A Synthesis of Disaster Resilience Measurement Methods and Indices

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Abstract

Disaster resilience has become an important societal goal which captures the attention of academics and decision makers from various disciplines and sectors. Developing tools or metrics for measuring and monitoring progress of resilience is a critical component that requires extensive research to achieve better understanding. However, different fields have different emphases and the knowledge gained from the various studies are scattered and fragmented. To provide an integration of the literature and reflect on the current state of resilience measurement, we conducted a synthesis analysis through a systematic review of 174 scholarly articles on disaster resilience measurement from 2005 to 2017. Using a review table designed for this study and content analysis, we extracted key information from each article on resilience definition, type of measurement method, resilience indicators used, and proposed adaptation strategies. Results indicate that 39.7% of the articles used qualitative methods for resilience measurement and 39.1% of the articles used quantitative methods. However, only 10.3% of all the 174 articles conducted empirical validation of their proposed resilience indices. The three most frequently suggested adaptation strategies were empowering local governments and leaders, raising community awareness, and enhancing community infrastructure and communication. These findings suggest that future research need to incorporate validation and inferential ability into resilience measurement. Extending from static resilience measurement to dynamic system modeling and bridging the disconnection between resilience scientific research and practical actions are also pressing needs.

Keywords:

disaster resilience measurement; synthesis analysis; resilience indices; validation; adaptation strategies.

1. Introduction

Disaster resilience analysis has increasingly been recognized as a powerful tool for providing substantive support for decision-making in fields such as hazard mitigation, risk assessment, and other environment, social, economic, or technological improvements (Norris et al., 2008; Nelson et al., 2009; Cutter et al., 2010). There is substantial literature in the broad field of resilience, vulnerability, hazards, disaster risk assessments, and sustainability, which cut across many disciplines. In particular, developing tools or metrics for measuring and monitoring progress of resilience is considered a top priority (National Research Council, 2012).

However, despite the abundant literature in resilience, there are relatively few studies on the actual measurement of disaster resilience or developing resilience measurement frameworks and indices. The difficulties in developing useful resilience indices are due to several factors (Lam et al., 2016). First of all, there is no consensus on the definition of resilience and how resilience is related to other similar terms such as vulnerability, recovery, adaptability, and sustainability. Different fields of study have different emphases on the concept of resilience, and this undoubtedly has affected the measurement approaches as well as the choice of indicators to measure. Secondly, it is not clear whether resilience should be an overall concept or it is specific to a certain type of hazard. It is not known whether the nature of the hazard will affect the measurement approaches and the associated indicators. In other words, will the resilience measurement and indicators be different if the hazard is drought or earthquake, as opposed to hurricanes and flooding? A search of the communalities and common indicators across space, time, and hazard type is necessary for robust resilience measurement and is needed to support effective decision making. Last but not least, few measurement studies focus on the validation of resilience indices. Often times, the indices are derived by combining a number of indicators that are considered to be important with their weights subjectively assigned. Without validation of the derived indices, it is difficult to justify them as an objective decision-making tool to monitor progress in resilience across space, time, and hazard type.

Given the current state of resilience measurement research, where it has diverse definitions, measurement approaches, indicators used, and practical application contexts, it would be useful to conduct a synthesis study on these various aspects so that new knowledge can be produced (Kemp and Boynton, 2012; Jordan and Javernick-Will, 2013). A carefully constructed synthesis study on resilience measurement methods and indicators will help piece the existing knowledge together into an integrated format and enable the development of ontology on resilience as a foundation for future information representation, analysis, and modeling. The synthesis study can also help identify future directions for research and support moving knowledge into decision making (Nyerges et al., 2014).

We conducted a synthesis study on resilience measurement methods and key indicators using published literature from 2005-2017. We posed four research questions: 1) what were the common definitions of resilience across disciplines and hazard types? 2) What were the common approaches to resilience measurement, and have the proposed resilience indices been validated with empirical evidence? 3) What were the most commonly used indicators to evaluate resilience? 4) What adaptation strategies have been proposed to improve resilience?

To address these questions, we first identified and collected existing relevant literature on disaster resilience measurement. Key information from the collected articles were then extracted through a review table designed by the authors to enable systematic content analysis. Through this synthesis study, the knowledge about resilience definitions, measurement methods developed, resilience indicators tested, and proposed adaptation strategies can be derived, and research gaps and future research directions can be identified.

2. Method

This study focused on published refereed journal articles on disaster resilience measurement. We used the *Web of Science* as the main search engine. The search was conducted in January 2017 for the period from 2005 to 2017. *Web of Science* is an online subscription-based scientific citation indexing service originally produced by the Institute for Scientific Information (ISI), and is now maintained by Clarivate Analytics. It provides functions for various types of citation search (Drake, 2004). It gives access to multiple databases that reference cross-disciplinary research, which allows for in-depth exploration of specialized sub-fields within an academic discipline.

We used the following procedure to search articles related to disaster resilience measurement. Since a huge number of articles would be retrieved if we use the topic search method only, we limited our keyword-based search to the title of the articles in order to yield the most relevant literature. Several keywords were used during the search, including ‘disaster resilience’, ‘resilience index’, ‘resilience indicator’, ‘resilience indices’, ‘resilience metrics’, ‘resilience measurement’, ‘measuring resilience’, ‘resilience assessment’, ‘assessing resilience’, ‘natural hazards’, ‘resilience framework’, and ‘disaster’. Additional search criteria included that the time period was from 2005 to 2017, document type was article, and the language was English. The search excluded several irrelevant research areas, for example, astronomy, physics, or sports, by checking the boxes on the screen to avoid retrieving a large number of irrelevant articles. This step resulted in a total number of 256 articles.

Next, we removed the duplicates or irrelevant articles in the assembled articles by manually checking the title and abstract of each article. Then, a total of 20 documents from the research team’s personal archive were added. These included the workshop report from the National Institute of Standards and Technology (NIST), technical report from *resilientnola.com*, and several highly relevant articles published in 2016 and 2017. Finally, the process resulted in 174 most relevant articles for the review.

To enable systematic content analysis and future ontological framework development, we designed a review table to extract and record major information items from each article. Each article has a unique ID number. The review table included five categories of information: publication information, research context, methodological framework, results and conclusion, and relevance. Table 1 lists the information items under each category. The 174 articles were then carefully reviewed and information were extracted and recorded using the review table.

Table 1. Information items in the review table

Category	Information Item
Publication information	• ID • Authors • Publication year • Paper title • Fist author's affiliation • First author's country • Journal name • Keywords • Number of citations
Research context	• Research object • Disaster type • Study area • Country of study area • Geographic scale
Methodological framework	• Concept definition • Description of other key concept • Measurement method • Specific measurement method • Method innovation • Variables used • Validation
Results and conclusion	• Findings • Conclusion • Adaptation strategies
Relevance	• Reviewer name • Date Reviewed • Reviewer's comments • Relevance to index creation • Relevance to adaptation strategies

In addition to the review table, we designed a resilience indicator summary table to record the resilience indicators if they were used in an article. In this table, indicators were classified into seven categories: social, economic, institutional, infrastructure, community, environmental, and other. The classification of resilience indicators was based on several proposed resilience measurement frameworks and indices, including the Baseline Resilience Indicators for Communities (BRIC) (Cutter et al., 2010), the Resilience Inference Measurement

(RIM) index (Cai et al., 2016; Lam et al., 2016), and the variables used in Sherrieb et al. (2010). During the review process, a reviewer put '1' under an indicator if it was used in an article.

Then, basic content analysis techniques on the review table and the indicator table, such as descriptive statistics, word cloud, and cross-tabulation, were used to derive consensus and new knowledge on community resilience definition, measurement methods developed, resilience indicators, and adaptation strategies proposed or adopted. The full list of articles, review table summary, and indicator summary table can be obtained from the authors.

3. Results

3.1 Overall summary

Table 2 lists the most cited articles in the reviewed collection. The number of times cited were recorded from the *Web of Science* in January 2017. These citation statistics suggest, to a large extent, the research emphases during the 12-year period.

Table 2. Ten most cited articles in the current collection

Publication year	Paper title	Authors	Publication name	Number of citations
2008	Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness	Norris FH, Stevens SP, Pfefferbaum B, et al.	American Journal of Community Psychology	888
2005	Social-Ecological Resilience to Coastal Disasters	Adger WN, Hughes TP, Folke C, et al.	Science	735
2008	A place-based model for understanding community resilience to natural disasters	Cutter SL, Barnes L, Barry M, et al.	Global Environmental Change	706
2007	Adaptation to environmental change: contributions of a resilience framework	Nelson DR, Adger WN, Brown K, et al.	Annual Review of Environment and Resources	633
2006	Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change	Janssen MA, Schoon ML, Ke W, et al.	Global Environmental Change	215
2010	Community Resilience: An Indicator of Social Sustainability	Magis K.	Earthquake Spectra	192

2010	Framework for analytical quantification of disaster resilience	Cimellaroa GP, Reinhornb AM, Bruneauc M.	Engineering Structures	188
2010	Disaster Resilience Indicators for Benchmarking Baseline Conditions	Cutter SL, Burton CG, Emrich CT.	Journal of Homeland Security and Emergency Management	162
2010	Measuring Capacities for Community Resilience	Sherrieb K, Norris FH, Galea S.	Social Indicators Research	130
2011	From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world	Ahern J.	Landscape and Urban Planning	125

A word cloud (also known as text cloud or tag cloud) is useful to revealing the most commonly used terms and their relative frequencies within a context. The more frequent a word appears in a source of textual data, the bigger and bolder it appears in the word cloud. The word cloud in Figure 1 was derived from the abstracts of all the 174 articles. Words of higher frequency are displayed in larger font.

As expected, resilience, community, disaster, and vulnerability were the most frequently appeared words and they are shown with the biggest font. Middle-font words are of second-highest frequency, and they included words such as adaptation, sustainability, mitigation, system, management, and capacity. Other middle-font words refer to the disaster type, which included words such as hurricane, flood, and earthquake. Smaller-font words included response, indicator, framework, social, natural, model, physical, health, recovery, ecological, and infrastructure, which are also considered important in resilience studies.

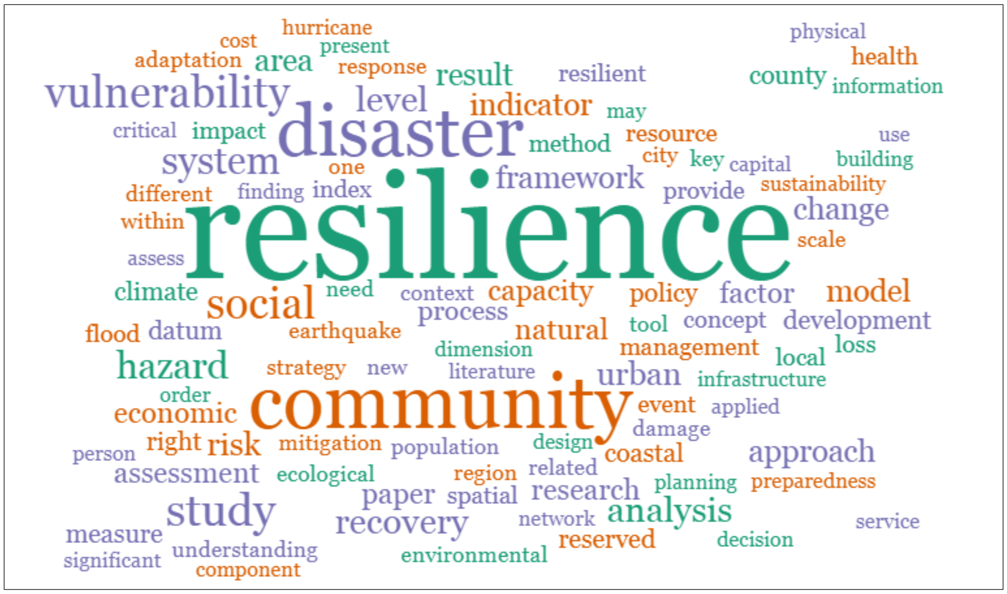

Figure 1. Word cloud derived from the abstracts of the reviewed 174 articles

We tabulated the information items on publication information and research context to gain knowledge about the research object, disaster type, research country, and study scale. Of the 174 articles, 104 of them studied the resilience of a community, which is viewed as the totality of social system interactions within a defined geographic space such as a neighborhood, census tract, city, or county. The remaining articles focused on the following: 16 on the resilience of urban systems, 13 on the resilience of an infrastructure (road network, buildings, electric power system, etc.), 11 on the resilience of an individual or a household, and 4 articles on the resilience of economy. The other research objects included government, social-ecological system, marine habitats, and others. A total of 15 articles did not specify any research object.

Table 3. Research object summary

Research object	No. of articles (%)
Community	104 (59.8)
Infrastructure	13 (7.5)
Individual/household	11 (6.3)
Urban system	16 (9.2)
Economy	4 (2.3)

Others (government, ecosystem, social-ecological system, etc)	11 (6.3)
Not specified	15 (8.6)

Table 4 lists the disaster types and their percentages. About 42% of the articles studied the resilience to general disaster. Coastal disasters and earthquake are the other two major disaster types. The category ‘Others’ includes disaster types such as heatwave, volcano, mangroves conversion, flu, management scenarios, water pollution, and chemical spill, with each disaster type being discussed in only one article.

Table 4. Disaster type summary

Disaster type	No. of articles (%)
General disaster	73 (42.0)
Coastal disaster	41 (23.6)
Earthquake	26 (14.9)
Climate change	6 (3.4)
Social event	6 (3.4)
Oil spill	5 (2.9)
Drought	3 (1.7)
Landslide	2 (1.1)
Fire	2 (1.1)
Others	10 (5.7)

Table 5. Country of research object summary

Country	No. of articles (%)
America	74 (42.5)
Australia	16 (9.2)
China	17 (9.8)
UK	12 (6.9)
Italy	10 (5.7)
Canada	8 (4.6)
Japan	7 (4.0)
Switzerland	3 (1.7)

Germany	2 (1.1)
New Zealand	2 (1.1)
Parkistan	2 (1.1)
Swedan	2 (1.1)
Iran	2 (1.1)
Others	17 (9.8%)

Regarding the research object, results in Table 5 show that 42.5% of the articles studied America, with Australia being the second highest one (9.2%). In terms of geographical scale, 28 articles studied the community level, 4 at the state/province level, 15 at the county level, 13 at the city level, 5 at the block group level, and 17 at the individual or household level (Table 6).

Table 6. Study scale summary

Geographical scale	No. of articles (%)
Community	28 (16.1)
State/province	4 (2.3)
County	15 (8.6)
City	13 (7.5)
Block group	5 (2.9)
Individual/Household	17 (9.8)
Facility	9 (5.2)
Others	32 (18.4)
Not specified	51 (29.3)

Table 7. Discipline summary

Discipline	No. of articles and percentages
Environmental Science	37 (21.26)
Geography	25 (14.37)
Health	16 (9.20)
Civil Engineering	14 (8.05)
Sociology	13 (7.47)
Urban Planning	11 (6.32)
Business and Administration	7 (4.02)

Interdisciplinary	6 (3.45)
Economics	6 (3.45)
Architecture	5 (2.87)
Psychology	4 (2.30)
Political Science	4 (2.30)
Education	3 (1.72)
Electronics and Automation	3 (1.72)
Disaster	3 (1.72)
Marine Science	2 (1.15)
Forestry	2 (1.15)
Tourism	2 (1.15)
Communication	2 (1.15)
Others	9 (5.17)

The article by discipline table (Table 7) shows that Environmental Science and Geography were the two disciplines dominating the literature on disaster resilience, followed by Health Sciences, Civil Engineering, Sociology, and Urban Planning.

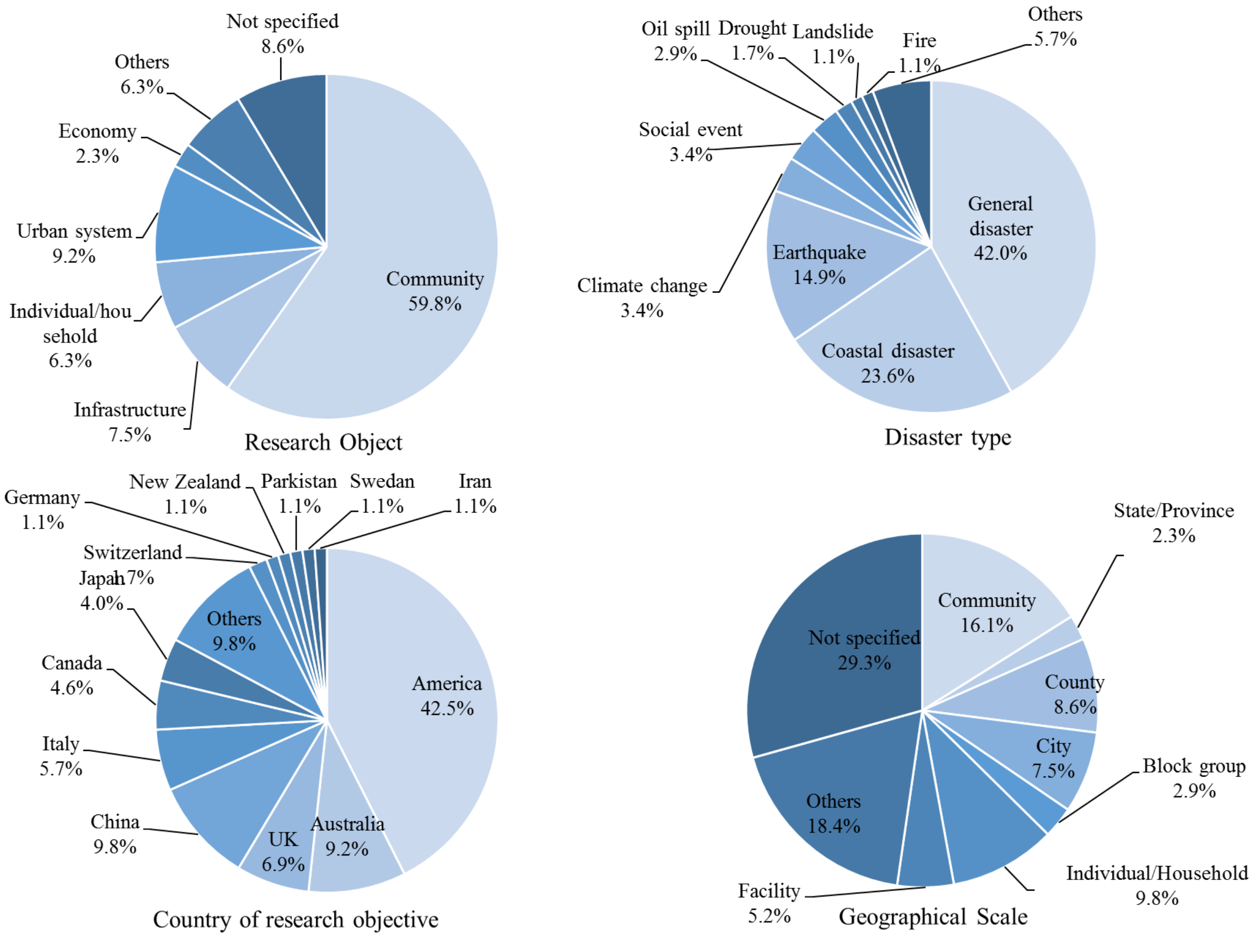

Figure 2. Overall summary

3.2 Resilience Definition

In answering our first research question of "what were the common definitions of resilience across disciplines and hazard types", the results show that most articles (161 out of 174) have attempted to define resilience, either directly or indirectly. Table 8 summarizes the most frequently used words in defining resilience across disciplines and disaster types. The first row lists the top 10 frequently used words in all the literature, which included ability, capacity, system(s), disaster, recover, social, absorb, change, vulnerability, and adapt. Figure 3 is the word cloud derived from the texts on resilience definitions, showing the frequently used words and their relative frequencies proportional to their font sizes. Table 9 lists the definitions, which further reinforces that "ability", "capacity", and "system" are essential elements in resilience measurement and analysis.

To further understand definitions of resilience across disciplines and hazard types, we used the same word frequency method to analyze the most frequently used words in defining resilience across the top three disciplines and hazard types. As shown in Table 4 and Table 7, the top three disciplines were environmental science, geography, and health, whereas the top three disaster types were general disaster, coastal disaster, and earthquake. The results (Table 8) show that 'system', 'ability', 'capacity', and 'recover' remained as the most frequently used words in defining resilience, regardless the discipline or disaster type.

Table 8. Top 10 frequently used words and number of articles used in resilience definition by discipline and hazard type

All (174 articles)		System (97)	Ability (90)	Capacity (74)	Disaster (54)	Recover (53)	Social (48)	Absorb (40)	Change (30)	Vulnerability (29)	Adapt (26)
Top 3 disciplines	Environmental science (37 articles)	System (26)	Capacity (18)	Ability (18)	Community (16)	Vulnerability (12)	Absorb (12)	Social (10)	Ecological (10)	Adapt (9)	Recover (8)
	Geography (25 articles)	System (19)	Ability (19)	Recover (12)	Disaster (11)	Capacity (11)	Absorb (11)	events (9)	Social (8)	Community (8)	Respond (7)
	Health (16 articles)	Community (18)	Ability (13)	Recover (7)	Social (4)	Resist (4)	Psychological (4)	Disaster (7)	Bounce (4)	System (4)	Risk (3)
Top 3 disaster types	General disaster (73 articles)	Ability (43)	System (44)	Capacity (29)	Disaster (36)	Social (23)	Recover (36)	Vulnerability (15)	Absorb (14)	Adaptive (12)	Hazard (20)
	Coastal disaster (41 articles)	Ability (20)	Capacity (18)	Social (13)	Recover (12)	Absorb (12)	Disaster (10)	Community (10)	System (17)	Hazard (14)	Adapt (8)
	Earthquake (26 articles)	Ability (12)	Recover (9)	Absorb (8)	Vulnerability (7)	Cope (7)	Disaster (11)	Shock (6)	Capacity (5)	Natural (5)	Disturbance (4)

Figure 3. Word cloud derived from the definition of 'resilience' from the 174 articles

Table 9. Definition of resilience from the ten most-cited articles

Article title	Definition of resilience
Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness (Norris FH et al. 2008)	Community resilience is a process linking a network of adaptive capacities (resources with dynamic attributes) to adaptation after a disturbance or adversity.
Social-Ecological Resilience to Coastal Disasters (Adger et al. 2005)	Resilience is the capacity of linked social-ecological systems to absorb recurrent disturbances such as hurricanes or floods so as to retain essential structures, process, and feedbacks.
A place-based model for understanding community resilience to natural disasters (Cutter et al. 2008)	Resilience is defined as the capacity of an individual (or community) to adapt (by resisting or changing) in order to reach and maintain its survival and functioning, the social aspect less formally relates to the capacity of individuals to recover with minimal disruptions.
Adaptation to environmental change: contributions of a resilience framework (Nelson et al. 2007)	Resilience is the amount of change a system can undergo and still retain the same function and structure while maintaining options to develop.
Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change (Janssen et al. 2006)	Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb change of state variable, driving variables, and parameters, and still persist.
Community Resilience: An Indicator of Social Sustainability (Magis K. 2010)	Community resilience is the existence, development and engagement of community resources by community members to thrive in an environment characterized by change, uncertainty, unpredictability, and surprise.
Framework for analytical quantification of disaster resilience (Cimellaro GP et al. 2010)	Resilience is defined as a function indicating the capability to sustain a level of functionality or performance for a given building, bridge, lifeline networks, or community, over a period defined as the control time that is usually decided by owners, or society (usually is the life cycle, life span of the system).

Disaster Resilience Indicators for Benchmarking Baseline Conditions (Cutter et al. 2010)	Resilience is as a set of capacities that can be fostered through interventions and policies, which in turn help build and enhance a community's ability to respond and recover from disasters.
Measuring Capacities for Community Resilience (Sherrieb K, Norris FH, Galea S. 2010)	Resilience is the community's ability to "bounce back" from severe stress, which includes four adaptive capacities: Economic Development, Social Capital, Information and Communication.
From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world (Ahern J. 2011)	Resilience is the capacity of systems to reorganize and recover from change and disturbance without changing to other states-- in other words, systems that are "safe to fail."

3.3 Resilience Measurement method

To answer the second question of "what were the common approaches to resilience measurement, and have the proposed resilience indices been validated with empirical evidence", we analyzed whether the measurement method was qualitative or quantitative and whether the measurement method has been validated with empirical evidence, either quantitatively or qualitatively. Table 10 tabulates the number of articles by the type of measurement method and the three major types of disasters (general disasters, coastal disasters and earthquake). Results show that 69 articles (39.7%) used qualitative methods, about the same number of articles (68) used quantitative methods, and 22 articles (12.6%) used both. (We note that the measurement methods discussed here do not necessarily mean that the articles had created a single or several indices.) Of the 73 articles studying general disasters, qualitative method was the top approach used (accounting for 45.2%). When the disaster type was specified as coastal or earthquake, the most commonly used approach was quantitative (accounting for 56.1% and 50% respectively).

Table 10. Measurement approach by disaster type summary

Method	No. of articles (%)			
	All articles	General disaster	Coastal disaster	Earthquake
Qualitative	69 (39.7%)	33 (45.2%)	12 (29.3%)	8 (30.8%)
Quantitative	68 (39.1 %)	21 (28.8%)	23 (56.1%)	13 (50%)
Both	22 (12.6%)	11 (15.1%)	5 (12.2%)	2 (7.7%)
Not specified	15 (8.6%)	8 (11%)	1 (2.4%)	3 (11.5%)
Total #articles	174	73	41	26

Survey questionnaire, in-depth interview, and focus group discussion were the three major qualitative resilience measurement methods used. Other qualitative methods also included self-assessment and comparative analysis. Quantitative studies often involved statistical and data mining methods, with correlation and multivariate regression analyses being most frequently used. The 22 articles that used mixed methods often involved using qualitative methods to derive indicators (e.g., interview, focus group, Delphi study), followed by quantitative methods to calculate the resilience index (e.g., weighted aggregation, principal component analysis, multiple regression).

A major challenge of resilience measurement is empirical validation, which is needed to verify if the index developed reflects the real conditions of damage and recovery. Empirical validation of resilience index and models with external reference data has been a persistent challenge. Only 18 of the 174 articles (10.3%) have done validation either in a qualitative or quantitative manner. We highlight four articles below to demonstrate the different approaches to resilience measurement. Appendix Table A1 lists the 18 articles.

First, as an example of resilience measurement study using qualitative method, Harte et al. (2009) conducted a case study of community resilience to fire hazard in an informal settlement, Imizamo Yethu in Cape Town, South Africa. To identify factors that may enhance community resilience, a field-based research survey was conducted five months after a major fire in 2004. The sampling was based on a ‘snow-balling’ technique, whereby an intermediary introduced the researcher to several families affected by the fire, and they in turn introduced more families. A total of 30 households were interviewed. Respondents were asked to nominate the most important factors that had enabled them to survive in the response and recovery phases of the 2004 fire. It was found that social networks, such as community institutions that foster community participation, and the resourcefulness of individuals were the most important factors underpinning resilience.

Cutter et al. (2014) developed the Baseline Resilience Indicators for Communities (BRIC) to quantitatively measure the inherent resilience of counties in the United States. BRIC comprises a common set of variables in six different domains or capitals - social, economic, housing and infrastructure, institutional, community, and environmental. First a sub-index for each capital at the county level was constructed by transforming the raw variables within each capital into 0-1 and assigning their positive or negative contributions to resilience. The combined arithmetic mean value of the variables resulted in a sub-index score. The six sub-index scores were then summed to construct a final composite resilience score using an equally weighted average method. The study reveals that counties in the Midwest and Northeast US had higher levels of inherent resilience than counties in the west or the south. BRIC provides a reference point for examining the current status of inherent resilience at the county level. However, the BRIC index lacks validation with external data. In other words, the selected variables have not been empirically tested; their positive or negative contributions to resilience scores were only theoretically assessed. Therefore, it is difficult to determine if the BRIC index can reflect the actual level of resilience of a community.

Burton (2015) measured the community resilience to Hurricane Katrina by census block-group for the counties bordering the Gulf coast in the State of Mississippi. His study is an example of using empirical data to validate the development of a resilience index. In his study, recovery was defined as the process of reconstructing communities to livelihoods and the built environment to the pre-disaster states. Field work was conducted at multiple time periods to document the spatial and temporal dimensions of the recovery process from 2006 to 2010. Five levels of recovery ranging from no recovery to full recovery were used. Through regression analyses, 41 out of the original 64 variables were identified as being statistically associated with the recovery process, thus they were included in the resilience measurement. Six subcomponents of the resilience index, including economic, institutional, infrastructure, community, and environmental components, were derived and the final resilience score was the summation of equally weighted average subcomponent scores. The aggregated index scores enable a comparative assessment of the resilience of the block groups in the study area.

Lam et al. (2016) documented the development of a new resilience measurement framework called the Resilience Inference Measurement (RIM) model. It is another example of using a statistical approach to derive a resilience index that also has empirical validation. The RIM model starts with collecting real data of three elements (hazard threat, damage, and recovery) for each community. K-means analysis is used to derive the resilience ranking of each community based on these three elements. Then, discriminant analysis is used to extract the social-ecological variables that best characterize the resilience ranking of a community. The discriminant functions derived can be used to compute the resilience score of each community. The same functions can be used to estimate the resilience scores of other study areas or at different time periods, provided that the assumptions of the statistical models are met. Thus, the RIM model also has an inferential ability. The RIM model has been applied to measure the community resilience to coastal hazards for the counties along the Gulf of Mexico (Lam et al., 2016), the census block-group communities in the Lower Mississippi River Basin (Cai et al., 2016), and the Caribbean countries (Lam et al., 2015). The same model has also been applied to measure the community resilience to the 2008 Wenchuan earthquake in China (Li et al., 2016) and drought resilience of the southwestern counties in the U.S. (Mihunov et al., 2017).

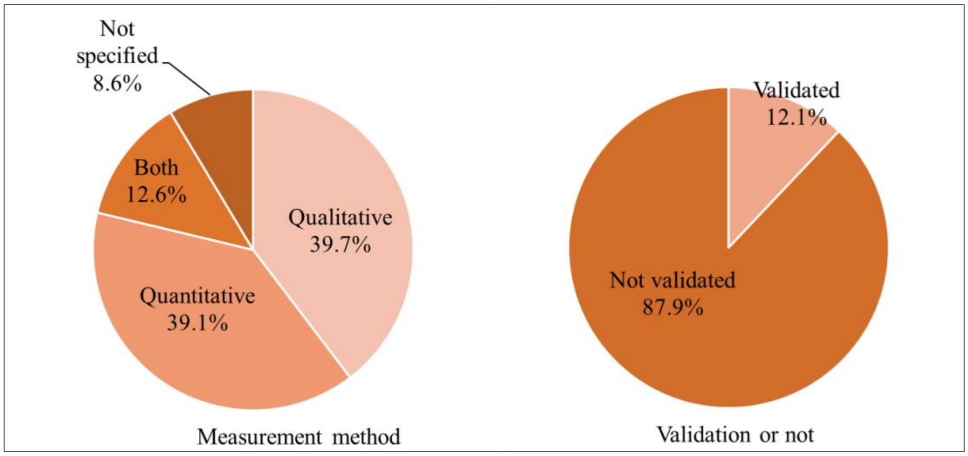

Figure 4. Measurement method summary

3.4 Resilience indicators

Regarding the third question of "what were the most commonly used indicators to evaluate resilience", the results show that 101 articles have used indicators in their analysis. We recorded from each of the 101 articles the indicators used and categorized them into seven categories, including social, economic, institutional, infrastructure, community, environmental/ecological, and others. Table 11 shows the resilience indicators used over 20 times in rank order.

Table 11. Most frequently used resilience indicators in rank order

Category	Most frequently used indicators	Specific indicator example	#times used
Economic	Income	Median household income	49
Economic	Employment	% labor force employed	44
Social	Education	% over 25 years old no schooling completed	43
Social	Age	% population 65 years and over	41
Institutional	Previous disaster experience	Disaster frequency	38
Infrastructure	Shelter capacity	Hotels/motels per 10,000 persons	28
Institutional	Social connectivity	% 1-person household	26
Social	Communication capacity	% Households with telephone service available	25
Institutional	Municipal service	% municipal expenditures for fire, police, and EMS	25
Community	Place attachment	% Population born in state of current residence	25
Infrastructure	Transportation access	% Households with at least one vehicle	23

Institutional	Mitigation	% population covered by Citizen Corps programs	23
Economic	Housing capital	% homeownership	22
Infrastructure	Medical capacity	Hospital beds per 10,000 persons	21
Infrastructure	Recovery	Debris removal	21
Community	civic involvement	Civic organizations per 10,000 persons	21

Two economic indicators, income and employment, were used over 40 times. Another popular economic indicator was housing capital. Commonly used social indicators included education, age, and communication capacity. Some institutional indicators were also considered to be very important, such as previous disaster experience, mitigation, municipal service, and social connectivity. The infrastructure component played a critical role in resilience index construction, with high usage found in four indicators, including shelter capacity, transportation access, medical capacity, and recovery. Place attachment and civic involvement were the two commonly used indicators in the community capital category. The frequency table for all the indicators is attached as Appendix Table A2.

Table 12 tabulates the top five indicators used in the top three disaster types (general disaster, coastal disaster, and earthquake) to see if the disaster type affects the associated indicators. The results reveal that education, income, and employment have gained consensus from researchers across disaster types. Previous disaster experience is also an important indicator in resilience measurement since it reflects the adaptation and learning ability of a community or a system from previous events.

Table 12. Most frequently used indicators used in the top three disaster types

Disaster type	Top 5 indicators used	#times used
General disaster	Education	22
	Income	22
	Previous disaster experience	20
	Community capacity	19
	Employment	19
Coastal disaster	Age	11

	Recovery	11
	Employment	10
	Income	9
	Previous disaster experience	9
Earthquake	Income	9
	Employment	6
	Education	5
	Housing capital	4
	Age	4

3.5 Adaptation strategies

To address the fourth research question of "what adaptation strategies have been proposed to improve resilience", we used the two information items in the review table: Relevance to index creation and Relevance to adaptation strategies. For Relevance to index creation, a reviewer assigns a grade from 1 to 3 to each article, with 1 indicating no index creation, 2 indicating somewhat relevant to index creation, and 3 denoting that the index was created using quantitative method. Similarly, for Relevance to adaption strategies, 1 denotes no adaptation strategies suggested, 2 means the article discusses general strategies, and 3 means the article points out specific strategies. Results show that 54.6% of all the articles did not focus on index created, whereas only 17.8% of all the articles created resilience index using quantitative method (Table 13). Similar ratios existed for Relevance to adaptation strategy, where 53.4% of the articles did not suggest adaptation strategies, 27.0% discussed general strategies, and 19.5% pointed out specific strategies (Table 14).

Table 13. Relevance to the creation of quantitative resilience index summary

Relevance to the creation of quantitative resilience index	No. of articles (%)
No index creation	95 (54.6)
Somehow relevant	48 (27.6)
Index created using quantitative method	31 (17.8)

Table 14. Relevance to adaptation strategy summary

Adaptation strategy	No. of articles (%)
No adaptation strategies suggested	93 (53.4%)
Discussed general strategies	47 (27.0%)
Pointed out specific strategies	34 (19.5%)

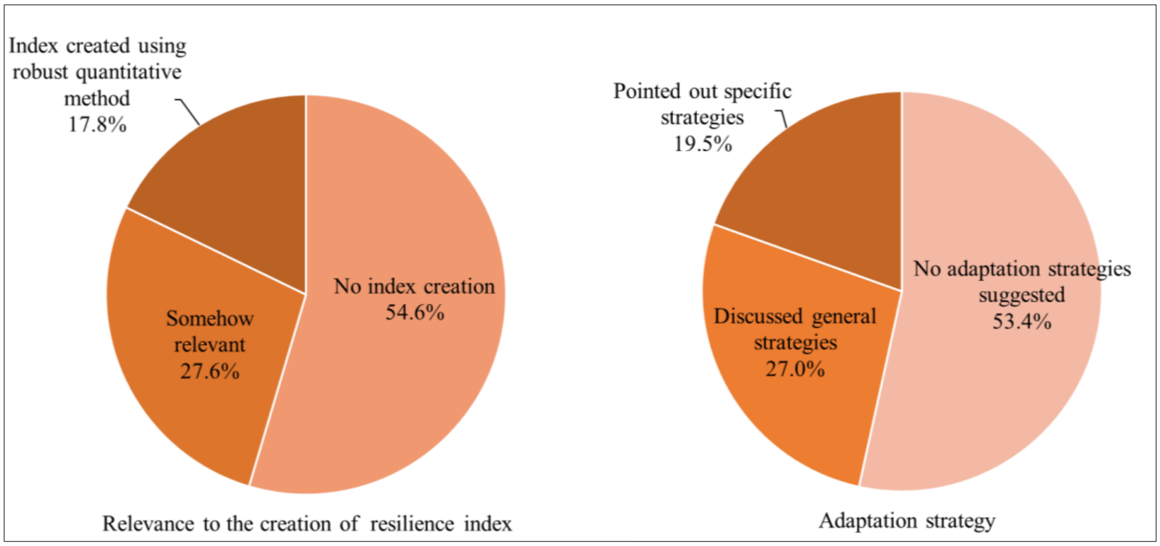

Figure 5. Index creation and adaptation strategy summary

Table 15. Cross-tabulation of Relevance to resilience index and Relevance to adaptation strategies

	Relevance to adaptation strategies			
Relevance to the creation of resilience index	No adaptation strategies suggested	Discussed general strategies	Pointed out specific strategies	No. of articles
No index creation	57 (60.0%)	27 (28.4%)	11 (11.6%)	95
Somewhat relevant	23 (47.9%)	10 (20.8%)	15 (31. 3%)	48
Index created using quantitative method	13 (41.9%)	10 (32.3%)	8 (25.8%)	31
No. of articles	93 (53.4%)	47 (27.0%)	34 (19.5%)	174

* Percentage values in parentheses were calculated using the row sum (# articles in each category of index creation)

Table 15 is a cross-tabulation of Relevance to resilience index creation with Relevance to adaptation strategies. The table shows that of the 95 articles that had no index created, only 11 articles (11.6%) pointed out specific strategies. The ratio increased to 31.3% (15 out of 48) in the category of Somewhat relevant to index creation, but down to 25.8% (8 out of 31) in the category of Index created using quantitative method. A full list of the 8 articles which had index creation with quantitative method as well as specific adaptation strategies suggested is included in Appendix Table A3. Below we describe briefly two examples from the list.

Ainuddin and Routray (2012) measured the community resilience to earthquake in two earthquake risk zones in Baluchistan. Their study first calculated the sub-component resilience indices for four subcomponents (i.e., social, economic, institutional, and physical), and then aggregated them into a composite community resilience index for the two zones. Based on the findings, the authors recommended a number of adaptation strategies, including improving the socioeconomic, institutional, and structural (housing) conditions of the community by raising the community awareness and preparedness, implementing building codes, and providing income-generating activities to enhance the community resilience to cope with earthquake hazards in the future.

DasGupta and Shaw (2015) used an indicator-based approach to assess coastal communities' resilience to climate related disasters of 19 coastal administrative blocks in Sundarbans, India. The study concluded with several broad adaptation strategies, including empowering local level institutions, providing adequate training and resources to initiate the adaptation planning, and strengthening community infrastructure and communication, the latter of which will help promote diversification of livelihood and create new employment opportunities.

The most frequently recommended adaptation strategies were as follows. First, local governments and leaders play an important role in adaptation planning and they need to be empowered, trusted, and given resources to. A series of mitigation programs and activities would need to be initiated by local governments and leaders. Second, raising community awareness and promoting resident education were considered to be an important strategy, which would help residents prepare for future disasters. Third, enhancing community infrastructure and communication was mentioned by several studies. It is a practical way to strengthen the physical capital (e.g., by increasing dam efficiency and road accessibility), while simultaneously promote the social and economic capital (e.g., by creating new employment opportunity and increasing livelihood diversification). Additional specific strategies were also mentioned, which included recruiting more spokespersons to explain disaster risk and mitigation in the language the community uses, encouraging personal savings as a reserve for emergency purpose, increasing communication effectiveness between government and community.

4. Discussion

This synthesis analysis presents a comprehensive picture of past efforts to measure disaster resilience. The diverse study objects, disaster types, geography scales, measurement methods developed, resilience indicators tested, and adaptation strategies recommended show that researchers have collectively devoted great efforts in addressing resilience measurement issues. At the same time, this analysis reveals that challenges in several domains still need to be addressed, and that more future research on these knowledge gaps is necessary.

First, the tabulation of resilience definitions across disciplines and disaster types indicates that although there are discrepancies in the definition of resilience, some common concepts have been used repeatedly across disciplines and disaster types. For example, ‘ecological’ is often considered important in the resilience definition by researchers from Environmental Science. Health researchers have frequently used the word ‘psychological’ when defining resilience to external disturbances or extreme events. The measurement approaches on general disasters were more often qualitative than quantitative, while the quantitative approaches were more frequently used when the disaster type was specified (e.g. coastal, earthquake).

Second, our findings reveal that only 45% of the 174 studies have attempted to create quantitative resilience indices (Table 13), despite that our search focused on resilience measurement. More importantly, very few (10.3%, or 18 articles) have used empirical methods to validate the resilience indices derived. Without validation, it is difficult to use the indices as reliable decision making tools. The difficulty of validation arises from several factors, including varying definitions of relevant concepts and data unavailability. Resilience itself is an abstract concept and is not directly observable (Burton, 2015; Lam et al., 2016; Cai, et al., 2016). Although our study helps in identifying the common concepts and terms used to define resilience (e.g., ability, capacity, system, and so on), these various concepts are also complex, multidimensional, and difficult to measure. For example, recovery is considered a critical component in resilience measurement and could serve as an external indicator for validation (Elizabeth and Javernick-Will, 2013; Lam et al., 2016). Some researchers have tried to use post-disaster population change or multi-period field work observation as feasible recovery measures, whereas others would find them not sufficient to capture the holistic picture of recovery (Burton, 2015; Cai et al., 2016; Li et al., 2016).

Third, data unavailability is another obstacle in resilience measurement and validation. For instance, researchers have used economic damage from disaster as a means of validating the indices. However, getting reliable damage data across different spatial and temporal scales is difficult. For fine-scale comparison, such as census-tract or block-group levels, various interpolation methods may need to be applied, which would result in error and uncertainty.

Improving data quality and availability is a top priority that should help advance the resilience studies.

Fourth, for the studies that developed resilience indices and measurement frameworks, few of them have considered the inferential ability (Lam et al., 2016). Most existing studies focused on measuring resilience in a certain region and at a certain scale without deriving inferential rules or equations for further use. Developing inferential models will not only enable the comparison of resilience at different locations but also provide the ability to predict future resilience when some conditions change. More research should be devoted to exploring the use of inferential statistical techniques such as regression analysis to help improve resilience measurement.

Fifth, another issue identified from the synthesis review is the gap between science and practice. Very few of the derived indices have been applied in real-world practice. Given that resilience measurement is intended to serve decision making in risk reduction and mitigation, there is a pressing need to translate the scientific findings into practical actions (Brujin et al., 2017). Of the 174 articles, only 8 articles have both created quantitative resilience index and proposed specific strategies. It has been reported that some practitioners found it easier to visualize individual variables than utilizing a composite resilience index for planning and management (Frazier et al., 2013). This may be due to the fact that the indices derived are difficult to apply and the casual relationships among variables are unclear. Finding an index that is easily applicable and meaningful remains to be a difficult challenge that needs to be tackled. It will take deeper and better understanding of the underlying resilience process and close collaboration between resilience researchers and practitioners to help bring the scientific products into practice.

Finally, to yield better understanding of the underlying resilience process, we need to extend resilience measurement from static measurement to system dynamic modeling (Cai et al., 2018; Lam et al., 2018; Li and Lam, 2017). Resilience is a dynamic process within a complex social-environmental system. However, for resilience measurement purpose, most studies viewed it as a static phenomenon and applied pre-event conditions to depict the state at a particular time (Cutter et al., 2008). These traditional snapshot measurement methods, while very useful, will not be able to capture the underlying interactions among different components within a system. To achieve a sound understanding of the resilience process, dynamic system modeling of how natural and human components coupled is the next step and is a vital component that needs future research.

5. Conclusion

This synthesis study aimed to derive commonalities and new knowledge from the fragmented body of literature on resilience measurement. Through analyzing 174 articles collected for the period 2005-2017, we found the following. First, the frequently used words to define resilience included (from the most frequent to the least) ability, capacity, system, disaster, recover, social, absorb, change, vulnerability, systems, and adapt. Second, regarding resilience measurement, 39.7% of the articles used qualitative methods and a similar amount of articles (39.1%) used quantitative methods, but only 10.3% (18) of the 174 articles have conducted validation in either a qualitative or a quantitative manner. Third, the most frequently used indicators used in resilience measurement were income, employment, education, age, and previous disaster experience. Fourth, the three most commonly suggested adaptation strategies were empowering local government and leaders, raising community awareness and promoting resident education, and enhancing community infrastructure and communication.

Although this study is limited to the literature on resilience measurement within a short time period, it has generated several insights into future directions for resilience measurement research. These future directions include the need to include validation in resilience index construction, the need to incorporate inferential ability in the measurement method, the need to make the method applicable and useful in practice, and the need to obtain better understanding of resilience process through dynamic modeling. Finally, building on this synthesis study, a future research step could be to develop an ontology to represent the knowledge on resilience measurement. Such a disaster resilience ontology can explicitly represent the knowledge structure of resilience and help improve the design of the database, search engine, and information management for resilience studies. The ontology could also benefit communication and sharing of research outcomes across different disciplines, identify future directions for research, and support moving knowledge into decision making.

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References

Ainuddin S, Routray JK. 2012. Earthquake hazards and community resilience in Baluchistan. *Natural Hazards* 63:909-937.

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. *Annals of the Association of American Geographers* 105(1): 67-86.

Bruijn KD, Buurman J, Mens M, Dahm R, Klijn F. 2017. Resilience in practice: Five principles to enable societies to cope with extreme weather events. *Environmental Science & Policy* 70 :21-30.

Cai H, Lam NSN, Zou L, Qiang Y, Li K. 2016. Assessing community resilience to coastal hazards in the Lower Mississippi River Basin. *Water* 8 (2): 46.

Cai H, Lam NSN, Zou L, Qiang Y. 2018. Modeling the dynamics of community resilience to coastal hazards using a Bayesian network. *Annals of the American Association of Geographers.* DOI: 10.1080/24694452.2017.1421896.

Cutter SL, Barnes L, Berry M, Burton C, Evans E, Tate E, Webb J. 2008. A place-based model for understanding community resilience to natural disasters. *Global Environmental Change* 18:598–606.

Cutter SL, Burton CG, Emrich CT. 2010. Disaster resilience indicators for benchmarking baseline conditions. *Journal of Homeland Security and Emergency Management* 7(1):51.

Cutter SL, Ash KD, Emrich CT. 2014. The geographies of community disaster resilience. *Global Environmental Change* 29: 65-77.

Drake MA. 2004. Encyclopedia of Library and Information Science. New York, N.Y.: Marcel Dekker.

DasGupta R, Shaw R. 2015. An indicator based approach to assess coastal communities' resilience against climate related disasters in Indian Sundarbans. *Journal of Coastal* Conservation 19:85-101.

Elizabeth J, Javernick-Will, A. 2013. Indicators of community recovery: Content analysis and Delphi Approach. *Nature Hazards Review* 14:21–28.Tim G. Frazier, Courtney M.

Thompson, Ray J. Dezzani, Danielle Butsick. 2013. Spatial and temporal quantification of resilience at the community scale. *Applied Geography* 42: 95-107.

Harte E, Childs IRW, Hastings PA. 2009. Imizamo Yethu: a Case Study of Community Resilience to Fire Hazard in an Informal Settlement Cape Town, South Africa. *Geographical Research* 47: 142–154.

Jordan E, Javernick-Will A. 2013. Indicators of Community Recovery: Content Analysis and Delphi Approach. *Natural Hazards Review* 14(1):21-28.

Kemp WM, Boynton WR. 2012. Synthesis in estuarine and coastal ecological research: What is it, why is it important, and how do we teach it? *Estuaries and Coasts* 35:1-22.

Lam NSN, Qiang Y, Arenas H, Brito Patricia, Liu KB. 2015. Mapping and assessing coastal resilience in the Caribbean region. *Cartography and Geographic Information Science* 42(4): 315-322.

Lam NSN, Reams M, Li K, Li C, Mata L. 2016. Measuring Community Resilience to Coastal Hazards along the Northern Gulf of Mexico. *Natural Hazards Review* 17(1): 04015013.

Lam NSN, Qiang Y, Li K, Cai H, Zou L, Mihunov V. 2018. Extending resilience assessment to dynamic system modeling: Perspectives on human dynamics and climate change research. *Journal of Coastal Research*, Special Issue No. 85.

Li K, Lam NSN. 2017. A spatial dynamic model of population changes in a vulnerable coastal environment. *International Journal of Geographical Information Science* 32(4): 685-710. DOI: 10.1080/13658816.2017.1407415.

Li X, Lam NSN, Qiang Y, Li K, Yin L, Liu S, Zheng W. 2016. Measuring county resilience after the 2008 Wenchuan earthquake. *International Journal of Disaster Risk Science* 7(4): 393-412.

Mihunov V, Lam NSN, Zou L, Rohli RV, Bushra N, Reams MA, Argote J. 2017. Community Resilience to Drought Hazard in South-Central United States. *Annals of the American Association of Geographers* 107: 1-17

Nelson R, Kokic P, Crimp S, Martin P, Meinke H, Howden SM, de Voil P, Nidumolu U. 2009. The vulnerability of Australian rural communities to climate variability and change: Part II—7 Integrating impacts with adaptive capacity. *Environmental Science & Policy*.

Norris FH, Stevens SP, Pfefferbaum B, Wyche KF, Pfefferbaum RL. 2008. Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *American Journal of Community Psychology* 41:127-50.

Nyerges T, Roderick M, Prager S, Bennett D, Lam NSN. 2014. Foundations of sustainability information representation theory: spatial-temporal dynamics of sustainable systems. *International Journal of Geographic Information Science* 28(5): 1165-1185.

National Research Council (NRC). 2012. Disaster Resilience: A National Imperative. Washington, DC: The National Academies Press.

Sherrieb K, FH Norris, Galea S. 2010. Measuring capacities for community resilience. *Social Indicators Research* 99:227-247.

Appendices

Table A1. The 18 articles with resilience measurement validation

Authors	Year	Title
Sherrieb K, Norris FH, Galea S.	2010	Measuring Capacities for Community Resilience
Gómez-Baggethun E, Reyes-García V, Olsson P, et al.	2012	Traditional ecological knowledge and community resilience to environmental extremes: a case study in Donana, SW Spain
Zandt SV, Peacock WG, Henry DW, et al.	2012	Mapping social vulnerability to enhance housing and neighborhood resilience
Cohen O, Leykin D, Lahad M, et al.	2013	The conjoint community resiliency assessment measure as a baseline for profiling and predicting community resilience for emergencies
Sudmeier KI, Jaboyedoff M, Jaquet S.	2013	Operationalizing "resilience" for disaster risk reduction in mountainous Nepal
Ouyang M, Dueñas-Osorio L.	2014	Multi-dimensional hurricane resilience assessment of electric power systems
Price ADF, Achour N, Miyajima M, et al.	2014	Hospital resilience to natural hazards: classification and performance of utilities
Eisenman D, Chandra A, Fogleman S, et al.	2014	The Los Angeles County Community Disaster Resilience Project-A Community-Level Public Health Initiative to Build Community Disaster Resilience
Pfefferbaum RL, Pfefferbaum B, Nitiéma P, et al.	2015	Assessing community resilience: an application of the expanded CART survey instrument with affiliated volunteer responders
Reams MA, Lam NSN, Cale TM, et al.	2013	Applying a community resilience framework to examine household emergency planning and exposure-reducing behavior among residents of Louisiana's industrial corridor
Singh-Peterson L, Salmon P, Goode N, et al.	2014	Translation and evaluation of the Baseline Resilience Indicators for Communities on the sunshine coast, Queensland Australia
Alshehri SA, Rezgui Y, Li H.	2015	Disaster community resilience assessment method: a consensus-based Delphi and AHP approach
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
Lam NSN, Qiang Y, Arenas H, et al.	2015	Mapping and assessing coastal resilience in the Caribbean region
Lam NSN, Reams M, Li K, Li C, Mata LP.	2015	Measuring community resilience to coastal hazards along the Northern Gulf of Mexico
Cai H, Lam NSN, Zou L, Qiang Y, Li K.	2016	Assessing community resilience to coastal hazards in the Lower Mississippi River basin
Li X, Lam N,	2017	measuring county resilience after the 2008 Wenchuan earthquake

Qiang Y, Li K, et al.		
Song J, Huang B, Li R.	2017	Measuring recovery to build up metrics of flood resilience based on pollutant discharge data: a case study in East China

Table A2. Frequency of resilience indicator used in the literature

Category	Variable	Frequency
Social Resilience	Education	43
	Age	41
	Transportation access	23
	Communication capacity	25
	Language competency	13
	Special needs	17
	Health coverage	18
Economic Resilience	Housing capital	22
	Employment	44
	Income	49
	Single sector employment dependence	16
	Business size	13
	Health Access	18
Institutional Resilience	Mitigation	23
	Flood coverage	11
	Municipal service	25
	Political fragmentation	10
	Social connectivity	26
	Previous disaster experience	38
Infrastructure Resilience	Housing type	20
	Shelter capacity	28
	Medical capacity	21
	Access/evacuation potential	20
	Housing age	11
	Sheltering needs	13
	Recovery	21
Community capital	Place attachment	25
	Political engagement	19
	Social capital-religion	17
	civic involvement	21
	Social capital - advocacy	16
	Innovation	7
Environmental/Ecological	land loss	2

others	erosion rate/subsidence	5
	biodiversity	2
	impervious surface	2
	coastal defense structure	2
	land Use	14
	migration/mobility	2
	race/ethnicity	3
	crime	2
	early warning	9
	gender	6
	exposure to hazards	10

Table A3. The 8 articles with both resilience index created and specific adaptive strategies proposed

Authors	Year	Title
Yan L, Xu X.	2010	Assessing the vulnerability of social–environmental system from the perspective of hazard, sensitivity, and resilience: a case study of Beijing, China
Ainuddin S, Routray JK.	2012	Earthquake hazards and community resilience in Baluchistan
Sun Y, Zhou H, Wang J, et al.	2012	Farmers' response to agricultural drought in paddy field of southern China: a case study of temporal dimensions of resilience
Kusumastuti RD, Viverita, Husodo ZA, et al.	2014	Developing a resilience index towards natural disasters in Indonesia
Tong TMT, Shaw R, Takeuchi Y.	2012	Climate disaster resilience of the education sector in Thua Thien Hue Province, Central Vietnam
Dasgupta R, Shaw R.	2015	An indicator-based approach to assess coastal communities' resilience against climate related disasters in Indian Sundarbans
Lam NSN, Reams M, Li K, Li C, Mata LP.	2015	Measuring Community Resilience to Coastal Hazards along the Northern Gulf of Mexico
Kamh YZ, Khalifa MA, El-Bahrawy AN.	2016	Comparative Study of Community Resilience in Mega Coastal Cities Threatened by Sea Level Rise: The Case of Alexandria and Jakarta