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Urbanisation and climate change effects on urban drainage performance

A case study of SUDS in a risk area in the city of La Paz, Bolivia

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Title

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Degree: Master in Urban Climate & Sustainability

Abstract

The city of La Paz in Bolivia has witnessed many disaster events attributed to a surplus of rainfall, causing flooding and landslides on urban settlements. This study presents a quantitative evaluation of the effects of urbanisation and changes in rainfall-induced climate change in the drainage system of a selected area in District Sur of the city. Initially, the urban sprawl was determined by analysing the land-use changes between 2000 and 2020, using GIS tools over Landsat 7 imagery. A collection of historical disaster events and projected rainfall patterns, based on scientific research, allowed constructing rainfall scenarios from existing storm data. A study area was selected based on the land-cover transformation, disaster occurrence and risk zones. These factors served as input data for the Storm and Water Management Model (SWMM) developed by the Environmental Protection Agency (EPA) of the United States. Two scenarios were considered in the digital model and simulation. The first scenario analysed peak flow, flooding, and overloaded elements under land-use changes, based on the urbanisation sprawl of 2003, 2013 and 2020. The second scenario added a design storm with climate factors of reduction/increment of rainfall due to climate change. Also, this scenario considered only the current conditions of land use as of those in 2020. In scenario 1, the results indicated that increments of impervious surfaces positively correlate with peak flows and flooding. The incidence is higher at the initial state of urban development. The imperviousness in the area grew from 25% in 2003 to 57% in 2013.

Moreover, scenario 2 proved that even with lower rainfall intensities in the future due to climate change, the network system still overloads. Therefore, a proposal was designed to determine the efficiency of implementing sustainable urban drainage systems (SUDS). It was confirmed by the model that through green roofs (GR) or permeable pavements (PP) as adopted solutions, peak flow and flooding reduce, as well as the overloaded elements. PPs had a better efficiency, with a 9,70% reduction in peak flow and 36% in flooding. While GRs had 2% and 22%, respectively. The results were discussed with a former and current municipality official, finding them beneficial for urban planning. However, it requires confronting issues related to institutional, monetary, planning and risk management to implement them. Still, this study provides valuable guidance for practitioners and public administrators, as it includes criteria for addressing potential risks due to drainage network performance. Furthermore, such results can help to assess areas located on risk zones to activate prevention measures and predict probable disaster events related to overloaded systems.

Keywords

Climate change, SWMM modelling, urbanisation, La Paz, SUDS, urban drainage

Originality statement. I hereby declare that this Master's dissertation is my own original work, does not contain other people's work without this being stated, cited and referenced, has not been submitted elsewhere in fulfilment of the requirements of this or any other award.	**Signature**

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ABBREVIATIONS

ACH	Achumani
AFD	Agencia Francesa de Desarrollo *(French Development Agency)*
AOI	Area of Interest
CC	Climate Change
DEM	Digital Elevation Model
ENSO	El Nino Southern Oscillation
EPA	Environmental Protection Agency
EPSAS	Empresa Publica Social de Agua y Saneamiento *(Social Public Company of Water and Sanitation)*
FD	Flooding
FW	Flow
GAMLP	Gobierno Autonomo Municipal de La Paz *(Autonomous Municipal Government of La Paz)*
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GIS	Geographic Information System
GR	Green Roof
IDB	Inter-American Development Bank
IDF	Intensity Duration and Frequency
LAC	Latin America and the Caribbean
LID	Low Impact Development
LUCE	Land Use Cover Evolution
LUSU	Ley de Uso de Suelo Urbano *(Law of Urban Soil Use)*
ND-GAIN	Notre Dame Global Adaptation Index
PDO	Pacific Decadal Oscillation
PP	Permeable Pavement
RD	Rainfall Decrease
RI	Rainfall Increase

ABBREVIATIONS

SENAMHI	Servicio Nacional de Meteorologia e Hidrologia *(National Service of Meteorology and Hydrology)*
SMGIR	Secretaria Municipal de Gestion Integral de Riesgos
SUDS	Sustainable Urban Drainage Systems
SWMM	Storm Water Management Model
TR	Tiempo de Retorno *(Return Period)*

CHAPTER 1: INTRODUCTION

1.1. Rationale

Climate change needs to be addressed globally due to the adverse effect on nature and wellbeing experienced by many countries and cities. Latin America and the Caribbean (LAC) is one of the most threatened regions worldwide since its cities rank among the most vulnerable to natural disasters [Gu et al., 2019]. This condition can be exacerbated by potential CC effects whether adaptation lags in the region [University of Notre Dame, 2021]. Additionally, the Northern hemisphere must take a different approach to tackle climate change (CC) than the Southern hemisphere, which faces a different reality due to local socio-economical and environmental conditions. These challenges are correlated to each hemisphere's level of development, where emerging economies should continue with mitigation endeavours to confront CC while developed ones mainly focus on emission reductions targets [Soler & González, 2020], as was included in the Paris Agreement of 2015. Moreover, the Global South requires enhancing collaborative research work for implementing solutions, since comparatively to the Global North, this absence deprives the region of achieving more advancements [Soler & González, 2020]. Thus, LAC faces more challenges to mitigate its effects while aiming to increase social welfare and surpass inequalities, including that it is amongst the most vulnerable regions [Gu et al., 2019].

However, the LAC region also needs to provide public services to satisfy the increasing demand for welfare as one of the world's highest urbanised regions. Around 80% of its population lives in cities, with a tremendous growth from 30% since the 1950s [Muggah, 2018]. However, this situation imposed more considerable challenges that are now added to the ones brought by CC. Many local levels of government (municipalities) in the region usually lack sufficient budget to allocate projects and programs to cover most of the necessities for society [Cenci, 2020]. Additionally, poor foresight planning endorses the lower rates of basic services coverage, e.g. housing, sanitation, or wastewater collection [Muggah, 2018]. Hence, practical actions and building resilience against climate change are usually out of these administrations' prioritised aims [Cenci, 2020].

Under these circumstances, the city of La Paz in Bolivia has witnessed natural disasters over the last decades, with some of them being connected to CC. However, it is still developing actions to reduce their negative impacts. These extreme events are either related to deficiency or surplus of rainfall. The most recent drought occurred in late 2016 when the lack of precipitation led to lower accumulation levels in dams that are a vital part of the drinking water system, affecting the regular provision of water to over 340 thousand people [Ayala, 2016]. Even though this situation was already foreseen years before from the academic field, it was not addressed on time [Hoffmann, 2016].

Regarding floods, the most harmful event occurred in February of 2002, with more than 70 people deceased and millions of USD dollars for infrastructure recovery [Hardy, 2009]. Also, in February of 2011, heavy rain and soil scouring derived into a landslide that dragged around eight hundred plots, displacing over a thousand families to other locations [Pagina Siete, 2020]. Moreover, the unfortunate event of 2002 triggered community attention to claim to public administrators in addressing flooding control and risk prevention. Then, the Autonomous Municipal Government of La Paz created the Secretariat of Integral Risk Management (GAMLP and SMGIR, for their acronyms in Spanish, respectively) to address these problems, increasing the public budget to prevent risks [Hardy, 2009].

However, most of the time, financial resources are limited to attend to various needs in La Paz. The budget report of 2020 assigned 6,6% for risk management and 10,5% for urban and rural infrastructure [GAMLP, 2021]. These amounts were equivalent to 16,49 and 26,24 million euros, respectively. Still, the Municipality required external sources to develop urban resilience. In 2020, the World Bank granted credit for approximately 59,02 million euros for the cities of La Paz and Santa Cruz de la Sierra for that objective. The grants aim to enhance urban drainage, build canals, and flood control and stabilisation [World Bank, 2020 & Money, 2020]. Nonetheless, this investment will focus mainly on large-scale infrastructure and conventional solutions.

Under the scope of infrastructure efficiency performance, drainage systems are usually observed from a broad perspective in La Paz. Local long-term planning includes canalisation and vaulting of different streams, peak flow control works, landslide prevision and control, and soil stabilisation [GAMLP, 2016]. This type of planning leaves localised and down-scaled solutions behind. The media continuously reports flooding or soil movement events during the wet season every year [Radio Fides, 2015; Página Siete, 2020 & Brújula Digital, 2020]. Land cover changes can increase surface runoff and provoke these incidents [Arjenaki et al., 2020]. In this understanding, this study aims to evaluate the incidence of urbanisation and potential changes in rainfall, due to CC, over the drainage network's functioning. Moreover, it intends to determine whether the inclusion of sustainable urban drainage systems (SUDS) can enhance its performance.

1.2. Research Question

What is the impact of urbanisation and climate change on the drainage system in La Paz?

This overarching goal was subdivided into a set of questions to complement the traced objectives, as follows:

i. How much have the urban areas grown?
ii. Are there any climate change effects on the hydrologic cycle of La Paz?
iii. How does the drainage system perform under different levels of urbanisation?
iv. Are SUDS a feasible solution to enhance the system's performance?

1.3. Aim and Objectives

This study aims to assess the impacts of climate change and urbanisation on the drainage system's performance using SWMM simulation software and include improvement alternatives for an area of interest in the city of La Paz, Bolivia.

- Analyse geospatial data identifying and quantifying land-use change and urbanisation sprawl in the urban area of La Paz in the last two decades using GIS tools.
- Elaborate a disaster database with rainfall-related events and identify potential changes in precipitation in La Paz through research review.
- Compile and analyse meteorological data regarding rainfall precipitation, and define scenarios considering climate change criteria.
- Select an area of study considering urbanisation growth, precipitation projected changes, and disaster events occurrence.
- Collect drainage network data and study its performance for current and projected scenarios using SWMM software in the study area.
- Evaluate results and potential sustainable drainage adaptation solutions for improving the study area drainage performance.

1.4. Methods

This study determined the expansion of urbanisation, represented as built-up areas, between 2000 and 2020 utilising remote sensing and land-use classification techniques of satellite imagery. Then, a disaster occurrence database was built and climate change influence in the area reviewed from scientific research papers. Later, precipitation data was analysed to determine potential changes in the future due to climate change influence, and scenarios for simulation were built. After, an AOI was selected considering the previous factors. It was also classified with higher-resolution images to comment on its evolution. After collecting drainage system network information and constructing a digital model, the AOI and precipitation scenarios were included in SWMM. This software enabled the calculation of the drainage system's performance in the AOI. After, SUDS alternatives were designed and incorporated into the digital model. Finally, the incidence of SUDS into the system was determined and discussed with representative stakeholders.

1.5. Dissertation structure

This document is comprised of six chapters. The first one, presented so far, includes an introduction to the topic with the delineation of its rationale, research question and objectives. Chapter 2 enters into the literacy findings and state of the art on the topics. In Chapter 3, the research framework is presented along with the sources and processing of data. Chapter 4 includes a deeper analysis of the general aim, revising the quantitative and qualitative research results. Chapter 5 discusses the findings and cross-reference them with procedures and conclusions done on the same topics. Finally, Chapter 6 provides the conclusions and recommendations found in this study.

CHAPTER 2: LITERATURE REVIEW

2.1. Rapid urbanisation

Around 55% of the people on the planet lived in urban areas by 2018, and it is estimated to reach two-thirds of the world's population by 2050 [Gu, 2019]. Between 1975 and 2015 urban population almost doubled, and built-up areas grew by a factor of 2,5 [Melchioerri et al., 2018]. The accelerated urbanisation growth experienced worldwide has been attributed to diverse socioeconomic factors where 70% to 80% of many countries gross domestic product (GDP) is estimated to be produced by cities [Gu, 2019; World Bank, 2020]. However, while urban population and economic growth are expected to increase in the coming years, the investment needed to address natural disasters will likely rise due to their frequent occurrence. [Gu, 2019]. Still, these fast-growing urban environments will continue to expand with regional variations.

Developed economies faced rapid urbanisation intensively during the industrial revolution. It primarily took place in Europe and North America in the 19th and early 20th centuries [Mondal, 2020]. Developing countries lagged but caught up later in the 1950s, with accelerated rates [Mondal, 2020]. Still, many developing countries are highly urbanised despite not having advanced industrial systems. This characteristic is correlated to natural resources exports, which proved to be statistically significant and economically meaningful in terms of GDP and urbanisation rates [Vollrath et al., 2016].

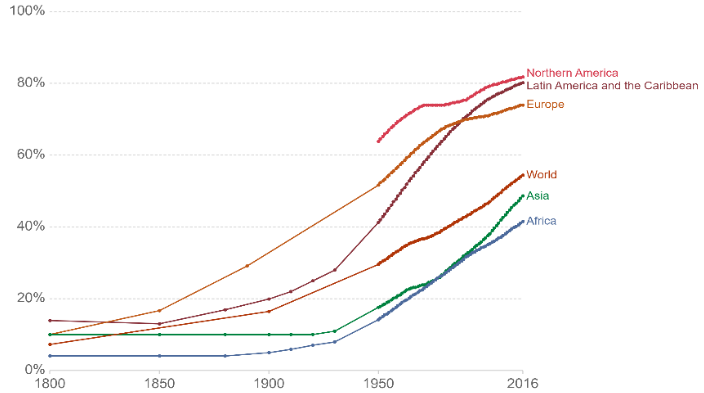

Figure 2.1 Share of the total population living in urban areas, from 1800 to 2016, by continent/region. Source: Ritchie & Roser, 2019

Despite decelerating its great urban sprawl in the last years, the LAC region is the second most urbanised region worldwide.

The latest statistics, provided by Szmigiera [2021], position Northern America first with 82%, followed by LAC with 79% as of mid-2020, while worldwide, the increase of urban population reached 56%.

One of the problems with Latin America current urbanisation degree is its large infrastructure gap. Poor foresight planning endorses lower rates of basic services coverage, e.g. housing, sanitation, or wastewater collection [Muggah, 2018], while changes in land use due to cities' expansion increase vulnerabilities.

The city of La Paz in Bolivia has combined characteristics of urban sprawl, poverty and vulnerability worth analysing. Its historical evolution made the city one of the most important in the country before, during and after colonisation. Because of its connectivity with Peru and the Pacific Ocean, mining sites in the southwestern departments, and to the east with the department of Santa Cruz [Barrientos, 2012], migration into the city soared. Nonetheless, current conditions are still inadequate, with a poverty gap of 16,4% and a high demand for land restricted by market supply, topography, and soil instability [GAMLP, 2019].

2.2. Latin America under the water

The impact of natural disasters is experienced widely around the globe, but some cities are more exposed and vulnerable than others. Gu [2019] investigated three spheres: i) exposure to natural disasters, ii) mortality level due to natural disasters, and iii) economic loss level due to natural disasters. The research accounted for cities with more than 300 thousand inhabitants and was classified into four categories: population size, region, development groups, and income groups. Also, the author considered six types of disasters: cyclones, floods, droughts, earthquakes, landslides, and volcanic eruptions. In the regional classification, LAC cities placed second and third place twice in the spheres mentioned above, respectively.

Additionally, the LAC region is one of the most vulnerable to the El Niño/La Niña phenomenon, bringing droughts and extreme rainfall events due to the water temperature shift in the Pacific Ocean [OCHA, 2019]. Four of the ten megacities presented a low exposure to droughts but are highly vulnerable to related economic losses. These cities were Mexico City (Mexico), Buenos Aires (Argentina), Rio de Janeiro (Brazil) and Lima (Peru) [Gu, 2019].

Figure 2.2 Number of people affected by the type of disaster in Latin America between 2000 and 2019. (Source: OCHA, 2019)

Still, flooding has been the most common type of natural-caused disaster in LAC in the last two decades. An UN-OCHA report compiled most of its data from the International Disasters Database (EM-DAT), showing that this category was the most significant in Latin America within the specified timeframe. Although droughts were the events that affected more people (see Figure 2.2), floods are the most common type of disaster in the region, affecting approximately 41 million people [OCHA, 2019]. This type of event has caused the death of 48.866 people in South America since 1926, while also affecting more than sixty-nine million people and causing damage over thirty-seven billion USD dollars since 1926 (see Table 2.1).

However, in the last decade, 2010 to 2020, 4.111 lives were lost due to flooding and inflicted an economic impact above 14,5 billion USD dollars.

Country	Total Affected	Total Deaths	Total Damages ('000 US$)
Argentina	14.489.902	860	11.072.210
Bolivia (Plurinational State of)	3.959.394	1.243	1.672.118
Brazil	20.270.374	7.989	9.975.254
Chile	1.657.667	1.245	2.297.600
Colombia	16.413.610	3.610	3.626.353
Ecuador	2.024.313	1.011	1.571.570
French Guiana	70.139	n/d	n/d
Guyana	671.048	34	634.300
Paraguay	2.012.117	199	96.557
Peru	6.200.436	2.243	3.293.000
Suriname	36.148	5	50
Uruguay	267.796	20	92.000
Venezuela (Bolivarian Republic of)	962.129	30.407	3.527.126
Grand Total	**69.035.073**	**48.866**	**37.858.138**

Table 2.1 Number of total people affected, total death toll, and total economic damage by flooding in South America (1926-2021) (Source: Own elaboration based on EM-DAT data, 2021)

2.3. The future of rainfall

Climate evolution has caught the attention of researchers in the last part of the 1990s [Le Treut et al., 2007] due to the impacts that it causes on the urban and natural environments and the regular functioning of the society at large, which can be compromised to disaster with either scarcity or abundance of rainfall. Moreover, some of the significant disasters related to CC result from extreme weather events. Droughts and floods rank amongst the most hazardous ones occurring as an alteration of the hydrological cycles. Likewise, climate projections indicate a more profound influence from global warming onto surface temperature, sea-level rise, and precipitation due to greenhouse gases (GHG) emissions [IPCC, 2014]. For instance, only regarding rainwater, the RCP2.6 scenario depicts percentual increases for most global land areas, mainly in the Northern Hemisphere and over the oceans in the Equator, with decreases in large surfaces of South America, Africa and Australia. While the RCP8.5 scenario can potentially increase average precipitation with considerable percentages (above 50%) in the poles and the Equator, noticeable decreases are foreseen inland and ocean areas of America, Africa, and Europe (see Figure 2.3).

Still, while some authors refer to the hydrological changes as a likelihood of emerging patterns of climate change [Dore, 2005], others declare that a specific extreme event impact cannot be assigned as the causation of climate change unequivocally [Shepard in OCC, 2018]. In contrast, others affirm that CC directly affects hydrological variations [Trenberth, 2011].

Dore [2005] noticed an overall increase in regional and continental precipitation, where usual wet areas are becoming wetter, and drier ones are experiencing harsher conditions. However, this pattern also varies at local scales and temporarily bases. El Niño Southern Oscillation

(ENSO) adds variabilities to “regular” behaviour in shorter year spans from two to seven years, mainly in the tropics and sub-tropics [Dore, 2005], but with global scale influence.

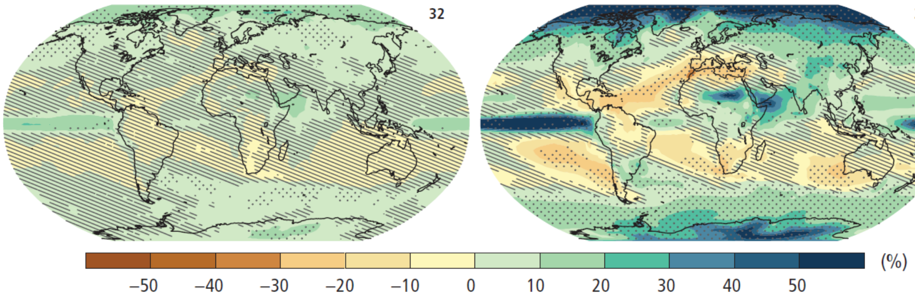

Figure 2.3 Change in average precipitation based on multi-model mean projections for 2081-2100 relative to 1986-2005 under the RCP2.6 (left) and RCP8.5 (right) scenarios. The number in the upper right corner represents the number of models used to calculate results. (Source: IPCC, 2014)

The aftermath of water availability, in deficiency or excess, reach diverse components of society’s development. These effects can be seen on food security when croplands and their products are lost due to flooding or droughts, affecting households supply [Devereux, 2007]. Food scarcity has then an impact on the prices in the market, with subsequent conflicts for society. Moreover, the hydro-powered energy sector can also be disturbed by water flow variances, leading to a more profound crisis in the production chain and living conditions [Magalhaes & Glantz, 1992]. Even so, human and natural systems’ vulnerability can increase due to anthropogenic causes and not only directly due to climate’s impacts [Meehl et al., 2000].

Therefore, adaptation and resilience become substantial to confront the global challenges of CC, but unfortunately, vulnerability plays an essential role in this regard. Developed economies like the ones from partner countries of the MUrCS Program[1]: Finland (3rd), UK (11th) and Spain (26th) place high in the Global Adaptation Index[2] (ND-GAIN) as of 2019, developed by the University of Notre Dame. Contrarily, LAC countries rank poorly, with Bolivia as the second most vulnerable in South America (133rd on the ND-GAIN out of 182 in total) and the fifth least prepared to mitigate the impacts of CC [Francois, 2016 & University of Notre Dame, 2021]. Although Bolivia is one of the lowest contributors of GHG emissions, with a global share of 0,06% as of 2019 [Ritchie & Roser, 2017], it is pretty vulnerable to CC due to extreme poverty, deforestation, changes in the ecosystems, unstable weather [Francois, 2016], and glaciers retreat [Rangecroft et al., 2013]. These features are added to the comprising factors of the ND-GAIN.

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[1] Master’s in Urban Climate and Sustainability Program

[2] The index is comprised of two main variables: vulnerability to climate change and readiness for adaptive actions. It was determined with 45 core indicators that include components of food, water, health, ecosystem services, human habitat and infrastructure in the vulnerability axis; and economic, governance and social readiness in the readiness axis.

Moreover, the vulnerability conditions of Bolivian cities like La Paz were exposed after rainfall-related disaster events, which led local governments and international entities to focus on improving infrastructure and planning as methods to enhance adaptation to climate change scenarios.

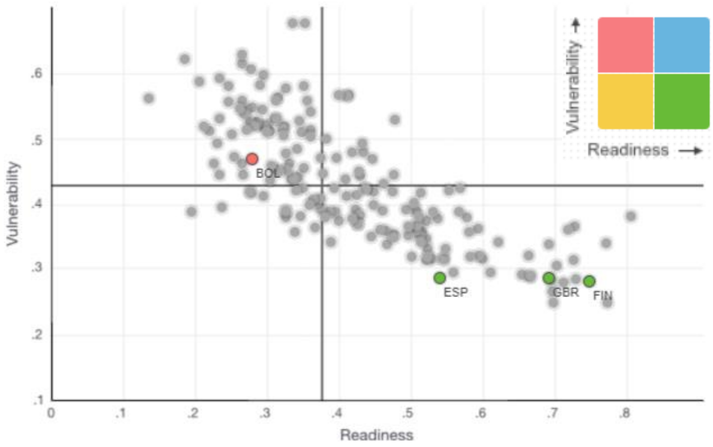

Figure 2.4 ND-GAIN Index for the United Kingdom (GBR), Finland (FIN), Spain (ESP) and Bolivia (BOL) as of 2019. (Source: University of Notre Dame – ND-GAIN, 2021)

2.4. The situation in the city of La Paz, Bolivia

La Paz in Bolivia is an interesting case concerning urban development and vulnerability because of its location and population, with over a million inhabitants. This city is the second most important city in Bolivia regarding GDP, with 24% of the country only topped by Santa Cruz de la Sierra [IDB, 2016]. It is settled on the basins' slopes that conform La Paz River watershed, at an average altitude of 3.600 metres above sea level, which varies between 3.000 and 4.000 metres (see Figure 2.5). It is divided into nine districts; seven are within the urban limits, and two are rural. However, the urban area occupies approximately 5% of the whole territory and lodges almost 93% of the population [GAMLP, 2015], contrasting with the rural occupation and population. This characteristic imposes pressure for housing and provision of public services in the urban area, in a context of increasing migration from close municipalities, constant transit from its neighbour city of El Alto [Arbona & Kohl, 2004], and other cities of Bolivia due to the importance of La Paz in the national development.

Moreover, the steep topography and geological features create different vulnerability ranges [GAMLP, 2011], which the Municipality aims to control through urban planning [GAMLP, 2021]. Nevertheless, when it comes to being applied into the territory, nuisance arises for public administrators whether compliance is not occurring. The GAMLP aims to enforce the city's development according to traced delimitations and land use through planning and legal instruments. The Law of Urban Land Use (LUSU, for its acronym in Spanish) is the latest norm updated with this objective [GAMLP, 2014]. However, irregular occupation and illegal plots trading are not uncommon, hampering the regular provision of services and public infrastructure works or delaying them due to legal conflicts [Veríssimo 2012; Vargas, 2014]. Additionally, many factors increment the vulnerability of the city. On a macro-scale, they are related to social behaviour and population, physical constraints and geological features, economic situation, public services provision, and institutional challenges [IDB, 2016: GAMLP, 2019].

Local authorities, researchers, and international cooperation had carried out different risks and vulnerability studies better to understand the spectrum of its factors and potential consequences. GAMLP [2011] and Flores [2020] had similar approaches utilising Geographic Information System (GIS) tools and data, not only including technical variables. The Municipality elaborated a Risk Map in 2011 based on two maps regarding hazards and vulnerability, including spatial multi-criteria evaluation – SMCE [GAMLP, 2011]. On his behalf, Flores built indicators for the socioeconomic and physical vulnerabilities and institutional capabilities. In addition, he created a diversity of cartographic maps to integrate them into a global vulnerability map [Flores, 2020]. On the other hand, the French Development Agency (AFD, for its acronym in Spanish) and the Latin America Development Bank (CAF) started working in 2019 on a climate change vulnerability index to increase the reaction capacity and resilience to CC [CAF, 2019].

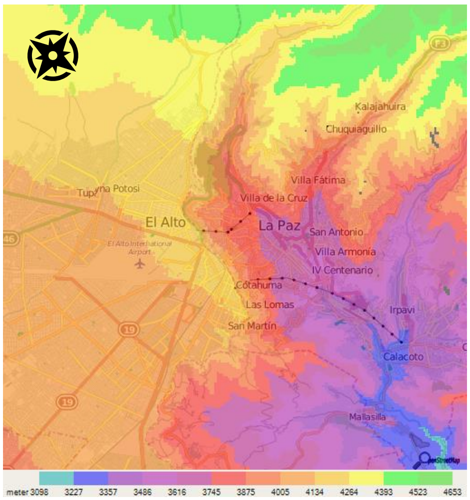

Figure 2.5 La Paz – El Alto elevation map. (Source: FloodMap, 2020)

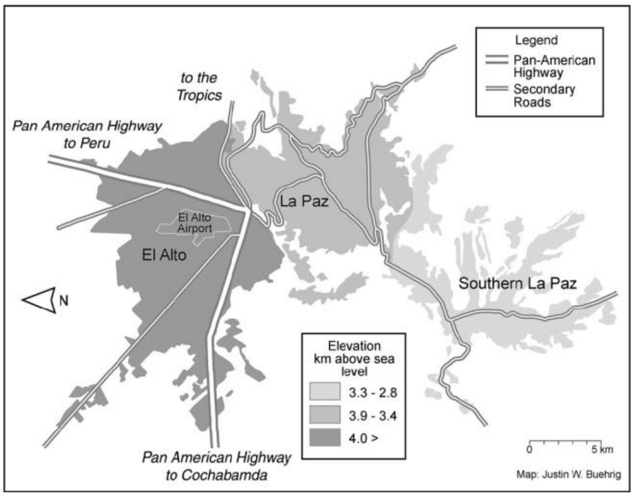

Figure 2.6 La Paz – El Alto metropolitan area. (Source: Arbona & Kohl, 2004)

It is no surprise that many actors are involved in this type of labour, as some significant historical events led to human and economic losses. One of the hazards in La Paz is directly related to the amount of rainfall precipitation, which can increase the risk of flooding, droughts, or landslides in vulnerable zones. In the last two decades, three major rainfall-related events occurred. The first and most harmful one happened in February 2002, when a combination of hail and heavy rain led to more than seventy human losses, and estimated figures between ten million [Hardy, 2009] and seventy million USD dollars [Fernández Illescas, 2016] in infrastructure damage. The second one happened in February 2011. Over 140 hectares of terrain slid down on that occasion, dragging more than 800 plots with it. Luckily, no human losses were reported since prevention measures were taken just before the event.

Nonetheless, the estimated recovery investment surpassed fifty million USD dollars [Pagina Siete, 2020]. Finally, from November 2016 until January 2017, a drought altered the regular provision of drinking water, especially in two urban districts (San Antonio and Sur), affecting over 340 thousand people [Ayala, 2016]. Although these tragedies were the most media-covered reports nationally and internationally, rainfall related events are expected. It is no coincidence that after “*Black February*” in 2002, the GAMLP created the SMGIR to forecast potential harmful events and prevent or mitigate their impact [Hardy, 2009].

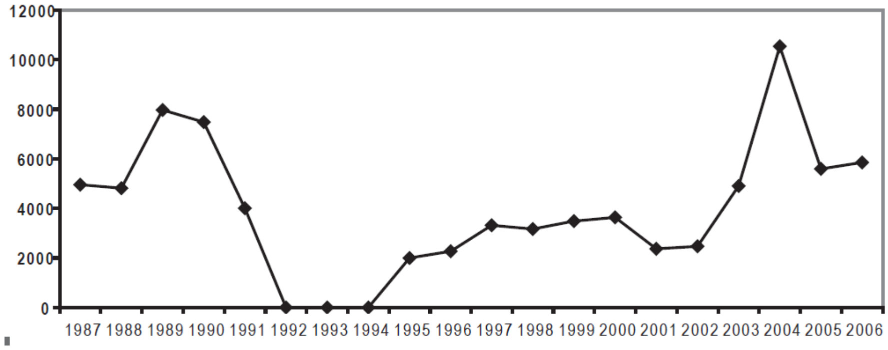

Figure 2.7. Risk management interventions made by the GAMLP each year in thousands of U.S. dollars. (Source: Hardy, 2009 based on Statistical Dossier La Paz 2000-2005)

Moreover, the tragedy of 2002 triggered actions from different actors, aiming to invest a diversity of resources on different solutions. Through the SMGIR, the Municipality increased the budget amounts for risk prevention [Hardy, 2009] and published the Map of Risks in 2011. Later investigations of the event determined some of its meteorological factors. Hailstorms and rainfall lasted for one and a half hours, with a descent of average surface temperature from 13 to 8 Celsius degrees [Villegas, 2002 in Hardy, 2009]. Rain gauges registered a total volume of precipitations of 39,4mm in one hour, from a total of 41mm in the day, being the most intense event recorded since 1976 [OPS, 2002 in Hardy, 2009]. The Municipality updated and published legislation in the LUSU of 2014 and runs awareness campaigns in the rainy seasons since clogging of the drainage system exacerbated the flooding [GAMLP, 2014; Fernández Illescas, 2016]. The International Development Bank (IDB) collaborated to develop a Master Plan for Urban Drainage for La Paz and El Alto [IDB, 2016]. Lastly, the World Bank has granted credit for approximately 59,02 million euros to improve the urban drainage system [World Bank, 2020 & Money, 2020]. Still, most of this planning and actions are focused on conventional and large-scale solutions, like channelling, vaulting, energy sinks and retaining walls.

2.5. SUDS and modelling: an approach to a solution?

Despite the term *sustainability* gaining more interest in stormwater management in the last century, sustainable urban drainage systems (SUDS) existed before 3000 B.C. They applied similar techniques to rainwater harvesting, detention ponds, or infiltration [Charlesworth et al., 2018]. However, since the 1990s, different terminology extended worldwide (e.g. low impact development – LID in North America and New Zealand; SUDS in the UK; water sensitive urban design – WSUD in Australia), but all these terms aim to improve water management and urban drainage [Fletcher et al., 2014].

However, more SUDS information, applications, research and projects are available from developed countries than those found from LAC. SUDS practical application was more notable in the United States of America (USA), Australia and the United Kingdom (UK), but it has been more informal in low-income countries [Reed, 2004]. A characteristic in many cities in the Global South is the uncontrolled and unplanned transformation of land use, affecting runoff [du Toit et al., 2021]. Additionally, some barriers to applying SUDS are lack of design information, reluctance to pioneer alternatives and institutional deficiencies [Reed, 2004]. Still, some examples regarding SUDS solutions in LAC involved permeable pavements, green roofs, retention ponds, and swales with different approaches and results depending on each context. Nevertheless, the design of SUDS in LAC has been growing with the implementation of computational innovations and planning needs.

The current technological advancements also reached the possibility of conventional and sustainable urban drainage design software, being SWMM an open-source, widely used option. The Storm Water Management Model (SWMM) is a public software co-designed by the Environmental Protection Agency (EPA) of the United States. It can be used for *‘planning, analysis, and design related to stormwater runoff, combined and sanitary sewers, and other drainage systems’* [EPA, 2020]. It can also be combined with GIS tools to integrate hydrological and hydraulic criteria into urban planning [Allende-Prieto et al., 2018]. In the city of Hohhot in China, Zhou et al. [2016] implemented an SWMM model to reflect the city’s land use for the years 1987, 2000, 2010 and a projected map for 2020, which is possible by including specific parameters in the catchment areas. Their results provided guidelines for cost-effective adaptation measures to cope with flooding caused by urbanisation growth. In a test catchment in northern Sweden, Borris et al. [2013] found that runoff volume correlates linearly to the imperviousness of the area. Hence, runoff increments are higher due to urbanisation rather than those ascribed to climate change. For example, a 10% reduction of imperviousness can decline runoff volume by 8%.

Moreover, the increase of green areas contributes to diminishing runoff flow, peaks and pollutant concentrations. For example, a study area in Beijing, China, was modelled, including a retrofit conversion in urbanised zones with 30% of rooftop areas to green roofs (GRs), 35% of paved areas converted to the permeable pavement (PP) and 10% of green areas to rain gardens. The reduction of peak flows was between 60,7 and 81,2% for different LID scenarios [Randall et al., 2019]. Similarly, in the city of Shahrekord in Iran, Arjenaki et al. [2020] provided disaggregated values for GRs and PP, with 46 and 21% efficiency reduction in peak flows, respectively.

Nonetheless, scarce SUDS and simulation cases were found for the study of drainage in Bolivia. One of them was carried out in Santa Cruz de la Sierra, which primarily focused on landscape ecology and resilience of the urban-rural relationship of the Pirai River. Castelli et al. [2017] found that urbanisation increased the peak runoff, jeopardising the Pirai River ecosystem services. However, they estimate that solutions like rain gardens and green roofs in new urbanisations can reduce this impact and suggest implementing waterscape-ecological planning into policies and as planning instruments.

Regarding modelling, three thesis documents that used SWMM were found on academic digital libraries, but it was only possible to get access to two of them. Osinaga [2011] aimed to reproduce the *Black February* event of 2002 in La Paz. In his methodology, the SWMM *links* were designed as open canals representing streets to determine vulnerability risk. Water velocity and height obtained in the results worked as inputs for tumbling stability and sliding stability. Zuazo [2015] worked on a watershed modelation in Cota Cota, verfying the impact of land-use change in the canal or River Jilusaya.

CHAPTER 3: **METHODS**

3.1. Research framework

This study approach is framed by the inductive research type, applying developed knowledge from remote sensing, hydrology, hydraulics, and computerised simulation packages to understand urban climate and infrastructure performance. Moreover, it combines qualitative and quantitative methods for determining the inputs for the further process of math-based simulation, under the scheme of a simulation research type.

As a result of the reasoning process and connection with the aim of this study, Figure 3.1 displays the research framework. It has been subdivided into three stages: i) the collection of raw data and its subsequent processing; ii) the simulation stage in which all previous data is included, and iii) a post-simulation stage in which a semi-structured interview was conducted. These components and stages are explained in more detail as follows.

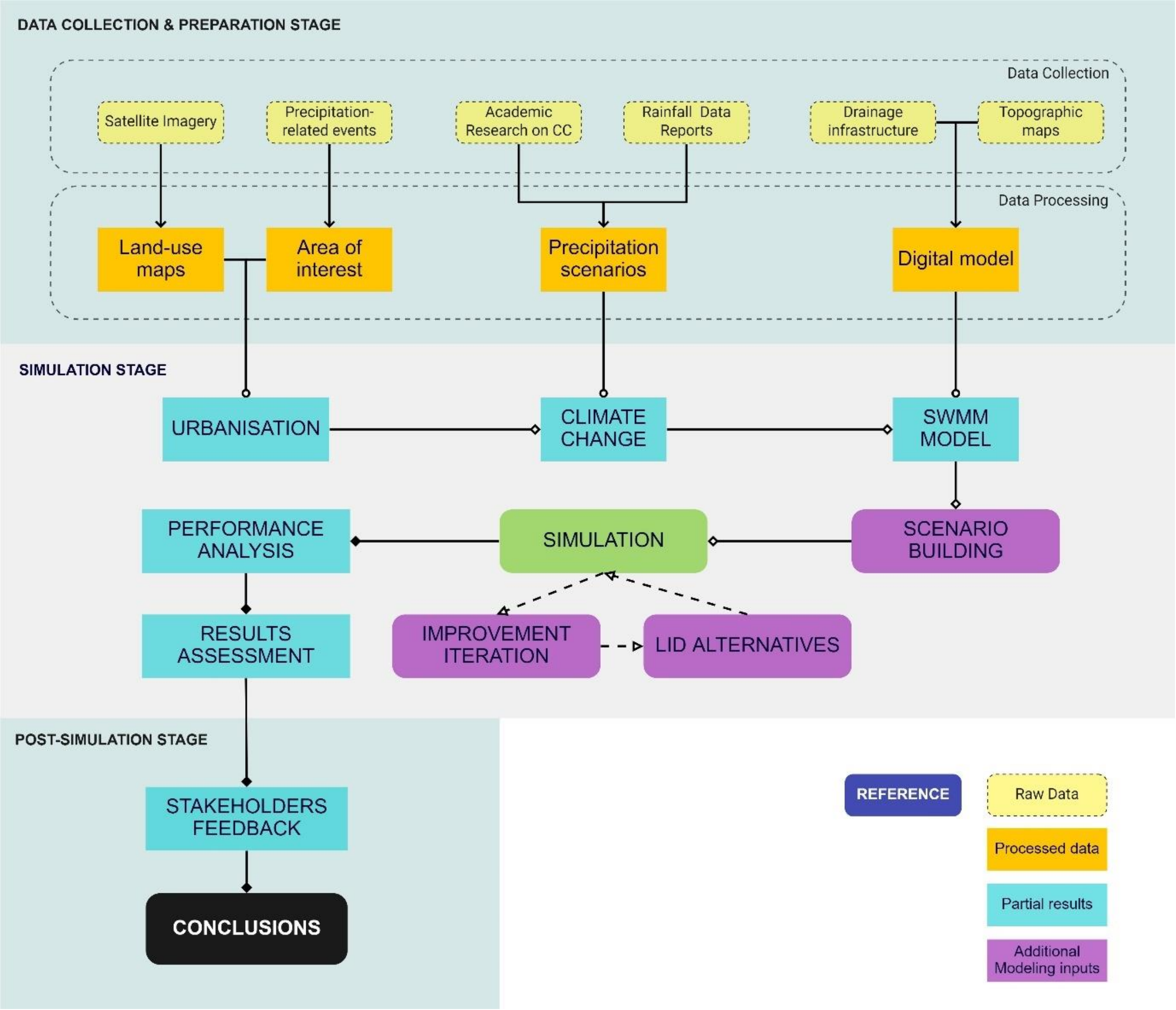

Figure 3.1 Framework flowchart designed and adopted for the study (Source: Own elaboration)

3.2. Data sources

The information utilised in this study was collected from different sources, from open-access ones to under request ones. Table 3.1 presents a summary of the sources.

Field	Data	Source	Characteristics	Location
Remote sensing	Landsat 7 imagery	Landsat	Multiband spectral with 30 by 30-metre resolution	Section 4.1
	QuickBird and GeoEye imagery	GAMLP	RGB composite image with 1,2 by 1,2-metre resolution	Sections 4.1 & 4.4
	Bing Maps imagery	Bing	Non-referenced RGB images with 0,57 by 0,57-metre resolution	Sections 4.1 & 4.4
Climate change	Research findings of climate change effects in La Paz, Bolivia	Academic, various	Academic research papers	Section 4.2
Data Management	Monthly and maximum daily precipitation	SENAMHI[3]	Data collected from ten weather stations in the urban limits	Section 4.3
Drainage infrastructure performance	Urban sub-catchments; design storm; drainage network	Various	Topographic map, drainage system database	Section 4.5 & 4.6
Low-impact development (SUDS)	Proposal based on system performance	Various	Research of LID application	Section 4.6

Table 3.1 Summary of data sources (Source: Own elaboration)

3.3. Data collection and preparation stage

3.3.1 Satellite imagery and Land-use cover maps

Two different sets of land-use cover maps were created based on the satellite imagery data. First, Landsat 7 images were obtained from the Global Visualization Viewer (GloVis) public database. Images corresponding to May 2000 and July 2020 were available with a cloud cover lower than 10%. Second, the maps were elaborated utilising a supervised classification technique in ArcMap v10.7.1. Six broad types of land use were identified through training samples: 1) built-up areas, 2) bare soil, 3) forests), 4) green areas, 5) agriculture, and 6) waterways. The resulting map was utilised to analyse the land-cover change within the

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[3] SENAMHI is the acronym in Spanish for *Servicio Nacional de Meteorología e Hidrología*, which is the national meteorological services in Bolivia.

delimited urban limits[4] on a broad scale. The surface occupation was determined for each category and urban district. Finally, built-up areas annual growth rate was compared with the population growth rate.

The second set of maps was created after defining the study area (see section 3.3.4 and Chapter 4) from higher-resolution images. The data was collected from the GAMLP open library, including RGB images from QuickBird (2003) and GeoEye (2013). Their resolution was 1,2 by 1,2 metres per pixel. Additionally, an image from Bing Maps of the year 2020 was created from mosaic aerial photos. It was previously coupled, georeferenced and resampled to match the resolution of the two previous sources. Then, the images were also classified with a supervised classification technique [Price, 2010], identifying different land-cover types each year. However, all the categories included: bare soil, compacted soil, creek/saturated soil, grass/low vegetation, roofs/tiles, trees/shrubs, developed areas, concrete, and pavement.

3.3.2 Rainfall-related disasters and Research of precipitation changes

A matrix database was constructed by collecting and reviewing online news media portals, institutional reports, and authorities' information. It included the type of event, rainfall intensity, storm duration, affected zones, district, human and economic losses, damage details, and the source type and source. Additionally, the Risk Map of La Paz, elaborated by the SMGIR, was briefly discussed along with the LUSU map.

Regarding potential changes in precipitation because of climate change, academic papers and reports were collected and reviewed. This information was focused on research representative to the area of La Paz and Bolivia. The findings were analysed and summarised to determine the potential rain pattern changes in the future

3.3.3 Rainfall data analysis

Rainfall data were collected from ten different stations within the urban limits of La Paz. This data was obtained from the open portal of SENAMHI and provided aggregated information of monthly accumulated precipitation and monthly maximum precipitation in a day. Then, it was analysed by season to identify probable trends. Finally, t significance of trends was evaluated with a non-parametric Mann-Kendall test (at 90% confidence level), which is widely used to evaluate trends in environmental time series [Thibeault et al., 2010].

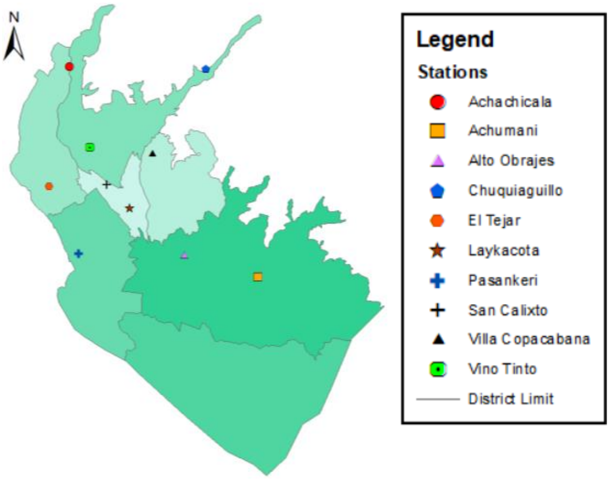

Figure 3.2 Location of rain gauges in La Paz (Source: Own elaboration based on SENAMHI and GAMLP data, 2021)

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[4] The GAMLP has divided its territory into nine macro-districts, with seven of them corresponding to the urban areas, and the rest two are rural districts.

The test considered data for i) maximum precipitation in 24 hours and ii) average precipitation, both across all ten stations and by season (wet and dry).

3.3.4 Area of interest (AOI) selection

The AOI was selected based on three considerations. The first one was the land-use cover evolution map aforementioned. Second, the occurrence of disasters according to the most common type of disaster. Finally, the vulnerability of the area according to the risk map of La Paz.

Then, results from the land-use classification at higher resolution were described, and its flowing patterns were exposed. Once the AOI was defined, urban sub-catchments were delimited based on topographic cartography, with contours every one meter. This information was collected from the Municipality but dated from before 2000. Therefore, the portion in the AOI that changes after 2000 was complemented with DEM from Google Earth, as it was the option with closer approximation to the cartography values. In total, sixty-one sub-catchments were delimited for their inclusion in the digital model.

3.3.5 Drainage system digital model

SWMM v5.1 was used to build the digital drainage system of the AOI. This software requires several inputs which were previously collected or processed. First, catchment areas were delimited based on urban geometry and topography in the selected site. Then, contour lines from a land survey map (elevations every metre) were complemented with a DEM from Google Earth to delineate the catchments in ArcMap v10.7.1. Finally, additional information was added to each catchment generated in ArcMap, like area, impervious percentage, pervious percentage, and their corresponding weighted Manning overflow (run-off = n) coefficients determined applying equation [1].

For pervious and impervious areas (n):

$$n = \frac{\sum_{i=1}^{n} n_i \times A_i}{\sum_{i=1}^{n} A_i} \qquad [1]$$

Where:

n_i = coefficient according to each land-use polygon in a single sub-catchment

A_i = area of each land-use polygon in a single sub-catchment, in square meters

The coefficients were assigned according to their physical representation on-site, which was determined based on their types of surfaces through supervised classification of the AOI at higher resolution (see Table 3.2)

Second, the software requires the drainage network system data. This information was obtained from the water company (EPSAS, for its acronym in Spanish). Then, elements inside the AOI were filtered with ArcMap to isolate the elements. Moreover, three sub-systems were identified, with three discharging points (outfalls in SWMM), sixty-three utility holes (nodes) and sixty pipes (links). These sub-systems were defined as Zone 1, Zone 2 and Zone 3 in the

AOI. Finally, the input data for outfalls, nodes and links were included according to the infrastructure database provided by EPSAS and complemented with the contour lines elevation value.

Literature reference	Study classification	Assigned value
Ordinary concrete lining	Concrete	0,013
Grassland/herbaceous	Grass/Low vegatation	0,220
Mixed forest	Trees/Shrubs	0,290
Developed medium intensity	Developed	0,028
Bare soil	Bare Soil	0,035
Gravelled surface	Compacted soil	0,020
Brick with cement mortar	Roofs/Tiles	0,014
Water	Creek/Saturated soil	0,030

Table 3.2 Adopted overflow coefficients based on values proposed by McCuen [1996], Jung [2010], Endreny [2011] and Liu [2018]. (Source: Own elaboration)

Finally, a rain gauge with a time-series synthetic design storm was required for the AOI. The design storm was calculated from intensity-frequency-duration (IDF) curves and a hyetograph. IDF curves were computed from precipitation data with Achumani station data considered the most representative station to the study area due to its proximity. Also, a precipitation analysis was done using the Gumbel distribution, widely applied to study extreme values, and predict unusual events regarding rainfall, temperature, or wind speed, among others [Meehl et al., 2000; Sánchez, 2013]. Design precipitations were determined as follows:

Reduced variables (YT):

$$YT = -ln^{\left(ln^{\frac{TRi}{TRi-1}}\right)}$$ [2]

Precipitation (XT') in mm:

$$XT' = u + (\alpha \times TRi)$$ [3]

Occurrence probability of Gumbel:

$$F_{(xT)} = e^{-e^{-\left(\frac{x-u}{\alpha}\right)}}$$ [4]

Design precipitation (XT) in mm:

$$XT = XT' \times f_c$$ [5]

Being:

$$\alpha = \frac{\sqrt{6}}{\pi} \times s$$

$$u = \bar{x} - (0{,}5772 \times \alpha)$$

Where:
TRi = return period, in years
s = standard deviation of the sample
$\bar{x}$ = average of the sample
f_c = correction factor = 1,13

The resulting maximum precipitations (XT) were calculated for return periods (TR) of 2, 5, 10, 25 and 50 years. Also, for durations below 24 hours considering duration coefficients determined for La Paz characteristics [Luna, 2009 in Zuazo, 2015], as shown in Table 3.3.

Storm duration, in hours									
1	**2**	**3**	**4**	**5**	**6**	**8**	**12**	**18**	**24**
0,590	0,680	0,750	0,800	0,805	0,810	0,827	0,860	0,930	1,000

Table 3.3 Storm duration coefficients determined for La Paz conditions by (Source: Own elaboration, adopted from Campos, 1978)

Therefore, IDF curves were determined following the equation established in the *technical regulation for designing urban drainage systems* [MMAyA, 2010] using equation [6].

IDF equation:

$$I = \frac{k \times TR^m}{t^n} \qquad [6]$$

Where:
k, m, n = adjustment parameters depending on the region
TR = return period, in years

Lastly, the hyetograph was constructed with the alternating block method with 5-minute intervals over sixty minutes, adopted as a critical duration scenario.

3.4. Simulation stage

3.4.1 Scenarios simulation

The simulation was run after defining calculation methods in SWMM and two scenarios to include urbanisation and CC factors. First, regarding methods, infiltration was determined by the software adopting the Horton formula based on an empirical process where infiltration decreases exponentially on time [EPA, 2015]. Then, routing was determined under the kinematic wave method based on the continuity equation where *‘acceleration and pressure terms in the momentum equation are negligible’* [Chow, 1988]. Moreover, as is the case of AOI, this method is utilised for dendritic networks and reduces computation time while maintaining numerical stability [EPA, 2015]. Later, friction losses were determined using the Hazen-Williams formulas as the main force equation.

Second, the scenarios were modelled in two parts. The first scenario included data of land-use changes evolution (LUCE) from 2003, 2013 and 2020. These changes were reflected in their subcatchments runoff coefficients due to urbanisation. The results permitted to compare peak flow and peak flooding differences and system performance by Zones (1, 2, and 3).

The second scenario included the current characteristics of the urban structure in the AOI, as of 2020 (LUCE 20), but adding a rainfall increase (RI20) scenario and a rainfall decrease (RD20) synthetic storms to determine the same parameters as in the first scenario.

3.4.2 Sustainable Urban Drainage System

Based on the results from the previous section, two types of SUDS were applied to the Zone with more unsatisfactory performance: green roofs (GRs) and permeable pavement (PP). In SWMM, these categories are labelled under low-impact development (LID = SUDS). Therefore, these proposals were also included in the SWMM model, with their corresponding features adopted from similar studies of Bai [2019] and Arjenaki [2020].

3.5. Post-simulation stage

Two semi-structured interviews were conducted with a former and a current municipality employee, relevant to the study because of their relationship with the topic. In the first case, Kheni Paton was the coordinating advisor to the City Council Presidency, more involved in the governmental and governance roles. In the second one, Eduardo Zamorano works as the technical advisor to the Secretary of Environmental Management, in close relation to the execution and technical approach. The interviews were carried out online and in Spanish; nonetheless, their transcriptions in English are included in Appendix A. The duration of both was close to thirty minutes each. The most relevant points concerning the study were rescued from these interviews. They complemented the findings to delve into the factors that facilitated their discussion.

CHAPTER 4: RESULTS

4.1. Urbanisation sprawl

A broad-scale land-use cover raster map for the urban area of La Paz allowed determining the growth of urbanisation between 2000 and 2020. Within the six land-use types identified, built-up areas expanded from 4.531 to 6.184 hectares, representing a 36,48% growth. On the other hand, bare soil experienced a fall from 8.951 to 7.281 hectares, an 18,65% decline. These two categories cover 90,47% of the 14.883 hectares in the urban limit as of 2020. Although the rest of the categories had minor changes, it is necessary to mention that green areas and forests have decreased. Figure 4.1 exhibits land-use cover comparative evolution in the last two decades, while Figure 4.2 includes detailed changes by category.

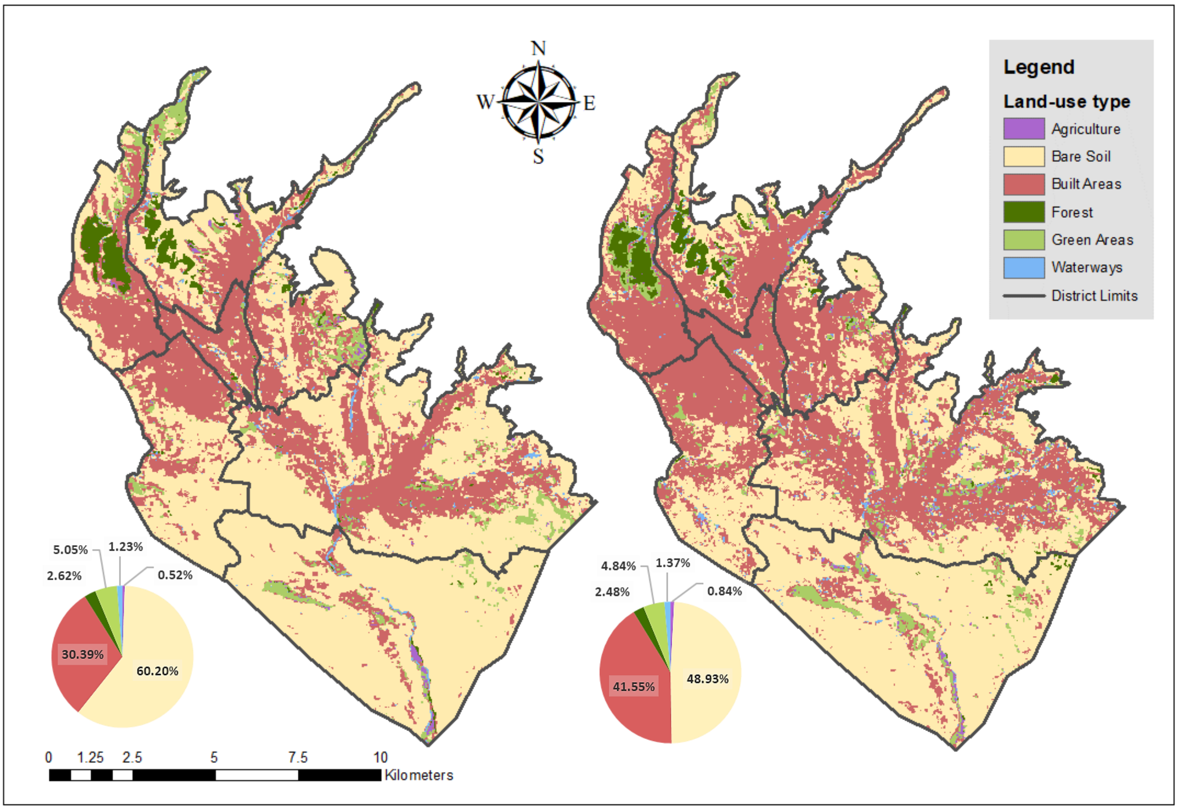

Figure 4.1. Land-use cover change in the city of La Paz. On the left, the year 2000, and on the right, the year 2020. (Source: Own elaboration based on Landsat 7 satellite imagery, 2021)

Nonetheless, these changes had different behaviour spatially, varying in each jurisdiction. Thus, Centro (city centre in English) is the most urbanised district area, with 87% of its surface covered by built areas, followed by Max Paredes with 60,71% and San Antonio with 57,02%. Moreover, within the 20 years, San Antonio had the most significant increase with 18,7%, followed by Periferica (18,13%) and Cotahuma (15,57%). Overall, the increment in built-up areas was 11,16% (see Figure 4.4).

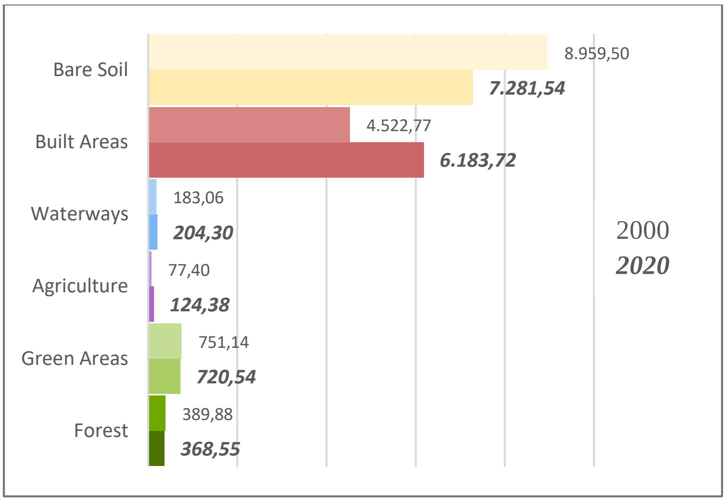

Figure 4.2 Land-use cover composition by category, in hectares (Source: Own elaboration, 2021)

Figure 4.3 La Paz's districts (Source: Own elaboration based on GAMLP data, 2021)

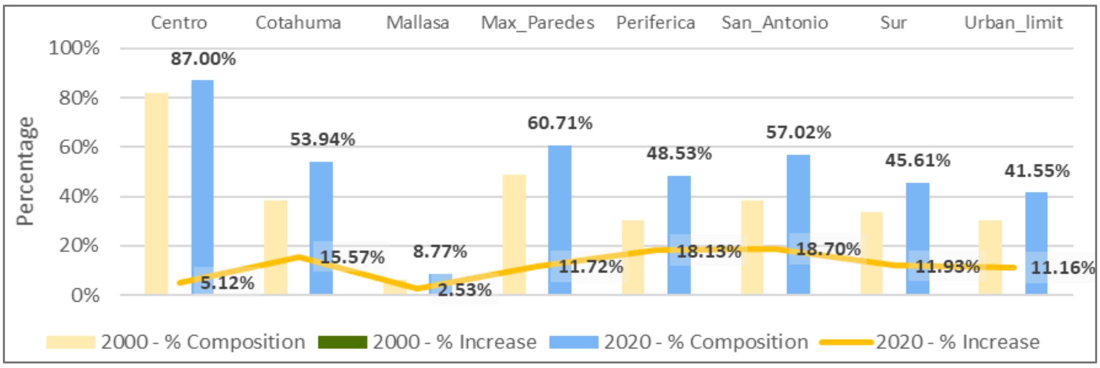

Figure 4.4. Percentual composition and increments for built-up area land-use cover, by district (Source: Own elaboration, 2021)

In the case of the bare soil, the districts of Mallasa (83,67%), Sur (45,77%) and Cotahuma (42,07%) are the ones with the highest occupation in this category. Nonetheless, all the districts have decreased this surface by 11,07% on average. The reduction has been led by Cotahuma (-16,69%), Periferica (-13,79%) and Sur (-13,55%), with a total of -11,27% within the urban limits. Therefore, until 2020, 48,93% of the territory was bare soil (see Figure 4.5).

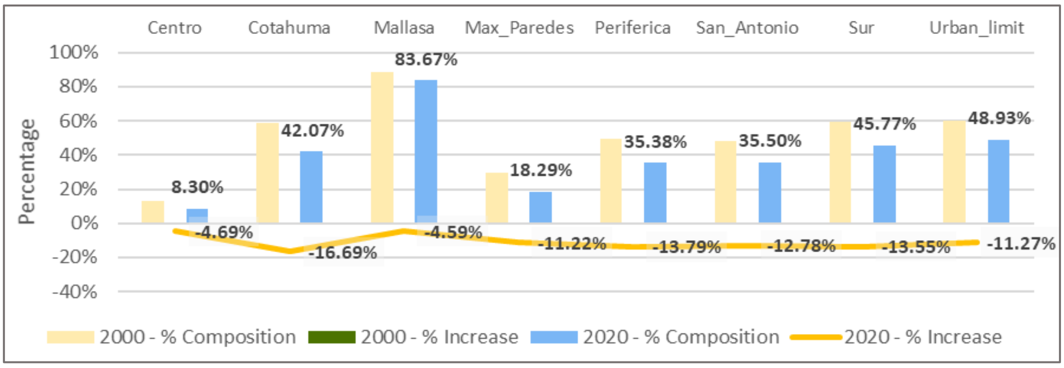

Figure 4.5. Percentual composition and increments (decrements) for bare soil land-use cover, by district (Source: Own elaboration, 2021)

For natural environments, most districts have green areas and forests coverage under 10%. Districts Mallasa, Cotahuma, and Sur had negligible changes, with 2,34%, 0,28%, and 0,19% respectively. On the contrary, San Antonio (-5,25%), Periferica (-3,95%), and Max Paredes (-1,41%) are the ones that experienced the largest declines in these two categories. In general, green areas decreased from 5,05% to 4,84%, while as forests from 2,62% to 2,48% an overall loss of 0,35% equivalent to 30,6 hectares.

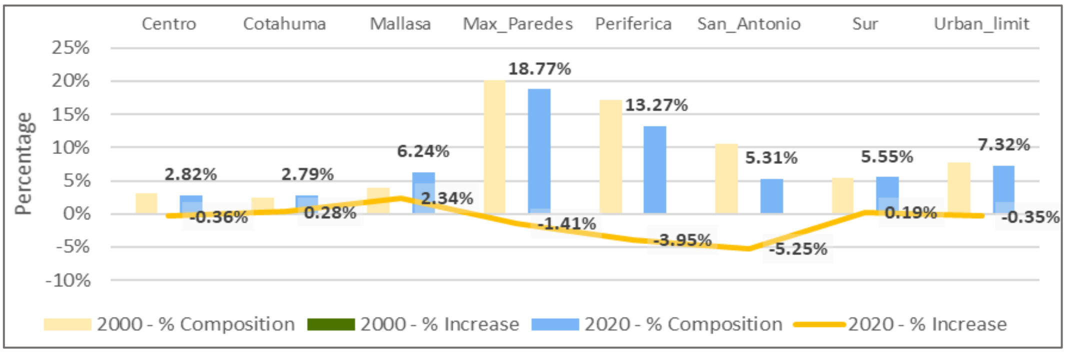

Figure 4.6. Percentual composition and increments (decrements) for forests + green areas land-use cover, by district (Source: Own elaboration, 2021)

However, when comparing the population with the urbanisation growth in the last two decades, a significant difference was determined, imposing challenges in the city's management. The population presented a higher increase pace; nonetheless, it can be possible that complementing the horizontal expansion, the city also experienced vertical growth to accommodate all these people. This significant development imposes enormous tasks for urban planning and its relation with risk management, primarily in high-risk areas prone to flooding and landslides.

Description	**Unit**	**Year 2000**	**Year 2020**	**% Increase**	**% Annual growth**
Total population	inhabitants	*749.621	*1.298.869	73,27%	3,66%
Urban population	inhabitants	**697.148	**1.207.949		
Built areas (urban)	hectares	4.522,77	6.183,72	36,72%	1,84%
Bare soil	hectares	8.959,50	7.281,54	-18,73%	-0,94%

*Table 4.1. Annual growth comparison for population and urbanisation in La Paz between 2000 and 2020. *projected values based on the GAMLP statistics report [2018] **estimated values based on urban population/total population ratio of 0,97 reported by the GAMLP [2016]*

4.2. Disasters and climate change incidence on precipitation

Sixteen significant incidents were catalogued and compiled during the 20 years frame, with most of them having occurred in district Sur. However, some of their impacts reached more than one district, as is shown in Figure 4.7. Details of these events are included in a matrix in

Appendix B. Unfortunately, it was impossible to collect data with broader specifics like the number of affected people or georeferenced location from the GAMLP[5].

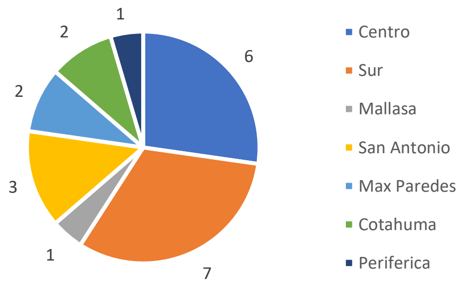

Figure 4.7. Precipitation related events in La Paz years 2000 to 2020, by district. (Source: Own elaboration, 2021)

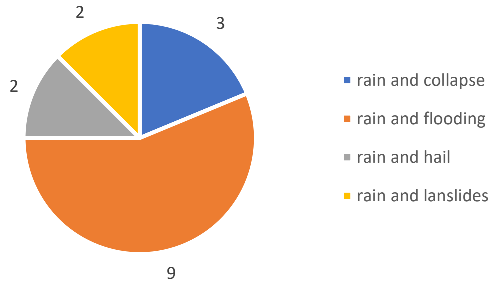

Figure 4.8. The number of extreme rainfall-related events years 2000 to 2020, by type of event. (Source: Own elaboration, 2021)

Moreover, the most repeating type of event was rain and flooding (Figure 4.8). Still, as mentioned in Chapters 1 and 2, the most media-covered disasters occurred in February 2002 and February 2011. Through the analysis of more academic and media sources of these two, it was possible to found a connection with peaks in rainfall. For example, Hardy [2009] stated that 96% of the day's total precipitation in the 2002 event was registered in one hour. Likewise, the GAMLP [2012] found an unusual peak in the monthly precipitation of 2011.

Figure 4.9 Flooding images from the event of 2002. On the left is a screen capture of a video. Its driver is coming out of the car through the window due to the current force (Source: GeoBiker, 2009). On the right an image of a city centre street covered with hail (Source: UrgenteBo, 2018)

Nonetheless, two main factors were identified in these types of disasters in La Paz. First, natural causes like heavy precipitation and topographic conditions for both cases, adding geological conformation for the case in 2011 [Hardy, 2009; GAMLP, 2012; Otero, 2016]. Second, there was a critical incidence of infrastructure regarding drainage systems and urbanisation patterns. For example, combined sewage networks and functional deficiency were critical in the 2002 flooding [Hardy, 2009]. Moreover, deteriorated pipes and use of septic tanks (due to limited

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[5] A request letter was sent to the Municipality on February 2nd of 2021. Unfortunately, until the date of elaborating this study, no response was sent by them.

sewer coverage) worsen infiltration and slopes erosion in the case of Callapa in 2011 [GAMLP, 2012, Otero, 2016]. In addition, human settlements in vulnerable areas increased the risk because of land-use change, lack of adequate stabilisation, and surface and underground water flow management [Otero, 2016].

Figure 4.10. Satellite image comparison of 2011 landslide. The image on the left was captured before the disaster in January, and the one on the right after stabilisation works in July (Source: Google Earth, 2021)

However, as a natural cause, uncommon rainfall records built upon the already vulnerable conditions of La Paz, and therefore, there was a necessity to analyse them. Thus, scientific research boarded the complex topic of CC through mathematical representations of Earth's climate system. Some of the most thorny and tested against historical observations are the General Circulation Models (GCMs) [IPCC, 2014]. They utilise grid cells, around 100 kilometres each, to represent the location (latitude, longitude and elevation) for different components such as oceans, land surface, atmosphere, and ice caps. These components contain equations calculated on the global grid for climate variables like temperature and rainfall (among others) because of the complexity of GCMs, which is tried to be simplified.

Even with the broad and detailed study of CC, few academic articles were found for the projections and estimates in Bolivia's future precipitation scenarios, difficulting the objective to identify the projections for La Paz. Moreover, the ones covering the Andes (a mountain range that crosses many countries on the west side of South America) and Altiplano (highlands) were selected due to the approximate conditions of the study. Still, there is no definite agreement for probable scenarios, but there is a tendency towards rainfall deficiency. Hence, Bolivia is expected to be one of the most affected countries by droughts and insufficient precipitation in South America [Winters, 2012; Rangecroft et al., 2013]. It is likely that during EN phases, the rain will tend to diminish [Vuille, 1999] between 10 to 30% [Minvielle & Gerraud, 2011]. This phenomenon will not affect only the Altiplano region (where the city of La Paz locates) but also other departments at lower altitudes and with warmer and more humid climates [Seiler et al., 2012]. Also, other authors point to probable increases in extreme events [Thibeault et al., 2010] triggered by Southern Oscillation during the La Niña phase [Vuille, 1999] or by growing GHG emissions in the future years, inducing up to 20% increments [Seiler et al., 2013]. Therefore, uncertainty is still present in La Paz's precipitation forecasts.

Nonetheless, research findings also identified different limitations from the downscaling of GCMs [Seiler et al., 2013], to the lack of input data for built patterns like PDO or ENSO (Seiler et al., 2012), to the uneven spatial distribution of stations [Canedo-Rosso, 2019], among others. Even so, these discoveries are presented in Table 4.2 to summarise them for later use in the next section.

Author	Year	Data and context	Key findings
Vuille	1999	High and Low index phases of ENSO complemented with radiosonde and stations data over the Bolivian Altiplano	Precipitation tends to be above average during La Niña summers and deficient during low index EN summers.
Thibeault et al.	2010	Multimodel and multi-scenario projections of eight precipitation and temperature-extreme indices for the Altiplano were studied	Annual cycle projections indicate a later rainy season characterised by less frequent, more intense precipitation.
Minvielle & Garreaud	2011	GCMs and precipitation data from rain gauges in the South American Altiplano	Regression analysis indicates a potential reduction in precipitation, around 10% to 30%, for the South American Altiplano considering moderate-to-strong GHG emission scenarios.
Seiler, Hutjes & Kabat	2012	PDO, ENSO and AAO in their positive and negative phases for the Bolivian Andes	Less rainfall in the Bolivian Andes due to EN during the wet season (DJF with -26 mm/month).
Rangecroft et al.	2013	Theoretical review of glacier recession evidence in the Bolivian Andes	80% of Bolivian glaciers in the Cordillera Real are predicted to disappear in the next few decades due to temperature increases and reductions in rainfall and snow.
Seiler, Hutjes & Kabat	2013	35 GCMs, 25 local stations for temperature, and 59 for precipitation were analysed to determine likely ranges of CC in Bolivia	CMIP3 GCMs tended towards less monthly rainfall (-9%), while CMIP5 tended towards more (+20%) in the Andes.

Table 4.2. Summary of scientific research of precipitation-related projections for the city of La Paz (Source: Own elaboration, 2021)

4.3. Precipitation analysis

Maximum day value in a year and accumulated monthly precipitation data were collected from ten meteorological stations in the urban limits of La Paz. Their records vary from 18 to 101 years of extension. In Figure 4.11, the rain amounts of the first type are displayed for each year, highlighting peaks in 2002, 2003, 2004 and 2011 events.

Furthermore, La Paz has a wetter season from December until February, although October, November and March are also rainy months, as seen in Figure 4.12. The average precipitation in these six months (wet season) was 82,02 mm, while the rest (dry season) was 16,31 mm. Consequently, the average standard deviation is ±18,25 for the dry season, while the wet one has a more significant value of ±48,75, as indicated below.

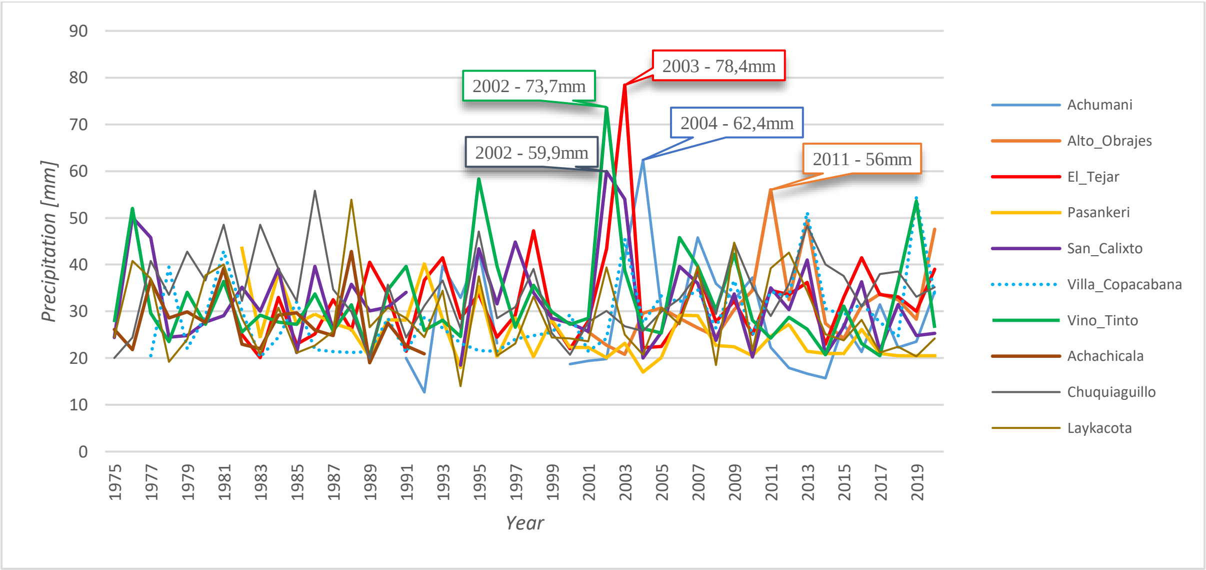

*Figure 4.11. Maximum daily precipitation records from 1975 to 2020 by station, in millimetres. *Note: Values earlier than 1975 records from San Calixto and Laykacota are not shown in the graphic. (Source: Own elaboration, 2021)*

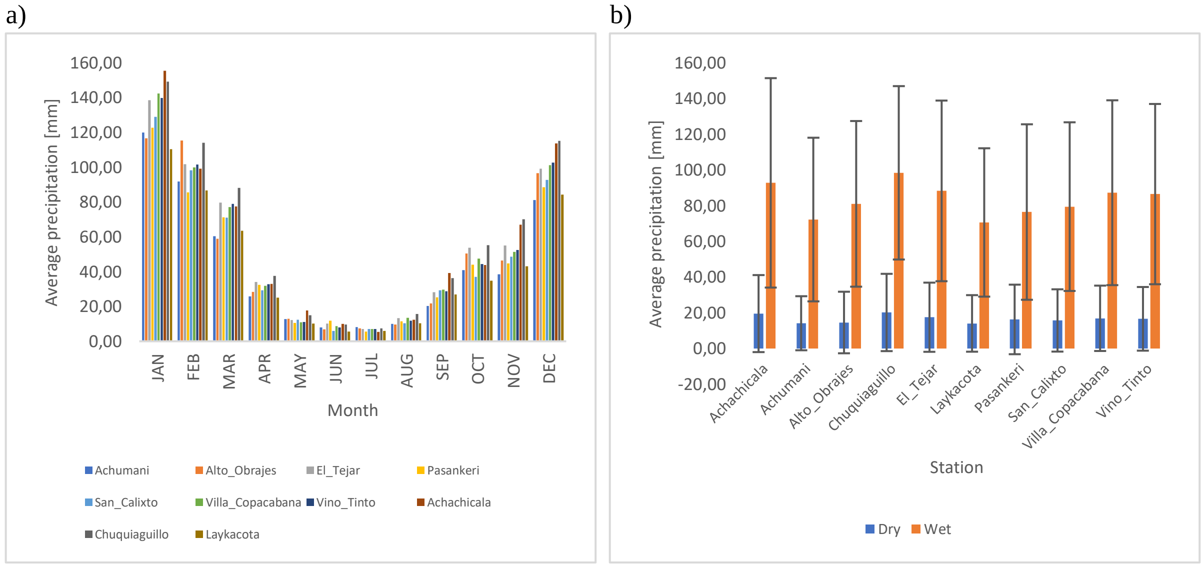

Figure 4.12. a) Average monthly precipitation in millimetres in each station, by month, and b) Average monthly precipitation in millimetres in each station, by season. (Source: Own elaboration, 2021)

The charts in Figure 4.13 include data from all ten rain gauges within the urban limits. It is fundamental to mention that more entries were available since the late 70s(6) when five stations started recording data with the already existing ones: San Calixto since 1917 and Laykacota since 1945. Thus, the apparent uptrend in the mean yearly precipitation (Fig. 4.13a) for the wet season was confirmed with a Mann-Kendall test of the data as statistically significant (p-value

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[6] Until 1974, 1013 valid entries were registered between San Calixto (stablished in 1917) and Laykacota (stablished in 1945). The rest eight stations were implemented from the late 70s: Vino Tinto (1975), Villa Copacabana (1977), Pasankeri (1982), El Tejar (1982), Chuquiaguillo (1975), Achumani (1991), and Alto Obrajes (2001). Achachicala started recording in 1975; however, it stopped working in 1992.

= 0,0502 < 0,1). Under the same logic, but for maximum yearly precipitation in 24 hours, an uptrend was also confirmed by the Mann-Kendall test with statistical significance (p-value = $2{,}54x10^{-8}$). The trends for both cases considered all available data across all ten stations from 1917 to 2020. However, these results can not confirm whether this pattern is directly correlated with climate change effects. Still, the test results for extreme events indicate a likelihood of surpassing the recorded values up to date in the future, during the wet season, with a confidence level of 90%.

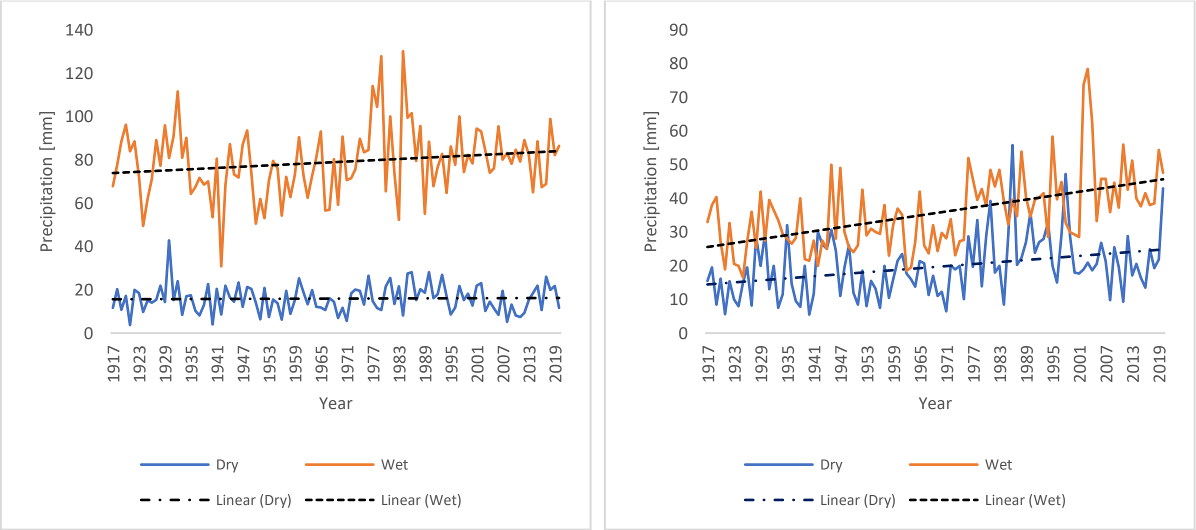


Figure 4.13. a) Average yearly precipitation (1917 to 2020) in millimetres considering all ten stations, by season, and b) Maximum yearly precipitation (1917 to 2020) in millimetres considering all ten stations, by season. (Source: Own elaboration, 2021)

Finally, to include CC effects on the drainage performance assessment, the following matters were considered:

- Research evidence still does not reach a common conclusion for the magnitude of CC effects on Bolivia's precipitation or La Paz. Thus, although there is an agreement with higher confidence towards temperature increment, future rainfall magnitudes are dubious.
- Climate projections obtained under downscaling scenarios from GCMs (Table 4.2) still preserve limitations, especially where orographic conditions are present.

So, under the possibility of increasing and decreasing future rainfall events, a factor of safety ± 20% was assumed for the precipitation values to be selected in the study area. This assumption was made pondering the results of Minvielle & Garreaud [2012], Seiler et al. [2013], and other authors. Therefore, this factor can be applied to the initial rainfall data to obtain IDF curves under a rainfall increase of 20% (RI20 scenario) and a rainfall decrease (RD20 scenario).

4.4. Site selection

An area of interest (AOI) was selected based on the results, overlapping with the following criteria: urbanisation sprawl, disaster occurrence including risk areas, and precipitation data. According to the risk map, macro district Sur congregates all these factors, where the urban growth reached high slope areas with many under high risk [GAMLP, 2011]. Most extreme events occurred there (Figures 4.7 and 4.8), and 15 out of 36 risk zones are distributed in their component districts (Obrajes, Calacoto and Ovejuyo).

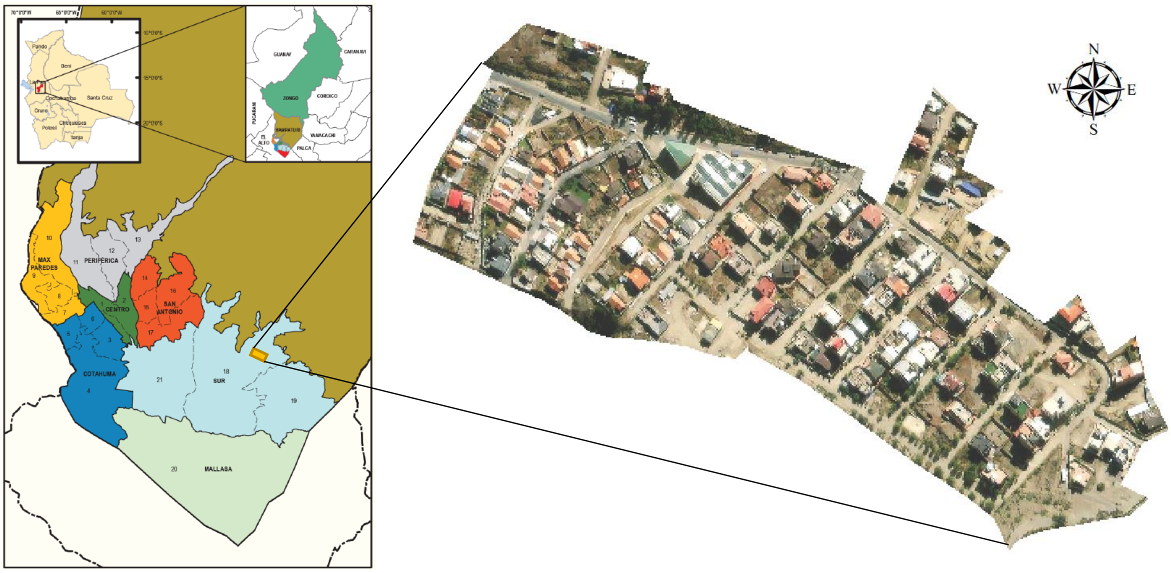


Figure 4.14. Study area location related to its position in the Municipality. On the top left corner is the map of Bolivia, and on the top right corner is the whole territory of the GAMLP (Source: GAMLP, 2019).

Therefore, twelve hectares in an urban catchment were selected as AOI. It locates in one of the 36 higher risk areas identified by the Municipality [GAMLP, 2012], in the Lomas del Sur sector in the Achumani district (see Figure 4.14).

The following figures illustrate the rapid urbanisation growth in almost two decades. While Figure 4.15a and 4.15b depict the expansion of built areas in the AOI's from the western side at a larger scale, Figures 4.15c and 4.15d confirm these changes at a higher resolution of 1,2 by 1,2-meter per pixel.

Through visual and spatial analysis, this radical transformation led to several land-cover changes. First, the creek on the northern side is now covered and vaulted, with an asphalt cover on top and represents the primary entry avenue into the AOI. Second, the bare soil in the southeastern side used to be part of the discharging area in the former creek's watershed, but now it has been taken over by residential households and streets. Third, the other creek on the southwest section was deviated a few meters south, giving more space for new developments. Finally, most of the shrubs and trees have reduced their density from the original composition. The perceptible changes described here can also be seen in more detail in Figure 4.15.

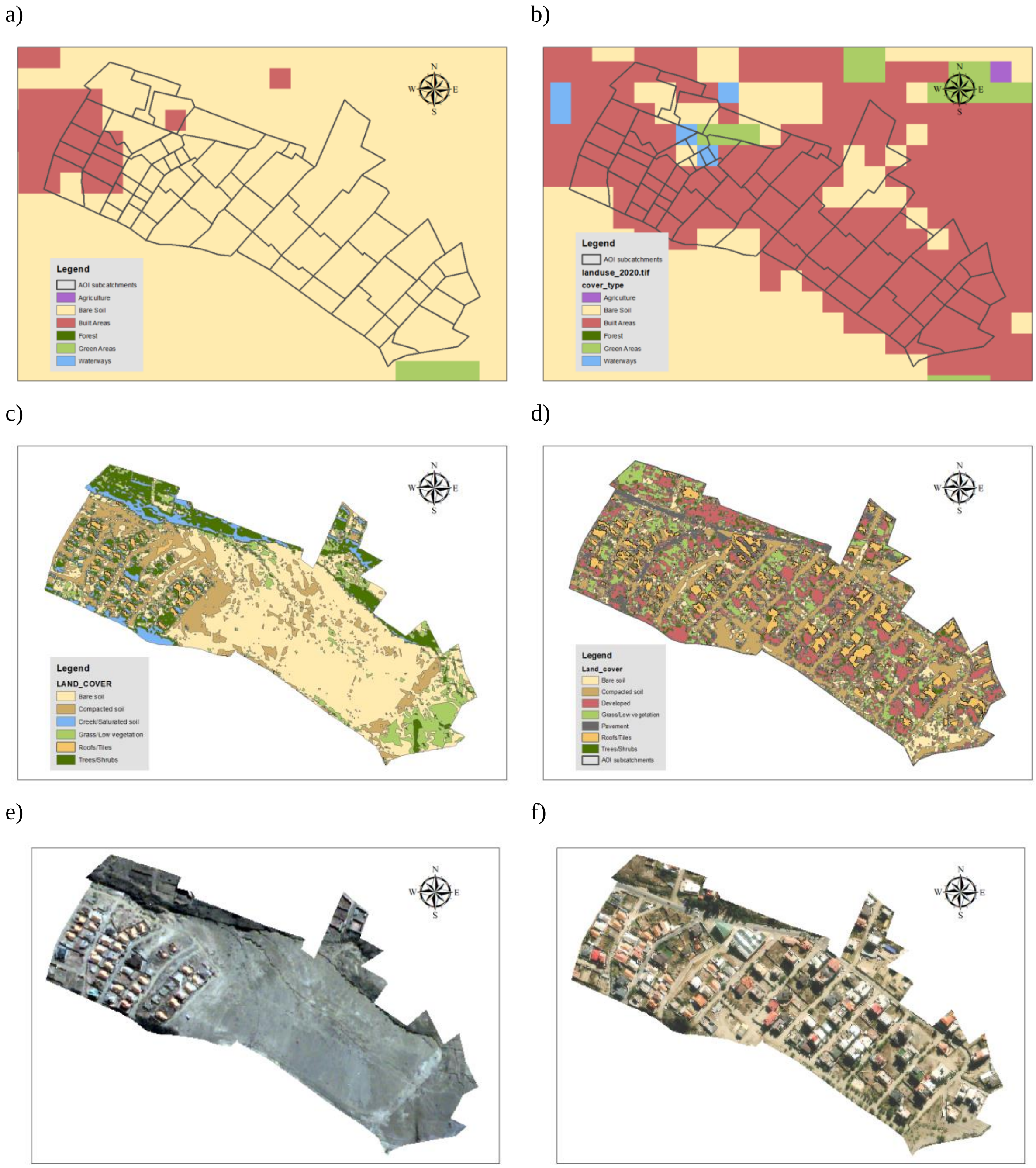


Figure 4.15. On the top. Land-use cover maps and AOI sub-catchments from Landsat 7 imagery a) for the year 2000 and b) for the year 2020.

On the middle, c) Land-use cover map from QuickBird commercial imagery year 2003, obtained from GAMLP, and d) Land-use cover map from the year 2020 obtained from a mosaic-composite image from BingMaps (0,6 by 0,6-metre), resampled to 1,2 by 1,2 metre per pixel to match QuickBird's resolution.

On the bottom, e) and f) same sources and years as in the two previous maps but for RGB images

Moreover, some other infrastructure characteristics in the area are directly related to the Law of urban land use (LUSU, for its acronym in Spanish). This Municipal law was approved in 2012 and established the norms and guidelines for settlement in La Paz. The AOI is mainly located in code 4PR, corresponding to buildable soil for household or residential purposes.

Also, another critical portion is on code A2, which is buildable soil for productive activities [GAMLP, 2021]. However, in this last case, most of this surface is currently occupied by households. The green areas (code AV in light green) and equipment types (code EQ in blue) from LUSU cover partially, but in a minor proportion, the sub-catchments in Zones 1 and 2. Still, the actual situation on-site follows partially the planning established by the GAMLP. Zone 3 lacks green areas both in planning and in reality. Most buildings coincide with the elevation limit indicated in the LUSU, with up to four stories high. Finally, there is no apparent invasion of zones delimited for streets, with some exceptions for EQ-dedicated areas in Zones 1 and 2. Hence, most of the settlements follow the indications provided by the LUSU.

Figure 4.16. Land-use types approved in LUSU and their distribution compared to AOI's zones (Source: Own elaboration based on LUSU map from the GAMLP, 2021).

4.5. Simulation of drainage network

The following section is divided into four components to distinguish urbanisation and climate change effects in the drainage system performance. Firstly, section 4.5.1 contains a brief description of the network in the AOI. Then, 4.5.2 presents the design storm was calculated for the following simulation. Later in 4.5.3, the system's performance was determined considering only land-use cover evolution (scenario 1). Finally, the last section includes results in the system with CC incidence (RI20 and RD20 scenarios) for the 2020 on-site conditions.

4.5.1 Drainage system description

The drainage system in the AOI was composed of 63 utility holes (nodes), 60 pipes (links), and 61 sub-catchments. Ground elevation raises from 3530,40 metres above sea level (masl) on the northwestern side to 3589,36 masl on the southeastern. Utility holes are built in concrete and range from 0,67 m to 2,75 m deep. All the pipes are made of PVC with an adopted roughness coefficient of 0,015. The total length of the pipelines is 2,10 Km. Lastly, the system in the AOI has three discharging points. They all dismiss the conducted water from the pipelines into the former creek on the northern side, covered and vaulted.

The system was subdivided into three zones due to its dendritic characteristic with three outfalls or discharge points.

There were three main flowing patterns typical for the three zones– the first one initiated from the starting utility holes with direction southwest towards north-east (1).

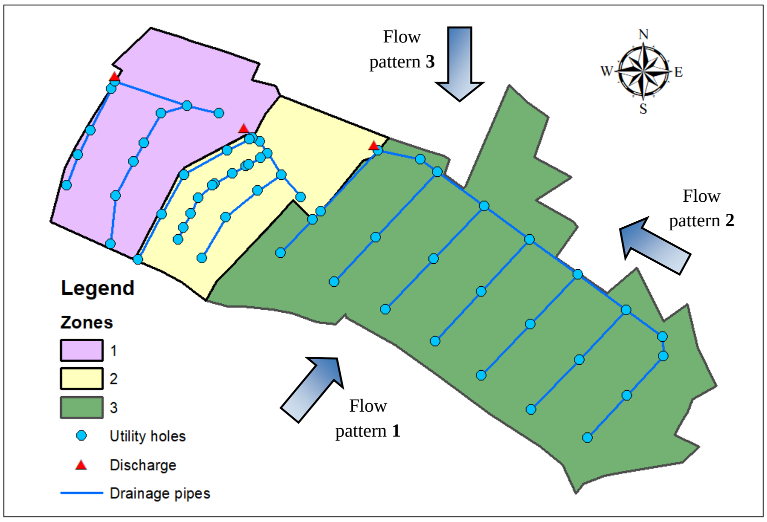


Figure 4.17. Drainage system's subdivision and flowing patterns

The second one went along the collecting pipeline on the northern part of each circuit with south-east to a north-west direction (2). Finally, a few sub-catchments had north to south directions. All these patterns follow the terrain's slopes (see Figure 4.17).

4.5.2 Design storm

Achumani (ACH) station was selected because of its proximity to the AOI (1,85 kilometres), making it representative of the conditions of the study area. The corresponding design storm was determined by applying equations [2][3][4][5], finding design precipitations for different return periods as shown in Table 4.3. The precipitation results are related to the occurrence probability, e.g., a 50% probability of experiencing a 30,95 mm rain event within two years. Moreover, the probability keeps increasing continuously for more significant rainfall events as the return period increases.

Return Period Years	Reduced variable YT	Precipitation (mm) XT'(mm)	Occurrence probability F(xT)	Design precipitation XT (mm)
2	0.3665	27.3911	0.5000	30.9520
5	1.4999	36.8811	0.8000	41.6757
10	2.2504	43.1644	0.9000	48.7757
25	3.1985	51.1033	0.9600	57.7467
50	3.9019	56.9928	0.9800	64.4018
100	4.6001	62.8388	0.9900	71.0078
500	6.2136	76.3481	0.9980	86.2733

Table 4.3. Design precipitations Achumani (ACH) station in millimetres by return period. (Source: Own elaboration, 2021)

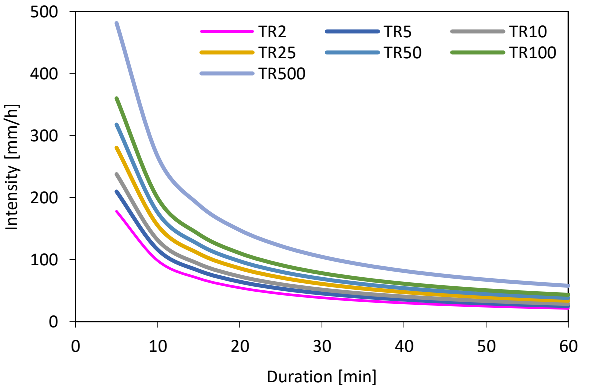


Figure 4.18. IDF curves for ACH station (Source: Own elaboration, 2021)

Finally, intensity-duration-frequency (IDF) curves were derived from Table 4.3 results and equation [6]. The resulting equation [7], with corresponding adjustment coefficients *K*, *m*, and *n*, enabled us to assess the stormwater network's performance presented in the following section.

IDF equation for drainage system assessment:

$$I = \frac{618{,}9227 \times TR^{0{,}180345}}{t^{0{,}85276}} \qquad [7]$$

Where:
I = storm intensity, in millimetres per hour
TR = return period, in years
t = storm duration, in minutes

Then, to complete input data for the simulation process, a synthetic storm was defined. For this step, the maximum precipitation value in a day was assumed to last sixty minutes, considering the extreme historical event of 2002. With this assumption, the design storm precipitation was determined in blocks of five minutes using alternating block method for TR of 2, 5-, 10-, 25-, and 50-years applying equation [7]. Finally, design hyetographs obtained by this method locate the maximum value mid-time of the storm (see Figure 4.19). These hyetographs were used in scenarios 1 and scenario 2, but the second included a ±20% factor in the initial precipitation data of the ACH station (Figure 4.11).

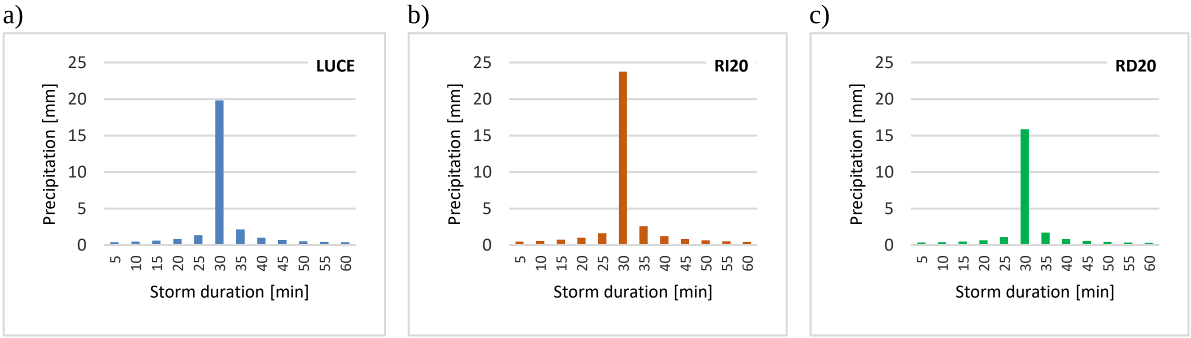


Figure 4.19. Example of calculated design storm in millimetres for TR of ten years. The left LUCE, the middle RI20, and the right RD20 scenarios for 60-minute storm duration. (Source: Own elaboration, 2021)

4.5.3 Scenario 1: Land-use cover evolution (LUCE)

Year	Pervious			Impervious			Total area [m^2]
	Area [m^2]	% of Total	Weighted n	Area [m^2]	% of Total	Weighted n	
2003	90.176,41	74,98	0,0817	30.087,14	25,02	0,0053	120.263,55
2013	52.174,21	43,38	0,0544	68.089,33	56,62	0,0119	
2020	41.525,42	34,53	0,0591	78.738,14	65,47	0,0139	

Table 4.4. Summary of pervious and impervious areas and weighted Manning overflow coefficients (Source: Own elaboration, 2021)

The urbanisation sprawl in the AOI imposed different hydrological conditions for drainage. Some of these changes involve the increment of more impervious surfaces in the form of residential developments, concrete parking spaces, roofs, cobbled streets, soil-compacted streets, and pavement. Hence, after delimiting the network's tributary areas (61 sub-catchments), SWMM required assigning individual manning overflow coefficients to each surface type according to their physical representation on-site (adopted from Table 3.2). Equation [1] was applied to determine every sub-catchment value. Appendix C includes a detailed table for each of them, whereas Table 4.4 included a summary of the results.

The change of imperviousness was confirmed by a more detailed analysis of all the sub-catchments coefficients (see Figure 4.20). In 2003, the mean percentage of the impervious area was 25,02%, increasing to 56,62% in 2013 and with a current 65,47%.

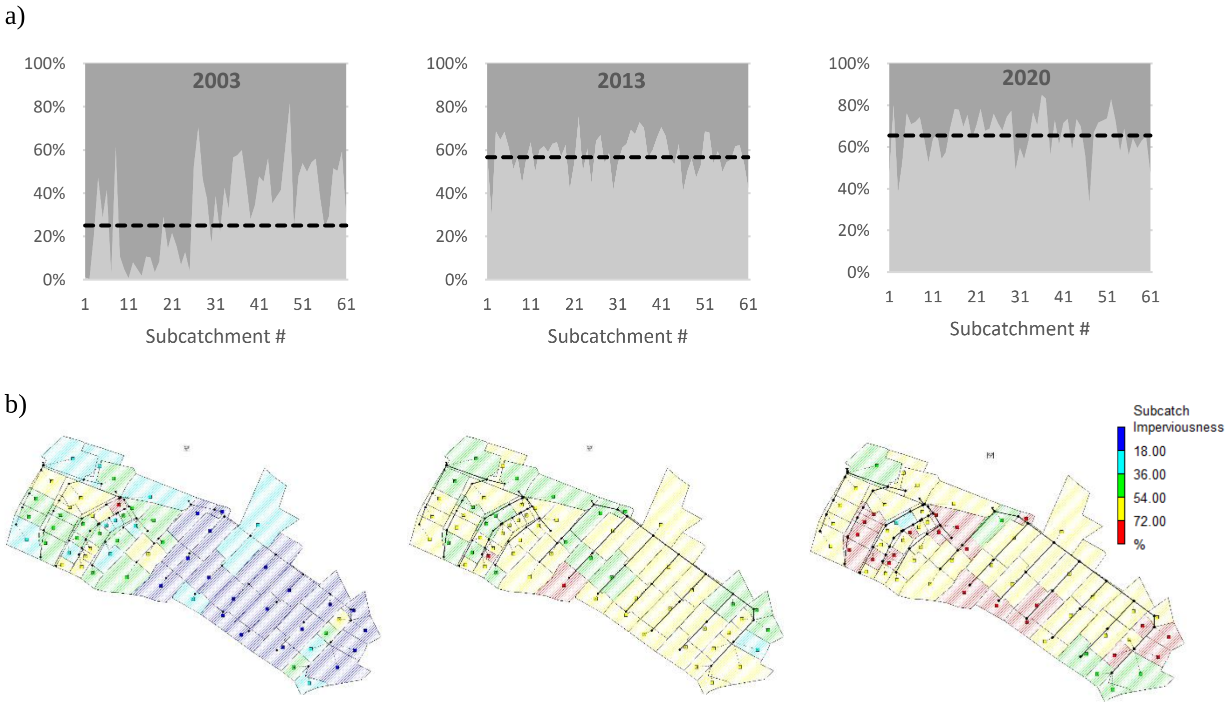


Figure 4.20. a) Weighted impervious area for each sub-catchment in percentage. On the left year 2003, on the middle 2013 and on the right 2020. The dotted line represents the year's weighted impervious percentage.

b) SWMM model of each subcatchments imperviousness percentage for years 2003 (left), 2013 (middle) and 2020 (right). (Source: Own elaboration, 2021)

Then, the simulation was performed for each LUCE in the digital model, including the design storm hyetographs for the aforementioned return periods. Results showcased a better overall performance considering the land-cover characteristics of 2003. For example, the inflow during peak storm (35 minutes) ranged from 114,42 litres per second (TR = 2 years) to 215,1 litres per second (TR = 50 years). Also, flooding flow oscillated from null to 41,23 litres per second within the same period (see Figure 4.21).

Moreover, the difference from peak flows due to cover evolution comparing 2003-2013 and 2013-2020 is noticeable for the flow (FW) and the flooding (FD). On average, the increase was 110,52% for 2003-2013 in FW, while it was 8,56% for 2013-2020. The percentage increase in FD for 2003-2013 was substantial (~480 to 3300% depending on TR), whilst 2013-2020 was around 14% on average. These incremental differences can be seen in the following figures.

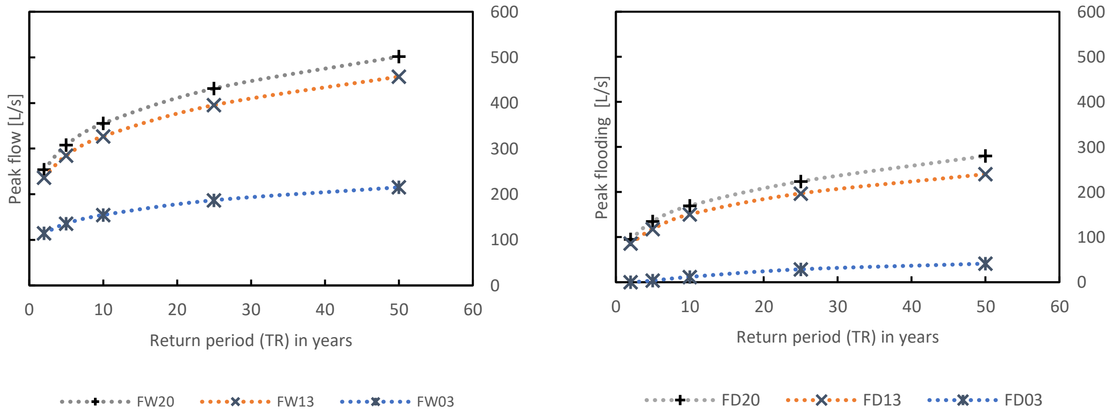


Figure 4.21. Comparison charts for the system's peak flow (FW) on the left and peak flooding (FD) on the right for years 2003, 2013, and 2020 by TR, in litres per second (Source: Own elaboration, 2021)

Additionally, 2003 presented fewer overloaded infrastructure with fewer flooded utility holes, less surcharged pipes, and minor flooding durations.

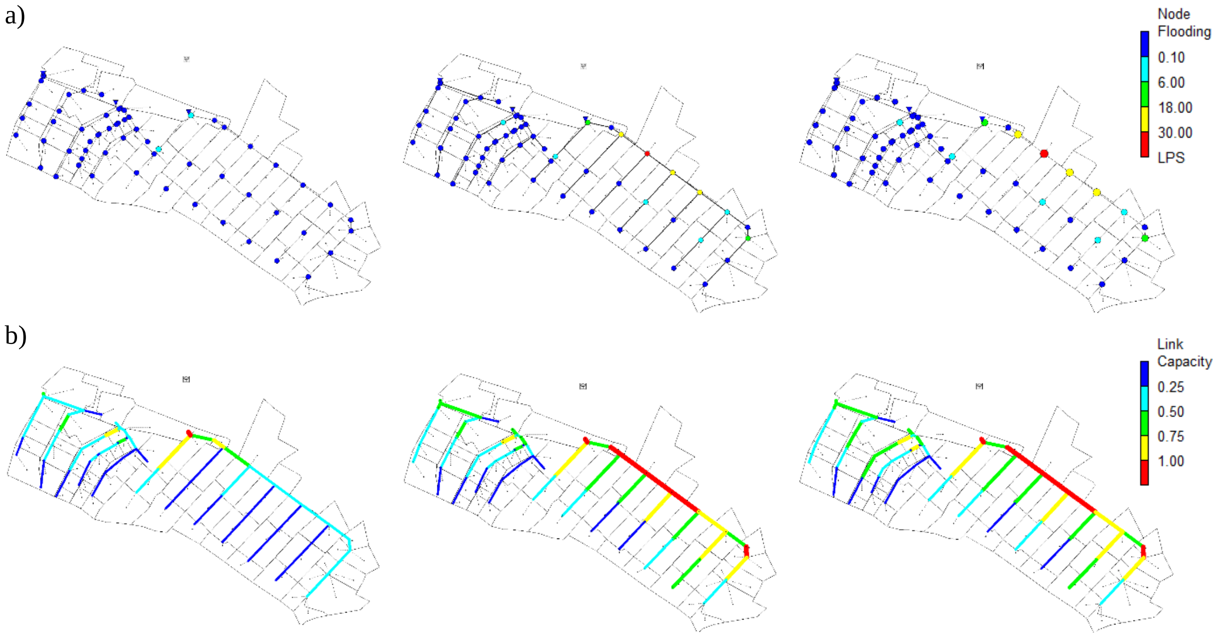


*Figure 4.22. SWMM results for TR = 10 years depending on land-use conditions in litres per second, including a) flooded nodes (utility holes). On the left year 2003, on the middle 2013 and the right 2020; and b) Same as in 4.20a, but for surcharged links (pipes). *Note: flow in each node and capacity in each link according to colour scale reference on the top right. (Source: Own elaboration, 2021)*

TR = 10 years	2003	2013	2020
# of flooded utility holes	4	11	12
# of surcharged pipes	2	8	10
Peak flow (L/s)	154,51	326,96	355,22
Peak flooding (L/s)	11,87	150,6	169,77
Peak storm time (min)	35	35	35
Max flooding duration (min)	6	14	16
Flooding volume (m^3)	4,05	63,33	76,02
Total inflow (L/s)	235,6	540,79	626,56
Total flooding (L/s)	13,5	211,11	253,41

Table 4.5. Summary of system's performance. Comparison for the return period of 10 years for the LUCE scenario. (Source: Own elaboration, 2021)

However, the patterns for FW and FD differ also spatially. Precedent charts and results cover the system's total flow, but zone 3 performance was inferior regarding specific overloaded points. Most flooded utility holes and surcharged pipes were in this zone, as shown in the figures above.

4.5.4 Scenario 2: LUCE20 + RI20 and RD20 addition

In this case, the results were determined to compare the drainage system performance in the current AOI conditions, meaning that only land-use cover of 2020 (LUCE20) characteristics was considered. Therefore, the following charts include peak flow (FW) and peak flooding (FD) values for LUCE20, RI20, and RD20 scenarios for the year 2020 exclusively.

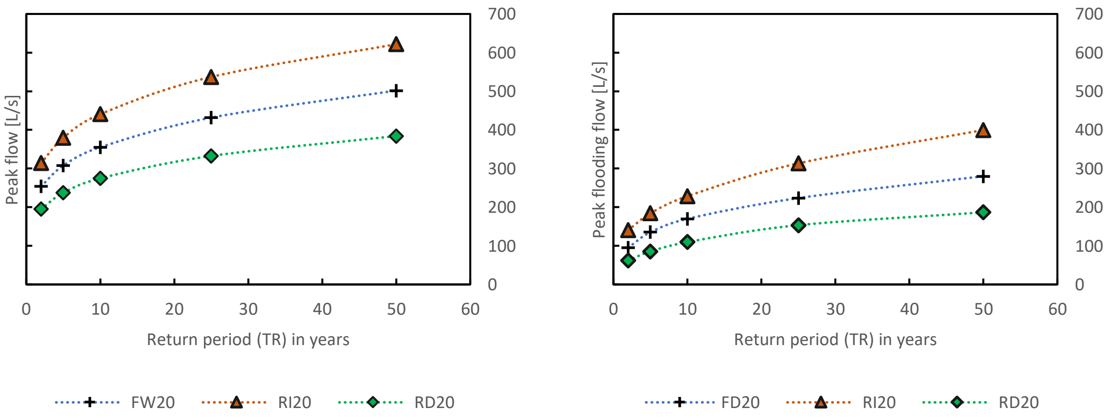


Figure 4.23. Comparison charts for peak flowing (FW) on the left and peak flooding (FD) on the right for the year 2020 scenarios by TR, in litres per second

Reasonably, the system performance of LUCE20 worsened under the RI20 scenario. Values at peak storm (35 minutes) ranged from 313,97 L/s (TR = 2 years) to 621,771 L/s (TR = 50 years). This increment was 23,86% on average compared to the results from LUCE20. Also, flooding flows oscillated from 140,48 L/s to 399,58 L/s within the same period (see Figure 4.23). Likewise, the percentage growth was 40,22%, as a mean value for all return periods. Therefore, the rise in FD for RI20 was proportionally larger. The system's performance had more overloaded elements than LUCE20 (11~26 flooded utility holes, 8~21 surcharged pipes, 15~20 minutes under flooding) for the different TRs.

Following the same logic, the system under the RD20 scenario performed better than LUCE20 but still presented overloaded elements. Peak flows fluctuated from 195,14 L/s to 383,98 L/s (same TRs as in the previous case), reducing 23,04%, on average. Likewise, flooding flows ranged from 62,24 L/s to 186,56 L/s. Still, many elements were overloaded (5~13 flooded utility holes, 4~11 surcharged pipes, 12~17 minutes under flooding) but had better results than those under LUCE of 2013 (see Table 4.6). The figures below summarise the system's elements performance for different return periods and scenarios.

TR = 10 years	**LUCE13**	**LUCE20**	**RI20**	**RD20**
# of flooded utility holes	11	12	16	11
# of surcharged pipes	8	10	13	6
Peak flow (L/s)	326,96	355,22	440,65	274,67
Peak flooding (L/s)	150,6	169,77	228,39	109,66
Peak storm time (min)	35	35	35	35
Max flooding duration (min)	14	16	17	15
Flooding volume (m^3)	63,33	76,02	99,52	50,74

Table 4.6. Summary of system's performance. Comparison for a return period of 10 years for the LUCE13, LUCE20, RI20, and RD scenarios. (Source: Own elaboration, 2021)

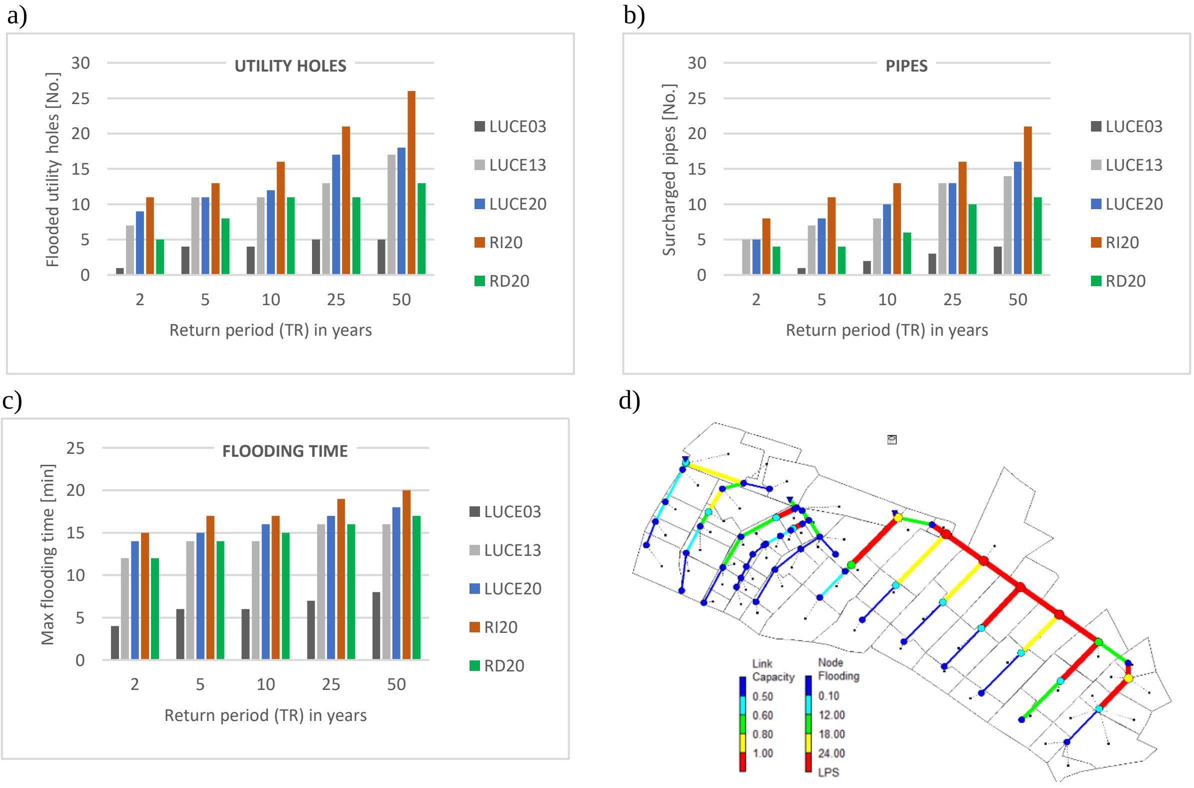


Figure 4.24. a) Number of flooded utility holes for different scenarios, by TR; b) Same as in 4.23a, but for the number of surcharged pipes; c) Same as in 4.23a, but for maximum flooded time detected on the system; d) SWMM result of overloaded infrastructure in scenario RI20 with TR = 25 years.

Lastly, for all return periods and scenarios, Zone 3 underperformed compared to the other two. This is because most of the overloaded elements in the system were in that zone under the different land-use covers and design storms. Therefore, the SUDS proposal focused only on this area.

4.6. Sustainable urban drainage systems (SUDS)

4.6.1 Selection criterion

As mentioned before, due to the current underperformance of Zone 3 in the AOI, two types of SUDS solutions (low-impact development – LID, in the SWMM nomenclature) were selected. Most of the streets in Zone 3 are cobbled, with a lack of maintenance on the sidewalks. Also, their width ranges from 4,0 to 6,5 metres for roads and 1,0 to 1,5 metres for sidewalks (see Figure 4.25). These restrictions led to select two options: green roofs and permeable pavement.

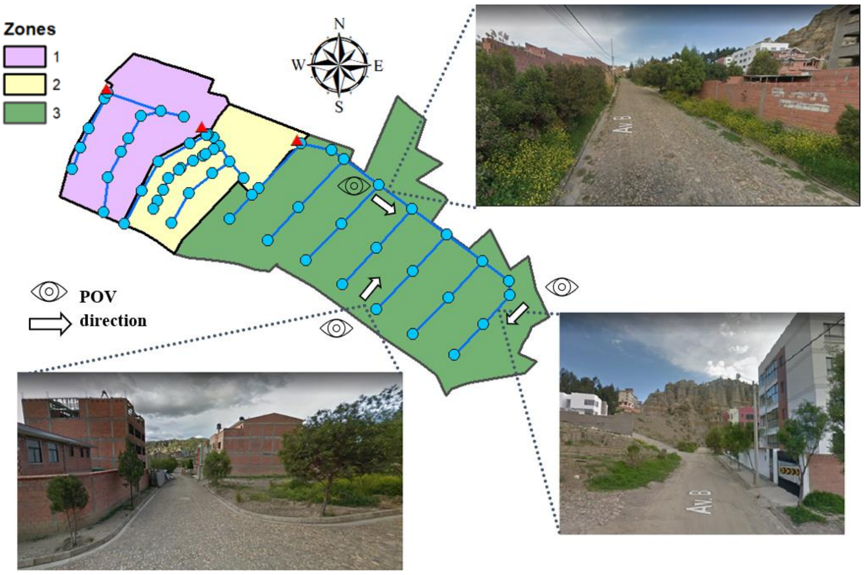


Figure 4.25. Infrastructure characteristics in AOI's Zone 3. (Source: Google Earth, 2021)

Thus, the selected SUDS solutions were located in apparent feasible positions considering data limitations. Nine apartment buildings were selected for the green roofs (GR) alternative due to their probable lower slopes on the roofs. Other requirements for retrofitting, such as the structure's load-bearing capacity [Cascone et al., 2018], roof orientation, height above ground, and maintenance levels [Wilkinson & Reed, 2009], were assumed as compliant. Likewise, in permeable pavement (PP), the type of sub-grade, also known as native soil [Shafique et al., 2018], is an essential factor. In the AOI, the soil is categorised as Qdz-a and Qr [GAMLP, 2012], considered permeable. So, similarly to GRs, the adoption of the PP solution assumed the suitability of the soil for this comparative study.

4.6.2 Green roofs and permeable pavement

With these considerations, the simulation was run for LUCE20, RI20, ad RD20 scenarios, including GR and PP in each case. The input parameters for GR and PP are included in Table 4.7, based on the research of Bai [2019] and Arjenaki [2020], respectively.

LID	Parameters	Green Roof	Permeable pavement	Unit
Surface	Berm height	50	30	mm
	Surface roughness	0,13	0,05	-
Pavement	Thickness	n/a	150	mm
	Void ratio	n/a	0,21	-
	Permeability	n/a	100	mm/h
Soil	Thickness	200	0	mm
	Porosity	0.5	0.5	-
	Field capacity	0.3	0.2	-
	Wilting point	0.1	0.1	-
	Hydraulic conductivity	0.5	0.5	mm/h
	Conductivity slope	10	10	%
Storage	Thickness	n/a	900	mm
	Porosity	n/a	0,75	-
Drainage	Flow exponent	n/a	0,5	-
	Offset height	n/a	6	mm
	Thickness	60	n/a	mm
	Void fraction	0,43	n/a	-
	Roughness	0,03	n/a	-
Slope	-	1	1	%
Plant cover	-	0	0	-

Table 4.7. Input parameters for proposed LID solutions. Source: Own elaboration, adapted from Bai [2019], and Arjenaki [2020]

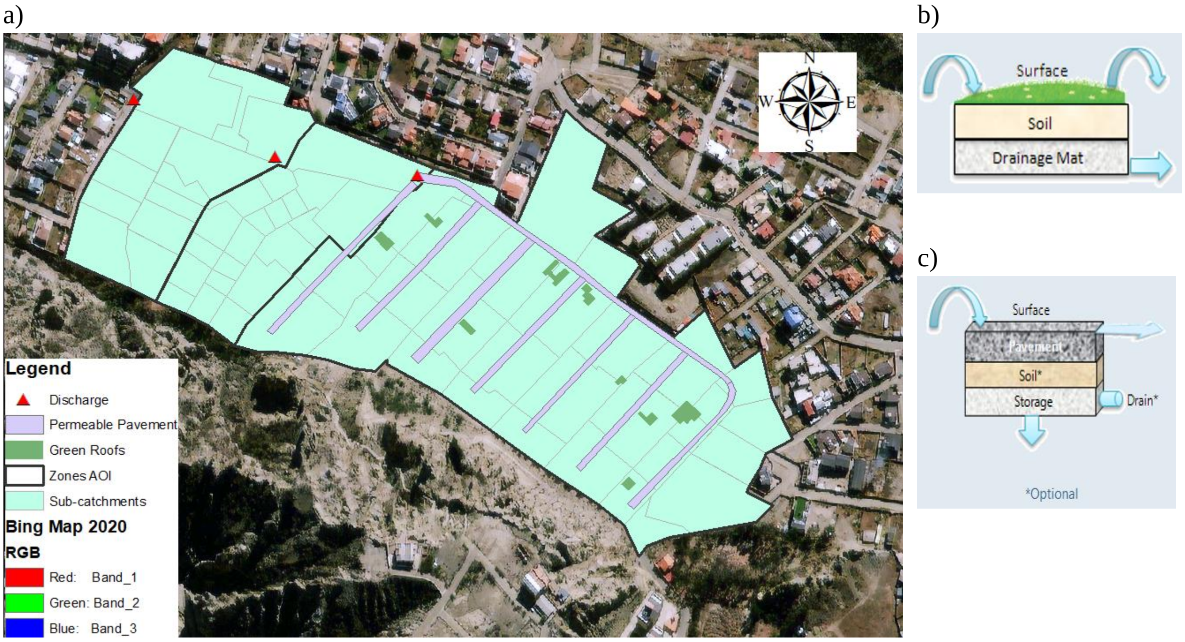


Figure 4.26. a) Green roofs and permeable pavements distribution over the AOI (Source: Own elaboration, 2021); b) Cross-section characteristics for green roofs in SWMM; and c) Same as in 4.26b, but for permeable pavements. (Source: EPA-SWMM, 2021)

In the GR alternative, peak flow (FW) reduction is negligible, while there is more effectiveness for peak flooding (FD) reductions. FW experimented percentual decrements of 1,65 ± 0,03 (*average value ± standard deviation)* in the LUCE20 scenario, 1,68 ± 0,02 in the RI20 scenario, and 1,62 ± 0,03 in the RD20 scenario considering the comparative results in each return period (TR). On the other hand, flooding in the system was reduced with the inclusion of GR. The percentual declines were 21,76 ± 2,21 in the LUCE20 scenario, 20,21 ± 2,35 in the RI20 scenario, and 23,61 ± 4,31 in the RD20 scenario, on average including all TRs.

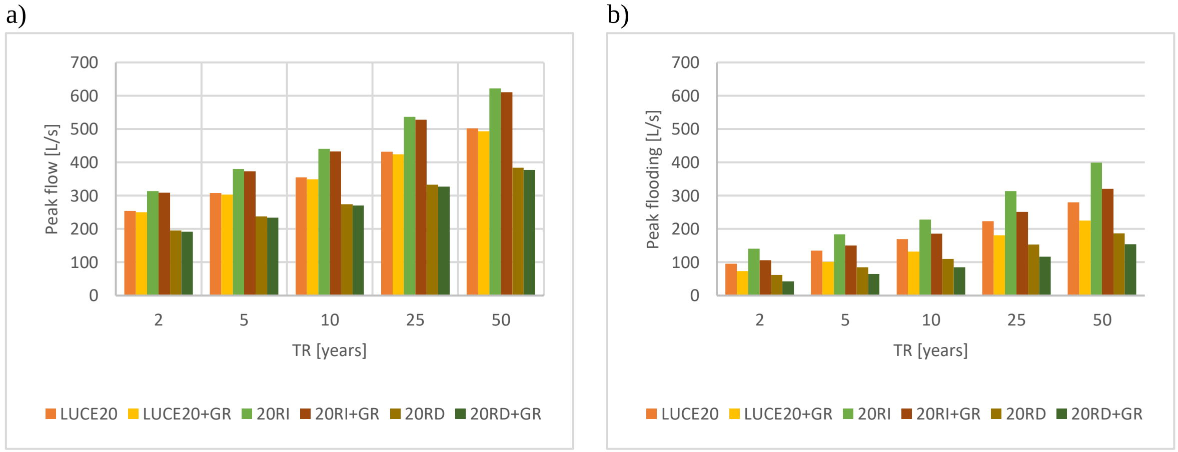


Figure 4.27. Comparison chart including green roofs alternative and different scenarios by return period (TR) for a) Peak flow and b) Peak flooding, both in litres per second. (Source: Own elaboration, 2021)

In the case of PP, the reduction of FW and FD were larger than in the first alternative. However, the area occupied by the PP is almost four times the one of GRs (see Figure 4.26). Still, the average percentual decreases in flow peak were 9,73 ± 0,22 in the LUCE20 scenario; 9,89 ± 0,22 in the RI20 scenario, and 9,82 ± 0,25 in the RD20 scenario. Under the same considerations, flooding presented declines of 35,46 ± 3,33 (LUCE20); 33,42 ± 2,77 (RI20); and 40,44 ± 5,22 (RD20), also on average for every TR.

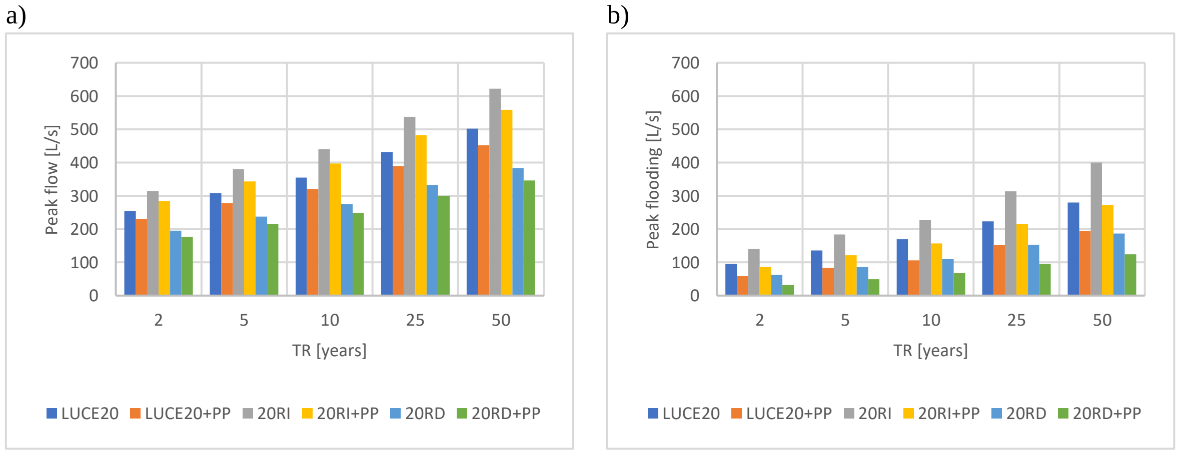
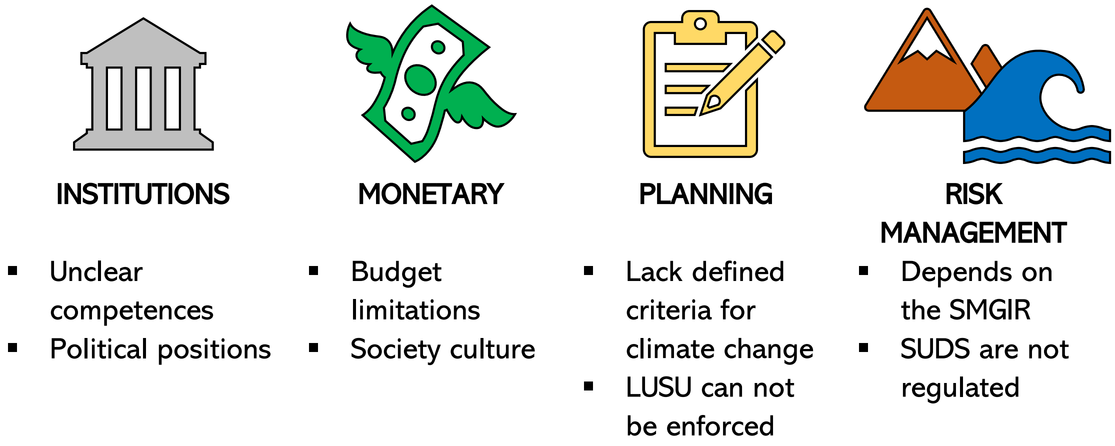


Figure 4.28. Comparison chart including permeable pavement alternative and different scenarios by return period (TR) for a) Peak flow and b) Peak flooding, both in litres per second. (Source: Own elaboration, 2021)

4.6.3 Stakeholders feedback

The results presented so far were summarised to two Municipality representatives, as mentioned in the methods section. From their feedback, four main topics condense the interviews, as shown in Figure 4.29.



INSTITUTIONS

- Unclear competences
- Political positions

MONETARY

- Budget limitations
- Society culture

PLANNING

- Lack defined criteria for climate change
- LUSU can not be enforced

RISK MANAGEMENT

- Depends on the SMGIR
- SUDS are not regulated

Figure 4.29. Main findings from the interview process (Source: Own elaboration, 2021)

Regarding the institutions component, one of the issues in the current drainage network management is the unclearness in responsibilities. Until 1996 the network was administered by the Municipality, but responsibility lied on Aguas del Illimani after a privatization process. Moreover, it changed once again in 2006 with the transfer made by the national government to EPSAS, a public company [Zamorano, 2021]. This situation left a *void* in the stormwater network management since EPSAS provides only the water and wastewater services. Even so, the political positions of the entities (GAMLP represents an opposition party to the national government) difficult the establishment of clearer competencies, added to the overlapping responsibilities implied in the laws [Zamorano, 2021].

In monetary terms, both interviewees pointed out the budget restrictions for any project under public domains. Moreover, Paton [2021] indicated that the Municipality aims to make alliances with the private sector in some opportunities due to this restraint since the GAMLP can not satisfy all the population demands. He also mentioned that it is usual to find illegal settlements in the newly developed areas, which add more issues to the financial plans because they usually occupy risk areas. This situation responds to a social culture which not always comply with the regulations that the GAMLP tries to impose.

When the discussion included the planning topic, two main subjects were covered. First, Zamorano [2021] stated that the current national regulations do not include specific criteria for assessing climate change diagnostic and vulnerability. Still, the Municipality is working with CAF to develop a vulnerability index that will offer elements for addressing risks like landslides and flooding. Moreover, until the last legislative period, the Municipality considered a norm to promote green roof. However, it could not be treated in detail due to the tax incentives proposal [Paton, 2021]. Second, despite the LUSU determining which areas can be occupied and the construction criteria, some people do not follow these regulations. This situation can be attributed to the rapid urbanisation and unscrupulous people trading plots illegally [Paton, 2021].

Finally, regarding risk management, this labour is the responsibility of the SMGIR. They are constantly working on this topic and have the legal competence to intervene. When urbanisation started to grow more than forty years ago, many areas did not have a zoning plan [Paton, 2021]. As the urban patches continue growing, some risks areas increased their vulnerability due to deficient infrastructure and drainage. Now, the SMGIR attends many of those risk zones because of stability deterioration. The proposal with SUDS was considered beneficial for the interviewees; however, these technologies are not included in the design regulations for drainage networks. Moreover, a stakeholder and cost-benefit analysis would be necessary before making any investment or intervention by the Municipality [Paton, 2021; Zamorano, 2021]

CHAPTER 5: DISCUSSION

5.1. Urbanisation patterns in La Paz on a broad and smaller scale

The urban development in La Paz between 2000 and 2020 has been consolidated over two main types of land-use cover. Built-up areas grew 36,72%, whilst bare soil decreased 18,73% in that period. These two categories had the most significant changes. On the other hand, the rest four categories identified (agriculture, forest, green areas, and waterways) had minor changes due to their composition percentage within the urban area of La Paz. As of 2020, bare soil occupied a 48,93% of the total urban territory and built-up areas a 41,55%, whilst green areas covered 4,84%, forests 2,48%, waterways 1,37%, and agriculture 0,84% (Figure 4.1). Therefore, urban sprawl was the most noticeable transformation in the last two decades in the form of built-up areas by replacing most of the bare soil surfaces and smaller portions of the other categories.

However, the built-up annual rate was lower than the average pattern of 5,40%, determined by Melchiorri et al. [2018] for lower-middle-income countries (the category of Bolivia) in LAC. La Paz urban area grew 1,84% annually, a significant inferior rate compared to the findings of the other authors. Although they did not focus exclusively on La Paz, they utilised remote sensing and satellite imagery with a similar timeframe analysis (25 years, from 1990 to 2015). Nonetheless, their research aimed to explain the global urbanisation patterns, so they utilised aggregated data from different sources[7] at a 1-kilometre spatial resolution. Conversely, this study used Landsat 7 imagery at a 30 by 30-metre spatial resolution. This resolution difference plays a crucial role in determining any spatial analysis. Choosing one over the other depends on the scope and objectives [Franklin & Wulder, 2002].

Furthermore, when comparing the annual population growth of 3,66% to the urban one, it was reasonable to expect a rapid horizontal expansion in La Paz. It is a city where 93% of its population occupies 5% of its territory [GAMLP,2016], highly concentrated in district Centro (15.756 inhabitants per square kilometre as of 2016) and scattered in Mallasa (210 inhabitants per square kilometre) [GAMLP, 2021]. The expansion characteristics were denoted by Arbona & Kohl [2004] due to socioeconomic and public policies factors. Also, location and connectivity played another fundamental role [Barrientos, 2012].

A scrutiny of the results also demonstrated that the transformation varied spatially in La Paz's seven constituent urban districts (Figures 4.4 to 4.6). In built-up areas, the growth was led by San Antonio (+18,70%), Periferica (+18,13%) and Cotahuma (+15,57%). Conversely, the districts of Cotahuma (-16,69%), Periferica (-13,79%) and Sur (-13,55%) experienced the largest bare soil reductions. Finally, regarding natural environments composed of forests and green areas, the aggregated loss had San Antonio in the first position (-5,25%), followed by Periferica (-3,95%) and Max Paredes (-1,41%).

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[7] The Global Human Settlement Layer (GHSL)

Despite land-use cover change being a global phenomenon [Melchiorri et al., 2018], there are underlying issues that are more perceivable in the Global South. These transformations often occur because of uncontrolled and unplanned growth, characteristic of many cities below the Equator, distancing green spaces from the urban hotspots to the peripheries [du Toit et al., 2021]. This situation is evident in La Paz, where the most extensive patches of green areas and forests are far off in the northwest (Max Paredes and Periferica districts) or south in the least urbanised district of Mallasa (Figure 4.1). Moreover, these two types of natural environments are unequally distributed amongst the districts, with significant differences between them, e.g., a 2,79% in Cotahuma and 18,77% in Max Paredes (Figure 4.6). These more pervious surfaces have implications for drainage [Borris et al., 2013] that can lead to disasters like flooding. However, this latter topic is discussed extensively in sections 5.2 to 5.4.

So far, the discussion has been centred on the broad-scale results (section 4.1). However, the following paragraphs delve into the site selection, presenting relevant land-use cover transformations (section 4.4). The changes were evident in the study area due to its higher resolution of 1,2 by 1,2-metres (Figure 4.15). The resulting maps were determined with remote sensing and supervised classification and provided a closer look into the urban fabric there. Former patches of trees, shrubs, saturated soils and creeks were replaced by other land-cover types like paved roads, cobbled streets, and residential development. However, besides the socio-economic benefits of urban growth [Gu, 2019], land-use cover changes had implications from a hydrological perspective. They influenced the AOI impervious areas increment as demonstrated by the weighted overflow coefficients (Table 4.4).

Also, the AOI settled on an area under high risk [GAMLP, 2012], but the zoning plan classified it as buildable soil [GAMLP, 2014]. This contradiction implies that the LUSU approved existing plots (in some cases) because they were already occupied and categorised as buildable. However, residential occupation in 2003 was still low, comprising around 30% in the AOI. Seventeen years later, the area was urbanised entirely (Figure 4.15). Therefore, the compliance with LUSU is not entirely satisfactory since some of the settlements were supposed to be green areas and equipment (Figure 4.16). This kind of incongruity deprived the area of having more greenery and pervious areas.

Still, it is essential to mention that a compromise regarding data consistency and precision had to be taken despite successfully obtaining land-use cover comparative maps and their resulting changes. This decision refers to utilising lower-resolution satellite images from open sources (Landsat 7 in this study), with a 30-meter pixel resolution compared to other commercial options. However, this approach was adopted due to the open to public data availability and disposal of images. Furthermore, the Landsat 7 mission has been recording earlier (since 1999) than others, e.g. 10-meter pixel RGB images from the European's mission Sentinel [EOS, 2021]. More so, even with the imagery from Quick Bird and Geo Eye provided by the GAMLP, at a 1,2-meter per pixel, it was not possible to utilise them due to the partial cover of data over the urban limits of La Paz. Still, the land-use cover evolution findings sufficiently pondered the city's extent and broad utilisation of Lansat 7 imagery in the GIS research field [Al-Kofahi et al., 2018; Melchiorri et al., 2018].

Nevertheless, the results can be refined with other higher-resolution images or classification techniques while also being assessed for accuracy. The latter can reduce the bias due to similar pixel wavelength values [Gómez & Montero, 2011; Texas A&M University, 2013].

5.2. Historical disasters and rainfall projections

A collection of different climate-related disasters pointed out that two of the most damaging events occurred during peak rainfalls and that flooding is the most common type of event in La Paz. This characteristic is the most common type of disaster in LAC [UN-OCHA, 2019] as well. Out of the sixteen extreme events identified through news media and technical reports, nine were caused by heavy rains that led to floods. The rest seven caused structures collapsing (3), landslides (2), and stormwater network clogging due to hail (2). The two most damaging events in the last two decades in La Paz coincided with the highest amount of rain precipitation in a day. On the 13th of February of 2002, the flooding that led to more than seventy humans deaths and enormous economic losses registered 39 mm of rain in one hour, out of the 41mm recorded that day [Hardy, 2009]. This value corresponds to the El Tejar station, confirmed by contrasting the data with the one obtained from SENAMHI (Figure 4.11). Contrarily, other available records showed higher amounts with 59,9 mm in San Calixto and 73,7 mm in Vinto Tinto stations. Also, the landslide of Callapa that dragged over 800 plots of land in 2011 (including 250 homes destroyed and 550 severely damaged) matched with the peak intensity of 56 mm recorded in the Alto Obrajes station. Even though local authorities and international organisations are aiming to build resilience [GAMLP, 2014; World Bank, 2020], the findings confirm the fragile position against extreme events, profiled as inadequate for the country [Francois, 2016; Gu, 2019; University of Notre Dame, 2021].

Still, the occurrence of these two significant disasters had two primary factors identified by researchers. One of them is the natural causes, including heavy precipitation, abrupt and steep topographic conditions, and adverse geological structures [Hardy, 2009; GAMLP, 2012; Otero, 2016]. Moreover, natural disasters will likely increase in the region [Gu, 2019] and cause floods and droughts [OCHA, 2019]. Although La Paz has already been through many flooding episodes (Figure 4.8), it experienced a severe drought in 2016, affecting the regular provision of water to over 340 thousand people [Ayala, 2016]. These natural causes can increase the vulnerability of areas under risk in the city. Unfortunately, risk management data seems to be unstructured. When elaborating this study, requiring information about historical disaster events, the person in charge of responding stated that they needed to compile it and detail it as was required. Otero [2016] confirmed this need when studying the landslide of 2011, suggesting it is crucial to compile and systematise historical information to carry out studies in risk management.

Moreover, the second factor can trigger the occurrence of a disaster when combined with natural causes. Poor foresight planning and significant infrastructure gaps were already identified by Muggah [2018] as an issue in LAC urbanisation. The limitations embedded in public administration usually rely on budget restrictions [Hardy, 2009; Cenci, 2020], which was confirmed when interviewing former and current municipal officials. Paton [2021] stated that the Municipality faces difficulties to address all the public demands and sometimes looks for counterparts to invest in projects. Furthermore, the stormwater network management in La Paz is ambiguous due to the competency uncertainty. Before 1996 it was administered by the municipal water company, but after 2006 it passed to a public entity administration. EPSAS is in charge of water and wastewater services provision, but apparently, this does not include the stormwater network [Zamorano, 2021]. Therefore, lack of drainage infrastructure maintenance due to the legal void and budget restrictions can increase risks, especially in combined systems like La Paz [Hardy, 2009].

Leaving aside the disaster occurrence topic and focusing on climate change and precipitation, it is still challenging to determine CC effects on local scales and whether past extreme events in La Paz were related to climate change. Academics attribute this obstacle to the limitations inserted in the existing climate models and the current computational capabilities to calculate more detailed results for scales lower than ~100 Km grids, as of AR5[8]. Although there is a higher confidence level regarding potential global temperature increases depending on GHG emission scenarios, the situation is more uncertain for precipitation in locations where orography plays a significant role [Seiler et al., 2012:2013], as is the case of La Paz. On the few articles studying the CC-induced rainfall variability for this city, the probabilities aimed either to increments and decrements with no consensus over the threshold. In this study, a simple trend analysis of data from ten stations inside the urban limits of La Paz was carried out finding a statistically significant uptrend, built by the maximum precipitation values recorded in a day for each year, from 1917 to 2020 (Mann-Kendall test p-value = 2,54x10-8 < 0,05). Nonetheless, it was impossible to identify the magnitude of CC effects on rainfall under this method, but only a probability of extreme rainfall events occurring in the future with a 90% confidence level.

Regarding positive findings, the construction of a primary disaster database with information collected from different sources allowed delimiting the analysis in a specific district (AOI in the District Sur). The selection of the AOI also took the risk map as an input to work on an area prone to risks, where this study results can be beneficial for the public administration [Paton, 2021; Zamorano, 2021]. On the contrary, disaster information could have been more detailed whether authorities collect this information for further studies, as mentioned by Otero [2016].

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[8] Fifth Assessment Report of Climate Change 2014, published by the IPCC.

5.3. Study area drainage performance

The land-use changes that occurred in the study area played a crucial role in the drainage performance of the network system. As the site developed and became more urbanised, the impervious areas increased (Figure 4.20). These changes varied from 25,02% in 2003 to 56,62% and 65,47% in 2013 and 2020, respectively. Therefore, the system's peak flow (FW) and peak flooding (FD) confirmed this finding when simulating three land-cover compositions under the same synthetic storm (scenario 1). The average FW increase was 110,52% for 2003-2013, while significantly lower for 2013-2020 with 8,56%. Flooding between 2003 and 2013 increased substantially (~1374%), whilst 2013-2020 was around 14%, both on average. The FD difference in the first range is attributed to values closer to null in 2003 (Figure 4.21). Moreover, in most return periods, the system performed overloaded, causing flooding in utility holes for up to eighteen minutes and up to sixteen surcharged pipes. These findings demonstrate a positive correlation between imperviousness and runoff, leading to overflow when the system's capacity is surpassed.

The situation aforementioned has negative implications for risk prevention. When the drainage system overflows through the top of the utility holes, exceeding flow runs down following the terrain slopes. In the case of the AOI, the dominant flow pattern goes from the southeast to northwest direction (Figure 4.17). Due to its combined-system feature, any infrastructure and plot down this path will receive the exceeding polluted waters. The flow can either accumulate on terrain depressions or cause erosion because of the current.

Moreover, when the pipes work at their total capacity, they originate the overflow and increase the pressure in the conduct, which can exacerbate filtration due to a lack of maintenance or replacement. The flooding of 2002 and the landslide of 2011 are examples of what can happen when a drainage system is overloaded. Nevertheless, these disasters had other triggering factors like heavy rainfall, steep topography, settlements on risk areas, and inadequate infrastructure [Hardy, 2009; GAMLP, 2012; Otero, 2016].

However, whether land-use conditions would have stayed the same as those of 2003, there were still probabilities of drainage system overloading in the future. Return period, also known as recurrence interval, is the reason for this because it is the probability that extreme events like floods or tornados will occur. For example, whether all storm conditions included in the model would congregate, it was expected that between 2003 and 2013, one extreme rainfall event would flood four utility holes (TR = 10 years, results from Table 4.5). Similarly, when analysing 2020 results, until 2030, it is expected to have twelve flooded utility holes under the assumed storm conditions.

These first results considered only land-use cover changes. Nonetheless, the drainage system still presented overloading even if precipitation in the future would decrease by 20%. Therefore, scenario 2 considered a factor of ±20% added to the initial rainfall data from the Achumani station. After determining the design storm for different TRs, the simulation was performed, including only the surface conditions of the year 2020. In the rainfall increase case (RI20), peak flow was 23,86% higher, while flooding was 40,22% greater than scenario one results, on average.

Conversely, under a rainfall decrease (RD20), peak flow dropped 23,04% and flooding 12%. These values resulted from an artificial modification of rainfall records trying to imitate potential precipitation changes in the future due to climate change. However, they also indicate that even if La Paz has less intensity on future storm events, the study area can still be affected by flooding and overflow, increasing risks.

Furthermore, the findings are comparable to the results provided by other authors, who also utilised SWMM and a similar approach to this study. For example, Borris et al. [2013] found a linear correlation between imperviousness and runoff volumes. A reduction of 8% in the runoff volume can be reached with a diminishment of 10% impervious surface. Relative percentages were found in this study but were proportionally inversed. The increase of urbanisation in 8,85% between 2013 and 2020 had a +8,56% effect on peak flow. Zhou et al. [2016] also found that the influence of urbanisation is proportional to the increments in peak flows. Although the percentages in those two studies are different from this one, it is crucial to mention that results depend on every case characteristics (rainfall data, design storm, network composition and features, among others). Also, the imperviousness of the study area connected to the land cover composition can vary in each case.

Finally, it is essential to mention that the results included in this study can vary depending on the input data. For example, the assumption made for the design storm duration of sixty minutes can significantly vary whether it is changed to two hours or more. This situation occurs because precipitation blocks in Figure 4.19 would spread over the time axis, reducing the precipitation values and displacing the peak storm time. Also, the overflow coefficients for the AOI were adopted from literature references (Table 3.2) and the surface cover type, assigned from remote sensing maps results (Figure 4.20). However, whether surfaces are recognised on-site and identified differently than the assumptions made can impact the simulation results for peak flow, flooding, and overloaded infrastructure.

5.4. SUDS effectiveness

Through the implementation of SUDS, in the form of low impact development (LID) solutions, the two proposed alternatives reduced the peak flow and peak flooding. They also lowered the overload in the drainage system. These results were obtained for different scenarios, including the land-use cover of 2020 (LUCE20), rainfall increase of +20% (RI20) and a rainfall decrease of -20% (RD20). Overall, permeable pavement (PP) offered higher reduction rates than green roofs (GRs) but required more area to do so, in a ~4:1 ratio. PP decreased peak flow by 9,70% on average for all three scenarios (LUCE20, RI20, RD20) and peak flooding by 36,44%. On the other hand, GRs average percentages were 1,65% and 21,86%, respectively.

The findings demonstrate that the inclusion of SUDS in existing networks can benefit the drainage systems' performance by reducing flow effectively. Moreover, while peak flows are lowered, they have a positive correlation with the decline of flooding. This link can be decisive in areas prone to flooding or erosion, reducing their vulnerability and disaster probability occurrence. As mentioned in this document, historical disaster events occurred for several reasons, with stormwater infrastructure deficiencies being one of them. Therefore, SUDS can alleviate the pressure set on the AOI due to its current infrastructure configuration (diameters, lengths, depths) and land-use cover (higher imperviousness), whether an extreme rainfall event happens in the area.

Regarding the two different proposed alternatives efficiency, permeable pavements performed better. However, the reduction of peak flow close to 10% is lower than the 21% found by Arjenaki et al. [2020]. Nevertheless, there are several differences between the studies. Arjenaki et al. worked on a much drier area in Iran, contrastable in the IDF curves. In that location, the intensity of a one-hour storm with a return period of two years was 9 mm/h, while this study had a value of 38 mm/h. Another difference relies on that the authors were able to calibrate their model (due to data) and run a sensitivity analysis, finding a direct relationship between subcatchments width and curve number (input data in SWMM) with runoff [Arjenaki et al., 2020]. Also, the area covered by permeable pavement in the Iran case was higher, around 22% on average spread over 14 subcatchments. This study covered 9,8% on average, spread over 27 subcatchments. Therefore, it can be inferred that in every research, intrinsic characteristics can give different results and that they cannot be compared between them unless they share similarities like location and weather conditions.

Furthermore, the same logic applies to the green roofs' proposal of this study. The efficiency results vary from the findings of Bai [2019] or Arjenaki [2020]; however, they all prove that SUDS are efficient in reducing runoff, flow, and flooding.

In the case of La Paz, the lower flow and flooding reduction for GRs can be attributed to its lower coverage in the AOI. Only nine rooftops were selected, meaning 1% of the total area in the AOI. So, compared to PP's ratio efficiency, the GRs offer a better solution since they reduce overload with a quarter of the surface required by the permeable pavement.

As mentioned in the last part of the previous section, the utilisation of SUDS is also subject to the possible biases produced by the assumptions in the model's initial conditions. Therefore, changes in storm duration, overflow coefficients or others can influence the results. Moreover, in this study case, the model could not be calibrated due to the impossibility of obtaining meteorological records at lower time intervals. This restriction is attributed to the measuring devices used by SENAMHI. However, according to Tscheikner-Gratl et al. [2016], an uncalibrated model can overestimate flooding. Therefore, they pointed out that whether data is available, it is highly recommended to do so.

5.5. Opportunities and challenges in adopting SUDS in La Paz

The proposed alternatives were presented to a former assistant to one of the nine city's counsellors (Kheni Paton) and the current technical advisor of the Municipality's Secretary of Environmental Management (Eduardo Zamorano). The main objective for this step was to obtain their opinions, perspectives, and feedback on the research topic regarding the feasibility of applying SUDS. From their answers, it was possible to identify institutional, monetary, planning and risk management challenges.

Both interviewees considered the findings valuable because these types of investigations can support the implementation of public policies. However, the implementation of SUDS can face some obstacles in the current conditions. The budget restrictions in La Paz [Paton, 2021; Zamorano, 2021] correlate with the pattern characterised in the LAC region [Cenci, 2020], impeding to narrow the infrastructure gap for many services [Muggah, 2018]. There is also unclarity regarding stormwater network management. The parties involved are discussing at the moment, with the GAMLP and EPSAS as the main actors [Zamorano, 2021]. The current zoning plan (LUSU) does not include climate change criteria, nor do drainage design regulations [Paton, 2021; Zamorano, 2021]. Therefore, public policies would need to be designed or reconfigured funded on studies like this one to justify and promote the use of SUDS. Even so, stakeholder and cost-benefit are required to intervene in public area domains [Paton, 2021; Zamorano, 2021]. The PP alternative is focused on this type of domain. Contrarily, the GR alternative would require to delve into legal and tax incentives constraints to incentive privates to adopt this type of solution [Paton, 2021].

5.6. Limitations

There were several limitations in this research that should be considered in the interpretation of results. First, the collection of data was limited due to the pandemic of Covid-19, which impeded visiting the city of La Paz and make an on-site recognition, especially once the AOI was selected. Under better circumstances, it could have been possible to identify the current land use in the area to contrast it with the results obtained in the classification process (section 4.4). More importantly, the adoption of runoff coefficients could have been refined since these values influence the simulation process.

Secondly, the coordination with the Municipality was not sufficient when collecting data regarding disaster events. The authorities transitioning during the elaboration of this study (because of recent elections) affected the possibility of acquiring detailed data.

Third, the meteorological instruments utilised by SENAMHI do not provide shorter time intervals when recording precipitation. Disaggregated data during the day simulates the network's performance more in detail and enables calibrating the model.

Fourth, updated topography and soils information can enhance the results and adopted SUDS solutions. The elevation for utility holes was adopted from contours of land survey maps of 2000. Moreover, the information did not cover all the AOI, so the resting values were derived from supplementary DEM elevations from Google Earth. An SRTM-DEM model was also utilised initially, but it offered more considerable differences when compared to the map contours. Also, it was assumed that the soil conditions would be sufficient for implementing permeable soils in the AOI when adopting SUDS. Land survey information can also affect the delimitation of the sub-catchments and their subsequent results in the simulation. The proposal can be affected whether soil laboratory tests are done, or detailed terrain configuration data is available.

Finally and foremost, there were assumptions regarding the storm design due to a lack of information and method approach. The first one was the storm's duration, with 60 minutes as a critical scenario, which might not reflect the common types of storms in La Paz. Lastly, the adopted climate factor of ±20% was only based on the possible ranges of change in rainfall. Although this assumption was based on academic research, the results from scenarios RI20 and RD20 are not definite. Nevertheless, these last two factors are crucial inputs in the simulation model.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

This research aimed to assess the impacts of climate change and urbanisation on the drainage system's performance of a study area in La Paz using SWMM software. Based on the quantitative and qualitative analysis of land-use cover modification and projected precipitations events, it can be concluded that urban sprawl and changes in rainfall-induced by climate change are crucial factors in the system's functioning. Furthermore, the results indicated that increments of impervious surfaces have a positive correlation effect on peak flows and flooding.

Moreover, through the findings of the system's performance, it was possible to simulate the inclusion of sustainable urban drainage solutions (SUDS) in the network. The results proved that permeable pavements and green roofs could effectively reduce peak flows and flooding.

Nevertheless, the assessment using SWMM for the simulation process had simplifications and assumptions which give uncertainties of the magnitudes of inflow and flooding. Notably, the hydrological input related to the storm duration and processing method for infiltration can be significant. Also, the overflow coefficients adopted can modify the results.

Still, this research demonstrated the potential overload of the system, creating overflow and flooding in the utility holes and drainage conducts under surcharged conditions. This situation raises the question of whether these effects can negatively affect the area's stability since it locates in a risk zone.

The simulation approach provides valuable guidance for practitioners and public administrators, as it includes criteria for addressing potential risks due to drainage network performance. For example, the study demonstrated that under heavy rainfall events, infrastructure capacity could be surpassed. Such results can help assess areas located on risk zones to activate prevention measures and predict probable disaster events related to overloaded systems. They also provide an alternative for implementing solutions through SUDS, which can ameliorate the peak flows while increasing permeability and reducing runoff.

6.2. Recommendations

Based on the findings, this study can be refined by addressing the conclusions and limitations in section 5.6.

Also, it is recommended to monitor rainfall precipitation with instruments capable of measuring data in shorter time intervals. A tipping bucket in the AOI can be beneficial for calibrating the model and adopting storm duration for the simulation.

Moreover, the land representation can be updated with a topographic or drone survey. This information can help refine the urban catchments delimitation and rim elevation for the utility holes. Moreover, location and elevation data from the different network components can be confirmed and adjusted, if necessary, with this survey.

Lastly, monitoring the AOI during the rainy season (December to February) is recommended to verify the occurrence of flooding, its duration, and magnitude. Cross-checking this information can also add up to the calibration of the model.

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APPENDIX

APPENDIX A – INTERVIEWS TRANSCRIPTS

Participant: Kheni Paton [K], former coordinating advisor to the City Council Presidency.
Date: 4th of August, 2021
Interviewer: Roberto Stohmann [R]

R: What is La Paz's position regarding climate and its future impacts?

K: With respect to climate change, at least what has been worked on until the previous municipal administration, and based on what has happened most of all in Callapa, in the 3 mega landslides that there were, the management and risks, normatively, has always focused on resilient management.

Precisely for this reason, the changes that have been requested, for example, in waste collection, because the burden of the climate impact on pollution in relation to what was taking place in La Paz was very high, a clear example of what happens in the rivers. La Paz has never been a city designed to cope with the amount of people and waste that they were going to generate in the future. The capacity of the city has been exceeded, which is why the Llojeta event (landslide of the municipal sanitary landfill), and other events happened. A clear example of urban planning in environmental impact issues is the Mallasa landfill. It is being worked with high technology and it is planned that in five years it will be used as green areas and recreational areas.

What happens in La Paz in this sense is that there are a lot of social demands, if it can be called that, because green areas are very quickly occupied and used by people where the characteristics of both the soil and topography are not adequate. For example, what has happened in Llojeta, construction on a landfill area that was never allowed and should never have happened, with serious consequences
As a municipality it has always had this vision, at least the last management, of being able to regulate based on caring for the environment with what has been possible.

R: There you are also answering me areas about what is currently being done in high-risk areas, although this corresponds more to the Risk Secretariat, in regulatory matters …

K: Yes, but also in the council the adjudication of green areas, the appointment of areas, and all that has been done a lot. But, as I told you, there is a big problem here, which is the lotters (illegal sale of land). Like what is currently happening in the Pura Pura grove, where land is being negotiated and houses are being built. This is due to political movements more than anything. There are people who believe that they have the right to enter the land and enjoy it, because unfortunately, due to its topography and how it is constituted, it has a large percentage of high-risk areas within its jurisdiction. So, if we do not have the resources to apply the necessary technology to transform or secure these soils, these soils would have to continue to be municipal property and of restricted use, such as green areas, equipment areas, etc. However, with the loads of housing that they have now, the consequences that occurred can be given. Unfortunately, this problem is not current, this problem is at least 30 years old, and loads on the ground are already noticeable in many terrains.

R: And related a bit to these zones, the area proposed in this study, according to the LUSU is in a buildable zone, but according to the risk map of 2011, it indicates that it is also a high-risk area. As I indicated, this study developed a disaster matrix for the last 20 years with information available from the web because first-hand information could not be collected. So the most recurring events are floods and landslides ...

K: What happens is that these areas when they have been urbanized, as in the case of the Achumani plateau, which must be 35 or 40 years ago. This area was handed over to the military through an agreement, and when it was urbanized, there was no comprehensive urban plan. Therefore floods occur, since both the pluvial and sanitary sewers are after the construction of the houses, that is, there were works after the settlement itself. So, these works have not allowed an urban design to be made of what the city can do. Landslides occur and the charges on the land are what detonate them. For example, 35 or 40 years ago, the solution that many people gave to household wastewater was direct discharges to streams or rivers, not even to septic tanks. This has caused that these same discharges are currently weakening the ground.

This is what has happened in Llojeta or Callapa. They are urbanizing and to build their drainage networks, they were willing to do it through a private sector. The problem is to do it through a private company and then pass the administration of this to the mayor's office, the network did not comply with all the regulatory requirements. This has happened in many areas, several inhabitants carried out the same procedure through private companies and when the time came to transfer that infrastructure to the mayor's office, they did not comply with all the regulations such as required pending, adequate material. Also, in many cases when a disaster occurred is when the problem arose. Floods were detected because the systems were poorly built and had to be rebuilt. As I tell you, this is recurrent in many areas. Personally, I think this occurs because of the rapid urban expansion in La Paz. In addition, there is also a social reason, since people are negligent and to save money they do not act as they should, causing problems in the long term.

R: Moving on to the fourth question, when any of these types of disasters occur, is there a procedure that you are familiar with?

K: Yes, there is a care protocol that I do not know in detail because it is from the Ministry of Risks (SMGIR), but when the primary care protocol is exceeded in its capacities, that is when the promulgation of emergency laws is requested and generation of alerts (yellow, orange, red). Then, at the request of the SMGIR, the Council is coordinated and one of the alerts is declared. According to their category, each one has its own protocol with different modes of action, and they are based on the risk assessment carried out by the SMGIR. This is then approved by the Council and ratified by Municipal Law. These laws allow the allocation of economic resources, mobilization of personnel, mobilization of equipment and machinery, generation of action plans, among others, avoiding going through all kinds of bureaucracy when an event does not have an alert declaration. This also streamlines risk management.

R: Now that you touched on the risk issue, the last map available is from 2011. Is an update planned for this or is there a plan as far as you know?

K: Not that I know of, but I understand that the SMGIR works with one that is updated from time to time online. If I'm not mistaken this is more dynamic, but I have no precise knowledge about it.

R: You mentioned to me how the stormwater network is managed, my question is the following, have you heard of urban sustainable drainage systems? Has a similar issue ever been discussed at the municipal proposal level or law for sustainable drainage and related issues?

K: There were private proposals for sustainable drainage, but I didn't hear it as real plans, just private proposals. Obviously in this it is necessary to speak if the Municipality is willing to face investments of this type.

R: Were they high investments that could not be covered?

K: yes

R: The two proposals that I presented to you have different characteristics. The one with green roofs is located on the roofs of buildings in private properties, in the permeable pavements they are located on roads of public domain. So how feasible would it be to do one or the other?

K: We were working on a bill for a green roof project precisely after the 2016 drought event. We were working on a water reconsideration plan in La Paz. For this we had proposed precisely to work in buildings applying green roofs, since by the number of people they are the ones who consume the most water. For this, a regulation or law had been proposed that works with tax incentives so that they can apply green roofs. Thus, the expenditure of expenses would not be on the part of the Municipality, but of each owner and thus obtain a benefit through the reduction of taxes and possible reductions of invoices. That was the mechanism that we were proposing for the generation of these technologies. However, permeable pavements were never discussed, which I believe is an interesting solution for reducing risks in some areas.

R: And what happened to this green roof project?

K: He stayed in a treatment commission and could not fully approve due to the tax issue. However, I think that it is not impossible, and it can be achieved. But as I told you, this project hoped that the neighbour voluntarily could apply the technology in his house and benefit. The municipality was not going to assume any type of investment.

R: But was the municipality going to provide technical assistance, create a design manual or something like that?

K: If there is someone to do it, no problem. In my point of view, the Municipality would not assume any investment expenses, but if it were willing to assume the technical costs (logistics, technical assistance)

R: Returning to the subject of permeable pavements, who would be in charge of the this topic?

K: Each sub-mayoralty (macro-district mayoralties). In this case it would correspond to the South sub-mayoralty. They will have to coordinate with EMAVIAS, SMGIR and public infrastructure.

R: Speaking of these actors, such as the mayor's office, companies and municipal secretariats, and the population, what do you think would be the challenges to be able to apply this type of proposed solutions?

K: There is a very big challenge on the economic issue that I witnessed in the mayor's office. The mayor's office always seeks not to assume the investment and seeks to have it assumed by private parties. There are many organizations and NGOs that I think would be very interested in seeing the issue of permeable pavement. I believe that the proposal for green roofs would have to be discussed directly with the neighbours. I think that nobody would bear the cost in a private property, which is the most difficult.

R: And are there any experiences you have had with neighbours that have worked?

K: Yes but focused on works of social good. For example, the construction of roofs was carried out in markets where it has been agreed that the neighbours would carry out the works with local labour, while the mayor's office would assume the costs of the materials. In addition to the material, the mayor's office would design and supervise the works. I know those kinds of examples. The problem that I find in the proposal for green roofs is that it is found in private properties, inside homes, and not like in these examples, which are areas of common use.

R: My idea with green roofs was to increase the green areas in the city, which are few, to also create a feeling of community in your own building and have a green area due to the limited space in the city and few existing recreational areas.

K: If I'm not mistaken, there is a construction incentive related to green areas at LUSU. I don't have the exact data, but let's suppose that if your green area occupies 30% of your land you can build one more floor. It would be interesting to apply green roofs in new construction. When you submit your construction plans for approval, they could include this technology. I think that is doable.

Participant: Eduardo Zamorano [E], technical advisor to the Secretary of Environmental Management.
Date: 6th of August, 2021
Interviewer: Roberto Stohmann [R]

R: What is La Paz's posture on climate change and its impacts?

E: There is a very large research gap at the national level. Specifically, in La Paz, some studies warn about certain scenarios of climate change referring to the availability of water resources. In addition, that study centers such as the UMSA, advise of the retreat of glaciers that are essential as the main source of supply for the city. So, this situation is obviously demonstrating, what are the deeds we have as governance in the sphere of the three levels of government, and the vulnerabilities are exposed, as for example in 2016. Although the water drought was due to institutional issues. There was also a phenomenon associated with El Niño that did not allow greater rainfall than those considered. That drastically altered the entire water regime for supply sources. Obviously, the municipality of La Paz in this context has always been trying to investigate and deepen to propose both structural and non-structural measures that allow us to mitigate and adapt to these consequences. For me it is fundamental is that base with which all the policies and water-environmental planning of the municipality should be developed. There is already a history, and also on the subject of risks such as the analysis in your study, the subject of floods is very recurrent in the city. So I think that the city of La Paz should focus all its planning and strategies towards a more resilient city because these phenomena are very evident. The objective is to propose measures that allow the development of the city, and include measures that can structure it in a better way.

R: Precisely what you were saying is what I found in the literature review for this work. They all agree on the issue of glacial retreat, in the lack of precipitation, in the 2016 event and in the 2002 event. Regarding the study itself, what I found with the simulation with a one-hour synthetic storm, although possibly the system is overloaded in this scenario, but even with longer storms the drainage system is likely to collapse. Then a flood is created, because the water will follow the slope downhill in the area. The related question is what is currently being done in high-risk areas? I know it is not up to your Secretariat, but I ask you if you have any knowledge about it.

E: Although climate change and risk management are transversal according to the regulations, with direct influence in these two areas, there is a specific secretary on the regulation of these aspects. But from the environmental point of view we obviously connect it a lot to the phenomena of climate variability and climate change, specifically with the last one. In environmental management issues, what is being proposed is to be able to identify the effects of climate change that could be expected in the city. In this context, a study has been developed and concluded in the 2020 management regarding the aggregate vulnerability index for the city of La Paz. This was in charge of the CAF with the support of universities in Europe, specifically Spain, and many recurrences of threats have been identified, the level of risk that the city has was weighed not only in water availability, but mainly in the occurrence of landslides and floods. In this framework, many measures have been proposed that have been socialized and have some terms. Now the work that is being done is to propose these measures, identify these high-risk areas that can be reduced with perhaps structural measures that will allow the Risk Secretary to act, but in non-structural issues the Environmental Management Secretary could help. It is in this area that municipal management is developing to focus on this theme that is very recurrent in the city. You will understand that there are a lot of threats and not only natural issues but also institutional threats, political threats, social threats that are part of a set of risks. I really believe that the city of La Paz in the areas that we develop can be considered a resilient city or on the way to establish itself under this concept because there are many threats associated with the management of the municipality.

R: Just as you mentioned, I found the CAF article related to the subject. I want to ask you if this vulnerability index is geographically located, as well as the risk map? Or are they just criteria to calculate the index based on some inputs?

E: It analyses both variables. In addition to considering climate change scenarios, it has a series of models and they have been able to adapt it to the best context available. Specifically, this study focuses on the city of La Paz with all the cartography that remains of the macro urban districts. Although an analysis is attempted in the rural macro districts, but it is very generic due to insufficient information. Overall, the city of La Paz's future depends and will depend on the development and planning of the rural macro-districts.

Mainly in the subject that understands me in the supply of the water resource is the Hampaturi dam. In my opinion, it is essential for the development of the city, or for the maintenance of the city of La Paz and its surroundings because the provision that it makes to the city from a suburban approach to supply three other municipalities. It reaches Palca, Achocalla and Mecapaca with its services. All these waters are exploited or extracted from Hampaturi, so if we talk about a vulnerability issue, it is more than a million people who depend on the conservation of these natural spaces of water sources in Hampaturi. In the worst hypothetical case, the weakest link would be that Hampaturi stops producing water from water sources or reservoirs, a million inhabitants would have to look for other settlements, since we would not have water availability because all the city's water bodies are contaminated. The issue of Hampaturi is very important for municipal planning, different activities and projects are being focused to recover a bit of the institutional framework in this sector in addition to having alliances with the community members, moving away from the political issue and focusing on the development issue. So we are working a lot with Hampaturi to provide the best public services that by right and law correspond to them, and also get closer to do a more strategic planning. In addition, it is the force that the three levels of government are trying to find because obviously not only the city of La Paz depends on them, but the entire urban area of the basin.

A: Now that you mention EPSAS, I want to address this related question of stormwater management because when I spoke with them and asked for information, there are many areas where sewerage is combined. How is this being handled with them? Since they have in this area (AOI) a combined network and supervision over the sanitary sewer system, but how do they assume responsibility for this infrastructure or for who attends them?

E: Within the framework of a project that is being developed together with EPSAS, both technical and later legal evaluations are being carried out to be able to define what the roles and responsibilities are, as you well said. There is a kind of competence gap in this area because formerly SAMAPA was the one who provided the potable water, sanitary and rainwater service until 1996. Later, the Republic of Bolivia gave AGUAS DEL ILLIMANI a concession contract for the provision of its services. Then, the inauguration of EPSAS was generated in 2006 and in 2013 its intervention by the national government. In all this context, the storm sewer system was left unattended, because although EPSAS provides the sanitary sewer service, there are many clandestine connections as it is a mixed sewer system. But, the municipality also executes storm sewer projects because of the issue of risks and disasters due mainly to landslides. I believe it is the most recurrent threat suffered by the city of La Paz due to its topography. So it is there that planning is being focused to be able to exercise greater regulation on this aspect. Although EPSAS provides maintenance to its sanitary sewer networks, which are also rainwater, it was identified that sometimes there is an overlap of tasks. Therefore, a need to establish responsibilities very well was identified. There are many complaints from the municipality with the issue of leaks through the EPSAS sewers from its drinking water networks. So obviously there were conflicts. Currently, we seek to identify the best terms so that a better service is provided to the citizenry.

R: Is there any projection or goal in time to define until when a law should be in place or to finalize this issue? How are you going to define who competes for what? Or do you have to take it to a higher level?

E: Decision-making is going to be taken to a more hierarchical level, but from a technical point of view, we are investigating this issue in order to effectively have the context or a more solid baseline that allows us to make decisions at the institutional level. The most advisable thing, as you say, could be the generation of a specific regulation. Subsequently, inter-institutional agreements or conventions must be formed with EPSAS that allow more monitoring of these aspects. There are many areas where the intervention will not be easy, mainly the old town for all the pipes in that sector. So it is very difficult if you do not have the specific plans of these collectors, it is very difficult to identify what the reality is with all the sewers. It is a job that demands a lot of attention, but it is within the framework of a project that is being generated. It is also necessary to bring it to legalization because in the regulatory context that is not something allowed. There should be differentiated canalizations or sewers because, in addition, a wastewater treatment project is being promoted for the city of La Paz. For this purpose, it is very necessary to achieve the separation of these waters so that only in the plant the sanitary waters are treated, and the rainwater has a good evacuation of the waters.

R: Due to the time that we have agreed to and elapsed, I want to quickly move on to the last three questions. The first, have you heard of urban sustainable drainage systems, or is there something within the municipality that is considering this type of solution?

E: I do know the concept, but this Secretariat does not have that responsibility. This theme is developed by the Risk Secretariat through its Storm Drainage Program. They are in this work and it would be up to that instance to issue its criteria, because from the point of view of environmental management we do not get to this in this area. I think it is a cross-cutting issue as I mentioned before, risk management and climate change go hand in hand. Surely there will be a lot of exchange of ideas and joint activities or development in this area because planning and carrying out different activities are cross-cutting themes.

R: From your point of view as a professional of the municipality, how feasible do you think it is to apply green roofs and permeable pavements in the area of this study? Because the intervention of green roofs is on private property. While the permeable pavement is a public area. So how feasible do you see that this can be carried out?

E: Well, identifying as you said these areas exposed to a degree of threat and quantifying the level of risk, I think it justifies the intervention to be able to apply either these measures or others that allow to guarantee the stability of the land and the houses, leaving a little from the context of urban planning whether they are illegal settlements or not. But I believe that these proposals would be highly recommended from municipal planning in those areas where these types of vulnerabilities and threats are identified. If there are other measures, I personally do not know them, that evaluation would have to be carried out mainly in monetary terms. You will understand that as a municipality there is always a cost-efficiency or cost-benefit approach. So the more these terms can be justified, I think that investments can be prioritized. At the end of the day, it is municipal competence. From a more comprehensive point of view, long-term planning should focus not only on municipal public action but perhaps add public-private partnerships. In those future developments, the investments are channeled for the construction of buildings and housing. These measures are contemplated in the corresponding areas. Clearly, this should be promoted through a municipal law that establishes the obligation for construction companies considering these criteria, to ensure not only the stability where the houses are going to be built but also depending on the characteristics of the basin. It will depend on how these structures would be positioned. I believe that the more proposals there are, already quantifying the investments, it is highly usable or profitable for the Municipality in its planning.

R: With that you also answer me what the challenges would be because it goes hand in hand with the investment issue as you mentioned. Finally, I wanted to ask you if you have any questions or issues that we have not touched on to discuss.

E: Well no. First I want to congratulate you, Roberto, I find it a very interesting job. It will surely be in the interest of any institution to have these concepts. The lessons learned that perhaps I could highlight from other cities would be somewhat more visible for an analysis, but going to the context of the city of La Paz, specifically the areas that you have identified, it would be very interesting to be able to interchange criteria with the actors involved in this area, mainly the risk department. Thus, it can be identified if they have contemplated within their intervention priorities or it is obviously an area that is not being considered for some aspects. You will understand that there are many evaluation criteria, so homogenizing this I think is very important. However, as you said, already applying climate change scenarios and seeing the overload that this type of area can have, it seems to me an interesting strategy to apply in planning. Probably at the national level, there is a lack of environmental and risk management with a focus and planning of climate change scenarios. It is possible that we are out of date on this issue due to the lack of research, lack of institutional support that could be provided by study centers and other academic units. Mainly, the heads of the sector, through the Ministry of Environment and Water. There is not much depth in these areas, and in the end the Autonomous Territorial Entities are left in this legal void because the policies in this area should be exercised from the sectoral sphere of competence. So, we continue to investigate and reinvent gunpowder from the municipalities due to the lack of a more solid and strong line, not from the head of the sector.

National legislation should be considered that incorporates the concepts of climate change, since the investment regulations do not clearly define the criteria for evaluations. Thus, the projects lack this scientific and technical basis. We should target as a country to develop this type of studies.

APPENDIX B – DISASTER MATRIX

#	Event date	Event type	Storm intensity (mm/h)	Storm Duration (min)	No. of affected zones	Evento District	Human losses	Economic losses (in millions USD)	Damage details	Source	Source Type	Published Date
1	10/02/2001	rain and collapse	n/d	n/d	1	Unspecified	4	n/d	A home collapsed due to humidity killing 4 children when a wall collapsed	BBC	News article	10/02/2001
2	19/02/2002	rain and hail	41	50	20	Centro; Sur	63	10	28 households destroyed and 126 households damaged; 146 people requiered medical attention; 50 mins duration in Laykacota, but overall was 39.4mm in 90 mins; before the event there were 3 previous days of intense rain; most infrastructure damage was caused to streets, drainage and vaults; energy, water and transport (bridges) infrastructure was also damaged; one million USD required for drainage systems only due to undermining; 150 hectares of crops affected in Rio Abajo corresponding to 450 peasant families; 11 vehicles destroyed (taxis); soil, underground water, and crops polluted due to combined system overflows (CSO) calle Mercado (Tunel San Francisco); flooding, clogged drains, vaults and retaining walls destroyed	OCHA; ActionAid	Assessment & Situation Report	02/03/2002 21/02/2002
3	22/01/2003	rain and flooding	n/d	n/d	5	Centro	0	n/d	calle Honda flooded; emergency municipal team movilised to attend the situation	La Razon	News article	22/01/2003
4	26/12/2003	rain and flooding	n/d	n/d	3	Sur	0	n/d	most affected areas: Seguencoma, Irpavi, Calacoto calle 8; clogged drains and pipes; flooding in households due to CSO	ANF	News article	26/12/2003
5	12/02/2006	rain and flooding	n/d	n/d	5	Sur	2	n/d	affected areas: Irpavi and Achumani; the Irpavi bridge was destroyed and the one in Achumani was damaged; many rivers had overflowed (Achumani, Huayllani, Calliri); in the previous days 5 cases were attended with affection to Los Leones and Libertadores avenues;	Europa Press	News article	13/02/2006
6	07/02/2010	rain and flooding	n/d	n/d	1	Mallasa	0	n/d	Lipari bridge was affected impeding to access neighboring municipalities in the south of La Paz	Opinion	News article	07/02/2010
7	26/02/2011	rain and lanslides	n/d	n/d	10	Sur, San Antonio	0	50	Kupini landslide; 140 hectares slided; 1188 families were affected from Valle de las Flores, Kupini II, Pampahasi Bajo Central, Metropolitana, Cerveceria, Santa Rosa de Callapa, Callapa, 23 de Marzo, Leonardo Da Vinci and Irpavi II; 800 lots were affected; 250 were destroyed and 550 severely damaged; later reports mentioned landslide was provoked by water leakage into a geologic fault; 34 million USD in housing destruction and 16.8 million USD in public infrastructure; Amongst the main factors for the event there were weakening of the slope produced by the deficiency in the sewerage systems, erosion produced in the Chujlluncani River, saturation of soils due to heavy rains, erosion of the Irpavi River in the Callapa sector, earthworks and housing construction in unsuitable areas	Pagina Siete	News article	01/03/2011

#	Event date	Event type	Storm intensity (mm/h)	Storm Duration (min)	No. of affected zones	Evento District	Human losses	Economic losses (in millions USD)	Damage details	Source	Source Type	Published Date
8	15/02/2012	rain and collapse	n/d	n/d	1	Max Paredes	3	n/d	A home collapsed in Achachicala	Opinion	News article	15/02/2012
9	04/12/2016	rain and flooding	n/d	n/d	2	Centro	0	n/d	Camacho and Simon Bolivar avenues were flooded along with other important streets in the city centre and Sopocachi; public transport service was affected due to the flooding on the route; on the 2nd of Decembre registered rainfall was 17.3mm; moreover, the city was going through a drinking water scarcity due to the drought season	Pagina Siete	News article	05/12/2016
10	11/03/2017	rain and flooding	n/d	n/d	3	Cotahuma; Max Paredes; San Antonio	0	n/d	In-household flooding due to CSO clog; lack of maintenance of network and intense precipitaton; 12 emergency cases were attended by the Municipality; the highest ammount of rain was on 26-02-17 with 10.8mm registered in the city centre rain gauge	Pagina Siete	News article	15/03/2017
11	08/02/2018	rain and collapse	n/d	n/d	4	Periferica	2	n/d	Affected zone in Kalajahuira, Vino Tinto, Irpavi II and Alto Tacagua, after a precipitation event a house collapsed killing one person in Kalajahuira; event was attributed to a precarious construction; 8 days before another person died due to the same reason but in Vino Tinto	El Deber	News article	09/02/2018
12	04/01/2020	rain and flooding	n/d	n/d	3	San Antonio; Centro	0	n/d	4 cases were registered in Achachicala, San Antonio and Centro; the emergency was attributed to the lack of infrastructure maintenance and pipe clogging	El Diario	News article	07/01/2020
13	07/02/2020	rain and lanslides	n/d	n/d	2	Cotahuma	0	n/d	Rain intensity provoked a landslide in Pasankeri and Niño Kollo;	Jornada	News article	08/02/2020
14	13/02/2020	rain and flooding	n/d	n/d	4	Sur; Centro	0	n/d	Streets and avenues were flooded with up to 50 centimetres above surface level; Costanera and Kantutani avenues had to be closed due to the flooding; some commerce and service services had to stop their functioning temporarily	Brujula Digital	News article	13/02/2020
15	25/12/2020	rain and flooding	n/d	n/d	1	Sur	0	n/d	One of the main collectors in Achumani was flooded due to obstruction, municipality contacted EPSAS to solve the case	Periodico Bolivia	News article	26/12/2020
16	30/12/2020	rain and hail	n/d	30	10	Sur; Centro	0	n/d	River water overflowed canal in Avenue Roma; 10 flooded points were reported to the emergency municipal unit due to clogging of drains and collectors; Simon Bolivar, UMSA, Las Cholas, Plaza de la Mujer and other areas were affected	ATB	TV report	30/12/2020

APPENDIX C – SUBCATCHMENTS' OVERFLOW COEFFICIENTS

YEAR 2003	**Pervious**			**Impervious**			**Total Area (m2)**	**Sum of Ai*ni**	***Input for SWMM***		
Catch #	**Area [sqm]**	**Area %**	**Sum of Ai*ni**	**Area [sqm]**	**Area %**	**Sum of Ai*ni**	**120.263,55**		***% Impervious***	***Impervious***	***Pervious***
1	4.233,882	0,990	739,603	42,920	0,010	0,888	4.276,803	740,491	1,004	0,000	0,173
2	1.708,716	0,998	248,241	3,499	0,002	0,070	1.712,214	248,311	0,204	0,000	0,145
3	824,386	0,790	65,912	218,775	0,210	4,334	1.043,161	70,246	20,972	0,004	0,063
4	606,646	0,528	54,603	542,551	0,472	10,799	1.149,197	65,402	47,211	0,009	0,048
5	836,676	0,714	49,179	334,658	0,286	6,693	1.171,335	55,872	28,571	0,006	0,042
6	431,939	0,586	24,475	304,939	0,414	6,099	736,877	30,574	41,383	0,008	0,033
7	1.702,002	0,977	238,181	40,371	0,023	0,807	1.742,373	238,989	2,317	0,000	0,137
8	313,507	0,387	16,509	497,593	0,613	9,828	811,101	26,338	61,348	0,012	0,020
9	1.184,045	0,892	134,460	143,836	0,108	2,824	1.327,881	137,283	10,832	0,002	0,101
10	2.624,871	0,954	134,180	125,888	0,046	2,518	2.750,759	136,698	4,576	0,001	0,049
11	3.523,236	0,995	133,875	18,599	0,005	0,372	3.541,834	134,247	0,525	0,000	0,038
12	3.434,620	0,920	364,777	296,876	0,080	6,443	3.731,496	371,220	7,956	0,002	0,098
13	1.556,694	0,953	87,887	76,437	0,047	1,529	1.633,130	89,415	4,680	0,001	0,054
14	3.737,908	0,982	147,315	68,063	0,018	1,361	3.805,971	148,677	1,788	0,000	0,039
15	2.873,482	0,893	164,460	344,839	0,107	7,521	3.218,321	171,981	10,715	0,002	0,051
16	1.261,514	0,897	47,098	145,000	0,103	2,815	1.406,514	49,913	10,309	0,002	0,033
17	3.026,632	0,966	116,412	106,960	0,034	2,139	3.133,591	118,551	3,413	0,001	0,037
18	5.034,278	0,917	478,240	454,509	0,083	9,452	5.488,787	487,692	8,281	0,002	0,087
19	1.201,015	0,708	52,601	494,726	0,292	9,865	1.695,741	62,466	29,175	0,006	0,031
20	2.989,006	0,856	106,507	501,115	0,144	10,022	3.490,121	116,529	14,358	0,003	0,031
21	7.726,112	0,784	997,607	2.126,010	0,216	48,431	9.852,122	1.046,038	21,579	0,005	0,101
22	2.636,070	0,845	98,825	483,858	0,155	9,574	3.119,928	108,399	15,509	0,003	0,032
23	2.183,991	0,932	79,568	158,380	0,068	3,168	2.342,371	82,736	6,762	0,001	0,034
24	3.573,395	0,873	206,298	519,509	0,127	10,390	4.092,904	216,688	12,693	0,003	0,050
25	443,914	0,961	49,471	17,784	0,039	0,500	461,698	49,971	3,852	0,001	0,107
26	1.737,243	0,477	226,151	1.908,370	0,523	42,431	3.645,613	268,583	52,347	0,012	0,062
27	731,969	0,294	90,638	1.753,537	0,706	34,092	2.485,506	124,730	70,551	0,014	0,036
28	410,782	0,536	15,122	356,266	0,464	7,125	767,048	22,247	46,446	0,009	0,020
29	1.716,453	0,624	101,593	1.035,539	0,376	20,617	2.751,992	122,210	37,629	0,007	0,037
30	2.033,566	0,835	171,703	401,099	0,165	9,458	2.434,665	181,161	16,475	0,004	0,071

YEAR 2003	**Pervious**			**Impervious**			**Total Area (m2)**	**Sum of Ai*ni**	***Input for SWMM***		
Catch #	**Area [sqm]**	**Area %**	**Sum of Ai*ni**	**Area [sqm]**	**Area %**	**Sum of Ai*ni**	**120.263,55**		***% Impervious***	***Impervious***	***Pervious***
31	508,662	0,613	112,209	320,746	0,387	9,497	829,407	121,706	38,672	0,011	0,135
32	1.225,442	0,783	182,046	339,380	0,217	6,953	1.564,823	188,999	21,688	0,004	0,116
33	758,180	0,576	100,107	558,722	0,424	10,517	1.316,902	110,624	42,427	0,008	0,076
34	377,127	0,671	26,677	184,987	0,329	3,691	562,114	30,368	32,909	0,007	0,047
35	283,947	0,435	51,509	368,570	0,565	8,244	652,518	59,753	56,484	0,013	0,079
36	137,476	0,424	29,057	186,966	0,576	3,623	324,442	32,680	57,627	0,011	0,090
37	151,784	0,401	22,035	227,161	0,599	4,155	378,945	26,190	59,946	0,011	0,058
38	414,483	0,557	67,734	330,105	0,443	6,585	744,588	74,318	44,334	0,009	0,091
39	242,587	0,721	50,387	94,019	0,279	1,962	336,606	52,350	27,931	0,006	0,150
40	242,564	0,656	36,482	127,348	0,344	2,498	369,912	38,980	34,427	0,007	0,099
41	168,788	0,521	6,280	154,910	0,479	3,093	323,698	9,372	47,856	0,010	0,019
42	565,529	0,547	20,606	467,557	0,453	9,351	1.033,086	29,957	45,258	0,009	0,020
43	221,119	0,437	36,512	284,572	0,563	6,706	505,690	43,218	56,274	0,013	0,072
44	565,946	0,648	86,321	307,774	0,352	6,041	873,720	92,363	35,226	0,007	0,099
45	329,863	0,615	44,650	206,492	0,385	4,085	536,355	48,734	38,499	0,008	0,083
46	630,641	0,586	132,254	445,832	0,414	10,578	1.076,472	142,832	41,416	0,010	0,123
47	362,875	0,387	37,257	575,362	0,613	11,016	938,237	48,273	61,324	0,012	0,040
48	120,173	0,184	7,584	532,883	0,816	10,105	653,056	17,688	81,598	0,015	0,012
49	2.955,185	0,762	665,073	924,144	0,238	25,743	3.879,330	690,817	23,822	0,007	0,171
50	875,119	0,522	129,375	802,241	0,478	17,199	1.677,360	146,574	47,828	0,010	0,077
51	702,097	0,461	127,047	819,531	0,539	15,604	1.521,628	142,651	53,859	0,010	0,083
52	394,508	0,502	73,063	391,862	0,498	7,560	786,369	80,623	49,832	0,010	0,093
53	335,250	0,457	69,189	397,914	0,543	7,846	733,164	77,035	54,274	0,011	0,094
54	1.319,982	0,440	208,548	1.679,447	0,560	32,573	2.999,429	241,121	55,992	0,011	0,070
55	1.563,480	0,621	313,890	955,538	0,379	26,144	2.519,018	340,035	37,933	0,010	0,125
56	1.366,686	0,760	346,006	432,502	0,240	11,992	1.799,188	357,997	24,039	0,007	0,192
57	1.906,075	0,709	272,244	781,544	0,291	17,607	2.687,618	289,851	29,079	0,007	0,101
58	505,214	0,485	88,949	536,343	0,515	11,416	1.041,557	100,365	51,494	0,011	0,085
59	717,437	0,497	126,790	727,353	0,503	14,215	1.444,790	141,004	50,343	0,010	0,088
60	760,133	0,407	122,046	1.106,829	0,593	21,177	1.866,961	143,223	59,285	0,011	0,065
61	3.169,513	0,710	786,521	1.296,002	0,290	32,898	4.465,515	819,419	29,022	0,007	0,176
TOTALS	***90.176,412***	***0,750***	***9.819,939***	***30.087,141***	***0,250***	***642,838***	***120.263,553***	***10.462,777***	***25,018***	***0,005***	***0,082***

YEAR 2013	**Pervious**			**Impervious**			**Total Area (m2)**	**Sum of Ai*ni**	***Input for SWMM***		
Catch #	**Area [sqm]**	**Area %**	**Sum of Ai*ni**	**Area [sqm]**	**Area %**	**Sum of Ai*ni**	**120.263,55**		***% Impervious***	***Impervious***	***Pervious***
1	1.763,396	0,412	86,754	2.513,019	0,588	51,637	4.276,415	138,390	58,765	0,012	0,020
2	1.191,294	0,696	43,576	521,110	0,304	10,761	1.712,404	54,337	30,431	0,006	0,025
3	325,563	0,312	13,203	717,177	0,688	14,537	1.042,740	27,739	68,778	0,014	0,013
4	403,771	0,351	36,208	745,677	0,649	14,549	1.149,448	50,758	64,873	0,013	0,032
5	370,241	0,316	57,983	801,092	0,684	15,481	1.171,333	73,465	68,391	0,013	0,050
6	287,575	0,390	20,358	449,304	0,610	8,526	736,880	28,884	60,974	0,012	0,028
7	846,403	0,487	68,546	891,636	0,513	20,987	1.738,038	89,533	51,301	0,012	0,039
8	350,240	0,432	38,212	460,860	0,568	10,041	811,100	48,253	56,819	0,012	0,047
9	733,832	0,553	48,127	593,908	0,447	15,384	1.327,740	63,511	44,731	0,012	0,036
10	1.204,258	0,438	135,469	1.544,773	0,562	31,873	2.749,031	167,343	56,193	0,012	0,049
11	1.294,491	0,366	133,216	2.246,646	0,634	45,828	3.541,137	179,043	63,444	0,013	0,038
12	1.862,344	0,500	177,465	1.863,241	0,500	40,990	3.725,585	218,455	50,012	0,011	0,048
13	650,406	0,399	81,637	981,473	0,601	20,664	1.631,879	102,300	60,144	0,013	0,050
14	1.449,192	0,381	210,897	2.356,646	0,619	48,261	3.805,838	259,157	61,922	0,013	0,055
15	1.312,379	0,408	159,973	1.904,018	0,592	39,379	3.216,397	199,352	59,197	0,012	0,050
16	522,039	0,371	54,415	884,440	0,629	19,287	1.406,479	73,702	62,883	0,014	0,039
17	1.140,744	0,364	111,221	1.992,839	0,636	40,719	3.133,583	151,940	63,596	0,013	0,035
18	2.355,625	0,429	274,567	3.129,978	0,571	66,556	5.485,603	341,123	57,058	0,012	0,050
19	638,977	0,377	76,785	1.057,670	0,623	21,452	1.696,647	98,237	62,339	0,013	0,045
20	2.026,093	0,581	179,611	1.464,025	0,419	31,543	3.490,118	211,154	41,948	0,009	0,051
21	4.520,300	0,459	656,809	5.327,784	0,541	113,119	9.848,084	769,927	54,100	0,011	0,067
22	763,878	0,245	63,790	2.353,335	0,755	50,004	3.117,213	113,794	75,495	0,016	0,020
23	1.165,912	0,498	112,449	1.176,455	0,502	24,234	2.342,367	136,683	50,225	0,010	0,048
24	1.610,777	0,394	182,673	2.478,383	0,606	48,399	4.089,160	231,072	60,609	0,012	0,045
25	254,027	0,552	14,407	206,521	0,448	4,227	460,547	18,634	44,842	0,009	0,031
26	1.304,237	0,358	165,836	2.334,279	0,642	49,879	3.638,516	215,715	64,155	0,014	0,046
27	824,693	0,332	103,775	1.660,858	0,668	35,300	2.485,551	139,076	66,821	0,014	0,042
28	353,178	0,460	20,572	413,870	0,540	8,532	767,048	29,104	53,956	0,011	0,027
29	1.132,718	0,412	152,521	1.619,279	0,588	35,517	2.751,997	188,038	58,840	0,013	0,055
30	1.421,899	0,584	113,099	1.012,576	0,416	21,741	2.434,475	134,840	41,593	0,009	0,046
31	383,268	0,463	69,433	444,812	0,537	9,317	828,080	78,750	53,716	0,011	0,084
32	607,358	0,388	93,884	957,468	0,612	20,761	1.564,826	114,645	61,187	0,013	0,060
33	490,478	0,372	73,481	826,401	0,628	18,456	1.316,878	91,937	62,755	0,014	0,056

YEAR 2013	**Pervious**			**Impervious**			**Total Area (m2)**	**Sum of Ai*ni**	***Input for SWMM***		
Catch #	**Area [sqm]**	**Area %**	**Sum of Ai*ni**	**Area [sqm]**	**Area %**	**Sum of Ai*ni**	**120.263,55**		***% Impervious***	***Impervious***	***Pervious***
34	172,413	0,307	20,391	389,683	0,693	7,883	562,096	28,273	69,327	0,014	0,036
35	213,982	0,327	36,700	440,754	0,673	8,048	654,736	44,748	67,318	0,012	0,056
36	88,270	0,272	14,704	236,172	0,728	4,678	324,442	19,382	72,793	0,014	0,045
37	112,706	0,297	16,009	266,238	0,703	5,360	378,945	21,368	70,258	0,014	0,042
38	324,475	0,436	56,495	420,112	0,564	9,734	744,587	66,229	56,422	0,013	0,076
39	134,161	0,399	28,367	202,445	0,601	4,596	336,606	32,963	60,143	0,014	0,084
40	125,973	0,341	23,525	243,939	0,659	5,247	369,912	28,772	65,945	0,014	0,064
41	95,259	0,294	9,779	228,438	0,706	4,482	323,697	14,262	70,571	0,014	0,030
42	346,577	0,335	31,561	686,509	0,665	14,235	1.033,085	45,796	66,452	0,014	0,031
43	219,637	0,436	40,044	284,504	0,564	5,804	504,141	45,847	56,433	0,012	0,079
44	406,733	0,466	80,501	465,637	0,534	10,199	872,369	90,700	53,376	0,012	0,092
45	197,903	0,369	35,658	338,452	0,631	7,426	536,355	43,084	63,102	0,014	0,066
46	636,249	0,591	146,987	440,222	0,409	9,137	1.076,471	156,124	40,895	0,008	0,137
47	465,428	0,496	89,321	472,808	0,504	10,903	938,236	100,224	50,393	0,012	0,095
48	287,562	0,440	46,656	365,494	0,560	7,956	653,057	54,611	55,967	0,012	0,071
49	2.042,159	0,527	340,143	1.832,476	0,473	36,359	3.874,635	376,502	47,294	0,009	0,088
50	790,713	0,471	140,505	886,565	0,529	17,020	1.677,278	157,525	52,857	0,010	0,084
51	480,186	0,316	82,694	1.041,445	0,684	20,099	1.521,630	102,794	68,443	0,013	0,054
52	249,401	0,317	40,952	536,969	0,683	10,215	786,370	51,166	68,285	0,013	0,052
53	337,283	0,460	61,966	395,882	0,540	8,487	733,165	70,452	53,996	0,012	0,085
54	1.212,604	0,404	189,404	1.786,818	0,596	40,997	2.999,422	230,401	59,572	0,014	0,063
55	1.260,675	0,500	210,745	1.258,661	0,500	24,555	2.519,336	235,300	49,960	0,010	0,084
56	821,408	0,457	135,526	977,682	0,543	21,145	1.799,090	156,672	54,343	0,012	0,075
57	1.191,529	0,444	211,392	1.493,805	0,556	31,833	2.685,334	243,225	55,628	0,012	0,079
58	398,493	0,383	57,542	642,122	0,617	13,546	1.040,616	71,089	61,706	0,013	0,055
59	543,004	0,376	85,252	899,330	0,624	17,254	1.442,335	102,506	62,352	0,012	0,059
60	861,257	0,462	144,008	1.003,058	0,538	21,437	1.864,315	165,445	53,803	0,011	0,077
61	2.573,968	0,576	333,249	1.892,032	0,424	46,304	4.466,000	379,552	42,365	0,010	0,075
TOTALS	***52.174,218***	***0,434***	***6.541,027***	***68.089,335***	***0,566***	***1.432,877***	***120.263,553***	***7.973,904***	***56,617***	***0,012***	***0,054***

YEAR 2020	**Pervious**				**Impervious**		**Total Area (m2)**	**Sum of Ai*ni**	***Input for SWMM***		
Catch #	**Area [sqm]**	**Area %**	**Sum of Ai*ni**	**Area [sqm]**	**Area %**	**Sum of Ai*ni**	**120.263,55**		***% Impervious***	***Impervious***	***Pervious***
1	2.242,771	0,525	207,452	2.031,431	0,475	43,206	4.274,201	250,658	47,528	0,010	0,049
2	339,544	0,198	55,878	1.371,287	0,802	26,477	1.710,831	82,355	80,153	0,015	0,033
3	644,686	0,619	45,166	396,273	0,381	8,577	1.040,959	53,743	38,068	0,008	0,043
4	546,027	0,475	87,418	602,560	0,525	13,774	1.148,587	101,192	52,461	0,012	0,076
5	278,753	0,238	48,151	892,580	0,762	20,116	1.171,334	68,268	76,202	0,017	0,041
6	214,676	0,291	42,601	522,202	0,709	10,669	736,878	53,270	70,867	0,014	0,058
7	485,908	0,279	71,748	1.252,685	0,721	27,878	1.738,593	99,626	72,052	0,016	0,041
8	208,159	0,257	27,005	602,942	0,743	12,176	811,101	39,181	74,336	0,015	0,033
9	473,146	0,356	62,897	856,160	0,644	19,054	1.329,306	81,950	64,407	0,014	0,047
10	1.302,683	0,474	241,210	1.446,494	0,526	34,684	2.749,177	275,895	52,616	0,013	0,088
11	1.280,925	0,362	195,973	2.260,912	0,638	50,085	3.541,838	246,058	63,834	0,014	0,055
12	1.248,877	0,335	201,638	2.476,278	0,665	51,858	3.725,155	253,496	66,474	0,014	0,054
13	746,994	0,458	100,630	884,118	0,542	18,492	1.631,112	119,122	54,203	0,011	0,062
14	1.620,547	0,426	285,429	2.186,005	0,574	48,293	3.806,552	333,721	57,427	0,013	0,075
15	989,568	0,308	162,868	2.226,233	0,692	49,476	3.215,801	212,344	69,228	0,015	0,051
16	304,776	0,217	58,810	1.101,597	0,783	24,600	1.406,373	83,411	78,329	0,017	0,042
17	697,578	0,223	141,160	2.436,009	0,777	49,317	3.133,587	190,478	77,739	0,016	0,045
18	1.665,764	0,304	298,051	3.821,692	0,696	76,560	5.487,456	374,611	69,644	0,014	0,054
19	418,113	0,247	70,433	1.278,038	0,753	27,674	1.696,150	98,107	75,349	0,016	0,042
20	1.263,134	0,362	203,675	2.226,983	0,638	47,417	3.490,117	251,092	63,808	0,014	0,058
21	2.907,256	0,295	507,928	6.941,055	0,705	145,181	9.848,311	653,109	70,480	0,015	0,052
22	676,438	0,217	90,258	2.437,744	0,783	49,011	3.114,181	139,270	78,279	0,016	0,029
23	758,277	0,324	148,568	1.584,091	0,676	33,325	2.342,368	181,893	67,628	0,014	0,063
24	1.277,381	0,312	250,677	2.813,510	0,688	63,130	4.090,891	313,807	68,775	0,015	0,061
25	110,678	0,241	15,647	349,409	0,759	6,470	460,088	22,117	75,944	0,014	0,034
26	1.048,283	0,288	176,757	2.595,847	0,712	56,331	3.644,130	233,087	71,234	0,015	0,049
27	798,974	0,321	143,335	1.687,191	0,679	33,779	2.486,165	177,114	67,863	0,014	0,058
28	196,409	0,256	36,333	570,639	0,744	12,362	767,048	48,695	74,394	0,016	0,047
29	623,504	0,227	99,657	2.128,491	0,773	41,143	2.751,995	140,800	77,344	0,015	0,036
30	1.246,598	0,513	240,998	1.185,714	0,487	24,552	2.432,312	265,550	48,748	0,010	0,099
31	335,483	0,405	79,387	492,879	0,595	12,798	828,362	92,186	59,500	0,015	0,096
32	716,701	0,458	110,923	848,127	0,542	17,414	1.564,828	128,336	54,199	0,011	0,071
33	485,117	0,368	58,699	831,811	0,632	15,591	1.316,928	74,290	63,163	0,012	0,045

YEAR 2020	**Pervious**			**Impervious**			**Total Area (m2)**	**Sum of Ai*ni**	***Input for SWMM***		
Catch #	**Area [sqm]**	**Area %**	**Sum of Ai*ni**	**Area [sqm]**	**Area %**	**Sum of Ai*ni**	**120.263,55**		***% Impervious***	***Impervious***	***Pervious***
34	131,698	0,234	24,031	431,108	0,766	8,557	562,807	32,588	76,600	0,015	0,043
35	192,722	0,295	39,450	460,560	0,705	10,404	653,282	49,854	70,499	0,016	0,060
36	48,779	0,150	7,664	275,657	0,850	5,198	324,437	12,862	84,965	0,016	0,024
37	63,862	0,169	10,577	315,083	0,831	6,089	378,945	16,666	83,147	0,016	0,028
38	326,621	0,439	52,583	417,967	0,561	9,278	744,588	61,861	56,134	0,012	0,071
39	91,031	0,270	19,289	245,575	0,730	5,733	336,606	25,022	72,956	0,017	0,057
40	143,370	0,388	26,254	226,538	0,612	4,819	369,908	31,072	61,242	0,013	0,071
41	91,882	0,284	11,824	231,105	0,716	4,621	322,987	16,444	71,552	0,014	0,037
42	273,438	0,265	51,142	759,648	0,735	15,885	1.033,086	67,027	73,532	0,015	0,050
43	207,208	0,411	40,001	297,384	0,589	6,748	504,592	46,749	58,936	0,013	0,079
44	232,946	0,267	47,056	640,774	0,733	13,292	873,720	60,348	73,339	0,015	0,054
45	161,745	0,302	17,189	374,609	0,698	6,641	536,354	23,830	69,844	0,012	0,032
46	474,234	0,441	101,729	602,238	0,559	15,422	1.076,472	117,150	55,946	0,014	0,095
47	625,919	0,667	134,889	312,318	0,333	7,754	938,237	142,643	33,288	0,008	0,144
48	216,016	0,331	46,695	436,327	0,669	10,443	652,343	57,138	66,886	0,016	0,072
49	1.098,758	0,284	223,607	2.773,297	0,716	61,688	3.872,055	285,295	71,623	0,016	0,058
50	460,853	0,275	100,797	1.216,401	0,725	26,346	1.677,254	127,142	72,523	0,016	0,060
51	399,744	0,263	75,436	1.121,886	0,737	21,095	1.521,630	96,531	73,729	0,014	0,050
52	134,148	0,171	17,713	652,221	0,829	11,689	786,369	29,402	82,941	0,015	0,023
53	203,325	0,277	36,113	529,839	0,723	10,108	733,165	46,221	72,267	0,014	0,049
54	1.264,814	0,422	235,109	1.734,609	0,578	34,263	2.999,423	269,372	57,831	0,011	0,078
55	787,719	0,313	160,078	1.731,217	0,687	40,108	2.518,936	200,186	68,728	0,016	0,064
56	791,755	0,440	128,926	1.006,765	0,560	20,926	1.798,521	149,852	55,977	0,012	0,072
57	962,511	0,358	168,119	1.724,064	0,642	37,599	2.686,575	205,719	64,173	0,014	0,063
58	420,092	0,404	80,471	619,729	0,596	12,547	1.039,820	93,019	59,600	0,012	0,077
59	531,275	0,369	90,600	909,761	0,631	16,754	1.441,036	107,355	63,132	0,012	0,063
60	646,993	0,347	114,261	1.217,704	0,653	26,214	1.864,697	140,475	65,303	0,014	0,061
61	2.368,529	0,530	480,184	2.097,404	0,470	47,639	4.465,933	527,823	46,965	0,011	0,108
TOTALS	***41.525,416***	***0,345***	***7.109,148***	***78.738,137***	***0,655***	***1.669,329***	***120.263,553***	***8.778,478***	***65,471***	***0,014***	***0,059***