environmental indicators that assess community resilience to floods. In the process of formulating the FES composite indicator, the study surveyed the existing CRA tools concerning floods in order to select the initial set of environmental indicators. The original set was further enriched by incorporating appropriate indicators that obtained from the domain of ESs assessment. Some of the conceptual CRA methods have explicitly discussed flood regulation but with very limited attention on nutrient recycling. As per the literature survey, these methods have no indicator to reflect how climate regulation enhances the predictability of precipitation despite the vast amount research that emphasizes how environmental knowledge enables the community’s ability to anticipate weather conditions and to be prepared; and how this ability has been threatened with the climate change. The ESs-based conceptual framework that has been developed in this study could emphasize the role of climate regulation and nutrient recycling along with the flood regulation. With that framework, a set of new ecological parameters such as predictability of precipitation and land use specific variations of; waste assimilation potential, waste generation potential, surface runoff and surface roughness were introduced to CRA tools.

The FES composite indicator has contributed to the theoretical development of CRA tools by consolidating the extant environmental indicators from several conceptual CRA methods; incorporating the indicators that developed in the domain of ESs into the domain of disaster resilience and introducing a set of new environmental parameters that reflect the natural reinforcements for disaster resilience.

The FES composite indicator also provides a great extent of flexibility in assigning utility scores and weighting. Hence, users can localize to the given context. FES provides a snapshot of the socio-ecological system at a given time. Nevertheless, the CRA tools that seek for dynamic indicators can customize the FES value as the percentage change for a given period of time. When employing the FES composite indicator in time series analysis, the reproducibility relies on the consistency of; weighting, utility scores, resolution of the data, and the boundaries of the spatial units.

This is a proactive indicator, therefore, could be employed in assessments that aim to evaluate a modeled future spatial development scenario. This has been targeted the decision-makers engages at national and sub-national levels where most policies and planning investments are been made. As the FES composite indicator was positioned on an ESs-based platform, which integrates multidimensional prospects of development, it could be incorporated into a wide range of resilience assessment frameworks.

The proposed FES composite indicator could orient policy and planning decision-making processes towards an integrated approach leading to more sustainable disaster resilience outcomes.

Chapter – 5

Geospatial indicators to assess community resilience

5.1. Introduction

This chapter presents the details of the proposed a set of geospatial indicators for CRA. This explains the process of formulating indicators and lists them along with justifications. The chapter further describes the methods of computing indicators and the data requirement, particularly considering the data-scares situations in developing countries.

5.2. Sub-objective

To select a set of geospatial indicators for incorporating into CRAs, particularly, which are capable of accounting the role of ecosystem services and the impact of the growth of built-up area on the flood resilience of socio-ecological systems.

5.3. Methods and materials

The study has reviewed community resilience assessment indicators from practicing tools as well as proposed frameworks in research articles. The initial attempt was to investigate from electronic databases including Google Scholar, MEDLINE through PubMed, and Scopus with no limitation on article type, and date. The search strategy was to initially perform machine extraction by keywords and then to screen the extracted articles manually. Screening criteria were having processed by geospatial analysis, applicability at the regional scale, relevance to floods and availability of data. The first search term ‘geospatial Indicator AND resilience’ applied for title, abstract and keywords yet could not extract a valid result. The next search terms attempted were ‘spatial indicator AND resilience’, ‘place indicator AND resilience’, and ‘location indicator AND resilience’. Geospatial indicators represent terrestrial activities, processes derived from geospatial analysis (De Smith, 2007) and widely applicable in decision-making science.

5.4. Findings of Literature survey: Geospatial indicators to assess community resilience to floods

Many of the extracted indicators found to have some possibility to geo-visualize if computed with spatial data. However, the manual screening was particularly aimed at the indicators that can be derived from the geospatial analysis. The limited application of geospatial analysis in assessing community resilience to floods shrank the extracted results into to 52 indicators. Except for the works of cutter et. al., and Kotze and Reyers many of the manually filtered indicators have basic algebraic processing of spatial data including ratio and density functions. Many of the extracted indicators are listed in the Paolo Cimellaro's comprehensive literature survey on extant indicators to assess community resilience to disasters (Cimellaro, 2016). The list of 52 indicators was further filtered into 34 by focusing on the relevance to floods and then into 25 considering the data availability (Table 5-1).

Table 5-1: The selected Geospatial indicators

ID	Indicator	Direction	Justification
1	Percent land area that is a wetland, swamp, marsh and mangrove	+	(Cutter, et al., 2008a); (Klein, et al., 2003); (Shaw, et al., 2010)
2	Rapid urban population growth (Percentage increase of urban population density)	-	(H. John Heinz III, 2002)
3	Percent deep permeable soil per ward	+	(Kotzee & Reyers, 2016)
4	Percent police, emergency relief services, and temporary shelters outside of hazard zones	+	(U.S. Indian Ocean Tsunami Warning System, 2007)
5	Percent of building infrastructure, not in Flood Inundation zones	+	Geis and Kutzmark, 1995 cited in (Cimellaro, 2016)
6	Percent of government offices outside of flood inundation zones	+	(U.S. Indian Ocean Tsunami Warning System, 2007)
7	Percent of commercial establishments outside of high hazard zones (flood, surge)	+	(U.S. Indian Ocean Tsunami Warning System, 2007)
8	Population living in high-intensity urban areas/ population density	-	(Cutter, et al., 2008a); (Shaw, et al., 2010)
9	Percent land area that does not contain erodible slopes	+	(Cutter, et al., 2008a)
10	Percent land area not in an inundation zone (100 years)	+	(Cutter, et al., 2008a)
11	Percent land area that does not contain impervious surfaces	+	(Cutter, et al., 2008b);
12	Percent land area with no forest and rangeland decline	+	(Shaw, et al., 2010)

ID	Indicator	Direction	Justification
13	Percent land area with no wetland decline	+	(Cutter, et al., 2008a); (Cutter, et al., 2008b); (Shaw, et al., 2010)
14	Percent area that has changed into urban areas (by urban classification)	-	(Cutter, et al., 2008a); (Shaw, et al., 2010)
15	Percent land area that is high-intensity urban development (80% or more impervious surface)	-	(Cutter, et al., 2008a)
16	Percent land area of developed open spaces/ green spaces	+	(Shaw, et al., 2010); (UNDP, 2014)
17	Principal arterial miles	+	Cutter et al., 2010; Bruneau and Tierney, 2007
18	Hospitals per square mile	+	Cutter et al., 2008a
19	Schools (primary and secondary education) per square mile	+	Cutter et al., 2010; U.S. Indian Ocean Tsunami Warning System Program, 2007; H. John Heinz III, 2002
20	Hotels and motels per square mile	+	Cutter et al., 2010
21	Density of commercial infrastructure	-	Allenby et al., 2005
22	Number of river miles	-	Berke and Campanella, 2006
23	Percent erodible soil per ward	-	(Cutter, et al., 2008a); (Kotzee & Reyers, 2016)
24	Land use diversity (Proportion of land use categories per ward, multiplied by the natural logarithm. The resulting product is summed across wards, and multiplied by −1)	+	(Kotzee & Reyers, 2016)
25	Wetland diversity (Proportion of flood attenuating wetlands per ward, multiplied by the natural logarithm. The resulting product is summed across wards, and multiplied by −1)	+	(Kotzee & Reyers, 2016)

5.5. Modifications of selected indicators

This study has made minor modifications to four of the extracted geospatial indicators with an account of spatial properties. Justifications for the modifications are given in Table 5-2.

Table 5-2: The list of modified indicators

ID	Indicator listed in Table 5-1	ID	Modified Indicator	Direction	Justification
2	Rapid urban population growth	26	Rapid urban growth (Percentage land cover change to urban areas from base year)	-	Existing indicator considers the increase of population whereas the proposed indicator considers the growth of urban land uses. Changes of land use can better explain the impact of built-up area on floods.

ID	Indicator listed in Table 5-1	ID	Modified Indicator	Direction	Justification
22	Number of river miles	27	Waterbodies Density (Waterbody area/total land area) #	-	Existing indicator considers the length of rivers as it is whereas the proposed indicator normalizes the effect of length by land area. Furthermore, the modified indicator includes bodies of water other than rivers as well.
18	Hospitals per square mile	28	Access to hospital (Inverse of Euclidean distance to the hospitals) #	+	Existing indicator considers only the number of hospital whereas the proposed indicator considers the distance to roads. Higher accessibility to hospitals increase community resilience
17	Principal arterial miles	29	Movement potential (Inverse of Euclidian distance to the road network) #	+	Existing indicator considers the length of roads as it is whereas the proposed indicator normalizes the effect of length by land area. Furthermore, the modified indicator considers the distance to roads because being closer to the high capacity roads facilitate evacuation and relief services.

Justifications of those minor modifications were presumed logically and yet to be tested. Therefore, the verification test considered both extracted indicators and modified versions.

5.6. Methods of computing geospatial indicators

Table 5-3 presents the set of 30 geospatial indicators to be tested as independent variables to assess community resilience to floods.

Table 5-3: Parameters of the selected Geospatial indicators

ID	Indicator	Direction	**Parameters** (per a given locality)
1	Percent land area that is a wetland, swamp, marsh, and mangrove	+	[(Extent of wetland + Extent of swamp + Extent of marsh + Extent of mangrove)/ Total land area] x 100
2	Rapid urban population growth (Percentage increase of urban population density)	-	[(urban population in the base year/Total land area)/ (urban population in the current year/Total land area)] x 100
3	Percent deep permeable soil per ward	+	(Extent of deep permeable soil area/Total land area) x 100
4	Percent police, emergency relief services, and temporary shelters outside of hazard zones	+	[(Number of police stations outside the flood area + Number of emergency relief services outside the flood area + Number of temporary shelters outside the flood area)/ [(Total number of police stations + Total number of emergency relief services + Total number of temporary shelters)] x 100

ID	Indicator	Direction	**Parameters** (per a given locality)
5	Percent of building infrastructure, not in Flood Inundation zones	+	(Number of building infrastructure outside of flood area / Total number of building infrastructure) x 100
6	Percent of local government offices outside of flood inundation zones	+	(Number of local government offices outside of flood area / Total number of local government offices) x 100
7	Percent of commercial establishments outside of high hazard zones (flood, surge)	+	(Extent of commercial establishments outside of flood area / Extent of commercial establishments) x 100
8	Population living in high-intensity urban areas/ population density	-	(Extent of high intensity residential area/ Total residential area) x 100
9	Percent land area that does not contain erodible slopes	+	(Extent of land area does not contain erodible slopes/ Total land area) x 100
10	Percent land area not in an inundation zone (100 years)	+	(Extent of high-intensity residential area/ Total residential area) x 100
11	Percent land area that does not contain impervious surfaces	+	(Extent of impervious surfaces/ Total land area)/100
12	Percent land area with no forest and rangeland decline	+	(Extent of forest per current year - Extent of forest per base year)/100
13	Percent land area with no wetland decline	+	(Extent of wetland per current year- Extent of wetland per base year)/100
14	Percent area that has changed into urban areas	-	(Extent of urban area by classification per base year- Extent of urban area by classification per current year)/100
15	Percent land area that is high-intensity urban development (80% or more impervious surface)	-	(Extent of area 80% or more impervious surface/ Total land area)/100
16	Percent land area of developed open spaces	+	(Extent of developed open spaces/ Total land area)/100
17	Principal arterial miles	+	Total length of arterials in miles
18	Hospitals per square mile	+	Number of hospitals/ Total land area in square miles
19	Schools (primary and secondary education) per square mile	+	Number of schools/ Total land area in square miles
20	Hotels and motels per square mile	+	Number of schools/ Total land area in square miles
21	Density of commercial infrastructure	-	Extent of commercial infrastructure/ Total land area
22	Number of river miles	-	Total length of rivers in miles
23	Percent erodible soil per ward		Extent erodible soil/ Total land area)/100
24	Land use diversity	+	The proportion of land use categories per ward, multiplied by the natural logarithm. The resulting product is summed across wards, and multiplied by −1
25	Wetland diversity	+	The proportion of flood attenuating wetlands per ward, multiplied by the natural logarithm.

ID	Indicator	Direction	**Parameters** (per a given locality)
			The resulting product is summed across wards, and multiplied by −1
26	Rapid urban growth	-	Percentage land cover change to urban areas from base year
27	Waterbodies density	-	Extent waterbodies/ Total land area
28	Access to hospital	+	Inverse of Euclidean distance to the hospitals
29	Movement potential	+	Inverse of Euclidian distance to road network
30	Fragility of Flood resilience-supportive Ecosystem Services (FES)	-	Weighted sum of the utility scores of soil hydraulic properties, land use specific variations, precipitation factor and slope

5.7. Data requirement to compute the proposed geospatial indicator

Table 5-4 provides the details of the required data for calculating the proposed geospatial indicators. The essential data needed is the land use map. Flood map is also needed for few indicators and rest of the requirements are specified below.

Table 5-4: Data requirement to compute the proposed geospatial indicator.

ID	Indicator	Land Use	Flood map	Other (specified)
1	Percent land area that is a wetland, swamp, marsh and mangrove	√		
2	Rapid urban population growth			Urban demographic data for two or more years
3	Percent deep permeable soil per ward			Soil permeability maps
4	Percent police, emergency relief services, and temporary shelters outside of hazard zones	√	√	
5	Percent of building infrastructure, not in Flood Inundation zones	√	√	
6	Percent of local government offices outside of flood inundation zones	√	√	
7	Percent of commercial establishments outside of high hazard zones (flood, surge)	√	√	
8	Population living in high-intensity urban areas/ population density	√	√	
9	Percent land area that does not contain erodible slopes			Slope Length-gradient map
10	Percent land area not in an inundation zone (100 years)		√	
11	Percent land area that does not contain impervious surfaces	√		Runoff coefficients by land use

ID	Indicator	Land Use	Flood map	Other (specified)
12	Percent land area with no forest and rangeland decline	√		
13	Percent land area with no wetland decline	√		
14	Percent area that has changed into urban areas	√		
15	Percent land area that is high-intensity urban development (80% or more impervious surface)	√		Runoff coefficients by land use
16	Percent land area of developed open spaces	√		
17	Principal arterial miles	√		
18	Hospitals per square mile	√		
19	Schools (primary and secondary education) per square mile	√		
20	Hotels and motels per square mile	√		
21	Density of commercial infrastructure	√		
22	Number of river miles	√		
23	Percent erodible soil per ward			Soil erodibility map
24	Land use diversity	√		
25	Wetland diversity	√		
26	Rapid urban growth	√		Land use data for a base year
27	Water bodies density	√		
28	Access to hospital	√		
29	Movement potential	√		
30	Fragility of Flood resilience-supportive Ecosystem Services (FES)	√		

As mentioned above, land use and flood map are fundamental in computing the proposed set of geospatial indicators. Among the other data, population statistics is readily available for all the countries hence not difficult to obtain. Nonetheless the environmental data including run-off coefficients by land use types, soil permeability maps, and soil erodibility map are not commonly available, particularly in developing countries. This study urged to cater for the need of developing countries where the pre-processed environmental data lacks. In such cases, it can be recommended to generate proxy data from available secondary sources and experts' opinion.

Accordingly, data for environmental parameters have been proposed to obtain under two-tires as Tier-1 and Tier-2 with a different degree of applicability. Table 5-5 compares the properties of two tiers. Assessors can select indicators from one tier or combine both tiers depend on the context of analysis.

Table 5-5: The comparison of Tier-1 and Tier-2 parameters

Criteria[#]	**Tier-1**	**Tier-2**
The required degree of the technical competency	High	Moderate to Low
Data requirement	High	Moderate to Low
Accuracy	High	Moderate to Low
The ability to Interpret to a broader stakeholder segment	Moderate to Low	High
# heuristic value judgment represented on a 3-point Likert scale as High, Moderate, Low		

Table 5-6 elaborate the parameters of the FES composite indicator as for how the inputs vary between tier-1 and tier-2.

Table 5-6: Environmental Indicators (I) and parameters selected for the FES composite Indicator (I)

I	**Ecological Parameters**	**Data and technical inputs required**	
		Tier-1	**Tier-2**
S	Soil texture	Laboratory testing-based data of soil hydraulic properties with the coordinates of sampling locations Or Soil hydraulic properties modeled by high-resolution satellite images	'Soil classification-based generic variations' of soil hydraulic properties And Thematic maps of soil and water bodies
	Soil Moisture		
	Soil organic matter		
	Coefficient of permeability		
K	Slope gradient	Surveyed contours (with contour interval <10m) Or Detected contours from high-resolution satellite images	Surveyed contours Or Spot heights
L	Vegetation Density	Environmental modelling based scores for the land-use-specific variations of the vegetation density	Experts' opinion based scores for the land-use-specific variations of the vegetation density
	Surface roughness of land cover by surface materials and percentage built-up	Environmental modelling based scores for the land-use-specific variations of permeability and soil erosion	Experts' opinion based scores for the land-use-specific variations of permeability and soil erosion
	Waste assimilative capacity of the ecosystems	Environmental modelling based scores for the land-use-specific variations of waste assimilative capacity with specific reference to the ecosystem thresholds	Experts' opinion based scores for the land-use-specific variations of waste assimilative capacity with specific reference to the ecosystem thresholds

I	**Ecological Parameters**	**Data and technical inputs required**	
		Tier-1	**Tier-2**
	Quantity and toxicity of waste (solid waste and waste water) generation potential by land use	Waste generation statistics based scores by land use type	Experts’ opinion based scores for the land-use-specific variations of waste generation potential
P	Rainfall intensity	Hourly rainfall data with the coordinates of weather stations	Isohyets of average annual/seasonal rainfall
	Predictability of precipitation	Spatial climate variation modelling based data on predictability of precipitation	Not available[#]

[#] This measure is not recommended for the Tier-2 because any non-spatial climate variation analysis could have high error unless been adjusted spatially.

5.8. Conclusion

The study has listed 30 geospatial indicators for assessing community resilience to floods. The key challenge faced by the practitioners in this context is the resource-consuming nature of bio-physical environmental data collection for regional geographies. Even if the data is available, modelling environmental parameters require sophisticated technical competency and access to software resources. Further, such processed environmental data might difficult to interpret to a particular segment of local stakeholders depends on their level of technical know-how. In order to overcome these challenges, the study proposed two-tiers of inputs where practitioners can either opt for one tier or a combined approach. The indicators could be chosen according to the data availability but with a meaningful account of completeness and mutual exclusivity. Even though it has been recommended to perform modelling with Tier-2 inputs, the accuracy could be significantly improved with the sophisticated environmental modelling applications presented in Tier-1. Therefore, such parameters are highly recommended in the circumstances where resources and stakeholders’ technical competency permit.

Chapter – 6

Proxy measures to verify community resilience

6.1. Introduction

This chapters explains the process of formulating an independent set of proxy measures for empirically verifying the proposed geospatial indicators. The chapter provides the details on formulating the system performance curve-based proxies to measure community resilience by empirical evidence on community responses (i.e., outcome variables of community resilience) to a selected flood event in Sri Lanka.

6.2. Sub-Objective

To formulate a system performance based proxy measure for empirically verifying community resilience concerning the empirical evidence on community responses to floods.

6.3. Methods and materials

First, the study selected an outcome variable for verifying community resilience to floods. The selection was based on a literature survey concerning existing verification studies on the domains of disaster recovery and disaster resilience. Secondly, the study developed a set of proxies to quantify the outcome variable with reference to the states of system performance curve. The developed proxy measures are corresponding to the three capacities of resilience, i.e., absorptive capacity, recovery capacity and transformative capacity.

6.4. The option to select an existing CRA index as the outcome variable of community resilience

CRA indices explain the baseline status of community resilience levels in a given population or a locality. Comparing the resilience indices computed by CRA tools against the proposed geospatial indicators seems meaningful for testing the power of the proposed indicators as predictors of community resilience to floods. Hence, this study reviewed the possibility of utilising an index computed by an existing CRA tool as a proxy measure for the purpose of verification in this study.

6.4.1. Absence of standardized CRA tools

Many scholars (Bennett *et al*, 2005, Carpenter *et al*, 2006, Fletcher *et al*, 2006, Darnhofer *et al*, 2010) have attempted to develop alternative methods to assess the resilience (Cabell & Oelofse, 2012, pp. 1-2). Among this array of resilient assessment methods, inductive approaches – "whereby one establishes a set of characteristics '*inductive*', which are judged to be relevant to resilience and attempts to measure these" (Winderl, 2014, p. 15) – were well taken by many practitioners due to its simplicity and workability. Application of inductive resilience assessment approaches appears to be a common practice, but there is a lack of agreement among existing inductive assessment tools. "There are many different methods utilized by governments, NGOs [non-governmental organizations] and businesses to assess resilience, but no internationally accepted standards" (Christiansen & Pretlove, 2014, p. 38). Whereas some countries have locally recognised resilience assessment tools that con be considered as accepted for the given context. Hence, as the next step, this study reviewed the CRA practice in Sri Lanka, where the proposed geospatial indicators are planning to be empirically verified.

6.4.2. Inconsistency among CRA practice in Sri Lanka

Building resilience has been prioritised as a necessity by the National Disaster Road Map of Sri Lanka which has been formulated under the Hyogo Framework Convention, UNISDR. However, there is no locally formulated community resilience assessment tool available to date. Developing a nationally accepted resilience assessment tool for Sri Lanka has been hindered primarily because it is a resource-consuming task as same as for many of the developing countries. Many of the developing countries do not have locally formulated Community Resilience Assessment tools. In the absence of such locally formulated assessment tools, the community resilience assessment practice in developing countries, is primarily based on tools imported from other countries. Per the best practices of developing countries, such tools are localized into the local conditions of the country before put into practice. However, in the context of Sri Lanka, no CRA tool has been localised so far.

In a milieu, where neither standardized CRA tool at global level, nor locally developed or localised CRA tool at Sri Lankan level, the study tested the applicability of three extra-local tools in the context of Sri Lanka. Results revealed no consistency among the resilience values computed by three CRA tools (please refer the details provided in section 3.4.2 which explained the results of the preliminary assessment).

On that basis, it was concluded as difficult to meaningfully verify the proposed set of geospatial indicators by selecting an existing CRA tools as the outcome variable within the context of this study. As the next step, the study surveyed literature on how community resilience measures have been verified in previous studies.

6.5. Literature survey on existing outcome variables to externally validate community resilience

Validation "assesses the explanatory power of an index using real world observations and can estimate the ability of an index to explain a variety of disaster losses, thereby giving confidence in index's ability and performance to end users" (Bakkensen, et al., 2016, p. 5). Further, Validation performs a vital role in identifying the relative importance of indicators (Burton, 2015); (Cai, et al., 2016) as well as clarifying which indicator/s should prefer in each decision (Bakkensen, et al., 2016). The limited studies on validation have revealed that "some variables were more strongly associated with actual recovery than others and thus were better proxies of resilience" (Parsons, et al., 2016). "The use of logical plausibility is presently most common in disaster resilience assessment because causal validation specifying the association between an indicator and disaster resilience or vulnerability is only recently attracting research focus (Rufat, et al., 2015)" cited in (ibid). Hence, even though validation is a major step in the process of creating composite indices, rarely performed in the context of disaster resilience studies (Bakkensen, et al., 2016); (Burton, 2015); (Cai, et al., 2016); (Irajifar, et al., 2015).

"Validation of a resilience index with external reference data has posed a persistent challenge…This is largely because community resilience is not a directly observable phenomenon and the validation of resilience index requires the use of proxies (Tate, 2012). Currently, there is no commonly recognized independent proxy data used in the validation of resilience assessment" (Cai, et al., 2016). Furthermore, "resilience is an emergent property of systems and can be very context dependent, particularly in spatial-temporal scales and perspectives (Carpenter *et al*, 2005)" (Cabell & Oelofse, 2012, p. 1). Therefore, developing a standard proxy data is a challenging task. Nevertheless, promoting resilience-oriented DRM requires such proxies that will allow decision makers to assess progress and implement sustainable governance structures to be employed (Nelson, et al., 2007, p. 411).

6.5.1. Literature based logical plausibility vs. external validation

The evidence supporting the relationship between resilience indicators and resilience-evidenced can be interpreted by literature-based logical plausibility or causal validation such as direct observation or indirect structural equation modelling (Parsons, et al., 2016). This study opted for external validation primarily because the literature-based logical plausibility has already been considered in the process of formulating geospatial indicators. Further, many authors have emphasised the relative importance of causal validation based on empirical evidence over theoretical validations. “While theoretical and meta-analysis index justifications are important in setting indices within the existing knowledge base, they do not guarantee that the metrics selected will meaningfully relate to specific outcomes of interest” (Bakkensen, et al., 2016, p. 5).

6.5.2. Qualitative methods vs. quantitative methods

“Previous studies on disaster recovery [and resilience] mostly employed qualitative and subjective information, obtained by social-audit techniques and participatory methods (e.g. focus group meetings, household surveys and key informant interviews)” (Irajifar, et al., 2015). Dwyer and Horney have employed three qualitative methods to validate disaster resilience indicators including a review of previously content-analysed pre-disaster recovery (PDR) plans, feedback from disaster recovery experts, and a case study of two communities recently affected by disaster and interviews with key informant interviews and expert focus group discussions (Dwyer & Horney, 2014). “However, recently a series of quantitative, systemic and objective recovery studies were conducted using direct observation and non-participatory methods (e.g. remote sensing, repeat photography and advanced field survey techniques) that allow detailed geocoded observations” (Irajifar, et al., 2015). These studies have employed quantitative methods including correlation and multivariate regression analysis. This study opted for a quantitative method primarily because the proposed geospatial indicators assess resilience quantitatively.

6.5.3. Measurable Outcome variables utilized in precedent studies

“Abrupt changes in performance of social systems occur in the case of disastrous events which can lead systems to be failed, leading to a major reduction or complete loss in performance with respect to some or all measures” (Michel Bruneau, 2003, p. 737). Assessing community resilience in the aftermath of a disaster is a specific task, which undertakes by recording the observations made throughout the recovery process. Such observations provide a detailed overview of how long it has been taken a system to be re-organized, which changes were irreversible and which could have been done to expedite the recovery process. Most of the measurable outcome variables are based on the findings of such empirical evidence on previous disasters.

According to Bakkensen et el, “three outcomes are commonly mentioned in relation to index resilience and vulnerability: property damages, fatalities, and frequency of disaster declarations (2016, pp.16-17). These three outcomes are logically related to resilience and vulnerability, and also appealing due to readily accessible data”. However, they have acknowledged that resilience is characterized by some more attributes including reductions in psychological stress, minimizing electrical losses, or speedier economic recovery (ibid, p.17). Peacock et al. have validated their resilience matrix using disaster losses and fatalities (2016).

Disaster recovery indicators are also important in validating community resilience even though it is only referring to a part of resilience. Burton et al, have validated a resilience index by the visual ranking of recovery photographs before and after Hurricane Katrina with reference to the gulf coast counties (cited in, ibid, p.5). Dwyer and Horney have utilized the data on economic recovery, housing recovery, and infrastructure systems recovery to validate disaster resilience in their qualitative assessment (Dwyer & Horney, 2014). Irajifar et al have employed house damage and reconstruction to measure recovery outcomes of disasters, and have acknowledged that the dynamic and complicated nature of recovery should be approached “as a multidimensional concept that includes social, economic, physical and environmental aspects” (Irajifar, et al., 2015). “The most frequently used recovery indicators are reconstruction of houses, critical facilities and lifelines, noncritical facilities and lifelines, transportation systems, number of building permits and population return (Bevington, et al., 2011); (Smith & Wenger, 2007, pp. 234-257); (Stevenson, et al., 2010, pp. 57-68)” (cited in Irajifar, et al., 2015).

Li et al have emphasised the importance of assessing the overall resilience with three dimensions of indicators, precisely, exposure indicators, damage indicators and recovery indicators (Li, et al., 2016). They have selected the seismic intensity as the exposure indicator regarding the *Wenchuan* Earthquake and have suggested choosing multiple exposure indicators when validating the resilience to floods. Their study mentions direct economic losses per capita as the damage indicator and population growth, GDP growth as recovery indicators.

Many scholars have preferred the above-mentioned three-dimensional approach of disaster resilience due to its ability cover a broad spectrum of disaster resilience. Hence, for the purpose of identifying outcome indicators in this study, findings of the literature survey were summarised according to the above-mentioned three-dimensional approach (Table 6-1).

Table 6-1: Summary of proxies for validating disaster resilience

Dimension	**Indicators**	**Sources**
Exposure	Frequency of disaster declarations	(Bakkensen, et al., 2016)
	Flood intensity	(Li, et al., 2016)
Damage	Property damages, House damage	(Bakkensen, et al., 2016); (Parsons, et al., 2016); (Irajifar, et al., 2015)
	Fatalities	(Bakkensen, et al., 2016), 2016; (Parsons, et al., 2016)
	Direct economic losses per capita	(Li, et al., 2016)
Recovery	Reductions in psychological stress	(Bakkensen, et al., 2016)
	Infrastructure systems recovery (minimizing electrical losses, critical facilities, and lifelines, noncritical facilities and lifelines, transportation systems)	(Dwyer & Horney, 2014); (Bakkensen, et al., 2016); (Irajifar, et al., 2015)
	Economic recovery, GDP growth	(Bakkensen, et al., 2016)
	Housing recovery, Reconstruction of houses, Number of building permits	(Dwyer & Horney, 2014); (Irajifar, et al., 2015); (Li, et al., 2016)
	Population return, Population recovery, Population growth	(Irajifar, et al., 2015); (Li, et al., 2016)

Source: Author prepared based on literature survey

“The choice of outcomes to use for empirical validation must be grounded in theory. One logical choice is to use the stated objective of an index as a guide” (Bakkensen, et al., 2016, p. 16). As mentioned in the theoretical framework of this study, resilience is being measured with reference to a desirable regime of function. In this study, the desirable regime of function has been defined as the level that community is free from fatality and have not fallen to a status where they cannot fulfil the access to basic needs, particularly food, shelter, and clothing. Empirically, it’s challenging to define when people cross such hypothetical status. However, for the purpose of verification, in this study, the status that failure to withstand the desirable regime of function has been attributed to the point community become unable to fulfil the basic needs with their own resources. Similarly, bouncing back to the desirable regime of function has been attributed to the point when they reach back to the point that can fulfil basic needs with their own resources. Considering the conceptual background, the following outcome variables were selected to be utilized in verifying the proposed set of geospatial indicators (Table 6-2).

Table 6-2: The selected outcome variables for verifying disaster resilience

Dimension	Indicators	Unit of measurement	Description
Exposure	Exposure to Flood	Land area	Inundated area as a percentage of total land extent
Damage	Persistence	Time	Number of days that people could fulfil their basic needs, with their own resources, after the onset of flood
	Peak failure	Population	Maximum number of people temporarily failed to fulfil the basic needs with their own resources, after the onset of flood
Recovery	Recovery	Time	How long it took for people to become able to fulfil basic needs with their own resources after the maximum failure.

The next section discusses how to measure these outcome variables with reference to a given flood.

6.6. Developing the system performance curve-based proxy measures to verify community resilience

6.6.1. Literature survey on existing methods to quantify community resilience by system performance curve

"The earliest, and simplest, the concept of resilience in engineering is equivalent to elasticity; i.e., the elastic deformation capacity of an element that deforms and stores energy when subject to loads and, upon unloading and releasing the stored energy, returns to its original form. Over time, the concept has been augmented through systems thinking" (Wang & Blackmore, 2009). System performance curve is widely employed to explain the disaster resilient behaviour of socio-technical systems despites the limited attempts to apply in socio-ecological systems. The early works of Michel Bruneau (Bruneau, et al., 2003) has utilized the system performance curve to quantify resilience based on 'resilience triangle' (Wang & Blackmore, 2009); (Bocchini, et al., 2014). The concept of resilience triangle has been derived from the system performance curve as mentioned above and explains the variations of system functionality over time. The resilience triangle approximates the loss of resilience due to a given extreme event. Figure 6-1 shows a graphical interpretation of the resilience triangle along with the algebraic expression presented in Formula 6.1. as A comprehensive overview of these measures is provided by Bocchini et al. (ibid).

Figure 6-1 illustrates the system functionality over a period of time considering t_0 as the onset of shock and t_r the time when functionality restore to initial level. The shaded area indicates the resilience triangle which measures the linear approximation of the recovery function. "One leg measures the quantity (1–robustness’), which expresses the loss of functionality due to the extreme event and the second leg is the total recovery time. Its value also can be expressed in terms of rapidity, which is the average slope of the recovery path. Finally, the hypotenuse is the linear approximation of the functionality recovery path” (ibid).

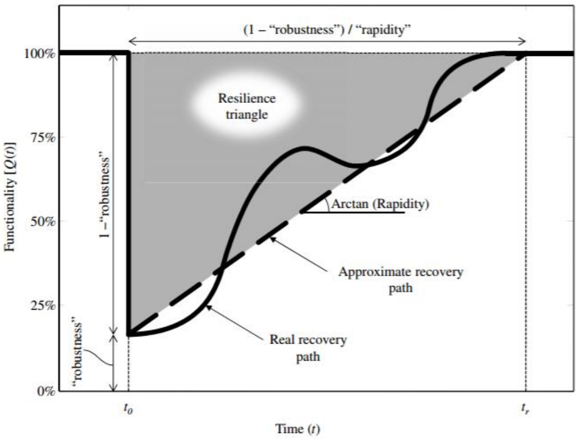


Figure 6-1: Resilience triangle[7]
Source: (Bocchini, et al., 2014)

A more accurate assessment that accounts for the actual shape of the recovery path of resilience has been developed by a group of scientists with reference to the structural resilience in earthquakes (Bruneau, 2006); (Bruneau & Reinhorn, 2007); (Bruneau, et al., 2005). Formula 6.1. algebraically expresses this measurement. The definition in Formula 6.1 connects the concepts of resilience and functionality analytically. (Bocchini & Frangopol, 2012).

$$R_L = \int_{t_o}^{t_r} [100 - Q(t)]dt \tag{6.1}$$

Where;

RL = the loss of resilience experienced by the system,
t_0 = the time instant when the extreme event occurs,
t_r = the time when the functionality of the system is fully restored,
Q = the percentage “functionality” (or performance) of the system,
t = time (ibid)

---

[7] “Resilience triangle (shaded area); at $t=t_0$ the external shock occurs, and $t=t_r$ the recovery is complete” (ibid)

Several analytical definitions of resilience have evolved from Formula 6.1 in the field of earthquake resilience and related applications in recent studies (Bocchini, et al., 2014); (Bocchini & Frangopol, 2013); (Wang & Blackmore, 2009).

Two research groups (Cimellaro, et al., 2010); (Bocchini & Frangopol, 2012) have independently developed Formula 6.2 in order to describe the area underneath of the recovery curve (refer figure 6-2).

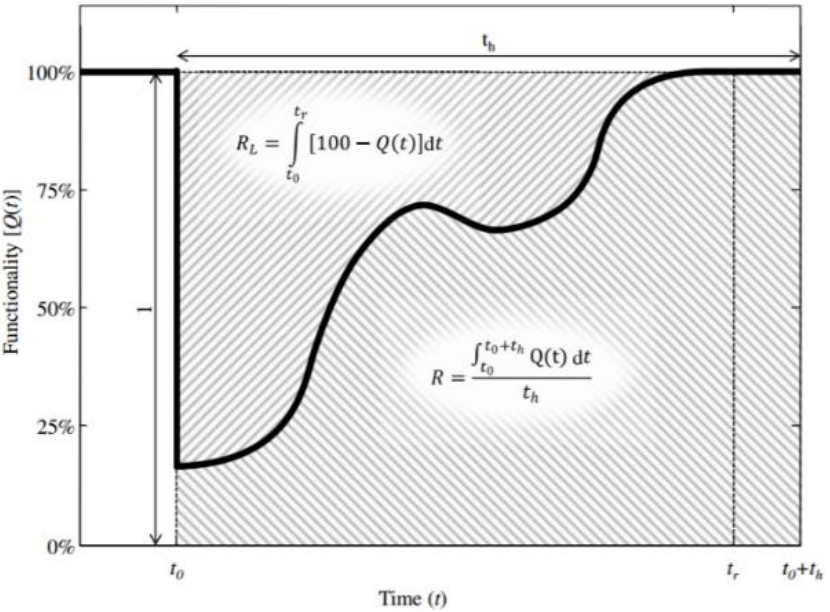


Figure 6-2: Resilience loss[8]
Source: (Bocchini, et al., 2014)

$$R \quad = \frac{\int_{t_o}^{t_0+t_h} Q(t)dt}{t_h} \tag{6.2}$$

Where;

R = resilience index

t_{he} = the time horizon investigated by the analysis (ibid)

---

[8] Resilience loss R_L as computed by formula 6.1 and resilience index R according to formula 6.2; the numerator of formula 6.2 is the underneath the recovery curve, and the denominator is the entire shaded area (with = t_h, height = 1) (Bocchini, et al., 2014)

"The numerator of Formula 6.2 represents the area underneath the recovery path Q(t); the denominator represents the value of resilience if the event did not occur or had no effects on functionality (i.e., $100\% \cdot t_h = t_h$). Formula 6.2 has the merit of combining all the dimensions, properties, and results of resilience in a single scalar metric defined over the interval [0,1]" (ibid).

The formula 6.1 has been further developed by a group of scientists with reference to the resilience of storm water drainage systems to flood (Mugume, et al, 2015). The latest work of Mugume et al has applied the mathematical function of indefinite integrals to quantify the resilience of storm water drainage systems against floods (Mugume, et al., 2015). The conceptual definition of resilience in Mugume et al's study has elaborated the absorption state with a slope which is closer to the behaviour of the real world system in floods.

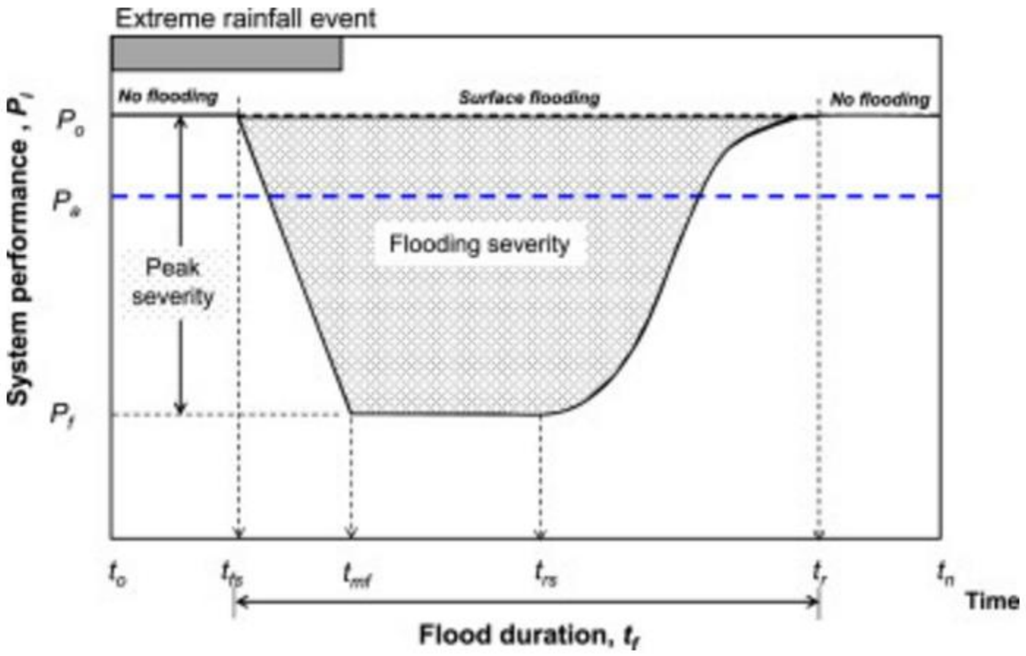


Figure 6-3: Flood severity measurement
Source: Mugume, et al, 2015

"The resulting loss of system functionality is estimated using the concept of *severity* (Hwang et al., 2015; Lansey, 2012). Severity is interpreted as a function of maximum failure magnitude (peak severity) and failure duration (Formula 6.3). In figure 6-3, severity can be estimated as the (shaded) area between the original system performance level, *Po* and the actual system performance curve, *Pi(t),* at any time *t* after occurrence of a given threat that leads to system failure" (ibid).

$$Sev_i = f[Sev_p, t_f] = \frac{1}{P_0}\int_{t_o}^{t_n}[P_0 - P_t(t)]dt \qquad (6.3)$$

This application has further improved the indefinite integrals-based function normalizing the resilience levels by actual system performance. This improvement facilitates the comparison of sub-systems regarding their resilience performances.

All of the above-mentioned studies have successfully quantified the resilience as an index that combines all resilience capacities into one measure. However, the decision of blending all different properties, actions, capacities into one has not been favourable for some applications (Bocchini, et al., 2014). Such combined measure has less utility to test the adequacy of indicators in representing different capacities of resilience. States of system performance curve represent distinct types of system behaviour such as plan and prepare to persist the perturbations, buffer the system degradation by absorbing shocks, recover the system following the learning and adaptation (Figure 6-4). Hence, this study attempted to derive a set of measurements from the system performance curve, corresponding to three resilience capacities concerned. The proposed measures have been principally derived from the interconnected concepts of Formula 6.1. and 6.3.

6.6.2. The proposed, system performance-based proxy measures

Persistence rate (Formula 6.4) measures the duration that the community system withstands the disturbances at least fulfilling the basic needs.

Persistence rate (P) of ith event

$$P_i = \frac{1}{Q_j}(t_f - t_0) \qquad (6.4)$$

Higher the persistent rate indicates a higher level of community resilience. Persistence rate primarily expresses community's preparedness as a result of long-term planning and adaptation. Hence, it partly captures the transformative capacity of a given system. In this study, the persistent rate has been measured by referring the ability that community can withstand floods without disrupting their basic needs.

The state when the community cannot persist further and compelled to seek external assistance to fulfil their basic needs is ‘t_{ds}’ where system starts degradation. When the degradation crosses the desirable regime of function ‘t_f’, occurs the system failure. Peak failure (Formula 6.5) and degradation rate (Formula 6.6) measured the magnitude of degradation.

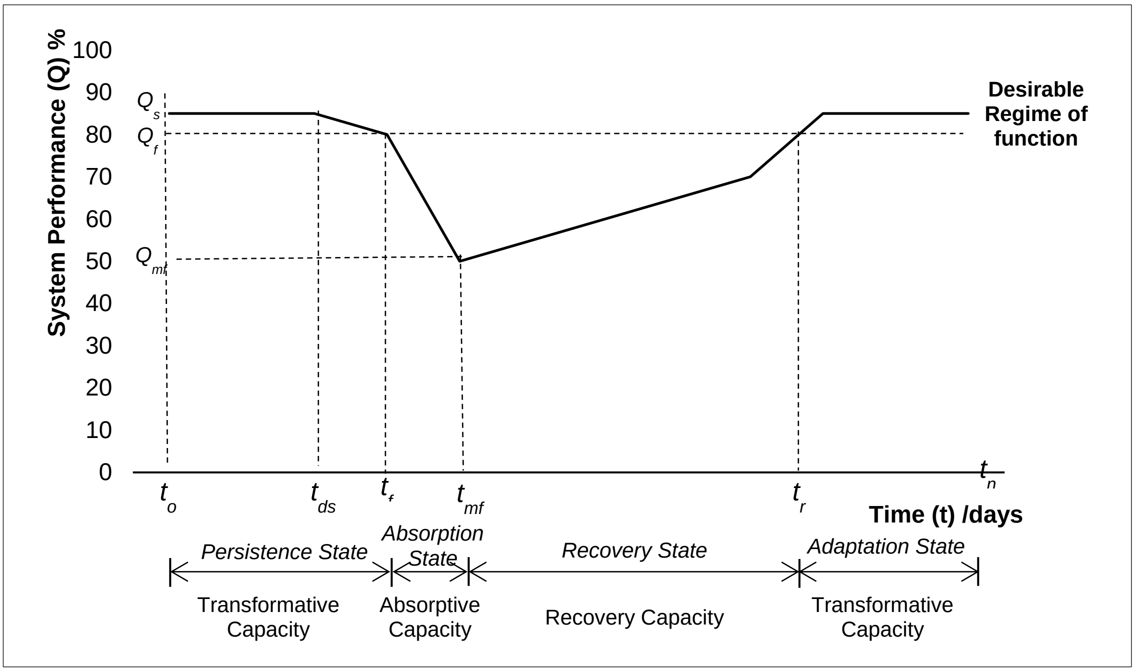


Figure 6-4: Conceptual system performance curve

Peak failure (F) of i^{th} event

$$F_i = \frac{1}{Q_j}(Q_s - Q_{mf}) \tag{6.5}$$

Degradation rate (B) of i^{th} event

$$B_i = \frac{1}{Q_j}\int_{t_f}^{t_{mf}}(100 - Q_i(t))\mathrm{d}t \tag{6.6}$$

Peak failure and degradation rate increases if the system cannot buffer floods by absorbing the shock. Hence, these two measures were attributed the absorption capacity of the system.

Recovery rate (Formula 6.7) measures the time taken to recovery considering the corresponding system performance at each point of recovery.

Recovery rate (R) of i^{th} event

$$R_i = \frac{1}{Q_j}\int_{t_{mf}}^{t_r}(100 - Q_i(t))\mathrm{d}t \tag{6.7}$$

Lesser the time taken to recover is better the recovery capacity of the system. Better the recovery capacity, higher the community resilience. In this study, the point system bounce off the desirable regime of function ‘t_r’ was attributed to the time when requires no more external assistance to fulfil their basic needs. Usually this the point when emergency relief calls off.

Accordingly, the persistent rate is theoretically plausible to have a direct relationship with community resilience whereas other three measures have an inverse relationship with community resilience.

6.7. Conclusion

In order to verify the proposed geospatial indicators, an independent set of proxies of resilience was required. For this purpose, the study developed four proxy measures to quantify the community resilience based on the population response data (i.e., people’s ability to fulfil the basic needs with their own resources, particularly after onset of a hazard) for a given flood event. The four proxies estimate resilience by system-performance correspondent to three resilience capacities.

Chapter – 7
Verification of geospatial indicators

7.1. Introduction

This chapter verifies the proposed set of geospatial indicators based on the flood event occurred in Colombo, Sri Lanka on May 2016. Downstream of the Kelani river basin is taken as the case study area that consists of 23 localities (N=23). The verification is twofold as first, test the association between resilience-evidenced and each geospatial indicator, and secondly, model the resilience by combining the verified geospatial indicators into a composite index.

7.2. Sub-objective

The sub-objective of the section is to verify the adequacy of geospatial indicators to assess the community resilience to floods in the context of Sri Lanka.

7.3. Methods and materials

7.3.1. Selection of Case Study

7.3.1.1.Colombo, Sri Lanka as the case study

Flood is the most frequent natural hazard in Sri Lanka. The low-pressure system occurred in the Indian Ocean on May 2016 caused torrential rainfall across Sri Lanka. Kelani basin, which is one of the main river basins in Sri Lanka, received 350 mm of total rainfall within three consecutive days from the 15th to 17th of May 2016. Flood was 6–12 feet in height, and the damage was recorded as the highest number of the flood-affected population over last six decades. (DMC, 2016). Per the situation report issued by Disaster Management Centre of Sri Lanka, over 200,000 people who reside in Colombo were affected by this flood (DMC, 2016). Property and livelihood losses were also significant because Colombo is the national capital that hubs commercial and economic infrastructure. Furthermore, the long-term trends also indicate a clear rise in the number of flood-affected population in Colombo over last 25 years (Figure 7-1).

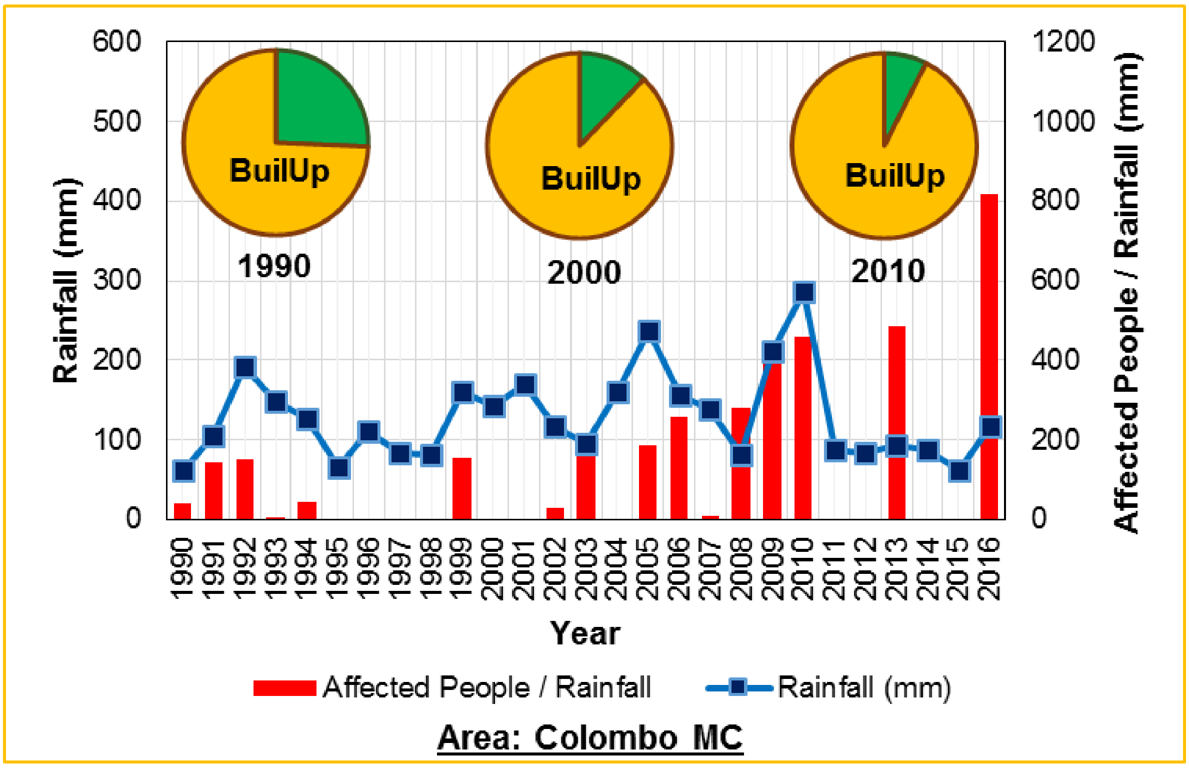


Figure 7-1: Increase of flood affected population in Colombo

This study was conducted in the lower drainage basin of the Kelani River including 23 DS Divisions that belong to the CMR, Sri Lanka. The Divisional Secretariat (DS) division is a local-government level, administrative unit in Sri Lanka, and there are 329 DS divisions in the country.

Figure 7-2 shows the selected study area including 23 DS divisions. People residing in 20 DS divisions were evacuated to 140 nearby welfare canters during the flood. The remaining three DS divisions (*Moratuwa*, *Dehiwala*, and *Ja-Ela*) had no people evacuated primarily because flood height has been lower due to elevation, and exposure was limited to a small percent of the area.

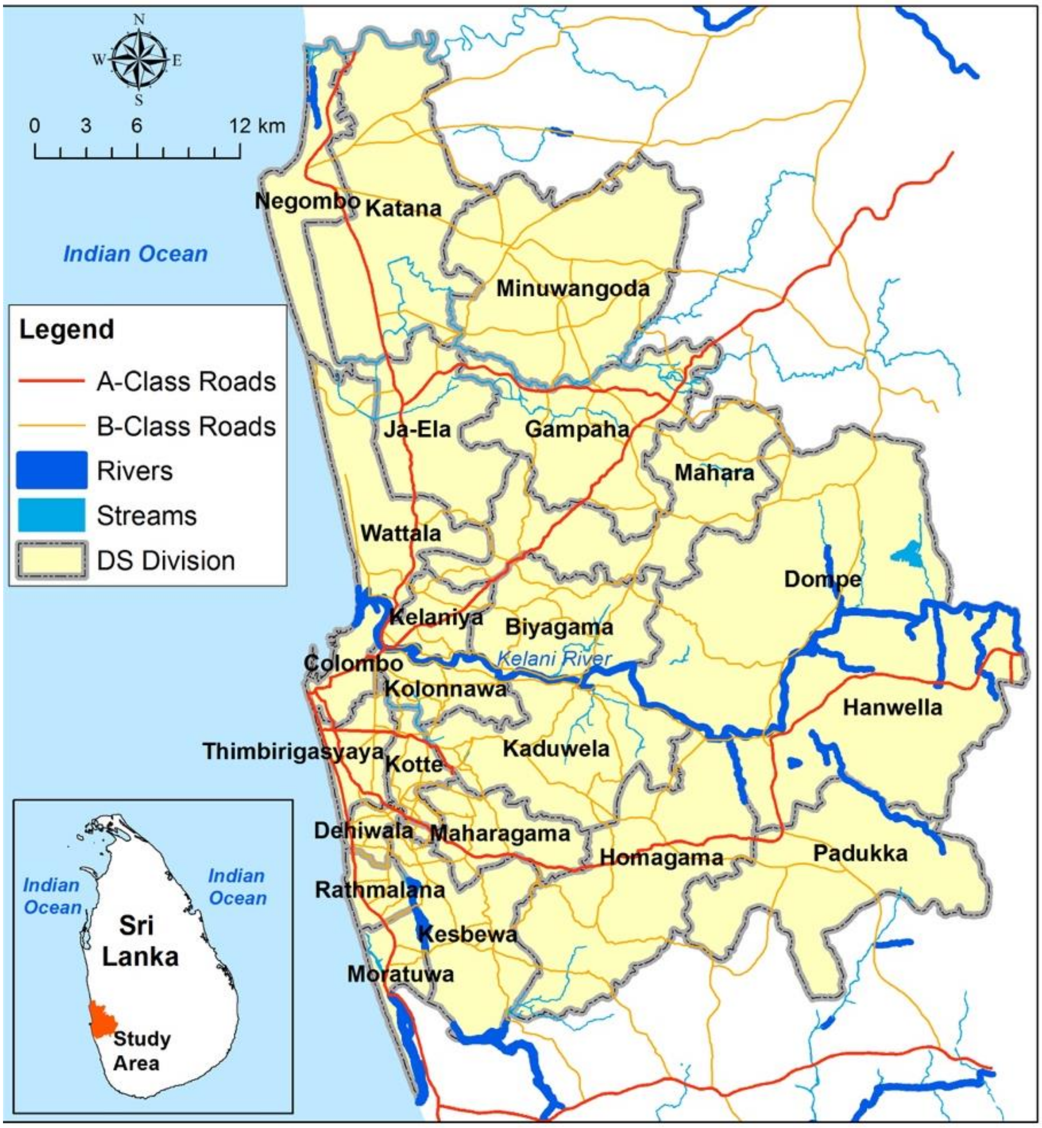


Figure 7-2: Map of study area- Colombo, Sri Lanka

7.3.2. Data acquisition

Table 7-1 and 7-2 contain the information about data acquisition for computing geospatial indicators for the case study area.

Table 7-1: Data requirement of the selected geospatial indicators

ID	Indicator	Data (code) *
1	Percent land area that is a wetland, swamp, marsh and mangrove	A
2	Rapid urban population growth (Percentage increase of urban population density)	G, B
3	Percent deep permeable soil per ward	E, J
4	Percent fire, police, emergency relief services, and temporary shelters outside of hazard zones	A, F
5	Percent of building infrastructure, not in Flood Inundation zones	A, F
6	Percent of government offices outside of flood inundation zones	A, F
7	Percent of commercial establishments outside of high hazard zones (flood, surge)	A, F
8	Population living in high-intensity urban areas/ population density	A, G
9	Percent land area that does not contain erodible soils	C, E
10	Percent land area not in an inundation zone (100 years)	E
11	Percent land area that does not contain impervious surfaces	A, I
12	Percent land area with no forest and rangeland decline	A
13	Percent land area with no wetland decline	A
14	Percent area that has changed into urban areas (by urban classification)	A, B, H
15	Percent land area that is high-intensity urban development (80% or more impervious surface)	A, I
16	Percent land area of developed open spaces	A
17	Principal arterial miles	A
18	Hospitals per square mile	A
19	Schools (primary and secondary education) per square mile	A
20	Hotels and motels per square mile	A
21	Density of commercial infrastructure	A
22	Number of river miles	A
23	Percent erodible soil per ward	J, E
24	Land use diversity (Proportion of land use categories per ward, multiplied by the natural logarithm. The resulting product is summed across wards, and multiplied by −1)	A
25	Wetland diversity (Proportion of flood attenuating wetlands per ward, multiplied by the natural logarithm. The resulting product is summed across wards, and multiplied by −1)	A
26	Rapid urban growth (Percentage land cover change to urban areas from base year)	A, B
27	Waterbodies density (Waterbody area/total land area)	A
28	Access to hospital (Inverse of Euclidean distance to the hospitals)	A
29	Movement potential (Inverse of Euclidian distance to road network)	A

Notes

* Refer Table 7-2 for details

Table 7-2: Data acquisition for computing geospatial indicators

Data type	**Code***	**Description**	**Year**	**Spatial scale**	**Source$^{\#}$**
Map data	A	Land use map	2014	1: 5000	Urban Transport System Development Project, Japan International Cooperation Agency, Japan
	B	Topographic map	1984	1: 50000	Survey Department, Sri Lanka
	C	Contour map	2012	1: 5000	Tsunami hazard map database, Coast Conservation, and Resource Management Department
	D	Rainfall Isohyets	2007	1: 10000	National Atlas, Survey Department of Sri Lanka
	E	Soil map	2007	1: 10000	National Atlas, Survey Department of Sri Lanka
	F	Flood inundation map	2016	1: 30,000	Disaster management centre, Sri Lanka
Tabular data	H	Population	2012	GN Division	Population census, 2012, Department of Census and Statistics, Sri Lanka
Classifications	I	Land use classification	2013	National	Colombo Development plan, 2013, Urban Development Authority, Sri Lanka
	J	Floor Area Ratio by Land use	2013	Regional	Colombo Development plan, 2013, Urban Development Authority, Sri Lanka
	K	Soil hydraulic properties by soil type	1961	National	The national soil survey published in Soil of Ceylon, 1961, Moormann, F.R and Panabokke, C.R., 1961
Experts' Opinion	M	Experts opinion on land use specific variations of FES (Likert scale 1-9 values)	2016	Regional, Sample survey (n=10)	A questionnaire survey processed by AHP method

Notes
* ID to link Table 7-1

7.3.3. Preparation of System Performance Curves for 23 DS divisions

Verification of indicators requires an independent set of outcome variables to surrogate community resilience. As mentioned in the chapter 6, community resilience is not a directly observable phenomenon. In order to overcome this inherent limitation practically, many studies have proposed to observe community resilience through the empirical evidence of population, housing, and infrastructure system responses to hazards. Theoretically, resilience is measured concerning a desirable regime of function. Empirically, it is challenging to define when people cross such hypothetical status. In this study, the desirable regime of function has been referred to as the status that community has not been fallen into a situation that they cannot fulfill the basic needs. Accordingly, the desirable regime of function was attributed to the community's ability to survive without obtaining external assistance for food, shelter, and clothing. Hence, the status that the community fails to withstand the desirable regime of function was related to the situation of temporarily falling into welfare centres because of the flood. Similarly, bouncing off to the desirable regime of function was attributed to the situation of leaving the welfare centre.

The number of population that stayed overnight in welfare centres was considered as the outcome variable. This includes people who self-evacuated in-advanced and those who were rescued during the flood. Daily data on the number of people that stayed overnight in welfare centers during the flood that occurred in May 2016 were initially collected from the Disaster Management Centre, Sri Lanka. However, the data was not available for all consecutive days. Hence, the missing data was obtained by interviewing the disaster management officers in 23 DS divisions. The data was plotted into a system performance curve where 'number of people that stayed overnight in welfare centres' indicates the performance of community resilience to the flood event over a period. Onset date of the flood was the 15th of May, and the residential population of each DS division was given as the initial performance level of the system. The time when no people remained in welfare centres were considered as the point which the system returned to the desirable regime of function.

In this study, individuals seek for minor assistance (i.e., food and clothing) was attributed to the point 't_{ds}' and community seeks major assistance (i.e., shelter at welfare centres) was attributed to the point 't_f'. However, data collection was limited to the number of people seeks shelter at welfare centres. Therefore, 't_{ds}' was taken as equals to 't_f' and 'Q_s' (i.e., initial performance of the system) as equal to 'Q_f' (i.e., system performance at the desirable regime of function.

In all four measures, the resilience has been normalized by population and the inundation area. The normalization facilitates the comparison by adjusting the differences of population size and percent area inundated among various localities to a notionally common scale. Hence, it indicates how a community system performs in flood irrespective of the effect of the size of population and inundation area. Normalizing by land area helps to reduce the Marginal Area Unit Problem (MAUP) that could arise due to comparing two spatial variables.

Accordingly, formulae 6.4 to 6.7 presented in chapter 6 has been modified as follows.

1. Persistence rate (P) of ith event

$$P_i = \frac{1}{P_j A_j}(t_f - t_0 \tag{7.1}$$

2. Peak failure (F) of ith event

$$F_i = \frac{1}{P_j A_j}(Q_s - Q_{mf}) \tag{7.2}$$

3. Degradation rate (B) of ith event

$$B_i = \frac{1}{P_j A_j}\int_{t_f}^{t_{mf}}(100 - Q_i(t))\mathrm{d}t \tag{7.3}$$

4. Recovery rate (R) of ith event

$$R_i = \frac{1}{P_j A_j}\int_{t_{mf}}^{t_r}(100 - Q_i(t))\mathrm{d}t \tag{7.4}$$

Where,

P_j = Total population of jth locality (DS Division)

A_j = Percentage inundated area (A) of jth locality (DS Division)

$$A_j = \frac{FI_j}{L_j} \times 100 \tag{7.5}$$

Where, FI is flood inundated built-up are, and L is the total land extent of jth locality (DS Division).

7.3.4. Framework of Analysis

First, this study computed the resilience level of 23 DS divisions by 30 geospatial indicators separately. Computation followed the methods as described in originals literature and geospatial analysis were performed by using a GIS software. Secondly, the study plotted the system performance curves of each DS Division with affected population data. Persistence rate, peak failure, degradation rate and recovery rate[9] were computed for each of the DS divisions based on system performance curves. Thirdly, the study tested the statistical association between geospatial indicators and system-performance measures. Association was tested by spearmen's correlation coefficient because the results of the normality test of many indicators revealed a free-distribution with several outliers. A two-tailed test was conducted due to the difference in directions. In interpreting the results, Spearman rank-order correlation coefficient (r_s) value equal or above 0.7 was considered a strong association and equal or above 0.5 was considered a moderate association. Coefficients (r_s) at confidence interval 0.01 were considered significant, and 0.05 were considered moderately significant.

The study anticipates the selected-geospatial indicators to have a direct association with persistence rate and inverse association with restoration rate and degradation rate. On the basis of these theoretically-plausible inferences, the association of three outcome variables with 30 geospatial indicators were statistically tested. The selected set of indicators comprised with continuous variables, mostly ratio and few interval variables. Pearson's coefficient (r), Spearman's rho coefficient (r_s), and Kendall's tau coefficient (τ) are the most popular indices can measure the strength of an association between two continuous variables (Hauke & Zkossowski, 2011). Pearson's coefficient is a parametric test with an assumption of normal distribution of variables whereas Spearman's rho coefficient and Kendall's tau coefficient are distribution-free, non-parametric tests. Further, Pearson's coefficient assumes a linier relationship between two variables whereas Spearman's rho coefficient and Kendall's tau coefficient assume a monotone relationship. Normality tests such as Kolmogorov-Smirnov Test and the Shapiro-Wilk Test and quantile-quantile (QQ) plots are employed to pre-test the distribution and mutuality. This study employed Shapiro-Wilk Test, QQ plots and many of the variables were found to be freely distributed with presence of several outliers[10]. Therefore, Spearman's rho coefficient and Kendall's tau coefficient association are more appropriate to test the association between the given variables. "Properties and comparisons of Ken-dall's τ and Spearman's r_s have been analysed by many researchers and they are still under investigation

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[9] Trapezoidal rule, which is a technique for approximating the definite integral, was employed in estimating recovery rate and degradation rate.

[10] "The null hypothesis for this test is that the data are normally distributed. The Prob < W value listed in the output is the p-value. If the chosen alpha level is 0.05 and the p-value is less than 0.05, then the null hypothesis that the data are normally distributed is rejected. If the p-value is greater than 0.05, then the null hypothesis is not rejected" (Hauke & Zkossowski, 2011).

(see e.g. Valz & Thompson 1994, Xu et al. 2010)", hence, many authors opt for Spearman's coefficient for ranks correlation (Hauke and Zkossowski, 2011). Considering the above points, this study selected Spearman's rho coefficient to test the association between community resilience outcome variables and 30 geospatial indicators.

Statistical analyses were performed in SPSS statistics 20.1 software package (N=23). This includes 23 flooded areas within CMR. Out of 23 flooded areas, people have not been evacuated to safe shelters in three areas. This is mostly because either the flood damage is limited to some non-residential areas or the flood height is manageable to stay in part of the house. A two-tailed test was conducted due to the difference in directions.

Interpretation of the strength of r_s is context specific, and this study referred to rule of thumb for interpreting the strength correlation coefficient given in Table 7-3. (Hinkle, et al., 2003).

Table 7-3: Rule of Thumb for interpreting the strength of a Correlation Coefficient

Size of Correlation	**Interpretation**
.90 to 1.00 (−.90 to −1.00)	Very high positive (negative) correlation
.70 to .90 (−.70 to −.90)	High positive (negative) correlation
.50 to .70 (−.50 to −.70)	Moderate positive (negative) correlation
.30 to .50 (−.30 to −.50)	Low positive (negative) correlation
.00 to .30 (.00 to −.30)	Negligible/No correlation

Source: Mukaka, 2012 A guide to appropriate use of Correlation coefficient in medical research,

In selecting the most significant indictors at each state, Spearman rank-order correlation coefficient (r_s) value equal or above 0.7 was considered as a strong relationship, and equal or above 0.5 was considered as a moderate relationship. r_s at confidence interval 0.01 was considered as significant and r_s at confidence interval 0.05 was considered as moderately significant.

7.4. Results and discussion

7.4.1. Association of geospatial indicators to community resilience

Geospatial indicators that revealed an association with at least one of the system-performance measures were considered as valid for community resilience assessments. In overall, out of 30 geospatial indicators, 14 showed either significant or moderately significant correlation. (Table 7-4).

Table 7-4: Geospatial indicators revealed a significant association with outcome variable/s

	Indicator		**Degradation rate**	**Peak failure**	**Recovery rate**	**Persistent rate**
1	Percent land area that is a wetland, swamp, marsh and mangrove	r_s	$.617^{**}$	$.694^{**}$	$.669^{**}$	
		Sig.	.006	.001	.002	
8	Population living in high intensity urban areas/ population density	r_s	$.569^{*}$	$.647^{**}$	$.583^{*}$	
		Sig.	.014	.004	.011	
10	Percent land area not in an inundation zone (100 years)	r_s	$.461^{*}$			$.537^{**}$
		Sig.	.031			.008
14	Percent area that has changed into urban areas	r_s				$-.742^{**}$
		Sig.				.000
16	Percentage land area of developed open spaces	r_s	$.562^{*}$	$.520^{*}$	$.713^{**}$	$.570^{*}$
		Sig.	.015	.027	.001	.011
18	Hospitals per square mile	r_s			$.478^{*}$	$.678^{**}$
		Sig.			.045	.001
19	Schools (primary and secondary education) per square mile	r_s				$.779^{**}$
		Sig.				.000
20	Hotels and motels per square mile	r_s	$.469^{*}$		$.525^{*}$	$.577^{**}$
		Sig.	.050		.025	.010
21	Density of commercial infrastructure	r_s	$.474^{*}$	$.491^{*}$	$.490^{*}$	
			.047	.039	.039	
26	Rapid urban growth (Percent land cover change to urban areas from base year)	r_s	$.791^{**}$	$.765^{**}$	$.865^{**}$	
		Sig.	.000	.000	.000	
27	Waterbodies density	r_s	$.702^{**}$	$.686^{**}$	$.709^{**}$	
		Sig.	.001	.002	.001	
28	Access to hospital	r_s	$.660^{**}$	$.557^{**}$	$.644^{**}$	$.561^{**}$
		Sig.	.001	.007	.002	.005
29	Movement Potential	r_s	$.526^{*}$	$.453^{*}$	$.584^{**}$	$.699^{**}$
		Sig.	.012	.034	.005	.000
30	FES Composite Indicator	r_s	-.032	-.103	-.179	$-.783^{**}$
		Sig.	.889	.649	.437	.000

** Correlation is significant at the 0.01 level (2-tailed)

‘Rapid urban growth’ recorded the highest correlation with degradation rate (r_s =0.791, p-value < 0.000), peak failure (r_s =0.765, p-value < 0.000) and recovery rate (r_s =0.865, P= 0.000).

‘Schools (primary and secondary education) per square mile’ recorded the highest correlation (r_s =0.779, p-value < 0.000) with persistence rate. Rapid urban growth concentrates built-up areas agglomerating buildings, infrastructure, and human activities. Inundation of such intensively urbanized locations can result in catastrophic failures due to many elements-at-risk within the system. Furthermore, rapid urban growth disrupts natural flood defence mechanisms of socio-ecological systems. For example, conversion of agricultural and other vegetative land uses into build-up areas reduces the infiltration, evaporation and increase the surface runoff, thereby weakening the absorptive capacity. Moreover, reclamation of water retention areas for urban development, as in the case of Colombo, reduces the water retention and detention of ecosystems perturbing the recovery process. The second most associated indicator is ‘schools per square mile.' The school is a community infrastructure which can be considered to represent the community’s social well-being. Community systems that have access to education and social well-being are resourceful to anticipate floods, plan in advance, and withstand disturbances. Per the above reasoning, initial results indicate that geospatial indicators can meaningfully detect the environmental and physical influences over community resilience.

7.4.2. Ambiguity in the direction of association concerning the states of resilience

As Table 5-1 shows, existing literature has mentioned a possible direction when interpreting the influence of each spatial indicator on community resilience. Positive direction refers to a status where the given indicator has a direct relationship with community resilience, and negative direction refers to inverse relationships. Results of this study revealed an ambiguity in the direction of six indicators when testing with different system-performance measures (Table 7-5).

All six indicators are theoretically presumed to have a positive relationship with community resilience. As presumed, all of them revealed a positive association with the persistence rate. Nevertheless, this set of indicators also revealed a positive association with degradation rate, peak failure and recovery rate. Positive association with persistence rate indicates higher community resilience, whereas the positive association with other three measures indicates lower community resilience.

Table 7-5: Ambiguity of Indicators

Indicator			Degradation rate	Peak failure	Recovery rate	Persistence rate
10	Percent land area not in an inundation zone (100 years)	r_s	.461*			.537**
		Sig.	.031			.008
16	Percent land area of developed open spaces	r_s	.562*	.520*	.713**	.570*
		p	.015	.027	.001	.011
18	Hospitals per square mile	r_s			.478*	.678**
		Sig.			.045	.001
20	Hotels and motels per square mile	r_s	.469*		.525*	.577**
		p	.050		.025	.010
28	Access to hospital	r_s	.660**	.557**	.644**	.561**
		p	.001	.007	.002	.005
29	Movement Potential	r_s	.526*	.453*	.584**	.699**
		p	.012	.034	.005	.000

In the cases of ‘percent land area not in an inundation zone', ‘hotels and motels per square mile' and ‘hospital per square mile', the degree of ambiguity is not severe. The association with persistence rate is moderately strong and highly significant, whereas the association with other measures are weak and less significant. Therefore, these indicators can be considered as maintaining a direct association with community resilience despite the minor internal inconsistency.

Percent land area of developed open spaces is often considered as a spatial feature indicating the urban resilience. Relative to other urban land uses, open areas infiltrate more, evaporate more and thereby runoff less. In case of Colombo, ‘percent land area of developed open spaces’ have revealed stronger and more significant association with recovery rate than the persistence rate. Detailed observations on Colombo case study noticed two possibilities that might have influenced the results. First, many of these developed open spaces are located within the floodplain of the Kelani River. Floodplains lay at lower elevations closer to water bodies and are often subjected to higher flood heights. Soil hydraulic properties of flood plains facilitate water retention and detention holding for a longer time. On the above ground, it is logical for any land use on the floodplain to take a longer time to recover. Secondly, some parts of the flood plain in Colombo are highly densified, including the vicinity of the developed open spaces. High-density development in floodplains increases the magnitude of damage making it difficult to recover once degraded. To support this reasoning, the study tested the relationship of percent land area of developed open spaces with elevation (r_s = -0.675, p-value < 0.000) and the population living in high-intensity urban areas (r_s = 0.846, p-value < 0.000). Accordingly, the ambiguity of this indicator can be interpreted as a result of multicollinearity with indicators that have inverse associations. Therefore, employing this indicator for assessing community resilience requires caution regarding the location and vicinity of such open spaces.

The real challenge of ambiguity could be noticed in ‘access to hospital’ and ‘movement potential', because these two indicators revealed highly significant associations to both directions. There is a similarity between them regarding constituents. Access to hospitals is based on Euclidian distance to hospitals, and movement potential is based on Euclidian distance to roads. The correlation between these two indicators is also highly significant and strong (r_s = 0.949, p-value < 0.000). However, there is no clarity as to whether such indicators represent resilience communities or non-resilient communities. Therefore, these two indicators should be avoided in resilience assessments despite the significant association. Overall, ambiguous indicators require further investigations to elaborate them with causal relations, primarily because ambiguity can threaten the internal validity of resilience assessment.

7.4.3. Geospatial indicators by the resilience capacities

The study investigates the adequacy of geospatial indicators for assessing distinct capacities of community resilience. As mentioned previously, four system-performance measures were attributed to three capacities such as persistent rate to transformative capacity, the inverse of recovery rate to recovery capacity, and inverse values of peak failure and degradation rate to absorptive capacity. The association of geospatial indicators with four system-performance measures infers their ability to represent the corresponding resilience capacities.

This study tested the association of 30 geospatial indicators with community resilience to floods. Some indicators were only associated with one capacity, while some of the others were only associated with either two or all three capacities. The Venn diagram provided in Figure 7-3 illustrates the coherent relationships of all indicators with three resilience capacities. Accordingly, three overlapping sets in the Venn diagram represent three capacities of resilience. Each set contain indicators that reveal significant ($p < 0.05$) associations with the corresponding system-performance measures. Indicators which are ambiguous concerning the direction to different resilience capacities have been underlined in the Venn diagram.

Three overlapping sets in the Venn diagram illustrates how geospatial indicators are associated with resilience capacities. 30 items in the Venn diagram represent the set of geospatial indicators tested in this study. Set ‘A’ refers to the absorptive capacity, set ‘R’ refers to the recovery capacity and set ‘T’ refers to the transformative capacity.

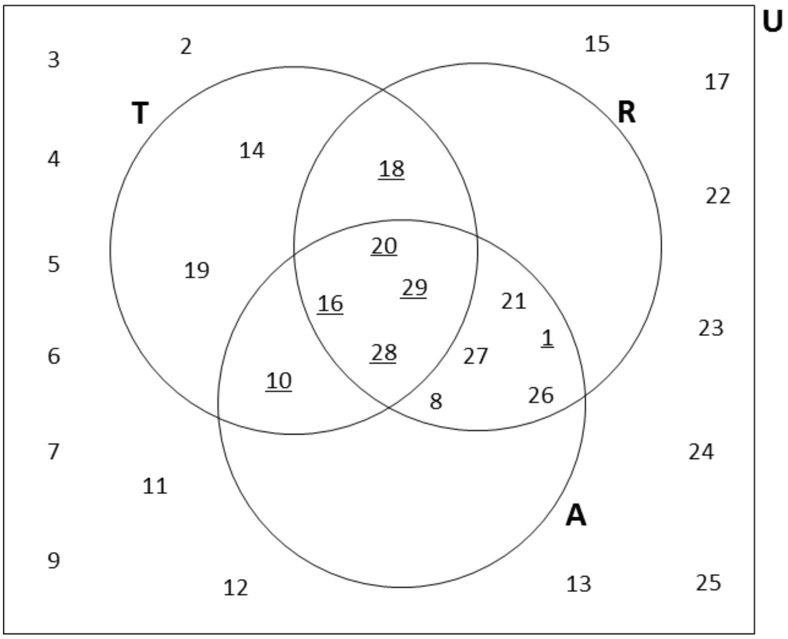

Figure 7-3: Relationships of indicators with resilience capacities

Followings are the detailed Inferences of the Venn diagram.

A = {1, 8, 10, 16, 20, 21, 26, 27, 28, 29}
R = {1, 8, 18, 16, 20, 21, 26, 27, 28, 29}
T = {14, 18, 19, 16, 20, 28, 29, 30}
(A∩R∩T) = {16, 20, 28, 29}
(T/ (A∪R) ′ = {14, 19}
(T∪A∪R) = {1,8,10,14,16,18,19,20,21,26,27,28,29,30}
(T∪A∪R) ′ = {2, 3, 4, 5, 6, 7, 9, 11, 12, 13, 15, 17, 22, 23, 24, 25}

Sets of absorptive capacity (A) and recovery capacity (R) contain ten indicators each following the nine indicators in the set of transformative capacity (T). Overall, geospatial indicators can represent all three resilience capacities. When comparing the relative component zones by capacities, only transformative capacity (T/ (A ∪ R) ′) contains indicators. ‘Schools (primary and secondary education) per square mile’ (r_s = 0.783, p=0.000) and ‘percent areas that has changed into urban’ ($r_s = -.742^{**}$, p=0.000) are uniquely to transformative capacity. In contrast, the unique indicators of other two capacities could not be distinguished.

If an indicator can represent all three capacities well, such indicators are better options for incorporating into assessment tools. If so, the assessment can perform efficiently with fewer data. However, any of the common indicators ($A \cap R \cap T$) cannot be confidently recommended due to ambiguity. Four indicators revealed non-ambiguous, significant associations with recovery and absorptive capacities. Rapid urban growth ($r_s = 0.791$, $r_s = 0.765$, $r_s = 0.865$ at $P < 0.01$) and water bodies density ($r_s = 0.702$, $r_s = 0.686$, $r_s = 0.709$ at $P < 0.02$) strongly and significantly associated with degradation rate, peak failure and recovery rate. 'Population living in high intensity urban areas' ($r_s = 0.569$, $r_s = 0.647$, $r_s = 0.583$ at $P < 0.01$) and 'density of commercial infrastructure' ($r_s = 0.474$, $r_s = 0.491$, $r_s = 0.490$ at $P < 0.05$) revealed moderate associations with the above. These four geospatial inidcators well capture how high urban density, which is due to the unplanned development in the case of Colombo, weakens community resilience making severe degradations and time-consuming restorations.

There were 14 indicators ($T \cup A \cup R$) that revealed significant associations with at least one resilience capacity. The rest of the 16 indicators has revealed no significant association ($(T \cup A \cup R)'$). However, this verification test is not capable enough to nullify the utility of these indicators, primarily due to the limited scope of transformative capacity. The study tested the transformative capacity by persistence state of the system performance curve (Figure 6-4). The persistent state covers only part of transformative capacity, and the rest must be tested with the adaptation state. The study could not test the long-term adaptation due to data constraints. Therefore, at least some of these indicators ($(T \cup A \cup R)'$) might show an association with the adaptation state.

Nevertheless, future studies can further verify the results mainly with three advancements. First, these findings are based on one critical flood event; therefore, the validity must be generalized after testing a series of flood events at different magnitudes. Secondly, the scope of the outcome variables in this study are limited to the function of fulfilling the basic needs, but the overall resilience of community can be captured by observing the other functions community systems and the other elements such as infrastructure resilience. Thirdly, several geospatial indicators could not be tested because the study area is an urbanized region where some land uses including forests, grasslands, and rangelands were not presented within the study area. Therefore, an expanded region including broader peripheries or agricultural region can further verify geospatial indicators.

7.4.4. Composite geospatial indicator to measure community resilience

The purpose of the composite geospatial indicator is to model the community resilience in a given locality. Spearmen's bi-variate correlation has revealed the associations of each geospatial indicator to the outcome variables of community resilience. Indicators those statistically significant and non-ambiguous were selected for performing regression analysis to test the predictability of geospatial indicators. For regression analysis, eight geospatial indicators were given as independent variables and the resilience-evidenced [as per the given flood incidence in Colombo] as the dependent variable. In order to formulate the resilience-evidenced indicator, the study utilized three performance-based outcome variables corresponding to three states of resilience. Then 20 DS divisions[11] were ranked[12] as per performance-based outcome variables. In The dependent variable was derived from the following formula (formula 7.1).

$$ER_i = R_i D_i / P_i \tag{7.1}$$

Where,
ER = Resilience-evidenced
R = The rank of ith DS division per recovery rate
D = The rank of ith DS division per degradation rate
P = The rank of ith DS division per persistence rate

As the dependent variable has been standardized, eight geospatial indicators were also assigned fractional ranks per cent[13]. Table 7-6 provides the summary of the overall fit statistics of the multiple linear regression model.

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[11] Initially 23 DS divisions were considered in the study. 3 division were excluded in this analysis because in these areas no people have been stayed in welfare centers overnight.
[12] Fractional ranks as per cent
[13] Each rank is divided by the number of cases with valid values and multiplied by 100

Table 7-6: Summary of the regression model

R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
				R Square Change	F Change	df1	df2	Sig. F Change
0.961	0.924	0.863	10.99	0.92	15.21	8	10	0.000

The composite geospatial indicator explains 86% of the variance in the data (adjusted r-squared = 0.863 at sig. F change = 0.000).

As the predictors have already standardized, unstandardized Beta weights which express the relative importance of independent variables were used in the linear regression function (Table 7-7). All indicators were statistically significant (sig. < 0.01) and multi-collinearity values were acceptable (VIF > 7).

Table 7-7: Coefficients of the regression model

Model	Unstandardized Coefficients		T	Significance	Collinearity Statistics
	B	Standard Error			VIF
(Constant)	63.733	29.845	2.13	0.058	
Percent population living in high intensity urban area	-0.786	0.171	-4.605	0.001	3.81
Percent land that has changed into urban areas	-.014	0.226	-0.062	0.002	6.70
Schools per square mile	0.429	0.211	2.031	0.007	5.84
Density of Commercial infrastructure	0.119	0.139	0.858	0.003	2.53
Waterbodies density	-0.405	0.122	-3.330	0.008	1.94
Rapid urban growth	0.527	0.115	4.571	0.001	1.46
Flood-resilience-supportive ESs (FES)	0.147	0.112	1.311	0.002	1.71
Hospitals per square mile	0.607	0.186	3.265	0.008	4.53

Note: ‘resilience-evidenced’ is the dependent variable; N=20

Based on the linear regression function, resilience levels of 20 DS divisions were estimated (Figure 7-4). Accordingly, *Colombo, Thimbiri. (Thimbirigasyaya), Kolonnawa* and *SJK* (*Sri Jayawardenepura Kotte*) shows the lowest resilience levels. Overall, Colombo-core area has lower resilience levels whereas peripheral; suburbs has relatively higher resilience levels.

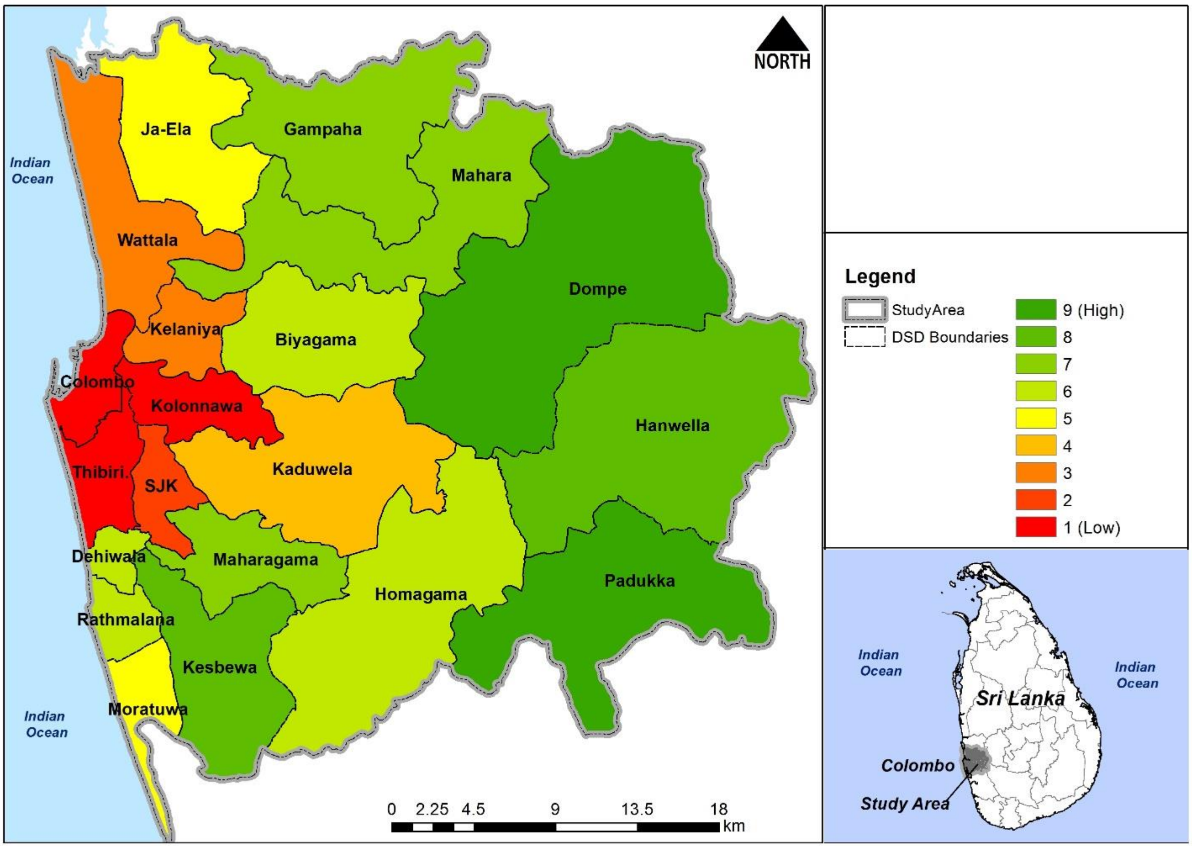

Figure 7-4: Estimated resilience levels by DS division

Scattergram given in figure 7-5 shows the distribution of the fractional ranks of the level of resilience-evidenced and estimated resilience level. Plotted values are distributed closely to the best-fit line indicating strong predictability of the model.

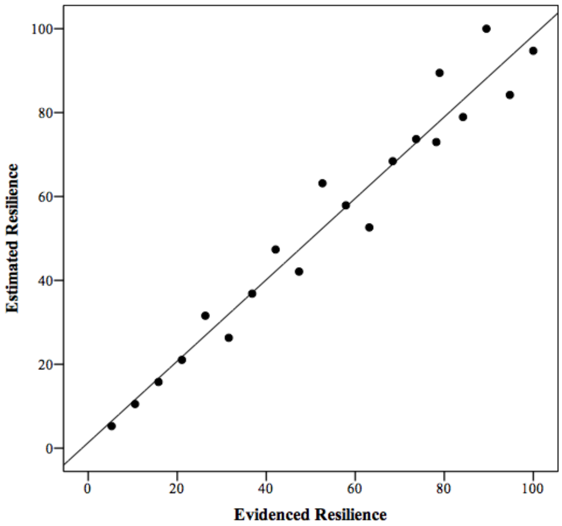

Figure 7-5: Resilience-estimated vs. resilience-evidenced

Figure 7-6 depicts the modelled resilience levels of the study area produced by geographically weighted regression analysis.

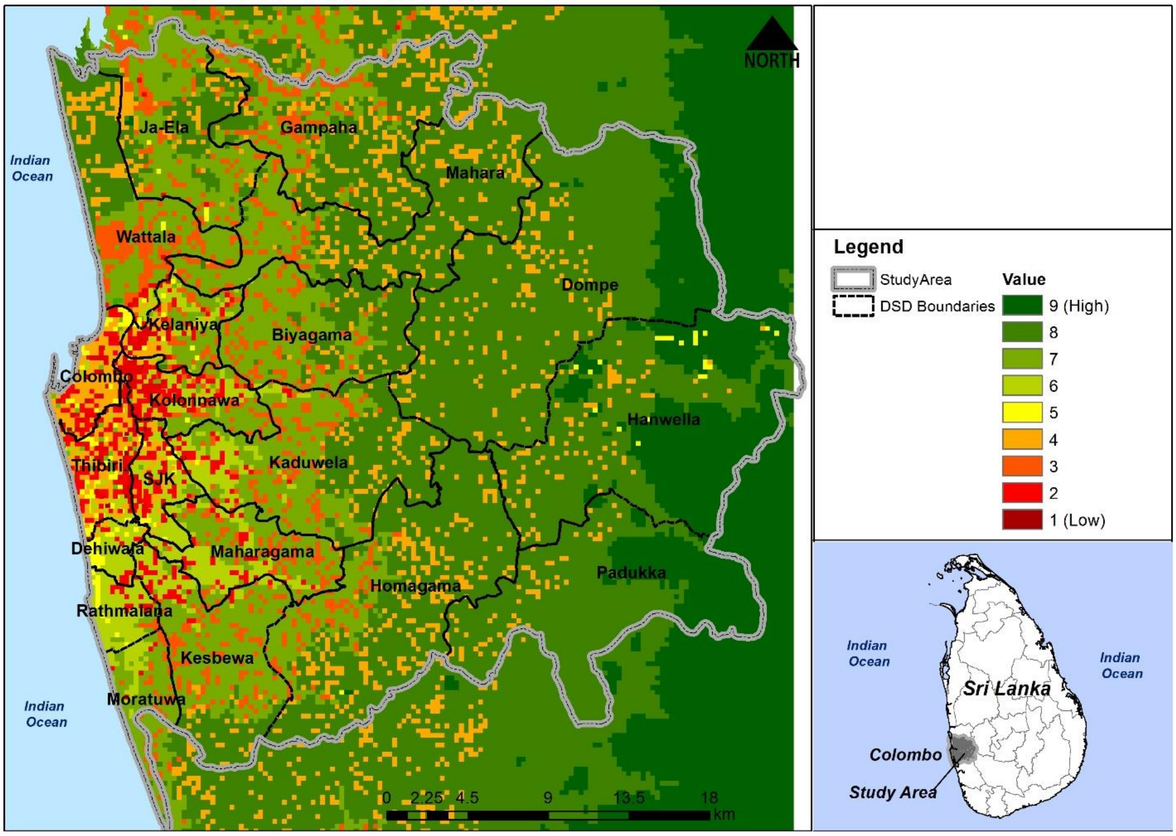

Figure 7-6: Geospatially modelled community resilience levels

The results depict geospatial variations of the community resilience levels within the case study region. This map can be utilized to rank locations (sites, wards, villages or other administrative units) in term of resilience. The Western part of the study area, which is highly concentrated with orange and red colour-coded cells (i.e., >5 in the 1-9 scale), is needed the high priority attention of the initiatives for building resilience. These high priority clusters shall be the foremost concern of the immediate community empowerment programs.

7.5. Conclusion

CRA tools play a vital role in decision-making for building community's resilience to disasters. Established resilience indicators can gain decision-makers' confidence in assessment methods. Hence, this paper attempted to verify the formulated geospatial indicators. First, the study applied the 30 geospatial indicators into 23 DS divisions in Colombo, Sri Lanka. Secondly, this study plotted the affected population data by DS division into system performance curves concerning the flood occurred in May 2016. Thirdly, the study statistically tested the association of geospatial indicators with each of the four system-performance measures. Findings revealed 16 indicators having a significant association with system performance measures, and the results discussed the ambiguities and cohesive nature of indicators regarding different capacities. The detailed analysis of this study could detect ambiguities regarding the association among distinct capacities. Decision-makers ought to be cautious of such ambiguities because it can weaken the internal validity of the assessment and can misguide resilience-building actions.

Verified geospatial indicators demonstrated the capability to represent all three capacities of resilience. Minimum or no change to urban areas and school density has uniquely represented the transformative capacity of the socio-ecological system. High densities of water bodies, residential population, infrastructure density and rapid urban growth mutually represented weakened absorptive and recovery capacities of the system. Overall, results clearly revealed that geospatial indicators could demonstrate the resilience processes and behaviours of socioecological systems; hence, they can be utilized to measure the community resilience.

Chapter – 8
Conclusion

8.1. Introduction

Chapter eight discusses the applicability of the proposed geospatial indicators and community resilience map and highlights the key contribution of this study to reduce flood risk by building community resilience.

8.1.1. Applicability of the proposed resilience indicator for risk management

CRA estimates the community's resilience level to a given risk. The objective of resilience estimation is to evaluate community resilience and formulate strategies for empowering the community with enhanced resilience. As building resilience is a risk management approach, the relevant strategies should also be able to manage the risk. Thus, this study assesses the applicability of the proposed geospatial indicators for reducing flood risk (Table 8-1).

Table 8-1: Risk management options based on the geospatial indicators

Element of Risk	**Geospatial Indicator**	**Risk management solutions**
Exposure	Water bodies density	The high density of water bodies triggers the flood exposure naturally. Even though it is a natural formation; the risk can be reduced through technological solutions. - Networking water bodies with redundant flood diversion options (e.g. dams, diversion canals) - Maintain the water flow by timely removal of debris deposits and desilting.
	Percent land that has changed into urban areas	These four indicators are related to the effects of the intensive built-up area which disturb the infiltration and evaporation processes. In order to minimize this effect, permeable surfaces should be maintained with minimum disturbance. Some physical planning regulation mechanisms to control the reduction of permeable surfaces are; - Reduce building coverage ratio[1] of physical constructions - Introduce permeable pavement designs and materials - Allocate regulatory open area[2] for land subdivisions
	Rapid urban growth	
	Percent population living in high-intensity urban area	
	Density of Commercial infrastructure	

Element of Risk	**Geospatial Indicator**	**Risk management solutions**
Vulnerability	Percent population living in high-intensity urban area	The high density of population, buildings and economic infrastructure are elements-at-risk, which increase the vulnerability. However, population, buildings and economic infrastructure have become indispensable components of settlements. Therefore, in order to reduce the risk, - High densities need to be desirable only at locations where the probability of the exposure is lower. This can be implemented by density control mechanisms. o Flood zoning[3] based on return period o Allocate flood buffers[4] at flood plains - Buildings and infrastructure should design and retrofit as to withstand floods o Elevation of foundations, structures o Use of flood damage resistant construction technology and materials
	Density of Commercial infrastructure	
Capacity (socio-economic)	Schools per square mile	Schools and hospitals are amenities which improve the general well-being of the community. Having access to social infrastructure can strengthen the community's capacity to cope floods. - Locate amenities at safer, accessible locations - Improve the service levels of public amenities
	Hospitals per square mile	
Capacity (bio-physical)	Flood-resilience-supportive ESs (FES)	FES harbours the natural flood defence mechanisms. While earth's life-support systems defence the floods, human interventions may increase the fragility. Hence, measures are to be taken to avoid any human intervention that perturbs flood-resilience supportive ESs by; - Controlling further damages of o reclamation of water retention areas o conversion of green spaces into built-up areas (e.g. deforestation, conversion of agricultural areas) - Reversing the negative consequences of already made damages o Afforestation o Relocation of built-structures to be out of the reclaimed sites

Notes:

[1] building coverage ratio is a building regulation.

$$\mathrm{BCR} = \left(\frac{\mathrm{B}}{\mathrm{A}}\right)100$$

Where BCR is Building Coverage Ratio (%), B is the building area, and A is the site area.

[2] The regulatory open area is a physical planning regulation. When subdividing a large land plot (the size is given) into smaller plots, a certain percentage (ratio is given) shall keep open without any construction.

[3] Flood zoning is a physical planning regulation. Flood zoning refers to considering the probability of flood when preparing land-use zonation regulations.

[4] Flood buffer is a physical planning regulation. Flood buffers regulate the physical constructions within a specified distance of setback from a water body.

8.1.2. Resilience map as a source of information

In flood risk reduction, hazard maps and risk maps are utilized as mandatory public information sources in many countries (European Commission, 2010). However, resilience map has not been legalized yet. Resilience map portrays the levels of resilience capacities across a geographical area and can also be utilized for resilience evaluation. Hence, we propose resilience map as a source of information that has to be made available to users in order to reduce the residual risk. Stakeholders of resilience map can be government officers, private sector investors, and citizens.

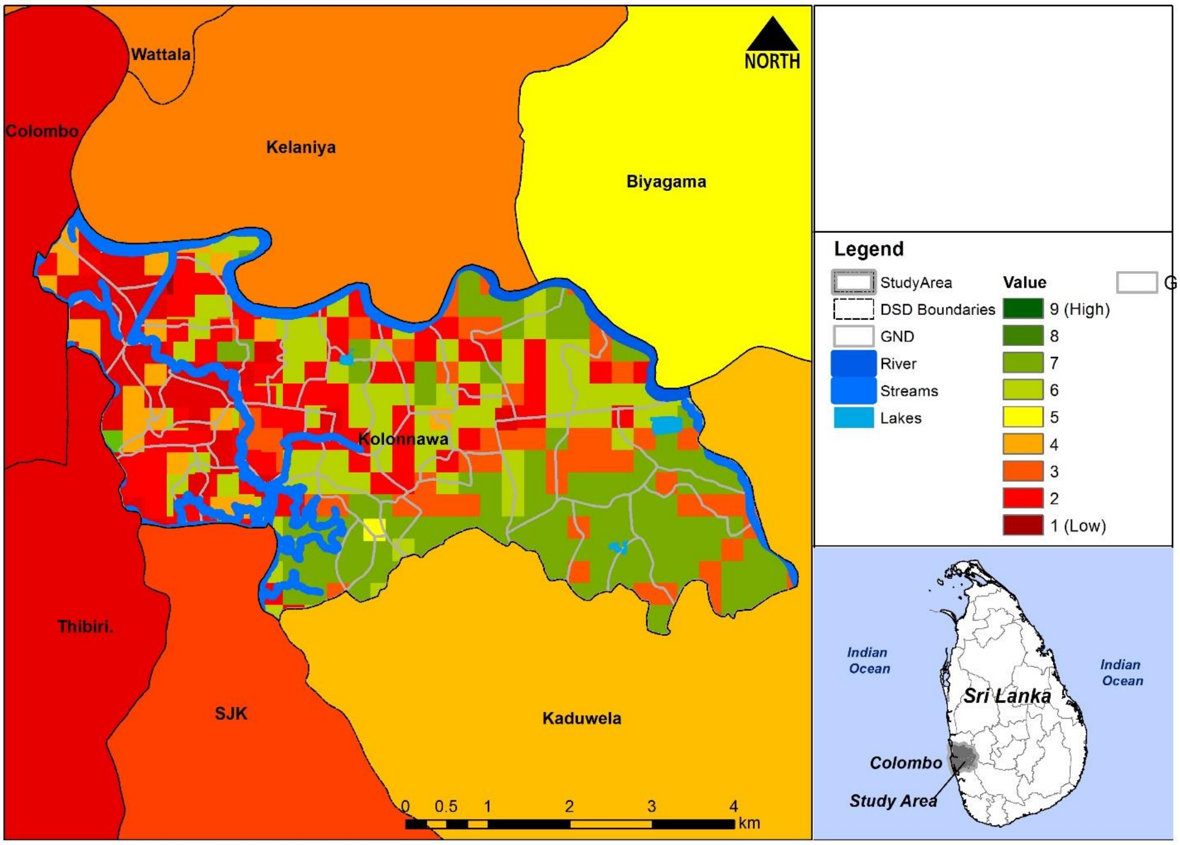

Figure 8-1: Detailed Flood resilience map of Kolonnawa town
Notes: The map has been prepared by utilizing the composite geospatial indicator that has been developed from this study. The map indicates the detailed sites (250m x 250m cells) of flood resilient communities. The proposed awareness program need to target the communities who settles within the least resilient (i.e., coded in red colour) sites.

Decision makers in public domain can utilize resilience map as a proactive tool in prioritizing and evaluating projects. Resilience assessment could be employed to evaluate the modeled future spatial/urban development scenarios. Modelling population distribution and land use changes is an essential part of development plans. Based on the modelled land use and population distribution, the resilience levels under the envisaged development scenario can also be modelled. Accordingly, the proposed geospatial indicators can be utilized in evaluating the impacts of future development scenarios upon community resilience.

Further, the resilience map can be utilized as information for prioritizing the sites for projects to build resilience. Building resilience is a continuous process of setting upper-level targets and improving systems to perform better. Ideally, each geographic location ought to operationalize these initiatives, yet the implementation is subjected to resources. Resources, which are scarce, should be allocated on the basis of priority. Resilience maps distinctly point the locations and communities that should be prioritized in resilience building-initiatives.

In addition, private investors can choose the most resilient site for particular types of investment projects. Currently, many of the flood insurance companies use flood risk map for estimating premiums. Resilience map can also provide useful information for this purpose.

Moreover, citizens have a right to be aware of the resilience status of their community. Being aware of the residual risk, provide an opportunity for people to plan and be prepared. Migrants communities who lacks local knowledge can use resilience map as a criterion to choose their locations, thereby, settle among better-resilient communities. In countries like Sri Lanka where community participation in urban development decision has made mandatory, resilience maps can be effectively utilized to convey the consequences of development actions on disaster resilience and motivate community towards self-driven initiatives.

8.2. Key contributions of the study

Repetitive evidence of catastrophic floods urges a global response to disaster risk. Building community’s resilience to confront disaster risk is an inevitable choice in making safer societies. Disaster risk management services as a precursor to Community resilience assessment (CRA). Building resilience operationalizes risk management through reducing vulnerability and exposure and strengthening the capacity to cope. Though the establishment of a sound resilience assessment methodology has become a necessity, measuring resilience in inherently complex socio-ecological systems entrenches an absolute challenge in the domain of decision-making science. Practitioners, who works in developing CRAs have approached inductively to measure resilience, particularly establishing a set of indicators that could be considered as relevant to resilience. In a context where many of the CRAs have predominated with socio-economic indicators, the preliminary review of this study revealed that the effects of biophysical environment on community resilience have not been adequately addressed.

Hence, this study attempted to develop a set of geospatial indicators for assessing community resilience capacities of socio-ecological systems to floods.

This study conceptualized flood as a natural phenomenon, which is an integral function of mutually interacting, interrelated and interdependent elements of socio-ecological systems. Most of the recent catastrophic floods can be considered as triggered by anthropogenic forcing as a result of weakened resilience capacities of systems. Thus, the proposed geospatial indicators have been principally focused on the roles of the natural environment in defending and the growth of built-up area in intensifying floods. Based on this principle, the study formulated a set of 30 geospatial indicators and tested the validity to assess community resilience against floods. Initial findings of the study listed 14 geospatial indicators that show significant associations ($p < 0.05$) to the resilience-evidenced measured by community responses to a selected flood event, occurred on May 2016 in Colombo, Sri Lanka. As a result of further analysis, the study selected eight geospatial indicators as independent variables and model the community resilience for the given case study area. Modelling results were statistically significant (adjusted r-squared = 0.863 at sig. F change = 0.000) to recommend geospatial indicators as powerful predictors of community resilience.

The next contribution of this study is developing a measurable working definition for community resilience. ‘community resilience to floods’ has been defined as the ability of a socio-ecological system to persist the disturbances; absorb the shocks, restore into a desirable regime of function; and strengthen the capacity to adapt and anticipate trajectories of floods. Accordingly, the resilience of a given community has been expressed as a function of absorptive capacity (A), Recovery capacity (R), and Transformative Capacity (T). This definition emphasizes the dynamic states of resilience as an emerging process. Such emphasis is essential to be made in assessing resilience because system responses are not linear. For instance, systems which were poor in absorbing shocks might emerge better with adaptation through learning and experience. Hence, the proposed capacity-based definition can measure resilience not merely as an aggregation of properties rather as a dynamically evolving process. In order to operationalize this definition, the study developed a set of proxy measures that estimate resilience by system-performance throughout each resilience state. The developed proxy measures have been utilized as outcome variables of the resilience-evidenced where developing such independent resilience data set is extremely required for current practice. The dynamics of indicators at different states of system performance curve embodies the processes of community actions through life-cycle stages of community resilience. Therefore, CRA indicator should signify each of the states, ensuring that all types of capacities are adequately accounted in the assessment.

Furthermore, this paper introduced a composite environmental indicator for assessing community resilience to floods, where many of the CRA tools lack pragmatic environmental indicators. The composite indicator has been built on the conceptualized inter-relationships between Ecosystem Services (ESs) and community resilience. The environmental parameters to measure the composite were identified by surveying the cross-disciplinary literature from the domains of ESs and disaster resilience. Application of the composite indicator was demonstrated by a case study in Colombo, Sri Lanka. The developed composite indicator consists of four proxy indicators (i.e., soil hydraulic properties, slope, land use, and precipitation factor) and parameters to measure them. The parameters have also been derived from the conceptualized relationship that elaborates ESs into a bundle of services including flood regulation, climate regulation, and nutrient recycling whereas many of the existing resilience assessment methodologies are focused only on flood regulation. Further, the composite indicator has organized the environmental parameters into two-tiers, facilitating a range of users including the once from data-constraint situations. Incorporating this ESs-based composite indicator into existing resilience assessment methodologies could direct community resilience-building initiatives towards the more sustainable outcomes. Hence, the synergy between ESs and community resilience could be recommended to be an effective approach to incorporate environmental indicators into extant CRA tools.

8.3. Conclusion and recommendations

The proposed geospatial indicators have contributed to the theoretical development of CRA by reviewing the extant CRA tools; consolidating and modifying existing geospatial indicators and introducing a composite environmental indicator. The indicators built on a geospatial platform enables decision makers to visualize the spatial variations of ESs. Visualizing the spatial variations facilitates the policy formulation and planning processes by geo-positioning the priority needs of communities where investment to build resilience is needed the most. The ability to be computed by a range of materials methods, and the ability to visualize geospatially have made these indicators capable of catering to the needs of policy and planning decision makers, even who work under data-scarce, technical resource-constraint situations.

In an urbanizing world where flood damages are outnumbered, geospatial indicators can provide profound insights into initiatives taken for building resilience. Geospatial indicators well capture the effect of increasing risk by the intensive growth of the built-up area and the perturbed natural flood defence mechanisms. Therefore, geospatial indicators can strongly be recommended in community resilience assessment tools. Further studies on assessing the validity and adequacy of indicators can make the assessment process more scientific and comprehensive leading towards promising initiatives to build resilience.

Overall, incorporating theoretically sound, non-ambiguous, statistically verified geospatial indicators into CRA tools can direct future policy and planning decisions towards more sustainable outcomes that empower communities to perform better during floods while ensuring a better quality of earth’s life support systems.

Academic Achievements

Publications in peer-reviewed Journals

1. **Chethika Abenayake**, Yoshiki Mikami, Ashu Marasinghe, Takashi Yukawa, Masahiro Iwahashi (2016) “Applicability of Extra-Local Methods for Assessing Community Resilience to Disasters: A Case of Sri Lanka”, Journal of Environmental Assessment Policy and management, World Scientific Publishing Europe Ltd., London, vol.18, pp.1-28

2. **Chethika Abenayake**, Yoshiki Mikami, Yoko Matsuda (2017) Validate geospatial indicators for assessing community resilience capacities to floods; a system-performance-based approach, Journal of Engineering and Applied Sciences, Medwell Publishing, Vol.12 (24) pp. 1-21 (In Press)

3. **Chethika Abenayake**, Yoshiki Mikami, Yoko Matsuda, Ecosystem services-based composite indicator for assessing community resilience to floods, Environmental Development, pp.1-18 (In review)

Publications in peer-reviewed conference proceedings

4. **Chethika Abenayake**, Yoshiki Mikami, Ashu Marasinghe, (2015) “Assessing Community Resilience to Climate-related Disasters: Exploring the Relative Importance of Indicators”, *Environmental Systems Research*, International Proceedings of Chemical, Biological and Environmental Engineering, IACSIT Press, Singapore, Vol.91, pp. 27-35

Awards

1. The **best poster presentation** of the ‘system safety’ session at the 4th International GIGAKU Conference, held on 19th-21st June 2015 at Nagaoka University of Technology, Niigata, Japan

Conference presentations

1. **Chethika Abenayake**, Yoshiki Mikami, Ashu Marasinghe, (2016) “Assessing Community Resilience to Climate-related Disasters: Exploring the Relative Importance

of Indicators” 5th International Conference on Climate Change and Humanity (ICCCH 2016), held on January 23-25, 2016, Pattaya, Thailand

2. **Chethika Abenayake**, Ashu Marasinghe, (2015) "Pragmatic Insights on Selection of indicators to Assess Community Resilience to Disasters" in 52nd Infrastructure and Planning Conference, ed. Japan Society for Civil Engineers, held on 21st-23rd November, 2015 Akita, Japan
3. **Chethika Abenayake**, Ashu Marasinghe, (2015) "Challenges of Employing Extra-Local Assessment Methods to Measure Community Resilience to Climatic Disasters" at the 4th GRIPS Student Conference held on 2nd September, 2015 at National Graduate Institute for Policy Studies, Tokyo, Japan
4. **Chethika Abenayake**, Ashu Marasinghe, (2015) "Assessing Resilience of Community to Climatic Disasters; Pragmatic Insights on Inductive Approaches" at The 4th International GIGAKU Conference, held on 19th - 21st June 2015 at Nagaoka University of Technology, Niigata, Japan
5. **Chethika Abenayake**, (2015) Participation in the doctoral student discussion at the Tokyo Conference on International Study for Disaster Risk Reduction and Resilience,14th - 16th January, 2015, University of Tokyo, Tokyo, Japan

Presentations to international panels

1. **Chethika Abenayake**, (2016) “Applicability of system safety principles in the domain of community disaster resilience” on 23rd June 2016, at Magdeburg University, Magdeburg, Germany

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Annexures

Annexure 1: **Applicability of three-step method in the domains DRM**

ISO 12100: 2010 (E)proposes a three-step method for risk reduction: inherently safe design, protective measures, and information for use. In the context of disasters, "disaster risk reduction (DRR) describes the concept and practice of reducing disaster risks through systematic efforts to analyse and manage the causal factors of disasters, including through reduced exposure to hazards, lessened vulnerability of people and property, wise management of land and the environment, and improved preparedness for adverse events" (UN, 2013, p. 12). UNISDR Global Assessment Report 2015 explains DRM as the implementation of DRR, which describes the actions that aim to achieve the objective of reducing risk (UNISDR, 2015). Accordingly, key risk management actions are prevention, mitigation, risk transfer and preparedness. The following sections discuss the applicability of the three-step method in reducing flood risk with reference to each step in order to compare them with DRM actions.

1. Inherent safety

Any location that reaches precipitated water has a potential of flooding. All human settlements require some form of precipitation for survival. Therefore, ideally, any community on the planet is not inherently safe from flooding. However, the probability of flooding varies from place to place. The flood frequency in some locations is extremely low as if no significant floods have ever been recorded within a given period of time whereas some locations being flooded annually or even several times a year. Though no land is inherently safe, the concept of 'inherent safety' can be conditionally applied in the domain of flood risk management considering the recurrence interval[14] or return period of floods.

Accordingly, the location of human settlements within the flood-safe zone can be considered as the inherently safe human settlement design option. The decision of 'flood-safe zone' is context-dependent. The Ireland office of public works defines the flood-safe zone as the

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[14] "The recurrence interval is based on the probability that the given event will be equaled or exceeded in any given year" (USGS,2015). For instance, if there is a 1 in 100 likelihood that 300mm of daily rainfall will fall in a given area during a year, then 300mm of daily rainfall is referred to have a 100-year recurrence interval.

probability of occurrence of fluvial events[15] less than 0.1% per year (PWD, 2009, p. 15). The United States Federal Emergency Management Administration (FEMA), defines the flood-safe zone as less than 0.2% annual chance of flood (FEMA, 2016).

A sample 'inherent safety' application is given below.

Hazard: The *Kalu* River overflows due to excess rainfall

Persons affected: People who travel to district capital (e.g. *Rathnapura*, Sri Lanka) for obtaining services from public institutions

Hazardous situation: Public institutions are located in the annual floodplain

Hazardous event: Flood occurred during the public day of the week

Harm: Commuters are trapped in public buildings

Inherently safe design: Relocation of the public buildings to a flood-safe zone (i.e., *Rathnapura* new town development project)

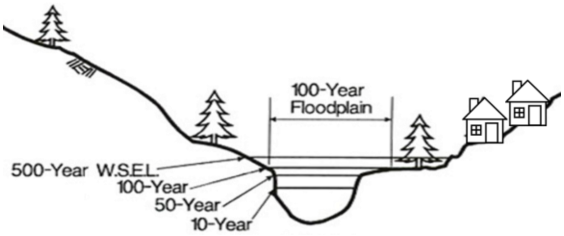

Figure 1-1: Schematic diagram of locating buildings at flood-safe zone
Note: W.S.E.L is standard for Water Surface Elevation Level

2. Protective measures

Safeguarding and complimentary protective measures can be implemented to reduce flood risk as proactive initiatives. The concept of protective measures can be made at various levels. The top-level solution would be flood diversion[16] schemes which prevent inundation of a given land

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[15] Fluvial flood events are associated with rivers and floods. This report as referred two types of floods as fluvial events and coastal events whereas the focus of this study is limited to inland floods, hence, do not discuss coastal floods.

[16] Flood diversion is a physical construction. "Flood Diversion and storage projects involve diverting floodwaters from a stream, river, or other body of water into a wetland, floodplain, canal, pipe, or other conduit (e.g., tunnels,

area. If this solution is not feasible, then the next level is to protect the individual units of buildings and infrastructure within the particular area. This may include the elevated built-structures (buildings, roads, etc.), thereby, essential functions of the system can be continued even with the flood. Residual risk can be further reduced by establishing early warning infrastructure such as evacuation routes, emergency shelter towers. So then, even if the lands get inundated, exposure of people can be minimized.

A sample ‘protective measure’ application is given below.

Hazard: The *Mahaweli* River overflows due to excess rainfall

Person affected: People who live in potential flood prone areas

Hazardous situation: Flood reaches while people resided in the houses constructed on the flood plain

Hazardous event: People and houses exposed to a high flood level

Harm: Drowning and fatal injuries, house damages

Protective measure: Construction of cascade-networked dams to retain excess rainfall (i.e., *Mahaweli* Scheme[17])

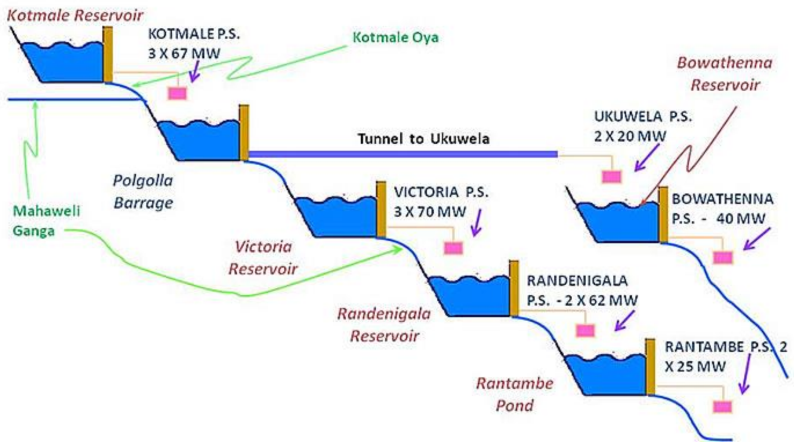

Figure 1-2: Schematic diagram of water diversion project of Mahaweli River, Sri Lanka
Source: River Valleys Development Board, Sri Lanka 2003

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wells) and storing them in above-ground reservoirs, floodplains, wetlands, green infrastructure elements, or other storage facilities” (FEMA, 2016).

[17] The primary objective of this project is not flood risk management, yet this scheme plays a vital role in protecting human settlements and agricultural areas within the drainage basin of the *Mahaweli* river.

3. Information for users

After reducing the risk by technically feasible protective measures, any remaining risk should be informed clearly to the users. Providing the information regarding the residual risk enable users to take actions towards safety. In reducing community flood risk, local knowledge that transferred through generations and obtained through experiential learning plays a vital role. In present day societies where community-based local knowledge management systems are highly disrupted due to the effects of urbanization, the flux of migration, gentrification and related social transformations, knowledge management has become an institutional responsibility. Therefore, provision of access to public information including early warning, conducting awareness programs and evacuation training have become indispensable assignments in flood risk reduction.

A sample ‘information for users’ application is given below.

Hazard: The *Kelani* River overflows due to excess rainfall

Person affected: a town is located in a potential flood prone area (e.g. *Kolonnawa* Town)

Hazardous situation: flood inundated the town

Hazardous event: housing, and economic activities perturbed for a period of one week

Harm: temporary displacement and loss of income for people

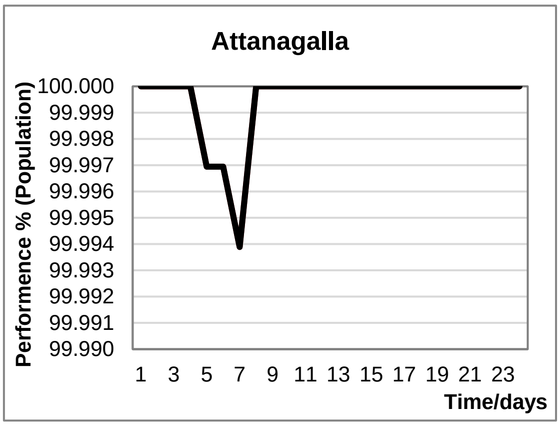
Information for user: Conduct a community level flood response awareness program with the participation of vulnerable people.

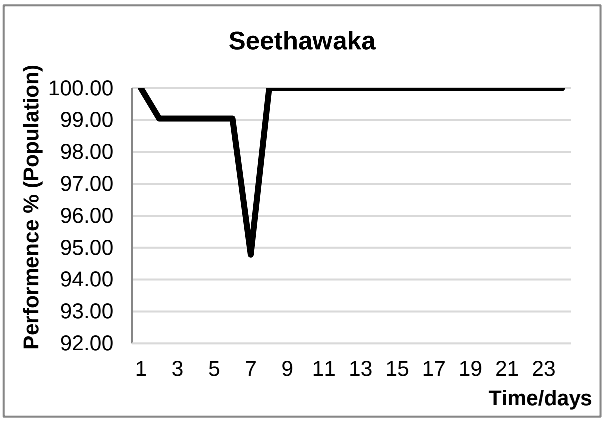
Overall, the three-step method of risk reduction can be considered as applicable in the domain of flood risk reduction. Prevention actions are correspondent to the concept of inherent safety while mitigation actions are correspondent to the concept of protective measures. Nevertheless, risk transfer and preparedness actions are more detailed and comprehensive in the domain of DRM than information for users.

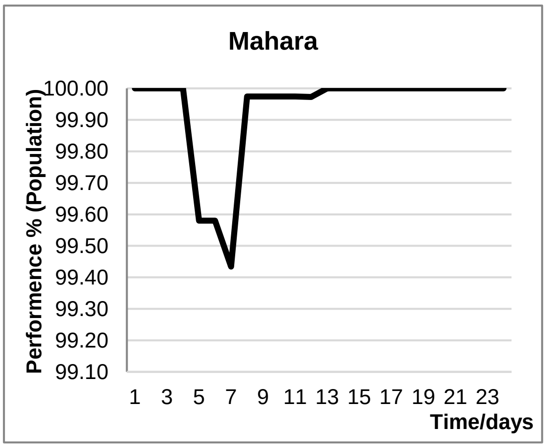
Per the comparability of the elements of risk and applicability of three-step risk reduction method, the risk reduction principles presented in ISO 12100: 2010 (E) and its umbrella standard ISO/IEC Guide 51: 2014 (E) were opted as the base of in developing the proposed resilience indicators for resilience assessment.

Annexure 2: **Behaviour of the system performance to the flood occurred on May,2016 by DS Divisions**

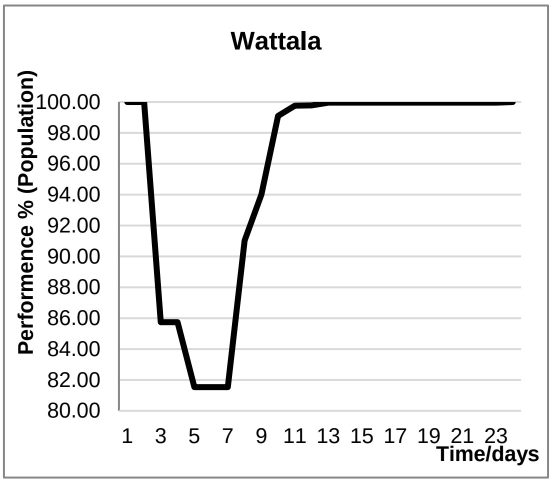
Attanagalla and Seethawaka are two adjacent DS divisions at the suburbs of Colombo which shows gradual degradation and quick recovery on immediate day. These systems show the best performance in recovery behaviour.

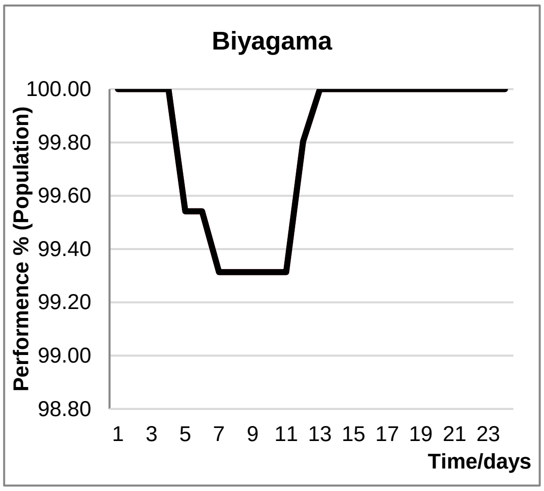


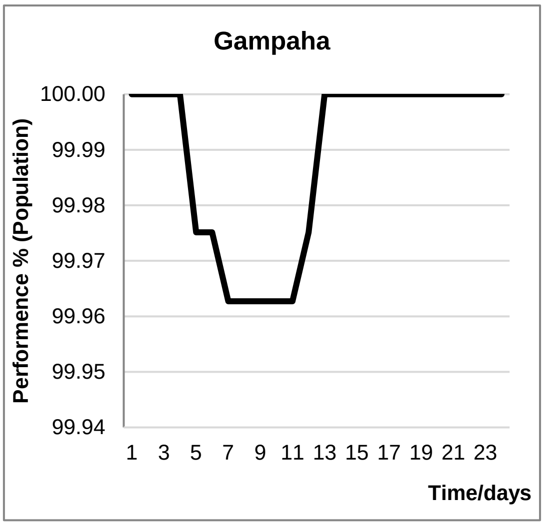


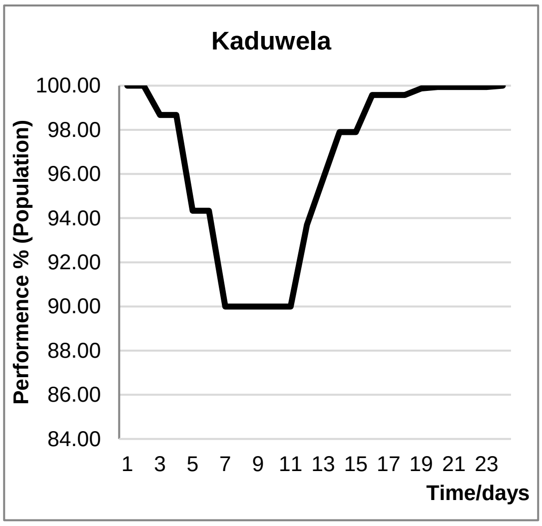


Wattala, Biyagama, Gampaha and Kaduwela also shows gradual degradation but recovery has a gentle slope.

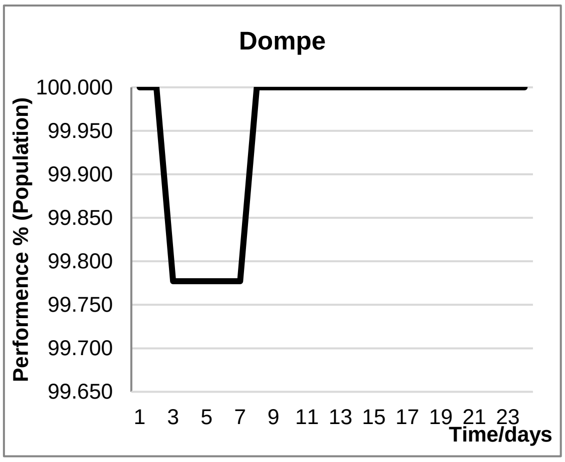


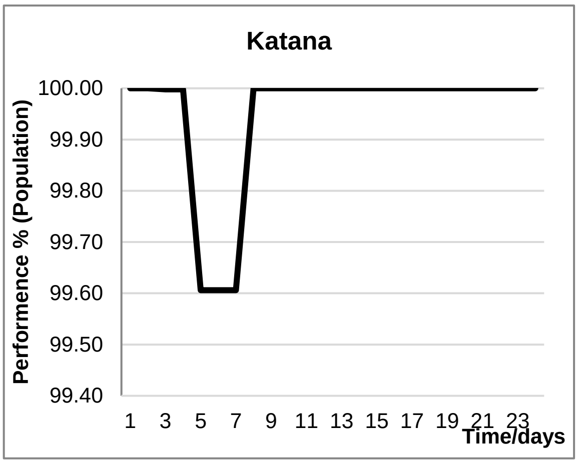


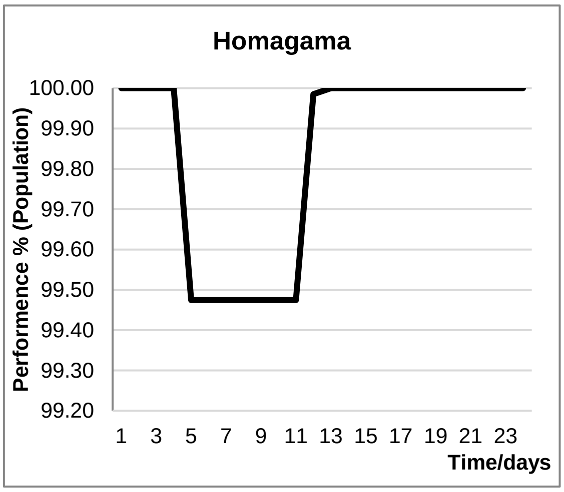


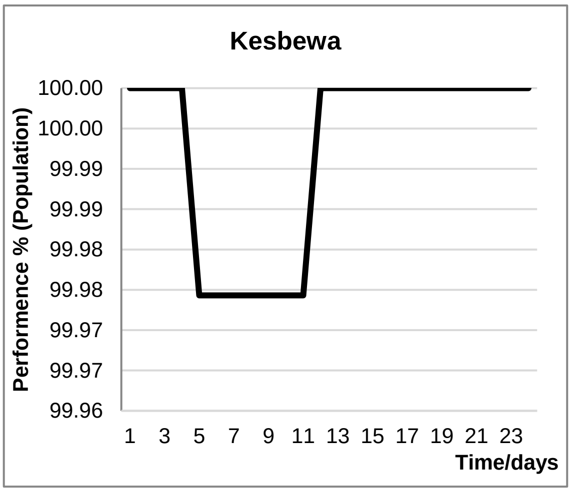


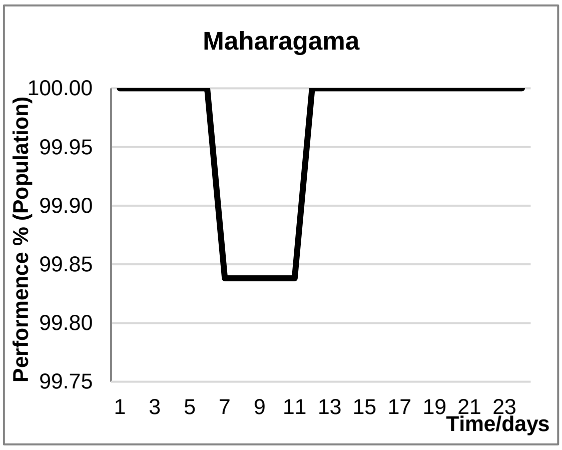
Many of the DS divisions, have been degraded at once, remained at peak failure for a period less than a week and recovered at once. Even though, the shape of the curves is similar, the resilience levels are somewhat different due to the magnitude of performance decrease.

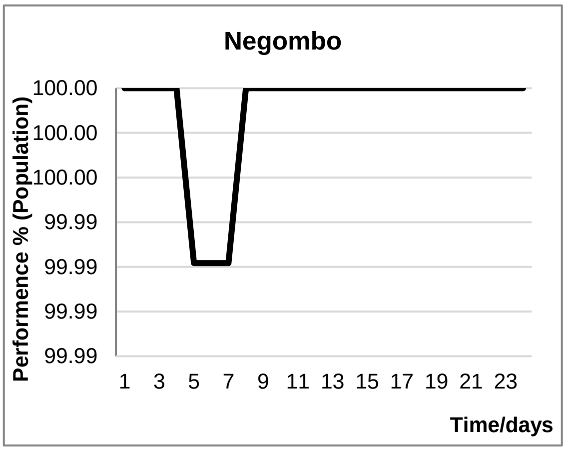

Dompe
Performence % (Population)
100.000
99.950
99.900
99.850
99.800
99.750
99.700
99.650
1 3 5 7 9 11 13 15 17 19 21 23
Time/days

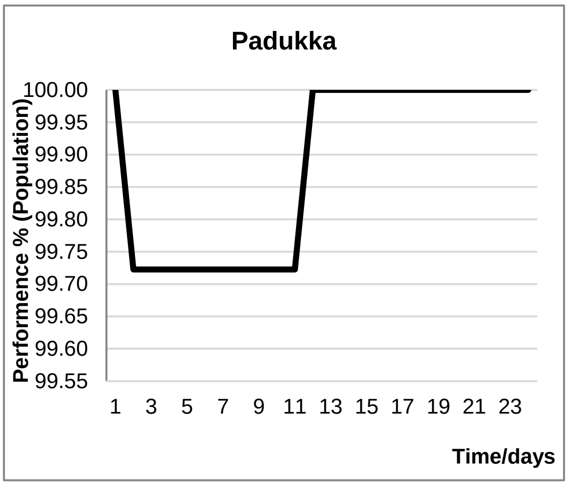

Katana
Performence % (Population)
100.00
99.90
99.80
99.70
99.60
99.50
99.40
1 3 5 7 9 11 13 15 17 19 21 23
Time/days

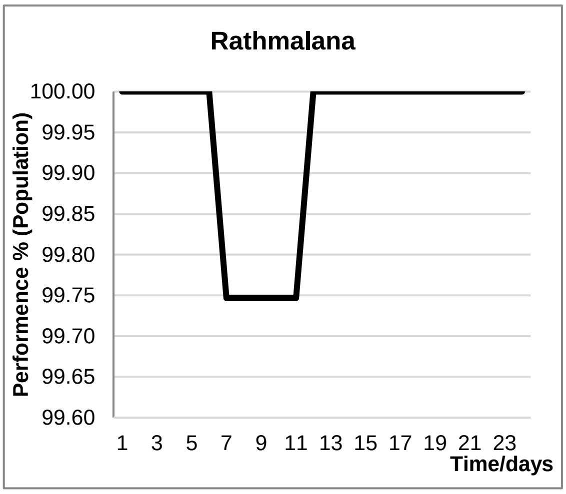

Homagama
Performence % (Population)
100.00
99.90
99.80
99.70
99.60
99.50
99.40
99.30
99.20
1 3 5 7 9 11 13 15 17 19 21 23
Time/days


Kesbewa
Performence % (Population)
100.00
100.00
99.99
99.99
99.98
99.98
99.97
99.97
99.96
1 3 5 7 9 11 13 15 17 19 21 23
Time/days


Maharagama
Performence % (Population)
100.00
99.95
99.90
99.85
99.80
99.75
1 3 5 7 9 11 13 15 17 19 21 23
Time/days


Negombo
Performence % (Population)
100.00
100.00
100.00
99.99
99.99
99.99
99.99
1 3 5 7 9 11 13 15 17 19 21 23
Time/days


Padukka
Performence % (Population)
100.00
99.95
99.90
99.85
99.80
99.75
99.70
99.65
99.60
99.55
1 3 5 7 9 11 13 15 17 19 21 23
Time/days


Rathmalana
Performence % (Population)
100.00
99.95
99.90
99.85
99.80
99.75
99.70
99.65
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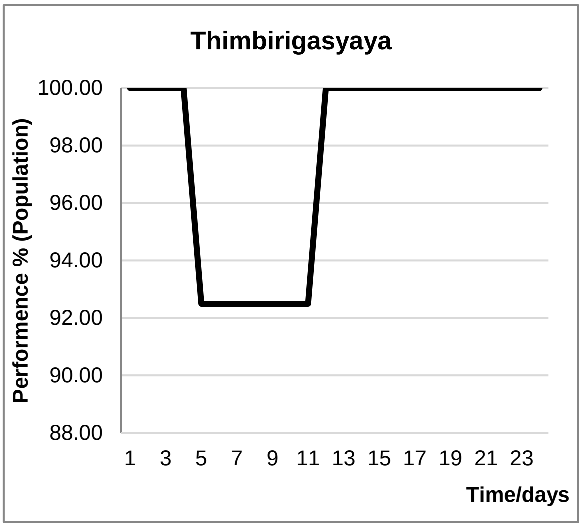
1 3 5 7 9 11 13 15 17 19 21 23
Time/days


Thimbirigasyaya
Performence % (Population)
100.00
98.00
96.00
94.00
92.00
90.00
88.00
1 3 5 7 9 11 13 15 17 19 21 23
Time/days

Kolonnawa, Colombo, Sri Jayawardhenapura Kotte and Kelaniya also show steep degradation at once and slow elastic slope of recovery. This type of curve indicates the least resilience behaviour.