INFRASTRUCTURE HAZARD RESILIENCE TRENDS: AN ANALYSIS OF 25 YEARS OF RESEARCH

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This is a post-peer-review, pre-copyedit version of an article published in *Natural Hazards*. The final authenticated version is available online at: https://doi.org/10.1007/s11069-017-2792-8

To cite this paper, please reference the version of record:

Opdyke, A., Javernick-Will, A., and Koschmann, M. (2017) "Infrastructure Hazard Resilience Trends: An Analysis of 25 Years of Research." *Natural Hazards*. 87 (2), 773-789. doi: 10.1007/s11069-017-2792-8

ABSTRACT

Hazard research has made significant strides over the last several decades, answering critical questions surrounding vulnerability and recovery. Recently, resilience has come to the forefront of scholarly debates and practitioner strategies, yet there remain challenges implementing resilience in practice, the result of a complex web of research that spreads across numerous fields of study. As a result, there is a need to analyze and reflect on the current state of resilience literature. We reviewed 241 journal articles from the Web of Science and Engineering Village databases from 1990 to 2015 to analyze research trends in geographic location of studies, methods employed, units of analysis, and resilience dimensions studied, as well as correlations between each of these categories. The majority of the studies analyzed were conducted in North America, used quantitative methods, focused on infrastructure and community units of analysis, and studied governance, infrastructure and economic dimensions of resilience. This analysis points to the need to: (1) conduct studies in developing country contexts and compare these contexts with developed nations; (2) employ mixed-methods for additional depth to quantitative studies; (3) connect units of analysis, such as infrastructure and community; and (4) expand on the measurement and study of environmental and social dimensions of resilience.

Keywords: resilience; infrastructure; literature review

1. INTRODUCTION

Disaster resilience has gained increasing recognition from policy makers, practitioners, and scholars as the path forward in hazard mitigation strategy (Arup 2014; Matyas and Pelling 2015; UNISDR 2015). In the face of climate change and growing urbanization, infrastructure resilience is increasingly important. Not only do infrastructure assets represent significant financial investments, they also provide essential societal value. Despite the pressing need to build resilient infrastructure, resilience remains abstract, creating challenges in actual implementation. This abstraction is partly derived from the complex web of research that has accumulated across disciplinary boundaries. Hazard scholars have studied resilience in diverse contexts, at different units of analysis, and using a spectrum of

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methods. These study characteristics represent more than just descriptive identifiers of studies; they have fundamentally shaped the existing resilience discourse.

While numerous fields have put forth definitions of disaster resilience, scholars have converged on a core understanding that resilience consists of resistive and adaptive capacities in economic, environmental, governance, infrastructure, and social systems (Romero Lankao 2010; Satterthwaite 2013; Jonkeren and Giannopoulos 2014; Kumaraswamy et al. 2015). In this paper, we draw upon this understanding, but focus more specifically on functionality of infrastructure, and define *resilience* as the resistive and adaptive capacities that support infrastructure functionality in times of crisis or stress, such as natural hazards. We do not attempt to challenge established definitions of the construct, but instead attempt to integrate and analyze the variety of research perspectives taken to study infrastructure resilience. By connecting different resilience perspectives, we hope to simultaneously reflect on gaps that exist in the body of knowledge. Towards these goals, we ask: *What trends exist in hazard literature on infrastructure resilience?* and *What gaps remain in the body of knowledge on infrastructure resilience*?

To address these questions, we will first summarize commonalities in resilience definitions and discuss five dimensions of resilience (economic, environmental, governance, infrastructure and social). We will then introduce our research method, which consisted of a systematic search of hazard literature, followed by the coding and analysis of 241 journal articles for resilience trends. Our analysis synthesizes trends in study location, research methods employed, units of analysis selected, and resilience dimensions studied. Additionally, we analyzed correlations within and between study locations, methods, units of analysis, and resiliency dimensions to determine interconnected themes that have characterized resilience studies over the last 25 years. Based upon the analysis and trends, we then discuss suggested directions for future research.

1.1. Defining Resilience

Definitions of resilience are scattered and often based on disciplinary boundaries, however, the core principles of resilience have remained consistent. Beginning in the 1970s, the concept of resilience emerged in hazard literature as "… *a measure of the persistence of systems and of their abilities to absorb change and disturbance and still maintain the same relationships between populations or state variables.*" (Holling 1973). Early hazard scholars grounded their work in ecological studies, but placed on an emphasis on *systems* – a guiding principle that is echoed in subsequent literature. Resilience made a surge in the late 1990s as social science scholars laid the foundation of a multidisciplinary approach to resilience. This era of research emphasized the local nature of resilience, such as Mileti's definition, "*Local resiliency with regard to disasters means that a locale is able to withstand an extreme natural event without suffering devastating losses, damage, diminished productivity, or quality of life and without a large amount of assistance from outside the community."* (Mileti 1999).

Building on the work of social science scholars, the first widely accepted definition of resilience from engineering stemmed from the Multidisciplinary Center for Earthquake Engineering Research (MCEER). The Center made a notable point to bound resilience at the community level and emphasize the role of social units, "*Community resilience to hazards is defined as the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of hazard-related disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future hazards."* (Multidisciplinary Center for Earthquake Engineering Research 2005). On the footsteps of MCEER's work, at the international level, the United Nations adopted the Hygo Framework for Action – a crucial step in outlining international resilience strategy. The United Nations proposed resilience as "*The capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the*

social system is capable of organising itself to increase this capacity for learning from past disasters for better future protection and to improve risk reduction measures." (UNISDR 2005).

Up until the early 2000s, much of the scholarly literature framed resilience as the ability to resist shocks and withstand extreme events. Subsequent literature made *adaptive* capacities a chief addition to the concept of resilience (Rose 2004; Norris et al. 2008). No longer was just resisting an initial shock sufficient; communities and systems needed to bounce forward in their response to events. More recent additions have integrated vulnerability literature into the scope of resilience (Chandra et al. 2011). The increasing relevance of urbanization and climate change have also made inroads to multi-hazard resilience, such as the definition outlined by the Rockefeller Foundation's resilience initiatives, *"The capacity of cities to function, so that the people living and working in cities – particularly the poor and vulnerable – survive and thrive no matter what stresses or shocks they encounter."* (Arup 2014).

These resilience definitions fundamentally each contain elements of three properties that Vugrin et al. (2010) put forward: (1) absorptive capacity; (2) adaptive capacity, and (3) restorative capacity. Absorptive capacity are attributes of a system that resist impact from a shock, adaptive capacities are the means through which change occurs to meet new demands, and restorative capacities enable a return to, or beyond, equilibrium. In conceptualizing resilience, each of these capacities serves a role in ensuring that systems rebound from a shock or hazard. An important distinction in many definitions is the specificity in the hazard being described. For example, there are stark differences in how an earthquake effects a community compared to a flood event. The duration of the event, energy released, and proximity are unique for every hazard event and thus, the traits required to achieve resilience differ (National Infrastructure Advisory Council 2009).

1.2. Resilience Dimensions

Dimensions – or the domain space – of resilience are characteristics essential in its operationalization. Built infrastructure is not isolated from social or economic influences; therefore, it is important to consider external factors when theorizing on infrastructure resilience. Resilience literature tends to consider five dimensions: *economic, environmental, governance, infrastructure, and social* (Cutter et al. 2010). The *economic* dimension of resilience refers to the capacity of systems to minimize, and rebound from, direct or indirect economic losses (Rose and Krausmann 2013). The *environmental* dimension concerns the perturbation of hazard impacts through ecological systems (Prior and Eriksen 2013). The *governance* dimension of resilience pertains to the function of organizations in managing facilities and post-disaster response activities (Bruneau et al. 2003). The *infrastructure* dimension of resilience focuses on the ability of the built environment to withstand and recover from disruptive events (Vugrin et al. 2010). Finally, the *social* dimension of resilience emphasizes the capacity of social ties and networks in limiting negative impacts from hazards (Aldrich and Meyer 2015). Exact terminology of these dimensions varies, however the underlying intent is similar. For example, a 'technical' dimension of resilience (e.g. Bruneau et al. 2003) is often referenced in engineering studies, however this can be seen as a sub-set of the larger infrastructure dimension identified in other studies.

2. RESEARCH METHOD

To analyze research trends of resilience, we performed a content analysis of academic literature in the hazard field. We analyzed trends in resilience studies through a systematic review, focusing on: (1) geographical location of research sites; (2) research methods employed; (3) units of analysis used; and (4) resilience dimensions studied. We will present findings from each of these individually, and then discuss relational trends through correlations that emerged.

Because resilience is a multi-dimension concept, we conducted a cross-disciplinary search to identify relevant literature to analyze. The goal was to summarize content that remained relevant to the field

of engineering and the built environment; therefore, this search was conducted in two databases: Web of Science and Engineering Village. Of the three primary applied science databases (PubMed being the other), Web of Science includes a breadth of articles, including economic and social studies, both identified to be crucial components of resilience, while focusing on higher impact journals. Engineering Village includes a greater percentage of articles with a technical focus on infrastructure systems (e.g. structural design). The search was conducted using a combination of the keywords "resilience," "infrastructure," and either "hazard" or "disaster" from 1990 through 2015. We selected the first two terms in order to identify scholarly work that explicitly identified resilience that pertained to infrastructure. Considerable hazard research has focused on infrastructure in a cross-disciplinary manner; we chose to focus on multi-dimensional factors that influence resilience of the built environment, aligning with the previously outlined resilience dimensions. To focus on hazards, we selected both of the terms "hazard" and "disaster," as these terms are used interchangeably. Boolean operators were used to search for appropriate combinations (including stems of the search terms) in keywords, titles, and abstracts. Within the search, only peer-reviewed journal articles were considered.

The search resulted in 294 articles in Web of Science and 262 articles in Engineering Village. Articles in psychology (e.g. Journal of Guidance and Counseling), medicine (e.g. Journal of Infectious Diseases) and computing (e.g. Institute of Electrical and Electronics Engineers) journals were removed from the analysis. Psychology articles commonly referred to infrastructure support services that affected individual resilience; medicine journals referred to infrastructure facilities in abstracts, but commonly focused on first responder topics; and computing journals used infrastructure to describe cyber networks. Using these criteria, 111 articles were removed from the Web of Science search and 176 articles were removed from the Engineering Village list. 51 articles were found in both databases and the duplicates were removed. The remaining 241 journal articles were then imported into NVivo qualitative analysis software for coding. A deductive coding structure was employed that analyzed and categorized content for each of the 241 articles into four macro coding categories: (1) location; (2) unit of analysis; (3) method and (4) dimension. For each of these themes, individual journal articles were considered the unit of analysis. The finalized journal articles represent a substantive sample of literature on the topic of infrastructure resilience that are extensible to the larger population of literature on the topic.

Within each of the macro coding categories, a combination of deductive and inductive coding was employed. For "location", we coded the geographic location of where resilience was studied in each article. These were coded into eight regions that are a consolidated version of the United Nations geoscheme. The "unit of analysis" category was coded inductively, resulting in the emergence of six categories: a) household; b) infrastructure; c) organization; d) community; e) region; and f) national. We consider infrastructure here as a unique unit as a large number of studies chose to focus their analysis on the design and operation of service delivery facilities. These studies chose not to associate findings at one of the other levels, such as community or regional. Within "method", articles were coded into deductive categories of qualitative, quantitative, or mixed-methods. Each of these macro categories was then coded inductively for methods that were used. For example, modeling, document analysis, and expert opinion were codes that emerged. Based upon a review of resilience concepts, we coded dimensions studied into five subcategories: a) economic; b) environmental; c) governance; d) infrastructure and e) social. We used resilience indicators as a means to understand what dimensions of resilience were discussed in articles. We therefore coded resilience indicators into the economic, environmental, governance, infrastructure, and social categories. For example, if a paper discussed household income as an indicator of economic resilience, this article was coded under the 'economic' resilience dimension.

Finally, we completed a correlation analysis between location, method, unit of analysis, and dimensions. This was useful in identifying trends and providing insights into areas of strengths, as well as gaps, that are present in the current resilience body of knowledge. From the previous coding, a matrix of correlations between each respective location, unit of analysis, method, and dimension was computed. Correlations within and between each of these areas of analysis were identified. We considered each variable to be binary in order to understand relationships between location, unit of analysis, methods, and dimensions. As such, we used Pearson's correlation coefficient in order to determine statistically significant relationships. All correlations with a p value less than 0.05 were considered significant.

3. TRENDS IN RESILIENCE STUDIES

In surveying the literature on resilience, we choose to focus on four primary traits of studies: geographic location, unit of analysis, methods, and dimensions studied. As scholars seek to advance knowledge of resilience, each of these traits are early decisions that drive research outcomes. By examining each individually, and then in combination through correlations, we hope to illuminate types of research that have been understudied where scholars can direct their attention in the future.

3.1. Geographic Location

Recent resilience frameworks have drawn attention to the importance of place (Cutter et al. 2014). This is one of the significant obstacles that hazard research still needs to overcome in order to produce a generalizable set of principles and metrics that can compare cases. In analyzing the location of existing studies, 58% were located in North America, 21% in Europe, 16% in Southeast Asia, 16% in Central, Eastern or Southern Asia, 14% in Australia and New Zealand, 8% in Africa, and 7% in the Middle East and South America. These geographic areas of study are displayed in Table 1.

Table 1: Resilience Studies by Geographic Location

Region	Relative Frequency of Studies
North America	58%
Europe	21%
Southeast Asia	16%
Central, Eastern and Southern Asia	16%
Australia and New Zealand	14%
Africa	8%
South America	7%
Middle East	7%
	N=241

Most studies in North America were focused in the United States, with a much smaller percentage in Caribbean or Central American countries (e.g. Silva et al. 2014; Taramelli et al. 2015). These studies investigated a large number of hurricanes and earthquakes in the United States (e.g. Reed et al. 2010), the 2010 Haiti earthquake (e.g. Comfort et al. 2011), and volcanic activity and drought conditions in Mexico (e.g. Gavilanes-Ruiz et al. 2009; Romero Lankao 2010). European studies (e.g. Ward and Paulus 2013; Baubion 2015) commonly emphasized flood control measures in a diverse range of nations. Studies in Asia were most commonly in China (e.g. Miao et al. 2014), Indonesia (e.g. Kusumastuti et al. 2014), and Japan (e.g. Cimellaro et al. 2014). These studies focused most heavily on the 2008 Chinese snowstorm, 2004 Indian Ocean tsunami, and 2011 Tohoku earthquake and tsunami, respectively. Australian and New Zealand studies often addressed recovery from the 2011 Christchurch earthquake (e.g. MacAskill and Guthrie 2015). Studies of Africa and the Middle East focused on heat wave and earthquake hazards, mostly in Turkey and South Africa (e.g. Harte et al.

2009; Orhan 2014), while South American findings most commonly stemmed from earthquakes in Chile (e.g. Comerio 2014).

By identifying where resilience has been studied, our review highlights that resilience has been predominantly studied in North America. There is a clear division between developed and developing countries. Only 13% of articles focused on developing countries, which are defined here using the International Monetary Fund (IMF) standard based on gross domestic product (GDP), export of goods and services, and population (International Monetary Fund 2015). Conceptualizations of resilience in emerging economies may hold additional insights into clarifying resilience debates due to the vast numbers of countries and cultures excluded from current work. Further, the economic and social impacts from hazards have been demonstrated to be proportionally greater in developing countries (Barakat 2003) and future research should seek to address this gap. Moreover, it was rare to find articles that examined more than one country, highlighting a gap in cross-country comparisons.

3.2. Unit of Analysis

Past work has identified critical gaps in resilience work at the community level (Smith and Wenger 2006), however, there has not been a comprehensive overview of the unit of analysis used across multiple studies. Here we separated infrastructure as a unique unit of analysis that focused on functional components of the built environment which were not explicitly associated with a socially defined boundary (e.g. community). Resilience studies of buildings could be considered a sub-component of community resilience, yet other infrastructure systems, such as water or power systems, can span across communities or regions. In these cases, the absence of societal context led to the creation of infrastructure as a standalone unit of analysis. The separation of infrastructure from socially defined boundaries has also been used in other resilience reviews. For example, Cutter (2016) found that 5 of 27 prominent resilience assessment approaches isolated infrastructure as the unit of analysis. From the content analysis, it was determined that 37% of studies were at the infrastructure level (e.g. water and power distribution systems), 35% at the community level (e.g. city or village), 23% at the national level, 9% at the regional level (e.g. state), 6% at the organizational level (e.g. firm or emergency management agency), and 3% at the household level. A comparison of units of analysis is shown in Table 2.

Table 2: Resilience Studies by Unit of Analysis

Region	Relative Frequency of Studies
Infrastructure	37%
Community	35%
National	23%
Regional	9%
Organization	6%
Household	3%
	N=241

The journal articles analyzed most frequently studied infrastructure as the unit of analysis. This was partly derived from the higher number of engineering focused articles within the two databases selected for review. The next noticeable trend is the large number of studies focused at the community level. Community bounded research has created a comparable space to frame resilience, but has simultaneously limited our understanding. For example, in loosely bounded communities, studies at the household level may hold new insights into resilience. Furthermore, community level studies are bound differently, with some based upon geographical boundaries, others based upon political boundaries, and still others based upon social or familial networks. These different ways of defining a

community make cross case comparative studies more challenging. At a higher level, only 9% of studies focused on regional linkages. Examples included analysis of regional transportation networks (e.g. Freiria et al. 2015), regional utility service delivery (e.g. Cimellaro and Solari 2014), and connecting early warning systems (e.g. Zia and Wagner 2015). Communities are a complex network of social and economic connections that are situated within regional and national contexts that merit further study. There are calls to scale resilience solutions (The National Academies 2012; UNISDR 2015), requiring additional study of regional and national networks to facilitate implementation of resilience frameworks. In future research, it will be critical for scholars to begin to connect localized resilience findings in order to produce a generalizable theory of resilience. Future research should continue to bolster comparable evidence at the community level, but should also seek to explore new units of study that expand understanding of how resilience is implemented at different levels.

3.3. Methods

A diverse range of methods were used within the resilience studies analyzed, which spanned a spectrum of quantitative and qualitative methods. 55% of articles used quantitative methods, 39% used qualitative methods, and 6% employed mixed-methods. Further analysis revealed that 31% of studies used simulation or other modeling techniques, 24% reviewed literature or proposed theoretical frameworks, 15% used geographic information systems (GIS), 9% used document analysis, 7% used questionnaires or surveys, 7% used expert opinion and 4% used network analysis. The relative frequency of research methods used in the analyzed literature is shown in Table 3. The most used method in the literature, modeling, included economic disruption analysis (e.g. Resurreccion and Santos 2013), infrastructure operability (e.g. Crowther 2008; Jonkeren and Giannopoulos 2014), recovery durations (e.g. Luna et al. 2011), and restoration capacity (e.g. Ouyang and Wang 2015). GIS has seen a sharp rise in recent years (10% increase annually since 2010 in articles reviewed), shown by its third ranked placement of methods, making contributions that reveal hazard risks using spatial relationships (Armenakis and Nirupama 2013).

Table 3: Resilience Studies by Methods

Method	Relative Frequency of Studies
Modeling	31%
Literature Review	24%
Geographic Information Systems (GIS)	15%
Document Analysis	9%
Expert Opinion	7%
Survey	7%
Network Analysis	4%
	N=241

There were a large number of studies that made use of quantitative modeling, developing the needed early foundation to begin to quantify resilience. These were particularly prevalent in the literature surrounding economic resilience (e.g. Armaş 2012). Although there were a smaller number of qualitative studies, these studies appeared to challenge assumptions in modeling approaches, pointing to empirical instances where communities, governments, and stakeholders did not heed social norms and legal regulations (Grove 2014). For example, many communities commonly neglect government imposed relocation, opting to stay in more hazard prone locations despite long-term financial implications. It is clear that there are a greater number of qualitative case studies needed to expand on empirical examples of resilience following disaster events and to validate findings generated through the development of simulation modeling. Conversely, there is a need to model new findings from qualitative research that uncover new individual, organizational, and institutional behaviors.

3.4. Dimensions

To further explore where resilience work has been situated, our content analysis explored resilience indicators employed within journal articles. Indicators are crucial to advancing the operationalization of resilience (Kahan et al. 2009). The analysis of dimensions of resilience revealed three most prevalently cited dimensions – governance (19%), infrastructure (18%) and economic (18%). A smaller, but still substantial number of articles (14%) proposed social indicators, and the smallest number of articles focused on environmental indicators (8%). A large number (23%) of articles did not fit within our definitions of resilience dimensions, as these focused on theoretical elements of resilience or did not explicitly operationalize a dimension of study. A summary of the relative frequency of appearance of the five resilience dimensions is shown in Table 4. The appearance of governance as the highest number of indicators is surprising, given that much of the broader discussion of resilience is focused on the other core dimensions. For example, the focus of Wilby and Keenan's (2012) study of flood adaptation measures includes flood insurance (economic), flood forecasting and warning systems (infrastructure), and natural coastal defenses (environment), yet they emphasize that none of these are possible without an enabling institutional environment (governance). The large number of empirical case studies included in our review point to institutional mechanisms as a key driver of resilience. In contrast, quantitative studies that have explored infrastructure design and economic modeling primarily focus on infrastructure and economic indicators. A lower number of articles citing social and environmental indicators may be due to the difficulty in assessing these dimensions of resilience, as these are often place based, requiring substantial knowledge of historical context and cultural norms.

Table 4: Resilience Studies by Dimension

Dimension	Relative Frequency
Governance	19%
Infrastructure	18%
Economic	18%
Social	14%
Environmental	8%

N = 241

3.5. Correlation Analysis: Statistical Relationships Between Location, Unit of Analysis, Methods, and Dimensions

In order to look beyond cursory trends, we further analyzed relationships between geographic location, unit of analysis, methods, and resilience dimensions using statistical correlation analysis. Below, we first discuss correlations within each category, starting with geographical regions, continuing with methods and unit of analysis, and ending with resilience dimensions. We then present the analysis across categories (e.g. methods and resilience dimensions). We found 112 statistically significant correlations between the four categorizations considered. 88 of these were found to be weak, 19 were moderate, and 5 showed strong correlation. Here we define strong correlations as having Phi coefficients greater than 0.5, moderate correlation between 0.3 and 0.5 and weak correlation between 0.1 and 0.3. We will discuss all of the observed strong and moderate correlations here and highlight several of the notable weak correlations. In particular, we will discuss all of the strong and moderate correlations found and will highlight a few of the key weak correlations.

3.5.1. Geography – Geography

In total, we found 3 strong correlations, 11 moderate correlations, and 8 weak correlations between geographic regions. A considerable number of the studies reviewed only focused on one region, despite past calls for greater cross-case comparison (Smith and Wenger 2006). We found that only

18% of studies focused on more than one geographic region. Our analysis focused on correlation between regions as our interest was in the state of global resilience progress and did not consider comparisons between countries within a given region. The divide between historically developing and developed regions was one of the major trends that surfaced. The 3 positive strong correlations found included geographic relationships between South America, Africa and the Middle East. Moderate positive correlations were found between Central, Eastern, and South Asia, South America, Africa, and the Middle East. Of regions with higher percentages of developed countries, Australia and New Zealand had moderate correlations with South America, Africa, and the Middle East. Europe also had a positive moderate correlation with South America. Overall however, there were few correlations that showed crossover between historically more developed regions (e.g. Europe) and less developed regions (e.g. Africa). In total 10 of the 14 strong or moderate correlations between geographies were between developing regions. This suggests that past studies were more likely to compare resilience within developed or developing regions, but there is sparse research that has bridged these studies in the body of knowledge.

3.5.2. Methods – Methods

For relationships between methods, we found 2 strong correlations, 4 moderate correlations, and 9 weak correlations. The most apparent relationship in methods was the absence of connection in journal articles between qualitative and quantitative methods. There was a strong negative correlation, Φ=-0.889, found between these categories of methods. Aligning with the previous discussion of qualitative and quantitative methods, only 6% of articles used a mixed-methods approach when studying resilience. This is not to suggest that all studies should employ both qualitative and quantitative methods, but rather to suggest that combining methodological approaches may generate new knowledge on resilience. The majority of correlations within methods were subsets of either qualitative or quantitative methods, yielding few insights, but reinforcing our primary finding of the disconnect between multi-method studies.

3.5.3. Unit of Analysis – Unit of Analysis

Two moderate negative correlations were found within units of analysis that were statically significant. The strongest correlation between units of analysis was a moderate negative correlation between infrastructure and community, Φ=-0.433. This suggests there has been a significant gap in studying infrastructure systems embedded within communities. The large number of studies that have focused on infrastructure appear to examine engineering and construction practice, but rarely make the connection to socially constructed boundaries. Given the social function and value of infrastructure, linking infrastructure to bounded communities is essential to bolster the application of resilience theory. We also found a moderate negative correlation between national units and infrastructure, Φ=-0.305. Given that national level studies are the precursor to smaller units of analysis, this is expected, however future work needs to build theory on how infrastructure units (e.g. bridges, buildings) fit into connected, national networks.

3.5.4. Dimension – Dimension

Within resilience dimensions, there were 7 statistically significant correlations. 108 (40%) of the 241 articles reviewed referenced at least one dimension. Of the 5 dimensions considered, all but three relationships were found to have statistical correlations, demonstrating an emphasis on studying resilience in a cross-dimensional context. In striving to achieve an integrated, cross-disciplinary theory of resilience, the dimensions that lack correlations prove the most insightful, as these should be areas of focus for future resilience theory building. The three pairs found to lack correlation were environmental-governance, environmental-infrastructure, and social-governance. A full list of correlations between dimensions are presented in Table 5. In examining those pairs that showed

correlation, the most apparent theme is the statistical links between economic and all 4 other resilience dimensions. The lack of relationships between environmental-governance and environmental-infrastructure undercuts a deeper theme in resilience literature, the lack of indicators for environmental factors. In the context of infrastructure resilience, there is further research needed to evaluate the relationship between environmental conditions and the built environment. The third relationship, governance-social, is surprising given larger number of studies referencing governance indicators. This theme points to the need to not only develop new, more robust social indicators but also to integrate these within existing frameworks that include governance and institutions.

Table 5: Correlation Between Resilience Dimensions

	Economic	Environmental	Governance	Infrastructure	Social
Economic	-	0.138*	0.215*	0.270*	0.241*
Environmental	0.138*	-	0.119	0.133	0.229*
Governance	0.215*	0.119	-	0.175*	0.109
Infrastructure	0.270*	0.133	0.175*	-	0.268*
Social	0.241*	0.229*	0.109	0.268*	-

N=241; * indicates statistical significance at P<0.05

3.5.5. Inter-Category Relationships

Finally, we also analyzed trends across the 4 categories. Our analysis found no strong correlations, 2 moderate correlations, and 62 weak correlations between categories. The first moderate positive correlation was between the social dimension and community as the unit of analysis, Φ=0.332, and the second was a moderate negative correlation between the governance dimension and modeling methods, Φ=-0.305. The first of these reinforces the prevalent theme of connecting social research at the community level. The second highlights the difficulty in modeling governance. While the largest number of studies cite governance, this suggests that these findings from qualitative research have yet to make inroads in quantitative methods. For the moderate correlations, we will discuss geographic trends first and then discuss the weak links that emerged surrounding methods and dimensions.

Geographically, we found 33 inter-category correlations. We found that studies in North America, Australia, New Zealand and Europe had weak correlations with research methods and units of analysis that were more localized and focused. For example, we found a weak positive correlation between North America and infrastructure as the unit of analysis, Φ=0.203. In contrast, regions that have a high number of developing countries, such as Southeast Asia, Africa, and the Middle East, had weak positive correlations with literature reviews or national levels of study, having a noticeable gap in methods that analyzed localized resilience. Building on our earlier discussion, this demonstrates that not only are there a disproportionate number of studies in developing countries (13%), there is a dearth of methods that have been used to examine resilience in developing countries. Part of the reason for this cursory overview of resilience in these contexts may stem from the units of analysis studied. For Africa, the Middle East and Southeast Asia, we found weak positive correlations with a national level of study. This suggests that research to date has focused at higher levels of study. While this is a promising start, additional study of community, infrastructure, organization, and household levels could greatly enhance our understanding of resilience in developing country contexts.

Of the quantitative method studies reviewed, the correlations found describe a unique set of units and dimensions studied that are in opposition to qualitative studies reviewed. We found that infrastructure as the unit of study had weak positive correlations with quantitative methods, Φ=0.202, and modeling, Φ=0.288. Reinforcing this theme, we also found that community as a unit of analysis had a weak negative correlation with quantitative methods, Φ=-0.223, namely modeling methods, Φ=-0.254. The

only positive relationship between a dimension and quantitative method was GIS and the social dimension of resilience, Φ=0.176. This combination of analyzing vulnerability using GIS has seen growth in recent studies (e.g. Busby et al. 2013; Cutter et al. 2014; Martin 2014). There were, however, several negative correlations between methods and dimensions studied. Chiefly, there was an absence of studying social, governance, and environmental dimensions using quantitative methods. These had weak negative correlations of Φ=-0.140, -0.188, and -0.222, respectively.

In contrast to quantitative methods, we found that studies using qualitative methods had different characteristics. We found a weak positive correlation between qualitative methods and community as the unit of analysis, Φ=0.256. We also found a weak negative correlation between infrastructure and qualitative methods, Φ=-0.207. In opposition to quantitative methods, we found weak positive correlations between qualitative methods and governance, social, and environmental dimensions. These had weak positive correlations of Φ=-0.201, -0.200, and -0.184, respectively. We did not find that the regional unit of analysis had any statistically significant correlations with methods, but did find that the national level had a weak correlation with literature review articles, Φ=0.169. For organizations, we found that the predominant method employed was surveys, Φ=0.262.

In summary, we found a method and unit of study divide between developed and developing countries. Developing country contexts frequently employed literature reviews to examine national trends, while developed regions employed a mix of approaches to examine resilience. Our findings also show that infrastructure has been studied through the lens of quantitative methods and communities through qualitative methods, yet existing literature sees relatively little exchange in units of study and methods.

4. DISCUSSION

Our review of resilience literature presents a promising picture of past efforts to unify theory. In particular, the diverse geographies, methods, units of analysis, and dimensions show that scholars have collectively adopted a cross-disciplinary approach to addressing hazards. Despite these gains, we have highlighted several areas where greater attention is still needed. In particular, there is a need to diversify geographies studied, continue to explore new methods and use mixed-method approaches, connect units of analysis, and ensure representative study of all dimensions of resilience.

There is substantial work that has emphasized the importance of place-based resilience (Cutter et al. 2008). Culture, norms, and past experience mean that resilience extends beyond surface level attributes. Further, in a placed-based understanding of resilience, resilience to what becomes a central question. While the importance of place is unequivocally adopted by scholars, little attention has been given to ensuring that resilience is studied in a balanced number of geographic locations. In UNISDR's (2016) analysis of global disasters from 1995-2015, weather-related disasters were on average 0.2% of GDP for high-income countries, whereas costs were on average 5% of GDP for low-income countries. In the same analysis, 9% of weather-related disaster deaths occurred in low-income countries and 31% of deaths occurred in high-income countries. UNISDR acknowledged that the smaller percentage of deaths in low-income countries is likely tied to underreported casualties. Moreover, 43% of disasters were found to have occurred in low or lower-middle income countries, despite our finding of only 13% of studies being conducted in these geographies. As a community, disaster scholars have inadequately studied these low-income country contexts despite the greater relative impact on nations. There is a pressing need to balance the research agenda and direct efforts toward the study of these critical contexts.

The diverse range of methods that are applied to study resilience continue to yield new insights. It is promising to see a robust number of quantitative methods used and a growing number of qualitative

approaches in the study of resilience. Modeling continues to push the boundaries of developing theory on complex systems and interactions, while case studies continue to explore these theories in practice. However, our analysis found that only 6% of studies used mixed-methods, and we posit that pairing research methods may yield new ways of understanding resilience. Future research should continue to explore new approaches through different epistemological lenses in the pursuit of contextually embedded knowledge.

In addition to targeting new geographies for study, another emergent finding from our literature review was the disconnect between infrastructure as a unit of study and social boundaries. Given that infrastructure is intended to serve a social function, there is a pressing need to integrate technical study of infrastructure within the context of communities. The absence of this demarcation has led to the abstraction of infrastructure resilience. For example, extensive work has been conducted on utility and building system resilience at the component level, with a number of proposed enhancements; yet there is sparse discussion of how these changes might conflict with social norms, use, and operation of these infrastructure systems. The connection of infrastructure and social boundaries is particularly important as indicator frameworks continue to develop and materialize.

Finally, despite the large presence of governance in articles, there was a disconnect in integrating governance with other resilience dimensions, such as social and environmental dimensions. The need for different governance in the face of different hazards has made this dimension elusive. For example, the lack of warning and rapid occurrence of earthquakes imposes rapid decision-making onto organizations, whereas slow developing hazards, such as droughts, prolongs institutional processes. Given the overlap in dimensions found, future work should seek to develop commonalities in indicators that can be adopted across hazard types. The objective for future work should be the integration of these emergent indicators into existing frameworks of measurement.

5. LIMITATIONS

Our work has taken steps in advancing infrastructure resilience by reviewing existing literature. One major limitation of our work is that we have not considered grey literature. Much of the progress on resilience in the last decade has occurred at the front lines of disaster response, recovery, and mitigation. As such, we acknowledge that recent, emerging work is missing from our content analysis. Despite the absence of peer-review for this literature, it holds significant insights to resilience that merit future study. Secondly, our selection of databases narrowed our search results. The selection of Web of Science and Engineering Village had a bias toward engineering articles, but given our focus on the role of infrastructure resilience, this yielded more relevant research articles. Further, there are articles that discuss infrastructure resilience that may not have included the selected search terms in their title, abstract, or keywords. There is also much published on the topic of infrastructure resilience in conference proceedings, however we selected to exclude these as their peer-review can be inconsistent across difference sources.

6. CONCLUSIONS

The concept of disaster resilience has been well theorized in the literature, however resilience is still difficult to study and apply practically. One of the present challenges is benchmarking progress on resilience. By analyzing resilience studies across disciplinary fields, we have condensed evidence-based instances of resilience applications that encompass economic, environmental, governance, infrastructure, and social systems. Our analysis characterized articles by geography, method, unit of analysis, and dimensions, revealing themes that exist across studies conducted from 1990 to 2015. Geographically, the majority of studies (58%) have focused in North America and only 13% of articles were found to discuss resilience in developing countries. Our findings further show that 55% of

articles used quantitative methods, 39% used qualitative methods, and 6% employed mixed-methods. Units of analysis have predominately focused on infrastructure (37%) and communities (35%), yet often do not connect the two. Finally, environmental and social dimensions of resilience were the least studied, 8% and 14% of articles respectively, demonstrating the need to investigate these areas of resilience.

Using correlations to unpack trends, our findings point to 4 future steps for resilience scholars: (1) investigate developing country contexts and conduct more cross-case comparisons, (2) employ innovative methods and strive for greater mixed-method studies, (3) situate infrastructure research within social boundaries, and (4) explore understudied elements of resilience, chiefly environmental and social dimensions. As scholars chart the future path of the resilience agenda, the inclusion of developing countries contexts has the potential to produce new insights and continue to extend the impact of the research community to populations most affected by disasters. To better explore the interdisciplinary nature of resilience, studies should seek to employ greater use of mixed-method approaches to understand linkages across dimensions. Furthermore, past work has notably isolated infrastructure and the built environment from its social boundaries. The connection of these two units is crucial for improved understanding of the contributions, and limits, of the built environment to community resilience. Lastly, the continued development of new indicators should ensure currently underrepresented dimensions, namely environmental and social, are adequately considered.

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