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Assessing Reliability, Resilience and Vulnerability of Water Supply from SuDS

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Abstract: In the last decades, the impacts of urbanization on the hydrological cycle have led to an increase in the frequency and magnitude of urban flooding events, also amplified by the effects of climate change. Sustainable Drainage Systems (SuDS) provide a revolutionary change in this field, improving the sustainability and resilience of cities. This research explores the integration of different SuDS with the aim of significantly reducing both flow volume and celerity of floods in a residual urban catchment area of metropolitan city of Querétaro (Mèxico), where extreme rainfall frequently occurs. This catchment is a representative suburb of urban pressure and environmental degradation problems. Currently, managing storm water under climate uncertainty through a multi-disciplinary approach is a major concern in this urban area. A 1D-2D coupling model of shallow water equations, finite volume method, unstructured meshing method, and hybrid parallel computing application defined the optimal configuration of SuDS at catchment scale to reduce the flood vulnerability in Querétaro. Specifically, in this paper we explore the management issues of the proposed SuDS configuration that acts as a water resource system with multiple purposes. A generic simulation model called MODSIM was applied to simulate the designed urban drainage system under a balanced IPCC future climate scenario in terms of reliability, resilience and vulnerability against water scarcity.

Keywords: stormwater flooding; sustainable drainage systems (SuDS); sustainable city; urbanization; MODSIM; supply indicators

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1. Introduction

Urban flooding is a growing concern influenced by factors such as climate extremes, urban growth, land-use changes and poor land-use planning. The negative impacts of flood events include loss of life, economic damage and environmental degradation. The problem becomes even more relevant in fast-growing cities due to their changing dynamics and increasing social vulnerability (Isia et al., 2023). The processes of urbanization, with unlimited demand from the social system and limited supply from the environmental system, generate - more likely in a neoliberal context (Calderón-Aragón, 2011) with high productive and economic growth - socio-natural risks (Lavell, 1996), particularly in the space of urban-rural transition: the urban periphery (Bazant, 2010). These spaces are occupied by poor people who do not plan ahead and are unaware of their susceptibility to hazard impacts (Aragón, 2007; Díaz-Caravantes et al., 2011; Eakin et al., 2010).

Urban Drainage Systems (UDS) are an integral part of the urban infrastructures that can significantly enhance its resilience against urban floods (Guptha et al., 2022). UDS are not able to cope up with extreme uncertain events (Valipour et al., 2020) that would require unsustainable engineered solutions in terms of enormous financial and environmental costs. An option to enhance the resilience against extreme events and urbanization could be nature-based solutions, i.e., Sustainable Drainage Systems (SuDS). SuDS can realize an integrated network of engineered vegetated areas and open spaces that complements centralized conventional drainage system infrastructures. Rain gardens, green roofs and porous pavements are examples of SuDS that can be used to protect natural

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ecosystem and to offer a wide variety of benefits to people and wildlife (Tang et al., 2021). The state-of-the-art in SUDS development and practical application has focused on technical aspects such as selection, location, and size optimization (Ortega et al., 2023) and performance assessment, i.e., reduction of runoff volumes and flow peaks (Damodaram et al., 2010) and cost-benefit analysis (Johnson and Geisendorf, 2019).

This literature clearly shows that most SuDS have not achieved wide-spread implementation worldwide due to the gaps in knowledge regarding designing, implementing, and maintaining SuDS or quantifying the benefits and co-benefits of their ecosystem services (Somarakis et al., 2021; Kõiv-Vainik et al., 2022).

SUDS planning, design, and management is a high-level complexity problem that requires a modeling exercise to predict the behavior of SUDS configurations (type, design, and location) and predict their impact in the existing urban system. This modeling exercise, in form of simulation, optimization or other tools like multi-criteria approaches, can be develop in a Decision Support Systems (DSS) framework. DSS is a valuable aid for SUDS widespread adoption, supporting SUDS design and SUDS spatial location (Veith et al., 2003).

To minimise the pressure on water resources, some SuDS (e.g., rooftop rainwater harvesting – RWH – systems) are widely used to provide an additional source of water (Shubo et al., 2020). These systems store stormwater runoff from rooftops and other impervious surfaces to supply different types of demands (e.g., households, irrigation, industries) possibly after temporary storage and treatment (Woods Ballard et al., 2015).

Although SuDS have been used for almost two decades, the implementation has been predominantly in temperate region. The implementation of SuDS results in a variation in water quantity and quality controls in tropical and subtropical regions, which receive more intensive and frequent rainfall events than temperate regions. Particularly in arid and semi-arid regions, the interconnection of SuDS can constitute a water resource system, simple or complex, with the additional objective to increase the performance in supplying different uses in urban areas. There are a variety of criteria one can use to judge and compare alternative system performances. In a pioneer paper, Hashimoto et al., 1982 presented the reliability-resilience-vulnerability (RRV) analysis that has defined the standard approach in the evaluation and selection of alternative design and operating policies for a wide variety of water resource projects. Some system performance objectives may be in conflict, and in such cases, models can help identify the efficient tradeoffs among these conflicting measures of system performance. These tradeoffs indicate what combinations of performance measure values can be obtained from various system design and operating policy variable values. These indicators are typically quantified across large sets of possible future climate scenarios (e.g., thousands of scenarios), generated either through downscaling of global climate model projections or through statistical hydrological models (Borgomeo et al., 2015). Hydrological models are generally calibrated at longer time-steps (monthly, seasonal, or annual) than their computational time-step (daily), because of better calibration performance, lower computational requirements, and the lack of reliable temporally-fine observed discharge data (particularly in developing countries). Generic simulation models can help identify nondominated tradeoffs among competing objectives or system performance indicators (Loucks and van Beek, 2017). Sulis and Sechi (2013) presented an extended state-of-the-art review on simulation and optimization modeling approaches in reservoir system operation problems. Specifically, Sulis and Sechi illustrated the application performances of five generic models for simulating multi-reservoir and multi-use water resource systems: AQUATOOL-SimWin (referred to as AQUATOOL in this paper) (Valencia Polytechnic University) (Andreu et al., 1996), MODSIM (Colorado State University) (Labadie et al., 2000), RIBASIM (DELTARES) (Delft Hydraulics, 2006), WARGI-SIM (University of Cagliari) (Sechi and Sulis, 2009) and WEAP (Stockholm Environmental Institute) (SEI, 2005). In this paper, MODSIM has been selected as the most promising for a preliminary analysis of alternative plans and policies on the water resources system as aggregation of different SUDS. MODSIM uses a minimum-cost network-flow optimization algorithm to allocate run-of-the-river flows and stored volumes among a specified set of demands according to the institutional framework governing the distribution of water. MODSIM

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is designed to allocate river flows and stored water based on physical and legal availability, while also capable of simulating complex operations such as river exchanges (i.e., water- market type trades), minimum instream-flow requirements, and multi-reservoir systems. Unregulated inflows to the model domain, consumptive and instream-flow demands, reservoir and channel evaporation, precipitation, exchanges with the groundwater system, reservoir storage rights and exchanges, and reservoir operating targets are each simulated as network elements within MODSIM (Shourian et al., 2008).

In this perspective, this paper presents a comprehensive methodology to assess the performance of SUDS in the metropolitan city of Querétaro (Santiago de Querétaro), where SUDS can be seen as a water system managed to improve the reliability and reduce the vulnerability of some uses in a peri-urban space. The metropolitan city of Querétaro (Santiago de Querétaro), capital of the State of Querétaro, Mexico, exemplifies this problem that peri-urban spaces are experiencing worldwide. Querétaro, founded in 1531, maintained a steady population and growth dynamic for almost four hundred years. However, in the last fifty years, with the onset of metropolisation and uncontrolled expansion, it has experienced an urban growth of about 10 times its 1970 size, occupying fertile and arable land, stream crossings and groundwater recharge areas.

Its attractiveness has turned it into a metropolitan area since the 1990s and it is currently composed of the municipalities of Querétaro, Corregidora, El Marques and Huimilpan: with 1,097. 025 inhabitants, it is the tenth most populated metropolitan area in the country, but its accelerated growth has caused the segregation of low-income populations in spaces unsuitable for housing on the outskirts of the city (Icazuriaga-Montes, 1994; González-Gomez., 2012) and areas with human overcrowding, a decrease in occupancy density, the degradation of ecosystems and the contamination of soil, water, air and noise, and above all, extraordinary rainfall events, known as 'flash floods', which, as the years pass, become more unstable and interact with disorderly urban growth, generating a greater possibility of disasters.

Adapting to a changing climate with more frequent and more intense floods also presents an opportunity to rethink urban development in this peri-urban space in Querétaro. By keeping a holistic view of the situation, the incorporation of various

SuDS elements can contribute to greener and more pleasant urban spaces with added benefits such as increased real estate values, increased biodiversity, increased traffic safety and more recreational opportunities for the local residents.

2. RRV Methodology

Performance measures quantify performance under the evaluated futures based on the objectives of the study, which may include water system measures of reliability or resilience as well as financial measures such as Internal Rate of Return or Net Present Value (NPV; Loucks and van Beek, 2017). Finally, vulnerability thresholds define the acceptable limit of each performance metric based on the planning objectives or stakeholder preferences, for example, a water reliability target of 95%. Specifying vulnerability thresholds may be challenging, when there is no empirical data about critical tipping points (such as a minimum discharge requirement for protecting downstream ecology) or when there is a lack of consensus among the experts. In such cases, analysts can define vulnerability thresholds based on the spread of historical or model-simulated performance, for example, based on the outcome at the 90th or 95th percentile value of an output variable (Kalra et al., 2015; Kasprzyk et al., 2013).

Several combinations of estimators of RRV have been proposed and some of these studies discuss which are the most appropriates. Loucks (1997) developed the Sustainability Index (SI), which is a product of RRV to assess the sustainability of a scenario in connection with a multi-objective risk assessment of a water resources system. RRV combination criteria have been applied to existing water resources systems (Kay, 2000; Kjeldsen & Rosbjerg, 2001; Karamouz et al. 2017; Yazdandoost et al. 2020), in some cases under extreme events (Behboudian et al., 2021). On the other hand, RRV combinations have examined the impacts of climate change and variability (Fowler et al., 2003).

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The use of indices of reliability, resilience and vulnerability (RRV) for classifying and evaluating water resource system performance was first suggested by Hashimoto et al. (1982). More recently, the ASCE Task Committee on Sustainability Criteria have recommended that these indicators are combined into an aggregated indicator of sustainability but this gives little indication of the relative system performance for each indicator.

Therefore here the original Hashimoto et al. (1982) indicators are used to examine the performance of the Yorkshire water resource system for each scenario, evaluating the outputs of the water resource system with reference to the imposed demands (Sediqi and Komori, 2004).

Firstly, a criterion, C, is defined for each water supply source, where an unsatisfactory value is one where the source is unable to provide a prespecified yield. The time series of simulated monthly values of either river flows or reservoir levels, X_t, are then evaluated to some future time, T. Here, the performance of the water resource system, is evaluated with reference to the imposed demands. Failure is defined as the inability of the system to meet the imposed demands. Each water supply source will have its own range of satisfactory, S, and unsatisfactory, U, values defined by the criterion, C (Hashimoto et al., 1982). The periods of unsatisfactory X_t are then defined as $J_1, J_2, \ldots, J_N$. In this study the focus is on water supply systems, and, therefore, the S state occurs when water supply is able to meet water demand and, hence, the U state is when supply cannot meet demand. Moving from time step t to t + 1, the system can either remain in the same state or migrate to the other state and W_t indicates a transition from an unsatisfactory to a satisfactory state.

$$X_t = \{X_1, X_2, \ldots, X_T\} \tag{1}$$

$$\begin{gathered} if\ X_t \geq C\ then\ X_t \in S\ and\ Z_t = 1 \\ \text{else } X_t \in U \text{ and } Z_t = 0 \end{gathered} \tag{2}$$

$$W_t = \begin{cases} 1, & if \quad X_t \in U \quad and \quad X_{t+1} \in S \\ 0, & otherwise \end{cases} \tag{3}$$

The oldest and most widely used performance criterion for water resources systems is reliability, CR, that measures the probability of failures. CR was defined by Hashimoto et al. (1982) as:

$$C_R = P\{X_t \in S\} \tag{4}$$

This paper applies applied definition is occurrence reliability, which can be estimated as

$$C_R = \frac{\sum_{t=1}^{T} Z_t}{T} \tag{5}$$

Resilience, CRS, gives an indication of the how quickly systems return to a satisfactory state once the system has entered an unsatisfactory state. Hashimoto et al. (1982) define resilience as a conditional probability:

$$C_{RS} = P\{X_{t+1} \in S | X_t \in U\} \tag{6}$$

and is estimated as the inverse of the mean value of the time the system spends in an unsatisfactory state, i.e.:

$$C_{RS} = \frac{\sum_{t=1}^{T} W_t}{T - \sum_{t=1}^{T} Z_t} \tag{7}$$

Vulnerability, CV, is a measure of how significant the likely consequences of failure may be, is defined by Hashimoto et al. (1982) as a measure of the likely damage of a failure event:

$$C_V = \sum_{j \in U} P(j)\, H(j) \tag{8}$$

where H(j) is the most severe outcome of the jth sojourn in unsatisfactory state and P(j) is the probability of H(j) being the most severe outcome of a sojourn into the unsatisfactory state.

It is important to note that these criteria, as defined in literature, may not be applicable as-is to all practical cases and may need to be modified on case by case basis. Sulis and Sechi (2013) argued that the maximum event as proposed by Moy et al. (1986) might be a better estimator than the event-based mean value of Hashimoto et al. (1982), i.e.

$$C_V = max\{max(C - X_t)_{t\in J_i}, i = 1, \dots, N\} \tag{9}$$

C value, that is the satisfactory, S, and unsatisfactory, U, states can be fixed as defined by the traditional probabilistic RRV method or can be defined in a fuzzy approach.

Given the total storage level in all system reservoirs (S) in the present month (t), the supply (D) for a use (j) in a water system is as function (f) of required levels of a performance index (Ind = {CR, CRS, CV }) over a time horizon (T):

$$f(D, T, t, Ind_j, S) = 0 \tag{10}$$

Here, a hierarchical approach for RRV criteria is proposed where the function f is explicit and the D is defined as function F of a required level (L) of CR. Specifically, given S in the system at t, D to j is calculated to guarantee a required level (L) of CR over T:

$$D = F(j, T, C_R(L), S, t) \tag{11}$$

Considering the calculated D, the CRS and CV values of j are defined as function G and B over a time horizon (Δ):

$$C_{RS} = G(D, \Delta, j) \tag{12}$$

$$C_V = B(D, \Delta, j) \tag{13}$$

3. The Menchaca Basin

The residual urban catchment area under study is the Menchaca sub-basin. This sub-basin is a peripheral area representative of urban pressure and with problems of environmental degradation, located in the eastern suburban area of the metropolitan area of Queretaro, in the Rancho Menchaca catchment area. The sub-basin is part of a topographic depression filled by sediments formed by the normal displacement of regional faults since the Miocene (Alaniz-Alvarez et al., 2001) and volcanic activity.

Groundwater has been strongly withdrawn over the last three decades in the study area, with a decline of the piezometric level exceeding 100 m and, consequently, land subsidence (Carrera-Hernández et al., 2016). The climate has classified this basin as a semi-arid region; however, in higher elevations (up to 2300), the climate shifts to semi-wet cold or wet-cold class. The rainy season is from May to October with annual values between 500 mm and 600 mm. This area was identified through the perimeter of areas subject to hydraulic hazard, then overlapping the value of potential damage, given by the product of vulnerability and exposed elements, to obtain the areas at highest risk. Its environmental characteristics, combined with the socio-economic disadvantages of the inhabitants, expose the population and their possessions to the damage and losses that rainwater run-off, especially in the peak rainy season, can cause. In fact, the basin is located in a valley with steep slopes and, consequently, the speed of its ephemeral water flow, which is formed during the rainy season, is accelerated. Its characteristics, therefore, give it a non-urban vocation. However, according to the urbanisation processes mentioned, colonies have already sprung up in the area, most of them lacking adequate services and facilities. The urbanization process has required the replacement of vegetation cover, which has left uncontrolled and unstable slopes, while roads have been built downhill. This has led to an increase in the formation and impact of urban flooding. The inhabitants, deprived of secure land ownership, are excluded from urban development plans and do not benefit from infrastructure to deal with the problem, while their daily activities, physical integrity and heritage continue to be affected.

Year after year, the inhabitants of these settlements have to face the problems caused by flooding and the debris that abounds in the streets where the canals overflow through the urbanized area, making it complicated and sometimes impossible for residents to pass.

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Thus, this situation causes economic losses for the population, as the need arises to close down businesses to prevent the water from entering and causing material losses, and likewise, both the working class and students see their activities interrupted due to the difficulty of crossing the outflow to reach their destination.

While there is a lack of economic resources to fix houses and streets so that they are not affected by rainwater runoff, the real background of the problem seems to be rooted in the situation of irregularity that divides the inhabitants, which in turn, originates in the processes of differential access to housing property and the processes of socio-economic segregation in Mexican cities in general (Bazant, 2010) and in the city of Querétaro in particular (González-Gomez, 2012).

About rainfall intensity and frequency, data published by the Municipal Planning Institute of the Municipality of Querètaro (2015) were used, calculated from data from the Querètaro Observatorio station (22013), which covers a particular area of influence for the Rancho Menchaca catchment area. It is observed that in one hour the probability of rainfall reaching 22.5 mm is high as it occurs with a return time of 2 years. This rainfall intensity can be classified as heavy rain, according to official rainfall intensity classifications, such as that of the National Institute of Meteorology of Spain, according to which it is considered heavy when the accumulation of rain in one hour is between 15.1 and 30 mm.

The methodological approach is based on the awareness that the knowledge of the actual climate context and its temporal pattern is actually extremely important for designing SuDS role in the future management of urban stormwater. In particular, the depth-duration-frequency ("ddf") curves represent the climate input typically used in hydrological modeling analysis (D'Ambrosio et al., 2023)

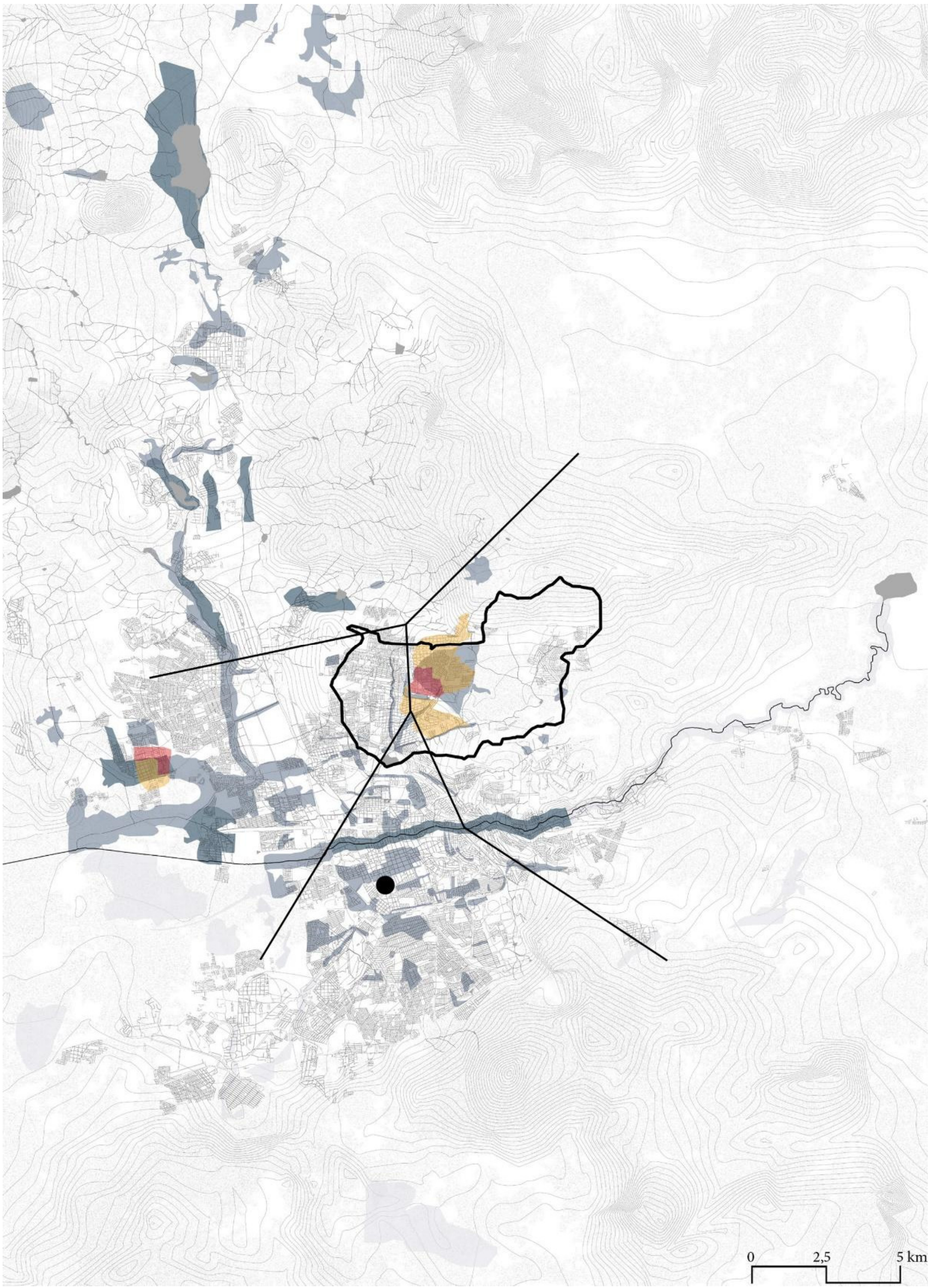

Figure 1. This map shows the areas most at risk of flooding in Querètaro and the Observatorio station (22013) from which the data in the previous tables were taken. Source: Own elaboration from climatological station data 2016 OPERANDO, Querètaro; Google Earth/Conagua; Atlas de Riesgos del Municipio de Querétaro 2015; ONU-Habitat 2020.

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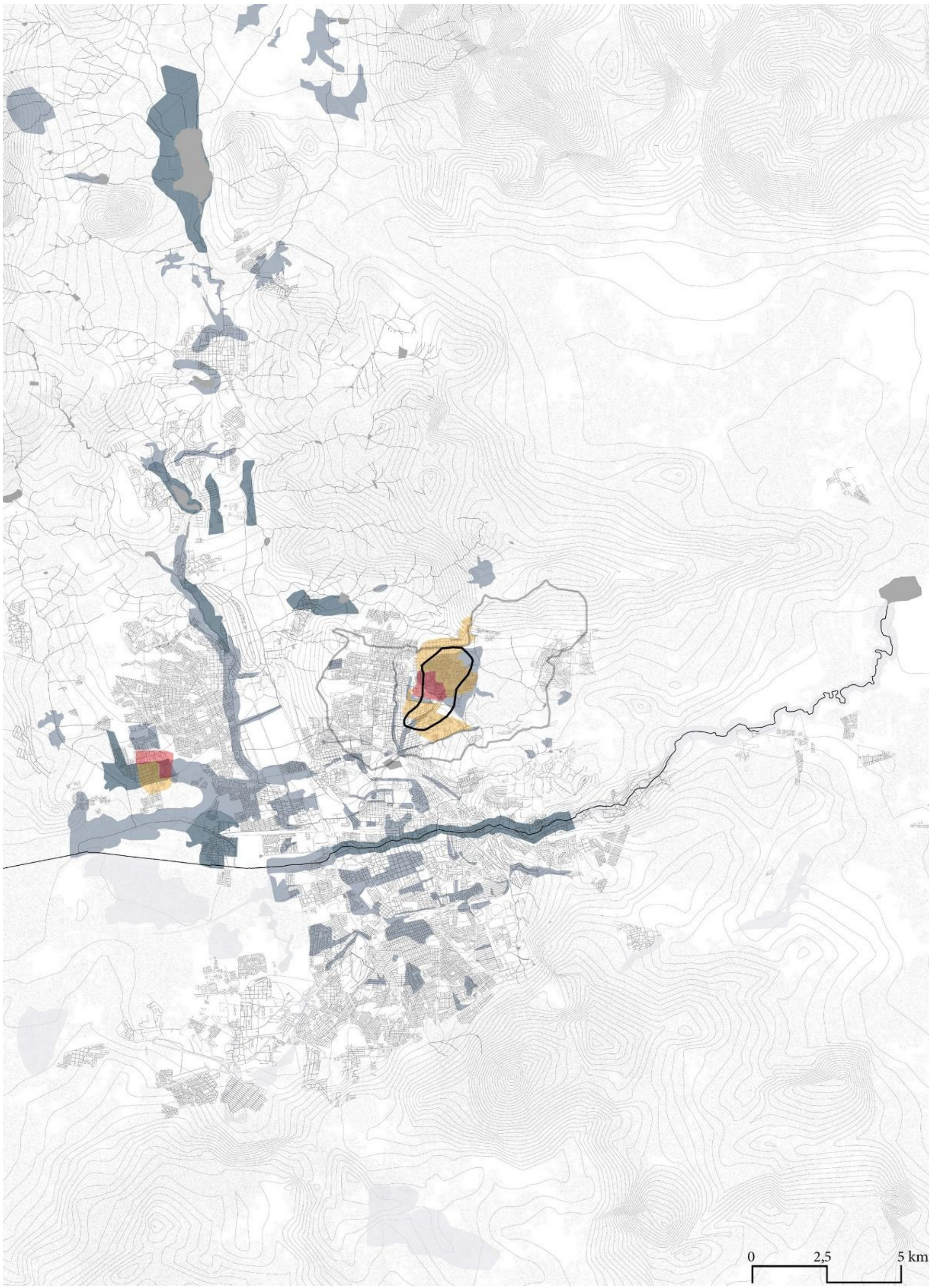

Figure 2. This map shows the areas most at risk of flooding in Querètaro and the Menchaca micro-basin. Source: Own elaboration based on mapping information from Atlas de Riesgos del Municipio de Querétaro 2015; ONU-Habitat 2020.

4. Water System of Suds

In the past, urban drainage management has only been approached from a hydraulic point of view, with the aim of draining and collecting rainwater from sealed surfaces and conveying it away from urbanised areas as quickly as possible. The scientific community has, however, pointed out that urban drainage management of this type entails a series of problems, especially in light of the effects of climate change with an increase in the frequency and intensity of extreme rainfall. The traditional method of hydraulic management is therefore proving to no longer be able to respond to the current needs of hydraulic protection of the territories.

In Menchaca, faced with the obvious limitations of the inhabitants, the ineffectiveness of the authorities and the recurring and dangerous urban flooding, three interventions are proposed to reduce the impact that contribute, above all, to improving vulnerability: a combination of infiltration systems through green roofs (1), lamination through an urban lamination park (2) and interception through a vegetated channel (3) that conveys water to the existing reservoir further downstream. These systems have been identified not as individual elements but as part of a larger discourse on the generation of public space in the proximity of the river, proposing a hydraulic, architectural and social intervention for a better quality of life (Figure 3).

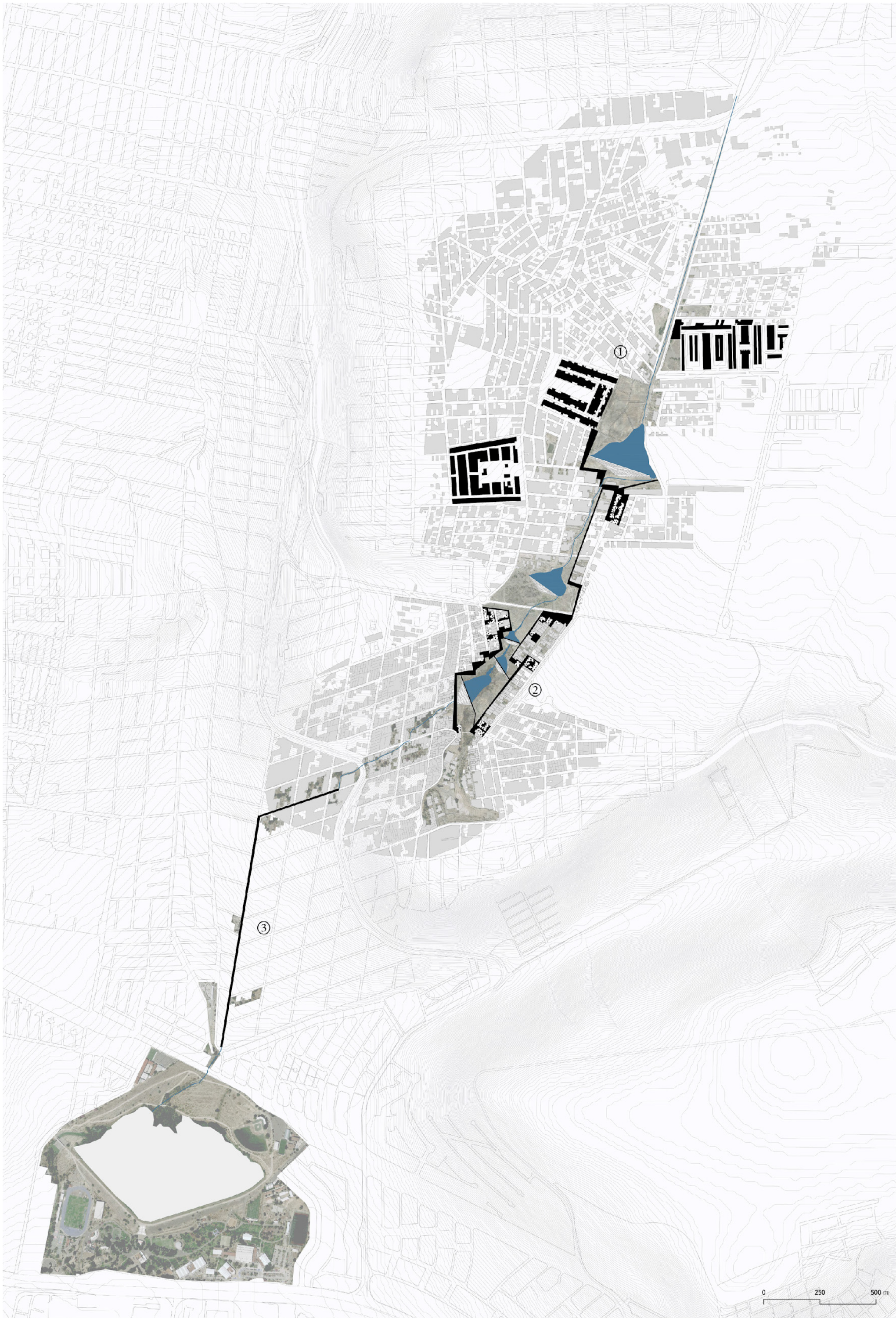

Figure 3. Intervention Masterplan: (1) Green roof; (2) Micro-lamination urban park; (3) Vegetated channel. Source: Own elaboration.

The most upstream intervention in the basin is the green roof (1), the main objective of which is to promote infiltration and delay the entry of water into the disposal system. This is a measure that is good for all cities, worldwide, where the area covered far exceeds that of the ground.

What was important to study, however, is the type of vegetation since we are in a semi-dry climate. The recommended plants to be placed on a roof in a naturalisation planting are those with a high resistance to direct sunlight and those that naturally store water in their tissues, such as succulents. It is also preferable to select Mexican species, without altering the vegetation by invading native ecosystems.

The vegetation proposed in the project consists of plants that can withstand long periods of drought, so-le, frost, with low substrate depth and low maintenance in general. These belong to the botanical families of Agavaceae, Cactaceae and Crassulaceae, belonging to the succulent group. Among the types of green roofs proposed in the literature, an extensive type of roof, with a minor sub-layer, has been chosen, which is suitable for thinking about re-roofing in existing buildings.

The most downstream intervention is the vegetated channel (3), the objective of which is the reduction of runoff. The slope of the road has been modified to channel water into the central vegetated lane, with a subterranean drainage system that channels water into the existing reservoir further downstream, and impermeable materials are replaced with permeable ones (Figure 4).

Figure 4. Vegetated channel across the peri-urban area. Source: Own elaboration.

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Between these two interventions is the proposed intervention of the urban micro-lamination park (2), which originates from the construction of three dams to create temporary water detention basins and to intercept sediment before it enters the urban area and creates problems.

In the past, the municipality has tried to intervene in the hydraulic problem of this area, particularly in the upper part of the basin, with the construction of two lamination basins.

Therefore, the opportunity was taken to identify this corridor, which is still partly natural and partly completely compromised by buildings, and to try, where possible, to free it of the superfluous constructions that insist on it in order to restore continuity and, through the subsequent construction of three new dams, to brake the flow of water and bring it to its destination according to the flow capacity needed to be contained in some way.

This, however, involved working in a particularly difficult fabric, and therefore the solution intervention also had to address the fundamental question of solving certain spatial and urban problems that the city, and this area in particular, extremely needs.

For this reason, starting from an engineering intervention aimed at reducing the vulnerability of this area, with the construction of the dams, the architectural project identifies this valley as an element of regeneration, of social redemption, so that the places of vulnerability reduction are freed from a purely engineering mono-function and appropriately designed also as places of public relations and new forms of living. From this point of view, the dams are not only dams with a protective function, but a sort of concretion that becomes a living space, conceived as formations that can be crossed, that can also become recreational spaces for children, a machine that, depending on the season, replaces functions: when there is a need to protect against water, it becomes a place that solves this problem, while in periods when there is no need, the place is not only a useless machine, but becomes a place of use, of active function. In addition, the dams themselves become an opportunity to create a connection from one side of the valley to the other, and the artificial hillsides, thanks to their shape, can help slow down the water, designing the dams on the assumption that they are overflowing.

5. Operation And Performance Of The System

The aggregation of SUDS can be seen as a water system of reservoirs and demands. The masterplan in Querètaro shows five reservoirs supplying 4 demands (Figure 6). Reservoir 1 is the largest operating reservoir in the system with a 36500 Cubic Meters gross storage capacity.

Practical real-time operations for multiple purposes require the specification of reservoir operating rules to determine the amount of water to release and storage for each reservoir at each time step. The presumption (Lund and Guzman, 1999) of these rules is that a system of reservoirs can be operated to produce greater benefits than operating the individual reservoirs independently.

The masterplan in Querètaro shows five reservoirs in series for multiple purposes (Figure 5):

- Reservoir 1: water supply for no-essential secondary residential demand (irrigation of public and private green, road cleaning);
- Reservoir 2: emergency water resource (tankers, users not served by the water mains, livestock watering)
- Reservoirs 3 and 4: flood control;
- Reservoir 5: recreation and flood control.

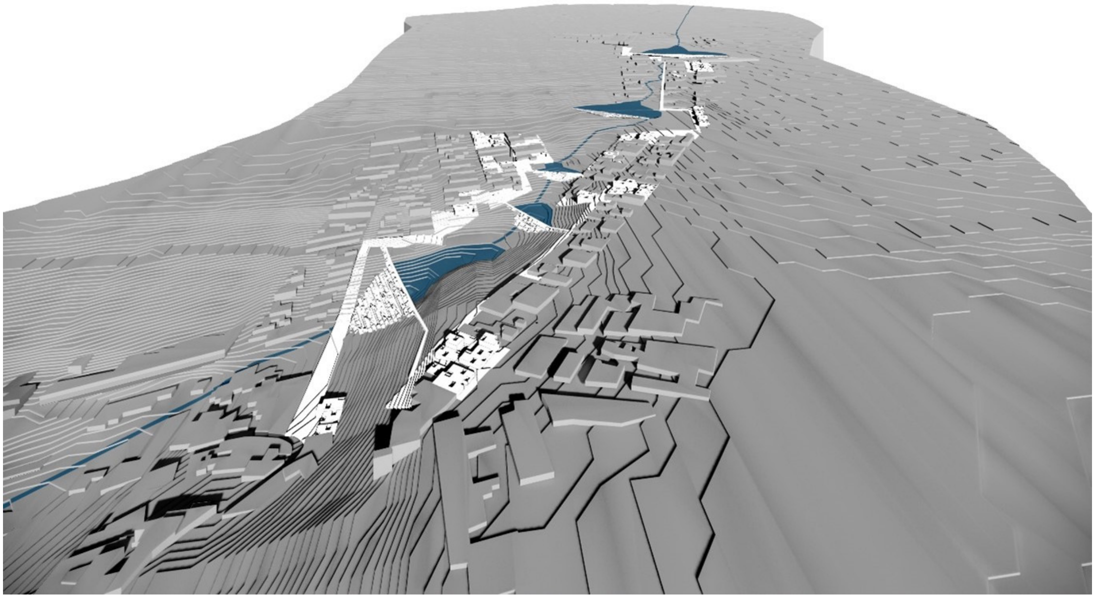

Figure 5. SuDS in form of water resource system. Source: Own elaboration.

Conceptual rules for reservoirs in series in Table 1 are adapted from Lund and Guzman. Operation for multiple purposes can be derived by combining these rules. For Reservoir 1 and Reservoir 2 providing water supply, a reasonable objective is to maximize the amount of water available. The resulting rule for single-purpose water supply reservoirs in series would simply be to fill the Reservoir 1 first and the Reservoir 2 last. For Reservoir 3 and Reservoir 4 with intermediate inflows and storage serving solely for flood control downstream, it is optimal to regulate floods by filling the Reservoir 3 first and emptying the Reservoir 4 first.

Table 1. Rainfall intensity – duration – frequency data in the sub-basin. UoM: intensity in mm, duration in hours, frequency as return period in years. Source: Instituto Municipal de Planeaciòn (2015).

T_r (years)	10 min	30 min	60 min	120 min	240 min
2	21.69	22.01	22.50	23.48	25.43
5	29.54	29.98	30.65	31.98	34.65
10	34.75	35.27	36.05	37.62	40.75
25	41.35	41.97	42.90	44.77	48.50
50	46.22	46.91	47.95	50.03	54.20
100	51.04	51.80	52.95	55.25	59.86
500	55.98	56.81	58.08	60.60	65.65
1000	60.00	60.90	62.25	64.96	70.37

Table 2. Seasonal operating rules in the system reservoirs.

	Season / Period	
Purpose	**Refill**	**Drawdown**
Water supply	Fill upper reservoirs (Reservoir 1) first	Empty lower reservoirs (Reservoir 2) first
Flood control	Fill upper reservoirs (Reservoir 3 and Reservoir 4) first	Empty lower reservoirs (Reservoir 5) first
Recreation		Equalize marginal recreation improvement of additional storage among reservoirs.

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Operation for multiple purposes can be derived by combining these rules. Fortunately, many of the operating rules presented here for Querètaro show compatibility between different reservoir purposes, such as flood control and water supply for refill periods on reservoirs in series.

In MODSIM, the water system was represented as a network of nodes and links, illustrated schematically in Figure 6. The nodes are representative of reservoirs and demands. The links are connections between the nodes and are representative of river reaches or canal/pipeline conveyors. Singular consumptive demands were aggregated for typology in two classes:

1. Non-essential water uses in residential compounds (3 nodes);
2. Secondary water uses (1 node).

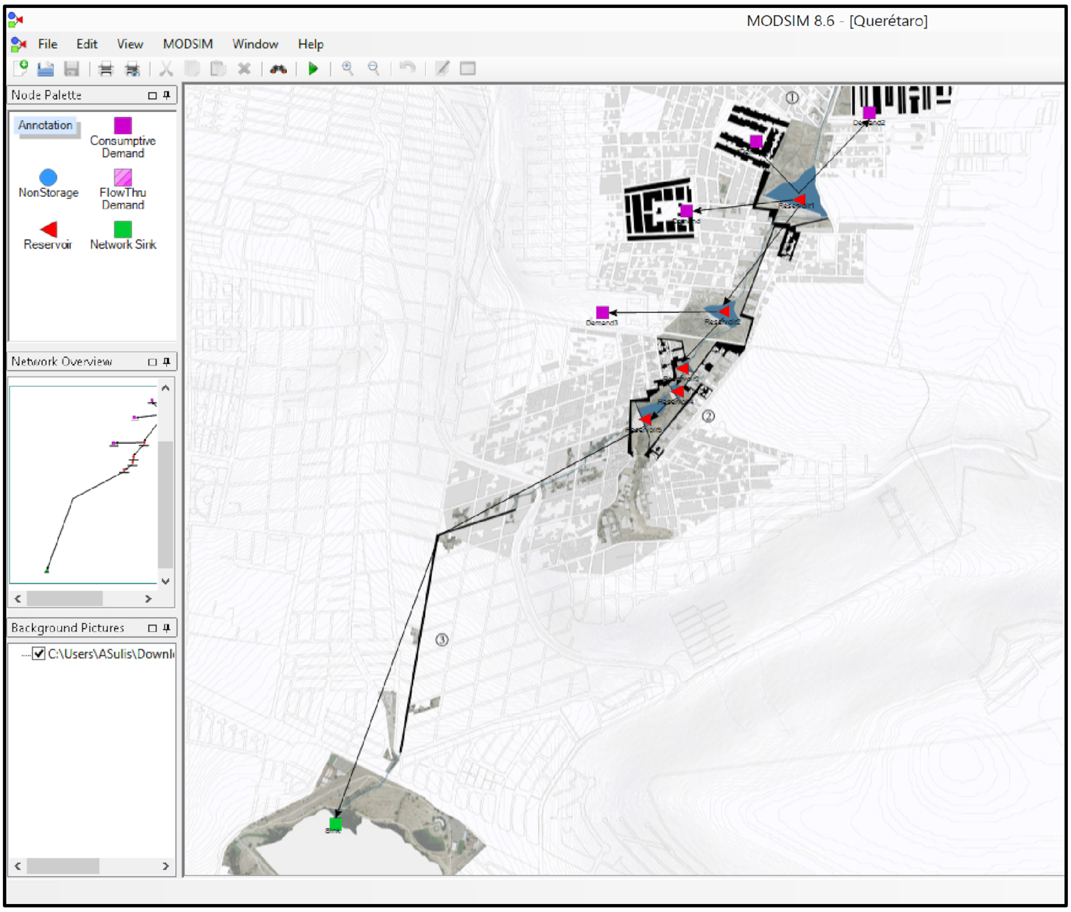

Figure 6. SuDS in the MODSIM graphical interface**.** Source: Own elaboration.

Water consumption in a community is characterized by several types of demand, including domestic, public, commercial, and industrial uses. Here non-essential demand is defined as the sum of domestic and public demand percentages for uses in the residential compounds, as the irrigation of public and private green, aesthetic uses (such as fountains and ponds), road cleaning and motor vehicle wash. It is assumed that supplies for non-essential uses can be reduced by the application of hedging rules in the reservoirs without significant comfort losses in the population. Specifically, irrigation of public and private garden (as green roof) in the *j*-compound is assessed as:

$$T_j = \sum_{i=1}^{12} \left[\left(\frac{D}{N}\right)_i S_{1,j} U_{1,j} + \left(\frac{D}{N}\right)_i S_{2,j} U_{2,j} \right] \quad (8)$$

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Table 3. Average monthly rainy days in Querètaro city.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D_i	2	1	3	7	10	16	20	19	17	9	4	3
N_i	31	28	31	30	31	30	31	31	30	31	30	31

Table 4. Compound (compound are numbered from North to South) total annual demands.

Compound	Private area (S_1) [m²]	Unitary monthly demand (U_1) [m³/m²]	Public area (S_2) [m²]	Unitary monthly demand (U_2) [m³/m²]	Total Annual (T) [m³]
1	30000	0.1	10000	0.15	8000
2	22000		7000		6000
3	28000		8000		7000

Other non-essential uses (named aesthetic uses, road cleaning and motor vehicle wash) in the residential compounds were assessed based on the estimation of a 4000 inhabitants and 3800 m of internal road length.

Secondary water uses are aggregated in a single node and referred to consumptive (water for wild animals in that area - e.g., dogs, cars, horses - and irrigation of two main athletic fields) and non-consumptive (water-based fire protection system and water tanks for residential uses during water scarcity) uses.

The current operating rules of the system prioritize water allocation to secondary demands. Recreation requirements have been considered as a restriction and are captured by the operating rules of the reservoirs. The main goal for reservoir flood control is to minimize the damage due to peak outflow from Reservoir 3, 4 and 5 at critical downstream locations in the urbanized area of Quéretaro. According to the critical designed section of downstream open channel, the maximum flow rate is assumed as 80 m^3/s. The goal of MODSIM is to minimize the number of maximum total outflow discharge from Reservoir 5 exceeding 80 m^3/s. The desired monthly pool volume is defined in a trial-and-error simulation approach. The rule curves at each reservoir is developed by MODSIM where releases are function of current water surface elevation and inflow rate.

Table 5. Main structure parameters of the existing reservoirs.

Reservoir	Surface area [m²]	Max total volume [m³]
Reservoir 1	18200	36500
Reservoir 2	8500	17000

Table 6. Main structure parameters of the designed reservoirs.

Reservoir	Crest length [m]	Height [m]	Max total volume [m³]
Reservoir 3	60	5	2100
Reservoir 4	65	6	3500
Reservoir 5	80	9	18500

The region is expected to diminish its annual average precipitation in a range of 10–20%, while its temperature is projected to rise from 1.5 °C to 2.5 °C in the next 50 years (PEACC, 2012). The climate change scenarios were obtained from a Global Circulation Models (GCMs) under the six IPCC emission scenarios, and a hydrological model was applied to determine monthly surface runoff under future climate conditions (year 2050) (Velázquez et al., 2015*)*. Here, we focus on the evaluation of SuDS performances over 500-year monthly runoff timeseries based on A1B IPCC scenario. A1B is the "balanced scenario" of A1 family, characterizing alternative developments of energy

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technologies. A1B gives runoff behaviors with high temporal variability with frequent droughts, alternating with months of substantially high runoff.

6. Results of RRV Analysis

MODSIM simulates the expected performance of the SuDS in Quéretaro at different total storage level (expressed as percentage total capacity) in the 5 reservoirs (Figure 6). Using Eq. 5, supplies that can be assured to a demand at an assigned level of reliability is calculated. For 10% wide ranges of total storage level, Table 9 shows the supplies to the secondary water uses with a 5% probability of failure. As 5% is the accepted probability of failure in supplying secondary demands, those demands are considered completely satisfied and the vulnerability is equal to zero at 95% of supply reliability. Resilience, as the inverse of the mean value of the time the system spends in an unsatisfactory state, is not calculated (Table 10). Supplies to non-essential water uses in residential compounds at 95% of reliability show significant reduction for low storage levels. Specifically, if a low (5%) probability of supply failure is required, the system can assure a low (44%) mean supply to non-essential uses in the case of a total storage level between 50% and 60% of the total storage capacity. Table 11 shows the high sensitivity of supplies to storage levels, significantly increasing from 44% to 93% for an increased storage level of 10%. For storage levels higher than 60%, the system can assure high supply (higher than 93%) with a high reliability (95%). The only use of an indicator (i.e., supply reliability) could describe a largely acceptable performance of the system. To evaluate the average resilience and vulnerability, two-time windows were selected (1 and 2 years) coherently with the storage behavior over which average vales were calculated. As expected, 1-year resilience was significantly low (18% of conditional probability) in the case of a total storage level between 50% and 60% of the total storage capacity. In term of the average time over 1 year, the result highlights that the system spends in an unsatisfactory state almost 5 months. The conditional probability remains significantly low even for high total storage level. For reservoir close to the maximum filling condition (90% - 100%), the unsatisfactory average time over 1 year is close to 2 months. This last result makes clear the non-resilience of the system as failure to supply to non-essential water uses are prolonged events. Resilience does not appear to be sensitive to the time window, at least for the considered length where 2-year resilience is within the interval ± 2% compared to 1-year resilience. These transition probabilities are independent on the length. This behavior can be reasonably justified by considering that failure structures are identical at each year.

Vulnerability as maximum event over the selected time windows (1 and 2 years) shows the expected behavior. Vulnerability significantly decreases with an increasing total storage level and slightly increases with a wider time window. In the case of a total storage level between 50% and 60% of the total storage capacity, non-essential uses are under high-stress conditions with maximum supply reduction of 62%; the latter increasing up to 70% over 2 years. Coherently, with an increased available stored water and without any hedging rule the vulnerability plunges to 1% and 6%, respectively over 1 and 2 years. Even in the case of a total storage level between 70% and 80% of the total storage capacity, the maximum supply reduction is largely acceptable (10% over 1 year) for non-essential uses.

MODSIM simulated iteratively the Quéretaro SuDS to find the reliability of completely satisfaction of level non-essential uses. Results show that a supply to non-essential water uses of 100% for total storage levels higher than 50% can be assured at 65% of reliability. At that level, the non-essential water uses are not vulnerable to water scarcity condition and resilience is not defined.

Table 7. Supply to secondary water uses at 95% of reliability.

Storage Volume	50 – 60 %	60 – 70 %	70 – 80 %	80 – 90 %	90 – 100 %
Supply	100%	100%	100%	100%	100%

Table 8. Resiliencies and vulnerabilities to secondary water uses at 95% of reliability.

Storage Volume	50 – 60 %	60 – 70 %	70 – 80 %	80 – 90 %	90 – 100 %
1-Year Resilience	-	-	-	-	-
2-Year Resilience	-	-	-	-	-
1-Year Vulnerability	0%	0%	0%	0%	0%
2-Year Vulnerability	0%	0%	0%	0%	0%

Table 9. Supply to non-essential water uses in residential compounds at 95% of reliability.

Storage Volume	50 – 60 %	60 – 70 %	70 – 80 %	80 – 90 %	90 – 100 %
Supply	44%	93%	95%	96%	98%

Table 10. Resiliencies and vulnerabilities to non-essential water uses in residential compounds at 95% of reliability.

Storage Volume	50 – 60 %	60 – 70 %	70 – 80 %	80 – 90 %	90 – 100 %
1-Year Resilience	18%	25%	35%	44%	43%
2-Year Resilience	20%	24%	33%	46%	41%
1-Year Vulnerability	62%	25%	10%	5%	1%
2-Year Vulnerability	70%	44%	22%	14%	6%

Table 11. Supply to non-essential water uses in residential compounds at 70% of reliability.

Storage Volume	50 – 60 %	60 – 70 %	70 – 80 %	80 – 90 %	90 – 100 %
Supply	98%	100%	100%	100%	100%

7. Conclusions

Year after year, the inhabitants of these suburban settlements have to deal with the problems caused by floods and debris that abound in the streets, making it complicated and sometimes impossible to pass, and the phenomenon is accentuated by social vulnerability that limits opportunities for mitigation and response.

The need to remedy this problem is then seized as an opportunity to intervene in this urban context that today claims a new look. Among the existing Sustainable Urban Drainage Systems (SuDS), the most appropriate ones have been studied and chosen according to the objectives they promote and have been customised for the needs of this case, which is a completely different context from those where SuDS are usually applied: the proposed solution through the designed SuDS system will increase the resilience of the Menchaca area to hydraulic risk, and bring interesting benefits in terms of ecosystem services such as climate regulation, hydrological regulation, and cultural values. The project promotes also an urban and architectural design in such a way that the preservation engineering works respond to other needs that are not only and exclusively those of reducing the vulnerability of the condition, proposing new forms of city living that are open and inclusive, guaranteeing fairer access to public services and a social dynamic where sharing, not segregation, is the norm.

Each applied criterion assesses different aspects of water resources systems and as such these criteria complement each other. This paper highlights that these criteria, as defined in literature, may not be applicable as-is to all practical cases and may need to be modified on case-by-case basis.

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