Assessing socio-economic vulnerability to climate change:

A city-level index based approach

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Abstract

The present study attempts to develop indices, indicating the vulnerability to climate change/environmental hazards, for Indian cities located in different bio-climatic zones. The indices generated in the study are based on socio-economic variables and provide a basic overview of the potential vulnerabilities faced by these cities in the context of climate disasters. Eleven cities located in six different bio-climatic zones have been studied. Various indicators of socio-economic vulnerability have been compiled and segregated into the following major components: infrastructure, technology, finance, social and space. This approach of segregation can aid identification of developmental needs essential for minimizing vulnerability. The proxy indicators have been standardized and agglomerated to obtain the respective major components. These components, thereafter, have been combined to obtain the overall vulnerability index. The indices are on a scale of 0-10. The results reveal that, among the selected cities, Jaisalmer is the most vulnerable and Pune is the least vulnerable. Further, the technological and financial indices vary significantly among the eleven cities, but their social capability and infrastructure are comparable. This index can assist in keeping track of vulnerability and planning disaster resilient cities.

Keywords: Vulnerability index; cities; India; climate change; socio-economic

1. Introduction

Cities are urbanized hubs of a state or country and reflect, to some extent, the degree of development in that state or country. Cities contribute crucially to the economy of a country. About 60% of the total GDP (Gross Domestic Product) of India is from urban areas (PRIA, 2013). Thus, cities are extremely important. Any disturbance like a natural hazard on a city has the potential to stagnate a state or a country until it is recovered to its normal circumstances. IPCC (2007) predicted that climate change will lead to increase in the frequency of extreme events such as heat waves, droughts or floods. IPCC (2012) has mentioned that, by the late 21st century, there can be increase in length and frequency of warm spells/heat waves and precipitation, and hazards such as droughts, floods and sea-level rise. Cities, generally, have a high population growth rate and are the most populous centres of a country. Thus, vulnerability extends to a large population in case of a hazard in a city. High population growth also strains existing infrastructure and natural resources, exaggerates the sprouting of informal settlements (Stephenson *et al*., 2010) and hampers planned development. This handicaps a city's coping capacity by impeding sound disaster resilient planning and thereby, might increase its vulnerability in case of an environmental hazard. Cities are considered to be contributors of the climate change problem as well as receivers of the problem (Bulkeley, 2013). This problem is aggravated in rapidly growing cities of developing countries like India. There is lack of governance, infrastructure, and economic and social equity leading to insufficient coping mechanisms in case of a calamity (UN Habitat, 2011).

Socio-economic Vulnerability Assessment involves assessing the vulnerability of a region to a hazard based only on its social and economic status. It is the probable vulnerability of a place to a hazard. It is assumed that better the socio-economic status of a place, lesser will be its vulnerability towards disasters, and better and faster will be its coping mechanisms. Indicators of social and economic status can include the region's per capita income; percentage of less privileged or dependent population like children, elderly and disabled; availability and extent of access to public amenities, etc. These assessments can be based on primary (Hahn *et al*., 2009) or secondary (Cutter *et al*., 2003) data. Social and economic inequalities lead to socio-economic vulnerability (Cutter *et al*., 2003).

An *index-based vulnerability assessment* is a comprehensive tool that helps in comparing and ranking areas in terms of vulnerability (Kelkar *et al*., 2011). Many studies have applied this approach. Rankings are developed by combining indicators. These indicators can be economic well-being and stability, demographic structure, institutional stability and strength of public infrastructure, etc. These indicators are given different weightage depending on its contribution to the area's stability/vulnerability. Indicators are manifestations of multi-dimensional factors. Composite indices are complex information from multiple variables reduced to a single variable. This makes indices a simple and useful decision-making tool (Kelkar *et al*., 2011).

Climate change can change the frequency of extreme events; and many hazards such as floods, droughts and coastal inundation and flooding have the potential to increase in the future (IPCC, 2012). Chaturvedi *et al*. (2012) have projected increase in temperature and precipitation in India by the end of the 21st century. This study aims to capture the socio-economic vulnerability of 11 Indian cities to varied climate or environmental hazard. The study attempts to conceptualize vulnerability as a function of the cities' socio-economic characteristics. A composite index of vulnerability has been constructed using a broad set of socio-economic indicators that are relevant across a range of hazards that the cities might experience. This index can be used as a simple tracking tool for vulnerability as most of the data used in the study is available for every decade from Government sources. India, being a developing nation, this socio-economic index can give valuable insights to identify the development needs that would contribute to minimizing vulnerability.

2. Methdology

2.1. Study sites

The study sites are Indian cities which have been selected randomly from each of the six bio-climatic zones of the country. It is assumed that all six of these bio-climatic zones are facing different climatic hazards. Although no climate variable will be included to build the vulnerability index, segregation according to these zones will help in comparing vulnerability between cities lying in the same zone and facing similar hazards.

India can be divided into six different bio-climatic zones (Bansal and Minke, 1988 as in Nayak and Prajapati, 2006) depending on the temperature and relative humidity experienced by the region. The bio-climatic zones and the criteria for classification are presented in Table 1. The criteria conditions have to prevail in the region for at least six months for the region to be classified in a bio-climatic zone. The cities selected from each of the six bio-climatic zones have been listed in Table 2.

Table 1: Classification of Climate

Climate	**Mean monthly temperature (◦C)**	**Relative humidity (%)**
Hot and dry	>30	<55
Warm and humid	>30	>55
Moderate	25-30	<75
Cold and cloudy	<25	>55
Cold and sunny	<25	<55
Composite	This applies, when six months or more do not fall within any of the above categories	

(Source: Bansal and Minke, 1988 as in Nayak and Prajapati, 2006)

Table 2: Cities selected from each of the six bio-climatic zones

Bio-climatic zones	**Region of India**	**Cities selected**
Hot and Dry	Western and the central part of India	Jaisalmer and Jodhpur
Warm and Humid	Coastal India	Mumbai and Chennai
Moderate	Generally hilly or high-plateau regions	Pune and Bengaluru
Composite	Central part of India	Delhi and Allahabad
Cold and Cloudy	High altitude regions	Shimla and Shillong
Cold and Sunny	Mountainous region	Leh (Ladakh)

(Source: Nayak and Prajapati, 2006)

2.2. Description of study area

2.2.1. Jaisalmer and Jodhpur

Jaisalmer and Jodhpur fall in the hot and dry climatic zone of India. Both the cities lie in the state of Rajasthan located in the north-western part of India. The region experiences high temperatures and heat waves during summer. Jaisalmer (456 persons/km^2) has a very low population density compared to Jodhpur (10828 persons/km^2).

Jaisalmer and Jodhpur are prone to droughts (Poonia and Rao, 2013). The greater districts of Jaisalmer and Jodhpur, in which the cities lie, have experienced several severe to moderate agricultural droughts in the past (Narain *et al*., 2000). Jodhpur is also prone to lesser rainfall. There has been insignificant changes in rainfall and temperature in Jodhpur, but a four-fold increase in population has led to changes in land-use pattern and inordinate demand on ground and surface water resources (Poonia and Rao, 2013).

2.2.2. Mumbai and Chennai

Mumbai and Chennai are metropolitan cities lying in the warm and humid climatic zone of India. Both are coastal cities and have suffered floods in the past (De *et al*., 2013). In July 2005, Mumbai experienced torrential rain, resulting in a severe flood which brought the city to a halt. Mumbai is the capital of the state of Maharashtra located in the western part of India. Chennai is the capital of Tamil Nadu, a state located the in south-east part of India. Chennai has the highest population density among all the study sites followed by Mumbai.

Mumbai is prone to floods (Ranger *et al*., 2011). This can be attributed both to its natural and man-made geography. Because of its natural geography, the city receives heavy and consistent rainfall during the monsoon season. Man-made structures near the coastline prevents natural run-off, leading to floods.

2.2.3. Pune and Bengaluru

Pune and Bengaluru lie in the moderate climatic zone and face urban floods. Pune is located in Maharashtra and Bengaluru is the capital of Karnataka. Karnataka is located in south-western India. They experience moderate summers and winters. Both the cities lie on the Deccan Plateau. Pune (5903 persons/km^2) has a lower population density than Bengaluru (19012 persons/km^2). Pune might experience increased frequency of floods in the future (English, 2012). Bengaluru is prone to urban floods and water scarcity (IIHS, 2014).

2.2.4. Delhi and Allahabad

Delhi and Allahabad have a composite climate. Delhi is the capital of India located in the northern part of the country. Allahabad is located in the northern state of Uttar Pradesh. These regions experience severe summers as well as winters. They are plain regions.

Delhi is prone to floods, heat waves, cold waves and droughts (Panda, 2011 as in Prashar *et al*., 2012). Allahabad shares the same fate and experiences floods, heat waves, cold waves and droughts.

2.2.5. Shimla and Shillong

Shimla and Shillong have a cold and cloudy climate. Shimla and Shillong are capitals of the northern state of Himachal Pradesh and north-eastern state of Meghalaya respectively. They are hill stations. Both the hill cities have grown rapidly and have unsustainable land use pattern.

Shimla already has a declining rainfall trend (Jain and Kumar, 2012) and can have droughts in the future. Shimla also faces floods and flash floods at times. Shimla has expanded in an unplanned manner. The city’s infrastructure and its ill-management hamper the natural run-off of water (UN Habitat, 2010).

Shillong also faces the same fate. It is prone to droughts as well as flash floods (Jamir *et al*., 2008). Shillong already faces flash floods and cyclones.

2.2.6. Leh (Ladakh)

Leh has cold and sunny climate. Leh is a part of the state of Jammu and Kashmir, located in the extreme north of India. No other region of India has such type of climate. It is located around 3,500 m above sea level. The region had faced severe flash floods in 2010. Leh experiences both floods and droughts.

2.3. Selection of indicators

Indicators are useful for quantitatively denoting constructs which are measurable as well as for representing latent constructs that are not directly observable (Hammond et al., 1995 as in Vincent, 2004). Indicator selection for constructing the index is a vital component of index-based vulnerability assessment. The selection of indicators can be based on varied and multiple criteria in accordance with the context of the study. Setting the criterion and subsequently, the selection of indicators can be deemed to be based on subjective judgement to an extent. The method of selection might also vary. For example, some studies have selected indicators directly from the literature (Hahn *et al*., 2009), some have followed the literature review with statistical data reduction techniques (Cutter *et al*., 2003) and some studies have also used Delphi technique (i.e taking experts' judgement by questionnaire survey) to select indicators (Jun *et al.*, 2013; Kim and Chung, 2013). Sometimes, the selection might also depend on the availability of data.

In this study, the indicators have been chosen such that they can capture the socio-economic capability of a city to face a natural hazard. These indicators can denote lack of access to resources, lack of information and technology, physically limited individuals, etc. (Cutter *et al*., 2003). The indicators in this study have been chosen on the basis of two studies by Cutter *et al*. (2003) and Kelkar *et al*. (2011). Both of these studies have conceptualized vulnerability broadly on the socio-economic set-up of their respective study sites. The study by Cutter *et al*. (2003) made an in-depth literature review for selection of indicators. Kelkar *et al*. (2011) constructed an index to assess the vulnerability of different Indian cities and is contextually similar to the present study. Hence, it is assumed that these two studies have included a diverse and thorough set of indicators which can be applicable to defining vulnerability of the selected cities in this study. Even though Kelkar *et al.* (2011) have specifically focused on Indian cities, some of the indicators used in the study have been excluded and additional indicators have been included in this study. This is done to have a more comprehensive perspective of vulnerability as well as to avoid repetition of similar indicators. Also, the above two studies have used a wide number of variables. But, for this study, data on each variable used in the aforementioned studies were not available. Hence, some variables could not be used because of data constraints. Also, some variables were modified to suit the Indian context. For example, Cutter *et al*. (2003) have used data on African-American, Asian etc. population assuming them to be the less privileged sections of the society. In this study these variables have been replaced by percentage of population belonging to scheduled caste and scheduled tribe category.

The IPCC (2007) defines climate change vulnerability to be composed of three factors: sensitivity, exposure and adaptive capacity. While studying a socio-ecological system, like cities, exposure variables generally quantify the vulnerability because of biophysical factors such as changes in temperature, precipitation, etc. Sensitivity indicates or quantifies the extent to which a system can be impacted by stressors or shocks because of its tenuous socio-economic or bio-physical characteristics. Sensitivity is indicative of reaction of a system to stresses or shocks on a shorter time-scale. Adaptive capacity generally quantifies the socio-economic characteristics that enable to adjust or cope with changes. Many studies have adopted this approach to assess regional vulnerability (Jun *et al*., 2013; Kim and Chung, 2013; Yoo *et al*., 2011). But there are studies which have focused more on the socio-economic characteristics of the region and thus, have undertaken different ways to categorize the mélange of indicators. For example, Kelkar *et al*. (2011) had segregated their indicators into elements of natural, built, infrastructural, social, human, governance, financial and technological. Similarly, Prashar *et al*. (2012) had segregated their indicators into five categories, namely physical, social, economic, institutional and natural. Rather than clubbing the whole lot of socio-economic variables under adaptive capacity or sensitivity, these studies have further broadened the dimensions of socio-economic vulnerability by this approach of segregation. Such segregation is instrumental in understanding and recognizing the fundamental capitals/dimensions (Kelkar *et al*., 2011) that a city might be lacking in, which is consequently resulting in increased vulnerability. This study also focuses on the socio-economic characteristics that define the vulnerability of the cities. Hence, the indicators in the present study have also been segregated in order to probe deeper into the different aspects of socio-economic vulnerability. The five categories or indices (major components) in the study are: infrastructure, technology, financial, social and space. The values of these five indices represent the vulnerability of the city in these five aspects. These five categories were chosen for classifying the indicators as it is assumed that they can significantly contribute in explaining the developmental scenario and vulnerability of the cities. Segregating the vulnerability index into these five dimensions will help in identifying the developmental needs in each of these cities.

The indicators used in the current study have been primarily drawn from two different studies (Cutter *et al*., 2003; Kelkar *et al*., 2011). Hence, a slightly different approach of categorization (compared to previous studies by Kelkar *et al*. (2011) and Prashar *et al*., (2012)) is followed to accommodate all the indicators considered in the study. For example, Kelkar *et al*. (2011) had used 'per capita area under green spaces' as well as 'percent built-up area' as indicators and categorized them as natural and built, respectively. They also considered population density and percent of population living in slums as indicators of built index. But the current study has included 'percent built area' (which might be complementary to per cent open spaces) along with two other indicators on population density and growth rate to quantify space index. Again, many of the indicators in Prashar *et al*. (2012) were based on perception of the community about the efficiency of amenities and services (eg. sanitation and waste disposal, good governance etc.). A survey was conducted to collect primary data on the indicators. The current study aims to exploit secondary data to construct a composite vulnerability index. Hence, the approach of selection of indicators and categorization in this study also slightly differs from Prashar *et al*. (2012).

The variables (sub-components) contained in each of the five indices are listed in Table 3. These sub-components are proxies for their respective index. It was assumed that all the indicators considered are relevant for each city for a range of hazards and improvement in these indicators will contribute to lower vulnerability. Infrastructure index consists of proxies about infrastructure availability at the household level and city level, for example, percentage of dilapidated houses and per capita expenditure in public amenities. Technology index talks only about communication facilitating devices available at the household level. Financial index consist of information about the per capita net district product, population availing banking services and population who are employed as main workers. The indicators contained in infrastructure, technology and financial index simply are measures of presence of basic necessities in a city, which can contribute to physical and economic security of its residents from any stress or shock. The study, however, does not necessarily assume that mere presence of these constructs is equivalent to lower vulnerability. Ill planning and management of developmental activities might increase vulnerability. For example, the space index gives information about the concentration of population in a city and the lack of open spaces which can be a result of ill developmental planning. The space index is a proxy for the extent of damage as well as the level of demand for resources (like medical aid, food etc.) in case of a disaster. Social index consist of information about the population who are physically and socially vulnerable because of inequity and marginalization.

All the indicators are standardized to percentages except: population density which is in persons/km^2, hospital beds and public expenditure which are in per capita allocation. The third column in Table 3 states whether there is an increase or decrease in vulnerability with the increase in the value of the sub-component. The fourth column tries to reason the inclusion of that index in the overall vulnerability index.

The required data have been collected from the Census of India (Registrar General of India, 2001 & 2011), economic reports of respective states, Bhuvan (ISRO's geoportal), research papers, etc. The entire 2011 census is not available to the public as of now, hence values for a few indicators (total no. of beds/per capita, per capita expenditure in public amenities, population above 60 years of age, growth rate and population density) have been taken from the 2001 census. Data of built-up area (indicator for space index) is of the year 2005-2006. Per Capita Net District Domestic Product values are of the year 2010. We did not pursue statistical extrapolation of data of 2001(or of other years) to obtain values for 2011, as the robustness of such methods is often debated. This is one of the limitations of our study as we were constrained by data unavailability. Hence, the results can be improved by using data of consistent years.

Because of city-level data unavailability and different governance structure of the cities, there has been overlap of city, district and state data. Majority of the data is city level. District-level data were used for domestic product; and percentage of disabled population, population above 60 years and female headed households. Also, most of the cities considered like Mumbai, Chennai and Bengaluru, are whole districts. Hence, the use of district-level data is inevitable. Delhi is a state as well as a city, hence state-level data have been used.

Table 3: Indices and their sub-components

Index	**Sub-components (with year of data in brackets)**	**Increase (+) or decrease (-) in vulnerability**	**Remark**
Infrastructure	% of dilapidated houses (2011)	+	Poor private and public infrastructure indicates poor economic status of the city which in turn indicates poor coping strength in case of a hazard. Some of the sub-components of this index will increase the vulnerability of a city and some will decrease
	% of households having grass/thatch/bamboo/mud/ plastic/polythene/wood/no mortar stoned, etc. wall (2011)	+	
	% of households with drinking water facility within premises(2011)	-	
	% of households having electricity (2011)	-	
	% of households having toilet facility within premise (2011)	-	
	% of households having bathroom within the house (2011)	-	
	% of households using LPG (Liquefied Petroleum Gas) for cooking (2011)	-	
	% of population having own (not rented) houses (2011)	-	
	Total no. of beds/per capita (2001)	-	
	Per capita expenditure in public amenities (2001)	-	*Table continued on next page*

Index	Sub-components (with year of data in brackets)	Increase (+) or decrease (-) in vulnerability	Remark
Technology	% of the households having radio (2011)	-	Technological availability is assumed to indicate better information dissemination. They also indicate better economic status of household.
	% of the households having television (2011)	-	
	% of the households having internet (2011)	-	
	% of the households having telephone (2011)	-	
	% of the households having mobile(2011)	-	
	% of the households having mobile & telephone (2011)	-	
Financial	Per Capita Net District Domestic Product (NDDP) at Current Prices (2010)	-	Population with better finances can access resources for coping with a disaster. Also, their future is more secured and availability of finances help them incur the losses after a disaster.
	% of households having banking services (2011)	-	
	% of main workers (2011) i.e. % of population having employment for more than 6 months of the year.	-	*Table continued on next page*

Index	Sub-components (with year of data in brackets)	Increase (+) or decrease (-) in vulnerability	Remark
Social	% of female population (2011)	+	In a society, there is inequity among different groups. Populations belonging to lower castes, old age, disabled, illiterates etc. are assumed to be the weaker sections of the society who either have less access to resources or are restricted by their physical incapability. However, inclusion of these sub-components does not denote that these sections of the population are responsible for a city's vulnerability. Rather, these are the vulnerable sections of the population because of a city's social structure and other factors like infrastructure (eg. absence of disabled friendly infrastructure) and finances (eg. absence of special schemes for women) which can result in their exclusion from the mainstream. *Table continued on next page*
	% of female headed households (2011)	+	
	% of population in SC (Scheduled Castes) category (2011)	+	
	% of population in ST (Scheduled Tribes) category (2011)	+	
	% of population below 6 yrs of age (2011)	+	
	% above 60 years of age (2001)	+	
	% of illiterates (2011)	+	
	% disabled population (2011)	+	

Index	Sub-components (with year of data in brackets)	Increase (+) or decrease (-) in vulnerability	Remark
Space	% growth rate (2001)	+	More the built-up area, more is the economic loss due to damage. More the population density, more the competition for resources after a disaster. All the sub-components of this index will increase the vulnerability of a city i.e. they have positive contribution towards vulnerability.
	Population density (2001)	+	
	% built-up area (2005-06)	+	

2.4. Vulnerability Index calculation

The calculation of index in this study follows the approach taken by Hahn *et al*. (2009) while calculating the Livelihood Vulnerability index (LVI). The values for a particular indicator for all the 11 cities are brought into relative terms by applying the same approach as that of the Human Development Index (HDI) given by Anand and Sen (1994), which is the ratio of the difference of the value for that city and the minimum, and the range of maximum and minimum value as depicted in Equation (1) (Gbetibouo and Ringler, 2006, Turvey, 2007, Hahn *et al*., 2009, Patnaik and Narayanan, 2009). This facilitates the next step of aggregation of indicators on different scales.

$$index_{s_c} = \frac{s_c - s_{\min}}{s_{\max} - s_{\min}} \qquad (1)$$

where s_c is the value of the indicator for city c, and s_{min} and s_{max} are the minimum and maximum values, respectively, of the indicator among all the cities.

The index value of each sub-component indicator for each city is calculated in the above manner. These sub-component indices are then combined to get the five different indices namely infrastructure, technology, financial capacity, social capacity and space. The values of these five indices represent the vulnerability of the city in these five aspects. Higher the value of the index, greater is its vulnerability in that aspect.

There have been different methods of aggregation of indices in the literature. Studies have employed statistical analyses which have used results of methods, such as Principal Component Analysis, as a means for aggregation (Easter, 1999; Cutter et al., 2003). Vincent (2004) chose not to take an average and took the weighted (decided by experts) sum of sub-indices as the overall index. Geometric (Moss et al., 2001; Brenkert and Malone, 2005) and arithmetic (Turvey, 2007; Patnaik and Narayanan, 2009) mean have also been utilized for aggregating. Bhattacharya and Das (2007) resorted to taking a combination of geometric and arithmetic mean. Geometric mean gives priority to low-value indicators whereas taking an arithmetic mean for aggregation will give a poor value only if all the contributing variables are poor (Bhattacharya and Das, 2007). The present study uses arithmetic mean for aggregation.

Studies in the past have also followed different methods of assigning weightages while formulating indices, ranging from giving equal weightage (Turvey, 2007) or unequal weightages (Vincent, 2004) based on expert judgements or subjective decisions, to employing statistical analysis (Cutter *et al*., 2003, Gbetibouo and Ringler, 2006). Since there are a manageable number of variables in each of the major components, data reduction statistical techniques are not pursued in the study. Rather, equal weightage is given to each indicator and a simple average is taken to compute the major component.

Some of the sub-components considered contribute to the increase of vulnerability, whereas some contribute to its decrease. Thus, the approach towards calculating the contribution of each of these sub-components is different.

In case of social capacity index and space index, all the sub-components contribute to the increase of vulnerability. Hence values of the respective sub-component indices are simply added and then averaged to get the overall social capacity index and space index (Equation 2).

$$M_c = \frac{\sum_{i=1}^{n} index_{s_c i}}{n} \qquad (2)$$

where M_c is the major component index for city c; $index_{s_c i}$ and n are the sub-components and the number of sub-components considered in the major component, respectively.

In case of finance and technology, all the sub-components contribute to the decrease of vulnerability. Thus, in these two cases the sub-component indices are added, averaged and then subtracted from unity to obtain the overall finance and technology index (Equation 3).

$$M_c = 1 - \frac{\sum_{i=1}^{n} index_{s_c i}}{n} \tag{3}$$

In case of infrastructure, most of the sub-components contribute to the decrease of vulnerability. Thus, the index value of these sub-components indicates the non-vulnerability. The vulnerability index is calculated by subtracting these values from one. These resulting figures along with the indices contributing to the increase of vulnerability are then averaged to obtain the vulnerability index in terms of infrastructure (Equation 4).

$$M_c = \frac{\sum_{i=1}^{n_n} (1 - index_{s_c i}) + \sum_{i=1}^{n_p} index_{s_c i}}{n_n + n_p} \tag{4}$$

where n_n represents the factors which are contributing negatively or decreasing the vulnerability and n_p represents the factors which are contributing positively or increasing the vulnerability.

All the five vulnerability indices are inflated by multiplying them with 10 for better comparison. Thus, all the indices are on a scale of 0-10. Greater the index, higher is the vulnerability.

The weighted average of these five indices is then taken to obtain the overall vulnerability index (Equation 5). The weights of the five indices are in accordance with the number of sub-components in each of these indices, ensuring that each indicator is contributing equally to the overall index **(**Sullivan *et al*., 2002 as in Hahn *et al*., 2009). It was assumed that, irrespective of the site, the contributing indicators would be the same and each indicator (or each major component) would contribute to the vulnerability of the place to the same extent, that is, the weightage of each major component remained the same while computing the vulnerability of each site. This approach avoids any further subjectivity by evading any dispute in provision of differential weights in accordance with characteristics of the regions. This also allows for easy comparison among the study sites (Cutter *et al.*, 2003, Turvey, 2007, Kelkar *et al.* 2011). To remove the bias, to some extent, of giving subjective weightage to the major components to obtain the overall index, a detailed discussion comparing the major components has been done.

$$Overall\ Vulnerability\ Index_c = \frac{\sum_{i=1}^{5} W_{M_i} M_{ci}}{\sum_{i=1}^{5} W_{M_i}} \quad (5)$$

Where subscript c represents the city, W_{M_i} represents the weight of each of the contributing indices and M_{ci} represents the contributing indices.

The overall vulnerability index is also multiplied with 10 to inflate it. Thus, the index is on a scale of 0-10. Greater the index, higher is the vulnerability.

The values of the obtained indices are also presented in vulnerability spider diagrams to facilitate comparison.

3. Results and discussion

3.1. All cities

Jaisalmer and Jodhpur, which fall in the hot and dry climatic zone of India, appeared to be the most vulnerable among all the cities. The least vulnerable of all is Pune, lying in moderate climatic zone of India. Mumbai is the least vulnerable city after Pune. Pune and Mumbai lie in different climatic zone but geographically these two cities are quite close to each other. Delhi and Bengaluru, having the same overall vulnerability index of 4.0, are the third least vulnerable cities. Thus, metropolitan cities (except for Chennai) appear to have lower overall vulnerability than rest of the cities. The cities, along with their overall vulnerability indices, have been ranked in Table 5. City with highest overall vulnerability index has been ranked 1. Thus, higher the vulnerability, higher is the rank of the city. Table 4 lists the values of the contributing indices. Figure 1 shows the contributing vulnerability indices in a spider diagram. Table 6 ranks the cities according to their contributing vulnerability indices. Jaisalmer has the highest vulnerability in terms of infrastructure and technology. Delhi has the best infrastructure and the lowest infrastructure index amongst all. Jaisalmer's infrastructure index is as high as 6.66 and that of Delhi is 3.15. Jaisalmer also has the highest technological index of 8.37 and Pune has the lowest technological index of 2.39. The range of technological index is vast (almost around 6 units). Jodhpur is the most vulnerable and Mumbai is the least vulnerable in terms of finances. The range of financial index is also large starting from 8.63 at the higher end to 3.10 at the lower end. Mumbai, having social index of 3.03, is also the least vulnerable among all in social aspect. Chennai has the highest social vulnerability index of 6.11. Chennai is also the most vulnerable in terms of space whereas Leh has the least space index. The space index ranges from 7.08 for Chennai to a meager 2.25 for Leh.

Table 7 lists the ranges of the indices. From the ranges of the indices, it can be inferred that the selected cities vary significantly in terms of technological and financial index. The high range of technological index is because of Jaisalmer whose index value is very distant from the rest of the cities. Jodhpur has the highest financial index of 8.63. Unlike the case of technological index where Jaisalmer has a distant stand alone index of 8.37, the financial index values of the rest of the cities tend to decrease consistently from 8.37 for Allahabad (the worst after Jodhpur) to 3.10 for Mumbai. The technological index jumps from 8.37 for Jaisalmer to the next value of 5.46 for Shillong. The range of space index is 4.08 showing lesser variability among the cities in terms of space availability. The infrastructure and social capability appears to be comparable among the cities as their ranges are the lowest (3.51and 3.08 respectively). Thus, the cities show high variability in terms of technology and lowest variability in terms of its social structure followed by its infrastructure.

Table 4: Values of the contributing indices and the overall vulnerability index

CITY	Infrastructure Index	Technology Index	Finance Index	Social Index	Space Index	Overall vulnerability Index
Jaisalmer	6.66	8.37	8.25	5.50	4.18	6.5
Jodhpur	3.39	5.05	8.63	5.54	5.76	5.1
Mumbai	4.40	3.46	3.10	3.03	4.93	3.8
Chennai	3.36	2.60	7.42	6.11	7.08	4.8
Pune	3.32	2.39	3.71	4.13	5.67	3.7
Bengaluru	3.64	2.79	4.98	4.22	5.48	4.0
Delhi	3.15	4.27	4.76	4.44	4.17	4.0
Allahabad	3.95	3.69	8.37	4.82	3.01	4.5
Shimla	3.54	4.82	4.44	4.02	4.25	4.1
Shillong	3.92	5.46	6.41	4.60	2.77	4.5
Leh	5.03	3.97	3.25	4.25	2.25	4.2

Note: Overall vulnerability is on a scale of 0–10. 0 indicates least vulnerability and 10 indicates highest vulnerability.

Table 5: Ranking of cities based on their overall vulnerability index

CITY	Overall vulnerability Index	Rank
Jaisalmer	6.5	1
Jodhpur	5.1	2
Chennai	4.8	3
Shillong	4.5	4
Allahabad	4.5	5
Leh (Ladakh)	4.2	6
Shimla	4.1	7
Bengaluru and Delhi	4.0	8
Mumbai	3.8	9
Pune	3.7	10

Note: Overall vulnerability is on a scale of 0 to 10. 0 indicates least vulnerability and 10 indicates highest vulnerability.

Table 6: Ranking of cities according to contributing indices

RANK	Infrastructure Index	Technology Index	Finance Index	Social Index	Space Index
1	Jaisalmer	Jaisalmer	Jodhpur	Chennai	Chennai
2	Leh (Ladakh)	Shillong	Allahabad	Jodhpur	Jodhpur
3	Mumbai	Jodhpur	Jaisalmer	Jaisalmer	Pune
4	Allahabad	Shimla	Chennai	Allahabad	Bengaluru
5	Shillong	Delhi	Shillong	Shillong	Mumbai
6	Bengaluru	Leh (Ladakh)	Bengaluru	Delhi	Shimla
7	Shimla	Allahabad	Delhi	Leh (Ladakh)	Jaisalmer
8	Jodhpur	Mumbai	Shimla	Bengaluru	Delhi
9	Chennai	Bengaluru	Pune	Pune	Allahabad
10	Pune	Chennai	Leh (Ladakh)	Shimla	Shillong
11	Delhi	Pune	Mumbai	Mumbai	Leh (Ladakh)

Note: Higher the rank, greater is the vulnerability

Table 7: Range of indices

Index	Difference between the highest and the lowest
Infrastructure	3.51
Technology	5.98
Finance	5.53
Social	3.08
Space	4.08
Overall Vulnerability	2.6

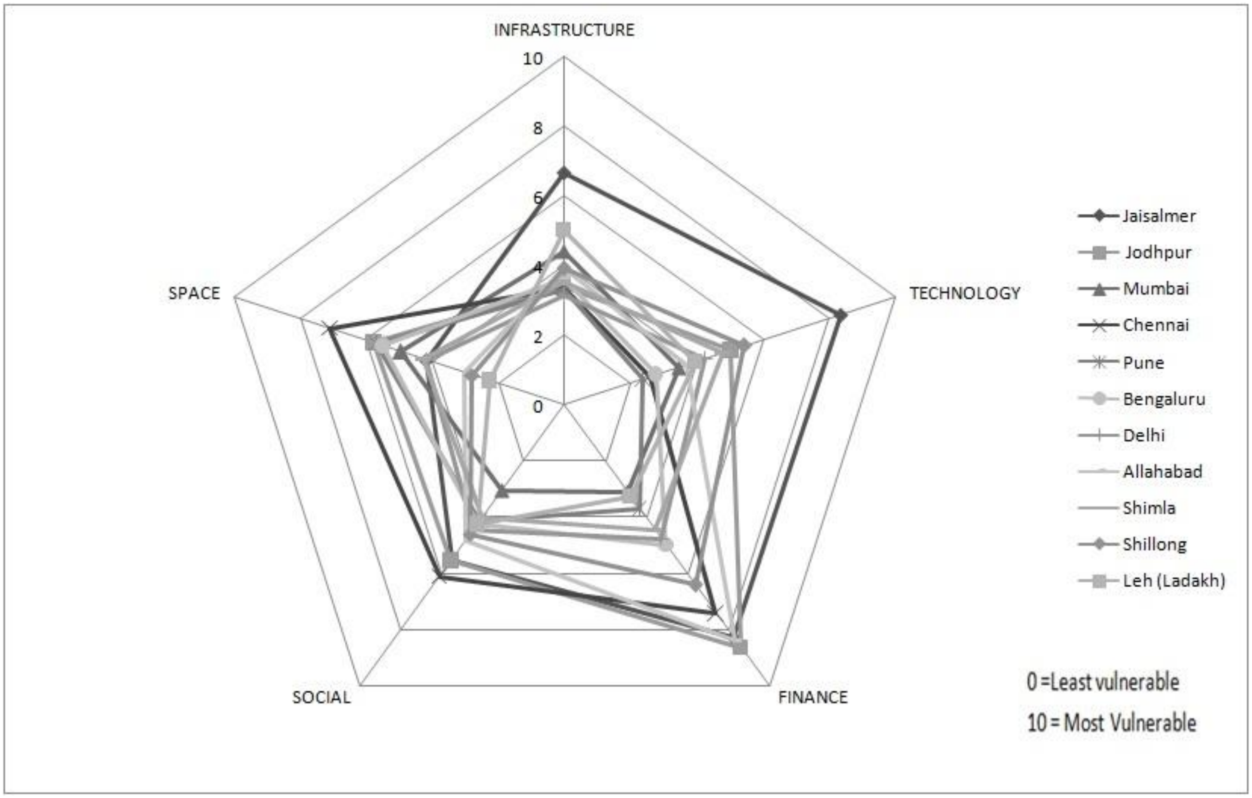

Figure 1: Spider diagram depicting the major components of vulnerability of all the cities

3.2. Jaisalmer and Jodhpur

Jaisalmer and Jodhpur fall in the hot and dry climatic zone of India. The overall vulnerability of Jaisalmer is 6.5 whereas that of Jodhpur is 5.1 (Table 4), that is, Jaisalmer is more vulnerable to climate hazards than Jodhpur. Jaisalmer's weakest aspect is technology (highest among all indices of the city) and strongest aspect is its space capacity (lowest among all indices of the city). Jodhpur is most vulnerable in terms of its financial index and least vulnerable in terms of its infrastructure index. Figure A1 (in Appendix) shows comparison of the indices of the major components of vulnerability for Jaisalmer and Jodhpur.

The increased overall vulnerability of Jaisalmer is because of very poor technology followed by poor financial capability and infrastructure. When available technology is compared, Jaisalmer has the highest percentage of population without access to internet, television and radio among all the study sites. In case of infrastructure, Jaisalmer has highest percentage of population without access to electricity and LPG. It has also one of the lowest numbers of hospital beds and lowest public expenditure. The infrastructure and technology index of Jaisalmer is as high as 6.66 and 8.37 respectively compared to only 3.39 and 5.05 respectively for Jodhpur. Jodhpur's contributing indices to infrastructure is lower than that of Jaisalmer but indices for number of hospital beds and public expenditure are comparable for both the cities. Jodhpur, having a space index of 5.76, is more vulnerable in terms of space availability than that of Jaisalmer having a space index of 4.18. The lower space index of Jaisalmer is because the city has the lowest population density among all and comparatively Jodhpur has quite a high percentage of built up area. Both the cities have similar vulnerability index in terms of its social and financial capacity. Their finance and social index are around 8 and 5 respectively. But nevertheless, Jodhpur is on the higher side of vulnerability than Jaisalmer in terms of its financial and social index. The contributing index of illiteracy and population below 6 years of age (to social index) is the highest for Jaisalmer among all the study sites. But Jaisalmer also has the least number of female headed female households. Both the cities have low Net District Domestic Product (NDDP), very low access to banks and low number of main workers, thus making their financial index comparable.

3.3. Mumbai and Chennai

Mumbai and Chennai both are metropolitan cities lying in the warm and humid climatic zones of India. Both are coastal cities. Chennai is more vulnerable than Mumbai to climate hazards. Chennai has a vulnerability index of 4.8 and that of Mumbai is 3.8 (Table 4). Comparison among Mumbai's indices shows that the city is most vulnerable in terms of its space availability and least vulnerable in terms of its social capacity. Chennai's vulnerability in terms of its finances is the highest and lowest for technology. Figure A2 (in Appendix) shows comparison of the indices of the major components of vulnerability for Mumbai and Chennai.

When the contributing vulnerability indices are compared, it can be seen that Chennai is far more vulnerable than Mumbai in terms of financial capacity, social capacity and space. Chennai has a finance index as high as 7.42 compared to a mere 3.10 for Mumbai. This is because Mumbai has one of the highest NDDP among all the study sites after Delhi. Mumbai also has better access to banks and a higher percentage of people are main workers in Mumbai than in Chennai. Chennai's social index (6.11) is almost twice of that of Mumbai (3.03). When we analyze the social capacity of the two cities, it was found that Chennai has one of the highest percentages of female headed households and has the highest percentage of population above 60 years of age. Mumbai has the lowest percentage of disabled population among all the study sites, thus improving its social capacity over Chennai. Chennai's space index (7.08) is two units greater than that of Mumbai's (4.98). Chennai has the highest population density and highest percentage of built up area among all the cities. But in terms of infrastructure and technology, Chennai is slightly better off than Mumbai. A large percentage of population in Mumbai does not have access to sanitation compared to Chennai. And Chennai houses the highest population having access to television and phone, thus improving its technology index over Mumbai.

3.4. Pune and Bengaluru

Pune and Bengaluru lie in the moderate climatic zone. Pune and Bengaluru have similar overall vulnerability. The overall vulnerability index of Pune is 3.7 and that of Bengaluru is 4.0 (Table 4). Both Pune and Bengaluru are most vulnerable in terms of their space availability and least vulnerable in terms of technology (when compared with the respective city's other indices). Figure A3 (in Appendix) shows comparison of the indices of the major components of vulnerability for Pune and Bengaluru.

Both the cities also have similar vulnerabilities in terms of infrastructure, technology, social capacity and space except for that of financial capacity which is higher by approximately unity for Bengaluru. This is because even though Bengaluru has a higher NDDP and larger number of main workers, the percentage of population having access to banks in Bengaluru is the lowest amongst all the study sites. Financial index is 4.98 for Bengaluru and the same for Pune is 3.71. The infrastructure index is around 3, technology index is around 2, social index is around 4 and space index is around 5 for both the cities. But, nevertheless, Bengaluru is on the higher side of vulnerability in terms of infrastructure, technology and social capacity. Pune has one of the best infrastructures (after Delhi) among the study sites. Comparatively, Bengaluru has quite a higher number of illiterates and disabled than Pune, which in turn increases its social capacity index. Pune, in fact, has the highest percentage of population having access to drinking water (a contributor to infrastructure index) and internet (a contributor to technology index). Space index of Pune (5.67) is higher than that of Bengaluru (5.48). Pune has the highest growth rate (a contributor to space index) among all the study sites.

3.5. Delhi and Allahabad

Delhi and Allahabad are in the composite climate region. Allahabad has a higher vulnerability than Delhi. Delhi's overall vulnerability is 4.0 and that of Allahabad is 4.5 (Table 4). Comparison with Delhi's own indices shows that Delhi's weakest aspect is finances and strongest aspect is infrastructure. And comparison with Allahabad's own indices shows that Allahabad is most vulnerable in terms of its finances. Allahabad has lowest index for space among all of its indices. Figure A4 (in Appendix) shows comparison of the indices of the major components of vulnerability for Delhi and Allahabad.

Delhi is more vulnerable than Allahabad in terms of space and technology. The space index of Delhi and Allahabad is 4.17 and 3.01 respectively. In fact, Allahabad has the least percentage of built up area, thereby decreasing its space index. The technology index of Delhi (4.27) is slightly higher than that of Allahabad (3.69). Allahabad is more vulnerable than Delhi in terms of its infrastructure, social and financial capacity. Delhi has the best infrastructure among all the selected cities. Financial vulnerability of Allahabad is drastically higher than that of Delhi. This is because NDDP of Delhi is the highest and that of Allahabad is the lowest among the selected cities. Allahabad's financial index stands at 8.37 and that of Delhi is 4.76.

3.6. Shimla and Shillong

Shimla and Shillong have a cold and cloudy climate. Shillong has an overall vulnerability of 4.5 and Shimla has a comparatively lower vulnerability of 4.1 (Table 4). When compared with the city's own indices, Shimla is most vulnerable in terms of technology and is least vulnerable in terms of its infrastructure. Similarly, Shillong is most vulnerable in terms of its finances and least vulnerable in terms of its space index. Figure A5 (in Appendix) shows comparison of the indices of the major components of vulnerability for Shimla and Shillong.

Shillong is more vulnerable than Shimla in all the aspects except for space. Shimla's space index of 4.25 is poor compared to that of Shillong (2.77). Population growth rate, a contributor to the space index, is the least for Shillong among all the selected cities. The infrastructure index of both Shillong and Shimla are 3.92 and 3.54 respectively. The technological index of Shillong (5.46) is higher by approximately unity than that of Shimla (4.82). Shillong has the highest percentage of population having access to mobile phone. The financial vulnerability of Shillong is also very high compared to that of Shimla. This is indicated by the financial index of 6.41 for Shillong and 4.44 for Shimla. Compared to Shillong, a higher percentage of population of Shimla has access to banking facilities. Social vulnerability of Shillong is 4.60 which is also higher than that of Shimla (4.02).

3.7. Leh (Ladakh)

Leh (Ladakh) has cold and sunny climate. Leh has an overall vulnerability of 4.2 (Table 4). In terms of finance and space availability, whose indices are 3.25 and 2.25 respectively, Ladakh has relatively low vulnerability. Comparatively, Ladakh has a high vulnerability in terms of its available infrastructure (5.03), technology (3.97) and social capacity (4.25). Leh has one of the poorest infrastructures after Jaisalmer. It has got the second best financial index after Mumbai. Even though the NDDP of the city is quite low, Leh has the highest percentage of population having access to banks and highest percentage of workers. Leh has the least space index among all the cities as the growth rate and population density of Leh is very low. Figure A6 (in Appendix) shows comparison of the indices of the major components of vulnerability for Leh.

4. Conclusion and limitation

The overall vulnerability indices indicate that the cities of Jaisalmer and Jodhpur are the most vulnerable among all the cities. Pune is the least vulnerable among all followed by Mumbai, Delhi and Bengaluru. Thus, metropolitan cities (except Chennai) seem to be on the lower end of vulnerability. The values of the contributing major sub-component indices are different for the different cities. Jaisalmer's high overall vulnerability can be attributed to its very high vulnerability in terms of infrastructure, technology and finance. Pune's contributing indices are all towards the lower end except for space index. Jaisalmer has the worst infrastructure and technology. Delhi has the best infrastructure and Pune is the most technologically advanced amongst all. Mumbai and Jodhpur are on the highest and lowest ends of finances respectively. Mumbai appears to be the strongest in social aspect and Leh in terms of space index. Chennai is the weakest in the social aspect as well as according to the space index. The cities vary significantly in terms of its technological index. Their social indices show the least variability.

These indices are relative in nature and are apt for comparison among the cities. But small difference in these overall indices can mask large differences in the values of contributing sub-components.

All the cities that have been considered for the different climatic zones are prone to different kinds of climatic hazard. Also, the extent of these hazards might be different for the different cities. But nevertheless, these indices which are non-inclusive of any climate variables give an indication of the cities' capability to cope with a natural hazard in context of its infrastructural, technological, social, financial and space capability.

The present study also has a few limitations. Data availability constraints have led to the inclusion of data variables from different years. It has been attempted, though, that the latest available data are used for the study. Thus, the study can be refined using data of the same latest available year. Secondly, the same sub-components have been used for calculating the indices of all the cities. But it might be possible that some of the sub-components accounting for vulnerability for some cities are irrelevant in case of some other city. For example, communities in Shillong and Leh are mostly female-headed. This trend is a part of their culture. Thus, for these two cities, it is debatable if the inclusion of percentage of female headed households in calculating the social index is the correct approach. Hence, social indicators (specifically percentage of female population, female headed households and population in SC and ST category) can be contextual and their relevance in the index might vary according to the social structure in the city. The literature and field study about the characteristics and demography of the cities might help choosing better proxies for calculating the indices. Again, the relevance of indicators might also vary with cities prone to different hazards. This aspect has not been dealt with in the current study. For example, percentage of built-up area (contributor to space index) might have varying degree of relevance for quantifying vulnerability towards floods and droughts. Greater built-up area might lead to poor run-off in case of floods and hence is an important contributor to a city's vulnerability. Open spaces or lower built-up area can help in water percolation and can facilitate ground water recharge, but it might not be as relevant for droughts as for floods.

Nevertheless, indicators of infrastructure, technology, finance and space have been assumed to be pertinent contributors to vulnerability arising from a range of hazards that all cities might be susceptible to. Again, this index caters to measuring only the socio-economic or inherent vulnerability. This index can be combined with a measure of the biophysical hazard to obtain an overall index. This combined index can give deeper insights into the city's vulnerability, but at the same time, can be segregated to understand the extent of contribution of the city's socio-economic and biophysical characteristics to the vulnerability. As the data used in the study are available from Government sources, this index provides an easy way of keeping track of vulnerability for policy-makers. Most of the indicators are from the Census of India which is compiled at the end of each decade. The index could be validated by correlating with the damage and loss suffered by the cities in the past (IIED, 2014). Strong correlation between the indices and loss will indicate that the indicators are reliable and can even be used for predicting future impacts. But, in the present study, it could not be done because of data unavailability at the city level. Thus, this calls for maintaining a database about disasters and their associated damage, loss etc in the future. The indicators and the results of this study can provide a broad overview of the vulnerability of the cities but city-level planners need to further identify indicators that are city-specific to track their vulnerability over time. This can contribute to planning disaster resilient cities.

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References

Anand, S., & Sen, A., 1994. *Human Development Index: methodology and measurement* (No. HDOCPA-1994-02). Human Development Report Office (HDRO), United Nations Development Programme (UNDP).

Bansal N.K. and Minke G., 1988. Climatic zones and rural housing in India, Kernforschungsanlage, Juelich,Germany.

Bhattacharya, S., & Das, A., 2007. Vulnerability to Drought, Cyclones and Floods in India. *European Commission BASIC Project, BASIC Project Paper*,*9*. http://www.basic-project.net/data/final/Paper09India%20Vulnerability%20to%20drought%20%20cyclones%20and%20floods%85.pdf

Brenkert, A. L., & Malone, E. L., 2005. Modeling vulnerability and resilience to climate change: a case study of India and Indian states. *Climatic Change*,*72*(1-2), 57-102.doi: 10.1007/s10584-005-5930-3

Bulkeley, H., 2013. Cities and climate change. Abingdon, Oxon:Routledge.

Chaturvedi, R. K., Joshi, J., Jayaraman, M., Bala, G., & Ravindranath, N. H., 2012. Multi-model climate change projections for India under representative concentration pathways. *Current Science*, *103*(7), 791-802.

Cutter, S. L., Boruff, B. J., & Shirley, W. L., 2003. Social vulnerability to environmental hazards. *Social science quarterly,* 84(2), 242-261. doi: 10.1111/1540-6237.8402002

De, U. S., Singh, G. P., & Rase, D. M., 2013. Urban flooding in recent decades in four mega cities of India. *J. Ind. Geophys. Union*, *17*(2), 153-165.

Easter, C., 1999. Small states development: a commonwealth vulnerability index. *The Round Table*, *88*(351), 403-422.

English, B., 2012. Cities, Climate Change, and The Big Opportunity: How Empowering the Urban Poor Can Improve Our Global Future.

Gbetibouo, G. A., & Ringler, C., 2009. *Mapping South African farming sector vulnerability to climate change and variability: A subnational assessment*. International Food Policy Research Institute (IFPRI) and Center for Environmental Economics and Policy in Africa (CEEPA).

Hahn, M. B., Riederer, A. M., & Foster, S. O., 2009. The Livelihood Vulnerability Index: A pragmatic approach to assessing risks from climate variability and change—A case study in Mozambique. *Global Environmental Change*, 19(1), 74-88. doi: 10.1016/j.gloenvcha.2008.11.002.

IIED, 2014. Developing a national framework to track adaptation and measure development in Cambodia. http://pubs.iied.org/pdfs/17259IIED.pdf?

IIHS: Indian Institute of Human Settlement, 2014. Future Proofing Indian Cities, Final Urban Diagnostic for Bengaluru. *Atkins*.

IPCC Fourth Assessment Report: Climate Change 2007. http://www.ipcc.ch/publications_and_data/ar4/syr/en/mains1.html.

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp. https://www.ipcc.ch/pdf/special-reports/srex/SREX_Full_Report.pdf

Jain, S. K., & Kumar, V., 2012. Trend analysis of rainfall and temperature data for India. *Current Science (00113891)*, *102*(1), 37-49.

Jamir, T., Gadgil, A. S., & De, U. S., 2008. Recent floods related natural hazards over West coast and Northeast India. *Journal of Indian Geophysics Union*, *12(4)*, 179-82.

Jun, K.S., Chung, E.S., Kim, Y.G. & Kim, Y., 2013. A fuzzy multi-criteria approach to flood risk vulnerability in South Korea by considering climate change impacts. *Expert Systems with Applications*, 40(4), 1003-1013. doi: 10.1016/j.eswa.2012.08.013.

Kelkar, U., Balachandra, P., &Gurtoo, A., 2011. Assessing Indian cities for vulnerability to climate change. *Proceedings of International Conference on Environmental Science and*

Development (ICESD), Mumbai, 7-9 January 2011. Asia-Pacific Chemical, Biological, and Environmental Engineering Society (APCBEES) and IEEE.

Kim, Y., & Chung, E. S., 2013.Fuzzy VIKOR approach for assessing the vulnerability of the water supply to climate change and variability in South Korea. *Applied Mathematical Modelling*, 37(22), 9419-9430. doi: 10.1016/j.apm.2013.04.040.

Moss, R. H., Brenkert, A. L., & Malone, E. L., 2001. Vulnerability to climate change: a quantitative approach. *Pacific Northwest National Laboratory (PNNL-SA-33642). Prepared for the US Department of Energy*. http://www.globalchange.umd.edu/data/publications/Vulnerability_to_Climate_Change.PDF

Narain, P., Sharma, K. D., Rao, A. S., Singh, D. V., Mathur, B. K., & Ahuja, U.R., 2000. India's Arid Region and the Current Drought. *Drought Network News (1994-2001)*. Paper 29. http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1028&context=droughtnetnews

Nayak, J.K., Prajapati, J.A. (2006). Handbook of Energy conscious buildings.

Patnaik, U., & Narayanan, K., 2009. Vulnerability and climate change: An analysis of the eastern coastal districts of India. MPRA Paper No. 22062. http://mpra.ub.uni-muenchen.de/22062/1/MPRA_paper_22062.pdf

Poonia, S., & Rao, A., 2013. Climate Change and Its Impact on Thar Desert Ecosystem. *Journal of Agricultural Physics*, *13*(1), 71-79.

Prashar, S., Shaw, R., & Takeuchi, Y., 2012.Assessing the resilience of Delhi to climate-related disasters: a comprehensive approach. *Natural hazards*, *64*(2), 1609-1624. doi: 10.1007/s11069-012-0320-4

PRIA: Participatory Research in Asia, 2013. Contribution of Urban Informal Settlement Dwellers to Urban Economy in India

Ranger, N., Hallegatte, S., Bhattacharya, S., Bachu, M., Priya, S., Dhore, K., Rafique, F., Mathur, P., Naville, N., Henriet, F., Herweijer, C., Pohit, S. & Corfee-Morlot, J., 2011. An assessment of the potential impact of climate change on flood risk in Mumbai. *Climatic Change*, *104*(1), 139-167. doi: 10.1007/s10584-010-9979-2

Registrar General of India, 2001.Census of India 2001. New Delhi: Government of India.

Registrar General of India, 2011.Census of India 2011. New Delhi: Government of India.

Stephenson, J., Newman, K., & Mayhew, S., 2010. Population dynamics and climate change: what are the links?. *Journal of Public Health*, *32*(2), 150-156. doi: 10.1093/pubmed/fdq038

Turvey, R., 2007. Vulnerability assessment of developing countries: the case of small-island developing states. *Development Policy Review*, *25*(2), 243-264. doi: 10.1111/j.1467-7679.2007.00368.x

UN Habitat, 2010. The state of Asian Cities 2010/11. https://rrojasdatabank.info/citiesasian1011-05.pdf

UN Habitat, 2011. Cities and Climate Change—Global Report on Human Settlements 2011. *London: Earthscan*.

Vincent, K., 2004. Creating an index of social vulnerability to climate change for Africa.Tyndall *Center for Climate Change Research*. Working Paper no. 56, 41.

Yoo, G., Hwang, J. H., & Choi, C., 2011. Development and application of a methodology for vulnerability assessment of climate change in coastal cities.*Ocean & Coastal Management*, *54*(7), 524-534.

The underlying research materials for this article can be accessed at:

Directorate of Economics and Statistics , Government of Maharashtra, 2011. Economic Survey of Maharashtra, 2010-11. http://mahades.maharashtra.gov.in/files/publication/esm_2010-11_eng.pdf

Directorate of Economics and Statistics, Government of Delhi, 2013. Estimates of State Domestic Product of Delhi 2012-13. http://www.delhi.gov.in/wps/wcm/connect/2fa0ea804efc4bceb075b9fe99daf05a/SDP+Report+2012-13.pdf?MOD=AJPERES&lmod=-2094237031&CACHEID=2fa0ea804efc4bceb075b9fe99daf05a

Directorate of Economics and Statistics, Government of Jammu and Kashmir. State Domestic product of Jammu and Kashmir. http://www.ecostatjk.nic.in/publications/nsdp.pdf

Economic Survey of Karnataka, 2010-11. http://planning.kar.nic.in/sites/planning.kar.nic.in/files/Economic_Survey/18Appendix.pdf

Economics and Statistic Division, State Planning Institute, Uttar Pradesh, 2009. District-wise development indicators Uttar Pradesh 2008. http://updes.up.nic.in/reports/districtwise-developmentindicator-2008web.pdf

Government of Tamil Nadu. State Income. http://www.tn.gov.in/dear/state%20income.pdf

Government of Rajasthan.Gross District Domestic Product of Rajasthan at Current Prices. http://www.statistics.rajasthan.gov.in/Upload/sixpages.pdf

Indian Space research Organisation (ISRO). Land Use Land Cover, 2005-06. http://bhuvan-noeda.nrsc.gov.in/theme/thematic/theme.php

Appendix

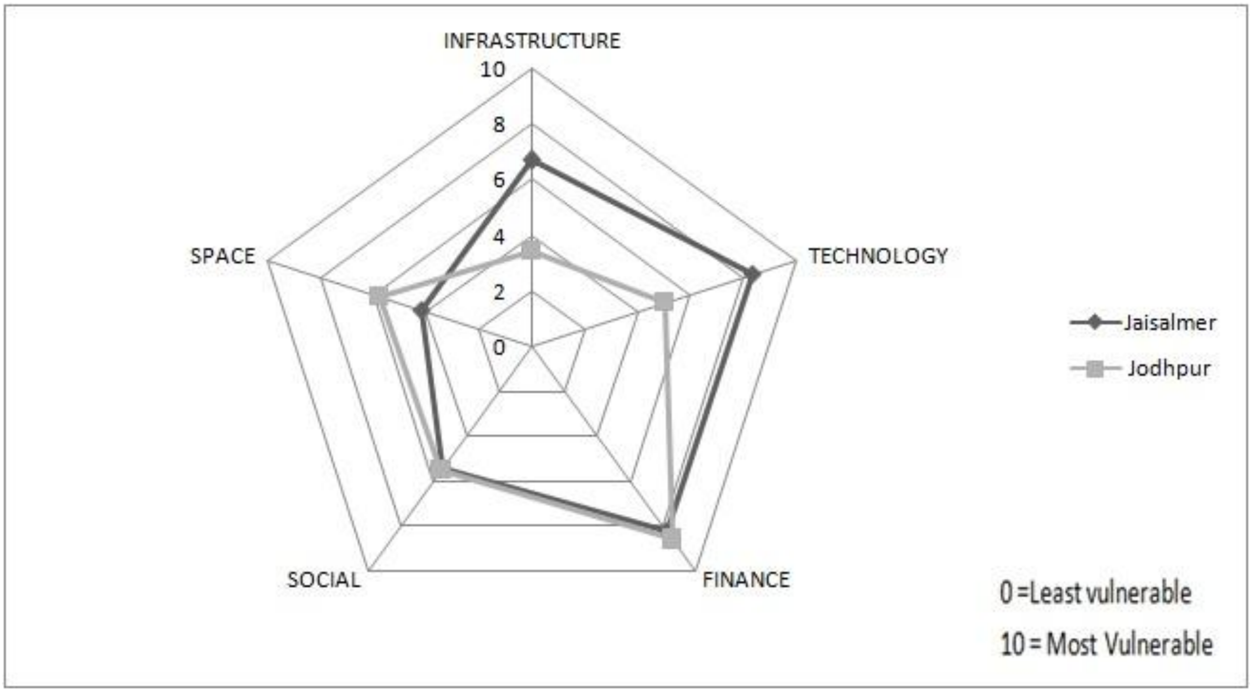

Figure A1: Spider diagram depicting the major components of vulnerability of Jaisalmer and Jodhpur

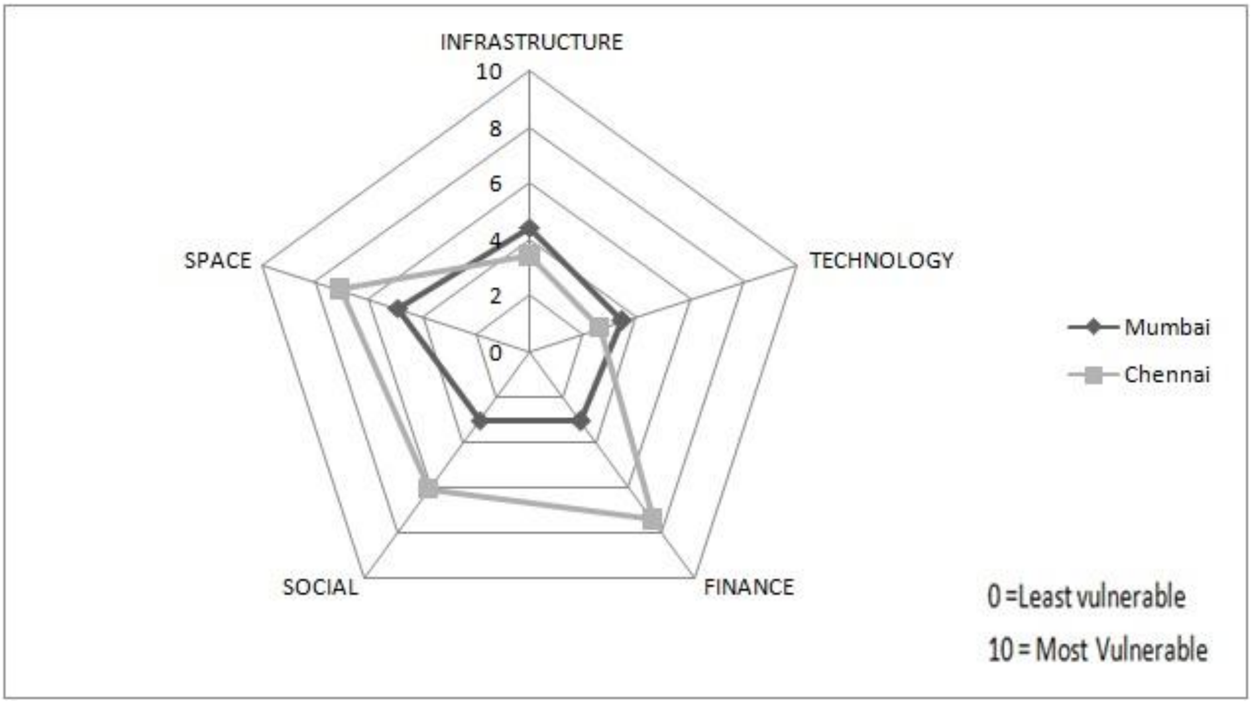

Figure A2: Spider diagram depicting the major components of vulnerability of Mumbai and Chennai

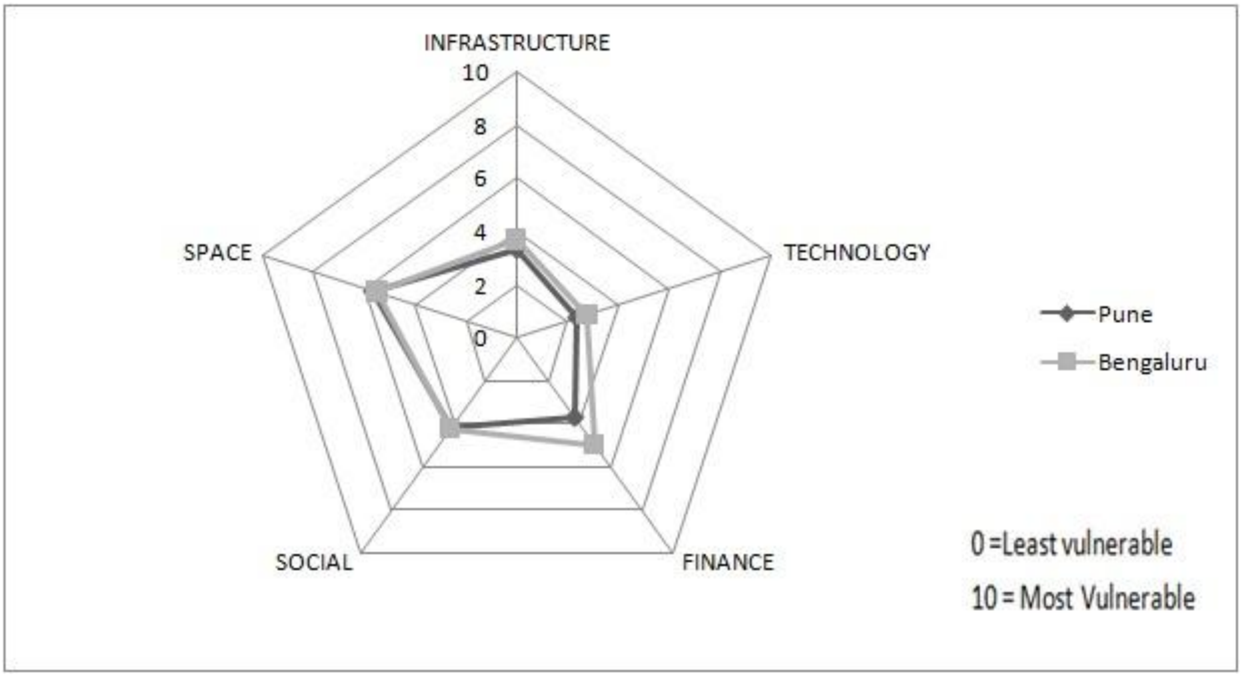

Figure A3: Spider diagram depicting the major components of vulnerability of Pune and Bengaluru

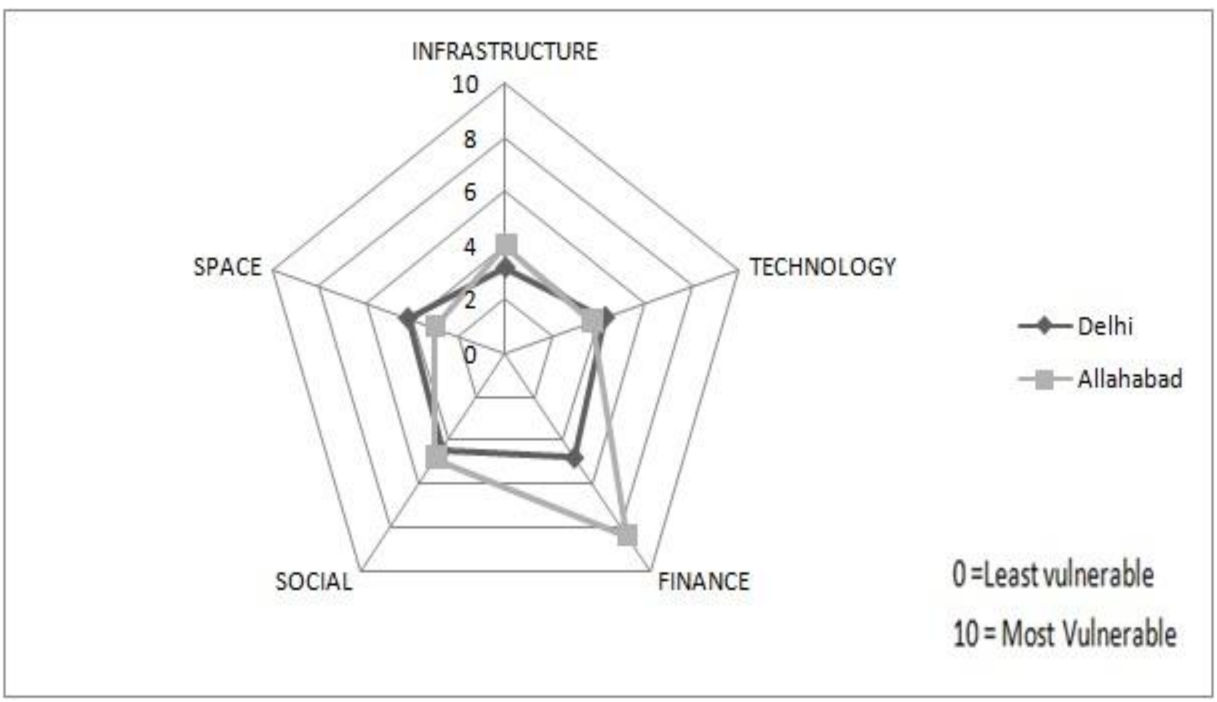

Figure A4: Spider diagram depicting the major components of vulnerability of Delhi and Allahabad

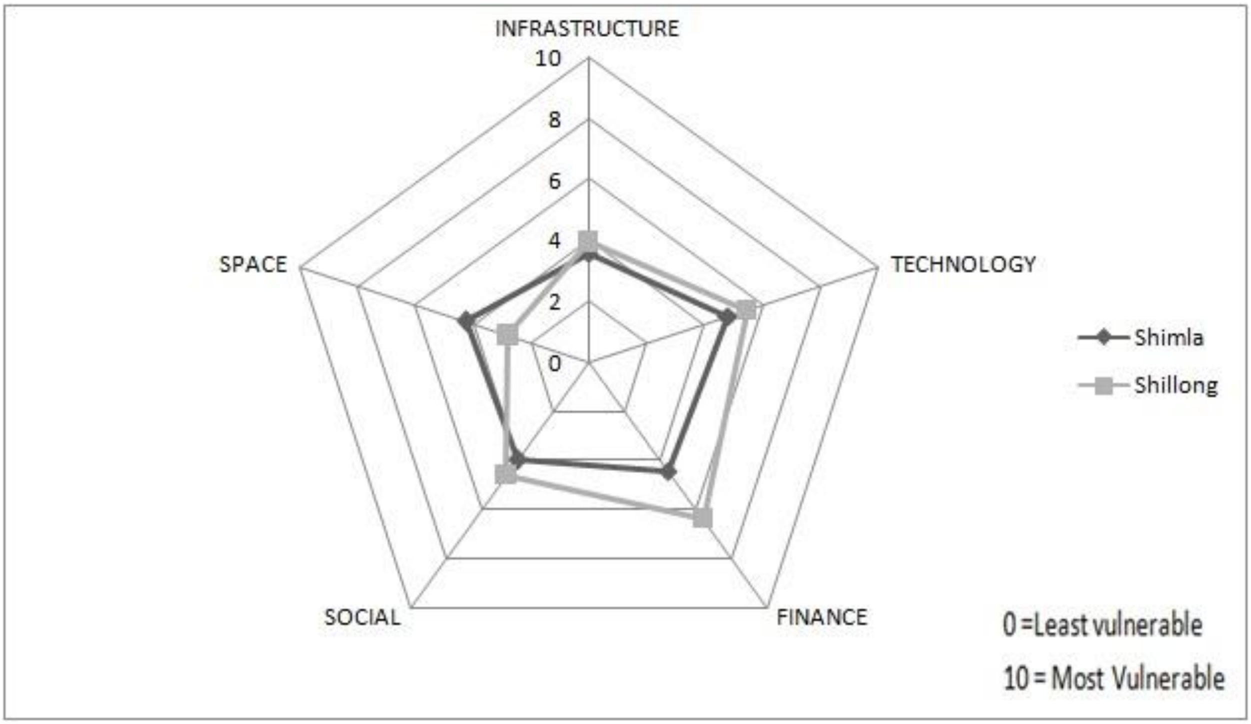

Figure A5: Spider diagram depicting the major components of vulnerability of Shimla and Shillong

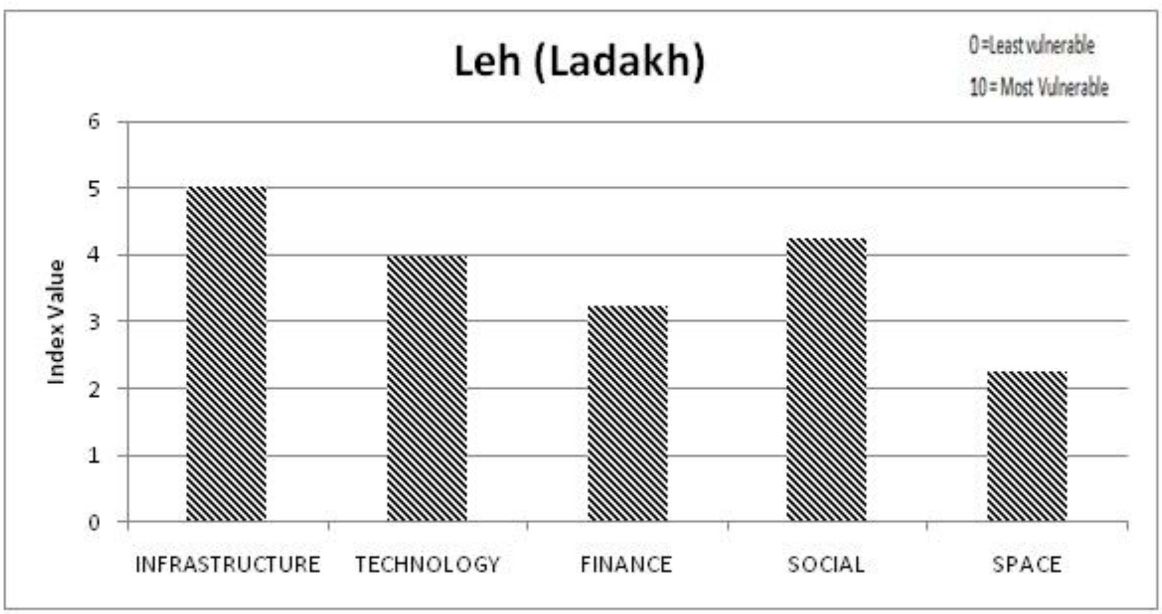

Figure A6: Bar diagram depicting the major components of vulnerability of Leh (Ladakh)