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ORIGINAL PAPER

Evaluation of food risk parameters in the Day River Flood Diversion Area, Red River Delta, Vietnam

Nguyen Mai Dang · Mukand S. Babel · Huynh T. Luong

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Abstract An interdisciplinary approach is necessary for flood risk assessment. Questions are often raised about which factors should be considered important in assessing the flood risk in an area and how to quantify these factors. This article defines and quantitatively evaluates the flood risk factors that would affect the Day River Flood Diversion Area in the context of integrated flood management in the Red River Delta, Vietnam. Expert analysis, in conjunction with field survey and Analytical Hierarchy Process (AHP), is applied to define and quantify parameters (indicators, subcomponents, and components) that contribute to flood risk. Flood duration is found to be the most prominent indicator in determining flood hazard. Residential buildings, population, and pollution are other fairly significant indicators contributing to flood vulnerability from the economic, social, and environmental perspectives, respectively. The study results will be useful in developing comprehensive flood risk maps for policy-makers and responsible authorities. Besides, local residents will also be able to implement suitable measures for reducing flood risk in the study area.

Keywords Floods · Flood diversion · Flood risk definition · AHP · Quantitative evaluation · Vietnam

1 Introduction

Natural disasters and their economic impact are increasing worldwide at an alarming rate. People, property, society, and the environment are suffering more and more from natural hazards. Any changes in contemporary society—such as population increase, economic

N. M. Dang (✉)
Faculty of Hydrology and Water Resources, Water Resources University (WRU), 175 Tay Son, Dong Da, Hanoi, Vietnam
e-mail: dang@wru.edu.vn; nmaidang@yahoo.com

M. S. Babel · H. T. Luong
School of Engineering and Technology, Asian Institute of Technology, Km 42 Paholyothin Road, Klong Luang, Pathumthani 12120, Thailand

development, urbanization, industrialization, deforestation, expansion of residential areas, increased labour mobility, population ageing—make society more vulnerable to natural hazards (Takeuchi 2006). The number of people affected by natural disasters averaged 147 million per year during 1981–1990, which increased to 211 million per year during the next decade (1991–2000). Flooding was responsible for two-thirds of these affected and caused over one-third of the total estimated economic damage (Pilon 2003). An integrated approach is crucial for flood protection (Evers 2006), and studies of flood hazards and vulnerabilities as well as flood risk should be directed towards adaptation activities (Huang et al. 2005; Apel et al. 2008).

Climate change is projected to increase the frequency and severity of extreme weather events. As a consequence, economic losses caused by natural catastrophes could increase significantly (Botzen et al. 2010). With rapid urbanization and climate change, flood disaster has been intensifying and threatening sustainable development and an integrated approach to flood risk management is needed (Shi et al. 2005). Integrated flood risk management explicitly recognizes the interrelationships between all risk management measures, their analysis, costs, and effectiveness and situates these factors within the changing social, economic, and environmental contexts (Hall et al. 2003). Urban expansion and consolidation and changing demographics within floodplains, changes in flood behaviour due to the development in catchments, and the influence of climate change on flood producing rainfall events and sea levels, all act to increase the exposure of the community to flood risk. Without effective flood risk management, the scale of the impact of flood disasters on people, property, local industry, and economics will increase (NFRAG 2008).

Flood hazard is the probability of the occurrence of a potentially damaging flood event of a certain magnitude in a given area within a specific period of time (Crichton 2002; Kron 2005). A number of factors (or parameters) contribute to the damaging potential of flood hazards. These factors can be quantified through indicators such as flood depth, duration, velocity, impulse (water level multiplied by velocity), the rate of the rise of water levels, warning time, and the frequency of occurrence. All these factors and indicators have a complex relationships and different effects (ESCAP 1991; Smith 1994; Green et al. 2000; Alkema 2003; Tingsanchali and Karim 2005).

Population growth and improved living standards with high-value belongings have increased the vulnerability of society towards flood hazard. These developments create new challenges for society and the environment. It would be gravely erroneous to ignore social and environmental problems, which are emerging in modern life and society. Developing economy and rising living standards require a safer environment. However, there is an obvious conflict of modernization—while industrialization and spending power create and utilize many products, they also leave behind huge amount of wastes that need to be disposed properly. Thus, it has become necessary to develop a wider framework for vulnerability assessment related to economic, social, and environmental aspects (Weichselgartner 2001; Green 2004; Dwyer et al. 2004; ADRC 2005).

Scientists widely describe risk as the uncertain product of a hazard and its potential loss (Crichton 2002; Kron 2005). The evolution of flood risk analyses has been developed parallelly with flood damage assessment. For example, in the 1970s, the flood losses estimation only focused on direct damages (Penning-Rowsell and Chatterton 1977). Afterwards, the indirect and intangible impacts were incorporated in flood damage assessment (Penning-Rowsell and Parker 1987; Green and Penning-Rowsell 1989; Miyata and Abe 1994; Simonovic 1999; DEFRA 2005). In the past few decades, flood analysis concentrated mainly on physical dimensions of flooding (quantity, area etc.) and on the direct damages of the event in economic terms. However, in the recent years, flood risk analysis has also encompassed socio-environmental vulnerability analysis—that is, an approach to integrated flood management. Weichselgartner (2001) states that a disaster happens inside society and not within nature and strongly recommends that social issues must be stressed upon more than physical aspects in the mitigation of natural disasters. Furthermore, Green (2004) defines vulnerability to flooding with respect to a system perspective, in which vulnerability is the relationship between a purposive system and its environment, where that environment varies over time.

Natural risk is a combination of three main components: natural hazard, value of the elements exposed to the hazard, and vulnerability of the elements at risk, as presented in Fig. 1. Crichton (2002) explains the risk as the area of an acute angled triangle formulated by three edges which represent independent components that contribute to risk. A vivid description of a three-dimensional pyramid has been developed from the risk triangle of Crichton. This pyramid delineates risk components via three dimensions, and the total risk is expounded as volume of the pyramid (Dwyer et al. 2004). Another presentation of disaster risk as well as the mechanism of natural disaster reduction is shown by ADRC (2005). The potential risk is the overlapping common area of three circles where each circle is a representative for one risk component—namely hazard, vulnerability, and exposure. The potential risk can be lessened in three ways: (1) by decreasing the level of vulnerability, (2) by reducing the exposure value, and (3) by reducing the hazard. In addition to analysing the mechanism of flood risk reduction, Kron (2005) also proposes a triangle that is constructed from the three components: public authorities (responsible for measures to be provided by the state), the people affected (individual solutions that are mostly non-structural measures), and insurance, which is stressed as a key component in diminishing the financial risk for individuals and society.

In summary, flood risk assessment requires interdisciplinary approaches and studies. Flood risk in terms of the people affected and economic losses emphasizes the need to apply an integrated approach to carry out flood risk analysis. Yet questions are often raised about factors that should be considered most influential for flood risk in the study area and also how to quantify these factors. The integrated flood risk analyses by Islam and Sado (2000), Alkema (2003), Shrestha et al. (2004), and Tingsanchali and Karim (2005), etc., only relies on qualitative weighing factors for underlying factors/indicators. Harker (1989), though, comments that some "errors" are made when providing judgments based solely on the qualitative weights given to the comparative factors, as this is a consequence of inconsistency in rating the importance among relevant factors. The analytic hierarchy process or AHP deals formally with these "errors" by estimating the overall weights using the information contained in the matrix of factors, in which the consistency ratio is estimated to measure how much inconsistency there is in filling the matrix of factors. This

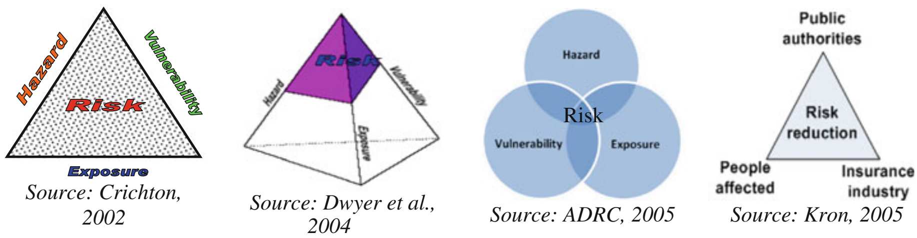

Fig. 1 Mechanism of creation and reduction of natural disaster risk

study proposes an approach to define flood risk factors and then to quantitatively evaluate the weighing factors for flood risk indicators using the AHP. The approach developed is then applied to a flood-prone area, the Day River Flood Diversion Area in Vietnam, as described hereafter.

2 Description of the study area

The catchment of the Red River System as depicted in Fig. 2 is about 169,000 km^2, of which 49% in the upstream lies in China (DHV et al. 2002). The Red River that flows through Hanoi, the capital city of Vietnam, comprises three major tributaries—the Da, Thao, and Lo rivers—that bring annual floods threatening the capital and the delta. Upstream reservoirs, namely Hoa Binh, Thac Ba, Tuyen Quang, and Son La, have a total storage capacity of 8.5 billion m^3 for flood control. In addition, the Red River Delta joins the Gulf of Tonkin that annually suffers from tropical typhoons that come from the Pacific Ocean. These typhoons bring potential perils affecting a large area of the Red River Delta including Hanoi. Observed data of hydro-meteorology show an increasing trend in floods, storms, and sea-level rise (Dang and Babel 2009) as indicated in Fig. 3. Such a situation requires adaptive measures that can deal with challenges in the near future. It is important to note that MONRE (2009) has projected that the sea level will rise in the Gulf of Tonkin by 0.65, 0.75, and 1.0 m in 2100 for low-, medium-, and high-emission scenarios, respectively.

The Day River is the tributary of the Red River System and branches off 35 km upstream of Hanoi. This river basin was designated to be the flood diversion area in 1937 and is one of the most important components of flood control system in the Red River. It protects 18.56 million people living in the Delta. Flood diversion to the Day River Basin is the final resort to reduce floodwater level in Hanoi and is only used in cases of emergency such as when upstream reservoirs are full or a dam breaks or there is a control gate failure. At present, the flood protection level for Hanoi and the Red River Delta is approximately once in 500 years, whereas the likelihood of using the Day River Flood Diversion Area is once in 50–100 years (DHV et al. 2002).

The operation rule of flood diversion structures (see Fig. 4) is described as follows: when floodwater level at Hanoi approximates to 13.40 m AMSL (above mean sea level) and it is forecasted that floods upstream will continue increasing while upper reservoirs are full, Van Coc sluice gates and the Hat Mon spillway are immediately opened to divert the flood from the Red River to the Day River Basin with a maximum discharge of 5,000 m^3/s (IWRP 2003).

In the past, there have been several occasions when the flood in the Red River was diverted into the Day River such as in 1939, 1940, 1941, 1942, 1945, 1947, 1969, 1971, 1977, and 1985 (IWRP 2001). The 1985 diversion was required because the dyke was broken at Hat Mon spillway (see Fig. 4). No flood diversion has taken place since 1985 due to the construction of the Hoa Binh reservoir in the upstream of the basin, which has been operated for flood control and regulation since 1989. This has reduced awareness of flood risks and has increased the encroachment of people and property into the floodway areas. That, coupled with an increasing population and economic development, has resulted in a dramatic land-use change (see Fig. 5). These changes can cause increased vulnerability to flooding. If public awareness and education on flood risk is not strengthened, any flood diversion into the area will result in a catastrophe.

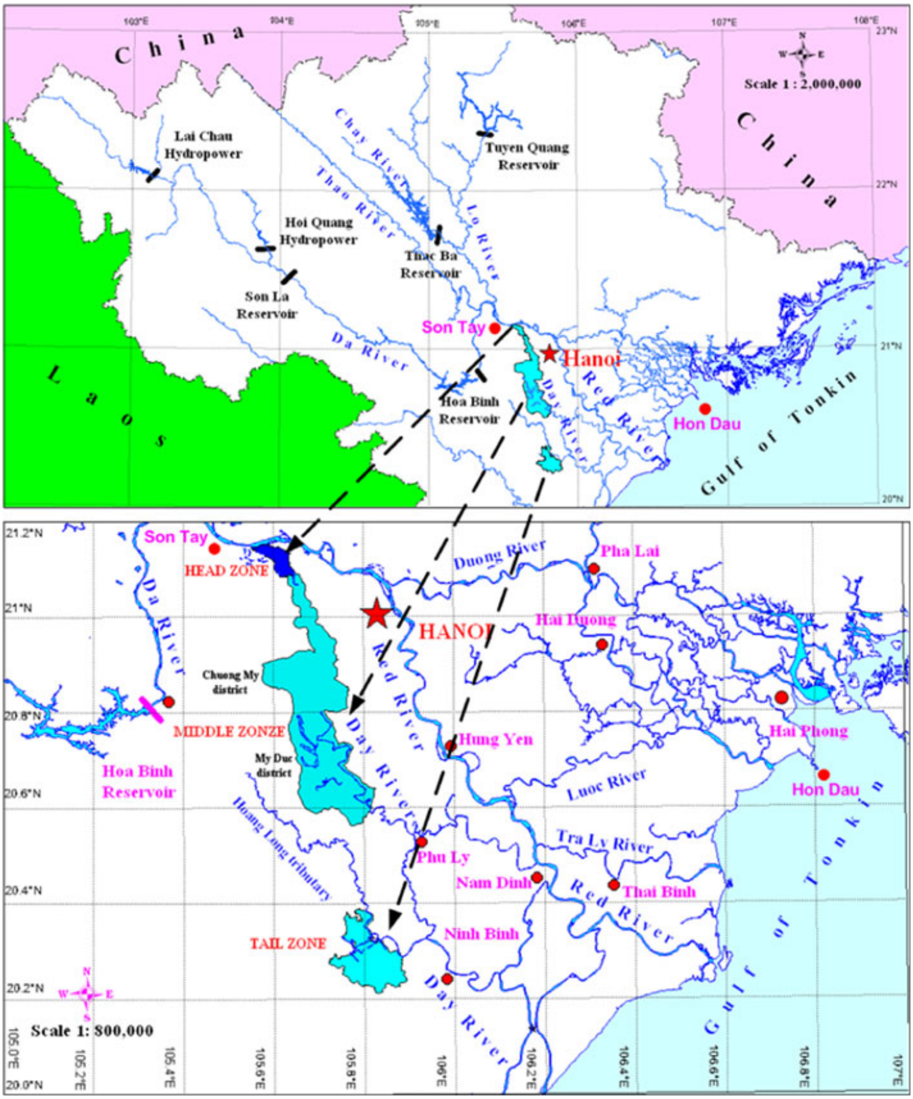

Fig. 2 Location of the Day River Flood Diversion Area, Red River System, Vietnam

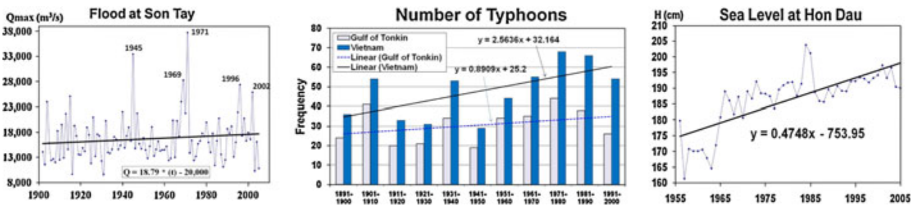

Fig. 3 Trends of floods, typhoons, and sea levels in the study area (*Source*: Dang and Babel 2009)

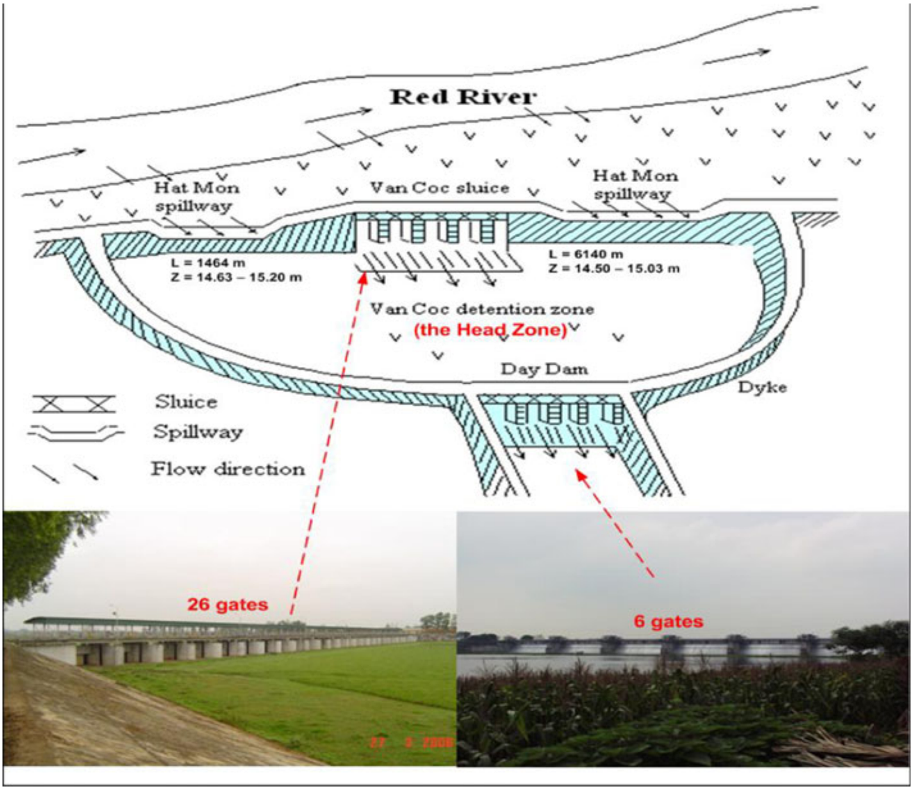

Fig. 4 Schematic of flood diversion structures in the Head Zone

The flood diversion area is divided into three zones. The Head Zone or the Van Coc storage area is considered the most dangerous area due to its proximity to the site of flood diversion structures. It has high velocity, short warning time, and potential erosion. The Middle Zone, the flood detention area in Chuong My and My Duc districts, suffers flooding for a long duration of one to two months that causes serious pollution and water diseases during flood diversion time (IWRP (Institute for Water Resources Planning) 2001). The Tail Zone, the lowland area in the downstream of the Day River and Hoang Long tributary, always suffers from flooding which originates from inside the Day River Basin. Thus, it is frequently used as an interior flood diversion area (not from the Red River) to detain floodwater in anticipation of a dyke break with a return period of 3–5 years. The flood diversion that occurred in early October 2007 is one recent example, and the flooding in the detention areas lasted about 2 months (CCFSC 2007).

3 Approach to evaluation of flood risk parameters

The nature of flood risk is uncertain, and the definitions of flood risk are diverse. It is, therefore, difficult to quantitatively assess flood risk since such a risk is a consequence of natural phenomena impacting human concerns that include lives, property, and capacity against hazards. The risk happens only when both natural hazards and human concerns

People living in the Head Zone

Housing in the Middle Zone

Dyke rescue against flood 2008 in the Middle Zone

Extreme flood 2007 in the Tail Zone

Fig. 5 Population and economic growth as well as flooding in the study area

occur together; otherwise, there is no risk. Flood risk is defined as a degree of the overall adverse effects of flooding. The term "flood risk" incorporates the concepts of threat to life and limb, the difficulty and danger of evacuating people and their possessions during a flood, the potential of damage to the structure and contents of buildings, social interruption, loss of production, damage to public property etc. Scientists agree that risk is a function of hazard, vulnerability, and exposure (values). However, several researchers have considered vulnerability and hazard together (Weichselgartner 2001; Shrestha et al. 2004; Tingsanchali and Karim 2005; Kron 2005, Apel et al. 2008). Similarly, this study also defines flood risk as a combination of flood hazard and flood vulnerability, in which exposure is considered a part of vulnerability, and describes it as follows:

$$\text{Flood Risk} = \text{Flood Hazard} \times \text{Flood Vulnerability}.$$

3.1 Definition of flood hazard

Flood hazard is defined as the probability of the occurrence of a flood event of a certain magnitude in a given area within a specific period of time. The consequences of the flood could be appraised through prime indicators such as flood depth, flood duration, flood velocity, the impulse of flood (product of water level multiplied by velocity), loads (sediment, salinity, chemicals, sewage, and debris), the rate of the rise of floodwater levels, and flood warning time. The depth of flooding and flow velocity play leading roles in defining flood damage because the integration of flood depth and velocity dominates the determination of the probability of infrastructure and building collapse and also poses a high risk to public health and loss of life. Debris loads bring additional losses as they increase the power of floodwaters. Flood duration particularly gears flood damage to indirect or intangible damage such as life disruption, stress, contamination, and the outbreak of diseases (Penning-Rowsell and Chatterton 1977; Green et al. 2000).

3.2 Definition of flood vulnerability

Flood vulnerability here is defined as the degree of damage caused by a hazard of a given magnitude for a specific element at risk (e.g. a stage-damage function). Weichselgartner (2001) and Green (2004) have synthesized a number of definitions and evaluation procedures of vulnerability. In general, the indicators of vulnerability cover loss potentials derived from the susceptibility of an individual or a community—for example, a house, a residential area or farmland, infrastructure (electricity, transportation, hydraulic works, school buildings, public utilities), social structure and environmental surroundings, human health (external stress, shock, or disease outbreak) etc.

Although the definition of vulnerability varies in concept, its subcomponents or indicators depend on the type of hazard and the goal of the vulnerability assessment, including specific characteristics of the study area. Based on the investigation by Weichselgartner (2001), vulnerability is studied in three distinct themes. The first theme: vulnerability as risk/hazard exposure in pre-existing conditions. In this framework, the sources (or potential exposure or risk) of biophysical or technological hazard are examined. This theme is characterized by a focus on the distribution of hazardous conditions, the human occupancy of the hazardous zone (floodplains, seismic zones), and the degree of loss associated with the occurrence of a particular event (flood, earthquake). The second theme is vulnerability in terms of social response and tempered responses. This theme focuses on coping responses, including societal resistance to hazards, and highlights the social construction of vulnerability, a condition rooted in historical, cultural, socio-economic processes that impact the individual's or society's ability to cope with disasters and adequately respond to them. The third direction—vulnerability as a hazard of place—combines elements of the two components but is inherently more geographically centred. In other words, this vulnerability is conceived as both a biophysical risk and a social response, but within a specific area or a geographical domain.

3.3 Criteria for selection of components and indicators

There are many factors related to flood hazard and flood vulnerability that have been discussed. Therefore, it is essential to identify the criteria for the selection of key factors involving components, subcomponents, and indicators, which can be applied to the study area. The selected indicators must be the most appropriate for flood risk analysis in the study area. The criteria considered in the present study are similar to those implemented by Dwyer et al. (2004). First, the criterion, its components, and indicators must describe the nature of flood risk; secondly, the data must be available, reliable, and reducible for each component and indicator of hazard and vulnerability; subsequently, the suggested components and indicators should be easily understood and should be able to explain the complexity of the concept of flood risk; finally, indicators must be quantifiable, recognizable, and measurable.

4 Quantification of flood risk parameters

Flood risk components, namely flood hazard and flood vulnerability, are divided into subcomponents, which are also separated into indicators that can describe potential flood damage in the Day River Flood Diversion Area. As mentioned earlier, the AHP method has been adopted in this research to quantify the weights given to each component, subcomponent, and indicator. Hence, both flood hazard and vulnerability are essential to develop the hierarchy in order to quantify flood risk components. Flood hazard relates to natural phenomena, whereas vulnerability relates to humans and involves people, possessions, and the surrounding environment. Flood hazard is explicit and can be evaluated by hydrodynamic modelling, but flood vulnerability is implicit and difficult to estimate. The proposed approach to define and quantify flood risk for the study area is illustrated in Fig. 6, in which the AHP has been adopted for a quantitative evaluation of relative weights to flood risk components. Figure 7 depicts the algorithm of AHP that was coded using the Visual Basic language to compute the relative weights to flood risk components for the study area.

4.1 About AHP

The AHP was first developed by Thomas L. Saaty in the 1970s and, since then, has been widely applied to a variety of areas (Harker 1989; Tran et al. 2003). It has been defined variously: a robust and flexible methodology for multi-criteria decision analysis (Saaty 1980); the art and science of decision-making but as an intuitive and relatively easy method for formulating and analysing decisions (Harker 1989); a tool to permit explicit exhibition of appraisement criteria and also a multi-attribute decision method, which refers to a quantitative technique (DeSteiguer et al. 2003).

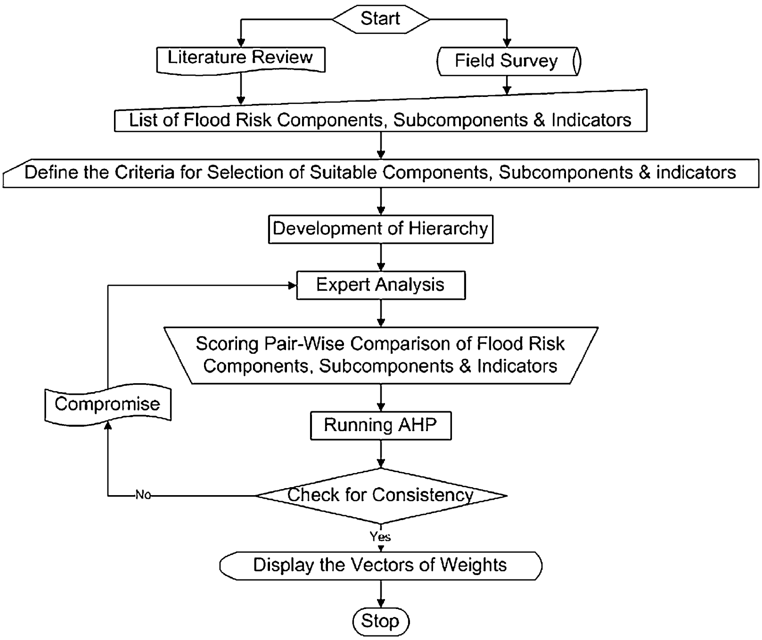

Fig. 6 Approach to evaluate quantitatively weighing factors for flood risk

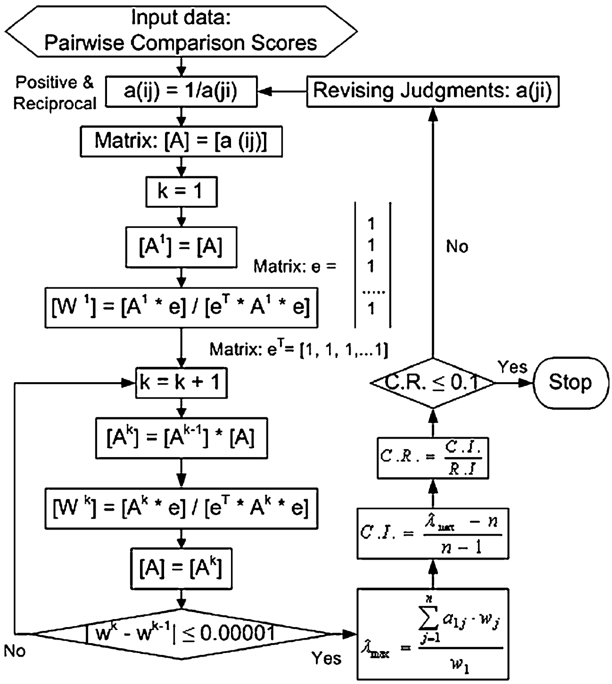

Fig. 7 Algorithm of the AHP

The AHP has been used in many practical problems in economics, transportation, education, resources allocation, planning, and integrated management. The AHP is extensively used because of a number of advantages; for example, it is a structured decision process and a quantitative process that can be documented and replicated; it is applicable to situations involving multi-criteria and subjective judgments; it can deal with both qualitative and quantitative data; it can be used to check the consistency of preference; and it is suitable for group decision-making (DeSteiguer et al. 2003).

The purpose of the AHP is to quantify the qualitative preferences among components or subcomponents as well as indicators or categories. The pairwise comparison of a set of objects (either criteria or alternatives) is used to evaluate interactive weights to the components. The scoring of pairwise judgments is based on the rule of Saaty with a 9-point system from 1 (in case of two activities contributing equally to the objective) to 9 (in case of the evidence strongly favoring one activity over another). The other scores such as point 3 refers to weak importance, point 5 is assigned to obvious preference, point 7 for a case of strong significance, and the even numbers, 2, 4, 6, and 8, are used when a compromise is needed between the odd numbers.

In Fig. 7, the matrix $A = [a_{ij}]$ is established following the rule that is positive and reciprocal. Coefficients of the matrix are calculated from scoring of the pairwise comparison of components, subcomponents, indicators, and the categories of flood risk through group discussions by experts. Then, the relative weights to components are derived from a mathematical processing of the matrix using the AHP algorithm. The desired weights are computed as the principal right eigenvector (or Perron right vector) of the matrix, which is accomplished by raising the matrix A to the growing power k. The increasing power k of matrix A is iterated until the difference of priority weight vector of the two last repetitions is less than the permitted error of 0.00001. In each iteration, the weights are always normalized so that it can be summed to 1 for convenience. Ultimately, the maximum eigenvalue (λ_{max}) of the matrix A is then defined. The preference factors are checked for consistency through the consistency ratio (C.R.), which is the ratio of the random inconsistency index (R.I.) to the consistency index (C.I.). The C.R. below 0.1 is typically considered acceptable but higher values require revising judgments since they are highly inconsistent (Saaty 1980; Harker 1987; Harker 1989; Tran et al. 2003). The C.I. was synthesized from λ_{max} and the order of the matrix (n). The R.I. is a function of n in the relationship given by Saaty (1980) as follows:

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R.I.	0.0	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

4.2 Development of hierarchy

The hierarchy of flood risk components is developed to build the matrices for applied AHP. Components, subcomponents, indicators, and categories are arranged like a tree root with four levels, as illustrated in Fig. 8. The goal level represents flood risk analysis of a region or a community from synthesizing land units (hamlets, communes, or flood cells that are used in this study). The second level depicts the two main components, such as flood hazard and flood vulnerability. Flood vulnerability is then formulated from three subcomponents: economic, social, and environmental.

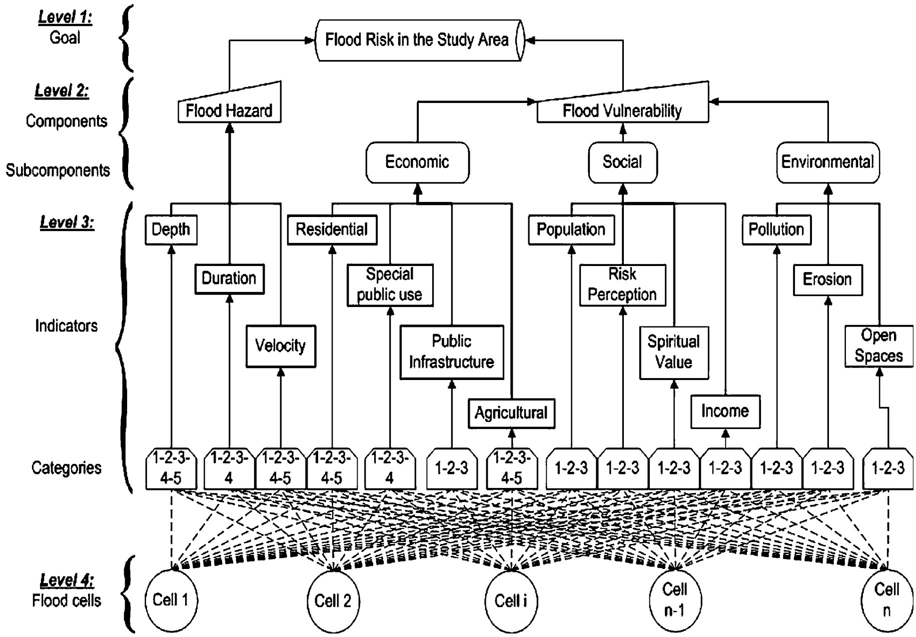

Fig. 8 Hierarchy for quantification of flood risk

The third level presents the indicators for hazard and vulnerability. Flood hazard is represented by three indicators: flood depth, duration, and velocity. Debris load is not considered for flood hazard due to data limitations. The economic subcomponent of vulnerability is mainly considered in four indicators such as residential (houses or buildings); agricultural (paddy fields, crops and vegetable, orchard gardens, grasslands and shrubs, and riversides); public infrastructure (roads and canals); and special public use buildings (schools, hospitals, markets, administrative buildings). The social subcomponent of vulnerability is referred to population, perception of flood risk, spiritual values (temples, pagodas, churches, historical monuments, museums, cultural characteristics), and income. The environmental subcomponent includes pollution sources (stagnant water and other contaminant sources); potential erosion areas (such as floodways, fallow lands, deep slope or downstream of spillways); and open spaces (tourist areas, resorts, golf courses, parks, farmlands). All the indicators are divided into 3 to 5 categories as indicated in Fig. 8.

The fourth level represents flood cells. The study area (the flooded area) is divided into flood cells of certain dimensions, for example the square-shaped cell with a size of 90 m by 90 m. Each flood cell contains characteristics related to flood hazard and the economic, social, and environmental subcomponents of flood vulnerability. Thus, magnitudes of all indicators in each cell are defined, and the relative weights are calculated. Consequently, the value of flood risk for each cell is integrated by summation of magnitudes of all the indicators with respect to their weights, and the comprehensive flood risk map for the study area is developed. The flood risk maps are developed with different scenarios of flood hazard as well as flood vulnerability. This part of the research will be published separately in the forthcoming paper.

4.3 Process of establishing relative weights to flood risk parameters

The procedure of establishing relative weights to flood risk parameters is described in Fig. 6. First, a review of literature on flood risk in conjunction with an extensive field survey among households in the study area is used to identify the flood risk parameters that most influence flood damage. Then, suitable parameters (components, subcomponents, and indicators) are selected based on the criteria mentioned in Sect. 3.3, and the hierarchy of flood risk parameters is developed as shown in Fig. 8.

Secondly, the authors propose the scores for matrixes of parameters including components, subcomponents, indicators, and categories of flood risk. A workshop was organized by the authors with support from the General Department of Dyke Management and Flood Control of the Vietnamese Ministry of Agriculture and Rural Development in April 2006 in Hanoi for expert analysis on the scores of those matrices. A total of 43 experts who are highly qualified and competent in the subject area were invited. They have been working in their respective fields related to the study and have professional experience in the Day River Basin, as well as in the Red River Delta. The experts are drawn from universities (10), research institutes (7), governmental agencies (5), provincial offices (5), district (7) and local authorities (9). The composition of the experts group is interdisciplinary as they represent different fields such as flood control and management (7), water resources planning and management (5), economics (6), sociology (6), environment (6), engineering (5), as well as administration (5) and decision-making (3).

A total of 20 score tables were designed for pairwise comparison of the elements of flood risk. The scores were initially discussed by the experts in groups. The groups were organized based on flood hazard and economic, social, and environmental aspects of flood vulnerability. Then, a plenary session of all the experts was organized to come up with a

Table 1 Pairwise comparison of categories of flood depth

Impact level	Depth (m)	<0.5	0.5–1.2	1.2–2.0	2.0–3.0	>3.0
Low inundation	<0.5	1	1/4	1/7	1/8	1/9
First floor inundation	0.5–1.2	*4*	1	1/5	1/6	1/7
Risk of death	1.2–2.0	*7*	*5*	1	1/3	1/4
Excessive depth	2.0–3.0	*8*	*6*	*3*	1	1/3
Building failure	>3.0	*9*	*7*	*4*	*3*	1

consensus on the final scores given to different parameters. These scores were then arranged in the form of matrices for the AHP. One example of the scoring is given in Table 1, which deals with flood depth, and also is the matrix [A] (see Fig. 7) as an input for the AHP. In the table, the italics portion contains values from the scoring which follow the rule of AHP, and the non-italics portion contains values which are the inverse values of the italics portion. This procedure ensures building a reciprocal matrix.

In addition, a household survey was also conducted in March and April 2006 with broad objectives of flood damage assessment (tangible and intangible, direct and indirect) and flood risk analysis including investigation into flood risk perception by the local people. This paper has used a part of the household survey to distinguish the opinion of the local people on flood risk perception in different zones of the study area. The sample size of the field survey was 800 households with 70 and 30% men and women, respectively. The age distribution ranges from 18 to 88 years, and the education level of the sample was mainly secondary school. The field survey results also support the definition and selection of flood risk parameters as well as scoring for the pairwise comparison of the parameters.

Finally, the scoring matrices contain qualitative scores. Thus, it is essential to convert them into quantitative values and also check for consistencies of such matrices. This is achieved by the AHP, where the process is in sequence from the alternatives level (flood cells) up to the goal level. The final output of the AHP is the relative weights given to the elements of flood hazard and vulnerability, and the results are provided in Tables 2, 3, 4, 5, 6, 7.

5 Quantification of indicators of flood hazard

Flood hazard is evaluated through three indicators as indicated in Fig. 8. The relative weights to indicators of flood hazard are presented in Table 2. The C.R. values less than 0.1 clearly indicate that the errors are fairly small, and thus, the final estimates can be acceptable.

Table 2 Relative weights to categories of flood hazard indicators

Category	Flood depth		Flood duration		Flood velocity	
	(m)	Weight	(days)	Weight	(m/s)	Weight
1	<0.5	0.0282	<1	0.0425	0.0–1.0	0.0286
2	0.5–1.2	0.0596	1–5	0.0853	1.0–2.0	0.0633
3	1.2–2.0	0.1588	5–10	0.2241	2.0–3.8	0.1174
4	2.0–3.0	0.2744	>10	0.6482	3.8–5.8	0.2344
5	>3.0	0.4800			>5.8	0.5563
	C.R. = 0.0944		C.R. = 0.0887		C.R. = 0.0942	

Table 3 Relative weights to categories of economic indicators of flood vulnerability

Category	Residential building		Special public use		Public infrastructure		Agricultural area	
	Houses/hectare	Weight	Category	Weight	m/hectare	Weight	Category	Weight
1	<10	0.0334	Hospital	0.2500	<100	0.1047	Riverside	0.0351
2	10–50	0.0634	School	0.2500	100–300	0.2583	Grassland	0.0649
3	50–75	0.1290	Market	0.2500	>300	0.6370	Paddy-field	0.1373
4	75–100	0.2615	Admin	0.2500			Vegetable	0.2700
5	>100	0.5128					Orchard	0.4929
	C.R. = 0.0530		C.R. = 0.0000		C.R. = 0.0332		C.R. = 0.0554	

Table 4 Relative weights to categories of social indicators of flood vulnerability

Category	Population		Risk perception		Spiritual values		Income	
	People/km^2	Weight	Category	Weight	Category	Weight	Million VND[a]/capita/year	Weight
1	<500	0.1007	Good	0.0881	Belief	0.3333	>6.0	0.0676
2	500–1000	0.2255	Average	0.1947	History	0.3333	2.4–6.0	0.1991
3	>1000	0.6738	Poor	0.7172	Culture	0.3333	<2.4	0.7334
	C.R. = 0.0739		C.R. = 0.0811		C.R. = 0.0000		C.R. = 0.0811	

[a] VND = Vietnamese Dong (at time of the survey in March 2006: 16,000 VND = 1 US$)

Table 5 Relative weights to categories of environmental indicators of flood vulnerability

Category	Pollution		Erosion		Open spaces	
	Source	Weight	Category	Weight	Category	Weight
1	Industries	0.6694	High	0.6144	Outdoor recreation	0.5396
2	Waste matter from human and domestic animals	0.2426	Medium	0.2684	Tourist attractions	0.2970
3	Stagnations of floodwaters	0.0880	Low	0.1172	Natural reserves	0.1634
	C.R. = 0.0061		C.R. = 0.0634		C.R. = 0.0073	

Table 6 Relative weights to indicators of flood vulnerability subcomponents

Category	Economic		Social		Environmental	
	Indicator	Weight	Indicator	Weight	Indicator	Weight
1	Residential	0.6087	Population	0.4673	Pollution	0.6738
2	Special use	0.2485	Risk perception	0.2772	Erosion	0.2255
3	Public infrastructure	0.1014	Spiritual value	0.1601	Open space	0.1007
4	Agricultural	0.0414	Income	0.0954		
	C.R. = 0.0909		C.R. = 0.0115		C.R. = 0.0739	

Table 7 Relative weights to indicators of flood hazard and to subcomponents and components of flood risk

Category	Flood hazard		Flood vulnerability		Flood risk	
	Indicator	Weight	Subcomponent	Weight	Component	Weight
1	Depth	0.0974	Economic	0.4000	Flood hazard	0.3333
2	Duration	0.5695	Social	0.2000	Flood vulnerability	0.6667
3	Velocity	0.3331	Environmental	0.4000		
	C.R. = 0.021		C.R. = 0.0000		C.R. = 0.0000	

5.1 Depth of flooding

The depth of flooding is divided into five categories, and their weights are defined as presented in Table 2. 'Low inundation' is set for water depth lower than 0.5 m, which is approximately the average elevation of the plinths of residential houses, schools, and public buildings. Flooding with low inundation does not disturb much the living and working conditions in the flooded area. However, if the flood depth is over 0.5 m, it may cause inconvenience to the people living on the first floor of houses. The flood depth greater than 1.2 m may result in heavy losses to agriculture or even create a risk of death if flood velocity is high. Water depth over 2.0 m is considered 'excessive depth' since it nearly submerges buildings and cottage houses, resulting in the loss of lives and structural damage. Flood depth in excess of 3.0 m corresponds to the height of the ceiling of most rural houses in the study area. This situation may lead to the house's or the building's collapse. It also will completely damage crops. The flooding depth over 3.0 m has a weight of 0.4800, which approximates to 50% of the total weight with respect to flood hazard, whereas the flood depth of less than 0.5 m had a negligible weight of 0.0282 (Table 2).

5.2 Duration of flooding

Flooding duration is classified into four categories. Flood duration of less than 1 day is labelled 'short duration', and it causes only a minor disturbance to the routine activities of people. The next is 'medium duration' with a duration of 1–5 days, which may cause damage to paddy and other crops. The flooding duration of 5–10 days might lead to contamination and impact health, and this level is called 'long duration'. The most serious situation is called 'very long duration' if the flood lasts for more than 10 days. Its consequences are heavy pollution, outbreak of waterborne diseases, risk to health and probable loss of lives. As can be seen in Table 2, the weight to flood duration longer than 10 days is nearly two-thirds of the total weight. This indicated that pollution and outbreak of diseases after flooding are very important in the evaluation of flood risk. The weight to flooding duration of 5–10 days is also significant and contributes 22% of the total damage to agricultural areas.

5.3 Velocity of floodwater

The velocity of floodwater is categorized based on the safety and stability of people, vehicles, and buildings in the flooded area. Tingsanchali (1996) describes that if the average water depth is considered to be 0.5 m, the velocity below 1.0 m/s is the borderline for vehicle instability. A higher velocity, from 1.0 to 2.0 m/s, may lead to unsafe wading, whereas velocity over 2.0 may cause damage to light structures. In addition, Smith (1994) cites a relationship of critical velocity versus depth for building failure. The relationship describes that if the depth ≥0.5 m, the velocity exceeding 3.8 m/s would create the collapse of a one-storey building, whereas velocity exceeding 5.8 m/s may lead to the collapse of two-storey buildings. Accordingly, in the present study, flood velocity is classified into five categories with respect to flood hazard. The weights to different levels of flood velocity are given in Table 2.

6 Quantification of economic indicators of flood vulnerability

Vulnerability indicators are grouped into three subcomponents of vulnerability. These subcomponents are economic, social, and environmental. Table 3 presents the relative weights to categories of economic indicators of flood vulnerability. Again, the C.R. values less than 0.1 clearly indicate minimal randomness and high consistency of weights estimated for these indicators.

6.1 Residential building

Residential buildings are highly susceptible because people and their property are directly affected by flood (ESCAP 1991). During the flood season, an area with high density of housing experiences more damage than other places with a lower density. Thus, vulnerability of an area to flooding is based on the density of housing.

The study area is mostly rural, so a house normally contains one main building, a kitchen, a yard, and a small garden. In a village with dense population, each household normally owns about 100 m^2 of land for housing—excluding paddy field and cropland—and hence correspondingly 100 houses/ha is considered high density. However, in farmstead areas, farmhouses are common and at least 1000 m^2 of land is used for housing (other than farming area), which is equivalent to a density of 10 houses/ha and is referred to as low density. The five categories for residential buildings as used in this study are presented in Table 3. High relative weights (0.5128) to housing density of greater than 100 signify a higher vulnerability and thus severer flood risks when compared to low-density areas.

6.2 Special public use

Special public use is grouped into four categories, namely hospitals, schools, market places, and administrative buildings. In general, such buildings are located in the centre of a commune, a district, and a province. Questions were raised by experts in the group discussion (mentioned above) to mark the relative importance among special public use buildings. The score matrix of factors was then defined. The final consensus is that the scores of the factors should be equal for all special public uses, i.e., all the elements in the matrix were given ‘1’. The output provided by the AHP is the equal weights to each of the factors, i.e., 25% contribution to the economic vulnerability with respect to special public use as given in Table 3. The scoring in this case is fully consistent with C.R. equals to zero.

6.3 Public infrastructure

In this study, public infrastructure refers to the network of traffic roads and canals, which is very dense in the study area and can be evaluated using the database of the geography information system (GIS) through its density (m/hectare). Since the construction cost of public infrastructure is high and exposed to flooding, public infrastructure is included in the vulnerability assessment from an economic perspective. The situation may be more serious if the roads or canals are in the floodways or directly connected with flood diversion sluices or spillways.

Such public infrastructure is essential and valuable for the public living in the study area. Besides direct damage from its failure, indirect and intangible damages due to interruption of traffic, irrigation, and drainage system can be very severe. Public infrastructure is classified into three categories, as presented in Table 3. The relative weight increases gradually with the increasing density of roads and canals.

6.4 Agricultural area

Agriculture is the largest land use in the study area and mainly consists of paddy fields, vegetable crops, and orchards. Grassland and shrub areas cultivated for cattle are also weighed against vulnerability. Moreover, strips along both sides of the river are used for the cultivation of different crops.

In the scoring for the weights to different categories of vulnerability to the agricultural area, orchards receive the highest weight because of the high economic return from orchards besides the fact that orchards are very sensitive to flooding due to a low resistance to inundation. Moreover, once destroyed by flooding, it would require a few years to replant the orchard crops compared to other annual crops such as paddy, which only require 4 months for new cultivation. During interviews conducted as part of the field survey, farmers revealed that they would first want to protect orchards from the flood, followed by other crops. Some farmland owners are willing to pay flood insurance for their orchards. Consequently, a higher relative weight to orchards is assigned through qualitative and quantitative scoring as shown in Table 3.

7 Quantification of social indicators of flood vulnerability

The second subcomponent of vulnerability is social vulnerability. It has four indicators: population, flood risk perception, spiritual values, and income. Table 4 presents the relative weights to social indicators of flood vulnerability.

7.1 Population

The most important social indicator of flood vulnerability is population as it is affected by physical and psychological health, water disease outbreak, and loss of lives. Normally in rural areas, the population density correlates with housing density: for example, an area with dense population would lead to higher density of buildings and vice versa. In this study, the density of houses is considered as an indicator of vulnerability from the economic aspect, whilst population density is used as an indicator of vulnerability from the social aspect.

Population density varies much from solitary to residential areas and is classified into three categories: low population density (below 500 people/km^2), average population density (500 to 1000 people/km^2), and high population density (over 1000 people/km^2). Table 4 presented the weights to social vulnerability as a function of population density. A sudden change in weight from 0.2255 to 0.6738 is seen from average population density to high population density. Thus, villages with dense population would be highly vulnerable and should be considered as special cases. Such villages are given very high scores. That is the reason why the weight to the category of high population density is much higher than that of the category of average population density. The consistency of weighting to population categories is acceptable due to the C.R. calculated as 0.0739.

7.2 Risk perception

The experience of the affected individuals with hazardous events is the greatest factor affecting risk perception and also a critical factor in determining the success of mitigation efforts (Burn 1999).

The Tail Zone of the study area is frequently flooded and experiences flood diversion with an average return period of 3–5 years from the Hoang Long tributary. The local residents in this zone are well aware and well prepared to fight the flood during the annual flood season, and hence, they have "good" flood risk perception. Accordingly, the weight with respect to vulnerability in this zone is relatively small (0.0881), as presented in Table 4. Flood risk perception is found to be "poor" in the Middle Zone where people disregard flood diversion from the Red River because they think that it is a rare event and may not occur. Thus, because these people's perception is subjective towards potential flood and they underestimate the risk, the weight was highest (0.7172). There is a dire need for public education and awareness of flood risk in this zone. The Head Zone reflects better risk perception than the Middle Zone because the former is impacted directly by flood diversion as well as annual floods from the Red River. The flood risk perception in this area is at an average level, which has the weight of 0.1947. The C.R. value in this case is rather high but still less than 0.1, hence acceptable.

7.3 Spiritual values

The spiritual values mentioned herein are categorized into three types: cultural, belief, and historical. The historically valuable structures are ancient structures that are considered an essential part of community life, and their loss is intangible and difficult to estimate in terms of cost. The study area has been settled for thousands of years. Many historical and cultural monuments and religious beliefs were established and kept alive that need to be respected and preserved today. Buildings of different religious beliefs in this study area include temples, pagodas, churches, and cemeteries; the historical structures include archaeological sites, historic monuments, and museums; places for cultural activities, festival venues, and sports and recreation centres are grouped as cultural buildings. Experts discussed and concluded that it is difficult to rate the order of spiritual elements, and hence all three elements of spiritual values are assigned an equal score of '1'. Final weights computed by the AHP are 0.3333 to each category in spiritual values, an indicator of social vulnerability.

7.4 Income

Poverty and whatever other factors that prevent society from development are also the causes of increasing vulnerability (Takeuchi 2006). Poverty affects people's capacity to protect themselves and their property, as well as their inability to live in areas having less exposure to risk (Pilon P 2003). Income concerns the ability to pay for services and facilities before, during, or after a flood event; otherwise, a person may not be well to overcome difficulties caused by a flood (Dwyer et al. 2004). It is clear that poor people will not be able to prevent and mitigate flood damages, and consequently, they are more vulnerable to floods. The richer residents, on the other hand, have enough financial resources to construct buildings with a garret or two storeys as well as with other facilities to better prepare against the floods, and they are less at risk in the flood season. In addition, rich people usually prepare carefully before a flood is expected and also have vehicles for evacuation. A worldwide statistics by Pilon P (2003) about the number of people killed in floods from 1975 to 2001 based on the income class showed that people who belong to categories of low-income and middle-income groups accounted for 50 and 49%, respectively, while the percentage of high-income category dead was only 1%.

The study area is rural, so the income of the local people is low and mainly comes from agriculture, except for some villages that are engaged in handicrafts, farmsteads, or sending hired labour to the cities which provide higher income. A minority of the people living in downtown areas of villages or districts may have high income because they do business or work for government agencies or enterprises. Based on the income level, the communities in the study area are divided into three groups: poor people with income less than 2.4 million VND (US$ 150)/capita/year who are considered most vulnerable and its weight is 0.7334; the middle class from 2.4 to 6.0 million VND (UD$ 150 to 375)/capita/year with the weight of 0.1991; and the high-income group with over 6.0 million VND (US$375)/capita/year has the least weight (0.0676), as shown in Table 4. The value of C.R. for income is the same value with that for flood risk perception and also satisfactory.

8 Quantification of environmental indicators of flood vulnerability

Evers (2006) mentions that the interaction between flood and the environment that water-related biotopes and especially floodplains is not only extremely important but also rich ecosystems with a huge variety of species and functionalities. This research defines that one of the most important contributions to flood vulnerability is environmental susceptibility, which is represented by three indicators: pollution, erosion, and open spaces, as seen in Table 5. The description and quantification of relative weights to categories of these indicators is presented hereafter.

8.1 Pollution

Pollution due to flooding is of most concern in the study area. Pollution is caused mainly by three primary sources: industries, waste matter from human and domestic animals, and stagnation of floodwaters. Although the study area is rural and undeveloped, there exist some small factories and industrial parks, especially trade villages. If floods are diverted into these areas, the floodwaters will reach the pollution sources from industries. The industrial contaminants then will spread widely in flood detention areas that seriously affect the health of the people and may also impact the cultivation of agricultural crops. The weight to the pollution from industries is highest (0.6694), thereby indicating that industrial pollution contributes maximally to environmental vulnerability. According to VSC (2005), the discharge standard of industrial wastewater in the study area belongs to Type B because the wastewater is discharged into the Day River which is used for navigation, irrigation purposes, or for bathing, aquatic breeding and cultivation etc. The standard of Type B assigns the limitations of concentration of some main substances in industrial wastewater as follows: temperature ≤40°C, pH = 5.5–9, BOD_5 (20°C) ≤50 mg/l, COD ≤80 mg/l, suspended solids ≤100 mg/l, arsenic ≤0.1 mg/l, mercury ≤0.01 mg/l, and lead ≤0.5 mg/l, etc. Thus, the wastewater source violating any of these standards is considered causing environmental vulnerability.

Wastes from human and domestic animals also cause pollution during and after flooding. Most of people in the study area are farmers with low or average income. Housing conditions are poor and latrines are normally simple and without septic tanks, leading to non-sanitary conditions, especially with floodwater drifting and spreading the waste matter in flood detention areas. Similarly, livestock and domestic animals such as cows, pigs, or poultry in farmsteads or households also discharge excreta. This becomes more serious during and after the floods because the human and animal wastes are not disposed properly. The weight to this category is computed as 0.2426 as given in Table 5.

Stagnation of floodwater may also contribute to environmental vulnerability due to degradation of water quality and spreading of waterborne diseases. However, the impact of this category to environmental vulnerability is considered much less than other sources, and consequently, the weight given to this source of pollution is calculated as 0.0880. The consistency in rating scores for pollution categories is acceptable with the C.R. value of 0.0061.

8.2 Erosion

The erosion indicator of environmental vulnerability in this study is considered related to the propulsive force of moving floodwaters if flood diversion from the Red River into the study area is implemented, but not by the kinetic energy of rainfall. The propulsive power can be called "impulse", which is the product of water depth multiplied by flow velocity. Erosion by floods may cause disturbances to the ground surface and vegetative cover and can even cause the failure of infrastructure. Alkema (2003) states that if the impulse is higher than a critical value (referred to as 1.0), the crops (or buildings) are considered to be completely destroyed. The damage is not only limited to the loss of one year's production but also includes the loss of future harvests until newly planted crops start to produce again. Moreover, Green et al. (2000) cite the criteria to define the structural failure of masonry buildings based on the impulse as follows: the impulse <3 m^2/s: inundation damage only; the impulse = 3–7 m^2/s: partial damage; and the impulse >7 m^2/s: structural collapse. ESCAP (1991) and Tingsanchali (1996) have also developed the relationship between water depth and flow velocity which causes flood risk.

Based on the flood conditions in the study area and the literature discussed earlier, erosion potential in this research is divided into three categories: high, medium, and low. High erosion potential is defined when the impulse is greater than 1.0 m^2/s, whereas medium erosion potential happens with impulse from 0.5 to 1.0 m^2/s, and low erosion potential occurs if impulse is lower than 0.5 m^2/s. The weights to these categories are 0.6114, 0.2684, and 0.1172, respectively.

8.3 Open spaces

Open spaces in this study refer to the areas with natural environment and are used for outdoor recreation, as tourist attractions and as natural reserves etc. These areas are susceptible to floods, particularly when floodwater is diverted from the Red River to the study area with a very high flow depth and velocity and for a long duration. Open spaces are grouped into three categories. The first category is for outdoor recreation such as golf courses, resorts, farmsteads, amusement parks; the second category is tourist attractions, for example, famous landscapes or heritages, well-known pagodas or temples, and scenic spots; and the third category is natural reserves such as national parks, safari parks, and wildlife conservation areas. The outdoor recreation areas are highly vulnerable to flooding and are difficult to recover after flooding; therefore, they are weighted with the highest value of 0.5396. Tourist attractions and natural reserves are less susceptible to flooding and can be recovered after a flood. This results in lower weights to these two categories as presented in Table 5. The C.R. of scoring for categories of open spaces is computed as 0.0073; this means the scoring is consistent.

9 Quantification of subcomponents of flood vulnerability

Flood vulnerability is represented by three subcomponents—economic, social, and environmental—as described in Fig. 8. The relative weights to these three subcomponents as well as the final C.R. values for each of the subcomponents are given in Table 6. The consistency ratio of 0.0909 in rating importance to economic indicators is higher compared to the other two but this value is still considered acceptable.

9.1 Economic

As discussed earlier, flood vulnerability from an economic perspective is quantified based on four indicators, i.e. residential buildings, special public use buildings, public infrastructure, and agricultural fields. Results in Table 6 show that the importance of residential buildings is much higher than that of other economic factors because it directly relates to humans and their property. The weight to residential buildings is 0.6087, whereas that to special public use buildings is 0.2485. The agricultural fields contribute the least to flood risk from the economic aspect with the weight of 0.0414. Public infrastructure has a weight of 0.1014.

9.2 Social

Social vulnerability is based on four characteristics as described in Table 6. Population is most important and makes up about half of the total weight (0.4673). The next important social factor is flood risk perception with a weight of 0.2772. Burn (1999) explains that the importance of risk perception originates from the fact that the local public estimates flood hazards based on their perception of risk, and risk perception also controls the effectiveness of flood warnings communicated. Therefore, a relative weight of 0.2772 assigned to risk perception is justified due to the importance of risk perception. Spiritual values account for a weight of 0.1601. Spiritual values normally belong to a community and are not personal and often suffer indirect or intangible damage, and their recovery after failure is difficult and requires relatively large financial resources. However, in comparison with other social indicators such as population and risk perception, the indicator of spiritual values is third in the order of contribution to social vulnerability due to sparse density of such value structures in the study area. The element that affects social vulnerability the least is income, with a weight of 0.0954, because variations in income in the study area are not much. Moreover, the income indicator has an indirect impact on social vulnerability, whereas population and flood risk perception directly affect social vulnerability.

9.3 Environmental

Rapid urbanization and industrialization lead to environmental changes that affect people as well as open spaces. Environmental protection is therefore of utmost concern today, and analysis of environmental vulnerability to floods is essential for finding appropriate solutions to reduce flood risk.

Environmental susceptibility is analysed using three typical indicators: pollution sources, which is of particular interest due to contaminants from industries, waste matter from people and domestic animals, and stagnation of floodwater; the erosion potential in the surroundings of the downstream of hydraulic structures, inside the floodways, steep areas, and fallow lands; and the open space or areas that are specially devoted to outdoor recreation including parks, golf courses, tourist attractions, farmlands, resorts, natural reserves etc.

A pairwise comparison is implemented to obtain the weights to environmental factors as presented in Table 6, in which pollution is rated the highest weight (0.6738), while the combined weight of 0.326 is to the other factors considered (erosion and open space). The field survey also indicates that local people are worried about pollution during and after flooding because it may lead to the outbreak of waterborne diseases and may have other health implications.

10 Quantification of components of flood risk

The relative weights to three indicators of flood hazard, to the three subcomponents of flood vulnerability, and to the two components of flood risk are presented in Table 7. The indicators of flood hazard are judged consistently as reflected by the value of C.R. of 0.021. The C.R. value of zero for flood vulnerability and flood risk means full consistency in filling the matrix of impact factors.

10.1 Flood hazard

Flood hazard is quantified based on the integration of three indicators:flood depth, flood duration, and flood velocity, as presented in Table 7. Flood duration, with a weight of 0.5695, is the most dominant factor in flood hazard as it is causes stagnant water, which is responsible for the decomposition of fauna and flora, water pollution, outbreak of water-related diseases, or even environmental disasters and loss of life. The weight given to flow velocity is 0.3333 and to the flood depth is 0.0974. These results are in contrast with the findings of Penning-Rowsell and Chatterton (1977) where the depth of flooding was found to be a key determinant of flood damage. Nevertheless, Parker et al. (1987), as cited by Green et al. (2000), conclude that flood duration can lead to increased flood damage in both aspects of direct and indirect losses. Furthermore, the indirect and intangible damage caused by floods is derived mainly from flood duration (Lekuthai and Vongvisessomjai 2001). In the field survey conducted as part of this study, local residents expressed that a longer duration of inundation was more feared than flood depth and velocity. To shorten flood duration, it is essential to improve the drainage capacity of the flood diversion area.

Flood velocity is also an important indicator contributing to flood hazard in the study area. Flood diversion into the Day River is implemented when the water level in the Red River at Hanoi is about 13.4 m (above MSL), which corresponds to a water level of 15.62 m MSL at the upstream of the diversion structure. With the flood detention area in the downstream of the structure at 6 m MSL, the resultant velocity of the diverted flood water is of very high velocity. This situation is very dangerous and threatens structural failure and risk of death in the flood detention region. Green et al. (2000) states that floodwater velocity is also a determinant of flood damage, and timber and masonry buildings are likely to fall if flood velocity exceeds 2 m/s and depth greater than 1.5 m.

10.2 Flood vulnerability

As stated earlier, flood vulnerability is assessed from economic, social, and environmental aspects. Most residents in the study area are farmers who consider the economic impact of the flood as the most important factor. Floods cause direct damage to paddy fields and other agricultural crops. Furthermore, floods cause destruction of property and buildings, and the recovery of these would require much financial support. The social aspect seems not as important as the economic and environmental aspects because the flood's impact on the social aspect would mainly be indirect. Social vulnerability contributes only 0.2 in overall flood vulnerability. Environmental conditions after flooding are also a main concern. Their importance equals the economic aspect with the weight of 0.4 (Table 7). During the survey, the residents of the study area related their experiences about pollution and water diseases, stated these to be extremely dangerous, and expressed how these aftereffects made them concerned and scared even before the occurrence of flood events.

10.3 Flood risk

Flood risk is contributed to by two components, flood hazard and flood vulnerability. The flood hazard component represents physical processes, whereas flood vulnerability represents susceptibility to damage or loss, the risk of human lives, property or human activities.

For the study area, flood vulnerability contributes more than the hazard to flood risk due to several reasons. Population in the study area has grown more than three times (from 2,00,000 to over 6,00,000) in the last fifty years. Currently, people with improved standards of living have more possessions than they owned in the past, and hence there was relatively less damage in the past when compared to the present. At present, there are many belongings that are prone to damage when in contact with water, especially electrical and electronic devices/appliances that are highly susceptible to humidity, water, and dust during and after the floods. Moreover, the flood diversion study area has not been used for a long time as the flood control system consisting of upstream reservoirs and dykes along the Red River can protect the local residents against floods with a return period of 125 years and less. People ignore the fact that they are living in a flood diversion area and, therefore, are subject to floods and underestimate flood risk. In addition to that, because of infrequent flood diversion, the flood detention zones as well as floodways are being occupied by residential buildings, cultivation, and other socio-economic activities. This shows that flood vulnerability is increasing alarmingly in the study area. Based on these arguments, the vulnerability component is rated double as important as flood hazard and the weights to them are 0.6667 and 0.3333, respectively, as depicted in Table 7.

11 Conclusions

The study develops a methodology to define and quantify components and indicators contributing to flood risk in the Day River Flood Diversion Area of the Red River Delta in

Vietnam. The questionnaire field survey was carried out to investigate the flood risk perception of the local people in the study area. Expert analysis has been implemented to develop a pairwise comparison of the categories of various flood risk components. Relative weights to different components are then computed using AHP, and their consistencies also are checked.

Flood duration is found to be contributing more to flood hazard than flood depth and flood velocity by interrupting the normal and routine activities of the people and creating water pollution after the flood. This finding also corresponds to pollution holding the largest weight among the environmental indicators of flood vulnerability. Industrial wastewater is considered the most dangerous among pollution sources and thus is given the largest weight contributing to the pollution indicator of environmental vulnerability. The economic and environmental subcomponents contribute equally to flood vulnerability and are double that of the social subcomponent. Economic vulnerability is imperative because the study area is undeveloped and the income level of residents is low. In contributing to social vulnerability, the indicator of risk perception is more appreciated (given more weight), followed by population. It is, therefore, essential to improve public awareness on flood risk to effectively decrease flood vulnerability in the study area. Overall, the contribution of flood vulnerability is twice that of flood hazard to flood risk. These findings are very significant in developing strategies in reducing flood risk in the study area.

Based on the findings of the research, it is recommended that flood risk reduction for the study area can be achieved by implementing measures that reduce flood vulnerability. Non-structural measures such as raising public awareness, flood warning and forecasting, flood proofing should be implemented to reduce flood vulnerability in the study area. Floodway clearance is also suggested in order to reduce flood duration, and pollution control measure must be applied.

The relative weights to flood risk factors developed in this study can be used in conjunction with flood hazard and flood vulnerability indicators to compute flood risk indices and to develop comprehensive flood risk maps for the study area. The hazard indicators can be estimated using the hydrodynamic modelling of the floodplain, and the vulnerability indicators can be extracted from the socio-economic and GIS databases of the study area. The flood risk maps thus developed will be useful to policy-makers and responsible authorities, as well as to local residents in finding suitable measures for reducing flood risk in the study area.

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