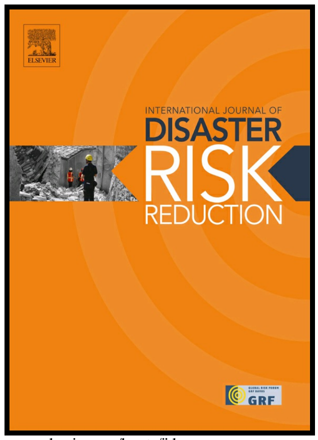

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Tropical cyclone disaster management using remote sensing and spatial analysis: a review

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Tropical cyclone disaster management using remote sensing and spatial analysis: a review

Abstract

Tropical cyclones and their often devastating impacts are common in many coastal areas across the world. Many techniques and dataset have been designed to gather information helping to manage natural disasters using satellite remote sensing and spatial analysis. With a multitude of techniques and potential data types, it is very challenging to select the most appropriate processing techniques and datasets for managing cyclone disasters. This review provides guidance to select the most appropriate datasets and processing techniques for tropical cyclone disaster management. It reviews commonly used remote sensing and spatial analysis approaches and their applications for impacts assessment and recovery, risk assessment and risk modelling. The study recommends the post-classification change detection approach through object-based image analysis using optical imagery up to 30 m resolution for cyclone impact assessment and recovery. Spatial multi-criteria decision making approach using analytical hierarchy process (AHP) is suggested for cyclone risk assessment. However, it is difficult to recommend how many risk assessment criteria should be processed as it depends on study context. The study suggests the geographic information system (GIS) based storm surge model to use as a basic input in the cyclone risk modelling process due to its simplicity. Digital elevation model (DEM) accuracy is a vital factor for risk assessment and modelling. The study recommends DEM spatial resolution up to 30 m, but higher spatial resolution DEMs always performs better. This review also evaluates the challenges and future efforts of the approaches and datasets.

Keywords Remote sensing, Tropical cyclone, Hazard, Vulnerability, Risk, Climate change

1 Introduction

Tropical cyclones are some of the most deadly natural disasters, typically generating sustained high winds, storm surges and intensive rainfall (Wang and Xu 2009). Globally, many coastal areas are affected regularly by tropical cyclone disasters (Li and Li 2013). The destructive characteristics of tropical cyclones are great threats to coastal people and the environment (Ward et al. 2011), resulting in the loss of more human lives than all other natural disasters (Li and Li 2013). During 1968-2010, on an average about 88 tropical storms formed each year across the world (Shultz et al. 2005; Weinkle et al. 2012). Out of these, 48 acquired the strength of a tropical cyclone (category 1 and 2) and 21 achieved the intensity of a major tropical cyclone (category 3, 4 and 5) (Weinkle et al. 2012). Over the last two centuries globally around 1.9 million people have lost their lives by cyclone disasters (Shultz et al. 2005). Tropical cyclones are also responsible for enormous damages in local economy and environment (Shultz et al. 2005; Pielke Jr et al. 2008; Hoque et al. 2016b). The intensity of tropical cyclones will probably increase under likely future climate change scenarios (IPCC 2007; Deo and Ganer 2014; Krishnamohan et al. 2014), and thus coastal people and environment will be more vulnerable to tropical cyclones.

Although, it is not possible to stop cyclone disasters, but their impacts can be minimised using a range of management approaches, e.g. response, recovery, prevention/reduction and preparedness (Khan 2008; Islam and Chik 2011; Moe and Pathranarakul 2006). Remote sensing and spatial analysis are efficient and accurate tools to provide useful information in every phase of cyclone disaster management (Hussain et al. 2005; Wang and Xu 2010; Rana et al. 2010). Remote sensing data combined with spatial analyses provide required information on changes to environmental conditions and infrastructure due to cyclonic impacts and are essential tools for reducing the impacts of future tropical cyclones. Developing and implementing appropriate approaches through mapping, monitoring and management, these tools serve to protect people, property and the environment. The most significant contribution of satellite remote sensing is repeated high spatial resolution (< 5 m pixels) satellite imagery both before and after the cyclone event to assess the impacts and monitor the progress of recovery (Klemas 2009; Martino et al. 2009; Wang and Xu 2010). Satellite remote sensing and spatial analysis can also be used predictively to assess the cyclonic risk through hazard, vulnerability and mitigation capacity mapping and to model potential future impacts under likely climate change scenarios (Azaz 2010; Roy and Blaschke 2013; Yin et al. 2013; Thompson and Frazier 2014). Furthermore, satellite remote sensing also plays an essential role in tracking tropical cyclones and providing accurate forecasting of landfall (Roy and Kovordányi 2012; Elsberry 2014). However, this is not a focus of the current paper. This paper focuses on non-metrological and oceanographic remotely sensed data, for examining changes to environmental conditions and infrastructure as well as assessing future impacts for effective cyclone disaster management.

A great amount of work has already been conducted in different phases of tropical cyclone disaster management using satellite remote sensing and spatial analysis (Lee et al. 2008; Wang and Xu 2009; Li and Li 2013; Poompavai and Ramalingam 2013; Rana et al. 2010). Various kinds of processing techniques and dataset have been incorporated in these studies. Visual interpretation, field transects, data mining and change detection incorporating moderate (5–30 m pixels) to high (< 5m pixels) spatial resolution satellite imagery are commonly used techniques for assessing tropical cyclone impacts and recovery. Single criterion, multi-criteria and various risk equations have been used for tropical cyclone risk assessment. For assessing the future impacts of a tropical cyclone under a climate change scenario, risk modelling has widely been used by many researchers (Rana et al. 2010; Bhuiyan and Baky 2014; Li and Li 2013). Some of these modelling tools are based on advanced modelling software, while others are simple Geographic Information System (GIS) based models.

In the context of the wide range of remote sensing and spatial analysis based approaches used for managing tropical cyclone disasters, it is very challenging to select appropriate datasets and processing approaches, since it is critical to understand the spatial and temporal effects of cyclone hazards. Additionally, it is required to ensure that the information produced is accurate and suited to the particular cyclone management task and context (Klemas 2009; Joyce et al. 2009b). This paper provides a comprehensive review of commonly used remote sensing and spatial analysis based approaches, specifically addressing their strengths and weaknesses in relation to data requirements for tropical cyclone disaster management. The paper begins with an overview of cyclone disaster management processes and their information requirements. This is followed by a critical evaluation of remote sensing, spatial analysis techniques and dataset to find out the appropriate processing techniques and dataset best suited to cyclone management tasks. The evaluation focuses on tropical cyclone impacts assessment and recovery, risk assessment and risk modelling approaches. The strengths and weaknesses, procedures and other pertinent issues concerning the different approaches and dataset are compared and discussed. The challenges and future research areas are also evaluated. Lastly, the paper summarises the best approaches and dataset recommended.

2 Tropical cyclone disaster management and its information requirements

Cyclone disaster management has two phases, i.e. post-disaster, response and recovery; and pre-disaster prevention/reduction and preparedness (Figure 1). Extensive sources of information are required at each of the phases of cyclone disaster management (Joyce et al. 2009b).

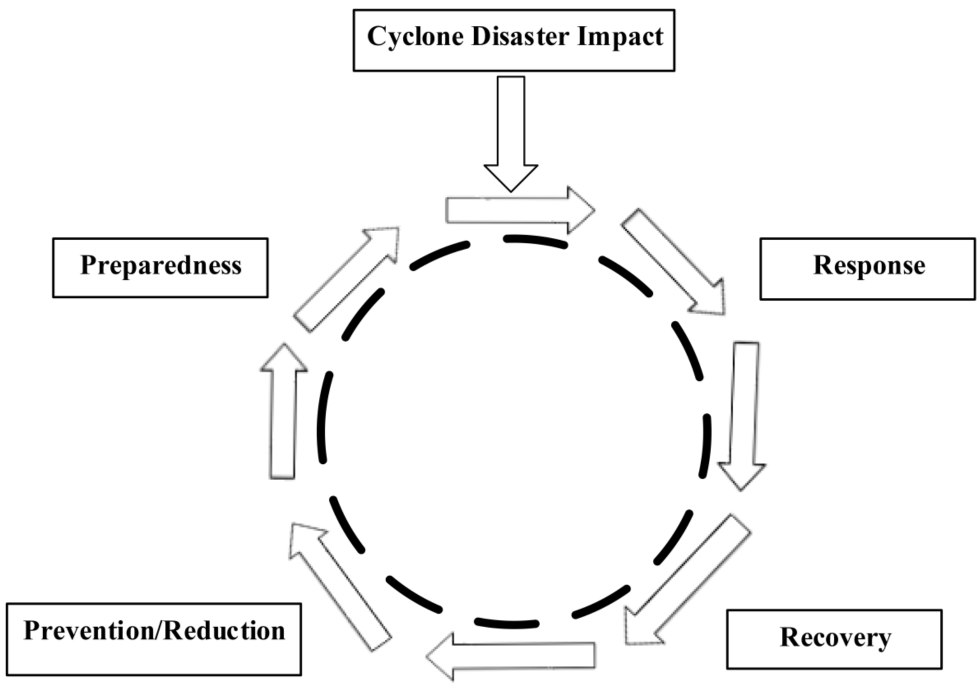

Figure 1. Cyclone disaster management cycle (adapted from Khan 2008)

The response phase includes the actions to reduce the impact of disasters protecting life and property during and immediately after the landfall of tropical cyclones (Joyce et al. 2009b). The activities considered in this phase are evacuation, relief, search and rescue, and management of natural resources (Khan 2008; Coppola 2006; Yamazaki and Matsuoka 2007). Spatial location, type and intensity, percentage of area and structures affected constitute the requisite information for supporting these activities. This information is derived through a process of overall impacts assessment (Joyce et al. 2009b). Conversely, the recovery phase includes restoration and reconstruction of the affected areas after the cyclone disaster, in particular, monitoring the progress of debris removal, reconstruction of settlements and structures (buildings, bridges, roads), and vegetation regrowth (Moe and Pathranarakul 2006; Joyce et al. 2009b). The required information is obtained through the process of recovery assessment (Joyce et al. 2009a).

Table 1. Summary of the information and data types required at each stage of cyclone disaster management.

Management Phase	Process	Type of information	Required data type	Scale	Accuracy
Response	Impact assessment	Area, amount, rate and type of impacts on particular landscapes	Moderate to very high resolution satellite imagery to produce multi-date land use and land cover	Local	Overall accuracy 85-90% for land use and land cover classification
Recovery	Recovery assessment	Area, amount, rate and type of recovery in the landscape e.g. debris removal, reconstruction, vegetation regrowth.	Moderate to very high resolution satellite imagery to produce multi-date land use and land cover	Local	Overall accuracy 85-90% for land use and land cover classification
Prevention/ Reduction	Risk assessment	The key infrastructures and areas at risk at present with spatial location, level of risk, factors liable for risk, and suitable mitigation options.	Storm surge height, cyclone frequency, land use and land cover from satellite imagery, tide ranges, cyclone wind speed, topography from Digital Elevation Model (DEM), precipitation, and population.	Local/ Regional	Overall absolute vertical accuracy of DEM within 20 m. Overall accuracy 85-90% for land use and land cover classification.
Preparedness	Risk modelling	The key infrastructure and areas that would be at risk in the future with spatial location under climate change scenarios, level of risk, factors liable for risk and probable mitigation strategies.	Historical cyclone wind speed and surge height, projected sea level rise, land use and land cover from satellite imagery, topography (elevation and slope) from DEM.	Local/ Regional	Overall absolute vertical accuracy of DEM within 20 m. Overall accuracy 85-90% for land use and land cover classification.

The prevention/reduction phase involves reducing the likelihood and impacts of cyclone disasters by incorporating required measures and planning (Showalter 2001b; Islam and Chik 2011). The process includes cyclone risk mapping through the mapping of hazards, vulnerability and mitigation capacity for producing required information (Joyce et al. 2009b; Taubenböck et al. 2008). On the contrary, the preparedness phase includes the development of required systems to manage any tropical cyclone disasters and to reduce their impacts (Coppola 2006; Khan 2008; Moe and Pathranarakul 2006). Monitoring the cyclone hazards, identifying probable affected areas, developing warning systems, adequately training to the volunteers and evacuation plans are considered part of the preparedness activities (Joyce et al. 2009b; Darsan et al. 2013). Cyclone risk modelling is an important process in this stage which can provide realistic scenarios identifying areas that may be affected in the future (Hussain et al. 2005). Table 1 summarises the type of information and data required at each stage of cyclone disaster management.

Identification of a suitable dataset is a pre-requisite to derive accurate information by appropriate processing techniques for effective cyclone disaster management (Joyce et al. 2014; Azaz 2010). Considering the wide ranges of available sources to produce the data types required for cyclone disaster management, it is yet challenging to identify the most suitable dataset (Li et al. 2011). There are several criteria, which can be considered in the selection of appropriate datasets. Spatial resolution, scale, accuracy, and the suitability of datasets in terms of particular processing techniques are the most remarkable ones (Joyce et al. 2009a; Li et al. 2011; Showalter 2001a).

3 Evaluation of remote sensing and spatial analysis techniques and the datasets appropriate for tropical cyclone disaster management

A range of studies has been conducted for managing tropical cyclone disasters using satellite remote sensing and spatial analysis techniques, and dataset with different degrees of success. Appropriate dataset and processing techniques are required for deriving more accurate and useful information for effective cyclone disaster management (Joyce et al. 2009b). The procedures, dataset, applications, strengths and weaknesses, and other issues concerning the various approaches are discussed and compared here to find out the most appropriate dataset and relevant processing techniques. The discussion is followed by tropical cyclone disaster management phases: response and recovery, prevention/reduction and preparedness

3.1 Response and recovery

Response and recovery are two essential phases of tropical cyclone disaster management. The location, amount, rate, type and percentage of the area and structures affected are required information for the response phase whereas area, type and rate of recovery in the landscape are essential for recovery phase (Khan 2008). Overall impact and recovery assessment are required processing in these two phases of management to generate supporting information. Various techniques and wide ranges of remote sensing data have been used for assessing the impacts and recovery of tropical cyclone disasters. Table 2 summarises the characteristics of remote sensing data suitable for tropical cyclone impact assessment and recovery. An overview of processing techniques including their advantages and disadvantages are presented in Table 3.

3.1.1 Change detection

Change detection is one of the most effective techniques that can be performed in a simple and straightforward way to provide an overview of post-disaster impact and recovery using multi-date moderate to very high spatial resolution satellite imagery (Lu et al. 2004; Wang and Xu 2010). Change detection is used to distinguish the differences in the state of an object/phenomenon between two different times of observation (Lu et al. 2004; Martino et al. 2009). Generally, there are two mainstream approaches in satellite image based change detection analysis for tropical cyclone impact assessment and recovery; one is pre-classification, and the other is post-classification change detection (Hussain et al. 2013; Joyce et al. 2009a). Pre-classification change detection approaches are applied without classification of pre- and post-disaster satellite images. On the contrary, the pre- and post-disaster images are needed to classify according to selected features in the landscape to apply the post-classification change detection approaches.

a) Pre-classification

The most useful approaches of pre-classification change detection for assessing tropical cyclone impacts and recovery includes image differencing, change vector analysis, principal component analysis and vegetation index differencing (Joyce et al. 2009a; Gillespie et al. 2007; Wang and Xu 2010). These approaches are algebra and transformation based comparisons, thus they cannot provide the complete change matrix (Lu et al. 2004). The complete change matrix includes the detailed change statistics of specific features between before and after disasters. The complete change matrix helps to identify the location, type and rate of the impacts as well as recovery of disasters in detail. These types of approaches are effective to provide a general overview of impacts and recovery within less processing time (Joyce et al. 2009a). Lee et al. (2008), Rodgers III et al. (2009), Zhang et al. (2013) and Bhowmik and Cabral (2013) applied vegetation index differencing for assessing the impacts and recovery of forest caused by tropical cyclones Herb (1996), Katrina (2005), Saomai (2006) and Sidr (2007). They used the normalized difference vegetation index (NDVI) changes values to assess the impacts and recovery, but were unable to provide detailed information in terms of the forests impacted and recovered.

Table 2. Summary of characteristics of remote sensing data suitable for cyclone impact assessment and recovery

Data type	Platform	Sensor	Spatial resolution (m)	Scene dimension	Repeat interval	Launch date	Coverage	Data sources
Optical	Worldview-1	Panchromatic	0.6	16 x 16 km	1.7 days	September 2007	Global	www.digitalglobe.com
	Worldview-2	Panchromatic Multispectral	0.46 1.85	16 x 16 km	1.1 days	October 2009		
	Worldview-3	Panchromatic Multispectral	0.31 1.24	16 x 16 km	1 day	August 2014		
	GeoEye-1	Panchromatic Multispectral	0.41 1.65	15 x 15 km	2-3 days	September 2008		
	Quickbird	Panchromatic Multispectral	0.6 2.4	18 x 18 km	1.5-3 days	October 2001		
	IKONOS	Panchromatic Multispectral	1 4	11 x 11 km	1.5-3 days	September 1999		
	RapidEye	Multispectral	5	77 x 77 km	1day	August 2008		www.planet.com
	ALOS	PRISM AVNIR	4 10	35 x 35 km 70 x 70 km	2 days	January 2006		http://global.jaxa.jp/
	Pliades-1	Panchromatic Multispectral	0.5 2	20 x 20 km	1 day	December 2011		pleiades.cnes.fr/fr
	SPOT-4	Panchromatic Multispectral	10 20	60 x 60 km	2-3 days	March 1998		www.astrium-geo.com
	SPOT-5	Panchromatic Multispectral	5 10	60 x 60 km	2-3 days	May 2002		
	SPOT-6, 7	Panchromatic Multispectral	1.5 6	60 x 60 km	1 day	September 2012 and June 2014		
	Sentinel-2A	Multispectral	10, 20, 60	290 x 290 km	5 days	June 2015		https://sentinel.esa.int/

Table 2 (Continued)

Data type	Platform	Sensor	Spatial resolution (m)	Scene dimension	Repeat interval	Launch date	Coverage	Data sources
Optical	Cartosat-2	Panchromatic	0.5	9.6 x 9.6 km	4 days	July 2010	Global	www.isro.gov.in/
	Resourcesat-1	Multispectral	5.8	141 x 141 km	5 days	October 2003		
	KOMPSAT-2	Panchromatic Multispectral	1 4	15 x 15 km	2-3 days	July 2007		www.kari.re.kr/
	OrbView-3	Panchromatic Multispectral	1 4	8 x 8 km	3 days	June 2003		earthexplorer.usgs.gov/
	Landsat-5	TM Multispectral	30	170 x 185 km	16 days	April 1984		
	Landsat-7	Panchromatic Multispectral	15 30	170 x 185 km	16 days	April 1999		
	Landsat-8	Panchromatic Multispectral	15 30	170 x 185 km	16 days	February 2013		
SAR	ALOS	PALSAR	10	250-350 km	2 days	January 2006	Global	http://global.jaxa.jp/
	Radarsat-1	Fine	8	50 x 50 km	24 days	November 1995		www.asc-csa.gc.ca/
	Radarsat-2	Spotlight Ultra-fine Fine	1 2 8	45-500 km	24 days	December 2007		
	Cosmo-Skymed	Spotlight Stripmap	1 3	10-200 km	1.5 days	June 2007		www.asi.it/
	TerraSAR-X	Spotlight Stripmap	1 3	10-100 km	2.5 days	June 2007		www.dlr.de
LiDAR	Airplane, UAV	ALTM Orion, ALS70, Falcon, LMS-S560-A, Harrier 68i	0.5-1	Daily coverage 1-100 km^2	Mobilized to order	Since 1986	Local	

They also demonstrated that optical images Landsat 5 and 7 (30 m resolution) and SPOT-4 (20 m resolution) were useful for assessing the impacts and recovery of forests.The principal component analysis approach found to be less effective for providing detailed information as used by Kwarteng (2010) for impact assessment of cyclone Gonu in Oman using IKONOS satellite imagery.

b) Post-classification

Post-classification change detection is a simple and extensively used change detection approach in natural disaster impact assessment and recovery (Wang and Xu 2010; Gillespie et al. 2007; Joyce et al. 2009a). It requires the rectification of pre- and post-disaster satellite images and their classification according to the selected feature in the landscape. A details matrix of change and the minimum external impact originated by atmospheric and environmental differences constitute some of the advantages of this approach (Lu et al. 2004). However, an error in the classification leads to impacts in terms of the changes results (Jensen 2009). Wang and Xu (2010) evaluated the pre- and post-classification approaches for assessing the hurricane damage to forests in the lower Pearl River in the United States using Landsat-5 imagery. They examine the image differencing, principal component analysis, change vector analysis and post classification comparison algorithm. The results proved that the post classification comparison algorithm contributed the highest accuracy (87%) with detail changes results among other approaches.

Two classification approaches are integrated with the post-classification comparison technique; one is pixel based and the other is object-based. Pixel-based is a more traditional and effective classification approach where the main focus of analysis is on the basis of the assumption that the algorithms work fully on the spectral analysis of pixels on an individual basis (Blaschke et al. 2014; Hussain et al. 2013). Despite its usefulness in the analysis of very low to moderate spatial resolution imagery, it does not provide the best results in the analysis emerging on high spatial resolution imagery (Lu et al. 2004; Hussain et al. 2013). Recent developments of object-based segmentation and classification approach now help solving the limitation of the pixel based approach where the main focus is built upon the concept of objects (the size, shape and context of the object) rather than on the spectral properties of the pixel (Lu et al. 2004; Hussain et al. 2013). This approach is not appropriate for low-resolution satellite imagery (Hussain et al. 2013). Yamazaki and Matsuoka (2007) examined the use of

IKONOS imagery for the earthquake damage assessment in Central Java. They investigated the traditional pixel-based and object-based classification for post-classification comparison. Their results revealed that object based analysis enhanced the accuracy over the pixel-based approach.

c) Others

The hybrid change detection is another approach and is a combination of pre- and post-classification change detection (Hussain et al. 2013). The pre-classification approaches, for example, image differencing are used to identify the changes area and afterwards, post-classification methods are applied to classify and analyse the detected changes area (Lu et al. 2004). This approach found to enhance the accuracy of changes to a greater extent (Yamazaki and Matsuoka 2007).

Table 3 Overview of remote sensing data and processing techniques to assess the tropical cyclone impacts and recovery

Data type	Technique	Advantages	Disadvantages	Examples
Multispectral moderate to high resolution	Vegetation index differencing	Minimise impacts of topographic effects and illumination.	Difficult to identify the type and rate of impacts and recovery. Random or coherence noise.	Bhowmik and Cabral (2013)
	Image differencing	Simple and easy to interpret the result.	No complete change matrix and requires optimal threshold selection.	Wang and Xu (2010)
	Principal component analysis	Decreases the data redundancy and give importance to various information in the derived components.	No complete change matrix and provides binary change. Difficult to interpret and label due to being scene dependent.	Kwarteng (2010)
	Change vector analysis	Capability to use any number of spectral bands and to produce detailed change information.	Hard to ascertain the land cover change trajectories.	Wang and Xu (2009)
	Post-classification comparison	Detailed complete change matrix and easy to analyse the location, type, rate impacts and recovery. Minimises the atmospheric, sensor and environmental impacts.	Final accuracy is linked to the individual image classification accuracy.	Klemas (2009)
	Visual interpretation	The analyst's skills and knowledge in the area are useful.	Unable to give detailed change information and it is non-repeatable. Time-consuming and results depend on analyst's skill and experience.	Chiroiu and Andre (2001)
	Data mining approach	Opportunity for searching large data sets and spatiotemporal patterns. Supports advanced clustering and classification approaches.	Complex to use and there is no integration between the data mining tool and mainstream image processing. No complete change matrix.	Barnes et al. (2007)

3.1.2 Visual interpretation techniques

Pre- and post-disaster satellite imagery and aerial photograph based visual interpretation have been carried out for assessing the damage to buildings and other structures in the past and more recent times (Chiroiu and Andre 2001; Yamazaki and Matsuoka 2007; Lu et al. 2004; Vatsavai et al. 2011). This technique can utilise the full experience and knowledge of experts in the analysis. The drawbacks of this method are the amount of time consumed for a large area analysis and the complexity in providing detailed quantitative damage results (Lu et al. 2004; Pesaresi et al. 2007). Al-Khudhairy et al. (2005) applied the visual interpretation technique for damage assessment with pre- and post-satellite imagery. The findings showed that it was very challenging to identify housing damage using higher than 2 m spatial resolution satellite imagery.

3.1.3 Data mining

Image-data mining is also an important approach for assessing tropical cyclone impacts and recovery. It contributes to detect and classify the tropical cyclone impacted features, for example, vegetation, buildings, roadways, railways etc. for damage assessment. This approach is also useful to identify blocked access routes and rescue/recovery staging areas for cyclone disaster response planning. It works by using a novel trellis structure known as the Q-tree (Barnes et al. 2007). Firstly, related high-resolution imagery is retrieved based on concerned query features. These features are then extracted from imagery using image analysis to develop a content-based query. Then σ-tree conduct queries within the archived imagery for a pixel space representation in order to compare the features of interest (Eklund et al. 2000). Barnes et al. (2007) developed and examined this approach for hurricane disaster assessment using IKONOS imagery. The results demonstrated the capability to detect damage and to explore the areas requiring an urgent response.

3.2 Prevention/Reduction

One essential form of information required for prevention/reduction phase of cyclone disaster management is the key infrastructure and areas at risk in relation to spatial location, levels of risk, factors liable for risk and suitable mitigation options. This information is usually derived from the risk assessment. Many techniques and a wide range of remote sensing and spatial data as evaluation criteria have been used for mapping the tropical cyclonic risk. Selecting appropriate equations, scales, criteria and their decision making process are crucial issues with risk assessment processing techniques as they provide more accurate and useful information (Dewan 2013c; Yin et al. 2013) .

3.2.1 Risk assessment equation

The risk is regarded as the probability of expected damage by a particular hazard (Li and Li 2013; Dewan 2013a). The most commonly used risk assessment equation is,

$$\text{risk} = \text{vulnerability} \times \text{hazard} \tag{1}$$

where, vulnerability is the extent to which a community and environment is likely to be affected by a particular hazard (Eckert et al. 2012; Rashid 2013), and hazard is an event (Islam et al. 2013; Blaikie et al. 2014) which can affect life, property and environment (Rashid 2013).

Several studies conducted by Rafiq et al. (2010); Eckert et al. (2012); Rana et al. (2010); Dewan (2013c); Khalid and Babb (2008) used this equation for tropical cyclone risk assessment. Over time, this equation is modified to produce more reliable output. It is essential to incorporate the mitigation capacity in the effective risk assessment procedure. The modified equation by Bobby (2012) and Li and Li (2013) therefore is,

$$\text{risk} = \text{vulnerability} \times \text{hazard}/\text{mitigation capacity} \tag{2}$$

Some recent studies claimed that it is critical to assess the exposure with the vulnerability and hazard evaluation in the risk assessment procedure (Poompavai and Ramalingam 2013; Rafiq et al. 2010). The final equation therefore is,

$$\text{risk} = \text{vulnerability} \times \text{exposure} \times \text{hazard}/\text{mitigation capacity} \tag{3}$$

This equation is a more logical and complete for assessing cyclonic risk. Table 4 gives an overview of some data and equations commonly used for assessing cyclonic risk.

Table 4 Overview of some data and equations used to assess the cyclonic risk

Data Type	Equation	Processing	Authors
ASTER DEM, spatial and field data	Risk = vulnerability × hazard	Risk assessment	Khalid and Babb 2008
SPOT, Landsat, ASTER GDEM and field Data	Risk = vulnerability × hazard	Vulnerability and hazard evaluation	Rafiq et al.2010
DEM, Satellite image, field data	Risk = vulnerability × hazard	Risk assessment	Rana et al. 2010
Iknonos, DEM,field and spatial data	Risk = vulnerability × hazard	Risk assessment	Eckert et al. 2011
Spatial and field data	Risk = vulnerability × hazard/capacity	Risk assessment	Bobby 2012
SPOT-5 Imagery, SRTM-DEM, spatial data, historical cyclone data	Risk = vulnerability × hazard	Composite risk assessment	Yin et al. 2013
Landsat 7 and IRS, spatial data	Vulnerability = exposure × susceptibility/coping capacity	Vulnerability	Roy et al. 2013
Spatial and field data	Risk = vulnerability × hazard	Risk assessment	Li and Li 2013
IRS-P6, Cartosat-1 (PAN), filed and spatial data	Risk = vulnerability × exposure × hazard /mitigation capacity	Direct risk assessment	Poompavai & Ramalingam 2013

3.2.2 Criteria and scale selection

Selection of appropriate criteria and scale are a critical part of cyclonic risk assessment approaches (Poompavai and Ramalingam 2013; Masood and Takeuchi 2012). The generation of detailed, accurate and reliable information depends on the appropriate criteria selection, data quality and their processing techniques (Dewan 2013c). Similarly, the size of the study area also plays a significant role in deriving detailed information (Dewan 2013a). Detailed local scale risk information can help to pinpoint suitable mitigation options and implement appropriate plans to reduce the impacts of tropical cyclones at the local level. Most of studies on tropical cyclone risk assessment using remote sensing and spatial analysis is on the regional scale, covering areas >1000 km^2 based on very limited criteria (Li and Li 2013; Eckert et al. 2012; Darsan et al. 2013; Yin et al. 2013; Rafiq et al. 2010; Khalid and Babb 2008). These studies show that limited criteria and a large (>1000 km$^{2)}$ study site affect the reliability and accuracy of risk information. Moreover, the studies that used DEM at 30 m resolution as evaluation criteria in the risk assessment procedure provided more accurate results compared to those used more coarse resolution DEM (Yin et al. 2013; Rana et al. 2010).

3.2.3 Multi-criteria decision making.

Several criteria are used in effective risk assessment procedure and require their weighting in the context of decision making analysis. Multi-criteria decision analysis (MCDA) is a suitable approach to analyse and weight particular criteria in the cyclone risk assessment process. Analytical hierarchy process, multi-attribute theory and outranking are the most common methods in this approach. Table 5 summarises these methods and outlines their individual strengths and weaknesses.

a) Analytical Hierarchical Process (AHP)

The analytical hierarchy process (AHP) is an effective tool in analysing multi-criteria to support the decision making process (Roy and Blaschke 2013; Malczewski 1999). It provides a decision making procedure that presents the problem through a hierarchical structure. Based on the qualitative judgement of experts and users, Saaty (1980) developed a nine-point scale to promote the priorities of criteria through the pairwise comparison matrix (Roy and Blaschke 2013). Uncertainty is closely related to any decision (Saaty 1988; Malczewski 2006). To overcome this challenge, a sensitivity analysis works well in this method to verify the consistency of a given decision in response to preferences to the criteria (Chen et al. 2001; Poompavai and Ramalingam 2013). This method is most popular for multi-criteria weighting (Malczewski 2010). Yin et al. (2013) examined the composite risk assessment of a typhoon in China's coastal area using spatial analysis and remote sensing data integrating many relevant criteria. The results confirm that analysis of more associated criteria using AHP provides more reliable and realistic risk assessment information.

Table 5 Comparison of critical elements, strengths and weaknesses of several advanced MCDA method

Method	Strength	Weakness	Example
Analytical hierarchy process	Theoretical foundation and accuracy are stronger. Easy to understand the pairwise comparison matrix and most popular weighting approach	Decision maker's true preferences are not directly present. It takes more time and cost for the purposes of generating a set of weights.	Mahapatra et al. (2015)
Multi-attribute theory	Overall scores are transferred into the same scale which makes it easier to compare. Tries to present the preferences of decision makers in a simple expression.	Comparatively complex method. The maximisation of utility by decision makers in this process is not sound.	Meyer et al. (2009)
Outranking	Simple ranking and does not to integrate into a single unit. Poor alternative in a single criterion could be eliminated from consideration.	It does not represent the true preference of decision makers in ranking. The used algorithms in this technique are comparatively complex.	Rogers et al. (2004)

b) Multi-Attribute Utility Theory

Multi attribute utility theory is an advanced method for weighting the criteria in decision making (Dyer 2005). It uses numerical scores based on different options on a single scale. In this method, all divergent criteria are transformed into a single 0-1 scale through utility value functions to undertake the overall decision. Stakeholder judgment is given more priority in this technique, as they are assumed more rational and knowledgeable in their judgments. Therefore, stakeholder's decisions are taken directly in criteria weighing without any modification. Gómez-Limón et al. (2003) applied this method for agricultural risk aversion. The results were found in a satisfactory level, however, they evaluated that in some cases this method does not give a true representation of a stakeholder's decision. Application of this technique for cyclone risk assessment in the current literature is still scarce.

c) Outranking

Outranking is also another sophisticated decision making method. The principle of this technique is that one alternative gets dominance over another. This technique denies that the single best alternative could be found, while dominance generally happens when one alternative shows better performance over another (Greene et al. 2011). Any kind of scale is not used for comparison like the AHP method. Actually, it serves the preference ranking of most suitable alternative rather than representing the true preference of decision makers (Kangas et al. 2001). Elimination Et Choix Traduisant la Realite (ELECTRE) and Preference Ranking Organisation Method for Enrichment Evaluations (PROMETHEE) are two approaches integrated within this Technique. Rogers et al. (2004) examined the outranking method PROMETHEE for contaminated sediment management. They found the technique more useful for integrating the expert's judgement with the stakeholder's value. Application of this technique for cyclone risk assessment in the current literature is also unavailable.

3.3 Preparedness

Risk modelling is a vital processing in the preparedness phase of cyclone disaster management and provides a realistic risk scenario of the future. It includes the level of risk with spatial location, key infrastructure and areas at risk, factors liable for risk and probable mitigation strategies. The accuracy of the risk model depends on the accuracy of the DEM, its scale, data quality and their processing techniques (Zerger 2002). Table 6 summarises the key data and methods used to model the tropical cyclone risk.

Several kinds of modelling techniques are incorporated during cyclone disaster risk modelling. Some of them are based on fully advanced modelling software and some of them on simple GIS-based processing. The Tropical Cyclone Risk Model (TCRM) is one of the advanced historical wind data based statistical models for modelling the hazard and risk associated with tropical cyclones (Middlemann 2007). Arthur et al. (2008) applied this model to investigate the return periods of cyclone hazards in the Australian region, and found it useful for deriving the required information. Skills in programming and enormous meteorological data are required for this model. Further, it is unclear whether it can work in other parts of the world.

Table 6 Overview of some data and methods used to model the tropical cyclone risk

Data	Method	Processing	Authors
Physiographic data, Eustatic sea level rise, land use data	Ad hoc mathematical model and numerical simulation	Risk modelling	Gambolati et al. (2002)
Historical cyclone and field data	wind hindcasting model	Risk modelling	Puotinen (2007)
Historical cyclone data	Tropical cyclone risk model (TCRM)	Risk modelling	Arthur et al. (2008); Middlemann (2007)
Historical cyclone data	SLOSH storm surge model	Risk modelling	Lin et al. (2010)
Historical cyclone data	GIS and remote sensing techniques based storm surge model	Risk modelling	Rana et al. (2010)
Historical hurricane parameters	CH3D-SSMS based storm surge model	Risk modelling	Condon and Peter Sheng (2012)
Cyclonic data, SRTM 3 data	Wind-based surge model	Storm surge modelling	Ozcelik et al. (2012)
Ikonos imagery, DEM spatial and field data	Storm evaluation index based	Risk Mapping in 10 year return periods	Li and Li (2013)
Ikonos imagery and field data	Inundation model	Risk model	Darsan et al. (2013)

Another model used by Puotinen (2007) is a wind hindcasting one based on historical cyclone data using GIS for modelling the risk of cyclone wave damage to coral reefs in the Great Barrier Reef. A long historical cyclone dataset of over 50 years and an experienced meteorologist are required to calibrate the meteorological data to run this model. Li and Li (2013) used the Gumbel and Pearson-III method for modelling the tropical cyclone storm surge risk on a 100 year return period based on 30 years storm surge data in a GIS environment. Their findings show that the risk was modelled accurately, but the produced information was less detailed due to the application at the regional scale.

The storm surge model is a widely used model for risk assessment, which is prepared based on previous cyclone meteorological characteristics and topographic data (Lin et al. 2010; Karim and Mimura 2008; Hoque et al. 2016a). The output of storm surge model is generally used as a basic input to generate an accurate future risk map (Frazier et al. 2010; Rao et al. 2007). The risk map provides essential information for future risk management decision making (Bhuiyan and Baky 2014; Karim and Mimura 2008). Generally, storm surge model can be prepared using simple GIS-based processing, or it can also use advanced program based modelling software. Rana et al. (2010) used GIS and remote sensing based simple and comprehensive storm surge model integrating historical cyclone data and DEM (30 m resolution). They modelled the tropical cyclonic risk to a 100 year return periods and found that model was effective to provide essential information for future cyclone risk management. This approach was also successfully used by Bhuiyan and Baky (2014); Dewan (2013b) in flood risk modelling in Bangladesh.

In a continuous changing climate, the sea level rise is going to be a major threat, and its impact on the tropical cyclone originated storm surge is expected to increase significantly (IPCC 2007; Sarwar and Khan 2007; Frazier et al. 2010; Tebaldi et al. 2012; Condon and Peter Sheng 2012). Condon and Peter Sheng (2012) applied high-resolution storm surge modelling based on a hydrodynamic model named CH3D-SSMS for evaluating future coastal inundation from hurricanes, under climate change scenarios in Southwest Florida. They used the complex local model, which required high expertise at a large scale, using an immense dataset that cannot be applied to other areas. By contrast, the sea level rise scenario and its impacts can be simulated easily with a GIS-based storm surge model (Hallegatte et al. 2011).

4 Challenges in managing tropical cyclone impact using remote sensing and spatial analysis

The use of remote sensing and spatial analysis for generating essential information for tropical cyclone disaster management is increasing substantially (Martino et al. 2009; Vatsavai et al. 2011). However, the provision of information in every phase of management is challenging and requires a large amount of datasets and expertise in processing software (Belward et al. 2007; Martino et al. 2009). Moderate to very high spatial resolution satellite images of pre-, post and few years following a tropical cyclone event are required for impact assessment and recovery (Yamazaki 2001). It is difficult to manage these satellite images for a particular area of interest within the required date and time. The collection of cloud free optical satellite images immediately after the cyclone is also challenging due to bad weather condition (Sande et al. 2003). Nevertheless, this challenge could overcome by SAR Data. Most of the moderate to high spatial resolution satellite images, for example, SPOT, Worldview, Quickbird, RapidEye etc. are not freely available and costly. These types of satellite images are also used for cyclone risk assessment and modelling. The selection of the appropriate processing technique is also another challenge. For example, many algorithms are associated with the change detection approach, and it is complicated to select a particular algorithm that can generate best results. In contrast, the selection of an equation, criteria, scale and processing technique for effective risk assessment are also challenging. Multi-criteria decision making processes over selected risk assessment criteria are more critical. The availability of up-to-date environmental and climate data are also a great constraint, specifically for developing countries. Another challenging task is to manage high-resolution DEM. These data are an essential input for the risk assessment and modelling. The development and application of a suitable risk model also require advanced expertise. Further, the accuracy assessment of remote sensing data and the validation of risk models are also challenging (Jensen 2009).

5 Future Directions

Technology based cyclone disaster management approaches have gained more popularity in recent years due to the rapid progress in the availability of data and the processing software. Many studies are reported using remote sensing and spatial analysis in the current literature for tropical cyclone disaster management. Several future directions could be noted to fill the current knowledge gaps in the literature. Object base image analysis has received more attention in the image classification approach, while the availability of moderate to high spatial resolution remote sensing data are increasing. However, multiple impact assessment and recovery of tropical cyclone disaster are rarely examined in the current literature through the object based moderate image resolution analysis using post-classification change detection approach. The selection of scale and criteria are vital issues in the risk assessment procedure. However, very few studies have fully exploited tropical cyclone risk assessment integrating multi-criteria at the local scale. Global climate change scenarios have potential impacts on tropical cyclone activities. Therefore, cyclone risk mapping and modelling should consider future climate change scenarios, in particular sea level rise. Moreover, further studies could be done using SAR and new emerging LiDAR data in every part of cyclone disaster management as current literature in this perspective is very limited.

With the substantial advancement of remote sensing and spatial analysis techniques, tropical cyclone disaster management will be more effective than in previous periods. Previously, limited spectral, spatial and temporal resolution of remote sensing data was a drawback for its wider application. In the past decade, this limitation of remote sensing data has been overcome due to the launching of more advanced sensors at the private and government level. These sensors provide remote sensing data at a much finer scale with a hyperspectral and advanced temporal resolution. The trend of upgrading sensors is expected to continue in the future. At the same time, spatial data is being updating frequently with the advances in technology and rising demand level. Several international organisations are supporting and financing the access to spatial data for researchers and agencies engaged in natural disaster management. Due to continuous progress in these areas, there is a strong prospect of significant improvements in cyclone disaster management.

6 Summary

The uses of remote sensing and spatial analysis have significantly increased and progressed for cyclone disaster management due to advancements in data availability and processing techniques. There are now diverse options to select the appropriate data and processing techniques to derive the most useful information for cyclone disaster management. The final selection of the most appropriate data and processing technique depends on data quality and availability, analyst expertise and project funding.

Table 7 summarises the recommended data types and processing techniques in the phases of cyclone disaster management. The spatial resolution of optical imagery is recommended up to 30 m resolution to generate the essential information for response and recovery phase of cyclone disaster management. However, but it can be varied according to the type of information which will be required from satellite imagery for a particular type of assessment. For example, to assess the vegetation disturbances causes by a tropical cyclone and its recovery, 30 m resolution satellite imagery was demonstrated to be effective, however for settlement, infrastructure etc. $\geq$ 10 resolutions is required for better and more reliable information. The object-based classification approach is recommended in post-classification comparison technique for impacts assessment and recovery due to its proven high classification accuracy. A pixel-based supervised classification could be an alternative in case of less moderate spatial resolution imagery, lack of expertise and availability of software.

Table 7. Recommended data types and processing techniques for different phases of cyclone disaster management

Disaster management phase and process	Data type	Processing technique	Comment
Response and recovery (Impact assessment and recovery)	Moderate to very high resolution (≤ 30 m) optical satellite imagery	Change detection (Post-classification comparison based on object based classification approach)	Object-based analysis software is expensive and challenging to develop a ruleset, but it increases the classification accuracy
Prevention/reduction (Risk assessment)	Historical cyclone data, population, moderate to high resolution (≤ 30 m) DEM, moderate to high resolution (≤ 30 m) optical satellite imagery	Multi-criteria decision making approach AHP Equation: risk = hazard × vulnerability × element at risk/adaptation	Requires a large data set
Preparedness (Risk modelling)	Moderate to high resolution (≤ 30 m) DEM, sea level rise, historical cyclone, moderate to high resolution (≤ 30 m) optical satellite imagery,	GIS-based storm surge model	DEM from LiDAR data is excellent due to high resolution and accuracy but costly. Optical moderately resolution DEM is a good alternative.

The most useful and advanced equation of risk assessment recommended is equation 3 in this paper for producing necessary information for prevention/reduction phase of cyclone disaster management. To use this equation effectively, it is recommended to use a multi-criteria decision making approach AHP in the risk assessment procedure. However, it is difficult to conclude how many criteria should be processed to produce required information as it depends upon the study context. Moderate to high resolution (≤ 30 m) optical imagery and DEM are recommended to generate associated spatial criteria layers in the risk assessment process.

The GIS-based storm surge model is suggested to use as a basic input in the risk modelling process due to its simplicity to derive required information for preparedness phase of cyclone disaster management. Historical cyclone and population data are found as crucial data in the cyclone risk assessment and modelling process. DEM accuracy is a vital factor in the risk assessment and modelling which highly influences the accuracy of derived information, especially in risk modelling. The recommended DEM resolution by this study is up to 30 m resolution. Higher spatial resolution DEMs (e.g. from Airborn Lidar DEM) always perform better, although vertical precision and accuracy are still essential factors to consider. The 30 m resolution DEMs which are now freely available from ASTER GDEM and SRTM1 are still useful for these applications. These could intensify the application of the cyclone risk assessment and modelling approach to a greater extent.

The output of this study will be a framework for environmental scientists, spatial data analysts, natural disaster professionals, emergency managers, hazard data producers and disaster risk insurers for the selection of appropriate datasets and processing techniques for generating cyclone disaster management information.

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