Conceptual and methodological frameworks for large scale and high resolution analysis of the physical flood susceptibility of buildings

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Abstract

There are various approaches available for assessing the flood vulnerability and damage to buildings and critical infrastructure. They cover pre- and post-event methods for different scales. However, there can hardly be found any method that allows for large scale pre-event assessment of the built structures with a high resolution. To make advancements in this respect, the paper presents, first, a conceptual framework for understanding physical flood susceptibility of buildings; and second, a methodological framework for its assessment. The latter ranges from semi-automatic extraction of buildings mainly from remote sensing with their subsequent classification and systematic characterisation to the assessment of the physical flood susceptibility on the basis of depth-impact functions. The work shows results of implementation and testing the methodology in a district of the city of *Magangué*, Magdalena River Colombia.

1 Introduction

Analysis of the flood susceptibility of buildings is scarce which may negatively infer the properly and efficiently allocation of risk reduction measures (e.g. UNISDR, 2004). There are various approaches available for assessing flood damage to buildings and critical infrastructure based on field data collected after an event such as FLEMO (Kreibich et al., 2010) as well as synthetic approaches for assessing the damage prior to a future event as e.g. HAZUS (Scawthorn et al., 2006) and HOWAD (Neubert et al., 2009). Differences between the assessment models for flood damage and flood vulnerability of buildings in terms of scale, input data, damage calculation and outputs with their uncertainties are shown by Merz et al. (2004) and Jongman et al. (2012). However, these methods up to now cannot easily be used for a large scale and high resolution assessment along large rivers because of insufficient detailed scales of land-use maps, non-existence, outdated state or restricted accessibility of cadastral and other data, lacking classification and characterisation approaches for the built structures, and extensive time and resource consumption of required field work for damage analyses.

Most frequently, institutions use questionnaires or forms for the assessment of damage after flood events, but the results of these surveys do not always cover a spatial reference, or they are not interrelated, or the forms are filled by experts who have different levels of knowledge about the damage assessment. This makes the systematic analysis of exposure and vulnerability a challenge. Moreover, validity of findings is difficult to judge on due to the huge variety of methods, tools, processes and models for damage calculation.

Against this background, a novel approach is proposed that particularly enables the classification and characterisation of buildings on large scale as well as systematic physical flood susceptibility assessment. High resolution images and digital surface models are used as data source for the building analysis because they are supposed to capture huge multidimensional information on settlement features in an instant of time and allow for high efficiency through principal global availability and relatively low costs compared to surveying the parameters on the ground (Navulur, 2006; Vu and Ban, 2010).

Here, the conceptual and methodological frameworks and results of implementing and testing of a methodology are presented. The conceptual framework supports an in-depth understanding of the physical aspects of vulnerability and its influence on social and economic vulnerabilities. Furthermore, it describes key features that shape the physical flood susceptibility of buildings.

The methodological framework comprises three modules: (i) methods for setting-up a building taxonomy for settlements, (ii) methods for assessing the physical susceptibility of buildings and (iii) methods for technological integration of the two modules using computer-based tools. Testing of the methodology was carried out in a study site of a developing country selected according to the availability of data.

2 Conceptual framework

With physical flood susceptibility, the paper addresses one key aspect of vulnerability. Concept of vulnerability has evolved from specific fields related to various hazards. For instance, Thywissen (2006) presents 35 definitions of vulnerability. Detailed concepts of vulnerability have been provided by numerous authors, such as Blaikie et al. (1994), Birkmann (2006) and Messner et al. (2007). The latter even summarise some indicators and criteria for determining vulnerability. According to UNISDR (2004), vulnerability generally is “the characteristic of a system that describes its potential to be harmed”. Schanze (2006) proposes to understand vulnerability as a “mathematical” function of susceptibility, value or function and coping capacity of a system considering the physical, ecological, economic, social and institutional dimensions (see Fig.1). For buildings, the physical dimension of susceptibility, function and coping capacity can be conceived as follows:

Susceptibility here in case of buildings is understood as their propensity to experience harm (Samuels et al., 2009) and determined by their structural design, intrinsic properties and the material used (Naumann et al., 2011). The susceptibility is related to fragility, weakness, sensibility or instability, here applied to a building which can suffer a physical impact, degradation, failure, loss of structural integrity, or deformation of its materials and its components causing incapacity in the building functionalities.

Function of buildings may be seen as the purpose for which they are designed for or exist. Building basic functions are: to support dead loads, live loads and environmental loads (Ochshorn, 2009) such as protection of their inhabitants from rainwater, rough weather, safeguard them against invaders and enemies, provision of a static structure for their activities, or demonstration of social status or lifestyle through the inventory, furniture or design.

Coping capacity in terms of buildings can be understood as their resilience (Brauch and Oswald Spring, 2011) which may be considered as the ability to quickly and efficiently regain to the initial state after an impact (c.f. Naumann et al., 2011). As well as Evans et al. (2006) define the physical resilience of buildings as protective elements that allow the constructions to recover quickly and easily.

Physical flood vulnerability can be seen as strongly linked to *social and economic vulnerability* because disturbance of the physical elements immediately interrupts or disjoins social and economic activities. For instance, the WHO (2009) finds sufficient evidence to link health problems to building moisture and biological agents, caused for example by sanitary sewer lines to back up into buildings through drain pipes or contaminated water from fuel tanks. Potentially, allergies or respiratory diseases may be triggered in the inhabitants by the presence of mould, muck, insects or toxic sludge in the building materials after a flood. It could be inferred that people living in houses with moisture are susceptible for particular diseases, infections or allergic reactions.

Moreover, structural impacts on buildings might be a reason for people to migrate or temporally or permanently move to other neighbourhoods. Therefore, in the social dimension, the estimation of potential negative consequences caused by a flood could be supported by an assessment of flood impacts on buildings.

The estimation of economic flood vulnerability might be assessed according to the impacts on buildings in combination with economic data. For instance, the assessment of physical vulnerability may provide the basis for the calculation of reconstruction costs, economic losses in stocks and for depth-damage functions. This information might likewise support the analysis of a potential compensation for losses depending on the quality of socio-economic information. Hence, potential consequences are categorised by a diverse typology, i.e. direct and indirect impacts or damages, which can be tangible or intangible. Tangible damages can be specified in monetary terms; intangible damage is usually recorded by non-monetary measures (Messner et al., 2007).

Therefore, physical flood vulnerability is not only understood as a mere component of risk and risk management but it can also be seen as a basic element for determining with better precision the interaction of people with the safety of their environment (UNEP, 2002). Reciprocally, the economic coping capacity regarding buildings requires the analysis of the economic resources for recovery or reconstruction activities. Hereby, the physical flood susceptibility is always a component of the physical flood vulnerability with both belonging to a flood risk system (c.f. Schanze, 2006).

Merz et al. (2004) identify the need for refinement and standardisation of data collection for flood damage estimation, and state that current depth-damage functions may have a large uncertainty. Additionally, these functions present relevant differences for damage assessment in terms of “damage categories, degree of detail, scale of analysis, the application of basic evaluation principles (e.g., replacement cost, depreciated cost) and the application or non-application of results in benefit-cost and risk analysis” (Meyer and Messner 2005).

To make a step forward particularly towards a systematic, transferable and standardised process, a reliable building typology approach for supporting a pre-event assessment of the physical flood susceptibility at large scale is required. Beyond, there is a need for methods that assist in standardised data collection on the building susceptibility on an overview level. Not at least, detailed damage analyses should be advanced to improve validity of local in-depth investigation and hence enable simulation of future vulnerabilities and risks. The proposed methodological framework focusses on the building typology approach and the standardised susceptibility assessment on a large scale.

3 Methodological framework

Operationalisation of the conceptual framework focusses on the physical dimension of sustainability on the one hand and on susceptibility as one of the components of vulnerability on the other hand. It makes use of three modules which refer to all relevant aspects influencing the physical flood susceptibility of buildings (Fig. 1). The modules set the frame for methodological requirements and can be dealt with alternative methods. Assessment is supposed to follow the numerical order of the modules.

The first module “Building taxonomy of settlements” addresses the set-up of a building typology as *building taxonomy*. This is based on the extraction of parameters from remote sensing data and GIS analysis. The building taxonomy allows for synthesising the analysis of the building susceptibility, because the surveys must not be done one by one, which would be very expensive, and information can be transferred to other buildings with similar characteristics. Subsequent identification of representative buildings is based on statistical analysis and membership functions.

The second module “Physical susceptibility of buildings” refers to the assessment of representative buildings from each building type with the aim of derivation of principal *depth-physical impact functions*. It relates the relevant building components including their heights, their dimensions and their materials to the susceptible volume of the building materials at different water levels. The material’s susceptibility is being estimated based on literature research and/or expert judgments. Depth-physical impact functions are derived from interrelations between the water level and the susceptible volume.

The third module “Technological integration” provides the computer and mobile tools for the operationalisation and automation of major methods. Thus, tools for integration of the building taxonomy and the depth-physical impact functions of representative buildings are developed to support the automatic processing. This module is supposed to be potentially integrated into a spatial decision support tool (SDSS) as proposed by McGahey et al. (2009).

3.1 Module 1: Building taxonomy for settlements

A building taxonomy can serve as a means of structuring settlements for a more detailed analysis in large river floodplains. Based on findings from earthquake engineering research (Brzev et al., 2011), which is creating an initial (beta) version of a building taxonomy for the World Housing Encyclopedia (WHE), a building taxonomy is developed in order to cluster the similar building in a group for reducing the effort to investigate the buildings. The presented approach modifies the proposal from Brzev et al. (2011) which only involves parameters describing the topological surrounding, geometric and roof surface characteristics.

The building taxonomy approach at first requires identification of the individual buildings. This can be done by predominately semi-automatic extraction from remote sensing data, depending on “the resolution of data, especially of the high data, on the selected method, on the scene complexity and incomplete cue extraction” (Sohn and Dowman, 2007). Once the buildings are identified, parameters or attributes may be discretised into classes called categories. A compendium of all categories can then be arranged in codes and leads to the building taxonomy. Finally, some representative buildings for each building type are selected for a posterior assessment.

3.1.1 Extraction of buildings from VHR data

Very high resolution (VHR) images from satellite sensors and aerial photos directly provide a lot of different levels of information on many phenomena, allow the differentiation of elements on the urban fabric such as building characteristics and even facilitate investigation of the temporal changes in an area (Fugate et al., 2010; Mesev, 2010).

Blanco-Vogt et al. (2013) describe how these parameters play a particular role in setting up building typologies in the context of flood susceptibility assessment using very high resolution spectral data together with digital surface models. Brenner (2010), Rutzinger et al. (2009) and Sohn and Dowman (2007) demonstrate a huge variety of methods and data sources for the extraction of different building features. Hence, the building features extraction cannot be carried out with just one method or follow a unique algorithm. Instead, its results depend on data source, quality of data, methods and expected accuracy.

The proposed building taxonomy approach bears on very high resolution spectral and elevation data for gathering building parameter that are key for the characterisation of the physical construction. These parameters are initially *building's outline*, *building height* and *building roof slope*. Once the building outline has been extracted, the parameters *size*, *elongatedness*, *roof form*, *adjacency*, *compactness* can be derived. Building height and building roof slope depend on the ground samples from digital surface models.

3.1.2 Derivation of the building taxonomic code

The parameters mentioned above are determined through continuous values (*size, height, elongatedness and roof slope*); discrete variables (*adjacency and roof form*) and interval scale variable as the values are ranked (*compactness*). It is important to note that building attributes are not always distributed according to a bell curve and the patterns of parameter values are not predictable.

An approach for finding patterns and classes between the building's characteristics is coding the data (Adriaans and Zantinge, 1996). Coding information allows systematically identification of variables and values and to ensure their validation. The data codification for each parameter corresponds to a category describing the building characteristics. The coding is initiated by induction. Each parameter is codified on the basis of the building's initial description; those categories are then improved in function of the emerging theoretical questions and the results from the empirical application.

The borders of the classes are adjusted through (i) statistical analyses: histogram diagram, scatter diagram and the correlation matrix in order to find trends and relations in the parameters and (ii) advice from experts (e.i. civil engineers, architects) who discussed the relevance of the classes for the subsequent susceptibility assessment. The building taxonomic code associates the quantitative data with the qualitative data of the categorisation. The validation is done comparing visually the building's characteristics with the codes which are revealing building patterns. As result of the process, Table 1 discloses the categories and codes for every parameter.

For instance, the code *‘1111111’* describes from left to right: *(1st digit: height*) a short building; size less than 150 m^2 (*2nd digit: size*); with square form in the space (*3rd digit: elongatedness*); very simple form (*4th digit: roof form*) and flat roof (*5th digit: roof pitch*); open space around the building larger than 66% (*6th digit: compactness*) and all sides exposed to open space (*7th digit: adjacency*). Two additional examples of the taxonomic code are displayed in Figure 3. The pictures show that the buildings with the code ‘1221123’ present similar roof eaves, whereof the buildings with the taxonomic building code ‘2121134’ contain a balcony and similar roof construction.

3.1.3 Selection of representative buildings

Representative buildings have been selected from each building type as samples for the subsequent assessment of potential flood impacts (see sect. 3.2). The selection of representative buildings for each type allows for the transfer of knowledge from in-depth investigations of individual buildings to other buildings with similar characteristics.

Representative buildings stand for “typical”, “prototype”, “archetypal”, or “common” buildings in a study area. Using histograms, the representativeness of the taxonomic codes with higher frequency in a particular area or district, can be separated. The other buildings with lower frequency are called non-representative buildings.

An approach for finding similarities between the representative buildings and the non-representative buildings is grouping the data using cluster analyses (MacQueen, 1967) which allows identification of groups of objects with similar patterns but differences from individuals in other groups. The selected representative buildings are the *K* clusters which contain p quantitative parameters. The similarities of non-representative buildings to the representative buildings are compared, taking values between {0, 1}, the “crisp” values belonging to a membership function. A membership function provides a measure of the degree of similarity of an element to a fuzzy set and helps to identify the borders between the typologies, where they are inherently vague (Coppi et al., 2006).

The sum of the assigned values gives the percentage of matching to a representative building. Then, the non-representatives are grouped to the building type with the largest values of membership depending on the degree of similarity. A threshold of similarity was selected of 80% for grouping the non-representatives to the representatives. The buildings under this threshold are considered atypical and hence also selected for the assessment. Inductive reasoning, iterative process and trial and error help to generate the membership functions and the rules for selecting the value of the sum for the matching in order to minimise the entropy for every case study.

3.2 Module 2: Physical susceptibility of buildings

Once the representative buildings in the study area have been selected, the assessment of their physical flood susceptibility is carried out. For this purpose, the potential flood impacts for representative buildings are analysed according to (i) identification of building components, (ii) assessment of building materials' susceptibility and (iii) derivation of depth-physical impact functions.

3.2.1 Identification of building components

Identification of building components consist of (i) recognition of relevant building components, (ii) measurement of their upper and lower height above ground, (iii) measurement of their relevant dimensions, (iv) distinction of the relevant materials and (v) calculation of material volume.

Building components can be categorised in structural components, shell components, non-structural components, connectors, inventory and finish components. An example of the list of shell, structure non-structured and inventory components that can be exposed to different water depths is depicted in the Fig. 4.

Non-invasive methods can be carried out for analysing the structure and shell components of buildings, such as the presence of basements, external windows, external doors, façade, external walls, some roofs characteristics, balconies, columns, beams, slabs. At least, these components must be distinguished and inventoried for the building susceptibility assessment. The components can be specified according to their position above the ground and related to water depths that could cover them.

The building size, perimeter, height, roof slope, width and length are calculated from the features extracted using the very high resolution data. The additional required dimensions can be measured by mobile mapping, multidirectional imaging, terrestrial photogrammetry, laser instruments, Apps, metre sticks, information provided by the manufacturer or known standard dimension for the calculation of the components' volume.

The surveys allow the experts to identify construction processes and material used for the representative buildings as well as the name of the materials for the region, because a material´s name can vary depending on the area. Finish materials should not be taken into account because of their diversity and complexity for differentiating them.

3.2.2 Assessment of building materials' susceptibility

Susceptibility means that the material will be harmed, worn or degraded due to the flood. In contrary to susceptibility, resistance or resilience is often viewed as a positive property meaning a receptor's ability to withstand an impact without significant alteration (resistance) or to be easily reconstructed (resilience; e.g. Naumann et al., 2011).

As a first step, the building material's resistance can be analysed according to international studies, such as BMVBS (2006), Committee and Resources (2006), Escarameia et al. (2006) and FEMA (2008) which qualify materials´ resistance giving linguistic terms. For this investigation, the lists of materials from the four institutions were compared and some similarities in the qualification were found, such as the qualification of resistance in brick face, brick common and standard plywood. There are as well, some differences in the quality of material resistance, depending on where the material is used into a component. Here, it is assumed that susceptibility is the opposite of resistance.

As a second step, expert knowledge method may assist the qualification of susceptibility depending on the use of materials and detailed information about the materials' properties. Aglan et al. (2004) describe some materials' properties which can be observed, inspected and monitored using the human senses.

The materials' properties selected for the qualification are: *resistant characteristics after flooding* (shearing, flaking/scaling, bending, cracks, buckling, swollen, none); *general appearance* (discoloured surfaces, efflorescence due to crystalline deposits of alkaline salts, none); *biological and chemical reactions characteristics* (mould growth, spreading odours, contamination due to its intern components, oxidation, none) and *type of process for repairing after flooding* (clean or washability, dry, paint, repair and replace, none); *natural drying speed* in number of days and if available, technical standards and specifications in construction based on ISO standards or codes produced by manufacturers' associations. Those properties should be documented, assessed and recorded photographically. The highest assessed value reflects that the material can generate the collapse of the component. The monitoring of the buildings' properties can help for susceptibility assessment in other areas. The formulas proposed by Hong and Lee (1996) are considered for determining the fuzzy set values of materials' susceptibility.

3.2.3 Derivation of depth-physical impact functions

These functions are developed in order to support damage assessment overcoming the lack of monetary values or refurbishment cost data. Similar to depth-damage functions, depth-physical impact functions are derived as a relationship between the depth of a flood and the susceptibility of the impacted material volume. Physical impacts in buildings are estimated on the basis of the potential *susceptible materials' volume* for components calculated in m^3, i.e. degraded material in relation to a maximal susceptibility of 1. The materials of the components are continuously impacted when the water level rises.

3.3 Module 3: Technological integration

The two previous modules are integrated using computer-based tools. The system architecture is developed for managing the collected information of the physical flood susceptibility assessment for representative buildings. The users can manage to collect data using smart phones, process, transfer and share the information. Various tasks can be carried out automatically such as calculation of the parameters, creation or editing of the taxonomic code, clustering the building types, selection of representative buildings and integration of information in depth-physical impact functions. A database in PostgreSQL can be designed for storing the data and integrating the building taxonomy and depth-physical impact functions using Python scripts of the ArcGIS™10 environment.

4 Implementing and testing the methodology in a study case

As follows, implementation and testing the methodology in the district "*Barrio Sur*" in the city of *Magangué* - Colombia located in the floodplain of the Magdalena River is shown.

4.1 Setting up the building taxonomy

4.1.1 Processing a semi-automatic extraction of buildings from remote sensing data

Planimetric and elevation information are required for the extraction of building features for the derivation of the building taxonomy. Building size, elogatedness, roof form, adjacency and compactness are derived from the planimetric information provided from stereo images of the UltaCAM sensor with ground sample distance of 0.15 m and 3 bands accessible for this study area. Elevation information from precise sources such LiDAR was not available for this area. Therefore, a DSM was photogrammetrically generated from the stereo photos for the extraction of the building height and building roof slope. However, resolution in altitude of this DSM did not exceed 2 m.

The semi-automatic building extraction process consisted in combining masks methods (Awrangjeb et al., 2010) and segmentation processes (Schöpfer et al., 2010). Segmentation was used for dividing the image into regions that are supposed to be the building roofs with similar spectral and topological characteristics. Using reference polygons of the building outline, the accuracy of the building extraction is calculated using the indexes proposed by Song and Haithcoat (2005) and Aguilar and Mills (2008); for a more general discussion of factors influencing accuracy see Sohn and Dowman (2007).

The building extraction process gave as result the detection of only 44% of the buildings. The inconsistencies for the building extraction in this selected area is due to the presence of corrosion of the roof materials, the occlusion of the buildings from tree and shadows and the low resolution of the DSM in combination with numerous small buildings. The latter has been overcome through additional field work. The issue of the DSM's resolution for this area was compensated validating it in the field work. Testing the methodology in other cases has proofed that the proposed resolution of the DSM with > 1 m significantly improves accuracy. The buildings that did not fit the criteria of accuracy were manually edited.

4.1.2 Deriving the building taxonomic

Once the building outline was delineated from the orthophotos and the resolution of the DSM was accepted as a preliminary source for the height extraction, the seven parameters were calculated according to Table 1 using the tool for the derivation of building taxonomic code for every building. A visual verification of the buildings belonging to the taxonomic code was conducted using pictures of the buildings taken in-situ in Colombia and Google Street View. As result in this district, 290 buildings in 77 taxonomic building codes were classified. Many building classes can indicate the heterogeneity of the building characteristics in the district.

4.1.3 Selecting the representative buildings

Based on the histogram, it was decided that 9 buildings are the threshold for considering the representative buildings, as result giving 7 groups of representative buildings. Other buildings are non-representative buildings, which were clustered to the representative using the membership function (Eq.1).

$$U_{R-nonR} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \\ 0.3 & 0.3 & 0.3 & 0.3 & 0.3 & 0.3 & 0.3 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (1)$$

Figure 4 shows three buildings that were randomly chosen using the stratified selection of samples, which are clustered to the representative buildings with taxonomic code ‘*2221123*’. This taxonomic code represents buildings with two storeys, size between 150 m² to 500 m², rectangle form in the terrain, roof form with less than 8 vertices, flat roof, open space area between 33 % to 66 % and two sides exposed to open space. The non-representative building '*2222122*' is clustered to this representative with a matching of similarity of 85.7 % and the non-representative building '*2222123*' is clustered to this representative with a matching of similarity of 92.86 %.

4.2 Assessment of the buildings' susceptibility

Published materials' resistance of the buildings studies in Colombia do not exist for being used as reference for the susceptibility qualification. Four experts were asked to assign the values for the five susceptibility properties described in the section 3.2.3. The knowledge of experts allows the qualification about the resistant characteristics after flooding, general appearance, biological and chemical reactions characteristics, type of process for repairing after flooding and natural drying speed of shell and structure components.

A first discussion about the susceptibility properties revealed different descriptions about the materials´ properties after the flood. Therefore, a consensus among the experts was reach based on a simplified Delphi approach. Then, the qualification of the materials has been computed for obtaining the fuzzy sets of susceptibility (see Tab. 2).

Building components and building material were identified and their position above the ground, and their dimensions were collected in-situ using an App in the smart phone. The susceptible volumes were calculated for these representative buildings as is shown in Table 3 for the building '*2221123*'.

After that, the derivation of the depth-physical impact function was carried out. Table 4 relates every susceptible volume of the component for a level of water depth. The water depths are depicted in the blue colour row. The potential degradation for every component continually increases from its lower height until the water level overtakes its upper height, as the water depth rises. Up here, the component degradation is assumed to be constant, when the flood continues to rise. The sum of the susceptible volume for the impacted components for every water depth is calculated in the green row.

This process was carried out for the three buildings for the derivation of the depth-physical impact functions (Fig. 5). The curves depict the potential deterioration in m^3 of the buildings' integrity. Hence, depending on the water depth, an amount volume in m^3 is degraded.

The next step consists on the derivation of a synthetic function for every taxonomic code. Then, each building taxonomic code has a *median depth-impact function* with its respectively standard deviation by water depth (see Fig. 6).

The information of the 7 synthetic functions for this study area can be transferred as long as the areas have similar conditions of development and are located in the same region, assuming that the buildings share similar construction materials. In this example, the information of median depth-physical impact functions of the representative buildings may be used for the assessment of flood damage to the buildings with similar characteristics located in the northern part of the Magdalena River floodplain.

5 Discussion

Testing the methodology derived from the conceptual framework led to useful results for a large scale and high resolution physical flood susceptibility assessment for buildings. The combination of modules 1 to 3 appeared to be effective in the classification and characterisation of the built structure and the subsequent susceptibility assessment. It proved as a systematic procedure with reduced efforts compared to extensive ex-post damage surveys or ex-ante synthetic damage simulation modelling. Consideration of the entire physical flood vulnerability would require the operationalisation of both the physical function of construction elements and their coping capacity in terms of physical resilience. To address these two, further research is needed that will face a particular trade-off between physical validity and resource efforts for the field work. However, investigation in this respect is likely to be included in the survey already required for the assessment of the physical flood susceptibility.

Transferability of the approach to other study regions seems mainly to depend on the accessibility of very high resolution data. Although there are currently certain limitations in many regions of the world, improvements may be expected from new sensors. There is a rapidly increasing trend towards the availability and accessibility of spatial data and improvements of their properties in terms of resolution. For instance, unmanned aerial vehicles may be supposed to provide support for the collection of very high resolution images and the improved accuracy of the extracted features.

Additionally, new free algorithms for features extraction play a role, such as SpaceEye (ICIS 2009) which allows processing of the global data of Google Earth with simple functions on the imagery such as segmentation and edge extraction. These technological advances will contribute in the near future to the collecting of a huge amount of data which require to be classified for the analysis of settlements.

6 Conclusions

So far, the conceptual and methodological frameworks presented in this paper are a novel approach that has some potential for assessing the physical flood susceptibility on a large scale. The implemented and tested methodology can prepare detailed civil engineering analysis in hot-spot areas as well as further social and economic vulnerability analyses.

The concept of flood vulnerability allows decomposition of methods for the physical flood susceptibility assessment. These methods, which are bundled in modules, can support an initial estimation of potential flood impacts on buildings.

Accordingly to the literature, very high data resolution of images and digital surface models are required for the extraction of building features. Then parameters building height, building size, elongatedness, roof form, roof slope, compactness and adjacency can be derived from these features. In the selected study case, a semi-automatic and manual processing was carried out for building outline extraction, and the values of building height and roof slope was automatically extracted and verified in the survey.

The reliability of the extraction of the parameters depends on accuracy of the building outline or building footprint, the resolution of the digital surface model and the complexity of the area.

The building taxonomic code composed by seven parameters can assist experts in identifying the relevant structural characteristics of a building. It should be appropriate for any region and can serve as a vehicle for transferring patterns of variables of settlements. It condenses the parameters in a brief format, establishing a clear link among the buildings' geometrical characteristics, and is extensible, adaptable and transferable to other study areas. As well as it is a trustful, standard, and automatic method and it helps to simplify the communication between the users who are dealing with building structure surveys in the urban areas. The validity of this building typology is borne out visually comparing pictures of the buildings with the obtained parameters in the taxonomic code. It is a valuable and reliable source of information, which can be used for synthesising field works also in other types of applications such as social science researches (e.g. living condition index, demographic studies, service availability), economic researches (e.g. insurance schemes, cadastral appraisals), energy assessment (e.g. Loga et al., 2012) and the assessment of other types of vulnerabilities.

Statistical and cluster analyses are good means for selecting representative buildings and grouping non-representative buildings to representative buildings using a membership function. This generates a value of matching, indicating the degree of similarity of a building to a representative building. The approaches of selecting the representative buildings via the building taxonomic code can help to reduce costs and time required for surveying of information in urban areas. Because, it makes the collection of data in field more effective and also allows transfer of knowledge about the building structure.

The determination of materials' susceptibility involves many uncertainties and different interpretations from the experts; some that is susceptible for one expert has another interpretation for another. Here, these uncertainties are attempted to be reduced integrating scientific and local knowledge. Two steps for an approximation can be carried out for its determination: (i) provision of information on the materials' resistance assuming that susceptibility is the opposite of resistance incorporating the resistance values from international approaches (e.g. BMVBS, 2006; Committee and Resources, 2006; Escarameia et al., 2006; FEMA, 2008); (ii) assessment of the materials' properties based on the expert which knowledge allows determining uncertainty associated with the vagueness of the materials' susceptibility. This information is important to be stored and evaluated in order to distinguish which building materials can suffer cracks, flaking, strain, brittleness, shrinkage, deflection, bending stress, buckling, shearing, expansion, or residual stress that affects the proper functionality after an event of inundation.

The derivation of depth-physical impact functions requires a structured collection of information on the relevant components of the representative buildings, such as their relevant materials, the materials' properties for their susceptibility qualification, their related dimensions such as width, length and thickness as well as the location above the terrain (lower height and upper height). Hereby, depth-physical impact functions are seen as a means of interrelation between the water depth and the degraded volume of the buildings' materials per component. The median depth-physical impact function is a synthetic function for every taxonomic code that reflects the range of potential impacts which can get a group of buildings with similar characteristics. This function may provide the basis for subsequent derivation of a depth-damage function as basic indicator of economic vulnerability and social vulnerability.

Taking advantage of the technological advances for data collection such as GPS in smart phones, Apps, data storing such as a database in PostgreSQL, and data processing such as Python scripts, new tools were developed for simplification and control process. They refer to derivation of taxonomic code for each building, selection of representative buildings and the integration of the methods for building susceptibility assessment.

As future work, the depth-physical impact functions should be tested for supporting the analysis of other types of vulnerabilities, assisting damage detection, refurbishment costs, and estimation of the loss with a monetary value. The material lists of the four named institutions with their resistance classes may be extended based on the qualification of materials´ properties, increasing the knowledge on various building materials in developing countries. This information may support the calculation of the susceptible volume for components in representative buildings supporting detailed civil engineering analyses.

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Table 1. Range of categories for the seven parameters of the building taxonomy

Parameter	Code	Description
Height	1	<= 7.5 m
	2	> 7.5 – 13 m
	3	>13 - 30 m
Size	1	0 -50 m²
	2	>150-500 m²
	3	>500-800 m²
	4	>800-1000 m²
Elongatedness (length/width ratio)	1	Square: 0.8-1.2
	2	Elongated rectangle:> 0.8 and < 1.2
Roof form	1	< = 12 vertices
	2	>12 vertices
Roof slope (Roof pitch)	1	<= 10 degrees
	2	>10 degrees
Index inversely compactness	1	> 66%
	2	>33 % - 66 %
	3	<= 33 %
Adjacency	1	All sides exposed to open space
	2	At least three sides exposed to open space
	3	Two sides exposed to open space
	4	One side exposed to open space

Table 2. Qualification of attributes of susceptibility

Component	Material	Resistant characteristics after flooding	Type of process for repairing	General appearance	Biological and chemical reactions characteristics	Natural drying speed	Fuzzy sets min-med-max
Roof	Concrete, steel plate and waterproofing	Peeling	Repair	Efflorescence	Mould growth and corrosion	2	0.30-0.31-0.42
Slabs	Concrete and steel plate	Buckling	Replace	Efflorescence	Mould growth	2	0.39-0.45-0.67
External fenestration	Wood	Peeling and bending	Replace	Efflorescence	Mould growth and odours	5	0.66-0.99-1.00
External fenestration	Coated aluminium	None	Drying and paint	Discoloured surfaces	Corrosion	1	0.19-0.30-0.33
External fenestration	Metal gate and fence	None	Drying and paint	Discoloured surfaces	Corrosion	1	0.27-0.49-050
External walls	Cement block and plaster	Cracking	Replace	Efflorescence	Mould growth	4	0.51-0.79-0.81
Floor	Terrazo	None	Clean	Discoloured surfaces	Mould growth	2	0.19-0.42-0.55
Floor	Ceramic tiles	None	Clean	Discoloured surfaces	Mould growth	2	0.19-0.28-0.30
Columns	Concrete and steel rods	Bending	Repair	Efflorescence	Corrosion	2	0.19-0.30-0.55
Foundation	Cast stone	Flexion and peeling	Drying	Efflorescence	Mould growth and corrosion	4	0.09-0.38-0.52

Table 3. Example of information collected for the analysis of susceptibility - Building *‘2221123’*

	Component	Lower height	Upper height	Material	Susceptibility	Volume material in m^3	Susceptible volume in m^3
Second floor	Roof	6.4	6.6	Plate in concrete, steel and waterproofing	0.31	39.22	12,16
	External fenestration	4.2	5.5	Wood	0.99	4.80	4,75
	External walls	3.4	6.4	Cement block and plaster	0.79	33.08	26,14
	Floor	3.3	3.4	Ceramic tiles	0.28	19.61	5,49
First floor	Slab	3.1	3.3	Concrete and steel plate	0.45	39.22	17,65
	External windows	2.5	3.0	Coated aluminium	0.30	1.00	0,30
	External walls	0.2	3.0	Cement block and plaster	0.79	32.08	25,35
	External doors	0.2	2.5	Metal gate and fence	0.49	1.00	0,49
	Floor	0.0	0.2	Terrazo	0.42	19.61	8,24
	Columns	-1.0	6.6	Concrete and steel rods	0.30	3.08	0,92
	Foundation	-1.0	0.2	Cast stone	0.38	11.82	4,49

Table 4. Derivation of the **building’s susceptible volume** for water depth related to the material of Table 3.

											0.31	12.16	
								0.99	4.75	4.75	4.75	4.75	
							0.79	8.03	19.80	26.14	26.14	26.14	
						0.28	5.49	5.49	5.49	5.49	5.49	5.49	
					0.45	17.65	17.65	17.65	17.65	17.65	17.65	17.65	
			0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	
	0.79	1.67	20.96	25.35	25.35	25.35	25.35	25.35	25.35	25.35	25.35	25.35	
	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	
	0.42	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	8.24	
0.30	0.40	0.41	0.59	0.63	0.64	0.65	0.66	0.73	0.83	0.89	0.91	0.92	
0.38	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49	
-1.00	0.20	0.30	2.50	3.00	3.10	3.30	3.40	4.20	5.50	6.20	6.40	6.60	**Water depth**
0.68	6.59	15.29	35.07	39.49	39.95	57.45	63.46	71.75	87.39	93.79	94.11	105.98	**Sum**

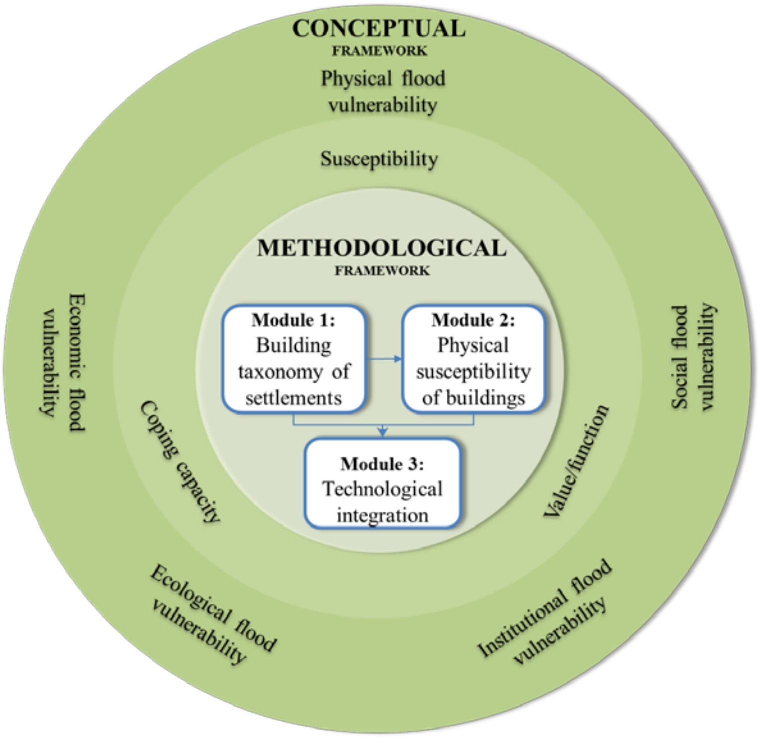

Figure 1. Frameworks of the methodology with dimensions of sustainability (outer circle), components of vulnerability (middle circle) and the modules (inner circle)

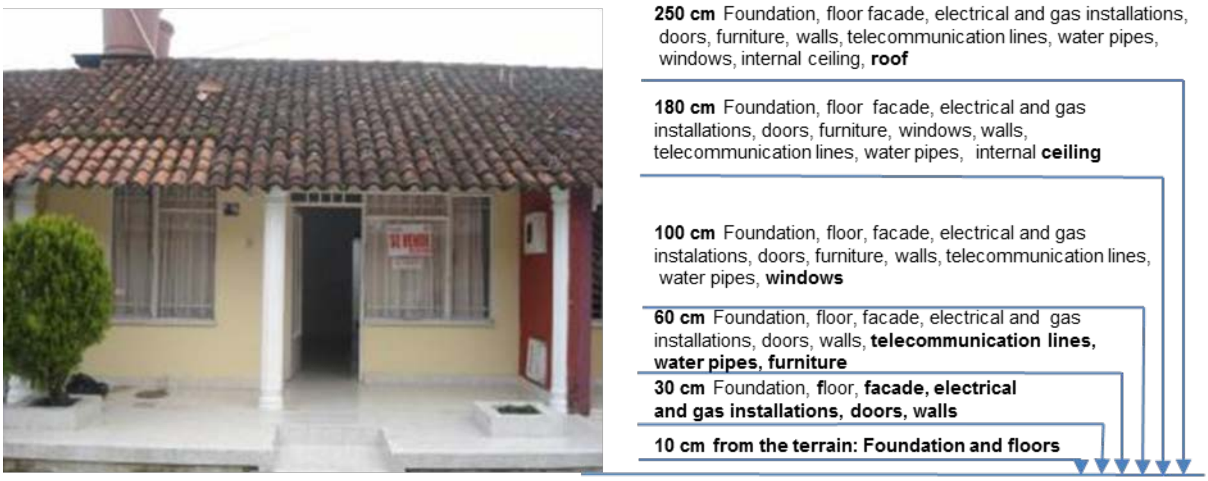

Figure 2. Relevant components of the building exposed to water depths

1221123

One storey, footprint size between 150 m² and 500 m², rectangle form in the terrain, roof form with less than 12 vertices, flat roof, open space area between 33 % and 66 % and two sides exposed to open space.

2121134

Two storeys, footprint size between 150 m² and 500 m², rectangle form in the terrain, roof form with less than 12 vertices, flat roof, open space area less than 33 % and one side exposed to open space.

Figure 3. Examples of the building constructions of the taxonomic code according to Table 1.

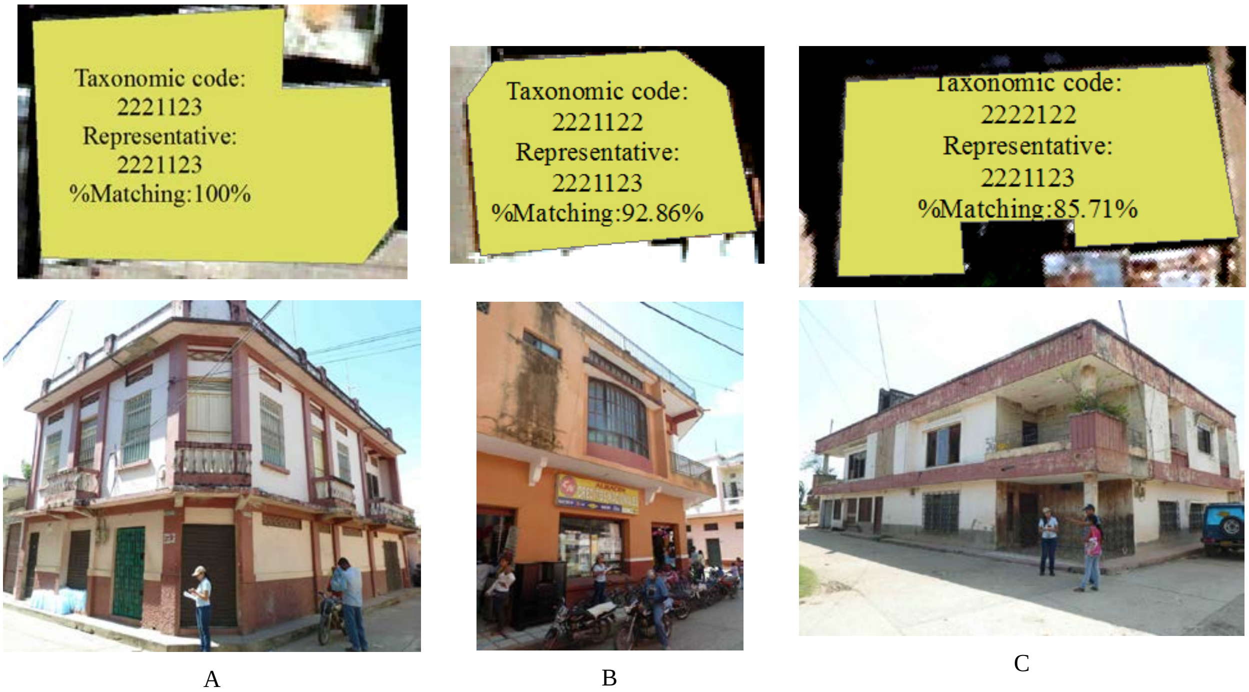

Figure 4. Representative buildings of the taxonomic code *‘2221123’* in *Magangué*

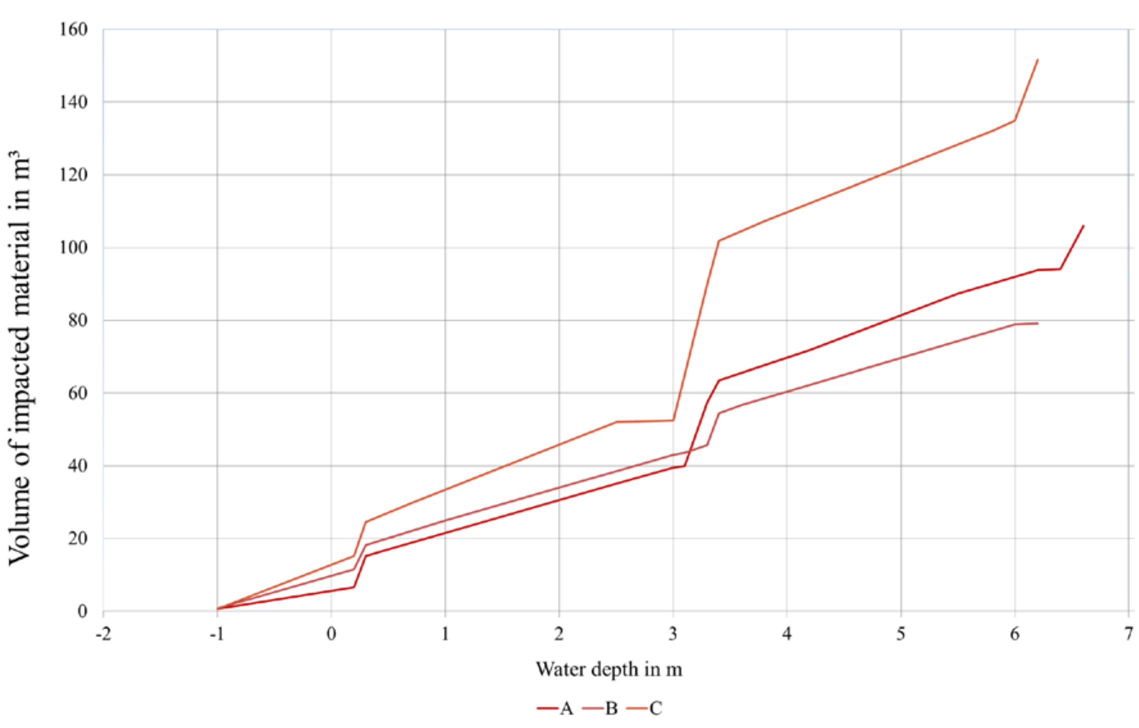

Figure 5. Depth-physical impact functions for the buildings A, B and C

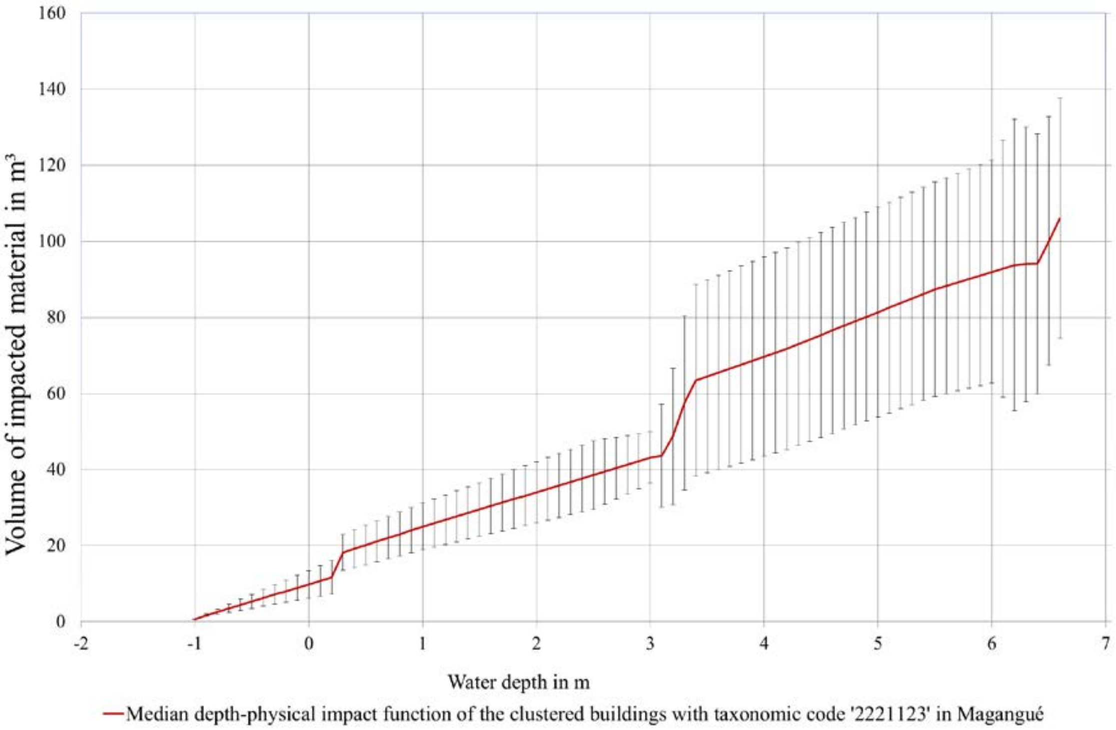

Figure 6. Median and standard deviation of the depth-physical impact functions for the taxonomic code ‘*2221123’* in *Magangué*, Colombia