Journal of
Geography & Natural Disasters

Ali et al., J Geogr Nat Disast 2017, 7:2
DOI: 10.4172/2167-0587.1000195

Review Article | Open Access

Advances and Challenges in Flash Flood Risk Assessment: A Review

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Abstract

Flash floods are considered to be one the worst kind of hazard. They are characterized by their suddenness, rarity, small scale, heavy rain and peak discharge, unpredictable, fast and violent movement. It has severe effects on human society in the form life losses, damages to property, roads, communication and on natural settings. Advances in hydrology, meteorology, engineering, using of GIS and remote sensing still not able to increase real time forecast. Researchers from developed countries have stressed to more focus to improve very short time an effective early warning system with collaboration of local communities for flash flood risk supervision. The valid inputs from natural and social science can play a vital role in risk reduction. In the flood hazard risk assessment, the analysis of various morphometric parameters of river basins is very essential. Community based participatory flood hazard mapping provides an essential detail, such as inundation areas, depth information, evacuation centers and routes, critical facilities, communication channels, evacuation criteria, emergency kits and many other items needs for an evacuation in hazard maps. Vulnerability is based on numerous components such as internal (assesses coping capacity of people or systems) and external (exposure of people) side of vulnerability. Risk assessment consists of two main components such as hazard (related to source and pathways) and vulnerability (related to the receptor and consequences). Flood disaster-related risk has increasingly become a global concern, and its vulnerabilities related to changes in demography, socioeconomic conditions, unplanned settlements, environmental degradation, stress on natural resources and climate change.

Keywords: Flash flood; Hazard; Vulnerability; Risk; GIS and remote sensing

Introduction

A flash flood or a rapid onset flood refers to short duration flooding with a comparatively high peak discharge of water in a particular place. Flash flood occurs within a few hours of heavy rainfall, rapid snowmelt or after a sudden glacier lake outburst or embankment failure or very rapid break up of an ice block which is due to rapid increase in temperature [1,2]. Flash flood stimulates shortly after sever rainfalls reaching up to 100 mm within 6 hours and extreme flow of high water and normally occur in small dry valleys. In the flash flood events unexpected increase in water close in streams and rivers and very high flow speed bring large amount of debris, boulders, uprooted trees, obliteration of infrastructures and constructed buildings stand in its path [3]. In the emergency response phase time of a flash flood is usually less than 6 hours. Flash flood usually occurs after the high intensity of rainfall in a certain area or a small basin with particular a geological setting like relief, slope, and a shape factor, drainage density of a watershed [4,5]. Soil outlines have persuasive effect flash flood runoff process such as soil permeability, shrinkage, expansion, root distribution and human activities [6].

Hydro meteorological vagueness with flash flood circumstances remains displays hitches in real time forecasting. The process of flash Flood prediction needs to evaluate and answer to the questions of flood prediction parameters such as watershed conditions (how water will move once it reaches the ground?), rainfall (how much and how much intense will the rain be?) and snowmelt (how much and how fast will it melt?) [7]. Over the last ten years in the developed countries, the accumulative struggle going on to make advancement in flash flood forecasting. Therefore, there has been effective progress in lead time up to six hours, like improvement in quantitative estimates and forecasts in precipitation and flow forecast models. Operative forecasting with convenient lead time is still a big challenge in meteorology, which mainly shows suspicions associated with rainfall [8-10].

Monitoring and illustration of rapid onset flood events are challenging for the reason that the space and time, fast and violent and also they are in frequency. The careful observations and gathering of previous event data can play a vital role in risk assessment [11]. Conventionally estimating of indirect peak discharges and rainfall highest records can be used to document these flash flood events in an area. Observing and forecasting of upcoming flash flood event needs a precise rainfall estimation in a small geographic area with scaling less than 1 km and within short time scales. Evaluation of community perception about the flash flood factors can also provide an in depth understanding the events. Therefore, flash flooding risk assessment with effective mitigation measures and the lead time forecast is essential for disaster risk reduction.

In the literature, there are numerous definitions of flash floods; it is referring to ups and downs with quite rapidly, no advance warning which commonly associated with extreme rainfall or any natural/artificial dam failure over a relatively small area [12]. According to Kelsch et al. [13] it can be triggered at any location of catchment, where, there is less time for warning and defense especially in the downstream area of the catchment. Therefore, by existing knowledge and installed meteorological instruments unable to achieve lead-time to activate the safety measures [14]. Flash flood risk assessment reviews provide an essential knowledge regarding flash flood concerns. Focusing on highest rainfall and discharge mostly provides a limited insight to response to the events. Most of the studies revealed than many countries carried

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Received March 27, 2016; **Accepted** April 07, 2017; **Published** April 11, 2017

Citation: Ali K, Bajracharyar RM, Raut N (2017) Advances and Challenges in Flash Flood Risk Assessment: A Review. J Geogr Nat Disast 7: 195. doi: 10.4172/2167-0587.1000195

out their own local own expertise, but still a reduction of flash flooding impacts is a main challenge for the authorities [15].

The rapid increase in human population, economic development, and a huge burden on current amenities, environmental degradation, and intensified land use such as human settlements are out spreading into hazard disposed areas [16,17]. With the today's intricacy in societies, it became a serious concern to develop effective mitigation measure and preparedness from such kind of hazards [18]. Flash floods can surprise people who are located in the middle of everyday doings and especially it has severe effects to the public who crossing the ways vulnerable to flooding. During the last one decade, approximately 13,000 causalities from such type of events all over the world [19].

Over the last many decades, there have been many differences found among social and natural scientists on vulnerability assessment approach, but the last few years, some attempts have been taken to bridge this gap [20,21]. Current trends in social science to assess vulnerability is based on a set of socioeconomic aspects that regulate the competence in the social order to cope the pressure and prepare to change or to bounce back from the effects of exposure to hazard [22,23]. So far, in every field susceptibility define in a mean which suit with their field objective. There are some important extents of susceptibility which mainly associated with societal and economic vulnerability, while in a differently described but linked to each. Disaster vulnerability research can be focused on two main dimensions. First one is based on the internal side which focuses on coping capacity of people while the second focused on exposure of people to stress [24-26]. The allocation of community based studies can improve flash risk reduction and also give effective results in early warning phase. In developed countries like North America and western Europe used a robust scientific and advance methods are prevailed, apart from that more recently social studies are also in cooperating in flash flood risk reduction [27]. The contribution of community based methods and approaches often brings in qualitative and quantitative way which focusing on participatory based flash flood assessment, which includes all social class perceptions, their involvement, communication and response issues. However, now physical sciences and engineering recognize agreed that their studies become very meaningful by engaging social science findings. Therefore, it plays a significant role has collaboration and implementing all findings in disaster preparedness, early warning, in response and recovery phases as well. The mountainous areas in Europe, US, and in Mediterranean regions are vulnerable to flash flooding, and every year severe damage to mountain habitat in the form of life loss, property and infrastructure. Recently, in developed countries researchers have called for increased attention on short lead-time warning in mountainous region as well [28]. The (HKH) mountains are the youngest mountains on the earth and still tectonically active and the region every year faced various natural hazards such as landslides, earthquakes, debris flows and flash floods. Over the last one decade the a number of flash flood event occurred along HKH mountains, consequently, hundreds of lives lost, severe damages to human settlements, properties, agricultural and infrastructure. It is considered powerful natural disasters along the HKH region. For such kind of hazard still there is no adequate consideration, mainly it is because of lack scientific research on mountain flash flood processes [29,30].

Materials and Methods

In the current study, PRISMA methodology was used for reviewing flash flood related literature. Total 90 articles were recovered using a Google scholar database, after a brief appraisal, almost 60 articles has included in order to meet our objectives. Some articles were omitted after appraisal because they did not relate the objectives of the topic. In order to collect relevant article, various keywords have been used in web browsing. The author used various keywords for obtaining relevant articles; natural hazards, hydro meteorological hazards, types of flood, flash flood, flash forecasting, flash flood risk assessment, GIS and remote sensing for flash flood risk assessment and community based flood risk reduction, climate change, mountain hazards. The major journals included in this review paper were from various journals such as, Journal of hydrology, Journal of geometrics and planning, Journal of geographic information system, Environmental hazards, Environ earth sciences, Natural hazards, Journal of risk analysis, Mountain research and development, International journal of disaster risk science, Hydrological processes, Conferences proceedings, Journal of Hydrometeorology, ICIMOD printed/ electronic reports and manuals.

Flash Flood Hazard Assessment

Flash flood mainly occurs due to thunderstorms and torrential rainfalls. They are very dangerous due to peak discharge received within the six hours, events can occur in the small catchment area and steepness of the slope is also a main factor in the destruction [31]. Risk assessment is an essential component risk management process. In the literature, many approaches and methods have established for assess risk of hazards. According to Colombo et al. [32], Gouldby and Samuals flood risk assessment have four essential elements such as characterizing the area, assessing hazards, assessing vulnerability and assessing risk. According to ICIMOD, flash flood hazard assessment has two essential parts such as assigning the flash flood intensity and probability level of hazard scenario. In order to pinpoint the incidence of flash flooding, assessing the risk and implement real forecasting with useful lead time is necessary. Flash floods are also termed as short fuse events. Hydrological based studies, deal with the investigation and analysis of watershed factors that affect the flash flooding such as geometric properties of the river basin and water channel flow.

GIS and satellite remote sensing based approaches and methods offer a very decent display by combining, manipulating and analyzing the information for the assessment of probable flash risk extents very swiftly and more proficiently [33]. In the flash flood hazard assessment, evaluation of various parameters of river basin is very essential such stream ordering, basin area, drainage density, stream frequency, bifurcation ratio, basin relief, ruggedness number and texture ratio. Drainage network of basins or sub-basins can be extracted using GIS and remote sensing technology. GIS and remote sensing can be utilized to examine the exposure of the land and the vulnerability of the society such as hazard maps and monitor the potential hazardous areas [34].

Overland flow or surface runoff is the flowing water that occurs when intensive rainfall or any other sources of flows over the land surface. The runoff rate and velocity be determined by rainfall intensity, soil characteristics and the shape factor of the basin. Land cover and soil characteristics are the major components of basin runoff, which determines the infiltration overland flow. Basin Morphometry such as relief, slope, drainage density and frequency, vegetation and land use is key factors that can contribute to flash flood susceptibility. During storm high stream density and frequency basins can maximize the probabilities for water to accumulate into channels in a short time and rapid dissemination along the river network, particularly if the basin is characterized by steeply sloping ground Flash flood storms are associated with strong convective thunderstorm cells within a small areal range, generally less than 15 km in diameter. Flash floods are commonly occurring where rainfall patterns are heavily influenced by orography. Therefore, small dry valleys and basins are mostly affected of flash flood events. The morphometric analysis is also very important to estimate the flash flood potential [35].

ISDR [36], highlight the need of community based flood hazard maps, such as inundation areas, depth information, evacuation centers and routes, critical facilities, communication channels, evacuation criteria, emergency kits and many other items need for an evacuation in hazard maps. Community based flood/flash flood hazard mapping with relevant information is essential part of the disaster reduction strategy. There are many approaches and methods for determining the hazard intensity and probable scenarios in the catchment. The flash flood hazard intensity can be determined by the level of the anticipated flooding such first; population very close to the stream, second; close to the stream, Third; moderately close to the stream, fourth; away from the stream. Community based participatory mapping approach with GIS is very helpful for flash flood hazard assessment and also hazard modeling. A combination of high resolution satellite data and fitting together community based developed maps can be used for mitigation, preparedness, response and recovery phase of a disaster. PGIS based maps provide community boundaries, settlement areas (houses) and their local names, agricultural areas, important infrastructures, evacuation routes, identification of safe locations, and also some vulnerable zones can be identified [37].

Flash Flood Vulnerability Assessment

The term vulnerability has served in the field of risk reduction, hazard and disaster management as well as in the areas of global environmental changes such as climate change [38]. Vulnerability relates to the degree of threat to a particular population or the capacity of a system, which can suffer and respond harmfully during the occurrence of any kind of hazardous event [39]. The concept of vulnerability assessment involves with various levels of risk, such as physical, social and economic aspects. Physical vulnerability related with building, livelihood related infrastructures, agriculture, hospitals, roads, communications systems and many other functioning of a society. Social vulnerability includes women, children, mentally and physically handicapped persons, elderly persons, poor people, and refugees. Whereas, economic vulnerability assessment is related to risk of the hazard and its impact on economic assets and processes. It also associated to direct and indirect damages such as damages to livelihood and social infrastructures, replacement expenditures and crop damages, loss of production and income disparities [40].

The frequency and magnitude of floods or flash floods are raised over the last few decades and the leading amount of deaths and property damage than any other natural hazard. Flash flood brings various types of vulnerabilities of societies which can be seen as economic, social, structural, agricultural and psychological. Vulnerability is based on various components internal side vulnerability refer to coping capacity of people or systems, while the external side of vulnerability focused on external influence such exposure of people to the flash floods. Physical vulnerability can be valued by exposing elements at risk in a populated area, during the process of surface runoff or peak discharge of water, like flow depths, accumulation heights, flow velocities and pressures can damage exposed elements. The physical vulnerability can be measured by means of cost-effective approach through ratio analysis between loss and value of every individual element at risk [41].

The findings of disaster related researches suggest that socially vulnerable people have low level disaster preparedness, which due to a number of reasons such low income, low education and awareness, less livelihood opportunities, poor housing system, health issues, no emergency food supplies and most importantly less concentration likely receive from disaster officials. Social vulnerability to flash flood can be assessed by identifying various variable such as flood insurances exist, financial investment, budget allocations, floods experiences, level of economic development, coping capacity, and availability of budget and capacity of institutional organizations. The flood vulnerability index can be developed by designating categories of vulnerability such as very small, small, high and very high vulnerability to floods [42,43]. There are two important variables in social vulnerability assessment which mainly focused on local embeddedness and secondly socioeconomic characteristic. Local embeddedness includes; social capital, collective efficacy, trust and solidarity with people, associations with each other and the local social network. Second socioeconomic characteristic; which based on household structure, educational status, disabled persons, diversity in employments and its opportunities, dependency ratio, current financial status and properties, political status and access to resources. All these variables strongly influence the social vulnerability within a region.

UNISDR confined that vulnerability is not only devastation caused by disasters to the physical elements; it has also negative impacts on the socioeconomic condition of the communities. A disaster has far reaching effects on the livelihoods structure of the household, and sustainable livelihood becomes an essential part in coping measure adaptations. Flash flood related vulnerability assessment; financial capital is an important determinant of vulnerability of households, as most of the household have low income, no savings and insurance. The people living along the flood prone areas are highly vulnerable, such as countries like India, Bangladesh and Pakistan suffer from extreme poverty conditions. In rural areas livelihood strategies are based on growing crops, rearing of animals, use of natural resources and members' migration to other areas [44].

Flash Flood Risk Assessment and Management

Risk appraisal is key measure in the disaster management. In the literature various approaches and methods have been created to evaluate the threat hazard. The Source-Pathways-Receptor-Consequence (S-P-R-C) model is very convenient to understand the concept of hazard, vulnerability and risk as shown in Figure 1. For assessing the risks there must be hazard and vulnerability (source/initiator, pathway and receptors). Risk assessment has two main components such as hazard (related to source and pathways) and vulnerability (related to the receptor and consequences). Susceptibility can be stated in terms of

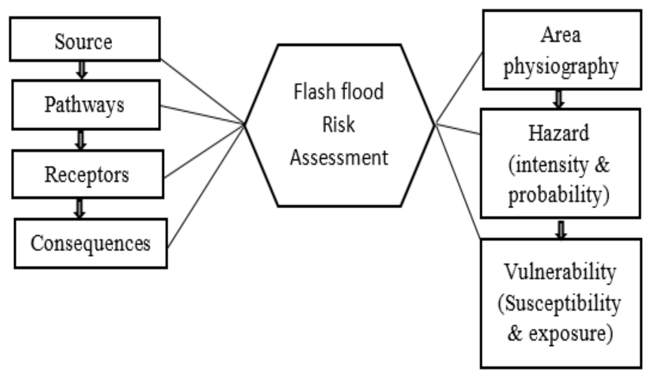

Figure 1: Flood risk analysis.

monetary and non-monetary items. For instance, high value elements can be included in the high vulnerability index, but risk quantification of some elements is very difficult such human life, ecological species and landscape. Exposure of elements denotes to the degree and extent of vulnerable features is probably to be affected when a flash flood happens. Exposure indicators are river morphology, proximity, elevation, frequency of flooding, intensity and velocity of stream water.

GIS and remotes sensing can offer influential tackles for risk assessment. Flash flood maps can be organized to outline susceptible areas prone to flooding. These maps are very useful for preparedness, decision making, response and recovery, and appropriate measures can take for impact reduction. GIS-based developed hazard maps are playing crucial role to minimize the harmful impacts of the hazard [45]. The assessment of flood risk and its geographic illustration is important for risk reduction measures at local level. Recently, strong focus is based on community participatory mapping and links to advanced spatial analysis. Identification of flash flood zones in a participatory manner has seen one of the effective ways to overcome the limited data to conduct GIS-based hazard delineation. Participatory GIS-based (PGIS) flood risk assessment have higher accuracy than a sophisticated risk delineation based on numerical and physical models. It is essential in a flood risk assessment to integrate and developed participatory GIS-based maps. These maps can effectively use at various levels in the disaster management process. Land use land cover change analysis is an essential parameter for flood risk assessment. Rapid and unplanned increase in land use in the watershed can increase flash hazard and vulnerability. GIS and remotes sensing techniques are very effective for integrating and assessing land use change within the flood prone areas. The assessment of land use, land cover change pattern at the watershed level is crucial to flash risk reduction [46].

Torrential and prolonged rainfalls, rapid snow melt, break up of ice jams, glacier lake outburst, landslide induces Lake Outburst and failure of man-made dams is the serious threats to mountain communities [47]. Concentrating on two categories of river flooding is very important; first static flooding occurs in areas with relatively plane topography, water rising slowly and flow velocity is normally very slow. In dynamic floods the water flow and velocity is so high and elements are at high risk due to rapid cutting and erosion as well as short lead-time which is not sufficient to activate the safety measures. The events of flash floods in mountainous areas have severe consequences mountain societies. The socioeconomic vulnerability assessment is an important component in disaster risk reduction [48].

UNISDR stress on disaster risk assessment, and disaster related risk is increasingly of global concern and increase vulnerabilities related to changes in demographic, technological and socioeconomic conditions, unplanned settlements, environmental degradation, stress on natural resources, climate change and development within high-risk zones. Mitigation measures are critical to reduce the effect of flash floods. Structural measures based on physical construction to reduce or avoid possible impact of natural hazards, such as check dams, embankment, barriers and evacuation shelters. Nonstructural measures not involving physical constructions that use training and awareness, policies and decisions, laws and risk education and research [49]. It should be noted that ecosystem friendly structural interventions are very essential in order to avoid negative consequence on riverine ecosystem. Climate change scenarios indicate that flash flood frequency and magnitude will be increased. There is need of effective approaches and methods for flash flood management under the changed circumstances. Therefore, integrate approaches and methods are essential for flash flood prone areas in order to minimize adverse effects [50-55].

Conclusion

This review paper discusses flash flood hazard vulnerability and risk assessment, including risk assessment approaches, methods, uncertainties and challenges. Flash flood is a hydrological event which develops within six hours of rainfall. It occurs within a short duration with a relatively high rainfall, high flow and rapid inundation in a dry area. Flash flood also termed as short fuse events, because of some distinctive characteristic that the process of forecasting is very different and challenging for this hazard than other type of hydro meteorological hazards. In meteorology, flash flood forecasting and lead time early warning still one of the challenging task [56-58]. Flash floods frequently occur in small catchments or in a small dry land, such areas often poorly gauged or ungauged. Hence, quality of remote sensed data is critical to flash flood forecasting. Mountainous areas are very sensitive to flash floods. Every year, in the HKH regions flash flood hazard has severe impacts to human society [59-61]. The main causes are thunderstorms, monsoon trough, rapid melting of snow and glacier lake outburst flooding. Increasing population growth and climate change impacts will be increased risk of more frequent and severe flash floods in the future. Therefore, flash flood hazard vulnerability and risk analysis need special attention in order to reduce severe losses.

Recently, in Europe and US the use of social science research approaches and methods has a significant contribution in flash flood risk reduction and warning. Engineers and physical scientist now recognized that their elucidations cannot be operated without engaging social science. The S-P-R-C model is favorable to understand the concept of hazard, vulnerability and risk. In assessing the risk, there must be hazard and vulnerability (source/initiator, pathway and receptors). The consequences depend on the exposure of the receptors to the hazard. Historical flash flood events are shown that deaths and property losses highly significant which are because of ineffective flash flood risk assessment approaches. There are four important steps in risk assessment; first step is based on characterization of area such as physical, social, geomorphological, hydro-meteorological, land use land cover and analysis of historical events. Secondly, determining the intensity of a flash flood (the strength of the flash flood) and developing alternative scenarios in the basin. Thirdly, vulnerability assessment which is based on physical vulnerability (susceptibility and exposure) and socioeconomic vulnerability (qualitative and quantitative indicators). Fourth, risk assessment is the combination of hazard intensity level, scenario, and total physical and socioeconomic vulnerability. Flash flood risk assessment is critical to management and planning for the future changes in frequency and magnitude such events.

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