



Vulnerability assessment in urban areas exposed to flood risk: methodology to explore green infrastructure benefits in a simulation scenario involving the Cañaveralejo River in Cali, Colombia

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Received: 5 April 2018 / Accepted: 2 August 2019 / Published online: 17 August 2019
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Abstract

Building resilient infrastructure is one of the major challenges faced by cities due to increasing urbanization rates and climate change. Furthermore, the application of vulnerability assessment frameworks is a significant challenge that requires the appropriate tools for decision makers. This text analyses an ongoing green infrastructure (GI) project in the city of Cali, Colombia, by presenting the assessment methodology and identifying the main benefits and vulnerability reduction possibilities resulting from the intervention. The main objective of this research focuses on (1) assessing the impact of flood risk in urban areas using GIS techniques; (2) mapping and quantifying vulnerability reduction due to the intervention in a simulation scenario; and (3) exploring the feasibility of GI projects as a tool for decision-making processes.

Keywords Vulnerability assessment · Green infrastructure · Flood risk reduction · Urban analysis · Environmental corridors—Cali

1 Introduction

The very rapid urbanization, increasing water demand and inadequate use of urban land have produced serious negative effects on water availability and quality, thus creating major challenges for urban sustainability. This text will analyse an ongoing Green Infrastructure (GI) project in the city of Cali, Colombia, included in the “Strategic inter-institutional plan of intervention in drainage systems PEISD for the mitigation of environmental and health risk of flooding in Cali” (*Plan Estratégico Interinstitucional de Intervención en Sistemas de Drenaje-PEISD, para la Mitigación del Riesgo Ambiental y Sanitario por inundación en Cali*). The project is financed by the local environmental authority DAGMA, the Cali

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public health and planning departments and the public enterprise of water and energy supply EMCALI.

Specifically, the study will focus on the south drainage system, composed of three major rivers of the city as well as several subsidiary channels. The selected project consists of the Cañaveralejo corridor, which is one of the three rivers running through the city. The Cañaveralejo corridor previously underwent intervention to mitigate urban flooding. However, the population living near the corridor is still exposed to flood risk, partly due to the inadequate handling of solid waste in the channelled areas and partly due to the urban characteristics of the area that prevent proper rainwater management.

This article will address the results of the vulnerability assessment study conducted in the Cañaveralejo corridor, the study area selected for the project. It will provide an overview of the methodology used to evaluate the current conditions in terms of vulnerability of the urban area next to the river. It will also present a simulation of potential conditions after green infrastructure intervention to calculate the vulnerability reduction in flood risk conditions as well as co-benefits for improving urban conditions.

1.1 Vulnerability assessment methodology and framework

Cities are the result of numerous processes. As such, they tend to concentrate both opportunities and risks. The most striking event in urban transition is the displacement of the population to urban centres across the world, accompanied by a considerable increase in the number of individuals and the size of cities, which occurs in nearly direct proportion to industrialization.

Until the 1950s, the rivers of Cali enjoyed the natural characteristics of “crucial importance to the community as a water supply, space for recreation, ornamentation, landscape, urban drainage and power generation” (DAGMA 2007). Since this time, the city began a major urbanization process because of changed economic models. In 1938, Cali was a city of approximately 100,000 inhabitants. With the arrival of railroads, the feeling of “prosperity” included not only Cali but also the small towns passed by the railway route, thus generating infrastructure growth to support economic and industrial growth and attracting migration. Migrants mainly included those in the black communities of the Pacific displaced by violence in the 1950s, who thus found an attractive region in which to live and work.

With the increase in waterproofed areas because of urban development, surface runoff increased significantly, which led to an increased risk of flooding. The loss of native vegetation, deforestation, and the presence of human settlements in hillside areas of the upper river basins are, among others, the main causes of the increased hazards related to flooding. Additionally, the “La Niña” phenomenon and changes in rainfall patterns and intensity due to recent climate variability have resulted in even greater effects for these highly urbanized areas.

Urban interventions for flood mitigation and the process of urbanization also disrupt the natural river ecosystem cycles, which, when altered, modify the habitats of different species, cut ecological connections originally present in the environmental corridors and therefore reduce landscape quality and environment values. The reduction in vegetation cover required for those “grey infrastructure” interventions interrupts the hydrological cycle of assimilation, infiltration and evapotranspiration. In the process of building grey infrastructure, part of the vegetation cover is removed, and the subsoil

is compacted, thus reducing the amount of water that can infiltrate and thereby greatly increasing the speed of water runoff on urban surfaces.

Among other effects generated by urbanization caused by changes in the natural environment are accelerated densification, reduced coefficient of soil infiltration, increased runoff retention times, and increased impermeability because of more “waterproofing” surfaces. The net result is reduced hydraulic capacity of the drainage sectors facing high volumes during rainy periods. This is the case in the south drainage system of Santiago de Cali, composed of the Cañavalejo, Melendez, and Lili rivers as well as different artificial canals that flow into the rivers and end on the Cauca River. This area is characterized by high urbanization rates and continues to present problems associated with rivers and canal flooding related to solid waste mismanagement, watershed erosion and limitations of the grey infrastructure built to mitigate flood hazards. All these issues are directly related to the capabilities and understanding of urban planning and community management processes as well as poor relationships with technicians and professionals responsible for interventions, which in turn do not contemplate the visions and particularities of the context in which the projects are conducted.

Disasters are unmanaged natural risks. These risks are socially constructed and result from erroneous development processes as well as the enhancing element of global warming. Reducing the number and severity of socio-natural disasters means tackling the development problems that increase the hazards and human vulnerability to disasters. These disasters occur when society or a human settlement is exposed to extreme conditions by abnormal natural phenomena, mainly torrential rains, extreme winds and landslides, among others. These natural factors have changed due to weather modifications which occur in all regions of the world. However, when socio-natural disasters occur, they are usually associated with areas of vulnerable impoverished populations, given the particular conditions facing the threats to which they are exposed (López and López 2015).

The vulnerability can be understood from different approaches. These include authors such as Bohle (2001), who analyses the vulnerability from both internal and external perspectives: internally as the ability to anticipate, address and recover from the impact of a hazard in contrast to the external perspective, which involves the degree of exposure to such threats. A second school of thinking refers to Davidson and Shah (1997), who define vulnerability as a component of disaster risk, differentiating exposure and responsiveness.

On the other hand, Turner et al. (2010) consider incorporating the concept of adaptation as an element that increases resilience. The latter concept is understood as the ability to recover after an extreme event. This approach to the concept of vulnerability also includes a link to the human–environment, thus making its interpretation a broader concept. Wisner et al. (2012) developed the idea from the political economy, seeking the causes, dynamic pressures and unsafe conditions that determine vulnerability.

Birkmann et al. (2006) developed a conceptual framework that identifies vulnerability in a cyclic system, considering hazard types, potential events, and interactions between society, economy and the natural environment based on exposure to such events. This framework includes social, economic and environmental dimensions, thus creating a link to sustainable development.

From this conceptual definition, it is possible to identify different methodologies used for vulnerability analysis, derived mainly from studies and works related to natural hazards and disaster risk management. However, this term is widely used in various fields, meaning that there is vulnerability from any real-world perspective while there is direct exposure to hazards (Cardona 2007).

The best-known models in the field of vulnerability assessment are focused on the analysis of risks from natural hazards. Among the main models that attempt to explain the interactions that describe the processes underlying vulnerability to threats, it is possible to highlight the SRM (social risk management strategy) from the World Bank, in which Holzmann and Jorgensen (2001) propose informal, market and public strategies to manage risk, while proposing the inclusion of a set of actors in the process. The model aims to identify elements and relationships versus risk management to achieve mitigation while increasing the resilience of households against different types of shocks.

On the other hand, the Pressure and Release model from Wisner et al. (2012), who conducted a study which showed how disaster risk must be analysed, considered not only natural threats but also the vulnerabilities created directly by people through their daily decisions. This view of the model proposed by Wisner et al. (1994) is important because it allows consideration of the existing social environment in relation to the hazards. Thus, the authors note that there cannot be a disaster if two conditions are not present: the occurrence of a threat and the existence of people in vulnerable situations. Accordingly, they proposed the PAR model, named for its acronym (Pressure and Release), as a tool to show how vulnerability is a social process that limits access to resources.

Cannon (2006) makes some progress with the initial work conducted with Wisner et al. (1994), proposing the following five elements as components of vulnerability: the stability of livelihoods, initial welfare (disaster pre-condition), self-protection, social protection and governability. The model aims to incorporate a social framework to study the structures and governance systems as conditions that determine the components of vulnerability. This position reveals poor self-protection and social protection conditions as factors and establishes mechanisms through which interventions can reduce vulnerability.

Under the approach of global vulnerability, Wilches-Choux (2007) and Benson and Twigg (2007) consider that the concept can be explained with a model that represents physical, social, economic, environmental, cultural, institutional, scientific and technological factors as well as politics. The fundamental contribution of the model is the possibility of proposing actions for vulnerability reduction within each of the components.

As a result, for this analysis of the environmental corridor of the Cañaveralejo River, we understand vulnerability to be “the physical, social, economic and environmental conditions that increase the susceptibility of loss within a community or society against the hazards” (Cardona 2007). Therefore, this understanding is based on some of the described models that best fit the conceptual search for construction of this research work. From a local perspective, several investigations of vulnerability have shown that the degree of preparation of a population against hazards varies with ethnicity and socio-economic status (Spence et al. 2007). Thus, inequality associated with social position of a group implies exposure or no exposure to a single threat in a disaster situation.

The following graph shows the variables included in the analysis of the Cañaveralejo river for vulnerability assessment divided into the following categories: i) social vulnerability and ii) spatial vulnerability, as well as some descriptive data captured by primary and secondary sources but not included in the multicriteria analysis in GIS and analysed only as a reference for the primary variables.

The methodology used to assess the vulnerability in the Cañaveralejo area follows these phases:

1. Social vulnerability analysis—Survey collection data for descriptive and relational analysis and georeferenced information to illustrate social phenomena by neighbourhood.

2. Spatial vulnerability analysis—Block by block field work to collect physical information with building and urban characteristics to include multicriteria analysis data. Secondary information includes descriptive data for relational analysis and general understanding of urban patterns.
3. Multicriteria analysis in GIS—The selected variables are georeferenced in a GIS database to make map aggregations and index calculations to create one final map showing vulnerability synthesis in the area.

1.2 Social vulnerability analysis

This component of the conceptual model aims to evaluate the social capacity and responsiveness of a population facing natural hazards such as floods. To understand social performance of the study area, this conceptual component is divided into (1) risk perception and (2) coping capacities. Both are analytic subsystems to evaluate subjective aspects of the community. As described in the theoretical framework in the introduction of the second part of this report, vulnerability should be viewed from a holistic approach to understand the root causes and the levels of fragility in the social perspectives that normally are related to poverty or unrecognized hazard exposure (Fig. 1).

This analysis has synthesized the evaluation of social vulnerability using variables that indicate hazard identification, events experienced in the past, willingness to intervene in their built environment and willingness to pay flood insurance. These variables were selected to facilitate data availability for the multicriteria analysis and were collected by a survey conducted during a field work phase. The survey results were the inputs for the first step in the methodology of the multicriteria analysis. Figures 2, 3 and 4 show the descriptive data from survey questions used to understand population composition and general characteristics by neighbourhood.

The largest part of the surveyed population has a current employment status of independent “Cuenta-propia” which in the current Colombian context means that persons in this situation have to pay in full for its own health insurance and in most of the cases refers to an informal situation with no access to other social security benefits. However, we also

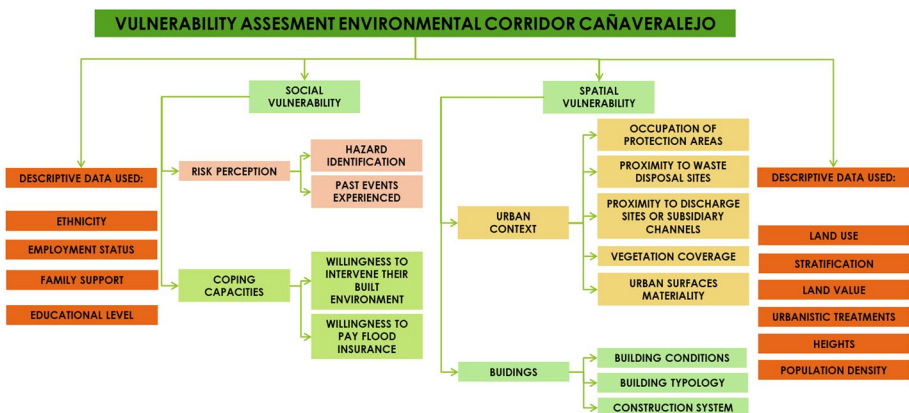


Fig. 1 Selected variables for vulnerability assessment exercise

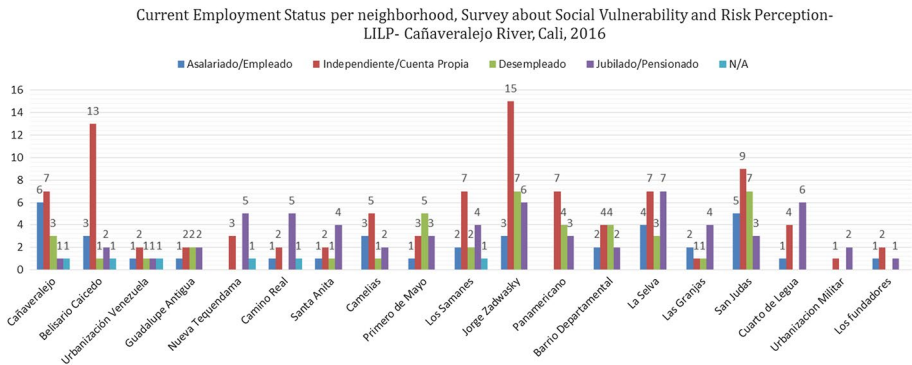


Fig. 2 Employment status—social vulnerability analysis

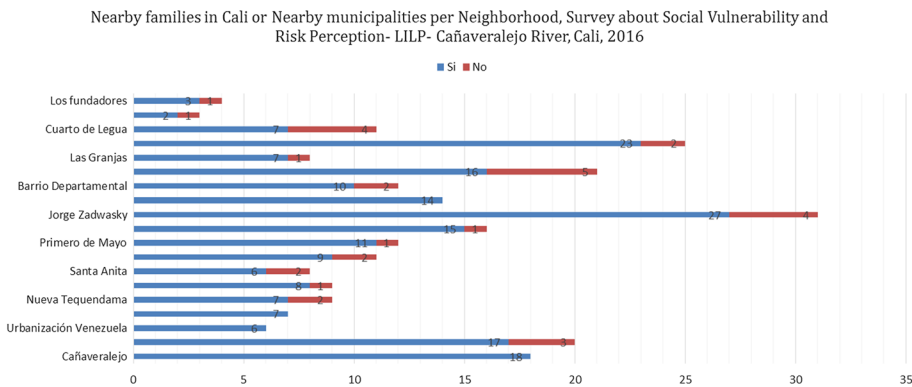


Fig. 3 Family support—social vulnerability analysis

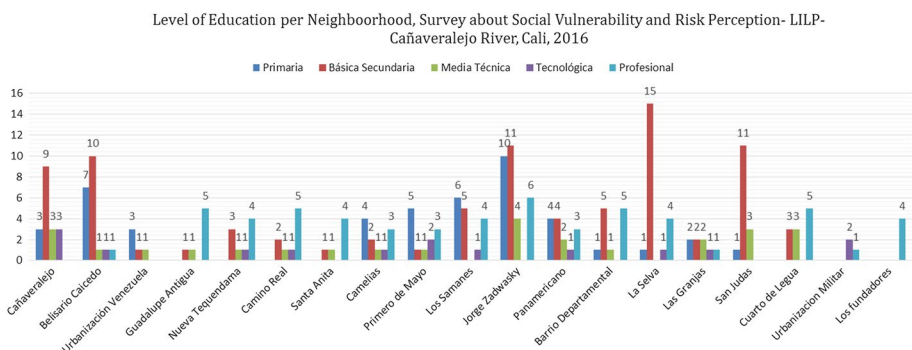


Fig. 4 Educational level—social vulnerability analysis

found neighbourhoods where the retired population (Jubilado/Pensionado in Spanish) is predominant, which means they have more available time for home-related issues.

Figure 3 shows that most of the surveyed population have close family members to turn to in an emergency as they answer positively to the question of having close relatives living

near to Cali (metropolitan area or neighbour municipalities) that they can be able to host them in case their homes were affected. In many cases, the family lives in the same neighbourhood or neighbourhoods also located on the Cañaveralejo River or canal. Therefore, it can be assumed that in the processes of migration and neighbourhood consolidation, family connections play a substantial role, and in the case of disaster, they could determine the responsiveness and coping capacity of that population.

Most of the surveyed population had basic primary and secondary education levels, especially in the middle and lower income areas that were analysed. This reveals some limitations in terms of technical understanding of the flood process. It also illustrates the fragility of the population regarding economic and social responsiveness which enhances their vulnerability due to limited capacity for action related to the knowledge of threats and intervention mechanisms.

As part of the first step of social vulnerability analysis, the following images show the georeferenced information from selected question in the survey. This information was used for multicriteria analysis using geographic information systems, with maps produced to illustrate the phenomena in the study area.

The indicators used are described in Tables 1, 2, 3 and 4, and the correspondent maps are presented in Figs. 5, 6, 7 and 8, where it is possible to see the dark areas as those with critical conditions regarding social vulnerability. These maps represent selected questions from the survey with a spatial component as the main criteria. Twenty-six questions were asked to participants but only 4 of them were used in the spatial analysis in form of indicators as proposed in the conceptual model for the GIS process, other questions were used to characterize the population and to understand through a relation of variables each spatial phenomenon.

Maps were produced georeferencing information from the survey, using the percentage obtained in each of the neighbourhood as representative data to explain the current situation related to the proposed indicators to evaluate social vulnerability. Those maps can

Table 1 Indicator description—hazard identification

INDICATOR ASSESSMENT	IDENTIFICATION OF A HAZARD SOURCE	QUANTITATIVE EVALUATION	QUALITATIVE EVALUATION
CRITICAL	Between 0 - 14% of the population in the neighborhood	1	Low percentage of the population who recognize a flood hazard, this condition decreases the responsiveness in an event
REGULAR	Between 15% - 30% of the population in the neighborhood	2	Medium percentage of the population who recognize a flood threat, this condition deteriorates their responsiveness in an event
OPTIMUM	More than 31% of the population in the neighborhood	3	Percentage of population with high recognition of the threat by flood, this generates an increase in responsiveness to an event

Table 2 Indicator description—past flood events experienced

INDICATOR VALORATION	PAST EVENTS EXPERIENCED	QUANTITATIVE EVALUATION	QUALITATIVE EVALUATION
CRITICAL	Between 51% and 100% of the population in the neighborhood	1	high percentage of the population of the neighborhood has experienced a flood event in the past.
REGULAR	Between 26% and 50% of the population in the neighborhood	2	Medium percentage of the population of the neighborhood has experienced a flood event in the past.
OPTIMUM	Between 0 and 25% of the population in the neighborhood	3	Low percentage of the population of the neighborhood has experienced a flood event in the past or never has experienced one in that place

Table 3 Indicator description—willingness to intervene in the built environment

INDICATOR VALORATION	WILLINGNESS TO INTERVENE THE BUILT ENVIRONMENT	QUANTITATIVE EVALUATION	QUALITATIVE EVALUATION
CRITICAL	Between 0% and 30% of the population in the neighborhood	1	Low percentage of the population of the neighborhood is willing to collaborate to make an intervention to improve its responsiveness to urban flooding
REGULAR	Between 31% and 70% of the population in the neighborhood	2	Medium percentage of the population of the neighborhood is willing to collaborate to make an intervention to improve its responsiveness to urban flooding
OPTIMUM	Between 71% and 100% of the population in the neighborhood	3	High percentage of the population of the neighborhood is willing to collaborate to make an intervention to improve its responsiveness to urban flooding

be understood as an evaluation in three scales: critical, regular and optimum, as shown in Tables 1, 2, 3 and 4 where each category is explained and assessed regarding the influence of floods, integrating people's perception as the main source of the information. All maps show the study area created from the official map of the city of Cali and buffers were created bounded by the administrative line of each neighbourhood.

Table 4 Indicator description—willingness to pay for flood insurance

INDICATOR VALORATION	WILLINGNESS TO PAY FLOOD INSURANCE	QUANTITATIVE EVALUATION	QUALITATIVE EVALUATION
CRITICAL	Between 0 and 25% of the population in the neighborhood	1	Low percentage of the population of the neighborhood is willing to pay for insurance to guarantee their life and home protection against urban flooding
REGULAR	Between 26% and 50% of the population in the neighborhood	2	Medium percentage of the population of the neighborhood is willing to pay for insurance to guarantee their life and home protection against urban flooding
OPTIMUM	More than 51% of the population in the neighborhood	3	High percentage of the population of the neighborhood is willing to pay for insurance to guarantee their life and home protection against urban flooding or already have one

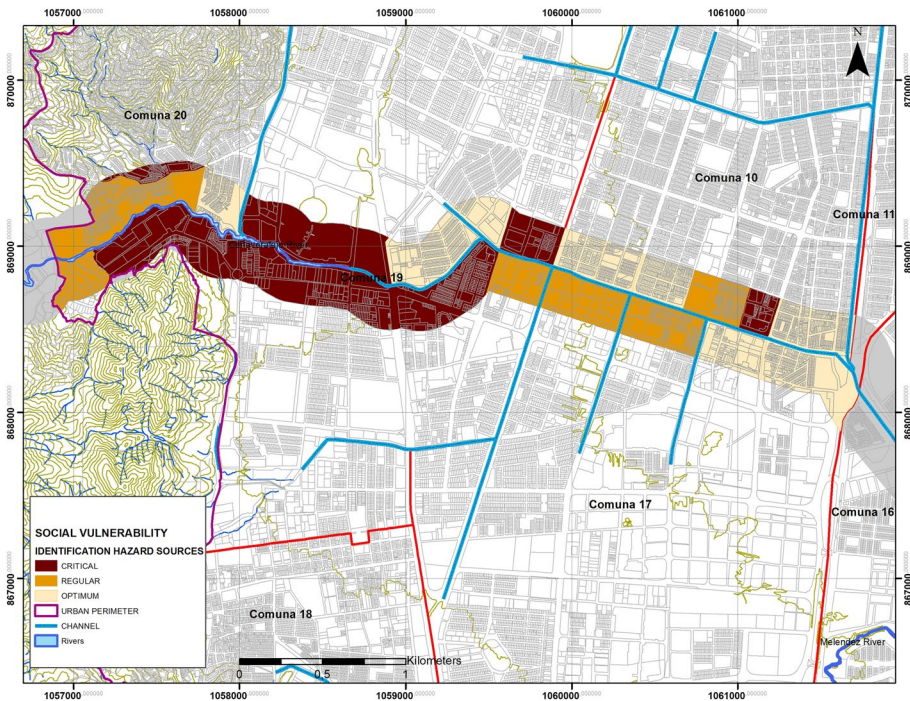


Fig. 5 Map of indicator—hazard identification

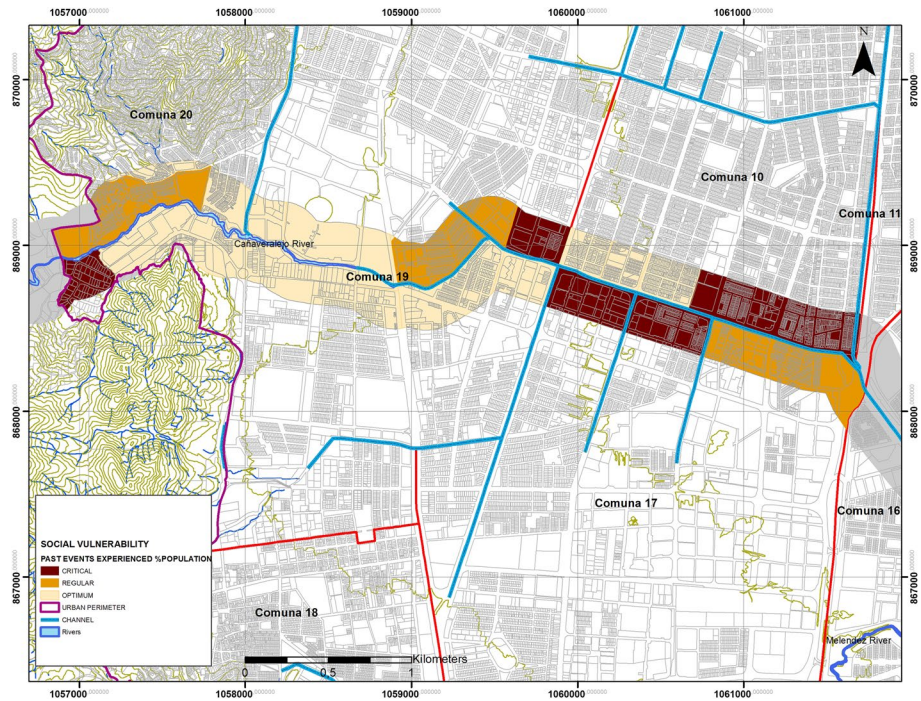


Fig. 6 Map of indicator—past flood events experienced

The two first maps show that people who never experienced an event before are unable to recognize flooding hazards as a risk in their neighbourhoods. This is related to the capacity for anticipation and is reflected in the indicator as critical because risk perception is valuable for understanding of social performance in an emergency. In conclusion, risk perception can be related in this analysis with past situations and experiences that can influence how people react and anticipate their own relation to possible hazards. On the other hand, Maps 3 and 4 show the relationship between high income and low levels of intervention or willingness to act to mitigate risk in contrast with the low-income areas, whose population is more receptive and available to help with flood mitigation actions. In that respect, low levels of insurance or even low willingness to purchase insurance exists in high-income areas as well, which means that this population prefers other types of solutions provided by the state or institutions.

In Cañaveralejo, maps can identify how the critical areas are related to those who do not recognize hazards and also with those who never experienced a flood situation in the past and are not willing to pay for insurance because they don't recognize the risk and as a subsequent situation are not interested in any intervention of their built environment. This is a perception of people about risk, but technical data will further identify possible situations in the near future that can affect those people, but they are not conscious of their own vulnerability because past experiences are a main issue that have influenced the perception and the ability to think in “solutions” to problems that are not identified by them.

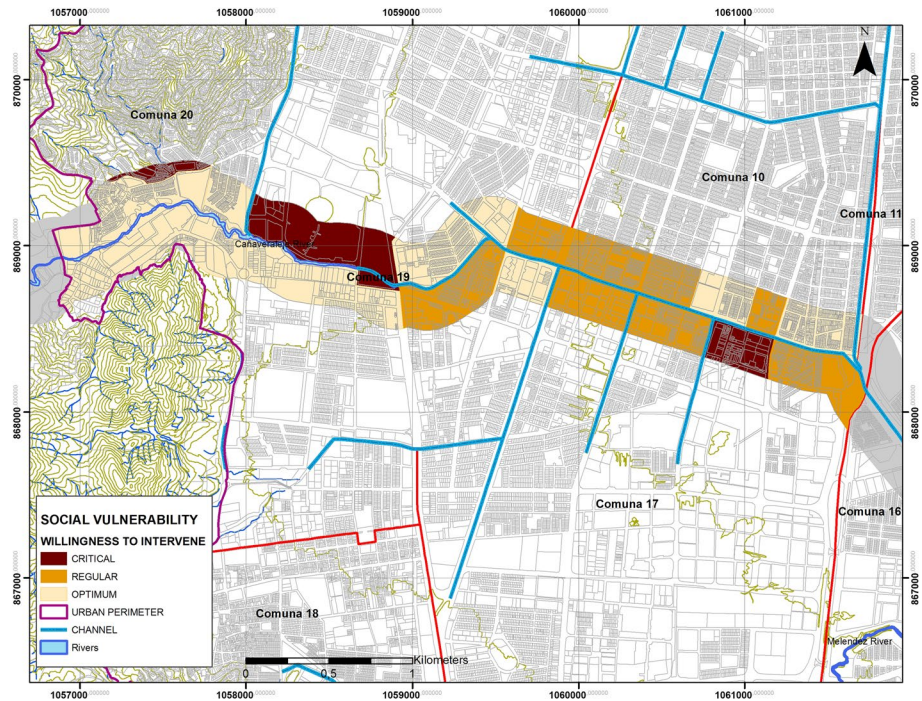


Fig. 7 Map of indicator—willingness to intervene in the built environment

1.3 Phase 2: Spatial vulnerability analysis

This second group of variables aims to identify evidence of fragility among buildings and the urban context using block by block collection data, with some descriptive data and data to be included in the multicriteria analysis. Spatial vulnerability refers to physical aspects of the environment in the study area. The selected indicators presented in this article aim to evaluate vulnerability divided in two categories: (1) the characteristics of the urban context and (2) characteristics of buildings. This information is consolidated and georeferenced to create spatial data for analysis in contrast with social information and flood risk-exposed areas.

The first category of analysis identifies aspects of fragility related to the landscape and environmental variables such as invasion of protected areas with informal constructions and activities such as parking lots and garbage disposal areas. Vegetation cover, proximity to sources of contamination (waste water or solid waste) and proximity to subsidiary canal intersections can increase the water level. The physical information in the second category provides data regarding the typology of buildings and their constructive systems as well as the building condition to evaluate the capacity to withstand an event.

Tables 5, 6, 7, 8, 9, 10, 11 and 12 show the indicator descriptions for each analysed category, explaining the different possible ranges to be evaluated as part of the vulnerability assessment in phase 2. The maps in Figs. 9, 10, 11, 12, 13, 14, 15 and 16 present the georeferenced information from each indicator used for the multicriteria analysis.

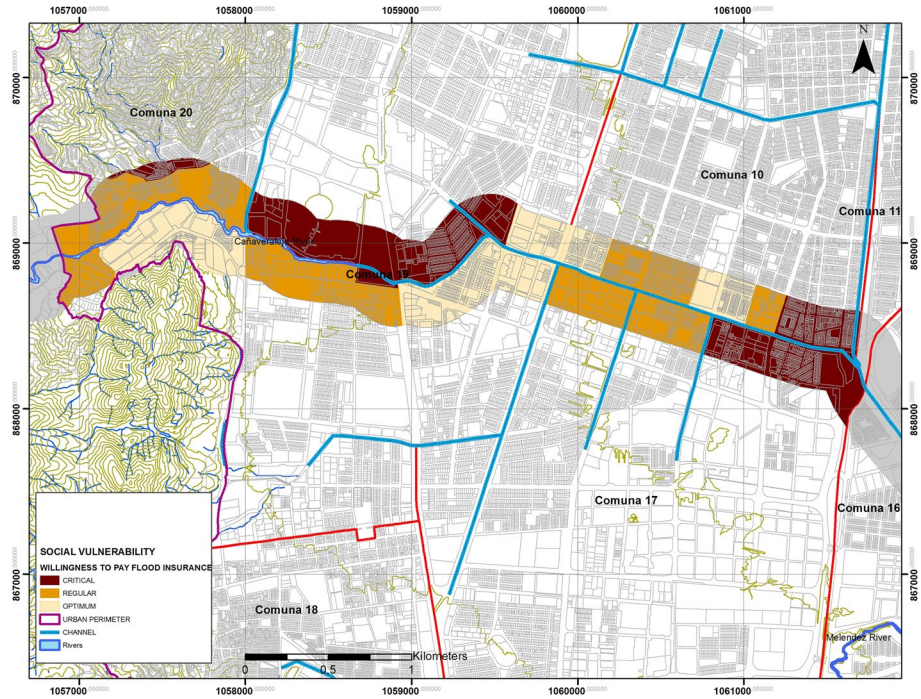


Fig. 8 Map of indicator—willingness to pay for flood insurance

Table 5 Indicator description—occupation of protected areas

INDICATOR VALORATION	OCUPATION OF PROTECTION AREAS	QUANTITATIVE EVALUATION	QUALITATIVE EVALUATION
CRITICAL	Less than 15 mts from the edge of the river or channel	1	Activities located in protection areas without any buffer zone or flood mitigation
REGULAR	Between 15 - 30 mts from the edge of the river or channel	2	Activities located in protection areas with some buffer area for water flow protection or flood mitigation
OPTIMUM	More than 30mts from the edge of the river or channel	3	Activities located out of the protected areas

Table 6 Indicator description—proximity to waste disposal sites

INDICATOR VALORATION	PROXIMITY TO WASTE DISPOSAL SITES	QUANTITATIVE EVALUATION	QUALITATIVE EVALUATION
CRITICAL	High impacted area between 0 - 100mts from the disposal site	1	Areas with high impact due to the generation of odors, rodents and the possibility of preventing the flow of river water or runoff in case of rain or rising water in the normal river condition
REGULAR	Medium impacted area between 101 - 500mts from the disposal site	2	Areas with sporadic presence of solid waste which causes a medium impact on the environment due to the effects of odors, water pollution, hindering the flow of water and related diseases
OPTIMUM	No impacted area more than 501mts from the disposal site	3	Areas with no impact or presence of solid waste that can cause health problems, deterioration of the landscape or cause clogging of the river and rainwater channels.

Table 7 Indicator description—proximity to discharge points or subsidiary canals

INDICATOR VALORATION	PROXIMITY TO DISCHARGE POINTS OR SUBSIDIARY CHANNELS	QUANTITATIVE EVALUATION	QUALITATIVE EVALUATION
CRITICAL	High impacted area between 0 - 50mts from discharge point or connection channel without caudal specifications	1	Areas with high potential for flooding by the effects of increased river flow due to liquid discharges from nearby houses and other subsidiary channels
REGULAR	Medium impacted area between 51 - 100mts from discharge point or connection channel without caudal specifications	2	Areas near to points discharge wastewater points or channels that meet partially the specifications to accommodate in case of an increase of flow.
OPTIMUM	No impacted area more than 101 mts from the discharge point or the connection channel without caudal specifications	3	Areas without the presence of wastewater discharges and channels with appropriate specifications designed to support the increased flows resulting from extreme rainfall

Table 8 Indicator description—vegetation coverage

INDICATOR VALORATION	VEGETATION COVERAGE	QUANTITATIVE EVALUATION	QUALITATIVE EVALUATION
CRITICAL	Areas with more than 41 mts from a group of trees	1	Area devoid of vegetation or spatial influence.
REGULAR	Areas between 11 - 40mts from a group of trees	2	Partially covered with vegetation and without the influence of any other complementary group arboreal area.
OPTIMUM	Areas between 0 - 10mts from a group of trees	3	Area with good vegetation cover and influence of other complementary arboreal groups

Table 9 Indicator description—urban surface materiality

INDICATOR VALORATION	URBAN SURFACE MATERIALITY	QUANTITATIVE EVALUATION	QUALITATIVE EVALUATION
CRITICAL	Impermeable	1	Impermeable surfaces such as concrete, bricks, steel without any channel to manage runoff
REGULAR	Mixed surface	2	Mixed areas with permeable and non permeable surfaces, can include channeled areas for runoff
OPTIMUM	Permeable	3	Green areas or permeable surfaces

Table 10 Indicator description—building conditions

INDICATOR ASSESSMENT	BUILDING CONDITIONS	QUANTITATIVE EVALUATION	QUALITATIVE EVALUATION
CRITICAL	Bad conditions	1	Buildings that meet less of 39% of the habitability defined as a stable structure, facades without deterioration, durable materiality and compliance with the urban regulations and also present informal conditions
REGULAR	Regular conditions and Vacant Lots	2	Buildings that meet between 40% and 79% of the habitability defined as a stable structure, facades without deterioration, durable materiality and compliance with the urban regulations
OPTIMUM	Excelent and good conditions	3	Buildings that meet between 80% and 100% of the habitability defined as a stable structure, facades without deterioration, durable materiality and compliance with the urban regulations

Table 11 Indicator description—building typology

INDICATOR VALORATION	BUILDING TYPOLOGY	QUANTITATIVE EVALUATION	QUALITATIVE EVALUATION
CRITICAL	single family housing	1	Low capacity to react to events with high probabilities of flood damage in 100% of the building by family
REGULAR	Bifamiliar housing	2	Possibility of reaction against flood events with capacity to deal with a flood event with the collaboration of the families living in the edificacion
OPTIMUM	Public space, vacant lots and Multifamiliar blocks	3	No direct impact on buildings and high capacities to react and deal with flood events in a common area.

Table 12 Indicator description—construction system of buildings

INDICATOR VALORATION	CONSTRUCTION SYSTEM	QUANTITATIVE EVALUATION	QUALITATIVE EVALUATION
CRITICAL	Fragile and unstable	1	Fragile and unstable construction system without the techniques suitable for building stability
REGULAR	poorly constructed durable technique and vacant lots	2	Buildings with a durable construction system but without formal specifications and techniques poorly implemented - vacant lots possibility of generating constructions comply with standard
OPTIMUM	Traditional and innovative techniques well applied - public spaces	3	Buildings with stable construction techniques or innovative building systems that generate sustainable options. Buildings complying with the regulations. Also here are considered public spaces for its connotation of spaces with high relevance to the community meeting.

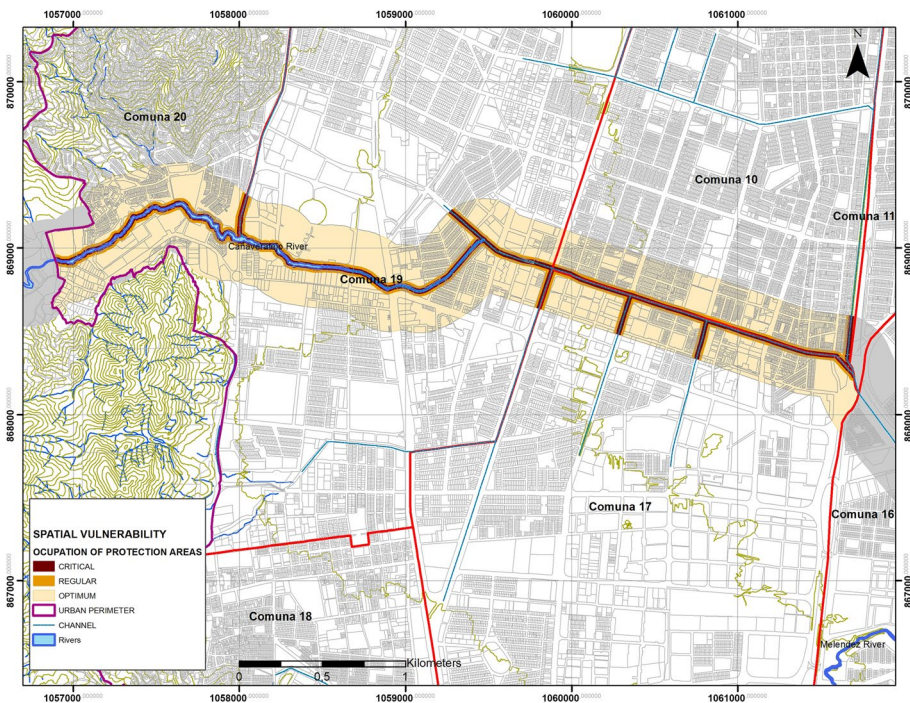


Fig. 9 Map of indicator—occupation of protected areas

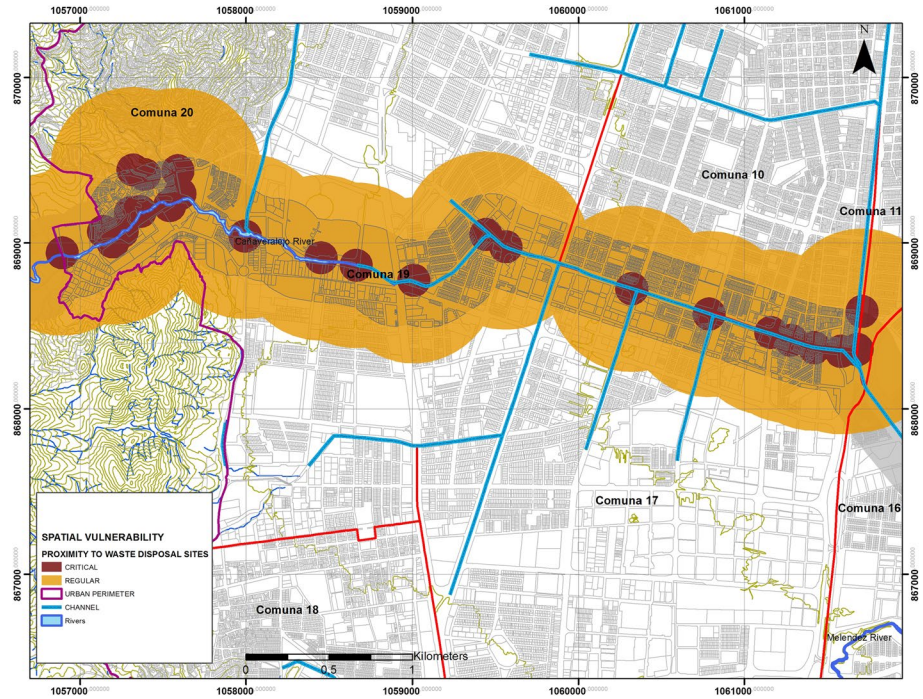


Fig. 10 Map of indicator—proximity to waste disposal sites

The colours on the tables correspond to the map colours representing the ranges from critical to optimum spatial vulnerability.

1.4 Phase 3: Multicriteria analysis in GIS

This vulnerability assessment aims to consolidate information based on mapping indicators to define the state of the Cañaveralejo River environmental corridor. With the use of a geographic information system (GIS), the mapping indicators allow incorporation of alpha-numeric and georeferenced information, thus resulting in a more realistic view of the study area in terms of physical and social vulnerability. In the case study, there were two modelling phases: one for diagnosis and another for the simulation of green infrastructure projects in the urban space where the GIS is used to determine the scope of the project intended to reduce vulnerability.

Through the design of a cartographic model, it was possible to overlay and analyse information by levels of hierarchy. This type of cartographic model is used to outline the functions of a geographic information system using a logical sequence to solve complex spatial problems. In the case of Fig. 1, all aggregation levels used to overlay information were spatialized.

The standards are the optimal values for each indicator which must respond to reduce system vulnerability. These standards are directly related to the proposed objectives for vulnerability reduction through green infrastructure projects, thus resulting in a

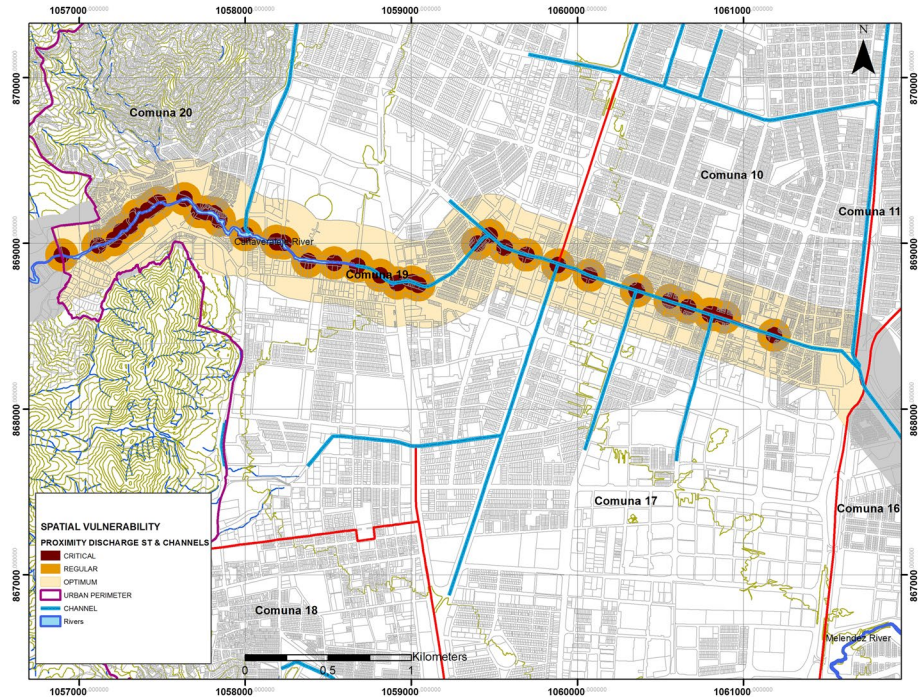


Fig. 11 Map of indicator—proximity to discharge points or subsidiary canals

systemic model which guarantees weighting or evaluation by each of the variables and indicators on the proposed subsystems and their potential relationships.

This model is based on multivariate information across each of the social and spatial vulnerability subsystems analysed. This means that each subsystem will first result in a map overlaying all the indicators analysed by each category. The idea is based on examining cartographic and numerical information for each of the spatialized and valued indicators to obtain a map using each subsystem as a preliminary index (social vulnerability index and spatial vulnerability index, Figs. 17, 18). Maps georeferenced the values of the indicators in each range of assessment, and the process is related to the conceptual model proposed and explained at the beginning of this text, overlaying maps and aggregating numeric data to obtain four maps: (1) urban context, (2) buildings, in the spatial vulnerability sub-component and (3) risk perception, and (4) coping capacities in the social vulnerability component. After this first aggregation the second phase of overlaying is focused on the spatial relation of the resulting maps: (1) social vulnerability plus (2) spatial vulnerability, aggregating numerical data to obtain maps in each category. Finally, the model overlays the two resulting maps according to the relationships established in the conceptual model (Fig. 1). The objective is to measure the state of vulnerability to floods. Therefore, it is necessary to overlay this resulting map (vulnerability index, Fig. 19) with a map of exposure (Fig. 20), which then presents the areas which have previously suffered flood events and are considered to be potentially threatened.

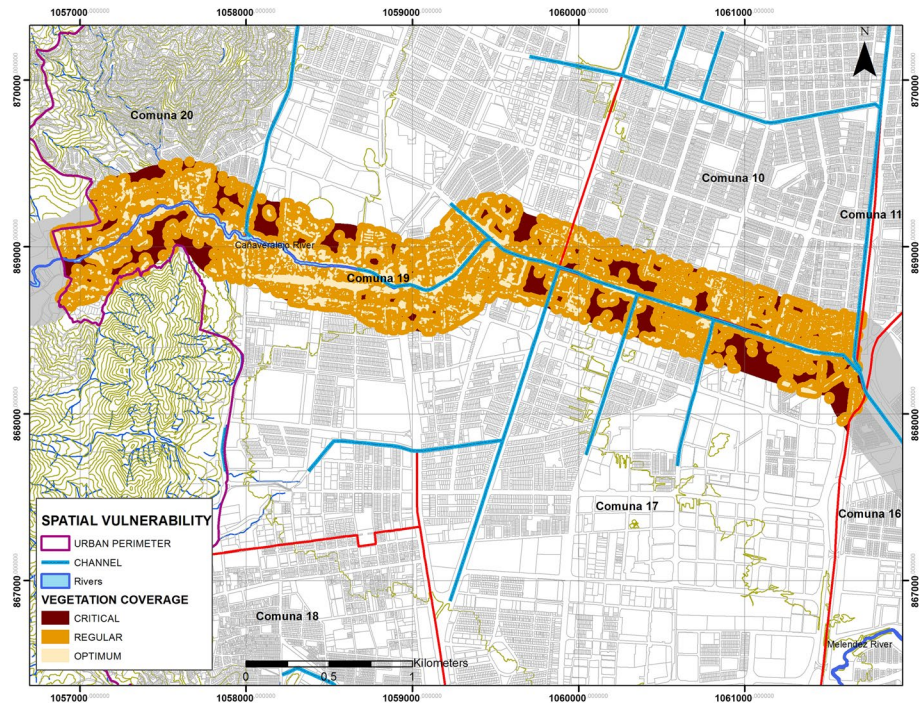


Fig. 12 Map of indicator—vegetation coverage

Finally, the analysis of results starts with comparison of the two maps representing the current flood vulnerability index (Fig. 21) and the simulation of the implementation project for vulnerability reduction (Fig. 22), showing the possible benefits of the proposal.

Figures 17 and 18 are the result of the different indicators overlaying in each one of the sub-components to assess corridor’s vulnerability. The first one, Fig. 17 shows in a map how the darkest areas representing critical and regular conditions in terms of social issues, are those unplanned areas, low and middle income or those with higher population densities and lack of urban facilities to face an unexpected flood event.

Figure 18 shows in a map a georeferenced areas resulting the overlaying data of physical conditions evaluated in the corridor, those dark areas correspond to the most vulnerable ones, representing in most of the cases public infrastructure, public spaces and abandoned areas or unoccupied ones, this could result in less private items exposed such as buildings and homes, but more public spaces exposed where the number of people is higher and infrastructure is expensive and the State is responsible for the maintenance and in the Colombian context this could result in a delay in the responsiveness capacity to face flood risk.

Vulnerability index in Fig. 19 shows a map overlaying Figs. 17 and 18 through a GIS conceptual model (see Fig. 1) consisting in an operative process that overlays numeric data from each map representing an indicator following the “algebra” proposed in the model. Each component: social and spatial vulnerability is created as a resulting map from the summation of the numerical data corresponding to the assigned ratings for

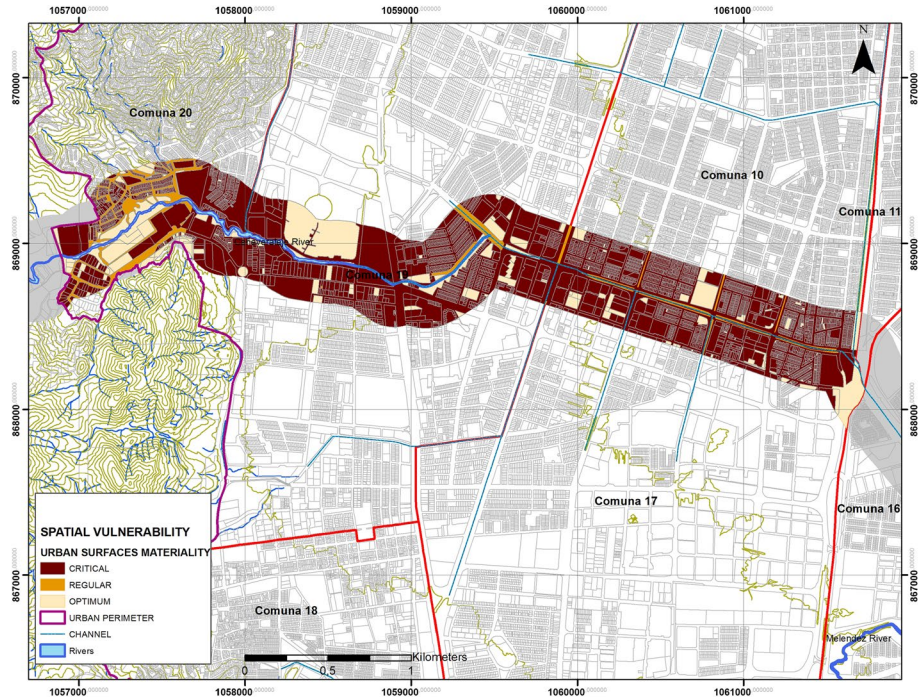


Fig. 13 Map of indicator—urban surface materiality

each one of the evaluation ranges: 1 critical; 2 regular; 3 optimal registered in the attribute tables of the shapefiles. This GIS model can diagnose a spatial area and simulate the intervention through the adjustment of data in the geodatabase as positive evaluation using the same rating criteria.

1.5 Flood risk in the Cañaveralejo River area

To know the flood hazard zones within the studied area of influence, a flood risk map was generated for the Cañaveralejo River area. It was created using the three following sources:

Historical information on previous flooding events, obtained by studying text and photographs from the local press. This process revealed the list of neighbourhoods that were most affected by flooding as well as some information about the higher flood levels achieved.

- Social vulnerability surveys of people who live near the Cañaveralejo River, to learn the vulnerability within the area of influence (approximately two hundred (200) metres on both sides of the river).

Most of these surveys were given to former residents of the neighbourhoods studied. This allowed us to learn whether they had experienced flood events, how many flood events they witnessed and when the events occurred. Using this information, it was possible to identify the neighbourhoods which suffered major effects of flooding.

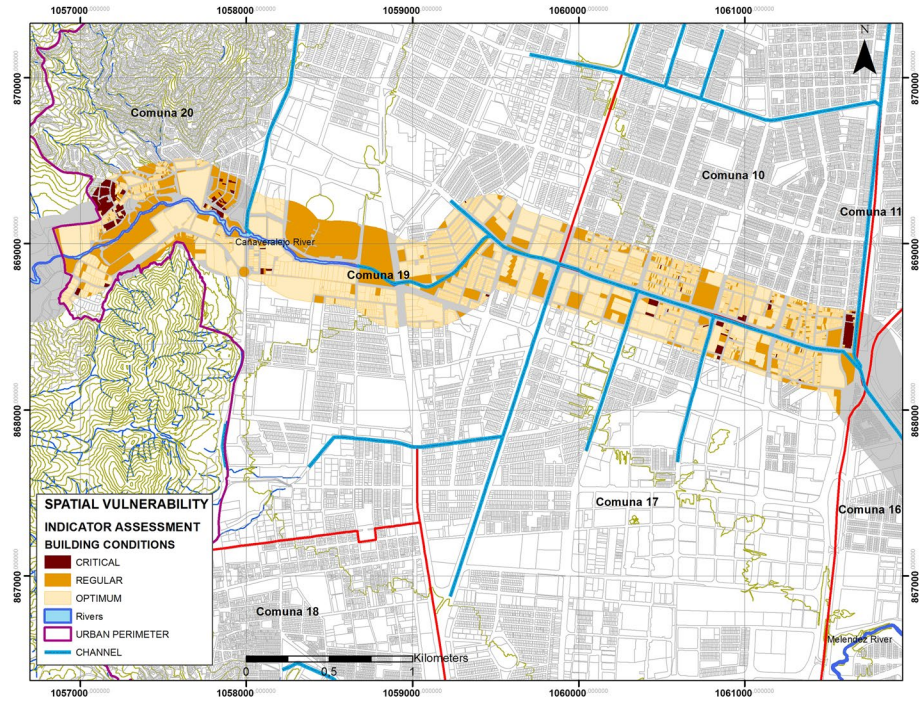


Fig. 14 Map of indicator—building conditions

- The most recent hydrologic and hydraulic Cañaveralejo river study was conducted by the Administrative Department of Environmental Management (DAGMA—Spanish acronym) in 2011. This study shown in the buffer of Fig. 20 ranged from the La Sirena intersection at the border of the urban perimeter to its end at the south interceptor canal and showed that the Cañaveralejo river was indeed susceptible to flooding. During the low rainfall season including the driest months of September and October, the average flow is fifty (50) litres per second. Additionally, the study provides a 100-year projection of maximum river water levels and indicates which areas are less capable of handling these levels, thus indicating which neighbourhoods are more vulnerable.

After collection and analysis of the information mentioned above, it was possible to create a flood risk area map for the Cañaveralejo River. Critical points included The Dam, the Urbanización Venezuela neighbourhood and its Eastern zone, which was already channelled, from 9th street to its end at the Ferrocarril canal. Figure 20 shows in blue the flood risk area revealed by overlaying the different information sources.

1.6 Green infrastructure benefits identified in the vulnerability assessment

The Cañaveralejo river environmental corridor includes infrastructure previously developed to reduce the risk of flooding (dry dams, dikes and rainwater and river canals). Currently, the local environmental authority is working on the design of a new intervention which includes urban design and landscape projects as well as infrastructure reinforcement. This new intervention could bring more social and environmental benefits and could be

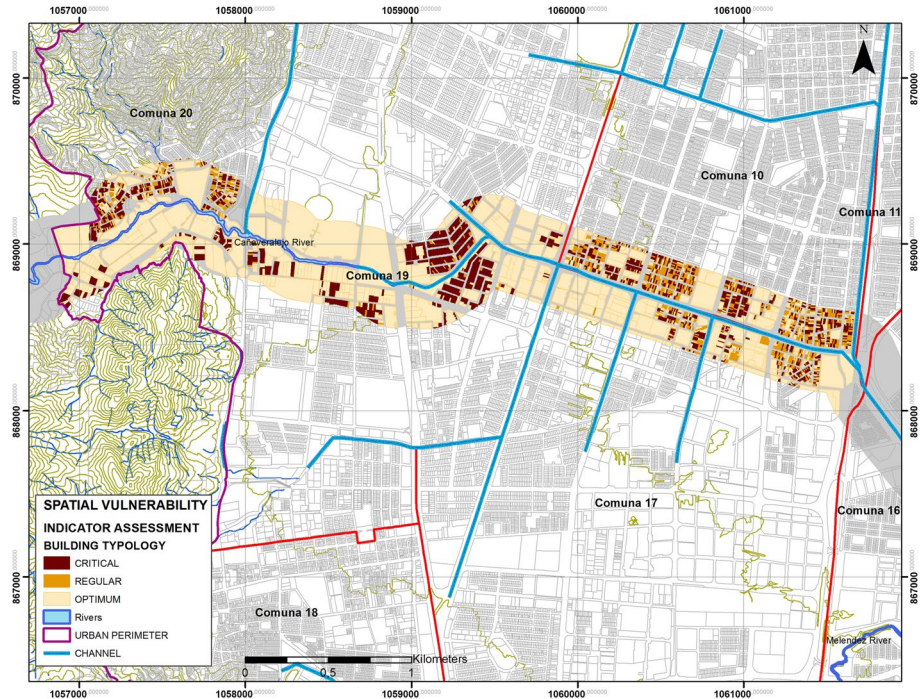


Fig. 15 Map of indicator—building typology

evaluated as part of a long-term intervention. However, the benefits have not been calculated and the impact of the interventions on real estate values has not been analysed.

The components of the Cañaveralejo River environmental corridor project aim to build urban resilience by:

- Strengthening the presence of natural systems in the urban grid
- Minimizing the risk of flooding
- Increasing the number and quality of public spaces in the impact area
- Triggering better social conditions because of the above factors.

Specifically, the main strategies proposed for the environmental corridor of the Cañaveralejo River project within the “river area” are focused on the following:

1.7 Ecosystemic connectivity

Reconnection and revaluation of the ecological corridor through landscaping, ecological restoration, reforestation and increased wildlife.

1.8 Transition between the built and the natural environment

Promote the permanence of protected species that inhabit the areas near the river. Conserve the different habitats in the urban context.

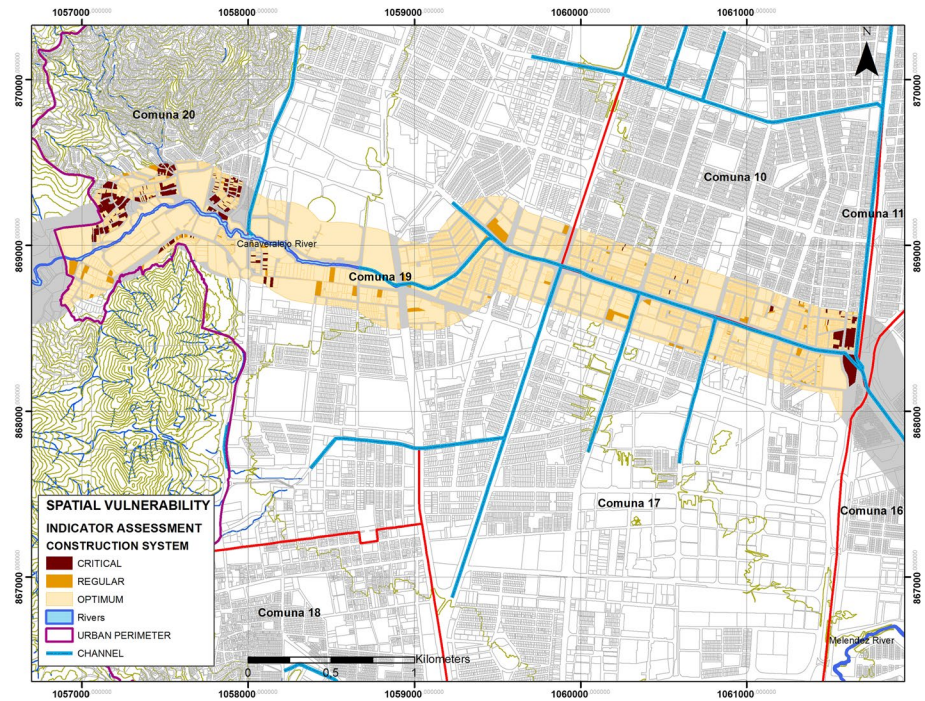


Fig. 16 Map of indicator—Construction system of buildings

1.9 Citizen interaction

Restore public access to the river to reverse its “urban barrier” status and integrate it with the city, offering opportunities for coexistence and social control. Encourage the location of educational, recreational and cultural facilities to improve the quality of life of inhabitants. Promote productive activities, urban farming and management of night lighting to ensure safety.

1.10 Urban eco-efficiency and flood risk reduction

Introduce integrated rainwater management with minimum use of hard surfaces, promoting the use of permeable materials that allow infiltration and continuity of the water cycle including design and implementation of sustainable urban drainage systems to mitigate flood risk.

The project characteristics include proximity to mixed-income neighbourhoods, combination of planned and implemented project phases, location surrounded by housing areas with different densities, various spatial attributes and levels of social diversity. The multiple benefits (risk reduction, social, environmental and economic benefits) of the project and the added value they bring to the area make a very promising case for the implementation of public policies and instruments in the LVC, through which partial recovery of the project investment (or capital for other public investments) may be achieved.

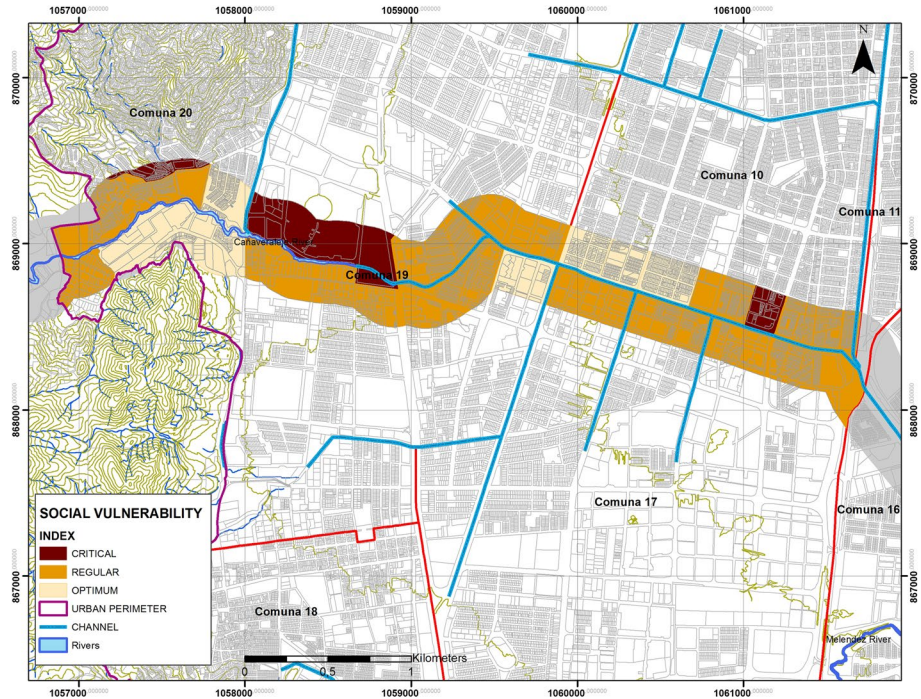


Fig. 17 Social vulnerability index

Some of the most dramatic damage to the Cañaveralejo River was caused by its canalization to prevent flood risk and promote urbanization in the 1950s. This process changed the riverbed and caused the loss of environmental identity by ignoring the natural elements at the river edges, replacing them with a built environment created based on the grey infrastructure approach. This intervention was intended to allow urbanization in the city centre and on the commune 10 area and above. However, the infrastructure used to prevent flooding in those areas was inadequate, and the areas near the built path of the river (different from the natural and original one) began to experience flooding events.

Flood events which occurred during the 1980s promoted the construction of a retaining dam located in commune 20, where the river still retains its original shape and landscape. The intervention succeeded in reducing flooding in the canal area due to rising river flow during rainy periods, but failed to incorporate other factors, thus causing flooding, garbage accumulation, and impairing management of urban runoff in conjunction with the other canals that are part of the south drainage system of the city.

The aim of the proposed institutional project is not only to integrate the flood mitigation infrastructure to face all problems and factors but also to restore the ecological connectivity between the green corridors of the city using strategies to transform the canals back into rivers. An attempt to restore the ecological character of the Cañaveralejo river/canal within the urban perimeter is necessary to appropriately include green infrastructure strategies to support the creation of new spaces with vegetation and green areas. At the same time, those projects will need to improve water quality through passive strategies that recover natural water cycles.

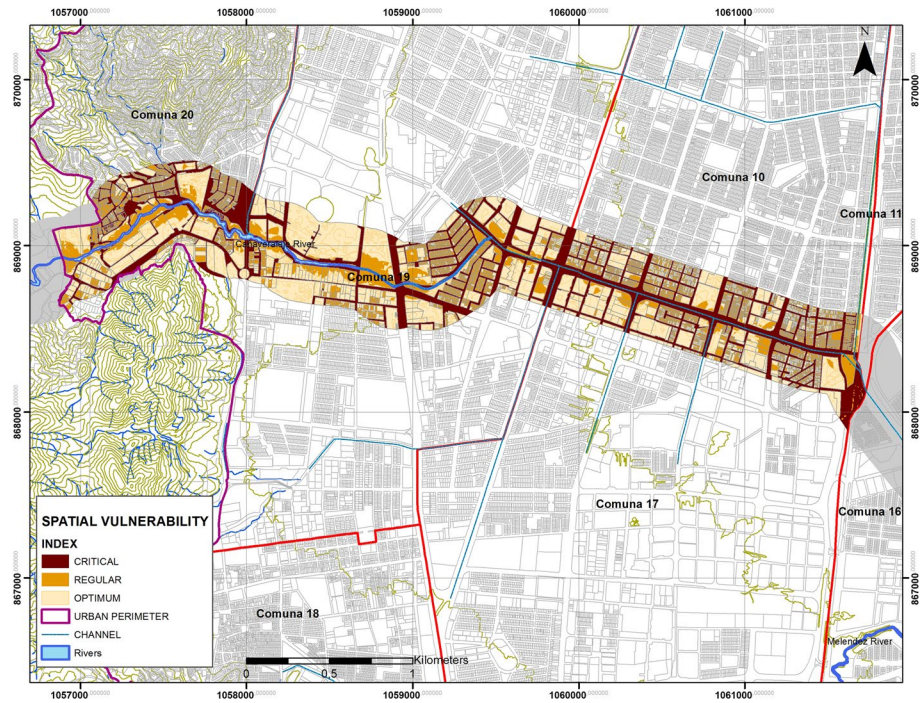


Fig. 18 Spatial vulnerability index

Any planned intervention within the Cañaveralejo canal area must consider that grey infrastructure interventions have already been conducted and that high-cost investments cannot be overlooked. For that reason, it is necessary to implement GI projects as complementary interventions in the canal area to improve landscape conditions and water management and enable integrated water runoff management. The project should address other factors that may cause flooding using natural elements with permeable surfaces, and it should generate better performance during intense rainy periods by combining grey and green infrastructure.

The Cañaveralejo urban environmental corridor aims to re-establish community recognition and respect for the river as a natural component of the urban structure by creating spaces for contemplation and appropriation of public space, with the addition of new vegetation to rebuild the lost ecosystem connectivity. Also proposed are new facilities that promote environmental emphasis and generate social control (CVC 2015).

These new public space proposals will be accompanied by green infrastructure alternatives such as sustainable urban drainage systems (SUDS) and eco-tones to generate transitions between the built and the natural environment at all scales of the project. To include alternatives for the priority intervention areas identified by different information sources, sketches were made based on community workshops to add GI strategies in those areas.

After analysing the characteristics of the proposed GI project, the next phase involves simulation of the GIS intervention using the cartographic design information and the database of current vulnerability conditions, thus obtaining the flood risk vulnerability

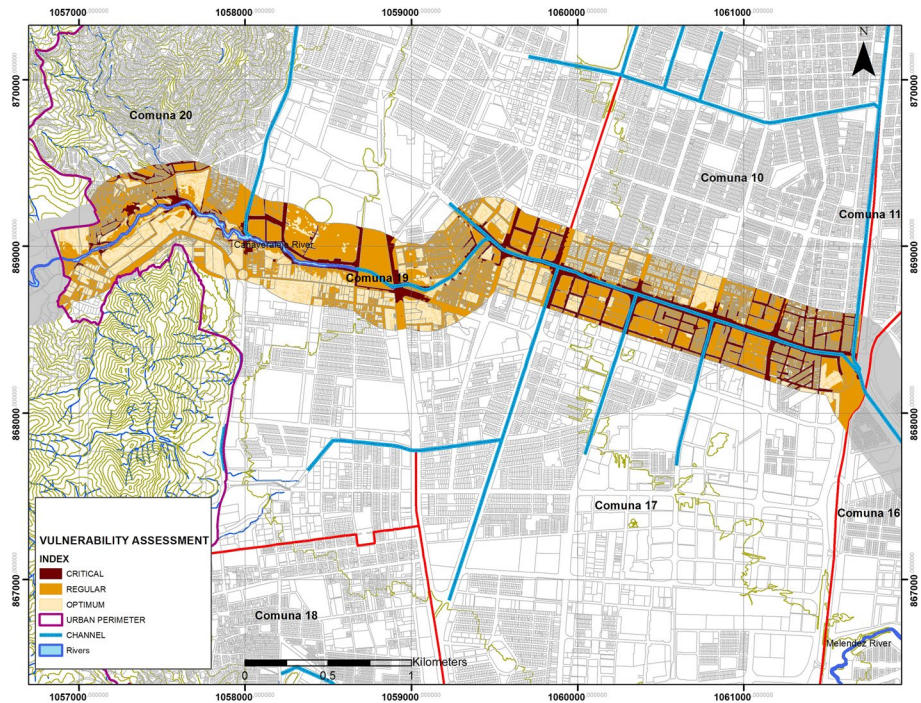


Fig. 19 Vulnerability assessment index (without project implementation)

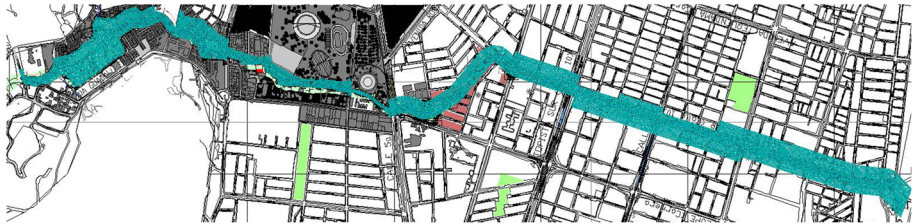


Fig. 20 Flood risk area of the Cañaveralejo river corridor

index in Fig. 22. This simulation includes potential future conditions and benefits from the GI project implementation as calculated in Table 13. The most important change between Figs. 21 and 22 in project simulation of GI is the critical area where the river becomes a “pluvial canal” in the red circle. This area in the proposal design has a GI component to increase permeable surfaces and reduce the amount of illegal water discharges that also increase the amount of water that reach the canal. GI infrastructure in this area allows to infiltrate part of the running water in streets and pedestrian areas to reduce flood risk in public areas as one of the major findings of the model; also this strategy increases the green spaces and vegetation cover areas to prevent heat stress and contributing to the micro-climate in the intervened area.

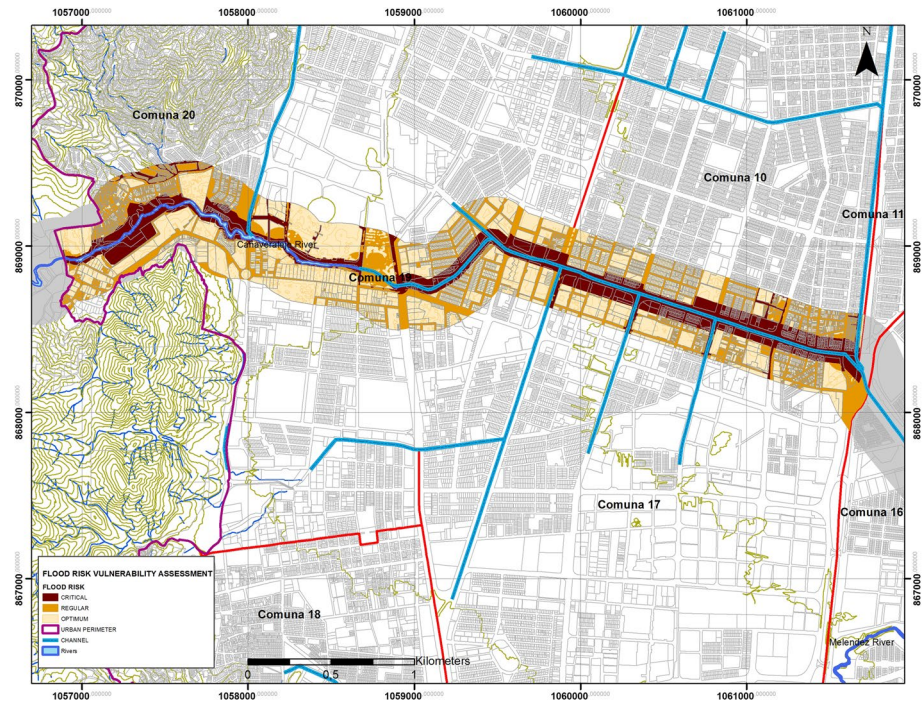


Fig. 21 Flood risk vulnerability index

2 Conclusions

The main impact of this research is aimed at recognition of the importance of green infrastructure projects for vulnerability reduction against flood risk in the urban environment. This project can promote resilient spaces capable of facing the impacts of climate and variability change.

The Environmental Corridor of the Cañaveralejo River Project brings elements of urban context improvement and focuses on the solution of problems arising from the intervention in public space with green infrastructure strategies. However, the elements for this research were modified by adding information provided in workshops involving the affected community. This information would have to be considered during project implementation to achieve the simulated results found here. Fortunately, these settings are part of the institutional project design process and can be easily implemented as an integral part of the intervention.

In the simulation of the project, there are some favourable indicators for the implementation of the project: (1) proximity to waste disposal sites: reducing the number of abandoned public areas without specific use, allowing a major appropriation of space and better management within environmental quality standards; (2) proximity to discharge points or subsidiary canals: this indicator shows significant improvement in terms of locating optimal areas and mitigating critical areas by implementing the proposed solutions, considering combined strategies to improve the sewage system to reduce river wastewater. Along with the implementation of landscape strategies, disposal of liquid

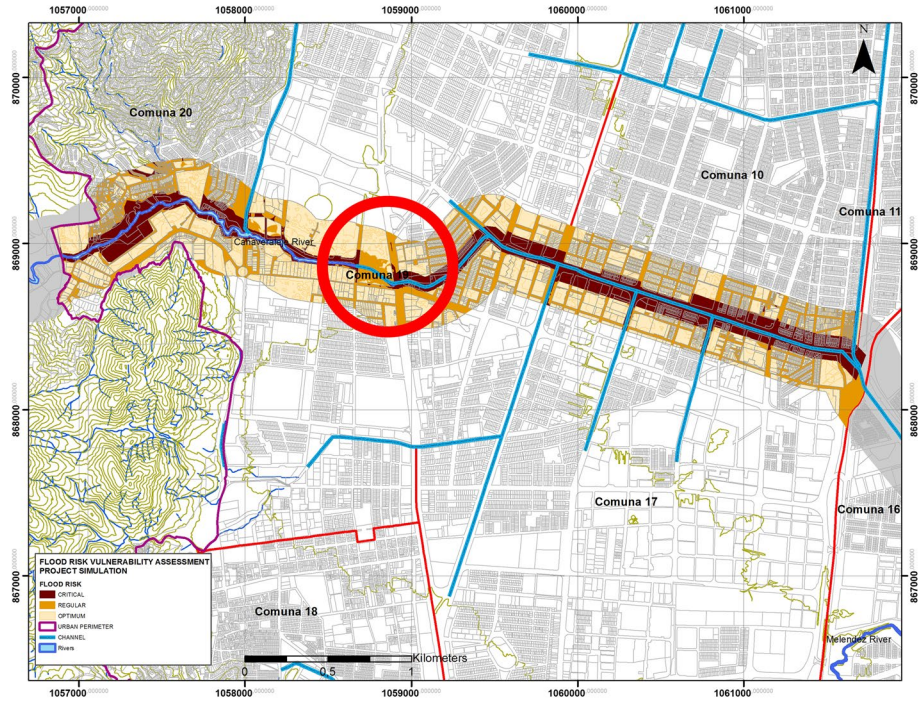


Fig. 22 Flood risk vulnerability index—project simulation

Table 13 Calculation of possible benefits from GI project implementation

INDICATOR	CURRENT SITUATION USING OPTIMUM VALUES	PROJECT SIMULATION USING OPTIMUM VALUES
Proximity to waste disposal sites	No Optimum Values	127 Ha
Proximity to discharge points or subsidiary canals	191 Ha	235 Ha
Vegetation coverage	51.35 Ha	243,2 Ha
Urban surface materiality	44.47 Ha	49,88 Ha

illegal discharges should be controlled and more elements should be provided to solve this problem.

A third positive indicator is (3) vegetation coverage: As one of the predominant landscape elements, the strategy of landscape design and the implementation of sustainable urban drainage systems permits reforestation of areas affected by tree removal for implementing grey infrastructure. Added to this strategy, the final positive indicator is (4) urban surface materiality: this indicator shows that some waterproof areas cause problems because of difficulty managing surface runoff. The affected spaces are now displayed as mixed areas provided with vegetation and soil layers to allow water infiltration and thus

improve drainage during rainy periods, thus providing significantly improved protection from flooding for the urban environment.

In the vulnerability assessment conducted with the initial GIS modelling, it was found that there were highly vulnerable zones in high-income areas. After the second project simulation, it was found that these areas benefitted from the reduced flood risk. Thus, it may be possible to simulate land value increases in these areas to identify mechanisms that permit the capture of land value to finance green infrastructure projects in lower income areas that cannot finance themselves.

Acknowledgements Funding was provided by Lincoln Institute of Land Policy (Grant No. IAL121515).

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