



Increasing Coastal Disaster Resilience Using Smart City Frameworks: Current State, Challenges, and Opportunities

Fahim Nawroz Tonmoy^{1,2,3*}, Samiul Hasan⁴ and Rodger Tomlinson⁵

¹ Civil Engineering School, Griffith University, Southport, QLD, Australia, ² School of Civil Engineering, University of Sydney, Sydney, NSW, Australia, ³ BMT, Brisbane, QLD, Australia, ⁴ Department of Civil, Environmental and Construction Engineering, University of Central Florida, Orlando, FL, United States, ⁵ Griffith Centre for Coastal Management, Griffith University, Southport, QLD, Australia

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*Correspondence:

Fahim Nawroz Tonmoy
fahim.tonmoy@hotmail.com

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Sea-level rise, storm surges, and floods in coastal cities have already threatened large population and infrastructure with potential to increase significantly in future as climate changes. Therefore, increasing disaster resilience has become a major priority for coastal cities. At the same time, recent development in information and communication technology, ubiquitous sensors, and advanced data science allow us to generate insights that were unimaginable before and can assist in better managing coastal disaster risks. In this paper, using an infrastructure resilience lens, we critically review a set of academic literature that focus on the new development of smart systems in coastal disaster management and a set of use cases that focus on their practical application in different coastal cities. We find that smart city technologies such as internet of things (IoT) and crisis informatics have significant potential and have been increasingly used in academic studies but their city-scale applications in coastal disaster management have been limited. We discuss the challenges and opportunities of using smart city frameworks for increasing disaster resilience of coastal communities.

Keywords: coastal disaster, smart city, resilience, vulnerability, internet of things, crisis informatics

INTRODUCTION

Natural hazard events have been an ongoing element in the coastal regions around the world. Flooding and erosion episodes in the coastal margins during storms, hurricanes or cyclones are putting a significant amount of assets, infrastructures, and communities at risk. Seventy-two percentage of the 63 most populated cities (with 5 million or more inhabitants in 2011) are located on or near the coast (United Nations, 2019). In one hand, population density in the hazard-prone coastal areas and megacities is expected to grow by 25% by 2050 (Hallegatte et al., 2013). On the other hand, a rise in sea level is likely to increase the frequency and impacts of these episodic coastal hazard events. In 2005, average global flood losses in the world's largest 131 coastal cities was approximately US\$6 billion per year with the potential to increase to US\$52 billion per year by 2050 due to sea level rise (Hallegatte et al., 2013). As a result, global investment and maintenance costs of protecting the coast from sea level rise estimated to be US\$ 12–71 billion per year in 2100 (Hinkel et al., 2014). Therefore, increasing resilience of our coastal cities, their infrastructure systems and community in general to these episodic natural disasters is very critical.

Cities are inherently complex with interactions among multiple systems (e.g., supply chains and transportation networks, water and energy networks, housing and business infrastructures, social networks), agents (individuals, businesses etc.) and institutes that manage or influence these systems and agents (Tyler and Moench, 2012). The impacts of natural disasters in a coastal city therefore stems from complex interactions among a potentially damaging physical event (e.g., flood, erosion, storm) and the vulnerability of these systems, agents, and institutes (Birkmann, 2006; Tonmoy et al., 2014). Therefore, increasing disaster resilience of a coastal city needs an understanding of inherent stresses and vulnerabilities of these multiple systems. Specifically disruption in vulnerable critical infrastructure systems such as water supply network, transportation network, electricity production and distribution systems, health care facilities etc. that are located in the hazard prone areas of a coastal city can result in significant social and economic disruption. Therefore major coastal cities around the world are putting emphasis on increasing disaster resilience of their critical infrastructure systems (Aerts et al., 2014). Here critical infrastructure refers to any infrastructure that provides a service to the maintenance of the well-being of the population and something that if disrupted might cause serious harm to the well-being of the community (Attwood et al., 2011).

On the other hand, information and communications technology (ICT) has seen significant advancements in recent years with different types of smart and connected technologies capable to generate real-time information at an unprecedented scale. Alongside there has been significant improvement in computational power to manage and analyse big datasets. Specifically, rapid advancements in artificial intelligence, ubiquitous sensing technology, smart city/infrastructure, availability of big data sources such as social media, mobile devices, infrastructure management systems (e.g., SCADA) allow us to collect and analyse data with details and coverage unimaginable before (Kitchin, 2014; Gupta and Gupta, 2016; Murayama et al., 2017). These advancements offer opportunities to develop data-driven decision support tools for a better understanding and management of coastal disasters in cities with a substantial potential to increase the resilience of coastal communities. Deploying these advanced ICT infrastructures within a city context to improve citizen services is often referred as “smart city” and has become the latest trend in urbanization (Hollands, 2008; Batty et al., 2012; Kitchin, 2015; Wiig, 2015).

The definition of a “smart city” is diverse and so are its applications. Two distinct understandings of smart cities are prevalent in the literature. First, smart cities are viewed as urban places with ubiquitous computing and digitally instrumented devices built into the very fabric of urban environments. Examples include wireless telecom networks, digitally controlled utility services and transport infrastructure, sensor and camera networks, building management systems, smart phones producing data about resident’s location, and activity etc. (Kitchin, 2014). These can make a city “knowable and controllable” and ultimately improve the performance and delivery of public services. A second view of smart cities is broader: this is seen as the development of knowledge economy

within a city driven by ICT as a central platform. This notion of smart cities is based on the fact that embedding ICT in urban infrastructure on its own does not make a city smart; rather its entire ecosystem (economy, community, infrastructure, environment) should be managed having ICT as one of the central platform (Hollands, 2008). A similar view is presented by Batty et al. (2012) where authors sketched the fundamentals of what constitutes a smart city and argued that smart cities should include smart economy (competitiveness and entrepreneurship), smart people (social and human capital), smart governance (participation in decision making), smart mobility (transport and ICT), smart environment (sustainable resource management and smart living (quality of life). In both schools of thought, however, a common theme is the need to enhance the sustainability and resilience of the city as a whole. This paper adopts the former definition in order to investigate to what extent smart city frameworks have been used around the world toward increasing coastal disaster resilience of critical infrastructure systems.

Disaster resilience of a city is often characterized in three distinct stages of a hazard event namely preparedness of multiple systems of the city to reduce potential impact of the hazard, ability to manage and respond during the event to minimize loss, and finally the ability to manage recovery of the affected systems from the hazard impacts (i.e., bringing the system to its normal state). A review of the use of communications technology during disasters in recent years shows that while it has played a positive role, its full potential has not yet been realized (Diane and Meier, 2009; Dunaway et al., 2017). Different smart city features have been implemented around the world for better management of all these three phases of disasters. City specific case studies have been released highlighting how cities have implemented smart features in their urban margins [e.g., (Caragliu et al., 2011; Bakici et al., 2013; Scuotto et al., 2016)] but not all of them attempted to tackle coastal disasters. Furthermore, some of these case studies do not appear in the peer reviewed literature as they are often published as project reports. On the other hand, there has been a number of academic peer reviewed research publications reporting on the innovative development and implementation of smart city features for disaster management of cities from a range of natural and man-made hazards (e.g., Alazawi et al., 2011, 2012, 2014; Ancona et al., 2015; Choi and Bae, 2015; Kumar et al., 2015; Lo et al., 2015; Hernández-Nolasco et al., 2016; Shalini et al., 2016). This peer reviewed literature often reports a specific application or innovation of using smart features in disaster management. Therefore, it is difficult to understand from this body of literature to what extent new innovations are infiltrating in practical applications and what are the major challenges and opportunities of implementing smart city features for increasing coastal disaster resilience. There are several review papers that highlight the broader application of smart city features, but mainly focusing on different aspects of the discipline e.g., review of definitions and terminologies of smart cities used around the globe, review of smart city governance, review of enabling technologies, review of IBM smart city projects etc. (Caragliu et al., 2011; Cocchia, 2014; Anthopoulos, 2015; Yin et al., 2015; Meijer and Bolívar, 2016). However, to the best of our knowledge, none of the review papers investigated both gray literature application case studies

and academic peer reviewed literature to analyse the variety of development and application of smart city features in coastal disaster management. This knowledge gap makes it difficult to anticipate future research directions and major development trends within the field of coastal disaster management.

To this end, the objectives of this study are: (1) to describe the broad characteristics of coastal disasters and their potential impacts on the resilience of city infrastructures; (2) to investigate a sample of case studies around the world to identify how coastal disaster resilience has been tackled using smart city features in those cities; (3) to analyse a sample of peer reviewed literature on disaster management and smart city to identify new innovation and development trends; (4) discuss current challenges, opportunities, and potential future research directions for this sector.

CHARACTERISTICS OF COASTAL DISASTER RESILIENCE IN CITIES

A number of coastal hazards can trigger a natural disaster in the coastal zone. Here it is important to make a distinction between “Coastal Hazards” and “Hazards in the coastal zone.” Where the first one is about hazards that are introduced by the action of sea and its interaction with the coast, the second one includes all hazards that are relevant for the coastal zone regardless whether they are due to action of sea or not (e.g., heatwave, landslide etc.). The scope of his paper is limited to the former. Different coastal hazards such as coastal flooding, erosion, sea level rise etc. propagate and have impact on coastal systems at a different time scale. As an example, while coastal flooding during a storm or cyclone is a rapid event with immediate impacts (in the order of hours and days), sea level rise has a slow onset with longer-term impacts (in the order of decades to centuries). Similarly, coastal erosion can have a rapid onset when a coastal storm or cyclone swept away significant part of the sand of a beach (in the order of days), but erosion can also have a moderate-term onset as a result of long-shore sediment transport where sediments are transported by waves from one beach to the other resulting in sediment deficit and erosion (in the order of seasons) and a longer-term onset where erosion of the coast increases as sea level gradually rises (in the order of decades and century) (**Table 1**). These time scales of coastal hazard govern the hazard impacts on coastal infrastructure. On top of temporal variation, these hazards also vary spatially as intensity of these hazards are amplified with specific geographic and geomorphic formation of the coastal area (e.g., low lying areas, erodible shoreline etc.).

In order to make coastal infrastructure systems robust against hazards that vary temporally and spatially, the concept of “resilience” is becoming increasingly popular among disaster management professionals and researchers. The definitions of resilience emanate from multiple disciplines (e.g., ecology, disaster management, engineering) and therefore are quite diverse in the literature (Cimellaro et al., 2010). In general, resilience is defined as the ability of a system to resist and/or to recover from a shock. Scholars use other terminologies as a measure of resilience such as flexibility and the ability to maintain

the status quo or to reorganize after stress or shock (Manyena, 2006; Bhamra et al., 2011). Resilience is also considered as an emergent property of a system to manage high variability and uncertainty in order to continuously pursue successful performance of a system (Cimellaro et al., 2010; Francis and Bekera, 2014; Kong and Simonovic, 2019; Kong et al., 2019). Tyler and Moench (2012) argued that the application of the concept of resilience to urban climate adaptation and hazard mitigation practice would help to address some of the “predict and prevent” approach and allow preparing infrastructure systems for climate change even under high uncertainty.

Disaster Risk Management (DRM) includes all activities, programmes, and measures which can be taken up before, during and after a disaster with the purpose to avoid a disaster, reduce its impact or recover from its losses (Khan et al., 2008). **Figure 1** shows the characteristics of a resilient infrastructure system in these three distinct phases of DRM. To better prepare for any future hazard, in the preparedness stage, several steps can be conducted such as understanding the characteristics of coastal hazards through modeling and engineering analysis, developing early warning systems, installing hazard mitigation measures, educating and informing communities about hazards etc. When a disaster is unfolding (e.g., crossing of a cyclone/hurricane over a coastal area) a resilient infrastructure system should be able to absorb physical stresses from the hazard and maintain serviceability even with reduced capacity and should have the capacity to restore the system to full operation mode once the stress from the hazard is over (e.g., providing backup, restore function etc.). Finally, a resilient system uses its learnings from an event, policies are implemented and capacity increased so that in the face to future disaster stress, the system can better cope and fight back quickly. For any critical infrastructure operator it is crucial to reduce the time the system spend between t_1 and t_2 .

INCREASING COASTAL DISASTER RESILIENCE IN CITIES USING ICT

Due to technological advancements as well as increased trend in natural and man-made disasters, the importance and scope of information and communication technology (ICT) in increasing disaster resilience have increased in recent years. Different phases of disaster management of infrastructure systems that are discussed in the earlier section (**Figure 1**), are benefitting from the recent advancement of ICT. Examples can be drawn from the use of early warning systems (in the preparedness phase), collection and analysis of real-time hazard information for effective coordination of disaster management and recovery operation (during the disaster), setting up of long-term monitoring systems for understanding trend of the coastal or climatic variable that are responsible for creating the hazard (during the post disaster state). At a global, regional, and national scale advanced information and communication technologies have been implemented for the generation and distribution of disaster alerts and warnings (be it coastal or not) (see **Table 2**). Among these, Common Alerting Protocol (CAP) and Emergency Data Exchange Language (EDEL) messaging

TABLE 1 | Characteristics of coastal disasters in cities.

Coastal hazards	Potential cause	Time scale of the hazard	Potential impacts to coastal cities
Coastal flooding	Coastal storms, cyclones, king tide etc.	Short-term with fast onset	Destruction of assets, infrastructure, and lives. Disruption of business, supply chain, and have negative impact on economy.
Coastal erosion	Soft and erodible geomorphology sometimes coupled with destabilization of the shoreline due to human intervention.	It can be short, medium and long term	Damage to nearby private properties and public infrastructure. Loss of sand on beach can also have negative impact on beach tourism.
Concurrent effect of catchment and coastal flooding	Excessive rainfall in the upper catchment coincide with coastal storm and/or king tide	Short term with fast onset	Due to coincidence of both catchment and coastal flood events, upper catchment flood waters are unable to escape in the coast. This often extend the impact of coastal flood beyond the coastal zone causing disruption in lives and economic activities.
Sea level rise	Increase global average temperature as a result of climate change	Longer term with slow onset	Permanent inundation in low lying areas, frequent inundation during high and king tide events. These can lead to loss of coastal properties and assets, decrease in property values, conflict between affected city residents and city authorities in terms of deciding “who to pay” for the increased requirement of coastal protection measures.

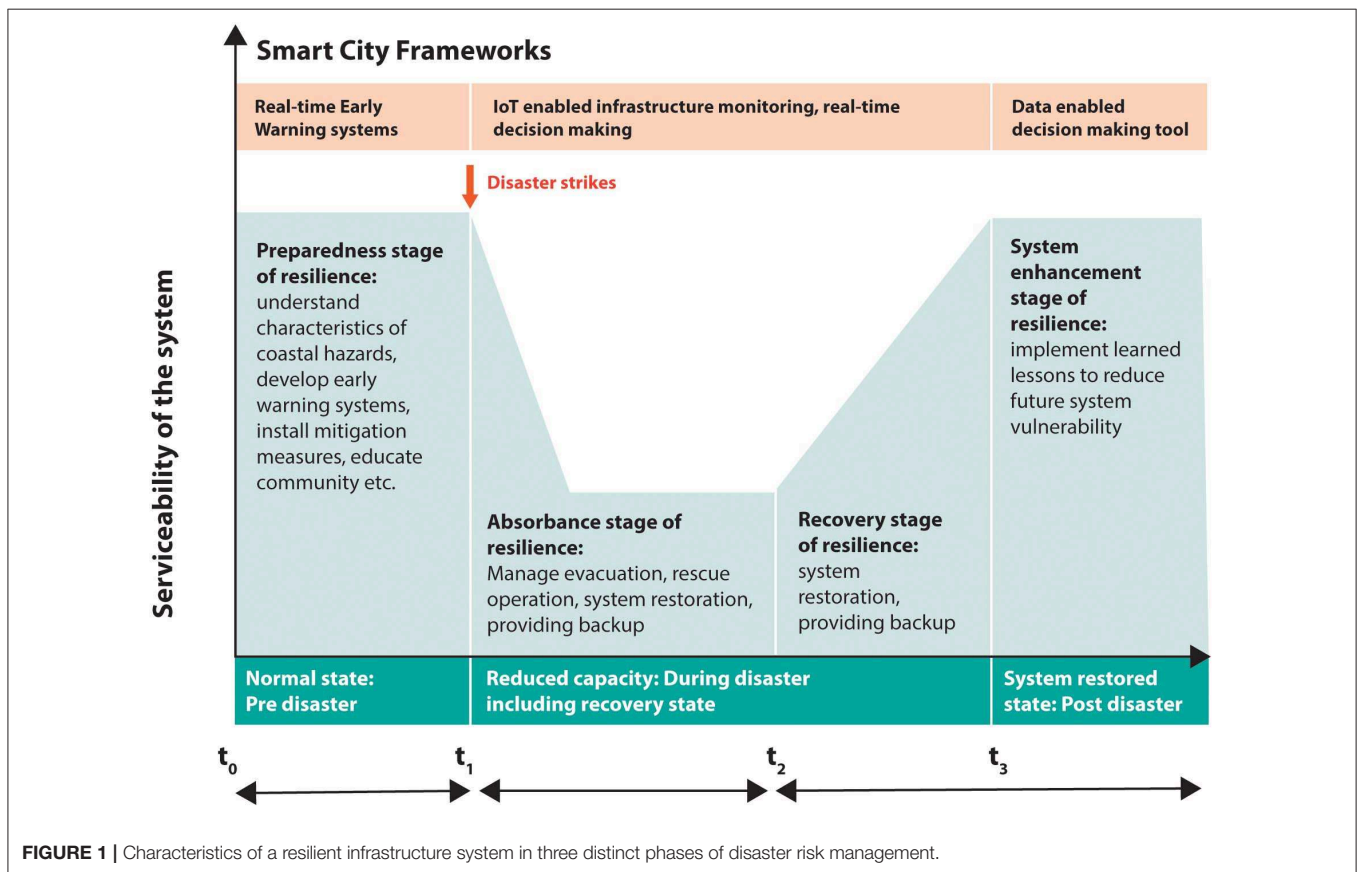


FIGURE 1 | Characteristics of a resilient infrastructure system in three distinct phases of disaster risk management.

standards have been adopted by developed nations such as in Canada, Australia, Japan and Taiwan etc. These systems allow these countries to facilitate automatic notification of certain natural hazards by sensor systems, analyse, and exchange results between emergency information systems and services. CAP and EDEL are international standards for exchanging emergency alerts in a digital format that allows a consistent alert message to be disseminated simultaneously over many

different communications systems. These consistent formats allowed development of critical services such as Google Alert, European public warning systems etc.

These global and regional alert systems act as early warning systems for coastal disasters and assist national, regional authorities to communicate the risk of the cyclones, hurricanes, flooding etc. to coastal communities so that they can take necessary measures to reduce their loss from the disaster. Owner

TABLE 2 | Example of ICT based global and regional disaster alert systems.

Global and regional disaster alert systems	References
CAP: Common Alerting Protocol, V1.2	http://docs.oasis-open.org/emergency/cap/v1.2/CAP-v1.2-os.html
EDXL-DE: Emergency Data Exchange Language Distribution Element	http://www.oasisopen.org/committees/download.php/17227/EDXL-DE_Spec_v1.0.html
IPAWS-OPEN (Integrated Public Alert and Warning System—Open Platform for Emergency Networks used in the US)	http://www.fema.gov/integratedpublic-alert-warning-system
GDACS: Global Disaster Alert and Coordination System	https://www.gdacs.org/
European Public Warning System (EU-Alert) Using Cell Broadcast	https://ec.europa.eu/programmes/horizon2020/en/news/emergency-alert-system-europe
Google Public Alerts	https://support.google.com/publicalerts/?hl=en

and operators of critical infrastructure systems also use these early warning systems to inform their disaster management activities. However, these global and regional alerts alone are not sufficient for managing disaster risks of critical infrastructure systems within a city. These critical systems often have complex and interdependent networks and increasing disaster resilience of such networks requires finer scale real-time information that goes beyond just the disaster alert systems.

To this end, recent development of sensors, their web of networks with ability to communicate via internet (i.e., internet of things) provide a tremendous opportunity to make better and real-time disaster management decisions for critical interdependent infrastructure systems. Specific opportunities of using ICT at a local scale coastal disaster management includes:

- Supplementing early warning systems with near-real-time to real-time analysis of hazard information. This will allow more pro-active decision making due to any disruption and recovery effort of a critical infrastructure failure.
- Opportunity to know more about how different infrastructure systems perform under stress during disasters (e.g., maintain physical integrity, cope with increased demand, cope with reduced capacity as result of disruption of connected services etc.), so that system vulnerabilities can be identified and initiatives can be taken to make them more resilient.
- Opportunity to use of data enabled decision support systems to prepare, manage, and recover from coastal disasters. Visualization and analysis of near-real-time information from sensors about the extent of the hazard, performance of the infrastructure etc. provides an opportunity to make informed decision about where and how resources should be allocated to recover lost infrastructure services

EMERGENCE OF THE SMART CITY CONCEPT AND ITS USE IN COASTAL DISASTER MANAGEMENT AT A CITY SCALE

The term “smart cities” has gained significant attention in academia, businesses and government in the last decade, especially in cities where ICT has been embraced as a development strategy. Cities that are embedding digital

infrastructure in the urban fabric for providing better service to its citizens through web access services, to better manage facilities and to promote entrepreneurship are often termed as “smart cities,” “intelligent cities,” “connected cities” etc. (Kitchin, 2014).

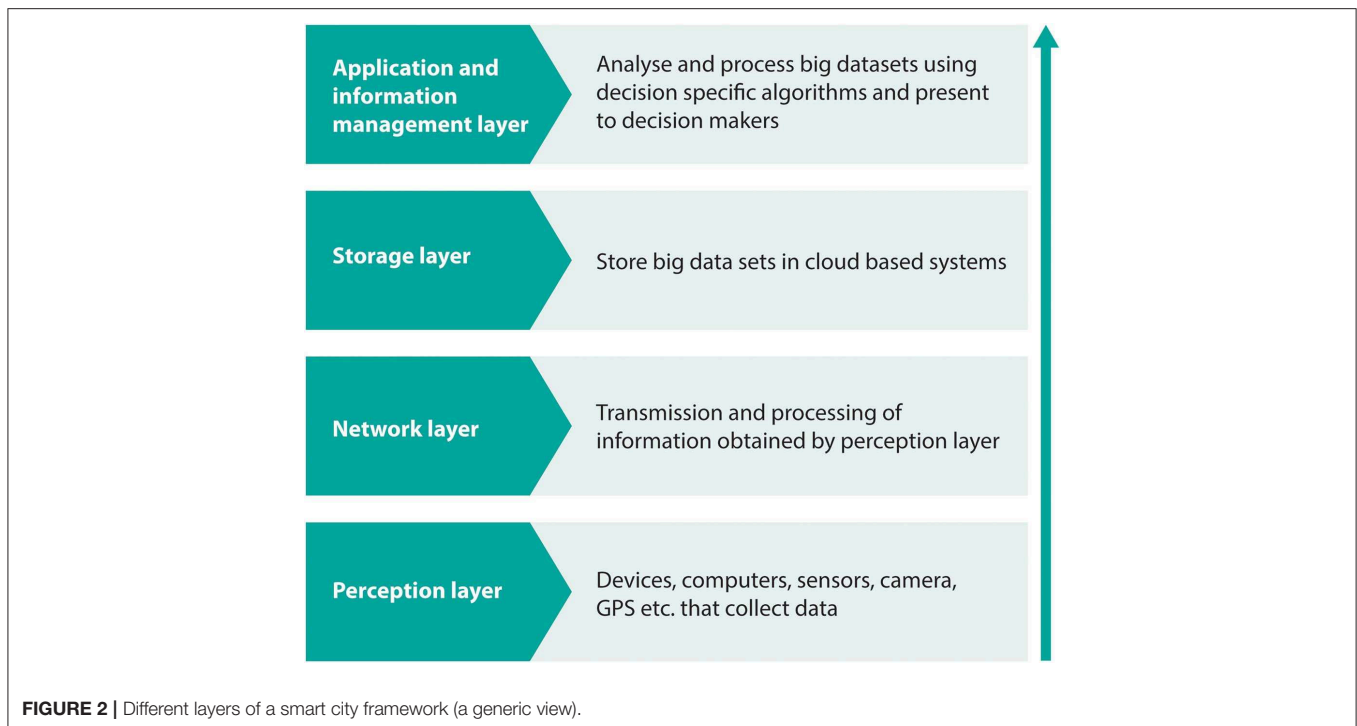
What Does a Smart City Framework Look Like?

There are four main layers in a smart city framework (**Figure 2**). A perception layer which includes range of sensors that can collect real-time or “near real time” data. This also includes a sensor or device management component to handle registration of new devices, assignment of unique identifiers, format data, etc. A network of sensors provides interfaces to interconnect heterogeneous information sources in a secure way and a data storage services to persistently store collected data. Finally this includes a layer which analyses and visualizes stored and real-time data stream. Visualization services include different formats like visual diagrams, reports, graphs, etc. Some of the specialized type of application also include analysis of georeferenced data and dissemination of alarms and notifications. This is beyond the scope of this paper to present detailed smart city frameworks and for more information readers are directed to following references (Alazawi et al., 2014; Sanchez et al., 2014; Scuotto et al., 2016). Rather, we investigate how this generic framework has been used for the coastal disaster management in cities.

Development Trend in Peer Reviewed Academic Literature

Selection of Peer Reviewed Academic Literature

In order to identify relevant academic papers we conducted an extensive search in the “Web of Science” database in early 2018. Initial search was conducted using key words “smart” AND “disaster management” within topics for the entire database and it yielded 223 papers (Type-1). This included papers related to disaster planning and management of all hazards which goes beyond the scope of the paper. We then refined the search by adding “coast” in the search term and it yielded only 6 papers. It was quite clear that these search terms are very narrow therefore we then expanded the scope of the search by making it “smart” AND “disaster management” AND “flood” which yielded 33 papers (type-2). Often flooding in the coastal city is a big issue



and used as a topic in the academic papers. However, by reading through the abstracts of this list it was evident that this list includes studies that are non-coastal in nature. In order to get a representative sample of coastal studies we replaced “flood” with “coast OR flood” and also included “IoT” (internet of things) along with our initial search term “smart.” Type 3 search criteria was “smart OR IoT” AND “disaster management” AND “coast OR flood” which yielded 18 papers. IoT has been one of the main driver of smart city developments and its inclusion in our search criteria allowed capturing technical papers that not necessarily use the term “smart” rather report their development using a more technical terms. A clear trend is visible in all these three sets that research on smart and innovative disaster management systems have been growing exponentially since 2010 (**Figure 3**). It is possible that we may have missed few papers, but our aim was not to find every paper that deals with smart city and coastal disaster, rather to find a representative sample of papers to understand major trend within this emerging body of work.

Analysis of Peer Reviewed Literature

Analysis of this final type-3 set of papers revealed two clear branches. First, a set of papers developed innovative IoT based smart systems for better identification and communication of hazard information (flooding, Tsunami etc.). **Table 3** shows key feature of these studies. **Table 3** maps seven studies from the type 3 sample (which specifically used IoT based smart systems) across their application, type of hazards they addressed, resilience stage which they aimed to cover and technologies used across four layers of smart city framework that are described in **Figure 2**. It shows that application of IoT based major innovations in our study samples mainly focused on managing two types of coastal

hazards, flood and Tsunami. While investigating the technologies that are used across different layers the smart city framework, it was found that in the “perception layer” along with different types of sensors, CCTV camera and smart phones are used for collection of real-time information. Collected information of the perception layer is transmitted by various mediums e.g., Wi-Fi, cellular, internet. Studies which conducted further analysis to generate insights often stored the data either in cloud based systems of local servers. Choice of storage was primarily guided by the size of data generated by the perception layer and analysis method that were used by the authors.

The second group of papers, often categorized as “crisis informatics,” reported use of different advanced analysis techniques (optimization, social media or crowd sourced information etc.) or advanced technologies such as virtual reality for better preparing and managing coastal disasters. As an example, Basu et al. (2016), collected situational information through interactive crowd-sourcing using SMS from the “crowd” present at the disaster site, and analyzed them to develop situational awareness to support appropriate decision-making regarding damage or need assessment during coastal disasters in India. Ai et al. (2016) combined a geographical information system and social media to develop a dynamic decision support system (GIS-SM-DDSS) that integrates geographical information with Twitter technology to enable self-organized information networks to support decision making and collective actions in emergency situations. Ogie et al. (2017) used network analysis to determine optimal sensor locations in developing countries, so that a low cost early warning system of coastal flooding can be implemented. Anbalagan and Valliyammai (2016) used real time social media contents such as micro blogs, tweets, posts

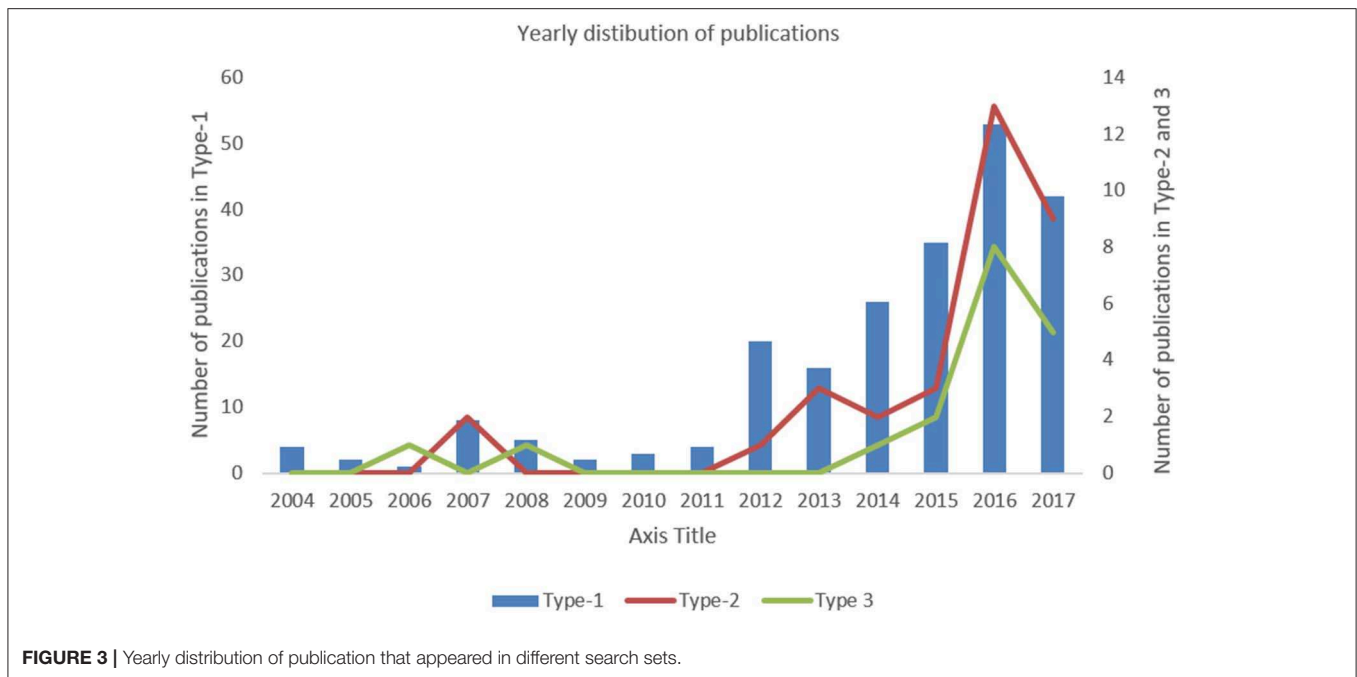


FIGURE 3 | Yearly distribution of publication that appeared in different search sets.

and multimedia content along with geographical location tags (geo-tags) to map the severity of the disaster. Kawai et al. (2015) developed a smart Tsunami drill system using virtual reality technologies to educate and increase awareness of Tsunami disaster among school children.

Implementation Trend at a City Scale

After investigating the development trends in the academic literature, we investigated, how cities are embracing some of these smart city features for managing their coastal disasters. Smart city projects are often reported as case studies to showcase city's progress in embracing new technology to serve its citizens. Among many other information, these case studies generally highlight key technical features of the implemented smart city projects. Analyzing a sample of such case studies can provide a sense about how new developments in the academic literature are translated into practical project implementation.

Selection of the Case Study Sample

A google search was conducted using key words "smart city" AND "Case study" to generate a sample of city specific case studies from the unpublished gray literature that document how city's smart city projects are implemented. Initial screening of the sample documents revealed that not all smart city case studies have disaster management related content. This is mainly due to the fact that some cities do not include disaster management as their focus while implementing their smart city, be it coastal or not, or the case study document that we selected may not have included the disaster management component of the city. Whichever is the case, our analysis discarded those case studies and retain only those that report any disaster management related features. In the next step some of the non-coastal city specific case studies were eliminated to ensure that our

final sample only consists of case studies that include coastal disaster management.

Table 4 shows the final list of the sample case studies. It should be noted that this list is not exhaustive and it is likely to miss some. However, the aim of this paper is not to develop an exhaustive list of case studies rather analyzing a sample in order to understand major trends.

Analysis of Selected Case Studies

Six sample case studies were analyzed to identify what types of coastal disasters were tackled by cities using smart systems, at what stages of the disaster were they used (e.g., early warning, during disaster, disaster recovery etc.), and what smart city features and systems were implemented in the city (**Table 4**). Flooding (coastal and riverine), cyclone (typhoon, hurricane, tornado, and thunderstorm), tsunami, and landslide have been tackled by these cities. Early warning systems of these hazards were most benefited as information about these hazards were collected, analyzed and communicated to citizens for better preparation. As an example, Tokyo's smart disaster early warning system covers a range of hazards, not just coastal, including earthquake. Technology vendor NEC has developed Tokyo's disaster resilience solution which includes observation systems, information gathering capabilities, data analysis and decision-making aids, together with an intelligent warning system, all linked together in an interoperable manner.

Another example is from Rio De Janeiro, which has a central disaster coordination and operation center. Since opening, the Rio Operations Center has integrated information and processes from across 30 different city agencies into a single operations center that provides a holistic view of how the city is functioning on a 24 h basis. The Operations Center serves as the nerve center

TABLE 3 | Example of studies reporting IoT based coastal disaster management systems.

Example	Type of application	Type of hazard	Resilience stage	Perception layer	Network layer	Storage layer	Application and information management layer
Hernández-Nolasco et al. (2016)	Use sensors to measure water level in rivers, lakes, lagoons and streams.	Flood	Preparedness and management of hazard	Sensor	Wi-Fi	No storage	Netduino apps are written using C# language and suitable for mobile applications
Shalini et al. (2016)	Use sensors to measure water level and send SMS to alert	Flood	Management of hazard	Sensor	Cellular	Cloud	
Lo et al. (2015)	Use CCTV to collect imagery and process them via machine learning algorithms to automate real time flood monitoring	Flood	Management of hazard	Visual imagery collected using CCTV	Internet	Cloud	Image detection and processing using machine learning algorithms
Kumar et al. (2015)	Early flood detection SMS service	Flood	Management of hazard	Sensor	Cellular	Local storage	Machine to machine processing
Ancona et al. (2015)	Early detection of flood using low power consuming sensors	Flood	Management of hazard	Ultra-Low Power Micro Controller together with rain gauge sensors	Internet	Cloud	IoT platform Thingworx
Aimmanee et al. (2016)	Adaptable devices such as foldable flood barriers and hydrodynamically supported temporary banks	Flood and Tsunami	Mitigation of hazard	composite cylindrical shell structure embedded with piezoceramic sensor	Cellular	No storage	Bio-mimicking column structures capable of high-velocity water interception and velocity detection in the case of tsunami.
Kitada et al. (2017)	Dessiminate disaster information to smart phone users even after the failure of transmission systems	Flood, Tsunami	Management of hazard	Smart phones	Internet	Local storage	Disaster servers designed using Java and MySQL

for the city, applying analytical models developed by IBM to more effectively predict and coordinate disaster management.

DISCUSSION

Increased potential of natural disaster events as a result of climate change along with rapid development and population growth in coastal cities have created significant risks and challenges for disaster management authorities. Rapid improvement in IT systems has fuelled growing interest in designing and implementing disaster management systems which can predict climatic conditions based on near real-time information, analyse them and communicate with citizens so that disaster impacts can be minimized. To this end a range of innovative systems, tools etc. are developed by the research and academic sector and some of them are making their way to practical city scale implementation. Among these, “smart-city” concept or framework is growing in interest among disaster management professionals, specifically in developed countries. A “smart-city” concept uses embedded sensors, live camera, radar to collect near real-time information and further analyse them to generate valuable insights for disaster management professionals. In the earlier part of the paper, our analysis of a selected sample of peer reviewed academic papers as well as gray unpublished literature revealed some interesting

facts about using ICT based smart city frameworks in disaster management and resilience.

Trends and Gaps

The present review highlights the lack of scalable smart city technologies for improving coastal disaster resilience, and as a result, the lack of at scale implementation of smart city frameworks from a coastal disaster resilience perspective. Our findings are summarized below:

- Various smart city technologies, platforms, analysis techniques and applications that are relevant to coastal disaster resilience have been identified. It is clear that the choice and appropriateness of the technology should be judged under the decision-making contexts for which it is developed (i.e., early warning or pre-disaster stage, disaster management when the disaster is unfolding or post disaster recovery etc.). Future applications and/or further development of a smart city tool for coastal disaster resilience depend on the specific decision-making context. Thus, the lens of decision-making contexts is absolutely necessary to assess the appropriateness of a smart city technology.
- While comparing the analysis findings of both peer reviewed literature and city scale case studies, it is clear that while peer reviewed literature is testing and trialing new approaches

TABLE 4 | Analysis of Smart city case studies for identifying key features of coastal disaster management.

City	Hazards	Stages of disaster addressed	Key smart city features
Tainan, Taiwan	Coastal and riverine flood	Early warning and disaster management	<ol style="list-style-type: none"> 48 remotely controlled pumping station to pump out flood water. They are controlled and monitor in real-time using 4G network. 20 Wearable real time video monitoring sets for outdoor use during typhoon seasons. They provide real-time video stream to disaster coordination center. Image recognition algorithms are used for water level automatic recognition. Water disaster management platform for coordination. Mobile app for disaster information access to citizens.
Barcelona, Spain	Coastal and riverine flood	Early warning and disaster management	<ol style="list-style-type: none"> Flash flooding early warning system which composed on a high-tech radar, a city wide network of sensors for monitoring rainfall in the catchment. Early warning system detect and forecast flooding and provide a series of reliable, understandable and timely warning messages to people at risk and to people in charge of managing that risk. Smart platform for information dissemination such as COWAMA tool in coastal cities and iBeach App for smartphones. They include information on wave, wind, tide and temperature as well as weather forecasts for all beaches of Barcelona. This app also allows the public to proactively warn others about the presence of jellyfish, establishing a means of collaboration between the public and the city council.
Tokyo, Japan	All hazard (including tsunami, typhoon etc.)	Early warning, disaster management and recovery	<ol style="list-style-type: none"> Tsunami is a major coastal hazard in Tokyo and therefore it has smart Tsunami warning and management systems in place. The Japan Meteorological Agency (JMA) and the central government are responsible for developing national emergency solution. On the other hand, when a coastal disaster strikes, cities such as Tokyo become the central coordination and response units. Key technical features of the coastal disaster management systems are: <ul style="list-style-type: none"> nine Ocean Bottom Observation Systems that connect 5,000km of submarine cable, 150 undersea seismometers, and seismometers in strategic locations in building foundations and other structures across the cities, Rain and water level gauges are equipped with sensors and transmit real time data using telecom networks. These data are analyzed and potential hazards are transmitted to cell phone users through cell broadcasting. Mobile users can update their status i.e., whether affected or not, locations etc. in a central system so that if required they can be assisted in their recovery.
Songdo, Korea	Riverine flooding, land subsidence	Early warning and disaster management	<p>Songdo U-disaster prevention system is in charge of spreading information when disaster occurs, monitoring for land subsidence, flooding, and corresponding to fires etc. Main functions include civil defense, spreading situation information to the National Disaster Management System, monitor weak lands for subsidence/flooding, monitor using CCTVs with high magnification during fires, and corresponding to fires. Because Songdo is built upon reclaimed land, monitoring for land subsidence and flooding is important. Key technical features of the disaster management systems are:</p> <ul style="list-style-type: none"> One satellite dish to receive and transmit data 3 water level monitoring camera for flood monitoring 3 flood sensors to detect changes in water level and to detect ground safety according to water pressure levels with in grounds.
Rio de Janeiro, Brazil	Coastal and riverine flooding and associated land slides	Early warning, disaster management and recovery	<p>The automated alert system notifies city officials and emergency personnel in the disaster operation center when a flood is forecasted. As opposed to a previous system in which notifications were manually relayed, the new alert system is expected to drastically reduce the reaction times to emergency situations by using instantaneous mobile communications, including automated email notifications and instant messaging, to reach emergency personnel and citizens. This forecasting system pulls data from the river basin, topographic surveys, the municipality's historical rainfall logs, and radar feeds and process them using a unified mathematical model. This model then predicts rain and possible flash floods, and has also evaluate the effects of weather incidents on other city situations such as city traffic or power outages. Key smart infrastructure behind this system are:</p> <ul style="list-style-type: none"> 1 weather radar with operating range of 250 km 164 rainfall stations that generate data automatically every 15 min, 26 gauged stations 164 audible alert stations with sirens 200 points of support to high-risk.
Orlando, USA	Coastal flooding, hurricane, tornadoes, thunderstorms	Early warning, disaster management and recovery	<p>OCAAlert is an alert system with nearly 14,000 registered subscribers that allows Orange County Government to contact citizens during an emergency by immediately sending message to email account, cell phone and smartphone with real-time updates, instructions on where to go, what to do, or what not to do, who to contact, open shelters, water distribution centers, evacuation routes and other important information under emergency situation. Key smart features are:</p> <ul style="list-style-type: none"> Feeds from Doppler radar and satellite for weather data Flood sensors in critical coastal locations Live camera feeds from expressways GIS based water management system fitted with sensors Automatic Vehicle Location (AVL) function that enables the staffs to track the movement of police cars, fire trucks, emergency medical vehicles etc. during disasters.

and techniques, city scale applications are leaning toward more matured approaches and technologies. As an example, in our study sample of the academic literature an innovative CCTV enabled and machine learning based visual monitoring system was used for automating and process real time flood monitoring using image processing. Whereas, this approach did not proliferate in our city scale case studies as cities mostly used conventional sensors. While, conventional sensing networks can only offer one-dimensional physical parameters measured by gauge sensors, visual sensors can acquire dynamic image information of monitored sites and provide disaster prevention agencies with actual field information for decision-making to relieve flood hazards (Lo et al., 2015).

- At present, there is a scarcity of studies investigating and applying smart city technologies for managing coastal hazards at a local government scale. However, coastal local governments commonly face such issues related to the management and planning for potential coastal hazards. As sea-level rises, this issue is likely to become more critical for coastal local governments (Torabi et al., 2017; Tonmoy et al., 2018).
- In peer reviewed literature “Crisis informatics” has become an emerging smart city framework that develops analytics approaches to extract, analyze, and predict online activities (e.g., tweets and Facebook posts) to address challenges in disaster warning, response, and recovery operations (Palen and Anderson, 2016). For instance, during a disaster, disseminating information effectively and timely plays a critical role in spreading awareness in a community. It requires a range of delivery techniques to reach the target audience using different media and communication means. Online social media (such as Facebook, Twitter) can serve as alternative channels to disseminate information to a wider audience. Applications of such crisis informatics can be found in many recent studies using social media data during disasters (Kryvasheyev et al., 2015; Thom et al., 2016; Sadri et al., 2018). Since crisis informatics is a relatively new field investigating the role of social media during disasters, most studies commonly focus on high-level correlations among the variables of interest when analyzing large-scale data sets (Palen and Anderson, 2016). However, many other questions (Gladwin et al., 2007; Murray-Tuite and Wolshon, 2013) about behavioral and social phenomena, critical to achieving disaster resilience, still remain open. These questions include: how to use social media communications to rapidly identify infrastructure disruption issues and monitor disaster responses and recovery efforts; or how to measure the effectiveness of the available information sources in warning message propagation using the topological properties of the social network observed?
- In city scale implementation case studies:
 - a) different types of early warning systems are developed for communicating detected coastal hazard (e.g., flood, cyclone) warnings to public through variety of mechanisms such as SMS alerts, social media, sirens etc.

- b) different types of remote sensing technologies such as water sensors, radar imagery etc. are used to monitor water levels in flood, tide and rain gauges or to continuously measure the water level variation within a large area (e.g., flood monitoring systems). As an example, flash flood alarming systems require a dense network of rain gauges for monitoring intense local rain storms both to ensure its survival in case of extreme weather and to have a more accurate collection of data. However, those data have to be interpreted using empirical models by correlating in real time the river level and the flow intensity for early flood forecasting and consequent anticipated alarming (Ancona et al., 2015).
 - c) application of other types of sensors such as temperature sensors, pressure sensors in this domain remain limited.
- One common theme emerged as IoT based software platforms are used in both academic literature and city specific case studies for deploying sensors, communicating collected near-real time data, their storage and analysis.

Lack of Use in Erosion Management

Although coastal erosion has been a major coastal hazard, but it did not appear neither in academic literature nor in city scale case studies. Long-term monitoring of shoreline changes is of significant importance for coastal erosion prediction and coastal planning. Using drones or fixed CCTV camera in combination with image analysis techniques can provide opportunity to implement coastal erosion monitoring of city's most erosion prone beaches (Turner et al., 2016). However, this lack of application of smart city frameworks in coastal erosion management brought up a critical point that *time scale* of coastal hazard governs the choice of ICT in disaster management. Coastal hazards not only vary in space (e.g., lower areas get inundated in coastal flooding) but also vary in time (e.g., while cyclones can cause inundation of coastal areas within days, increase in sea level rise may cause inundation gradually over decades). The time scale of coastal hazards often determines the choice and characteristics of the ICT feature that are to be used for risk management. As an example, for managing longer-term coastal hazards such as sea level rise, it is important to understand trends and therefore monitoring tides, sea levels, sediment transport etc. are critical with relevant ICT features such as implementation of monitoring systems with sensors being used (Harley et al., 2015). On the other hand, ICT features for managing coastal storms and cyclones require real-time information to feed early warning systems therefore relevant ICT features and sensors with capability to transmit real time information are used.

Not All Smart City Projects Include Smart Disaster Management

ICT have been used for providing early warning to coastal hazards at both global and local scale (Application of local scale mostly in developed countries). Analysis of a sample of smart city gray literature case studies suggest that not all smart city

projects around the world have incorporated smart ICT features for managing coastal hazards. There is a chance that not all features get reported in case studies therefore this needs to be further investigated.

FUTURE DIRECTIONS AND CHALLENGES

Major Research Questions

Major Research Questions That Need to Be Addressed Include.

- How can we design and implement a smart city decision support system for coastal hazards which includes the vast range of stakeholder concerns and decision-making contexts related to disaster management?
- How can we develop models to better understand infrastructure interdependency at a local government or city scale and integrate them with smart city platforms?
- Will it be possible or effective to develop one smart city tool that can satisfactorily address all the key disaster management issues in coastal areas, or will it be more effective to create an ensemble of smart city platforms with properly designed interfaces allowing information and decision exchange among various platforms?
- How can we create a smart city platform with linked models and data interoperability for modeling coastal hazards and use them for the development of smart decision making under different types of disaster management contexts (pre disaster, during disaster, and post disaster) in coastal areas?

Opportunities for Implementing Smart City Framework for Coastal Disaster Management

Use of a smart city framework provides a basis for monitoring coastal activities and there are significant opportunities to integrate them with computational models of floods (coastal, riverine, Tsunami) and erosion. These models are developed and validated and used for identifying hazard prone areas. Combining these models with real-time information using smart city frameworks can provide opportunity to disaster managers' to dynamically characterize coastal hazards as they unfold. This is especially critical for cyclone or hurricane as their track changes dynamically and so does areas that are likely to get affected by the cyclone or hurricane. Combining validated numerical hydrodynamic model of coastal inundation with real-time information of cyclone track can assist disaster managers to prioritize evacuation dynamically as cyclone changes its track. Not only cyclones, flood models can also be integrated with smart systems to understand concurrent events of catchment flooding and coastal surge. All of this knowledge can then be integrated with socioeconomic and demographic information (i.e., location of vulnerable populations, critical infrastructure, old structure etc.) to better inform disaster management.

Challenges for Implementing Smart City Framework for Coastal Disaster Management

One of the main driving factors of this framework is power and communication systems which are vulnerable to any man-made or natural disasters including coastal ones. If we lose either we will lose the effectiveness of the whole system. Use of these smart systems will increase in future in managing different infrastructure layers and the connectivity will only increase. Smart city technologies will make different city functions more interdependent. Emergency services depending on data analytics or artificial intelligence will have to depend on the availability of the sensors. However, these interdependencies will be a major challenge in future as there are gaps in our understanding about infrastructure interdependency at a local scale that are arising from these smart infrastructures (Tonmoy and El-Zein, 2013; Hasan et al., 2015; Ersoy, 2017).

Although academic literature is developing innovative new smart systems and analysis techniques, they are often designed and tested in isolation. Integration of these systems to serve a common goal such as disaster management at a city scale across different city systems still remains an unresolved challenge. Transferring a newly developed prototype of smart technology for disaster management into a real-life city scale implementation to inform existing disaster management (DM) decision-making protocol is difficult. DM sector is often very hierarchical and often can be resistant toward getting information from different sources that might affect central command under emergency situation. At the same time, multi-asset integration of disaster management is challenged by data sharing although some progress has been made. As an example, safe data sharing initiative has been initiated and implemented across multiple infrastructure operators in Australia to support managing critical infrastructure during disaster events (Australian Government: Department of Infrastructure, 2018).

Because of the complexity of the disaster management issues in the coastal region and a diverse range of stakeholders and available smart systems, it will be a nearly impossible task to build a super-smart city platform to support a wide range of disaster management related decision-makers. Instead, a more pragmatic approach will be to build interfaces amongst different aspects of the problem linking models, platforms and their outputs. Such an interoperable approach of decision support system will be able to fit different smart technologies, analysis techniques in the decision support platform depending on the disaster management decision context. Also, there is a need for a consistent benchmark of relevant data sets to be able to integrate them within smart city compatible decision support systems.

CONCLUSIONS

A disaster resilience framework has been presented to assess current state of research and application of smart city frameworks in disaster management within coastal cities. A

set of academic literature and city specific application case studies were reviewed. We find that smart city technologies such as internet of things (IoT) and crisis informatics have significant potential and have been increasingly used in academic studies but their city-scale applications in coastal disaster management have been limited. We have identified critical gaps, RandD needs and practical challenges to foster development

of smart city oriented decision support systems for coastal disaster management.

AUTHOR CONTRIBUTIONS

FT research idea and manuscript preparation. SH and RT research idea enhancement and review of draft.

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