



Urban flood vulnerability assessments: the case of Dire Dawa city, Ethiopia

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Received: 6 October 2018 / Accepted: 28 June 2019 / Published online: 9 July 2019
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Abstract

Dire Dawa city is identified as one of the most flood-affected cities in Ethiopia. Classifying village-level flood vulnerability using flood indicators is a new approach to Dire Dawa city. Analysis of different flood vulnerability factors underpins sustainable flood risk management and the application of Flood Vulnerability Index (FVI) approach is the hub of this study. Relevant data were collected from 110 households sampled from purposely selected 10 villages found in Dire Dawa city. The flood vulnerability index was used to compare, classify and rank villages in terms of their flood vulnerability levels. For this purpose, 24 sets of indicators which are strongly affecting the levels of flood vulnerability were assessed from social, economic and physical perspectives. The FVI of each village was computed with unequal method of weighting indicators. The findings of the study revealed that Dire Dawa city villages were experiencing varying levels of flood vulnerability. Accordingly, villages 05, 06, 07 and 09 were identified with high flood vulnerability level while villages 03, 04 and 08 and villages 01, 02 and extension village were identified with medium and low level of vulnerability, respectively. Interestingly, the findings of the study confirmed that social factors contributed much for flood vulnerability in Dire Dawa city. Hence, future urban flood risk planning and management endeavors in the city of Dire Dawa must be underpinned by proper utilization of the flood vulnerability map developed addressing social vulnerability component through both structural and non-structural urban flood risk management measures.

Keywords Dire Dawa · Ethiopia · Flood indices · Social vulnerability

1 Introduction

Flood is considered as the most recurring, widespread and harmful natural disaster causing devastating effects on the lives of millions of people and their properties, as well as infrastructure and the natural environment (EM-DAT 2015; Vojinović 2015; Douben

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2006). The frequency of flood occurrences is increasing all over the world and exposing large numbers of people to flood-induced hazards (Kha et al. 2011; Khan et al. 2011; Erena et al. 2018; Erena and Worku 2019, De Paola et al. 2018). The report of Intergovernmental Panel on Climate Change predicts that by 2100, climate change is expected to increase the number of vulnerable people in both developed and developing countries (IPCC 2015). From residential point of view, the effects of natural hazards like floods are more likely pronounced among the urban poor living in cities particularly in developing countries (Villordon and Gourbesville 2014; Balaban-Senol 2009).

The effect of flood vulnerability can be mitigated in different ways. Among this, vulnerability assessment and mapping is one. The notion of vulnerability is changing with time and made the definition complex (Grecu et al. 2017). However, following the document of Intergovernmental Panel on Climate Change (IPCC 2001) third assessment report, flood vulnerability is defined as a degree to which a natural or manmade system is exposed to, sensitive to and/or unable to cope with adverse effects of hazards. The report further defines exposure as the degree of extrinsic factors exposed to significant variations, sensitivity as the degree of intrinsic factors affected by dangerous phenomena likely to suffer harm and lack of coping mechanisms as limitations and incapacity of a system to adapt and reduce adverse effects of experienced hazards (Balica and Wright 2009; IPCC 2001).

Vulnerability describes the degree to which an area, people, physical structures or economic assets are exposed to loss, injury or damage caused by the impact of the hazard (Dandapat and Panda 2017). Hazard is a dangerous event that has a potential to cause loss of life, injury on human health and damage property and environment (UNISDR 2012). Risk is the expected loss of lives, property damaged and disrupted environment due particular events for a given area and reference period (UNISDR 2012). Risk is obtained by combining hazard, vulnerability and exposure. *Exposure* is defined as the number of assets such as “people, property, systems or other elements present in hazard zones that are thereby subject to potential losses” (UNISDR 2012). Vulnerability adversely affect people’s ability to prevent and mitigate hazardous events and it precede risks.

The extent and level of flood-induced damage depends on the characteristics of the affected people and infrastructure condition of the area (Choudhury et al. 2015; Kuhlicke et al. 2011). As a result a group of communities that have the same level of exposure to a natural hazard can experience varying levels of damage because of diverging capacities and abilities of groups to handle the impacts. The varying capacity of handling damage can be resulted from characteristics of a people and their situation that influence their capacity to predict, cope with, resist and recover from the impact of a natural hazard (Wisner 2004). Therefore, analyzing causes of vulnerability, who is vulnerable, why people have different levels of vulnerability is an integral part of flood risk managements (Oulahen 2016). Vulnerability is expected to happen under certain conditions of exposure, susceptibility and resilience (Fuchs et al. 2011). Indicators of vulnerability are important parameters to illustrate the characteristic of vulnerable groups from social, economic and physical perspectives.

Floods and droughts have been a prominent hazard over Africa in general and Ethiopia in particular. For instance, in sub-Saharan Africa, the cumulative effect of floods and droughts together were responsible for around 80% of deaths related disasters and 70% of economic losses (Ndaruzaniye et al. 2010; De Paola et al. 2014). Compared to drought hazards that have got detailed and better coverage, information regarding the intensity and scale of urban settlements’ exposure to flood risks in African cities are still limited (Adelekan 2011; Nkwunonwo et al. 2015). Sadly, flooding and flood-induced vulnerabilities have been undermined and neglected, and only very little attention was given to Ethiopia.

Currently, the impacts of floods have gained importance because of the increasing amount of people, economic activities and ecosystems that are impacted by its adverse effects (Greco et al. 2017; Erena and Worku 2018). Historical information and recently recorded documents show that Dire Dawa city is much affected by flood risk than other disasters. As a result, urban flooding risk remained to be the most devastating natural disaster affecting more people and causing property damage than any other kind of disasters.

Developing specific local urban flooding vulnerability indices is the hub of developing sustainable flood risk management as the development of such indices immensely contributes for better understanding of flood hazards, flood vulnerability assessment and flood risk perceptions in a given locality. The objective of this study is to analyze flood vulnerability in Dire Dawa city based on social, economic and physical factors underpinning vulnerability in the study area. In a nutshell, the findings of the study are strongly believed to improve urban flooding risk management in the city.

2 Methodology

2.1 Description of the study area

This study was conducted in Dire Dawa city, Ethiopia. The city is located in the Eastern part of the country and serves as the transit city between Ethiopia and Djibouti. Geographically, the city is found between 9°25'N and 9°45'N latitude and 41°40'E and 42°50'E longitude. The city is found in the dawn stream of surrounding mountains (Fig. 1). The elevation of the city ranges from 1000 to 1600 m above sea level, while the flood inducing mountains

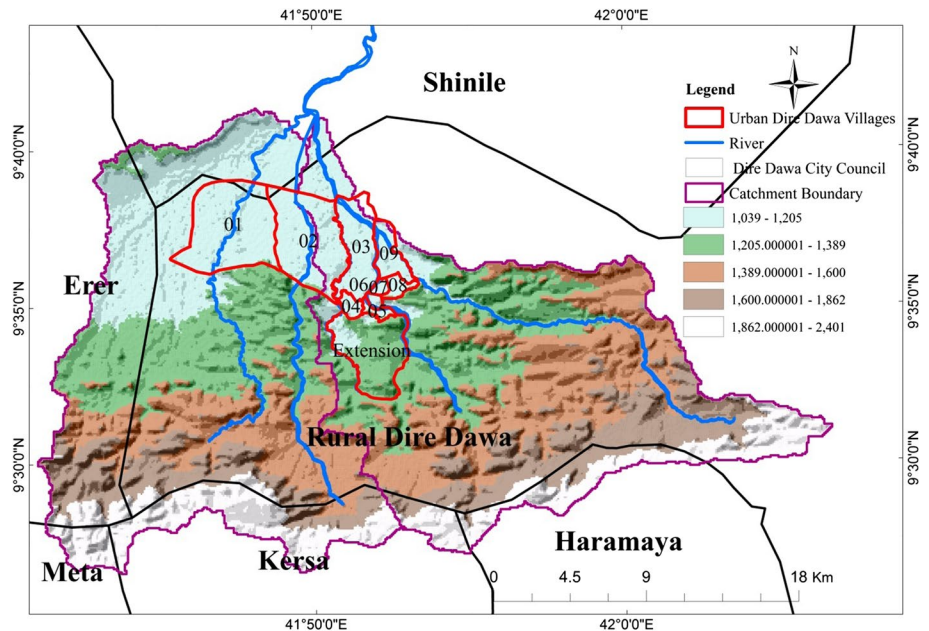


Fig. 1 Map of the study area watershed

of the upper catchment reaches up to 2400 m above sea level. Dangago is the highest mountain located in the upper part of the watershed. The city is dissected by five large and small streams (Dechatu, Goro, MelkaJabdu, Laga Hare and Butuji rivers). All rivers draining the city made their origin from the surrounding highlands of Kersa, Haramaya and Meta districts (Fig. 1). The city is bordered in the North, East and West by Somali Regional State and in the South and South West by Oromia Regional State. The hydrological information of the watershed such as rivers, slope, landform and elevation that determines flow directions extracted from DEM are also presented in Fig. 1.

The total population of Dire Dawa city is estimated to be 400,000 people (IDP 2006). Moreover, according to projected report of 2007 CSA, in 2013 Dire Dawa city population was estimated to be 466,000 with annual growth rate of 2.7% (CSA 2013). Because of its tropical location, Dire Dawa is experiencing bimodal distribution of seasonal rainfall with peak rainfall in April and August months. By virtue of being surrounded by various mountains and drained by the tributaries of several major rivers, the city has always been subjected to periodic flooding. The study was conducted among 10 urban villages of Dire Dawa city where the people are under the threat of flood hazards.

2.2 Study population sampling

The analysis and assessment of vulnerability was conducted with reference to Dire Dawa city villages (locally referred to as kebele). Village is the lowest administrative unit of Ethiopia. This study was conducted in 10 villages (01, 02, 03, 04, 05, 06, 07, 08, 09, and extension). Particular emphasis was given to villages experiencing high flood area due to their proximity to rivers specifically to villages located close to Dechatu river. To get reliable information regarding flood vulnerabilities, survey was conducted among 60% of the selected villages (03, 04, 05, 06, 07, 08 and 09) which has been reported for their flood proneness. Since villages with low level of flood risks are far from the Dechatu river, excluding these villages has no effect on the results of the study. The sample villages were selected purposively based on the information obtained from elders, municipality reports and proximity to the most floods inducing river and further confirmed from Environmental office departments of the city, which is highly involved in flood management and adaptation strategies. Sample households from each purposively selected village were selected using systematic random sampling. Accordingly, the first household of each village were selected randomly and the subsequent households were selected at a fixed interval of every 10th households. From 1163 households that fall inside flood hazard zones, a sample size of 10% (110) households were picked for household survey sampling. Finally, data were collected through questionnaire-based survey from one hundred and ten (110) households.

2.3 Selection of flood vulnerability indicators

The indicator-based flood vulnerability assessment has been acknowledged as the most appropriate for evaluating population groups at all levels (UNISDR 2008; Salami et al. 2017). However, the real conditions that determine flood vulnerability are site-specific, localized and hazard-dependent. As a result, the numbers of widely accepted indicator are very limited. To practically assess vulnerability of specific study area, identification of variables that made a specific people vulnerable to flood hazard and how these variables make an effect is a primary activity of this study. Therefore, the selection of flood vulnerability indicators of Dire Dawa city was governed by availability of data, personal observation and

results of previous research works. Accordingly, 24 indicators for which data were available and which best fits to the local vulnerability conditions were combined into the composite vulnerability index (Table 1).

2.4 Data sources

This study employed the collection of both primary and secondary data from primary and secondary data sources. Field survey was employed to collect primary data. The information was collected through questionnaire-based interviews at household levels and personal observation. The questionnaires were designed based on selected indicators. The secondary data were collected from various secondary sources through document and literature review. The data sources for each indicator are summarized hereunder (Table 1).

2.5 Data analysis

The identified flood indicators were classified as exposure, susceptibility and resilience and arranged in a manner convenient to compute flood vulnerability index (FVI). The FVI were

Table 1 Selected flood vulnerability indicators of Dire Dawa city with respective data sources

| No | Indicator | Data sources | Abbreviation |
|----|---------------------------------------|--|--------------|
| 1 | Flood frequency | Survey | FF |
| 2 | Flood duration | Survey | D |
| 3 | Flood water depth | Erena et al. (2018) | FD |
| 4 | Flood velocity | Erena et al. (2018) | V |
| 5 | Village proximity to the river | Building map of Dire Dawa city and Erena et al. (2018) | PR |
| 6 | Population density | CSA | PD |
| 7 | Population in flood area | Survey | PFA |
| 8 | Emergency services | Survey and government reports | ES |
| 9 | Early warning | Survey | EW |
| 10 | Past flood experience | Survey | PE |
| 11 | Houses with poor materials | Survey | HPM |
| 12 | Old people 65+ | CSA (2013) | OP |
| 13 | Female-headed household | CSA (2013) | FHH |
| 14 | Education level | Survey and CSA (2013) | EL |
| 15 | Family size | CSA (2013) | FS |
| 16 | Dikes–levees | Survey | D–L |
| 17 | Presence of flood protection measures | Survey | PFM |
| 18 | Evacuation route | Survey | ER |
| 19 | Insurance | Survey | Fi |
| 20 | Communication network | Survey | CN |
| 21 | Slope | DEM | S |
| 22 | Cultural heritage | CSA and building map of Dire Dawa city | CH |
| 23 | People access to sanitation | Survey | PAS |
| 24 | Industries | Survey and building map | IND |

computed based on unequal method of FVI weighting method developed by Iyengar and Sudarshan (1982). Finally, an accurate village level flood vulnerability maps were created using ArcGIS software.

2.5.1 Data arrangements and normalization of indicators

The data collected from various sources were arranged in the form of a rectangular matrix with rows representing villages and columns representing indicators. Each indicator is in different units and scale of measurements. The UNDP's Human Development Index (HDI) method of normalization was adopted to obtain the indicators free of units and scales (UNDP 2006). Furthermore, normalization was adopted to standardize the value of each indicator so that they all lie between 0 and 1. Finally, the index of normalized score was constructed by using unequal weights to all indicators. Before normalization, the indicators were arranged in relation to functional relationship with vulnerability. Indicators can have two type of functional relationship with vulnerability. Some have positive relationship and increase the level of vulnerability. The others have negative relationship and decrease the level of the vulnerability.

Many authors agree that vulnerability is a function of exposure, susceptibility and resilience (Cardona 2013; Smit and Wandel 2006; Balica et al. 2012; Balica 2007; IPCC 2001). Therefore, the general formula for computation of FVI demands categorizing the indicators as [exposure (E), susceptibility (S) and resilience (R)]. Exposure represents values that are present at the location where floods can occur. These values can be human being, properties, infrastructure, cultural heritage, agricultural fields and the like. Though there are different working definitions of exposure, the theme concept of exposure is defined as “the predisposition of a system or its elements to be affected by a flood due to its location in the same area” (Balica 2007; Fuchs et al. 2011; Veenstra 2013). Susceptibility is described as the potential of a system to be harmed by a hazardous event such as flooding, caused due to fragility, relative social or economic weaknesses or disadvantageous conditions (Cardona 2013; Balica 2007; Veenstra 2013). Resilience is the ability of a system to adjust to changes or threats, to avoid, mitigate or absorb potential damage, to cope with the consequences without loss or to even take advantage of opportunities (IPCC 2001; Pelling 2012; Veenstra 2013).

Both exposure and susceptibility have a positive influence on vulnerability, and resilience has a negative influence on vulnerability. For the indicators that have a positive relationship, the normalization was done using the formula given below:

$$Y_{ij} = \frac{X_{ij} - \text{Mini}(X_{ij})}{\text{Maxi}(X_{ij}) - \text{Mini}(X_{ij})} \quad (1)$$

where Y_{ij} is normalized value.

X_{ij} is the value of the indicator j corresponding to village i .

After normalization, the score of these indicators made to lie between 0 and 1. The value 1 is corresponding to that village with maximum value and 0 is corresponding to the village with minimum value. In this condition, the higher the values of the indicator correspond to the higher the vulnerability and vice versa. The summation of the two factors (exposure and susceptibility) that have positive relationship with vulnerability yields the higher vulnerability index.

On the contrary, indicators falling under resilience category have a negative relationship with vulnerability. For the indicators with negative function relationship with vulnerability, the normalized score is computed using the formula given below:

$$Y_{ij} = \frac{\text{Maxi}(X_{ij}) - X_{ij}}{\text{Maxi}(X_{ij}) - \text{Mini}(X_{ij})} \tag{2}$$

It is obvious that the indicators falling under resilience category have negative relationship with vulnerability. As a result, the values of these indicators are expected to yield negative result showing that these indicators are decreasing the level of vulnerability. However, the application of Eq. (2) was used to avoid the negative sign on the values of the normalized scores. Resilience can have a positive effect on vulnerability if it is defined as lack of resilience (Veenstra 2013). Hence, the application of Eq. (2) was used to display data as lack of resilience and to avoid the negative sign on the values of the normalized scores. Lack of resilience was used, because it eases the process of FVI assessment. This results in two possible equations, one with a summation and one with a product.

According to Villagrán de León (2006) and Wannasai et al. (2013) FVI is computed by the formula:

$$\text{FVI} = \frac{\text{Exposure} * \text{Susceptibility}}{\text{Resilience}} \tag{3}$$

This equation can be changed if resilience is presented as 1/lack of resilience.

$$\text{FVI} = \text{Exposure} \times \text{Susceptibility} \times \text{Lack of resilience} \tag{4}$$

According to Balica (2007), the equation for vulnerability assessment at urban sectors with the same three factors is presented as:

$$\text{FVI} = \text{Exposure} + \text{Susceptibility} - \text{Resilience} \tag{5}$$

The Seventh Framework Programme (2011) defined the FVI as follows, with the factor resilience defined as 1/lack of resilience:

$$\text{FVI} = \text{Exposure} + \text{Susceptibility} + \text{lack of coping capacity} \tag{6}$$

Based on the equation used, the indicators could have different format, while the result of the FVI is the same. For the ease computation of FVI, the data of this study were arranged on the basis of equation developed by Seventh Framework Programme. This equation helps to employ the summation relationship between all vulnerability indicators. Therefore, the FVI equation used in this research follows the formula presented under (Eq. 6).

Vulnerability is a multidimensional process which includes four components of social, economic, environmental and physical variables (Huang et al. 2012). So flood vulnerability is different for people in different condition (Pandey et al. 2014). This means each villages experience different levels of social, economic and physical vulnerabilities. Flood Vulnerability Index (FVI) for all vulnerability components was computed using the formula given below:

Flood Vulnerability Indices for Social component

$$\text{FVI} = \frac{\text{PD, PFA, CH, OP, PE, EL, PAS, FHH, FS, CN}}{\text{EW, ER, ES}} \tag{7}$$

Flood Vulnerability Indices for Economic component

$$\text{FVI} = \frac{\text{IND, PR, HPM}}{\text{Fi}} \tag{8}$$

Flood Vulnerability Indices for Physical component

$$FVI = \frac{V, D, FD, S, PFM, FF}{D - L} \tag{9}$$

The equation presented shows the indicators as a ratio to omit the units. Each indicator has its own range of values between 0 and 1. Finally, these values are summed up to generate the intended index values.

Note that during the computation of FVI, the lacks of resilience indicators under all components were rearranged on the basis convenient to apply summation equations. Finally, based on the arrangement of the data the total FVI of each village is computed as:

$$FVI \text{ total} = (E + S + R \text{ social} + E + S + R \text{ Economic} + E + S + R \text{ physical}). \tag{10}$$

The overall methodology of the study is presented under Fig. 2.

2.5.2 Constructing vulnerability index with unequal method of weighting

Weighting is a critical activity that determines the relative impacts of indicators applied in the process (Handayani et al. 2017). There are two ways of weighting flood vulnerability indicators. These are equal weighting and unequal weighting methods. Many vulnerability scholars advocate the use of equal weights for every indicator (Kha et al. 2011). These scholars prefer this method because of either assuming equality of the indicators or lack of better weighing method (Wannasai et al. 2013). In normal circumstances, all indicators cannot equally influence the flood vulnerability of an area. Therefore, this study employed unequal weighting method of vulnerability indicators developed by Iyengar and Sudarshan (1982). This methodology is statistically sound and well suited for the development of composite index of vulnerability to flood hazards (Salami et al. 2017).

According to this methodology, the data were arranged as M representing villages, K indicators of vulnerability and $x_{ij}, i = 1, 2, \dots, M; j = 1, 2, \dots, K$ are the normalized scores (Salami et al. 2017). The level of i th zone, \bar{y}_i , is assumed to be a linear sum of x_{ij} as

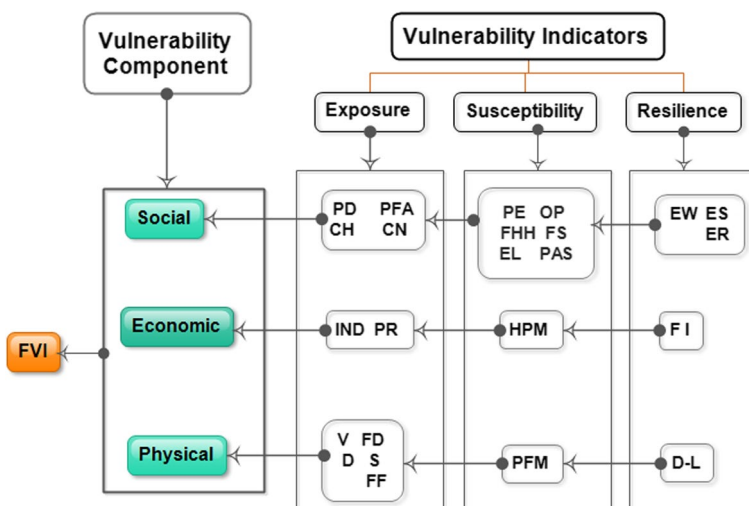


Fig. 2 Flowchart showing flood vulnerability component and indicators of Dire Dawa city

$$\bar{y}_i = \sum_{j=i}^k W_j X_{ij} \tag{11}$$

where $s w'$ ($0 < W < 1$ and $\sum_{j=i}^k W_j = 1$) is the weighting

According to Iyengar and Sudarshan’s method, the weightings are assumed to vary inversely of variance over the regions. Hence, the weights of W_j are computed by the formula:

$$W_j = C / \sqrt{\text{var}_i(X_{ij})} \tag{12}$$

where C is a normalizing constant

$$C = \left[\sum_{j=1}^{j=k} 1 / \sqrt{\text{var}_i(X_{ij})} \right]^{-1} \tag{13}$$

This method was chosen to ensure that large variation in any one of the indicator not highly dominate the influence of the other indicators and do not distort the inter-village comparisons. In this case, the computed value of vulnerability index lies between 0 and 1, with 1 corresponding to maximum vulnerability and 0 indicating no vulnerability at all. Finally, applying Eqs. (6–10) the computed FVI of each village is ranked according to their index value of vulnerability developed by Balica (2007).

Based on vulnerability index value, the vulnerability map of Dire Dawa city was developed in GIS environment with graduate color red indicating villages with high vulnerability to floods and green color representing low vulnerability to floods (Table 2).

3 Result

Based on combined effects of climate change and anthropogenic factors, Dire Dawa city has been experiencing flood-induced risk. Hence, vulnerability assessment of the city is found to be reliable process for identifying, categorizing, quantifying and ranking the vulnerabilities of the villages, irrespective of their sizes.

3.1 Indicators functional relationship with vulnerability

The functional relationship of indicators and vulnerability determines the level of vulnerability at each village. Furthermore, indicators-vulnerability functional relationship helps

Table 2 Flood vulnerability ranking (Balica 2007)

| Index value | Descriptions |
|-------------|-----------------------------------|
| <0.01 | Very low vulnerability to floods |
| 0.01–0.25 | Low vulnerability to floods |
| 0.25–0.50 | Medium vulnerability to floods |
| 0.50–0.75 | High vulnerability to floods |
| 0.75–1 | Very high vulnerability to floods |

to guide the way data is arranged for normalization and calculation of FVI. The indicator-vulnerability functional relationships of the indicators were developed based on previous study results, theoretical assumptions and sampled population responses. The 24 selected vulnerability indicators of Dire Dawa city and their relationship with vulnerability are presented under Table 3.

3.2 Normalization of indicators

Each indicator was measured in different units and scale of measurements. Before computing the FVI, the outputs of each identified indicators need to be converted into a normalized dimensionless number values between 0 and 1. The raw data of each the identified 24 indicators are presented under Table 4.

Normalization demands functional relationship arrangements of indicators with vulnerability. Before normalization, the index values should have positive correlation with vulnerability (Žurovec et al. 2017). This was used to use summation method of FVI for all vulnerability factors of vulnerability (Exposure, susceptibility and Resilience). Under this condition, the higher value means the higher vulnerability and vice versa. Normalization is used to make the indicators dimensionless and comparable. The development of dimensionless number was derived using the predefined minimum and maximum values from the spatial elements under consideration. For indicators with a positive relationship with Vulnerability, Eq. (1) has been applied for normalization. For indicators with a negative relationship with vulnerability, Eq. (2) was applied for normalization. The normalized value of Dire Dawa city vulnerability indicators are summarized under Table 5.

3.3 Summarizing and weighting indicators

Following the normalization process, indicators were summarized into composite and weights were assigned based on their degree of influence on vulnerability. The standard deviations of the normalized scores across the villages, their reciprocals and the weights for each indicator were computed by the formula given under Eqs. (11–13). In the literature, several methods were used to give weight to indicators either equal weights (simple average of the scores and Patnaik and Narain methods) or unequal weights (expert judgment and Iyengar and Sudarshan's methods) or multivariate statistical techniques (principal components and cluster analysis method) (Kissi et al. 2015). The weight of individual indicator was obtained by multiplying the weight of each indicator to their respective normalized score of indicators. The individual weights of each flood indicator are summarized under Table 6.

This study employed an unequal way of Iyengar and Sudarshan's weighting method to all indicators. Accordingly, each indicator has got a unique value of weight that determines its peculiar level of influence over the vulnerability of the study area. The final weighted vulnerability values of each indicator are summarized under Table 7.

3.4 Computation of flood vulnerability index (FVI)

The study area FVI was computed on the basis of social, economic and physical perspectives. The social FVI were computed on the basis of 13 (PD, PFA, CH, CN, PE, EL, FHH, OP, FS, PAS, EW, ES, ER) indicators that explain how social entities are exposed and

Table 3 Flood vulnerability indicators of Dire Dawa city and their functional relationship

| No | Indicators | Abb | Factors | Unit | Relationship with vulnerability |
|----|---------------------------------------|-----|----------------|-------------------|---|
| 1 | Flood frequency | FF | Exposure | Year | The higher flood events, the higher the vulnerability (+) |
| 2 | Flood duration | FD | Exposure | Days | The higher flood duration, the higher vulnerability (+) |
| 3 | Flood water depth | D | Exposure | m | The higher flood depth, the higher vulnerability (+) |
| 4 | Flow velocity | V | Exposure | m/s | The higher the velocity, the more the vulnerability (+) |
| 5 | Proximity to the water | PR | Exposure | m | The closer the village to the river, the higher vulnerability (+) |
| 6 | Population density | PD | Exposure | P/Km ² | The higher the density, the more the vulnerability (+) |
| 7 | Population in flood area | PFA | Exposure | # | The higher population in flood zone, the higher the vulnerability (+) |
| 8 | Emergency services | ES | Exposure | % | The higher % of people helped during flood, the lower the vulnerability (-) |
| 9 | Early warning | WS | Resilience | % | The more warning system, the lower vulnerability (-) |
| 10 | Past flood experience | PE | Resilience | % | The lower % of past experience, the higher the vulnerability (-) |
| 11 | Houses with poor materials | HPM | Susceptibility | # | Higher number of houses with poor material, the higher vulnerability (+) |
| 12 | Old people 65+ | OP | Susceptibility | % | The higher the % of elderly, the higher the vulnerability (+) |
| 13 | Female-headed household | FHH | Susceptibility | % | The higher % of female-headed household, the higher vulnerability (+) |
| 14 | Education level | EL | Susceptibility | % | The higher % of education level, the lower the vulnerability (-) |
| 15 | Family size | FS | Susceptibility | % | The higher % of family size, the higher the vulnerability (+) |
| 16 | Dikes–levees | D–L | Resilience | % | The higher length of protection measure, the lower the vulnerability (-) |
| 17 | Evacuation route | ER | Resilience | % | The higher % of evacuation route, the lower the vulnerability (-) |
| 18 | Presence of flood protection measures | PFM | Resilience | % | The higher flood protection measures, the lower vulnerability (-) |
| 19 | Flood insurance | FI | Resilience | # | The higher # of insured companies, the lower the vulnerability (-) |
| 20 | Communication network | CN | Resilience | # | The higher # of people get information, the lower vulnerability (-) |
| 21 | Slope | S | Resilience | % | The higher the slope, the higher vulnerability (-) |
| 22 | Cultural heritage | CH | Exposure | # | The higher # of historical buildings, the more vulnerability (+) |
| 23 | People access to sanitation | PAS | Exposure | % | The lower % of access to sanitation the higher the vulnerability (-) |
| 24 | Industries | IND | Susceptibility | # | Higher # of industries, higher vulnerability (+) |

Table 4 Raw data sets of 24 flood vulnerability indicators of Dire Dawa city

| Indicator | Villages | | | | | | | | | |
|-------------|----------|------|------|--------|--------|--------|--------|--------|------|-----------|
| | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | Extension |
| PD (%) | 474 | 2049 | 1685 | 14,031 | 16,307 | 23,816 | 28,753 | 18,524 | 8924 | 365 |
| PFA (#) | 0 | 0 | 620 | 4 | 792 | 2650 | 938 | 0 | 710 | 18 |
| CH (#) | 2 | 1 | 26 | 0 | 1 | 3 | 1 | 2 | 2 | 0 |
| IND (#) | 1 | 6 | 3 | 2 | 1 | 1 | 0 | 0 | 5 | 1 |
| PR (hh#) | 0 | 0 | 155 | 1 | 198 | 530 | 134 | 0 | 142 | 3 |
| S (%) | 2.91 | 2.95 | 2.87 | 7.4 | 15.8 | 9.6 | 3.97 | 16.5 | 3.5 | 11.5 |
| V (m/s) | 3.1 | 1.5 | 7 | 1.5 | 5.4 | 6.5 | 6.5 | 0 | 5.4 | 6.5 |
| D (m) | 2.3 | 2.3 | 3.7 | 1 | 2.3 | 3.3 | 3.3 | 0 | 3.7 | 4.2 |
| FD (h) | 3 | 1 | 4 | 2 | 12 | 12 | 12 | 3 | 12 | 1 |
| PE | 15 | 7 | 16 | 18 | 40 | 15 | 38 | 20 | 32 | 12 |
| AS (%) | 35 | 30 | 20 | 40 | 18 | 19 | 19 | 35 | 22 | 45 |
| OP (%) | 18 | 16 | 25 | 20 | 47 | 45 | 38 | 20 | 29 | 15 |
| FHH (%) | 22 | 20 | 32 | 25 | 38 | 60 | 54 | 26 | 42 | 18 |
| EL (% illi) | 25 | 20 | 32 | 30 | 29 | 35 | 46 | 25 | 71 | 19 |
| FS (#) | 4 | 4 | 4 | 4 | 6 | 5 | 5 | 5 | 6 | 4 |
| CN (#) | 2 | 2 | 4 | 3 | 7 | 4 | 5 | 3 | 5 | 2 |
| HPM (%) | 8 | 10 | 9 | 8 | 13 | 10 | 15 | 9 | 70 | 2 |
| FF (year) | 5 | 10 | 2 | 5 | 1 | 1 | 1 | 5 | 1 | 10 |
| ES (%) | 10 | 6 | 18 | 15 | 20 | 20 | 20 | 12 | 20 | 7 |
| WS (%) | 74 | 55 | 80 | 75 | 90 | 92 | 95 | 82 | 77 | 65 |
| ER (%) | 30 | 45 | 18 | 20 | 15 | 12 | 10 | 20 | 10 | 35 |
| PFM | 20 | 15 | 55 | 50 | 65 | 70 | 65 | 20 | 60 | 15 |
| D–L (km) | 0 | 0 | 2 | 0.2 | 0.5 | 0.8 | 1 | 1- | 1.5 | 0 |
| FI | 1 | 6 | 3 | 2 | 1 | 1 | 0 | 0 | 5 | 1 |
| PR (hh#) | 0 | 0 | 155 | 1 | 198 | 530 | 134 | 0 | 142 | 3 |

susceptible to flood events. On the basis of social flood vulnerability, the villages fall under two flood vulnerability zones identified by (Balica 2007). Accordingly, six villages were falling under low vulnerability to floods (0.01–0.25) while four villages were falling under medium vulnerability to floods (0.25–0.5). The results of social vulnerability indicate that village 05, 06, 07 and 09 experiences medium vulnerability to social components (Table 8).

In the same way (4) indicators were used to explain the determinant of communities' vulnerability to economic flood disaster. The composite vulnerability index of economic component was calculated for each village. By considering the composite index of exposure factors, the villages qualify two classes of flood vulnerability interpretation developed by (Balica 2007). Accordingly, village 08 falls under very low vulnerability to floods. The rest all were classified under low vulnerability to floods (Table 9).

The physical component of FVI considered indicators which evaluate the sensitivity of physical factors to flood events. Eleven (7) indicators were used to explain the determinants of communities' Vulnerability to physical flood disasters. Considering the composite index of vulnerability to physical component, all villages fall under small vulnerability to flood events (Table 10).

Table 5 Normalized data sets of 24 flood vulnerability indicators of Dire Dawa city

| Indicator | Villages | | | | | | | | | |
|-------------|----------|------|------|------|------|------|------|------|------|-----------|
| | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | Extension |
| PD (%) | 0.00 | 0.06 | 0.05 | 0.50 | 0.60 | 0.80 | 1.00 | 0.60 | 0.30 | 0.00 |
| PFA (#) | 0.00 | 0.00 | 0.20 | 0.00 | 0.30 | 1.00 | 0.40 | 0.00 | 0.30 | 0.01 |
| CH (#) | 0.08 | 0.04 | 1.00 | 0.00 | 0.04 | 0.10 | 0.04 | 0.08 | 0.08 | 0.00 |
| IND (#) | 0.20 | 1.00 | 0.50 | 0.30 | 0.20 | 0.20 | 0.00 | 0.00 | 0.80 | 0.20 |
| S (%) | 0.00 | 0.01 | 0.00 | 0.30 | 0.95 | 0.50 | 0.08 | 1.00 | 0.05 | 0.60 |
| V (m/s) | 0.40 | 0.20 | 1.00 | 0.20 | 0.80 | 0.90 | 0.90 | 0.00 | 0.80 | 0.90 |
| D (m) | 0.50 | 0.50 | 0.90 | 0.20 | 0.50 | 0.80 | 0.80 | 0.00 | 0.90 | 1.00 |
| FD (h) | 0.20 | 0.00 | 0.25 | 0.08 | 1.00 | 1.00 | 1.00 | 0.20 | 1.00 | 0.00 |
| PE | 0.20 | 0.00 | 0.30 | 0.30 | 1.00 | 0.20 | 0.90 | 0.40 | 0.80 | 0.20 |
| PAS (%) | 0.60 | 0.40 | 0.10 | 0.80 | 0.00 | 0.04 | 0.04 | 0.60 | 0.10 | 1.00 |
| OP (%) | 0.10 | 0.03 | 0.30 | 0.20 | 1.00 | 0.90 | 0.70 | 0.20 | 0.40 | 0.00 |
| FHH (%) | 0.10 | 0.05 | 0.30 | 0.20 | 0.50 | 1.00 | 0.90 | 0.20 | 0.60 | 0.00 |
| EL (% illi) | 0.10 | 0.02 | 0.25 | 0.20 | 0.20 | 0.30 | 0.50 | 0.10 | 1.00 | 0.00 |
| FS (#) | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.50 | 0.50 | 0.50 | 1.00 | 0.00 |
| CN (#) | 0.00 | 0.00 | 0.40 | 0.20 | 1.00 | 0.40 | 0.60 | 0.20 | 0.60 | 0.00 |
| HPM (%) | 0.09 | 0.10 | 0.10 | 0.09 | 0.20 | 0.10 | 0.20 | 0.10 | 1.00 | 0.00 |
| FF (year) | 0.50 | 0.00 | 0.90 | 0.50 | 1.00 | 1.00 | 1.00 | 0.50 | 1.00 | 0.00 |
| ES (%) | 0.30 | 0.00 | 0.90 | 0.60 | 1.00 | 1.00 | 1.00 | 0.40 | 1.00 | 0.10 |
| WS (%) | 0.50 | 0.00 | 0.60 | 0.50 | 0.90 | 0.90 | 1.00 | 0.70 | 0.60 | 0.30 |
| ER (%) | 0.60 | 1.00 | 0.20 | 0.30 | 0.10 | 0.06 | 0.00 | 0.30 | 0.00 | 0.70 |
| PFM | 0.10 | 0.00 | 0.70 | 0.60 | 0.90 | 1.00 | 0.90 | 0.10 | 0.80 | 0.00 |
| D–L (km) | 0.00 | 0.00 | 1.00 | 0.10 | 0.25 | 0.40 | 0.50 | 0.50 | 0.75 | 0.00 |
| FI | 0.20 | 1.00 | 0.50 | 0.30 | 0.20 | 0.20 | 0.00 | 0.00 | 0.80 | 0.20 |
| PR | 0.00 | 0.00 | 0.30 | 0.00 | 0.40 | 1.00 | 0.25 | 0.00 | 0.27 | 0.01 |

The overall index of vulnerability was obtained by summing up the composite FVI for economic, social and physical components. The result of total FVI of the city shows that three villages (05, 06, 07 and 09) had the highest vulnerability index, while villages (03, 04 and 08) and village (01, 02, extension) had the low and medium vulnerability index, respectively. The spatial distribution of overall flood vulnerability results for 10 villages of Dire Dawa city is depicted under Fig. 3, with green corresponding to regions of comparatively lower vulnerability, yellow and red color shaded region representing medium and high vulnerability to floods, respectively.

4 Discussion

The analysis and assessment of FVI of Dire Dawa city visually identified villages which are comparatively high, moderate and less vulnerable villages across the city on the basis of three vulnerability components social, economic and physical perspectives. The overall Flood Vulnerability Index (FVI) of the ten villages shows that village 09 followed by village (06, 05 and 07), respectively, are the most vulnerable villages to flood events. On the

Table 6 Variance, standard deviation and weight of vulnerability indicator

| Village | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | Ex. | Mean | Var. | St. dev. | 1/st. de | Weight |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|------|----------|----------|--------|
| PD (%) | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 | 0.03 | 0.04 | 0.02 | 0.01 | 0.00 | 0.4 | 0.1 | 0.4 | 2.8 | 0.04 |
| PFA (#) | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.05 | 0.02 | 0.00 | 0.01 | 0.00 | 0.22 | 0.10 | 0.31 | 3.18 | 0.05 |
| CH (#) | 0.004 | 0.002 | 0.048 | 0.000 | 0.002 | 0.005 | 0.002 | 0.004 | 0.004 | 0.000 | 0.15 | 0.09 | 0.30 | 3.31 | 0.05 |
| IND (#) | 0.01 | 0.04 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.04 | 0.01 | 0.34 | 0.11 | 0.33 | 3.02 | 0.04 |
| S (%) | 0.00 | 0.00 | 0.00 | 0.01 | 0.03 | 0.02 | 0.00 | 0.04 | 0.00 | 0.02 | 0.35 | 0.15 | 0.39 | 2.54 | 0.04 |
| V (m/s) | 0.02 | 0.01 | 0.04 | 0.01 | 0.03 | 0.04 | 0.04 | 0.00 | 0.03 | 0.04 | 0.61 | 0.14 | 0.37 | 2.71 | 0.04 |
| D (m) | 0.02 | 0.02 | 0.04 | 0.01 | 0.02 | 0.04 | 0.04 | 0.00 | 0.04 | 0.04 | 0.61 | 0.11 | 0.33 | 3.05 | 0.04 |
| FD (h) | 0.01 | 0.00 | 0.01 | 0.00 | 0.03 | 0.03 | 0.03 | 0.01 | 0.03 | 0.00 | 0.47 | 0.21 | 0.46 | 2.17 | 0.03 |
| PE | 0.01 | 0.00 | 0.01 | 0.01 | 0.04 | 0.01 | 0.04 | 0.02 | 0.03 | 0.01 | 0.43 | 0.12 | 0.34 | 2.91 | 0.04 |
| PAS (%) | 0.024 | 0.016 | 0.004 | 0.032 | 0.000 | 0.002 | 0.002 | 0.024 | 0.004 | 0.040 | 0.37 | 0.13 | 0.36 | 2.75 | 0.04 |
| OP (%) | 0.00 | 0.00 | 0.01 | 0.01 | 0.04 | 0.04 | 0.03 | 0.01 | 0.02 | 0.00 | 0.38 | 0.13 | 0.36 | 2.77 | 0.04 |
| FHH (%) | 0.004 | 0.002 | 0.012 | 0.008 | 0.021 | 0.041 | 0.037 | 0.008 | 0.025 | 0.000 | 0.39 | 0.12 | 0.35 | 2.83 | 0.04 |
| EL (%) | 0.005 | 0.001 | 0.012 | 0.010 | 0.010 | 0.015 | 0.024 | 0.005 | 0.049 | 0.000 | 0.27 | 0.09 | 0.30 | 3.38 | 0.05 |
| FS (#) | 0.000 | 0.000 | 0.000 | 0.000 | 0.035 | 0.018 | 0.018 | 0.018 | 0.035 | 0.000 | 0.35 | 0.17 | 0.41 | 2.43 | 0.04 |
| CN (#) | 0.00 | 0.00 | 0.02 | 0.01 | 0.04 | 0.02 | 0.03 | 0.01 | 0.03 | 0.00 | 0.34 | 0.11 | 0.33 | 3.06 | 0.04 |
| HPM (%) | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05 | 0.00 | 0.20 | 0.08 | 0.29 | 3.48 | 0.05 |
| FF (year) | 0.02 | 0.00 | 0.03 | 0.02 | 0.04 | 0.04 | 0.04 | 0.02 | 0.04 | 0.00 | 0.64 | 0.16 | 0.40 | 2.48 | 0.04 |
| ES (%) | 0.01 | 0.00 | 0.03 | 0.02 | 0.04 | 0.04 | 0.04 | 0.01 | 0.04 | 0.00 | 0.63 | 0.16 | 0.40 | 2.48 | 0.04 |
| WS (%) | 0.02 | 0.00 | 0.03 | 0.02 | 0.04 | 0.04 | 0.05 | 0.03 | 0.03 | 0.01 | 0.60 | 0.09 | 0.30 | 3.31 | 0.05 |
| ER (%) | 0.03 | 0.04 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.03 | 0.33 | 0.11 | 0.34 | 2.97 | 0.04 |
| PFM | 0.004 | 0.000 | 0.025 | 0.021 | 0.032 | 0.035 | 0.032 | 0.004 | 0.028 | 0.000 | 0.51 | 0.17 | 0.41 | 2.43 | 0.04 |
| D-L | 0.00 | 0.00 | 0.04 | 0.00 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.00 | 0.35 | 0.12 | 0.34 | 2.90 | 0.04 |
| FI | 0.01 | 0.04 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.04 | 0.01 | 0.34 | 0.11 | 0.33 | 3.02 | 0.04 |
| PR (hh) | 0.000 | 0.000 | 0.014 | 0.000 | 0.018 | 0.046 | 0.012 | 0.000 | 0.012 | 0.000 | 0.22 | 0.10 | 0.31 | 3.18 | 0.05 |

Table 7 Unequal weight-based values of Dire Dawa city flood vulnerability indicators

| Indicators | Villages | | | | | | | | | Extension |
|------------|----------|-------|-------|-------|-------|-------|-------|-------|-------|-----------|
| | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | |
| PD (%) | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 | 0.03 | 0.04 | 0.02 | 0.01 | 0.00 |
| PFA (#) | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.05 | 0.02 | 0.00 | 0.01 | 0.00 |
| CH (#) | 0.004 | 0.002 | 0.048 | 0.000 | 0.002 | 0.005 | 0.002 | 0.004 | 0.004 | 0.000 |
| IND (#) | 0.01 | 0.04 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.04 | 0.01 |
| S (%) | 0.00 | 0.00 | 0.00 | 0.01 | 0.03 | 0.02 | 0.00 | 0.04 | 0.00 | 0.02 |
| V (m/s) | 0.02 | 0.01 | 0.04 | 0.01 | 0.03 | 0.04 | 0.04 | 0.00 | 0.03 | 0.04 |
| D (m) | 0.02 | 0.02 | 0.04 | 0.01 | 0.02 | 0.04 | 0.04 | 0.00 | 0.04 | 0.04 |
| FD (h) | 0.01 | 0.00 | 0.01 | 0.00 | 0.03 | 0.03 | 0.03 | 0.01 | 0.03 | 0.00 |
| PE | 0.01 | 0.00 | 0.01 | 0.01 | 0.04 | 0.01 | 0.04 | 0.02 | 0.03 | 0.01 |
| PAS (%) | 0.02 | 0.02 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.04 |
| OP (%) | 0.00 | 0.00 | 0.01 | 0.01 | 0.04 | 0.04 | 0.03 | 0.01 | 0.02 | 0.00 |
| FHH (%) | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.04 | 0.04 | 0.01 | 0.02 | 0.00 |
| EL (%) | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.00 | 0.05 | 0.00 |
| FS (#) | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.02 | 0.02 | 0.02 | 0.04 | 0.00 |
| CN (#) | 0.00 | 0.00 | 0.02 | 0.01 | 0.04 | 0.02 | 0.03 | 0.01 | 0.03 | 0.00 |
| HPM (%) | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05 | 0.00 |
| FF (year) | 0.02 | 0.00 | 0.03 | 0.02 | 0.04 | 0.04 | 0.04 | 0.02 | 0.04 | 0.00 |
| ES (%) | 0.01 | 0.00 | 0.03 | 0.02 | 0.04 | 0.04 | 0.04 | 0.01 | 0.04 | 0.00 |
| WS (%) | 0.02 | 0.00 | 0.03 | 0.02 | 0.04 | 0.04 | 0.05 | 0.03 | 0.03 | 0.01 |
| ER (%) | 0.03 | 0.04 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.03 |
| PFM | 0.00 | 0.00 | 0.02 | 0.02 | 0.03 | 0.04 | 0.03 | 0.00 | 0.03 | 0.00 |
| D–L (km) | 0.00 | 0.00 | 0.04 | 0.00 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.00 |
| FI | 0.01 | 0.04 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.04 | 0.01 |
| PR (hh) | 0.00 | 0.00 | 0.01 | 0.00 | 0.02 | 0.05 | 0.01 | 0.00 | 0.01 | 0.00 |

contrary, village 02, 01 and extension villages were, respectively, identified as the least flood-vulnerable villages of Dire Dawa city. The rest of the three villages (04, 08 and 03), respectively, qualified the (Balica et al. 2012) classification of “vulnerable to floods.”

4.1 Characteristics and implication of the social vulnerable villages

Based on the vulnerability assessment results, villages with red color were identified as the most flood-vulnerable regions. The spatial distribution of this village shows that most of these villages are located along Dechatu River that crosses the center of the city. The analysis of this study identified that the higher overall vulnerability of these villages (07, 06, 05 and 09) were mainly resulted from the higher value of social vulnerability components and related exposure and susceptibility indicators and higher lack of resilience work in these villages (Table 8).

The finding of the study further identified that these villages were the oldest villages located at the center of the city. As a result, they experienced poor housing condition, lack of appropriate planning and haphazard expansions to the river side. The international literatures confirmed that places with high population density and higher number

Table 8 Dire Dawa villages flood vulnerability to social component

| Villages | Exposure | | | | | | | Susceptibility | | | | Resilience | | | FVI social |
|----------|----------|------|-------|------|------|------|---------|----------------|--------|------|------|------------|------|------|------------|
| | PD | PFA | CH | PE | CN | EL | FHH (%) | OP (%) | FS (#) | PAS | EW | ES | ER | | |
| | | | | | | | | | | | | | | | |
| 01 | 0.00 | 0.00 | 0.004 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 | 0.01 | 0.03 | 0.11 | |
| 02 | 0.00 | 0.00 | 0.002 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.04 | 0.07 | |
| 03 | 0.00 | 0.01 | 0.048 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.03 | 0.03 | 0.01 | 0.20 | |
| 04 | 0.02 | 0.00 | 0.000 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.03 | 0.02 | 0.02 | 0.01 | 0.16 | |
| 05 | 0.02 | 0.01 | 0.002 | 0.04 | 0.04 | 0.01 | 0.02 | 0.04 | 0.04 | 0.00 | 0.04 | 0.04 | 0.00 | 0.31 | |
| 06 | 0.03 | 0.05 | 0.005 | 0.01 | 0.02 | 0.01 | 0.04 | 0.04 | 0.02 | 0.00 | 0.04 | 0.04 | 0.00 | 0.30 | |
| 07 | 0.04 | 0.02 | 0.002 | 0.04 | 0.03 | 0.02 | 0.04 | 0.03 | 0.02 | 0.00 | 0.05 | 0.04 | 0.00 | 0.32 | |
| 08 | 0.02 | 0.00 | 0.004 | 0.02 | 0.01 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.01 | 0.01 | 0.18 | |
| 09 | 0.01 | 0.01 | 0.004 | 0.03 | 0.03 | 0.05 | 0.02 | 0.02 | 0.04 | 0.00 | 0.03 | 0.04 | 0.00 | 0.28 | |
| Ext. | 0.00 | 0.00 | 0.000 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.01 | 0.00 | 0.03 | 0.10 | |

Table 9 Dire Dawa villages flood vulnerability to economic component

| Villages | Exposure | | Susceptibility | Resilience | FVI economic |
|----------|----------|---------|----------------|------------|--------------|
| | IND (#) | PR (hh) | HPM (%) | FI | |
| 01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.02 |
| 02 | 0.04 | 0.00 | 0.01 | 0.04 | 0.09 |
| 03 | 0.02 | 0.01 | 0.01 | 0.02 | 0.06 |
| 04 | 0.01 | 0.00 | 0.00 | 0.01 | 0.03 |
| 05 | 0.01 | 0.02 | 0.01 | 0.01 | 0.05 |
| 06 | 0.01 | 0.05 | 0.01 | 0.01 | 0.07 |
| 07 | 0.00 | 0.01 | 0.01 | 0.00 | 0.02 |
| 08 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 |
| 09 | 0.04 | 0.01 | 0.05 | 0.04 | 0.13 |
| Ext. | 0.01 | 0.00 | 0.00 | 0.01 | 0.02 |

Table 10 Dire Dawa villages flood vulnerability to physical component

| Villages | Exposure | | | | | Susceptibility | Resilience | FVI physical | Total |
|----------|----------|-------|--------|-------|-----------|----------------|------------|--------------|-------|
| | V (m/s) | D (m) | FD (h) | S (%) | FF (year) | PFM | D–L (km) | FVI | |
| 1 | 0.02 | 0.02 | 0.01 | 0.00 | 0.02 | 0.00 | 0.00 | 0.07 | 0.20 |
| 2 | 0.01 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.19 |
| 3 | 0.04 | 0.04 | 0.01 | 0.00 | 0.03 | 0.02 | 0.04 | 0.19 | 0.45 |
| 4 | 0.01 | 0.01 | 0.00 | 0.01 | 0.02 | 0.02 | 0.00 | 0.07 | 0.26 |
| 5 | 0.03 | 0.02 | 0.03 | 0.03 | 0.04 | 0.03 | 0.01 | 0.20 | 0.56 |
| 6 | 0.04 | 0.04 | 0.03 | 0.02 | 0.04 | 0.04 | 0.02 | 0.21 | 0.58 |
| 7 | 0.04 | 0.04 | 0.03 | 0.00 | 0.04 | 0.03 | 0.02 | 0.19 | 0.53 |
| 8 | 0.00 | 0.00 | 0.01 | 0.04 | 0.02 | 0.00 | 0.02 | 0.09 | 0.27 |
| 9 | 0.03 | 0.04 | 0.03 | 0.00 | 0.04 | 0.03 | 0.03 | 0.20 | 0.62 |
| Ext. | 0.04 | 0.04 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.10 | 0.22 |

of poor people represented by slum area are likely to be classified as high vulnerable areas (Yoo et al. 2014; Kumar et al. 2016). The findings of this study also correspond to previous studies conducted in Dire Dawa city. The report of UN-HABITAT showed that at least 15,000 dwellers living in high-risk flooding areas in the city of Dire Dawa were located in the inner villages close to Dechatu River (UN-HABITAT 2008). Likewise, the study conducted by Alemu (2015) identified villages 06, 05, 09 and 03 as the flood-vulnerable sites. Moreover, poor living condition and making houses from inappropriate materials in flood-prone areas were reported as main causes to identify flood-vulnerable villages (Alemu 2015). However, the findings of this study further identified and classified all villages in terms of their level of flood vulnerability by analyzing various flood components and 24 flood indicators that can directly or indirectly determines the vulnerability level of the villages. Based on the results of social component villages 03,05,06,07 and 09 were found as the most social vulnerable villages.

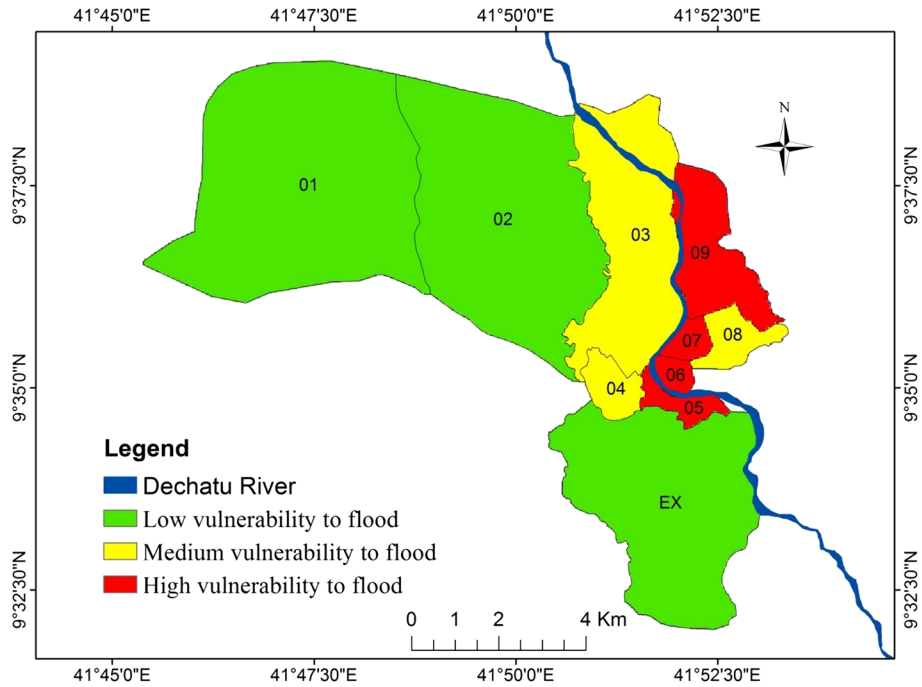


Fig. 3 Flood vulnerability maps of Dire Dawa city

On the other hand, the social vulnerability assessment of the city identified villages 01, 02 and extension) as the less flood-vulnerable villages. These three villages have very good resilience in most of the examined components. The currently operating master plan of Dire Dawa city identified these villages as the expansion site of the city, and these villages were not yet over populated. This helped the villages to have relatively good access to the indicators identified under resilience factors such as evacuation route, emergency services, flood protection measures and good planning strategies. The case of these villages showed a significant similarity with studies conducted in Bangladesh where villages with less density and better facilities were less likely vulnerable to flood (Handayani et al. 2017).

Knowing the distribution of the individual social vulnerability components can be an important input for planners, emergency managers, and others (Adger et al. 2005). Hence, reducing social inequalities in flood vulnerability is the right thing to be done at most (Walker and Burningham 2011). Among all vulnerable components, social vulnerability is the most costly of all vulnerabilities. Vulnerable assets can be rebuilt, vulnerable infrastructure and environment can be regenerated, but the loss of life is remained to be a loss with no replacement. Hence social vulnerability needs a priority among other vulnerable components. The findings of this study and previous studies of Kumar et al. (2016), Yoo et al. (2014) and Handayani et al. (2017) indicated that population density and distribution of public infrastructures plays a significant role in minimization of vulnerability level. Therefore, it is very important to ensure that the people and facilities are evenly distributed across the cities. According to Jabareen (2006), population density is a critical determinant to have sustainable urban growth. This calls for maintaining population density in combination with sufficient allocation for settlements, including urban infrastructures and green

spaces contribute significantly attempt to minimize vulnerability levels (Handayani et al. 2017).

4.2 Characteristics and implication of the economic vulnerable villages

Economic vulnerability is used to identify the potential impacts of hazards on economic assets and processes. The effect of economic vulnerability is insignificant in the case of Dire Dawa city. As an example, among four villages identified as high flood-vulnerable areas, only village 09 has a significant economic vulnerability (0.13). In general, the effects of economic vulnerabilities are low because of various reasons. At the first place, there were fewer industries in the inner cities of the city whose damage costs a huge asset. Secondly, most of the flood-susceptible houses were made up of poor, cheap and less costly materials easily available in the area. As a result, the economic cost of the damage may not be pronounced. However, it should be noticed that less economic vulnerability mean is not to mean that the number and damage at household level is less. Rather the result of this study shows that most of the flood-vulnerable villages of Dire Dawa city are inhabited by economically poor people. Therefore, as a manses of vulnerability minimization these villages need economic empowerment to improve their ways of life and housing conditions.

4.3 Characteristics and implication of the physical vulnerable villages

Physical vulnerability identifies the vulnerability of an area depending on geographic proximity to the source of hazards (Wisner 2004). Physical vulnerability is another important component that contributed for overall vulnerability analysis of Dire Dawa city. As shown in Table 10, villages 06, 05 and 09 are relatively exposed to higher physical vulnerabilities. This shows that the contribution of physical vulnerability to overall flood vulnerability of Dire Dawa city is significant. The result of physical vulnerability is used to estimate the impacts of hazardous events on physical structures. According to Ciurean et al. (2013), the key assessment of physical vulnerability indicators to flood was employed to quantify the forces and pressures that flooding is likely to exert on structures such as building, bridge, dam, etc.

Measuring physical vulnerability become an effective step toward risk reduction and the promotion of a culture of disaster resilience (Kasperson and Archer 2005). It is clear that most of the physical vulnerability indicators such as flood depth, flood frequency and flood duration used to know the extreme points of flood events that cause a physical damage on different structures. Hence, the result plays a significant role in determining suitable flood protection measures of a given area (Mani et al. 2014; Mollaei et al. 2016). In the study area, attempt of flood management is not a new phenomenon. Following the devastating flood of 2006, the city government is allocating huge budget to stem flood-induced risks, human casualties and property damage by using structural methods. Accordingly, long retaining walls of 6 km have been constructed along Dechatu and Goro rivers. Despite the ongoing flood management efforts, flood continues to present the greatest threat among socioeconomic and infrastructural wellbeing of the city. Unexpectedly, the supposed flood protection wall itself has been the victim of extreme flooding. This is because of inappropriate analysis of physical vulnerability indicators that identify the margin of physically vulnerable areas that govern the construction of structural methods. Therefore, it is recommended that houses, infrastructures, permanent retaining walls and other engineering-based defense mechanisms should be constructed out of the inundated areas where the

maximum flood level touches. Moreover, the result of this study identified the overall vulnerability level of villages as small vulnerable, vulnerable to floods and high vulnerability to floods. This result helps the city municipality, NGOs and other concerned organs where to start flood management interventions.

5 Conclusions and recommendations

For the cities experiencing increasing flood-induced vulnerabilities, it is imperative to develop approaches and tools that help to minimize the effects of hazards. This study adopted indicators based on assessment of flood vulnerability. The study identified 24 indicators for which data are available and which best reflects the local vulnerability conditions. Flood vulnerability Index (FVI) assessment method was used to compare the vulnerability levels of the villages across the city. Methodologically, the indicators were weighted using unequal weighting method developed by (Iyengar and Sudarshan 1982). As a result, each identified variables obtained different weights. The computations of Flood Vulnerability Index (FVI) were used to determine the village levels of vulnerability based on social, economic and physical factors. The overall FVI identified four high vulnerable villages (05, 06, 07 and 09), three medium vulnerable villages (03, 04 and 08) and three low vulnerable villages (01, 02, extension) to flood disaster risk. The results of FVI further indicated that the higher overall vulnerability of these villages (07, 06, 05 and 09) was mainly resulted from the higher value of social vulnerability factors. This shows that flood vulnerability index (FVI) in this study is more sensitive to social vulnerability factors. Moreover, the study identified that the economic vulnerability component is less significant to determine the overall vulnerability effect of the city. From the social vulnerability perspective, the study identified village 03, 05, 06, 07 and 09 as the most social vulnerable villages that needs an immediate attention for risk minimization activities. In general, FVI result is found to be a powerful tool for mapping of vulnerable villages of Dire Dawa city. Using these indicators, one can clearly compare the vulnerabilities of communities in different components and perspective which can later be adopted for similar cities in Ethiopia and other countries in the world. It is highly recommended that the flood vulnerability map developed for the city is properly utilized for future flood risk planning and management, and social factors of flood vulnerability are given due attention to reduce the negative effects of flooding disaster risk in the city. In nutshell, the identification of comparative vulnerability levels of the villages is intended to drive relevant policy actions and may assist the primary stakeholders for flood disaster risk management in the city identifying priority areas in Dire Dawa city and other cities and towns in Ethiopia.

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