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REVIEW ARTICLE

A systematic review on approaches and methods used for flood vulnerability assessment: framework for future research

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Abstract
Floods have always been associated with widespread devastation and destruction since the emergence of human civilization. The intensity of this disaster has been increasing due to accelerated impact of human activities. Flood vulnerability is very diverse in nature and is multidimensional and a topic of vital significance. Hence, flood vulnerability assessment assumes greater significance since magnitude of destructions varies over space and time. The study makes a credible attempt to present a coherent review on the approaches and methodologies used for assessing flood and its vulnerability. A time frame of 1990–2018 was chosen for analyzing varied works carried out flood vulnerability and susceptibility assessment. Articles from Scopus and other reputed journals were used to review the works on flood assessments. Methods and approaches were examined by considering most-cited authors and keywords used in their works. The study revealed a gap existing between methods and approaches for evaluating flood vulnerability which can be incorporated by using high-resolution data along with using multidimensional approach for assessing vulnerability. Furthermore, this study calls for comprehensive flood assessment using artificial neural network, hydrodynamic models and geospatial techniques to provide a vivid visualization of flood susceptibility. The study may prove helpful in analyzing different components of vulnerability and guiding research gaps in methodology to be used for assessing flood vulnerability at spatial scales.

Keywords Flood vulnerability · GIS · Remote sensing · Vulnerability · Hydrodynamic model · Flood vulnerability index (FVI)

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1 Introduction

Flood is a natural phenomenon causing devastation at a very large scale, disrupting normal life and raising social, economic and ecological vulnerability. Centre for Research on the Epidemiology of Disasters (CRED) has defined flood as being a state of rise of water level in a coastal areas, lakes, streams and channels. Flood is the most common wide-reaching natural hazard impacting around 250 million people in the world (UNISDR 2013). It is one of the biggest natural disasters to society and has attracted the attention of various scholars to see it in the context of increasing impact of climate change. The increasing population and amalgamation of assets have resulted in increasing susceptibility to flood in built-up areas. The impact of flood is likely to increase in future due to growing population (Kay et al. 2006). The impact is projected more on the world's population living within 100 km of the coast by 2030 (Lloyd 2008). Recent consequences of flood have raised various concerns about climate change and the degree to which anthropogenic activities affect global climate (Kay et al. 2011; Schaller et al. 2016). Frequency of flood is also expected to increase as a result of increase in population growth (Keating et al. 2014). Transformation of pervious surface into impervious surface due to rapid urbanization has caused reduction in infiltration, affected natural runoff and increased flood events. In recent years, average flood losses have increased to an average of about USD 40 billion. Studies have revealed increased cases of flood disasters between 2010 and 2013 (Keating et al. 2014). Continuous flood events have been observed in megacities such as Ho Chi Minh, Jakarta, Manila, Kolkata, Mumbai and Chennai. In USA, flood disaster accounted enormous damages and loss of lives during 1953–2010 than any other natural disaster (Kerjan and Kunreuther 2011).

The years of 1980, 1993, 2002 and 2004 witnessed large number of people affected due to flood hazard. Nearly 2.3 billion people were affected by flood between 1995 and 2015 accounting for 56% of the total population of the world. In South America alone, around 560,000 people were affected due to flood hazard during 2005–2015. Flood hazard created grim conditions in the least developed nations causing huge trauma to human population, widespread losses to infrastructure, threat to life and economic prosperity. It has produced catastrophic conditions and huge damages to lives and property in nations such as Bangladesh, Mozambique, Germany, India, China and USA during the last decade (Kreibich et al. 2005). The disaster is not only bounded to developing nations but also its impacts are being pronounced in the most urbanized and industrialized nations of the world. Hurricane Mitch can be cited as an important example which has caused widespread destruction and approximate economic losses of US$ 3.64 billion in El Salvador, Honduras, Guatemala and Nicaragua of Central America during 1988 (Buvinic 1999). Andrew hurricane also led damages of around US$ 30 billion in these areas (Yang 2008). Flood losses and their potent impact on human beings can also be considered directly with the location of their occurrence. High densely populated regions are likely to have more impact of inundation, and these damages vary with the assets. In urban areas, the flood has created the problem of water pollution leading to higher cleanup cost and exacerbating health problems (Ramsbottom et al. 2012). Flat surfaces are experiencing higher inundation experiencing widespread damages (Kron 2015). A demonstration by Emergency events database (EM-DAT) data has revealed that 36 countries have been facing the damages of USD 1 billion to property, livestock and other crops since 1990. Australia, India, China, Bangladesh, Canada, Japan, Pakistan, Thailand and USA have also experienced 1-year flood damage exceeding USD 5 billion (OECD 2016).

Floods have been found as most occurring phenomena in many parts of India causing huge damages to life and property and resulting in socioeconomic and ecological vulnerability. Unexpected rainfall during southwest monsoon, intensification of tropical storms and depressions, siltation in riverbed, inefficiency of rivers to carry heavy discharge have been identified as major causes of flood occurrence in India. Floods in India during 1980–2010 have been more harmful to the Indian economy as compared to the other forms of disasters and also ranked the second highest human lives affecting disaster after drought (UNISDR 2013). The major flood affected basins of the country are basins of mighty rivers namely *Ganga, Mahanadi, Brahmaputra, Cauvery* and *Krishna* as suggested by National Flood Commission. Flood affected the major states such as Arunachal Pradesh, West Bengal, Assam, Orissa and Bihar. The years 1977 and 1978 have recorded highest deaths affecting on an average 3.2 crore population in India, while 2001 has recorded highest damages to public utilities. National Flood Control Program was launched in 1954 with the aim to provide measures to tackle flood losses and to provide relief and resilience to affected population (CWC 2007).

Flood vulnerability is a root cause of human devastation creating food insecurity, outburst of various waterborne diseases, damages to crop productivity and infrastructure. Moreover, women and children are more vulnerable as 85% of deaths among women and children occurred during disasters (Neumayer and Plümper 2007). Social vulnerability differs from one place to another and the level of connectedness directly affects implementation of policies (Gurney et al. 2017). Identification of flood-prone region is therefore prerequisite to address vulnerability among communities. The capacity of communities to face the impact of flood is another essential aspect (Few 2003). Polskey et al. (2007) addressed the various dimensions of vulnerability and effective model to assess the vulnerability in terms of socioeconomic status. Pelling (1997) examined flood vulnerability at household level to understand the extent of exposure to floods among the local community of Georgetown and how the residents have been adapting to flood damages. Brouwer et al. (2007) examined flood in Bangladesh and observed it as a major contributor to vulnerability and income disparity. Other scholars have also made significant attempts to understand vulnerability to floods (Clark et al. 1998; Balica et al. 2013; Kellens et al. 2013). Walker and Burningham (2011) made an attempt to assess social vulnerability to flood in the light of previous case studies and found that social vulnerability is an outcome of flood exposure. Hydrodynamic- and GIS-based modeling has proved to be effective in flood vulnerability assessments. Seenath et al. (2016) highlighted that GIS-based flood vulnerability assessments are advantageous for large areas, while finer details of flood characteristics can be examined through hydrodynamic models. Balica et al. (2013) identified that deterministic approaches have considerable limitations over parametric methods in flood vulnerability assessment. However, integration of these two methods can efficiently interpret vulnerability scenario in a region. These scholars examined flood risk in a region as a product of probability and consequence.

The recent development of machine learning, artificial intelligence (AI), artificial neural network (ANN) with geospatial techniques has revolutionized the methodologies and approaches of flood vulnerability assessment. Various savants have accentuated that comprehensive flood susceptibility assessment using machine learning models and GIS-based analysis play an important role in flood studies (Tehrany et al. 2014; Shafapour Tehrany et al. 2017; Khosravi et al. 2018; Shafizadeh-Moghadam et al. 2018). Ahmadlou et al. (2018) embryonically utilized ANN and Bat algorithm for assessing susceptibility to flood. The authors examined the weights and relationship of flood acclimating parameters in order to identify the influencing variables. Machine learning-based models with less uncertainty have been proved efficacious than conventional methods. Chapi et al. (2017) notably analyzed flood susceptibility in Haraz watershed of Iran using hybrid and ensemble models. They emphasized that the selection of suitable parameters with effective model can seamlessly be helpful to assimilate flood susceptibility.

Examining vulnerability is an integral part of flood risk analysis. For a long time, several approaches have been used to assess flood vulnerability. Thus, it is significant to understand its various dimensions for a systematic comparative assessment. The present paper is an attempt to review the previous researches on flood vulnerability to make a comparative analysis of various methodologies used for flood studies. Flood vulnerability assessment assumes vital importance in view of its diverse and multidimensional nature. Various scholars around the world have assessed flood vulnerability using several methodologies and approaches. Some of the major areas of researches have been found on health, socio-economic aspects such as income, livelihood, infrastructure and ecological vulnerability to flood hazard. Spatial analysis using geospatial techniques occupied a prominent place in social sciences for evaluating and analyzing the impact of flood. Flood inundations, geomorphological characteristics of the streams, ground characteristics and flood risk assessment mapping have been effectively carried out using geospatial techniques including remote sensing data and GIS. The aim of this article is to present a comprehensive portray of previous works related to vulnerability, flood hazard and flood vulnerability. The paper has been divided into two sections. The first section deals with the conceptual development of term vulnerability around the world and how it is associated with climatic hazards and disasters. The second section is devoted to the conceptual development of flood vulnerability and a range of methods and approaches for its evaluation. The major objective of this study is to analyze methodologies and prepare an inventory for future flood vulnerability assessment.

2 Methodology

For presenting a brief review on various works on flood vulnerability, several studies were selected from different journals at global level (Table 1). A time period (1990–2018) was considered for reviewing earlier published works (Fig. 1). Science citation index journals were used for selecting the studies and identifying diverse ways to address vulnerability to flood (Fig. 2). To overview different works on flood vulnerability, an expanded list of different scholarly articles along with citation index and web of sciences have been prepared and analyzed. Several keywords associated with flood vulnerability were taken into consideration for identifying different methodologies and approaches. These keywords included vulnerability assessment, flood, flood risk, flood risk assessment, flood risk management, flood vulnerability, flood vulnerability index and flood vulnerability assessment. Various case studies around the world were selected for the review (Fig. 3).

A list of keywords was prepared from reviewed studies, and a total number of 500 keywords were identified. These keywords are associated with methods for vulnerability and flood-related aspects. A list of keywords used in various journals indexed in Scopus database (https://www.scopus.com) was prepared. Articles from various journals related to vulnerability to natural hazard, flood risk assessment and flood vulnerability were reviewed to evaluate the weightage of works related to flood vulnerability in the work. A list of most-cited scholars along with their major work throughout the selected time period was prepared (Online Appendix).

Table 1 Articles, abstracts and keywords assessed within different international journals (1990–2018)

Journals	Vulnerability (record in no.)	Flood Vulnerability (record in no.)	Flood Risk Assessment (record in no.)	Floods (record in no.)	Flash Floods (record in no.)	Urban Floods (record in no.)
Springer link	188,673	474	701	209,848	5731	1004
Geomatics, Natural Hazards and Risk	119,590	125	214	30,287	1498	86
Disasters	1902	44	41	3627	111	85
Natural Hazard	1739	118	156	2547	396	111
Environment and Urbanization	735	23	35	6174	239	17
Environmental Science (Science Direct)	3730	341	365	6767	163	629
Geomorphology	770	9	17	3431	319	10
Journal of Hydrology	1498	16	86	6698	551	96
Journal of American Water Resources Association	350	10	17	2921	121	73
Environmental Earth Sciences	673	14	9	1822	129	23
Hydrological processes	656	13	72	3633	312	90
Risk, Hazard and Crisis in Public Policy	105	5	2	98	3	4
Journal of Geographical Society of India	64	2	0	236	7	1

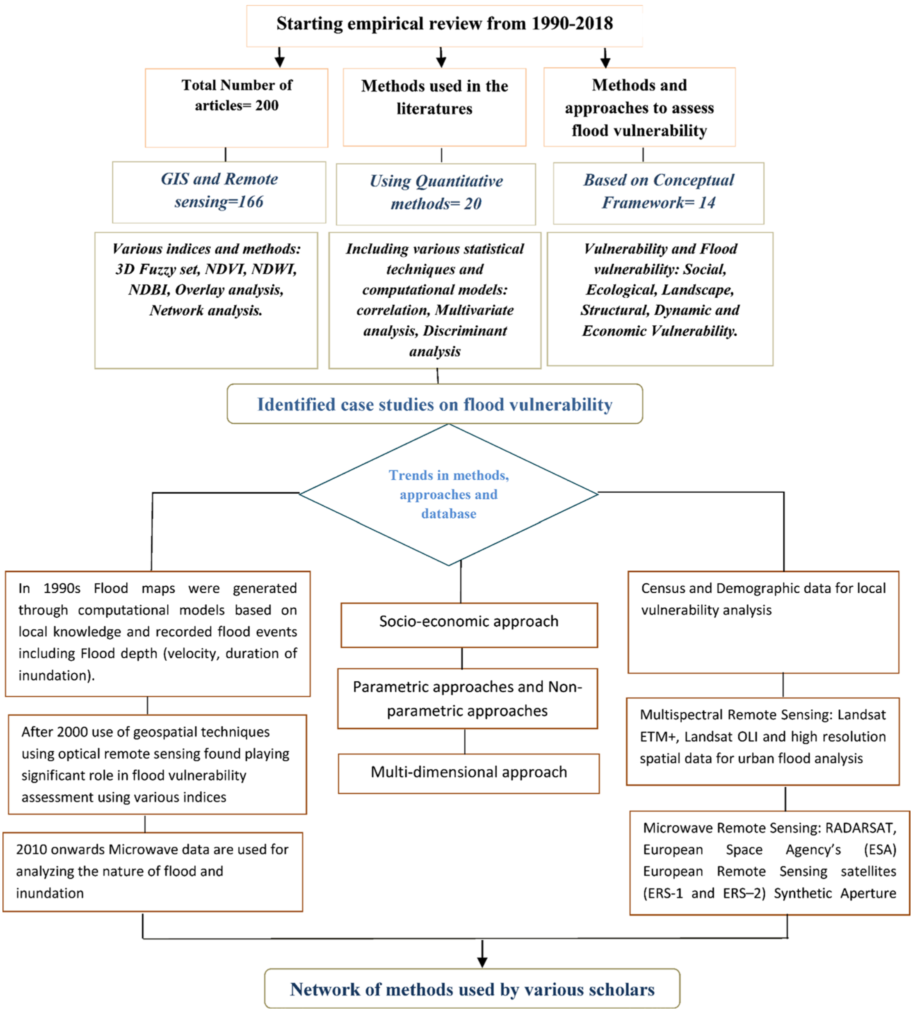

Fig. 1 Methodological framework of empirical review

2.1 Keyword analysis

A list of keywords was prepared while reviewing various studies and represented graphically (Figs. 4, 5). Analysis of keyword used various works helped in assessing the quality work related to flood vulnerability and its various dimensions. These keywords were comprised different methods and approaches used in earlier works.

2.2 Authors and citations record (1990–2018)

Vulnerability among researchers has been a major concern since decades mainly in context of natural disasters. A list of different works on flood vulnerability has been

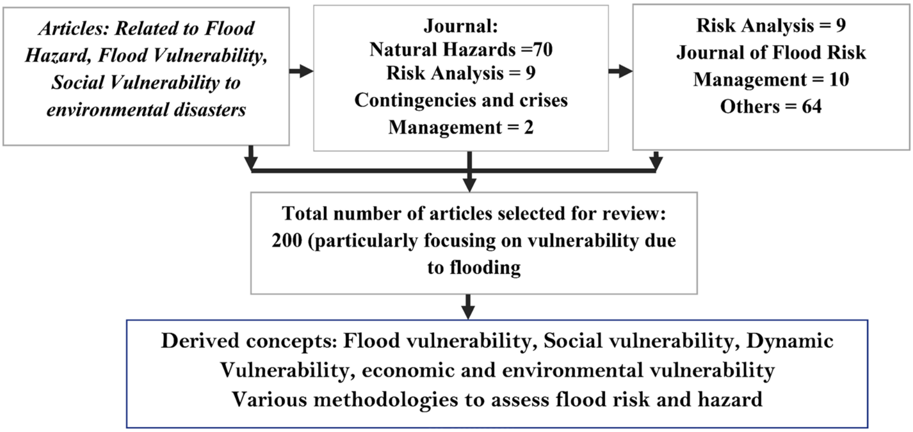

Fig. 2 Selection of articles for review

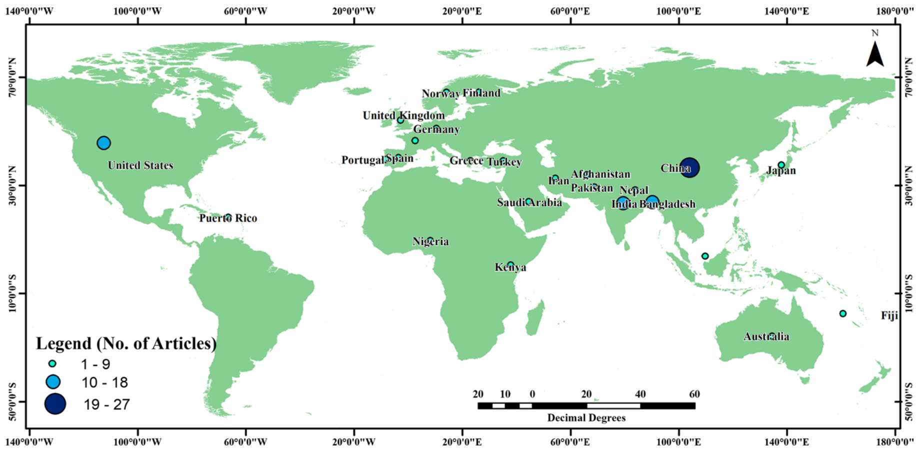

Fig. 3 Identified case studies on flood vulnerability

analyzed in this section. Author and citation record have been presented in Online Appendix. A network analysis was prepared using Gephi (version 0.9.2) to demonstrate most-cited scholars and methods for flood vulnerability assessment (Fig. 6). The concept of vulnerability has largely been expanded by various scholars including Cutter, Turner, Timmerman and Adger. In case of vulnerability to natural hazards important contributions were addressed by Cutter and Adger. Ratick, Brouwer, Revi, Kron and Balica are the cited scholars who emphasized vulnerability assessment. Cutter highlighted vulnerability due to natural hazards, floods and cyclones in USA. Kubal, Haase, Meyer, Messner and Scheuer evaluated specifically flood vulnerability.

Vulnerability at large was assessed in context of social vulnerability. Flood has more linkages with land transformation, failure in hydraulic structure, sea level rise and climate change. However, several studies have given weightage to climate change particularly for inducing floods and consequent vulnerability in a region. For the evaluation

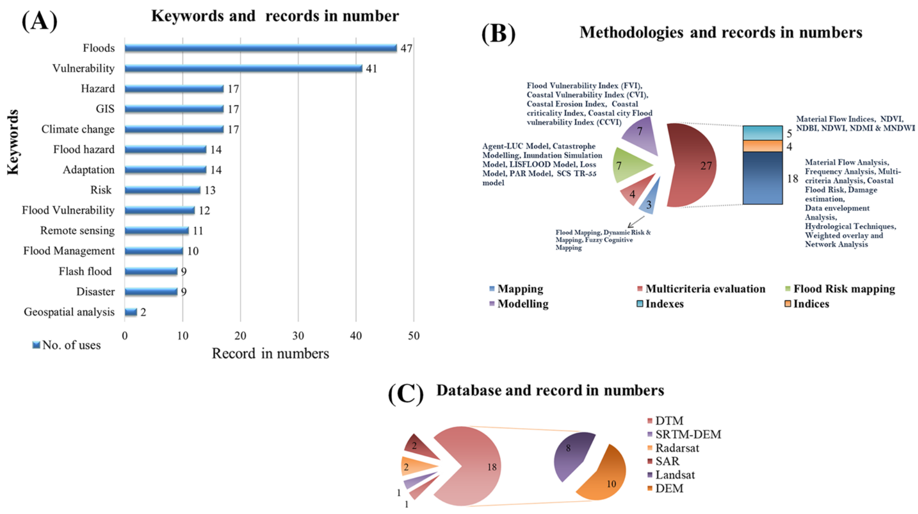

Fig. 4 Identified keywords and methods

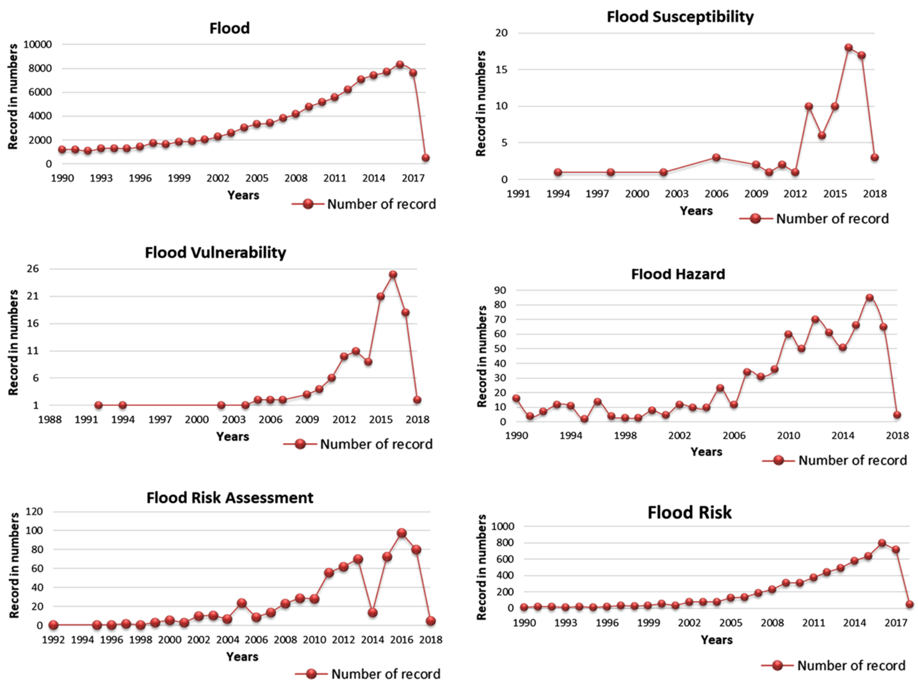

Fig. 5 Graphical representation of number of articles published since 1990. *Source*: Scopus database (https://www.scopus.com)

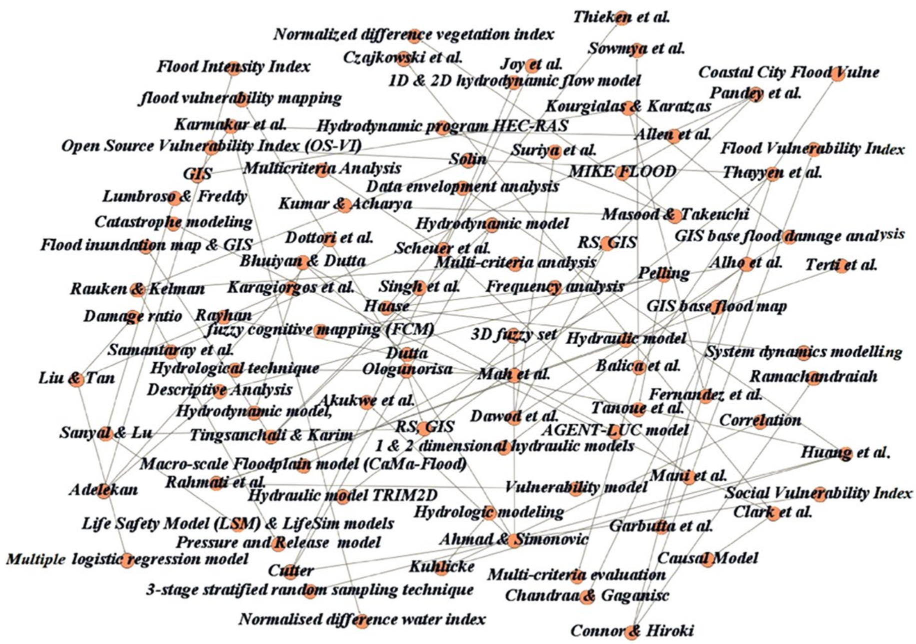

Fig. 6 Network of methods used by various scholars

of social vulnerability various statistical techniques along with geospatial analysis have been attempted to address flood hazards.

3 Definition and concept of vulnerability among researchers

From the review of various studies, it is found that earliest attempt to define vulnerability was made by Timmerman (1981) who emphasized the need to investigate the term and the situations associated with vulnerability. He presented an enormous compilation of all the definitions and models for assessing vulnerability so as to make an understanding about the concept of vulnerability and resilience. IPCC (2007) defined vulnerability as a function of magnitude, the rate of climate change, climate variability and extremes.

World meteorological organization (1980) observed a significant relationship between fluctuations in climate and vulnerability. The level of vulnerability and resilience is different in varied environments. Scale has been found an essential element in assessing vulnerability in certain locality and needs analysis (e.g., Cutter 1996; Turner et al. 2003). It should be seen from the perspective of time that how the scenarios have been shifting over the period to assess vulnerable population. One of the important tasks to assess vulnerability is to find out the various approaches and models such as risk-hazard (RH) model and pressure-and-release (PAR) model (Turner et al. 2003).

One of the important contributions to define and explain vulnerability came from Susan L. Cutter (1996) who reviewed several studies since the 1980s. The term "vulnerability" has been immensely used in researches especially in relation to climate change which has led to a misconception about the actual meaning of vulnerability. Some of the efforts were proved partly effective in defining vulnerability with reference to climate change. Thus, vulnerability is often confused with other nomenclature in researches (Füssel 2007). Clark et al. (1998) presented a combined theme and works on examining vulnerability mostly in relation to environmental hazards. Various cited scholars such as Cutter and Liverman have presented a significant framework of vulnerabilities in their respective works. According to Liverman (1990) the concept of vulnerability should be equated with other associated concepts such as marginality, adaptability, susceptibility, fragility, resilience and risk. The scholar also examined vulnerability in response to global environmental change during 1990–2017. Kasperson et al. (2012) expanded the concept of vulnerability by taking into consideration the various aspects such as risk, coping capacity, robustness, sensitivity, criticality and exposure. Cutter (2003) defined vulnerability as a situation where people and places are at risk and which reduces their ability to respond to different environmental hazards. Cutter further added that science of vulnerability needs an integrative approach to illustrate all the components such as natural, social, engineering system and their complex interactions. Also, vulnerability varies spatially (the nature of the topography varies over the place). Thus, it is important to suggest different solutions to various places. Therefore, different assessment techniques led to a diversified framework of methodologies leading to origin of a range of factors that affects resistance and resilience. The difference in the conceptualization of vulnerability also evolves from the different nature of works done by scholars. Variation can be seen by the type of circumstances and places. For example, in case of climatic disasters, vulnerability varies according to the nature of disasters. Cutter (2001) suggested disasters as large-scale events which have significant impact on human society arising out from hazards. Examples can be cited as tornadoes, blizzards, earthquakes and anthropogenic-induced disasters such as pollution and industrial plant failures. Two main key components of vulnerability are evolved namely risk from a situation and coping capacity of the vulnerable people. Coping ability refers to the ability to overcome from the impacts or to absorb them through adaptation. The need to assess vulnerability to climate arises from an understanding how do people adapt to varying climatic conditions. Vulnerability to natural hazards has always been highlighted in substantial volume of researches. Sometimes lack of accurate data hinders the vulnerability assessment generally in case of geophysical risk. Moreover, vulnerability is human induced which is mainly associated with disasters (Chakraborty et al. 2005).

Apart from the perspective of biophysical hazards, the concept of vulnerability is to be conceived in a specific geographical domain. The areas of adequate risk and susceptibility to any natural hazard can easily be identified after vulnerability assessment (Weichselgartner 2001). Adger (2006) has addressed vulnerability to climate change and the challenges in adaptation and resilience. He also laid emphasized development of measures to reduce risk of climate change and various extreme events in order to reduce vulnerability and damages.

4 An overview of different works on flood vulnerability

4.1 Concept of flood vulnerability

Flood vulnerability refers to the exposure, susceptibility and ceaselessness of people or any region to flood hazard and inability to cope up with its impacts. The need for understanding flood vulnerability arises because evaluation and assessment of flood vulnerability can lead to effective flood management and in reducing its impacts on various sectors of the society. The concept of vulnerability has its origin from social sciences and nowadays increasingly noticeable in researches on disasters. The concept of vulnerability is multidimensional in nature and consists of various components such as risk, exposure and sensitivity. Since recent decades, a long debate has been generated among scholars on the capability to evaluate, allocate and statistically measure the vulnerability among various groups. The field of vulnerability has seen an extensive growth and development during the last four decades within the framework of hazard vulnerability to include the socioecological dimensions (White and Haas 1975). Various methodologies have been used for effective assessment of all the dimensions of vulnerability including the spatial, geographical, ecological, economic and social dimensions (Sahana and Sajjad 2018).

Different scholars have tried to quantify the flood vulnerability in their works. Besides, several organizations are also playing a key role in quantifying flood vulnerability empirically. For example, the United Nations Educational, Scientific and Cultural Organization (UNESCO) has evaluated flood vulnerability employing the following equation:

$$\text{Vulnerability} = \text{Exposure} + \text{susceptibility} - \text{resilience}$$

This implies that flood vulnerability directly depends on susceptibility of the people, events and their inability to cope up with the impacts. Thus, flood vulnerability is based on various elements such as severity of flood event, how much risk is related to hazard and the damages associated with the event. Scheuer et al. (2011) emphasized that besides socioeconomic factors, ecological parameters should be taken into consideration while addressing vulnerability to floods in any region.

Flood vulnerability can be assessed by categorizing it into various classes viz environmental, economic and social vulnerability. These components can be assessed using various indicators, age, population density, deprived settlements, inability of accessing basic services can be taken as indicators for evaluating population vulnerability to flood. Environmental component can be assessed using indicators like degraded forest and land degradation. Poverty, land resource base and accessibility to infrastructure can be considered for social and economic components. Cultural system, gender and economy can also be included in the flood hazard vulnerability model. However, the modification has been seen in the notion of vulnerability over the last 20 years in context of flood vulnerability index (FVI). Thus, its modified definition includes exposure, susceptibility and resilience (Zevenbergen et al. 2008).

The term “risk” in the context of flood hazard was introduced by Knight (1921), and it has been applied in various aspects of adaptation to a system. The concept of flood risk is strongly referred to the probability of high damage and losses to environmental, social and economic conditions because of flood occurrence. Deterministic approach of flood risk comprises the use of physically based modeling for the estimating likelihood of flood hazard and flood damages which leads to evaluate the economic consequences of the flood risk in a region (Balica et al. 2013). In the field of Geography, the term vulnerability has been in use since the conceptualization presented by Timmerman. A new dimension of flood vulnerability can be seen in case of urban areas and megacities which is now a focal point of researches (Anderson 1992; Kandel 1992; Mitchell 1989). Vulnerability to floods can be a cumulative consequence of risk and response and generally reduces the welfare of society leading to poverty and deprivation. Risk, response and poverty are thus independent in case of flood hazard (Rayhan 2010).

4.2 Different approaches and methodologies for assessing flood vulnerability

There has been a growing concern to mitigate flood losses for decades. Thus, it is imperative to examine risk perception, risk assessment and risk communication under the domain of flood risk management. Some of the researchers have also carved out different methods and approaches to assess the flood losses (Kellens et al. 2013). During the 1990s, more consideration was given to field analysis, physical and socioeconomic approaches in flood vulnerability analysis. After 2000 with the advancement of geospatial technology like remote sensing data mainly Landsat and multispectral data provided an edge in spatial vulnerability assessment. After 2010, use of three-dimensional hydrological modeling became evident in GIS environment.

Recently, advance land imager (ALI) data and other high-resolution microwave data capable of determining flood inundation and turbidity are been increasingly used in flood vulnerability analysis (Amarnath 2014). For example, high-resolution airborne radar data have been more useful in examining local flood inundation (Murdukhayeva et al. 2013). RADARSAT data, synthetic aperture radar (SAR), Sentinel-1 & 2 are being given due importance to analyze flood vulnerability in view of their well-timed image delivery. Moreover, flood susceptibility assessment based on advance machine learning algorithms with GIS-based modeling has been gaining momentum (Chapi et al. 2017; Ahmadlou et al. 2018; Khosravi et al. 2018; Shafizadeh-Moghadam et al. 2018; Hong et al. 2018b).

Studies have depicted an inverted U-shaped curve of flood vulnerability of lower-, middle- and higher-income countries as a result of balance between various historical socioeconomic efforts and growth to lessen the crises of damages leading to lessening downward and upward trend (Tanoue et al. 2016). Cutter (2003) elucidated integrating risk and its relationship with hazard mitigation. She used a model named as "Hazards of place" to assess the social vulnerability and its further expansion. A composite social vulnerability score has been worked out by using social vulnerability index for the country level social and demographic data of various social indicators. Importance of factor analysis has been highlighted in the assessment of vulnerability. Combining social vulnerability with biophysical risk would be effective in analyzing vulnerable population at local, regional and national scale.

Another major work by Cutter et al. (2009) entitled, "Social vulnerability to climate variability hazards: a review of the literature" highlighted that hazard has potential impacts on people and how risk and vulnerability is related to disasters. The author also provided an important framework of all the previous studies during 2000–2009 to develop an understanding of vulnerability to hazards. Various methods, indices and approaches have been discussed for assessing vulnerability in the light of all previous studies. The emphasis was not only on benefits of approaches but also to identify the existing gap between them.

Lee et al. (2014) utilized fuzzy tops is based on a level cut set for the assessment of flood vulnerability. The method is useful in decision making for water resource management. Parametric approaches are advantageous in decision making and assessing vulnerability related to disasters and climate change. Parametric approaches have been used since decades, but these have been closely associated with multicriteria decision making method (MCDM). In case of flood vulnerability assessment lots of uncertainty exist within the indicators related to social, economic and environment components. Fuzzy set identifies and reduces these uncertainties giving crisp output. Multicriteria approach for flood risk assessment developed by Meyer et al. (2009) covers all aspects of economic, social and ecological vulnerability. Hong et al. (2018a) emphasized the significance of fuzzy logic approach and data mining technique to delineate the non-flood and flood-vulnerable areas. Hong et al. (2018b) utilized integrated adaptive neuro-fuzzy inference system and GIS to spatially examine the flood susceptibility in Hengfeng County in Jiangxi Province, China. Use of multicriteria approaches is effective in analyzing flood inundation along with assessment of economic damages. In case of urban areas, multicriteria approach is beneficial for assessing vulnerability because of high population density, diversified nature of economic activities, valuable property and infrastructure (Kubal et al. 2009). Concept of flood risk and vulnerability has been evolved by Kubal et al. (2009) using multicriteria approach for flood risk mapping following Meyer et al. (2009). Multicriteria approach is effective in assessing weights of different indicators, but it requires developing individual component for single criteria evaluation (Scheuer et al. 2011). Multicriteria analysis and GIS have proved efficient tools for assessing flood risk (Zelenáková et al. 2015).

Spatial and temporal aspects assume greater significance in flood vulnerability analysis. In terms of flood, scale covers various aspects of vulnerability and its conceptual development. Certain methods like DISFLOOD combine different models to assess various dimensions of vulnerability (Fekete et al. 2010). Another crucial component of flood risk analysis is to integrate all the indicators to one index. One such effort was made by World Water Assessment Programme (WWAP) covering 23 United Nations agencies for developing flood vulnerability index initiated by UNESCO. Flood vulnerability index (FVI) integrates all the components of floods such as climate, hydrogeology, countermeasures and meteorological components (Connor and Hiroki 2005). FVI is the only parametric approach to assess the flood vulnerability at a very large scale, whereas the deterministic approach has good scientific base but are limited in vulnerability evaluation. Flood vulnerability does not directly evaluate flood risk but contributes to risk assessment and involves social, economic and environmental aspects of vulnerability (Balica et al. 2013).

Hahn et al. (2009) used a livelihood vulnerability index (LVI) to assess the vulnerability to climate change. LVI is mainly derived for assisting development organization for preparing policies toward vulnerability (Balica et al. 2009). Messner and Meyer (2006), in their work reviewed the national level existing approaches in flood damage assessment. They included all the categories related to degree and scale of analysis existed in national level approaches of vulnerability. Flood vulnerability evaluation needs a systematic approach. Emergy systematic approach can be useful in highlighting exposure, sensitivity, susceptibility and adaptive capacity. Mapping emergy indices can help in assessing vulnerability to flood. Management of infrastructure and regional planning are the crucial factors affecting flood vulnerability (Chang and Huang 2015). Flood information system uses analysis tool in detecting changes in the land use and enabling mapping the spatial vulnerability, inundation and identification of the vulnerable areas (Karmakar et al. 2010). Greco and Martino (2016) evaluated coastal vulnerability index (CVI) to assess socioeconomic conditions of coastal community. Coastal erosion index (CEI) was also used in their study for the empirical assessment of vulnerability. The foregoing discussion revealed that advancements in methodologies, approaches and database yielded more accurate results for flood vulnerability analysis.

4.3 An overview of different works on flood hazard and flood vulnerability in case of developing nations

Floods have always been devastating in case of developing nations. Around 7000 islands identified vulnerable to this hazard mainly during monsoons located between Philippine and South China. Other developing nations such as Iran, China, India, Nepal, Bangladesh and Vietnam are experiencing flood since decades (WWAP 2006). Flood has been always a major concern of researchers to address its impact and associated vulnerability in developing countries.

Varied climate types pose threat to flood risk in many developing nations as these are associated with extreme weather and climate events including heavy rainfall during monsoon and cyclone. Thus, for analyzing varied nature of floods different hydrodynamic models have been prepared in these nations. Somehow these models are found limited in number to address and predict flood in case of Asia, Africa, Bangladesh and other developing nations due to lack of hydrological and physiographical data (Sanyal et al. 2013). Dingguo et al. (2007) in their work identified flood vulnerability in Lake Poyang region and identified around 55% of the region as vulnerable to floods. Assessment of physical and social vulnerability together especially in these nations is essential since poverty is quite visible and access to resources is limited. Karagiorgos et al. (2016) tried to minimize the gap between researches in science and humanities in case of vulnerability by addressing both physical and social vulnerability together as an integral component of vulnerability. They identified infrastructure, building design, and quality of material for assessing physical vulnerability and age, gender, health facilities, emergency services for social vulnerability. Bhalme and Mooley (1980) utilized flood area index (FAI) to assess the severity of flood in India. Lack of protection measures was found one of the main reason of flood in Dhaka, and the use of digital elevation model (DEM) was found for flood modeling (Masood and Takeuchi 2012). Another study by Ni et al. (2010) selected population, death, economy and agriculture for analyzing multidimensional flood vulnerability using data envelopment analysis method (DEA method).

5 Various dimensions of flood vulnerability

5.1 Ecological vulnerability

Floods have always been associated with large-scale destruction not only to life and property but also to environment. Adger et al. (2005) highlighted vulnerability to flood, cyclone and climate change. Ecological footprint is one of the important components of vulnerability. They suggested that sustainability and functionality and adaptation are the important parameters for assessing ecological vulnerability. Adger and Brown (2009) in another study found climate change as a major threat to adaptation leading to social, economic and environmental vulnerability. The term ecological vulnerability can be understood at various hierarchical levels including nature of organism and their population, species community, type of ecosystem and topography. For assessing ecological vulnerability, it is essential to address the adaptation of various organisms within a specific climate or after the occurrence of any event. Adaptation, sustainability and functionality are thus the key components of ecosystem vulnerability (De Lange et al. 2010). Cai et al. (2011) utilized fuzzy interval-stochastic programming (MIFISP) model for assessing functionality of wetland in enhancing the extent of flood. Topography and hydrological characteristics have profound influence in building the ecosystem of wetlands.

5.2 Social vulnerability

Various scholars have assessed and evaluated social vulnerability to climate change and extreme events associated with them. The circumstances and conditions where people and different social–cultural groups adapt them to climate change are the integral part of social adaptability and resilience which is mainly linked to their economic activities and nature of the wetlands. Social vulnerability directly interferes welfare of livelihood and associated with insecurity of different social community. The vulnerable groups can be identified in terms of shortage of income, inaccessibility of resources and leading to social and economic crises (Adger 2006). Brown and Damery (2002) identified flood vulnerability keeping in mind social vulnerability and emphasized the usages of more technical solutions in flood risk management rather than focusing on rigid deterministic approaches. Tas et al. (2013) made an attempt to assess the flood vulnerability among lower-income people. Coping strategies for such groups are essential to reduce the flood impact (Turner et al. 2003). Optical data provide efficiency in flood mapping, demarcation of flood-vulnerable areas and better analysis of weather events. Digital elevation models and flood hazards maps are essential in determining flood depth and can be effective in identifying flood-vulnerable regions especially in case of India (Gangwar 2013).

Cutter (1996) highlighted the ambiguous nature of researchers toward the use of empirical approach in managing hazardous waste and reducing its impacts on human health. This came into light under the environmental justice movement of USA during the 1990s. Price (1978) had made a significant attempt to evaluate the impacts of Brisbane floods during 1974 and 1976 on the mental and physical health on the residents of Brisbane. He used cluster analysis (earlier used by Abraham in 1976) for evaluating psychiatric behavior. The study found psychiatric behavior more among women under age of 65 years. One of the major attempts to relate flood vulnerability to human health came from Melick (1978) who tried to correlate the emotional disorder among workingmen of Pennsylvania with flood using data collected through personal interviews of the respondents. Durkin et al. (1993) adopted an epidemiological approach to study the disability among children (2–9 years) affected by flood events between 1988 and 2000 in Bangladesh. The authors have used a systematic approach to examine the exposure of flood hazard and resultant posttraumatic stress.

5.3 Economic vulnerability

The impact of disasters not only disrupts the livelihood but also hinders economic development. Infrastructural damages are associated with floods and resilience takes a lot of time and capital to cope up with impacts. Several works around the world revealed that flooding has been associated with large-scale economic vulnerability. Van Der Veen and Logtmeijer (2005) have prepared map of economic hotspot in South Holland which are more vulnerable to flood especially due to dense population and diverse nature of economic activities. This economic vulnerability has been visualized in GIS to identify more vulnerable hotspots. Housing, demographic characteristics and income are the most vital parameters of economic vulnerability. Thus, economic vulnerability can be evaluated in the context of income and wealth (Felsenstein and Lichter 2014). Brooks et al. (2005) addressed governance, infrastructure, demographic and physiographic vulnerability factors. Thus, the nations can be classified into various vulnerability categories on the bases of socioeconomic indicators. Mainly, developing nations are found more vulnerable to natural hazards. Identifying vulnerability to flood at community level or local level is essential as damages are severe. Posey (2009) examined the relation between the coping capacity of flood and socioeconomic vulnerability in the floodplains of USA.

6 Results

Flood and its relative impacts have been prioritized within earlier researches. Floods and vulnerability were assessed separately within academic framework. Vulnerability has been emphasized in previous studies in terms of damages caused by natural hazards. Scopus database analysis revealed that more than 8000 research works are basically concerned with flood (Fig. 5). The main focus of the researches has been on social, environmental and economic vulnerability. Recent works on flood vulnerability reveal the use of more appropriate approaches and methods to evaluate the susceptibility of place or people to flood. Fuzzy set was found essential in identifying flood risk vulnerability over space and time. Catastrophe modeling, hydraulic modeling, flood onset inspection and multicriteria methodology were in great use for flood hazard analysis. Indicators are important tools for assessing flood vulnerability, and we reviewed all the indicators in flood vulnerability studies and made an inventory of such indicators that could be utilized for future studies (Table 2). Rufat et al. (2015) also presented a systematic review of the works carried around the world on social vulnerability and flood vulnerability and examined various indicators that have been used to estimate vulnerability. Geospatial techniques including remote sensing data and GIS have been found more useful in providing spatial overview of flood-vulnerable areas. Keywords also suggest that use of geospatial techniques have become more useful in flood hazard assessment and estimating flood vulnerability. Scopus database showed that the highest number of studies has been conducted on flash floods followed by urban floods and coastal floods (Table 3).

There is wide range of work done on floods and its impact on society at global level. Coping capacity, risk perception and resilience have been found key parameters for flood vulnerability. After analyzing different works on floods and vulnerability, it has been found that in case of flood assessments various techniques are in use since decades. However, introduction of remote sensing and GIS in flood risk assessment has been given more meaning to the flood analysis. Academic works related to floods were found varied in nature. Flood vulnerability in relation to social, environmental and economic context was more attempted (Fig. 7).

7 Discussion

Different components of vulnerability can be assessed together in one model. Social vulnerability is directly related to inability of any group or community to cope up with impacts of any event. The weaker section of society has been considered more vulnerable to flood and other environmental hazards. Cutter (2003) integrated all the elements of vulnerability including biophysical factors, potential risk and mitigation using a place hazard model for analyzing social vulnerability. Kumpulainen (2006) highlighted the previous attempts to expand the concept of flood vulnerability in context of natural

Table 2 Different indicators for assessing flood vulnerability

Vulnerability	Indicators	References
Social/residential vulnerability	Age Gender Health: mental, physical Local integration Emergency services Coping capacity	Box et al. (2016) and Oulahen et al. (2015)
Economic	Income Occupation Total GDP of the region Direct economy losses	Box et al. (2016) and Greco and Martino (2016)
Dynamic vulnerability	Space Time	Terti et al. (2015)
Physical/Structural Vulnerability/Landscape Vulnerability	Infrastructure Building design Quality of building design Vegetation cover and agricultural productivity	Karagiorgos et al. (2016), Hatzikyriakou and Lin (2017), Zelenáková et al. (2015) and Sahana and Sajjad (2018)
Geomorphological/geophysical	Topography of the surface Geo-hydrological characteristics of stream Elevation Slope	Codjoe and Afuduo (2015)
Environmental	Agricultural productivity Deterioration of wetland Deforestation	Dingguo et al. (2007)
Risk perception	Awareness of the event Knowledge-based flood management Preparedness for the event Risk denial/acceptance Trust in officials	Codjoe and Afuduo (2015)
Building vulnerability	Flood inundation timings, frequency and velocity of moving water, depth of flood water	Walliman et al. (2012) and Mehebub et al. (2015)

Table 3 Categories of floods identified in the studies (1990–2018). *Source*: Scopus database (https://www.scopus.com)

Categories of floods	Number of articles	Rank
Urban floods	311	2
Rural floods	4	8
River flooding	59	5
Flash floods	947	1
Coastal floods	198	3
Storm surges	7	7
Glacial lake outburst	76	4
Rainstorm	9	6

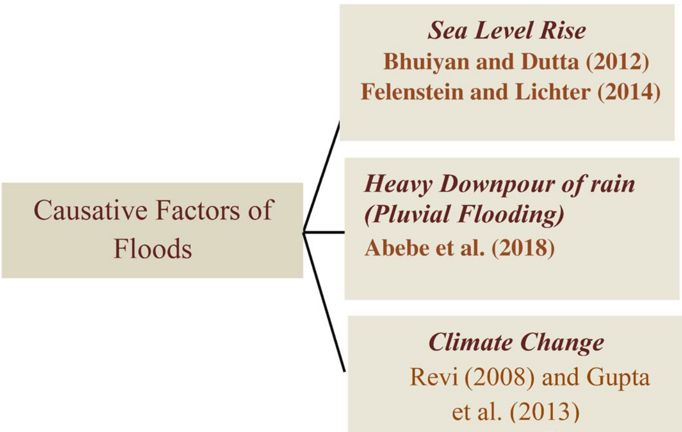

Fig. 7 Factors causing floods in various studies

hazards. He synthesized indicators based on their weightage for generating maps of more vulnerable region of natural hazards.

Though flood vulnerability has been evaluated by the researchers using various approaches and methods, yet it needs their further expansion. Geospatial tools and statistical techniques should be applied for assessing flood risk and vulnerability in the affected regions. These methods provide a meaningful flood analysis particularly in those regions where scarcity of resources is a matter of concern. At present, there is a wide range of global flood analysis models in the collaboration with various organizations, for example, Global Flood Awareness System (GloFAS) being independent of political and social boundaries provide daily forecasting of floods since its existence. Thus, such collaboration can be helpful in better spatial visualization of flood events and the vulnerable areas can easily be delineated.

Scientific work on flood and its related aspects has found a greater place in science and social science researches and in Scopus database. Since the world is experiencing climate change and variability thus previous researchers were more inclined toward flash floods, coastal floods and riverine floods. The world is becoming more urbanized and accordingly urban flood vulnerability has given more consideration in the previous researches. However, scientific analysis of other categories like storm surges, rainstorm and rural flood using parametric approaches is needed.

8 Conclusions

The present study endeavored various aspects, methods and approaches of flood and its vulnerability assessment since the 1990s. More than 200 articles of most-cited scholars (from 1990 to till date) were deeply reviewed to make a sound and coherent analysis on various methods. Keywords represented methods and important database and record of flood-related studies for identifying the trend of flood vulnerability assessment have been shown through graphical representation. Advancements in methodological framework and approaches of flood vulnerability assessment were scrutinized emphasizing the recently used models. An inventory of popularly used indicators for flood vulnerability and methods of its assessment were examined. The findings revealed that flash floods, coastal floods and urban floods were more attempted by the researchers. However, scanty information on flood due to storm surge, rainstorm and rural floods was observed. Hence, such floods should accord priority especially in developing countries. Earlier, the major emphasis was laid on site characteristics, depth of inundations and topography. However, many discrepancies in methods and approaches for site-specific flood vulnerability assessment were noticed. Advancement in geospatial techniques particularly remote sensing data, GIS, three-dimensional hydrological models and machine learning-based algorithms have revolutionized flood susceptibility and vulnerability assessment. The findings also revealed use of non-parametric methods in the absence of adequate flood data. Susceptibility approaches and models such as coastal vulnerability index (CVI), flood vulnerability index (FVI), multicriteria analysis, analytical hierarchy process (AHP), sustainable livelihood analysis, logistic tree model, ensemble models, bivariate regression analysis, artificial intelligence and GIS-based mapping are being given weightage to flood hazard vulnerability assessment by scholars. Gaps between methods and approaches can be minimized by expanding the concept of flood vulnerability. Multidimensional approach, machine learning-based models, high-resolution satellite data, hydraulic model and selection of effective flood conditioning parameters are suggested for in-depth flood hazard analysis. Use of multidimensional approach, sophisticated models, site-specific indicators and fine-resolution satellite data are a way forward for future vulnerability assessment.

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