Journal of Engineering and Applied Sciences 13 (13): 4949-4960, 2018
ISSN: 1816-949X

Validate Geospatial Indicators for Assessing Community Resilience Capacities to Floods; A System-Performance-Based Approach

[1]Chethika Abenayake, [2]Mikami Yoshiki and [3]Matsuda Yoko
[1]Department of Information Science and Control Engineering, Graduate School of Engineering,
[2]Department of Management and Information Systems Science,
[3]Disaster Prevention Systems Group, Department of Civil and Environmental Engineering,
Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka, 940-2188 Niigata, Japan

Abstract: Community resilience assessment methodologies play a vital role in decision-making for building community's resilience to disasters. Established resilience indicators can gain decision-maker's confidence on assessment methods. Hence, this study attempts to assess the validity and adequacy of a set of geospatial indicators extracted from existing methodologies. First, the study extracts 29 geospatial indicators to assess community resilience to floods and applies them for 23 divisions in Colombo, Sri Lanka. Second, this study plots the affected population data by division into system performance curves concerning the flood occurred in May, 2016. Third, the study develops system performance curve-based measures to quantify the three capacities of community resilience: transformative capacity, absorptive capacity and recovery capacity. Then the study statistically tests the association of geospatial indicators with each of the system-performance measures. The study has obtained spatial data for mapping geospatial indicators from national databases and the affected community data from the records of disaster management officers. Findings revealed 16 indicators having significant association with system-performance measures and the results discuss the ambiguities and cohesive nature of indicators regarding different capacities. This study has established a pilot initiative to validate a set of geospatial indicators where many of the practicing community assessment tools have little or no geospatial indicators. Furthermore, this study applies a set of system performance curve-based measures to externally validate the community resilience capacities. Therefore, the study contributes with comprehensions to make community resilience assessments tools more powerful in guiding communities towards resilience.

Key words: Disasters, resilience capacities, methods, socio-ecological systems, guiding communities, assessments tools

INTRODUCTION

Every year, thousands of people around the world struggle to confront floods. A flood is a hydro-meteorological hazard that has accounted for 47% of all weather-related disasters (1995-2015) affecting 2.3 billion people in the world during the past decade (UNISDR., 2016). Out of all hzards, floods pose the widely districuted natural risk to life today. Floods often inundate 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 (USAID, 2016). This global commitment emphasizes to mainstreme urban development and disaster risk reduction programs towards building resilient communities. Directing these initiatives to cater the needs of the most vulnerable and the least resilient communities is a sustainable development challenge.

Resilience assessment is a policy and planning tool that has been developed to facilitate decision-making on resilience-building initiatives (Abenayake *et al*., 2016). "Resilience measures (i.e., assessments) are helpful in identifying disaster risk, taking productive steps toward its reduction and getting stakeholders together to build capacity to prepare for respond to, recover from and more successfully adapt to threats" (Cutter, 2016). Despite

Corresponding Author: Chethika Abenayake, Department of Information Science and Control Engineering, Graduate School of Engineering, Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka, 940-2188 Niigata, Japan

several utilities, "community resilience assessment tools have not yet been appropriately integrated into planning and policy-making process" (Sharifi and Yamagata, 2016). One of the key reasons is a lack of consensus and confidence in the assessment tools among practitioners. "Although, community resilience to disasters is still an emerging field and index developers often describe their products as frameworks or baseline assessments, there is little utility unless they can be confidently used to inform decision-makers" (Bakkensen *et al*., 2017). In such context, this study has focused on two properties of resilience indicators, validity and adequacy, that are indispensable prerequisites in building decision-maker's confidence in community resilience assessment methodologies.

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, there by giving confidence in index's ability and performance to end users" (Bakkensen *et al*., 2017). Furthermore, Validation performs a vital role in identifying the relative importance of indicators (Burton, 2015; Cai *et al*., 2016) and clarifying which indicator/s should be used in each decision (Bakkensen *et al*., 2017). 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 (Parsons *et al*., 2016). Hence, even though validation is a major step in the process of creating composite indices, it is rarely performed in the context of disaster resilience studies (Bakkensen *et al*., 2017; Burton, 2015; Cai *et al*., 2016). External validation of community resilience indicators has posed a challenge primarily because community resilience is not a directly observable phenomenon and the validation of resilience indicators requires the use of proxies (Tate, 2012; Cai *et al*., 2016). "Currently, there is no commonly recognized independent proxy data used in the validation of resilience assessment" (Cai *et al*., 2016). Few cross-disciplinary studies have developed proxies based on the system performance curve concerning the evidence of previous hazard events. This study focuses on system performance-based measurements and has attempted to utilize them for validating community resilience indicators.

Endorsing the adequacy of resilience assessment tools to represent community's capability plays a vital role in the credibility of resilience assessment indicators. Sharifi and Yamgatha (2016)'s recent study emphasizes that "there is a paucity of studies that evaluate community resilience assessment tools in terms of their suitability of guiding communities towards resilience" Ealcin *et al*. (2011) have evaluated the ability of community resilience assessment frameworks in the United States to account for four resilience actions: plan, absorb, recover and adapt (Larkin *et al*., 2015). Sharifi and Yamagata have also assessed these four actions concerning 36 community resilience assessment tools that practice in several different countries (Sharifi and Yamagata, 2016). Findings of those studies revealed that many of the assessment methodologies have mediocre performance in adequately covering all 4 types of actions that drive community's resilience. The studies mentioned above have initiated a policy dialog on some potential opportunities for improving community resilience assessment methodologies. This study attempts to constructively contribute to this line of studies primarily with two advancements. First, current recommendations are based on theoretically-validated heuristic evaluations. The study performs a statistically-supported, external validation based on empirical evidence. Second, the studies mentioned above have focused on community assessment methodologies whereas this study is focused on a set of geospatial indicators that has been filtered from several existing methods.

The overall objective of this study is to test the validity of geospatial indicators in assessing community resilience to floods and to investigate the adequacy of geospatial indicators for evaluating the three capacities of resilience. The three capacities are persistence capacity, absorptive capacity and recovery capacity. These capacities correspond to the plan, absorb and recover actions discussed in previous studies. Nevertheless, due to the deficiency of empirical data, this study does not discuss community's ability to perform long-term adaptation from the 4 actions that have been examined in previous studies. The scope of this study is limited to floods and particularly focused on geospatial indicators that are input variables of existing composite resilience indices. This study provides a set of validated geospatial indicators along with their capability to consider distinct types of capacities that are required to make communities resilient.

MATERIALS AND METHODS

Colombo, Sri Lanka as the case study: Sri Lanka, being a tropical Island country is highly susceptible to the adverse consequences of hydro-meteorological disasters (Ranjan and Abenayake, 2014). Flood is the most frequent natural hazard in Sri Lanka. The low-pressure system occurred inthe 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 15-17th of May 2016. Flood was 6-12 feet in height and the damage was recorded as the highest number of flood-affected population over last 6 decades (DMC., 2016). Per the situation report issued by Disaster Management Center 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. This study was conducted in the lower drainage basin of the Kelani River including 23 DS divisions that belong to the Colombo Metropolitan Region, 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 1 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.

Selection of geospatial indicators to assess community resilience to floods: Geospatial indicators represent terrestrial activities and processes derived from geospatial analysis that are widely applicable in decision-making science. The study has extracted geospatial indicators from practicing methodologies and proposed frameworks. 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 manually screen the extracted articles. Screening criteria were having processed by geospatial analysis, applicability at the

Fig. 1: Map of study area

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'. Many of the extracted indicators were 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 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 (Cutter *et al*., 2008a, b; Kotzee and Reyers, 2016). Many of the extracted indicators are listed in the Paolo Cimellaro's comprehensive literature review on extant indicators to assess community resilience to disasters (Cimellaro, 2016). The list of 52 indicators was further filtered into 34 indicators by focusing on the relevance to floods and then into 25 considering the data availability. This study has made minor modifications to four of the extracted geospatial indicators while considering geospatial properties. Justifications of those minor modifications were presumed logically and yet to be tested. Therefore, the validation test considered both extracted indicators and modified versions. Table 1 presents the set of 29 geospatial indicators to be tested as independent variables to assess community resilience to floods.

Table 2 contains the information about data acquisition for computing geospatial indicators for the case study area.

The set of 29 indicators (Table 1) were geospatially processed for the case study area in Colombo using a GIS (Geographic Information System) Software.

Table 1: The selected geospatial indicators for theoretical validation

ID	Indicators	Direction	Justification	Data (code) *
1	Percent land area that is a wetland, swamp, marsh and mangrove	+	Barnes *et al.* and Klein *et al.* (2003)	A
2	Rapid urban population growth (Percentage increase of urban population density)	-	(Centre for Science Economics and the Environment in 2002)	G, B
3	Percent deep permeable soil per ward	+	Kotzee and Reyers (2016)	E, J
4	Percent fire, police, emergency relief services and temporary shelters outside of hazard zones	+	(US Indian Ocean Tsunami Warning System Program 2007)	A, F
5	Percent of building infrastructure not in flood inundation zones	+	Geis and Kutzmark (1995) Cimellaro (2016)	A, F
6	Percent of government offices outside of flood inundation zones	+	(US Indian Ocean Tsunami Warning System Program in 2007)	A, F
7	Percent of commercial establishments outside of high hazard zones (flood, surge)	+	(US Indian Ocean Tsunami Warning System Program in 2007)	A, F
8	Population living in high-intensity urban areas/ population density	-	Cutter *et al.* (2008a)	A, G
9	Percent land area that does not contain erodible slopes	+	Cutter *et al.* (2008a)	C, E
10	Percent land area not in an inundation zone (100 years)	+	Cutter *et al.* (2008a)	E
11	Percent land area that does not contain impervious surfaces	+	Cutter *et al.* (2008b)	A, I
12	Percent land area with no forest and rangeland decline	+	Geis and Kutzmark, Cimellaro (2016)	A
13	Percent land area with no wetland decline	+	Cutter *et al.* (2008a, b)	A
14	Percent area that has changed into urban areas (by urban classification)	-	Cutter *et al.*, (2008a)	A, B, H
15	Percent land area that is high-intensity urban development (80% or more impervious surface)	-	Cutter *et al.* (2008a)	A, I
16	Percent land area of developed open spaces	+	Geis and Kutzmark, Cimellaro (2016)	A
		+	Cutter *et al.* (2008a)	A
17	Principal arterial miles		Bruneau and Reinhorn (2007)	
18	Hospitals per square mile	+`	Cutter *et al.*, (2008a)	A
19	Schools (primary and secondary education) per square mile	+	Cutter *et al.* (2008) (US Indian Ocean Tsunami Warning System Program 2007; Centre for Science Economics and the Environment 2002)	A
20	Hotels and motels per square mile	+	Cutter *et al.* (2010)	A
21	Density of commercial infrastructure	-	Allenby	A
22	Number of river miles	-	Berke	A
23	Percent erodible soil per ward	-	Cutter *et al.* (2008a) and Kotzee and Reyers (2016)	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)	+	Kotzee and Reyers (2016)	A

Table 1: Continue

ID	Indicators	Direction	Justification	Data (code)*
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 and Reyers (2016)	A
26	Rapid urban growth (Percentage land cover change to urban areas from base year)#	-	Minor modifications made to indicator 2	A, B
27	Waterbodies density (Waterbody area/total land area)#	-	Minor modifications made to existing indicator 22	A
28	Access to hospital (Inverse of Euclidean distance to the hospitals)#	+	Spatial adjustments made to existing indicator 18	A
29	Movement potential (Inverse of Euclidian distance to road network)#	+	Spatial adjustments made to existing indicator 17	A

*Refer Table 2 for details; #Indicators modified/introduced by this research (26, 27, 28, 29)

Table 2: Data acquisition for computing geospatial indicators

Data type/Code*	Description	Years	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: 50,000	Survey Department, Sri Lanka
C	contour map	2012	1: 5,000	Tsunami Hazard Map Database, Coast Conservation and Resource Management
Department				
D	Rainfall isohyets	2007	1: 10,000	National Atlas, Survey Department of Sri Lanka
E	Soil map	2007	1: 10,000	National Atlas, Survey Department of Sri Lanka
F	Flood inundation map	2016	1: 30,000	Disaster Management Center, Sri Lanka
Tabular data				
G	Population	2012	GN Division	Population Census, 2012, Department of Census and Statistics, Sri Lanka
H	Land use classification	2013	National	Colombo Development Plan, 2013, Urban Development Authority, Sri Lanka
Classifications				
I	Floor krea ratio by land use	2013	Regional	Colombo Development Plan, 2013, Urban Development Authority, Sri Lanka
J	Soil hydraulic properties	1961	National	the National Soil Survey Published in Soil of Ceylon, 1961 by Soil Type Moormann and Panabokke, 1961

*ID to link Table 1; #The study has used published data

Formulation of system-performance measures to evaluate community resilience: Validation of indicators requires an independent set of outcome variables to surrogate community resilience. As mentioned in the introduction, 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 centers because of the flood. Similarly, bouncing off to the desirable regime of function was attributed to the situation of leaving the welfare center.

The number of population that stayed overnight in welfare centers 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 Center, 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 centers' 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 centers were considered as the point which the system returned to the desirable regime of function.

The system performance curve is widely employed to explain the disaster resilient behavior of socio-technical systems despite the limited attempts to apply in socio-ecological systems. The early research of Bruneau *et al.* (2003) have utilized the system performance curve to quantify resilience based on the 'resilience triangle' (Wang and Blackmore, 2009; Bocchini *et al.*, 2013). Later studies have developed this by using mathematical functions of indefinite integrals that measure either the area above performance curve (Bruneau, 2006; Bruneau and Reinhorn, 2007; Bruneau *et al.*, 2005) or the area under the performance curve (Cimellaro *et al.*, 2010a, b; Bocchini and Frangopol, 2012). A comprehensive overview of these measures is available elsewhere (Bocchini and Frangopol, 2010). In addition, the latest work by Mugume *et al.* (2015) has applied a mathematical function of indefinite integrals to quantify the resilience of storm water drainage systems to floods. 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. These 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 and capacities into one measure has not been favorable for some applications (Bocchini, *et al.*, 2013). Such combined measure has less utility to test the adequacy of indicators to cover different capacities of resilience. States of system performance curve represent distinct types of system behavior such as planning and preparing to persist the perturbations, buffering the system degradation by absorbing shocks and recovering the system following the learning and adaptation Fig. 2. Hence, this study has formulated four measurements to quantify three selected states of system performance curve that correspond to three resilience capacities concerned. Persistence rate (P) of ith event:

$$P_i = \frac{1}{(P_jA_j)(t_f - t_0)} \tag{1}$$

Peak Failure (F) of ith event:

$$P_i = \frac{1}{(P_jA_j)(Q_s)} - Q_{mf} \tag{2}$$

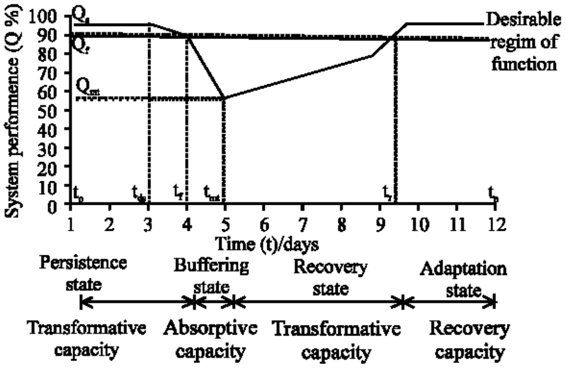

Fig. 2: A conceptual illustration of system performance curve

Degradation rate (B) of ith event:

$$B_i = \frac{1}{(P_jA_j)} \int_{t_f}^{t_{mf}} (100 - Q_i(t))\,dt \tag{3}$$

Recovery rate (R) of ith event:

$$R_i = \frac{1}{(P_jA_j)} \int_{t_{mf}}^{t_r} (100 - Q_i(t))\,dt \tag{4}$$

Where:

P = Total population of jth locality (DS division)

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

$$A_j = \frac{FI_j}{L_j} \times 100 \tag{5}$$

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

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 a flood irrespective of the effect of the size of population and inundation area.

Persistence rate (Eq. 1) measures the duration that the community system with stands the disturbances while fulfilling the basic needs. A higher 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, persistent rate has been measured based on the duration that residents can endure floods without leaving their houses.

The state when community cannot persist further and compelled to seek external assistance to fulfill their basic needs is 't_{ds}' where system starts degradation. When the degradation crosses the desirable regime of function 't_f', the system failure occurs. Peak failure (Eq. 2) and degradation rate (Eq. 3) measure the magnitude of the degradation. Peak failure and degradation rate increases if the system cannot buffer floods by absorbing the shock. Hence, these two measures are attributed to the absorption capacity of the system. In this study individuals seeking the assistance within the community members was attributed to the point 't_{ds}' and community seeking shelter at welfare centers was attributed to the point 't_f'. However, data collection was limited to the number of people seeking shelter at welfare centers. Therefore, 't_{ds}' was approximated to equal 't_f' and 'Q_s' (i.e., initial performance of the system) was approximated to equal 'Q_f' (i.e., system performance at the desirable regime of function).

Recovery rate (Eq. 4) measures the time taken to recover considering the correspondent system performance at each point of recovery. Decreased time taken to recover indicates a higher recovery capacity of the system. A higher recovery capacity indicates a higher community resilience. In this study, the point system based on the desirable regime of function 't_r' was attributed to the time when no people stayed overnight at the welfare center.

Accordingly, the persistent rate has a direct relationship with community resilience whereas other three measures have an inverse relationship with community resilience.

Framework of analysis: First, this study computed the resilience level of 23 DS divisions by 29 geospatial indicators separately. Second, the study plotted the system performance curves of each DS division with affected population data. Persistence rate, peak failure, degradation rate and recovery rate were computed for each of the DS divisions based on system performance curves. Next, the study tested the statistical association between geospatial indicators and system-performance measures. Association was tested by Spearmen's correlation coefficient because the Shapiro-Wilk test and QQ plots of many of the 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.

RESULTS AND DISCUSSION

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 29 geospatial indicators, 13 showed either significant or moderately significant correlation (Table 3).

'Rapid urban growth' recorded the highest correlation with degradation rate ($r_s = 0.791$· $p<0.000$), peak failure ($r_s = 0.765$, $p<0.000$) and recovery rate ($r_s = 0.865$, $p = 0.000$). 'Schools (primary and secondary education) per square mile recorded the highest correlation ($r_s = 0.779$, $p<0.000$) with persistence rate. Rapid urban growth concentrates physical development 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 defense 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.

Ambiguity in the direction of association concerning the states of resilience: As Table 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

Table 3: Geospatial indicators revealed a significant association with outcome variable/sec

ID	Indicators	Outcome	Degradation rate	Peak failure	Recovery rate	Persistent rate
1	Percent land area that is a wetland, swamp, marsh and mangrove	r_s	0.617**	0.694**	0.669**	-
		Sig.	0.006	0.001	0.002	-
8	Population living in high intensity urban areas/ population density	r_s	0.569*	0.647**	0.583*	-
		Sig.	0.014	0.004	0.011	-
10	Percent land area not in an inundation zone (100 years)	r_s	0.461*	-	-	0.537**
		Sig.	0.031	-	-	0.008
14	Percent area that has changed into urban areas	r_s	-	-	-	0.742**
		Sig.	-	-	-	0.000
16	Percentage land area of developed open spaces	r_s	0.562*	0.520*	0.713**	0.570*
		Sig.	0.015	0.027	0.001	0.011
18	Hospitals per square mile	r_s	-	-	0.478*	0.678**
		Sig.	-	-	0.045	0.001
19	Schools (primary and secondary education) per square mile	r_s	-	-	-	0.779**
		Sig.	-	-	-	0.000
20	Hotels and motels per square mile	r_s	0.469*	-	0.525*	0.577**
		Sig.	0.050	-	0.025	0.010
21	Density of commercial infrastructure	r_s	0.474*	0.491*	0.490*	-
			0.047	0.039	0.039	-
26	Rapid urban growth (Percent land cover change to urban areas from base year)	r_s	0.791**	0.765**	0.865**	-
		Sig.	0.000	0.000	0.000	-
27	Waterbodies density	r_s	0.702**	0.686**	0.709**	-
		Sig.	0.001	0.002	0.001	-
28	Access to hospital	r_s	0.660**	0.557**	0.644**	0.561**
		Sig.	0.001	0.007	0.002	0.005
29	Movement potential	r_s	0.526*	0.453*	0.584**	0.699**
		Sig.	0.012	0.034	0.005	0.000

**Correlation is significant at the 0.01 level (2-tailed) *Correlation is significant at the 0.05 level (2-tailed)

Table 4: Ambiguity of indicators

ID	Indicators	Outcome	Persistence rate	Degradation rate	Peak failure	Recovery rate
10	Percent land area not in an inundation zone (100 years)	r_s	0.537**	0.461*	-	-
		Sig.	0.008	0.031	-	-
16	Percent land area of developed open spaces	r_s	0.570*	0.562*	0.520*	0.713**
		p	0.011	0.015	0.027	0.001
18	Hospitals per square mile	r_s	0.678**	-	-	0.478*
		Sig.	0.001	-	-	0.045
20	Hotels and motels per square mile	r_s	0.577**	0.469*	0.525*	-
		p	0.010	0.050	-	0.025
28	Access to hospital	r_s	0.561**	0.660**	0.557**	0.644**
		p	0.005	0.001	0.007	0.002
29	Movement Potential	r_s	0.699**	0.526*	0.453*	0.584**
		p	0.000	0.012	0.034	0.005

**Correlation is significant at the 0.01 level (2-tailed); *Correlation is significant at the 0.05 level (2-tailed)

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 the association with different system-performance measures (Table 4). 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.

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. Second, 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, $p<0.000$) and the population living in high-intensity urban areas (r_s = 0.846, $p<0.000$). 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, $p<0.000$). 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.

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 correspondent resilience capacities.

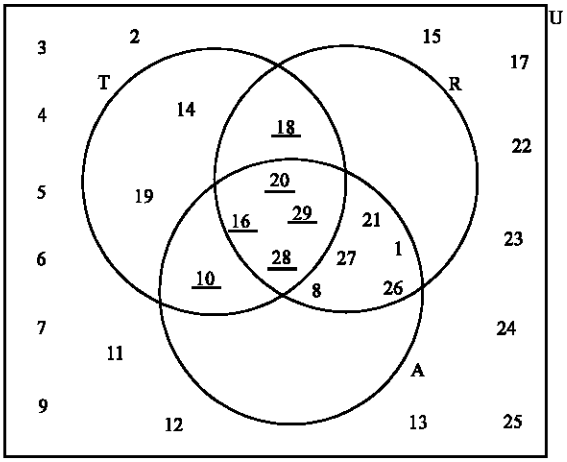

Fig. 3: Relationships of indicators with resilience capacities three overlapping sets in the Venn diagram illustrates how geospatial indicators are associated with resilience capacities. The 29 items in the venn diagram represent the set of geospatial indicators tested in this study. Set ‘A’ refers to the absorptive capacity, Set ‘R’ refers to the recovery capacity and set ‘T’ refers to the transformative capacity

This study tested the association of 29 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 Fig. 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 correspondent system-performance measures. Indicators which are ambiguous concerning the direction to different resilience capacities have been underlined in the Venn diagram.

Followings are the detailed inferences of the Venn diagram:

- $A = \{1, 8, 10, 16, 20, 21, 26, 27, 28, 29\}$
- $R = \{1, 8, 18, 16, 20, 21, 26, 27, 28, 29\}$
- $T = \{14, 18, 19, 16, 20, 28, 29\}$
- $(A\cap R\cap T) = \{16, 20, 28, 29\}$
- $(T/(A\cap R)' = \{14, 19\}$
- $(T/A\cup R) = \{1, 8, 10, 14, 16, 18, 19, 20, 21, 26, 27, 28, 29\}$
- $(T \cup A\cup R)' = \{2, 3, 4, 5, 6, 7, 9, 11, 12, 13, 15, 17, 22, 23, 24, 25\}$

Sets of absorptive capacity (A) and recovery capacity (R) contain ten indicators each following the eight 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 ($T/(A \cup R)'$) 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 13 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 validation 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 (Fig. 2). 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 validate 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. Second, 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. Third, 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 validate geospatial indicators.

CONCLUSION

This study consolidated a set of 29 geospatial indicators from existing community resilience assessment methodologies and tested their validity and adequacy to assess community resilience against floods. Per the literature review, geospatial indicators were very limited in existing assessment methodologies. Initial findings of the study listed 13 geospatial indicators that show significant associations to system-performance measures. 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 assessment and can misguide resilience-building actions.

Validated 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. The dynamics of indicators at different states of system performance curve embodies the processes of community actions through life-cycle stages of community resilience. The aggregated resilience index should signify each of the state, ensuring that all types of capacities are adequately accounted in the assessment.

Statistically validated indicators can be employed in resilience assessment methodologies with high reliability. Overall, results clearly revealed that geospatial indicators can demonstrate the resilience processes and behaviors of socioecological systems hence, they can be utilized to measure the community resilience. Particularly, geospatial indicators well capture the effect of increasing vulnerability due to the intensive physical development and perturbed natural flood defense mechanisms. In an urbanizing world where flood damages are outnumbered, geospatial indicators can provide deep insights into resilience-building initiatives. Therefore, geospatial indicators can strongly be recommended in community resilience assessment tools.

SUGGESTIONS

Further studies on assessing the validity and adequacy of indicators can make the assessment process more scientific and comprehensive leading towards promising resilience-building initiatives.

REFERENCES

Abenayake, C., M. Yoshiki, A. Marasinghe, Y. Takashi and I. Masahiro, 2016. Applicability of extra-local methods for assessing community resilience to disasters: A case of Sri Lanka. J. Environ. Assess. Policy Manage., 18: 1-28.

Bakkensen, L.A., C. Fox-Lent, L.K. Read and I. Linkov, 2017. Validating resilience and vulnerability indices in the context of natural disasters. Risk Anal., 37: 982-1004.

Bocchini, P. and D.M. Frangopol, 2010. Optimal resilience-and cost-based postdisaster intervention prioritization for bridges along a highway segment. J. Bridge Eng., 17: 117-129.

Bocchini, P. and D.M. Frangopol, 2012. Restoration of bridge networks after an earthquake: Multicriteria intervention optimization. Earthquake Spectra, 28: 426-455.

Bocchini, P., D.M. Frangopol, T. Ummenhofer and T. Zinke, 2013. Resilience and sustainability of civil infrastructure: Toward a unified approach. J. Infrast. Syst., Vol. 20,

Bruneau, M. and A. Reinhorn, 2007. Exploring the concept of seismic resilience for acute care facilities. Earthquake Spectra, 23: 41-62.

Bruneau, M., 2006. Enhancing the resilience of communities against extreme events from an earthquake engineering perspective. J. Secur. Educ., 1: 159-167.

Bruneau, M., A. Filiatrault, G. Lee, T.D. O'Rourke and A. Reinhorn *et al.*, 2005. White paper on the Sdr Grand challenges for disaster reduction. Multidisciplinary Center for Earthquake Engineering Research, USA.

Bruneau, M., S.E. Chang, R.T. Eguchi, G.C. Lee and T.D. O'Rourke *et al.*, 2003. A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake Spectra, 19: 733-752.

Burton, C.G., 2015. A validation of metrics for community resilience to natural hazards and disasters using the recovery from Hurricane Katrina as a case study. Ann. Assoc. Am. Geographers, 105: 67-86.

Cai, H., N.S.N. Lam, L. Zou, Y. Qiang and K. Li, 2016. Assessing community resilience to coastal hazards in the Lower Mississippi River basin. Water, 8: 1-18.

Cimellaro, G.P., 2016. Urban Resilience for Emergency Response and Recovery. Springer, Berlin, Germany, ISBN:9783319306568, Pages: 522.

Cimellaro, G.P., A.M. Reinhorn and M. Bruneau, 2010b. Framework for analytical quantification of disaster resilience. Eng. Struct., 32: 3639-3649.

Cimellaro, G.P., A.M. Reinhorn and M. Bruneau, 2010a. Seismic resilience of a hospital system. Struct. Infrastruct. Eng., 6: 127-144.

Cutter, S.L., 2016. The landscape of disaster resilience indicators in the USA. Nat. Hazards, 80: 741-758.

Cutter, S.L., L. Barnes, M. Berry, C. Burton and E. Evans *et al.*, 2008a. A place-based model for understanding community resilience to natural disasters. Global Environ. Change, 18: 598-606.

Cutter, S.L., L. Barnes, M. Berry, C. Burton and E. Evans *et al.*, 2008b. Community and regional resilience: Perspectives from hazards, disasters and emergency management; CARRI research report, 1. Community and Regional Resilience Institute, South Carolina. http://www.resilientus.org/wp-content/uploads/2013/03/FINAL_CUTTER_9-25-08_1223482309.pdf.

DMC., 2016. Flood extent for Kelani ganga river basin and surrounding. Disaster Management Centre, Colombo, Sri Lanka. http://www.dmc.gov.lk/IndexInnundationMaps.htm.

Klein, R.J., R.J. Nicholls and F. Thomalla, 2003. Resilience to natural hazards: How useful is this concept?. Global Environ. Change Part B Environ. Hazards, 5: 35-45.

Kotzee, I. and B. Reyers, 2016. Piloting a social-ecological index for measuring flood resilience: A composite index approach. Ecol. Indic., 60: 45-53.

Larkin, S., C. Fox-Lent, D.A. Eisenberg, B.D. Trump and S. Wallace *et al.*, 2015. Benchmarking agency and organizational practices in resilience decision making. Environ. Syst. Decisions, 35: 185-195.

Mugume, S.N., D.E. Gomez, G. Fu, R. Farmani and D. Butler, 2015. A global analysis approach for investigating structural resilience in urban drainage systems. Water Res., 81: 15-26.

Parsons, M., S. Glavac, P. Hastings, G. Marshall and J. McGregor *et al.*, 2016. Top-down assessment of disaster resilience: A conceptual framework using coping and adaptive capacities. Intl. J. Disaster Risk Reduct., 19: 1-11.

Ranjan, E.S. and C.C. Abenayake, 2014. A study on community's perception on disaster resilience concept. Procedia Econ. Finance, 18: 88-94.

Sharifi, A. and Y. Yamagata, 2016. On the suitability of assessment tools for guiding communities towards disaster resilience. Intl. J. Disaster Risk Reduct., 18: 115-124.

Tate, E., 2012. Social vulnerability indices: A comparative assessment using uncertainty and sensitivity analysis. Nat. Hazard., 63: 325-347.

UNISDR., 2016. The human cost of weather-related disasters 1995-2016. United Nations International Strategy for Disaster Risk Reduction, Geneva, Switzerland.

USAID., 2007. How resilient is your coastal community?. United States Agency for International Development, Washington, USA.

Wang, C.H. and J.M. Blackmore, 2009. Resilience concepts for water resource systems. J. Water Resour. Plann. Manage., 135: 528-536.