Enhancing megacities' resilience to flood hazard through peri-urban nature-based solutions: Evidence from Mexico City

Abstract

Floods are one of the most frequent natural hazards in almost every country, with climate change exacerbating their frequency and intensity. Nature-based solutions (NbS) can be a cost-effective way to make human settlements more resilient to flooding. However, decision-makers need reliable information on which to base NbS policy and funding. This research estimates the potential of peri-urban NbS to regulate water flow and the benefits downstream through the development of supply and demand indicators for the context of complex megacities. In our Mexico City case study the supply indicator is the runoff coefficient, which is spatially estimated across peri-urban areas, and the economic value is estimated using replacement cost (grey infrastructure). The demand indicator identifies flood-prone areas based on spatially explicit ponding events and avoided costs of insurance flood claims data and estimates with parametric cost functions. The supply indicator provides straightforward information for decision-makers to spatially target conservation in peri-urban areas where runoff coefficients are high combined with flood-prone areas, while the lowest coefficients reinforce the importance of policies for protected areas. In combination with demand indicator information, we find NbS in peri-urban upstream catchments is cost-effective compared to avoidable flood-related costs and alternative investments in grey infrastructure.

Keywords: Nature-based solutions, urban floods, peri-urban areas, water flow regulating ecosystem service, Mexico City, spatial analysis.

1. Introduction

Climate change is projected to increase the severity and frequency of flooding (IPCC, 2019; 2022) and poses adaptation challenges to human settlements. Floods are the most common type of disaster, with 168 flood events worldwide annually (CRED, 2022). In low and middle-income countries, other anthropogenic factors, such as urban expansion and weak institutional frameworks, generate additional complexity (Abass et al., 2022). Flood disasters are not random events but the result of urban expansion with insufficient provisions for extreme rainfall events. Megacities must design more effective flood risk policies that consider innovative strategies, particularly nature-based solutions (NbS) to enhance flood resilience and adaptation to climate change (UNEP,2021; Meng et al., 2022; Kabisch et al., 2017). The United Nations has urged governments to implement integrated policies and plans for climate change adaptation and to develop and implement holistic disaster risk management policies at all levels (UN, 2015, SDG 11b).

However, there are few policies enacted to integrate NbS in megacities for flood risk reduction (UNODRR, 2022). Decision-makers need information about alternatives to reduce flood risk, but whereas engineering companies that build grey flood infrastructure systems across megacities often have established partnerships working with governments (Meng et al., 2022; Tellman et al., 2018), presenting a cost-benefit analysis for alternatives like NbS can be complicated by the lack of modelling on a specific intervention and indicators on the economic benefits to inform decision-makers.

Where peri-urban communities and urban settlements are interconnected due to topographic conditions, understanding the potential role of natural assets in peri-urban areas should be a priority to reduce vulnerability (TEEB, 2010). Previous research on NbS in urban areas covers heatwaves, water management, or air pollution (Kabisch et al., 2017; Babí-Almenar et al., 2021). There are also studies specific to flood hazards; however, the focus is often on cities in developed countries, particularly European cities (Davis and Naumann, 2017; Stürck et al.; 2014; Sohn et al., 2020; Ferreira et al., 2020; 2021; Maragno et al., 2018; Nedkov and Burkhard, 2012). NbS are being studied and adopted in Singapore, Berlin, and other European cities (Ferreira et al., 2020). In terms of specific interventions, a project in the United Kingdom proposes expanding wetlands and woodlands in upstream areas to protect downstream cities.[1]

There is a need for more NbS research to prevent flood events in the complex context of megacities in developing countries. Previous studies have focused on the potential of ecosystems but without specific information on demand areas (Gunnell et al., 2019; Enu et al., 2023), the role of green infrastructure within the urban area (Jörgense et al., 2015), peri-urban ecosystems with no connection to urban floods (Ece et al., 2017), location of waterlogging sites (Liu et al., 2022), concerns about land use change and anthropogenic factors (Idowu and Zhou, 2023; Abas et al., 2022), and flood site-specific cases (Irvine et al., 2023). Few studies have analysed how NbS may regulate water flows from peri-urban to urban areas in developing countries (Zambrano et al., 2017; Gunnell et al., 2019), and there is a general lack of economic indicators.

Worldwide, several megacities have experienced recurrent flooding, such as Hong Kong, Shanghai, New York, and other coastal cities where heavy rains and rising sea levels have intensified in recent years (Jeroe et al., 2014). These compound floods are mainly caused by cyclones (Lai, et al., 2023; King, 2023). A different type of flood, such as those occurring in Mexico City, Rome, and Beijing are caused by heavy rainfall events, where waterlogging is spatially concentrated in low-lying areas, resulting in traffic congestion, loss of property, and sometimes human lives (Liu, et al., 2022; Di Salvo et al., 2017). Idowu and Zhou (2023) also find that heavy rains are the main source of severe floods in megacities such as Guangzhou, Tokyo, Jakarta, Seoul, Mexico City, São Paulo, Cairo, Lagos, Los Angeles, Moscow, Buenos Aires, and London, even though not all are coastal cities.

A problem in low- and medium-income countries is that large urban areas are losing valuable ecosystem services with land-use changes from urban expansion, such as water provision ecosystem services in Shanghai (Chen et al., 2019). However, while megacities can import water from nearby areas, runoff control must be provided locally as the impact of extreme events requires in situ and nearby mitigation action. Therefore, understanding the rainfall flows across a megacity with hazardous topography and the connection with downstream at-risk settlements can inform NbS investments within a more integrated flood risk management framework.

[1] Find out more information on OuseWEM, available at [OuseWEM Project - Yorkshire Dales Rivers Trust (ydrt.org.uk)]

Theoretical framework

NbS in peri-urban areas is a specific area of analysis (Ramírez-Agudelo et al., 2020), because peri-urban ecosystems can be rich in natural capital that supplies regulating ecosystem services critical for climate change adaptation and which provides an "insurance value" (Baumgärtner and Strunz, 2014; Unterberger and Olschewski, 2021; Soto-Montes-de-Oca, 2020). This insurance value can reduce the risk and losses of flooding (Dadson et al., 2017, cited in Paavola and Primmer, 2019). However, peri-urban areas are under pressure due to population growth, road construction, and economic development that combined drive land use change (Su et al., 2014; Heider et al., 2018), which results in 'ecosystems' degradation and the reduction of ecosystem services provision (Hasan et al., 2020). Biodiversity loss caused by urban expansion and climate change can accentuate disasters (UNEP, 2021). Although various policy instruments can promote biodiversity conservation, such as protected areas, payment for ecosystem services (PES), and reforestation programs (for instance, in OECD countries, Bark and Crabot, 2016); these instruments do not typically recognize the insurance value against floods provided by peri-urban natural areas. Developing planned systems that effectively employ environmental assets to reduce the potential risks of flooding and other climate hazards in cities requires specific analysis (McPhearson et al., 2015).

Flood risk in urban areas depends on multiple factors, including weather (intensity and spatial distribution of rainfall), topography, sewage systems (flood hazard), population density, and economic and cultural assets (exposure) (WWAP, 2012; Di Salvo et al., 2017). Reducing and slowing upstream water flow in peri-urban areas with vegetation and soil management can play an important role in urban risk management, particularly in areas with hazardous topographic conditions (Collentine and Futter, 2018). NbS are typically multifunctional as they can deliver multiple ecosystem services, such as water flow regulation and cultural ecosystem services. However, if individuals do not perceive the water flow regulation services, preserving and restoring natural capital is unlikely to be a policy priority (Constanza et al., 2017; Dasgupta et al., 2021). It suggests a role for indicators that estimate the value of ecosystem services and prioritize ecosystems and the services they deliver based on their relative contribution to individual or social objectives (Farber et al., 2006; Constanza et al., 2016). Indicators could include the number of people who benefit from these ecosystem services, the availability and cost of substitutes, or the cost of losing these services (Constanza et al., 2016). A consideration in megacities of developing countries is that indicators need to be developed on the availability of information and consider that although data may be dispersed and patchy, it can still be helpful for decision-makers.

The ability of NbS to provide insurance against the impacts of extreme flood events requires considering the spatial context of ecosystems and beneficiaries that are vulnerable to floods (Anderson et al., 2017). The importance of upstream land use and the role of planning to maintain its vegetation was documented in UNEP's Community Risk Profile Tool (UNEP, 2008). Idowu and Zhou (2023) report that in 12 megacities, including Mexico City, there is a statistically significant relationship between floods and urban growth patterns (edge expansion and leapfrogging). However, typically, urban planning does not integrate NbS, and there are challenges in capturing insurance value in governance arrangements because of its public or club good characteristics and because it is typically a co-benefit and not the target of resource management (Paavola and Primmer, 2019). Designing policy instruments to manage the insurance value might require new institutional structures to facilitate collaboration between authorities and stakeholders involved with risk management, risk transfer, and urban planning through insurance schemes, nature conservation, and management of agricultural and peri-urban areas within a catchment. However, implementing such measures can be challenging, especially in agricultural areas and other natural land-use types, because they can result in foregone farm and 'landowners' income (Collentine and Futter, 2016) and because policy instruments to maintain or compensate for this insurance value are absent.

Mapping spatial relationships of ecosystem services flows is key to identifying their supply and demand areas (Schirpke et al., 2019; Chen et al., 2019) and to targeting conservation and restoration interventions to maintain or enhance ecosystem services (Gunell et al., 2019, Stürck et al., 2014). Maragno et al. (2018) identified priority areas for interventions using a flood vulnerability index and estimated the flood reduction capacity of green infrastructure under different scenarios. Nedkov and Burkhard (2012) produced a risk function with exposure to flooding, considering the vulnerability of settlements and hydrological models. Stürck et al. (2014) produced models with flow regulation supply indicators, incorporating information on land cover, land use, and management combined with flow regulation demand in European river catchments to identify priority areas for interventions; these were all upstream of conurbations. Arabameri et al. (2019) used a similar approach using peri-urban information of slope, distance to stream, and land use/land cover to observe the determinants of flood occurrence in an Iranian study catchment.

Producing specific and reliable information about the cost of flooding in a complex system such as megacities is fundamental to understanding the benefits of any NbS intervention. Wolf et al. (2015) outline that demand for provisioning ecosystem services is often assessed at large administrative unit levels because statistics are available at regional, country, or continental levels. Nevertheless, flood risk is often localised, creating an additional complication for demand indicators for regulating ecosystem services to enter the decision-making process. In the UK, indicators of flood risk benefits consider flood depth, providing damage estimates per property to assess investments to reduce flood risk and coastal erosion.[2] Similarly, economic modeling used flood depth to estimate flood costs under climate change scenarios in six low- and middle-income countries (Yin, et al., 2021).

This paper contributes to the literature on NbS to improve megacities resilience to flood risk by producing spatial demand and supply indicators that estimate the benefits of interventions. To study the potential and feasibility of using NbS to reduce flood risk, we develop a spatial analysis of the supply side through the water flow regulation ecosystem service provided by peri-urban areas and the demand for this service in flood-prone urban areas in our Mexico City case study. By linking the demand and supply sides, this analysis highlights the links between urban flooding and the current state of peri-urban areas and, by extension, the potential of NbS interventions to maintain water flow regulation through conservation and to provide augmented water flow regulation through targeted restoration.

2. Methods

2.1 Case study

Mexico City is prone to flooding as the megacity is in an endorheic basin where water flows down from surrounding mountain areas and collects in the lower urbanised area[3]. The city has a long water management history that has been resized over time, based predominantly on grey urban infrastructure disconnected from green infrastructure solutions (Tellman et al., 2018; Manuel-Navarrete et al., 2019).

[2] For further guidance, see the Environment Agency's Flood and Coastal Erosion Risk Management Appraisal Guidance (Environment Agency 2010) and the online Flood and Coastal Erosion Risk Management Handbook and Data for Economic Appraisal 2017.

[3] See, https://storymaps.arcgis.com/stories/d18dfd899a3842fbacfbafcc6e9ce5f3

Two mega tunnels drain combined waste and rainfall water; however, investment in the secondary drainage system has not received the same attention, with insufficient sewer capacity and poor maintenance explaining more localised problems. Precipitation varies from 668 mm/yr in the urban area to 1,306 mm/yr in the peri-urban area (Soto and Herrera, 2019). In the period 1961-1990, rainfall events with an intensity of 30 mm to 40 mm in 24 hours were the most frequent (180 events), while events with an intensity greater than 70 mm in 24 hours were recorded less than 20 times; however, climate change scenarios project more extreme events; with events of 60 mm to 70 mm in 24 hours increasing by 150% (Soto and Herrera, 2019).

The Mexico City Government has recognized flooding as one of its most pressing urban vulnerabilities (GCM, 2020). Official documents explain this vulnerability as a combination of topography, vast urbanisation, lack of open green spaces, and total dependence on the extensive subterranean drainage system (GCM, 2015). Recommendations for flood risk management include strategies to delay and retain water in surrounding mountainous areas to prevent runoff into the city (GCM, 2015; 2020). However, the success of such a NbS approach requires specific information on how the urban and peri-urban areas are connected, including estimates of the benefits of the water flow regulation ecosystem service.

Although more than half of the territory of Mexico City is reported as conservation land, only 14% of the total is within some category of protected area (Ocampo, 2021). Around 76% of this conservation land is communal and ejido land, with the remainder either private or government property (Heider et al., 2018). Heider et al. (2018) found that human settlements, particularly illegal settlements, have increased in the conservation land. There are other government programs and actions relevant in the peri-urban areas, such as payment for ecosystem services (PES) to incentivise conservation, and programs that provides funding to communities promoting sustainable agriculture, community forest rangers and reforestation activity (Cetina et al., 2022).

2.2 Indicators for NbS demand

On the demand side, two indicators for flood-prone areas are developed. These indicators are a proxy for the spatial distribution of associated direct property losses (infrastructure or vehicle damage) and indirect disruption to traffic flows. The first indicator is at the municipality level and uses Mexico City's Risk Atlas data. Spatial and other information about ponding events (floods) is recorded. This official information was used to systematize reports of stormwater ponding events during 2016-2020, including the date, location, and depth. The Risk Atlas does not have systematic information about affected households, infrastructure, or costs. The second indicator uses neighbourhood level information from 2017 to 2020 from Mexico City's Secretary of Finance about the public flood insurance scheme (GCM, 2022) providing not only information on flood-prone areas but also the number of households affected and insurance payouts. Maps and tables of affected areas are produced.

To investigate the flood events' economic impact, we estimate two indicators using different avoided cost approaches (Constanza et al., 2016). The first uses estimates based on the above-motioned insurance data that provides information on the costs of different events, and the second uses estimates of flooding costs with parametric functions (Baró-Suárez et al., 2011). For the latter, the likely cost of floods considers the flood depth and the marginal index (associated with the Social Development Index-SDI) of residential areas (i.e., to approximate the goods or assets lost, such as a radio, TV, refrigerator, washing machine, car, computer, bedroom furniture, and clothes, in a typical household of each category). This comparison between insurance cost and estimated econometric function cost provides a range of the costs for affected households.

2.3 Indicators for NbS supply

On the supply-side, the runoff coefficient is estimated. The runoff coefficients range from 0 to 1, where a larger value means very low infiltration and high precipitation runoff. Peri-urban runoff coefficients were calculated considering slope, soil characteristics, vegetation type, and precipitation (Mc Cuen, 1998; Musa, et al., 2013; Gökbulak, et al., 2015).

The estimates of replacement cost and avoided cost utilise a NbS restoration scenario that simulated the reforestation of 20 hectares of agricultural and bare land in a 148-hectare micro-watershed in the peri-urban area adjacent to an at-risk urban area. Data from the National Meteorological System (climate), the National Institute of Statistics and Geography (INEGI) (topography), and the Ministry of the Environment of Mexico City (soil and land use) were used as model inputs. Land use cover was updated to 2020 through a visual interpretation of Google Earth®'s satellite images. Scenarios of extreme rainfall events (60 mm and 100 mm/day) were used to estimate the runoff volume (in m^3) towards low-lying urban areas using the Soil and Water Assessment Tool (SWAT) (Neitsch, et al., 2011), which has been widely used worldwide (Ghezelsofloo, et al., 2022).

The replacement cost approach (Mburu et al., 2007; Constanza et al., 2016) estimates the value of flood prevention by comparing the NbS scenario with a hard-engineered solution. A review of grey infrastructure alternatives that could replace the water flow regulating ecosystem service provided by peri-urban areas (Mburu et al., 2007) was undertaken. Next, we estimated the cost of flood control barriers to prevent the damage. To do this, we obtained market relevant costs from a Mexican company that designs and installs collectors, pipes, and small-scale storage systems. The avoided cost approach (Constanza et al., 2016) compares a no-action scenario (no NbS scenario) with estimated flood costs of affected househols described in Section 2.2.

3. Results

This section describes the spatial analysis of the demand and supply indicators. A NbS restoration scenario integrates the two indicators and estimates the value of NbS in flood mitigation.

3.1 Demand-side indicators

3.1.1: Flood-prone indicators

In the period 2016-2020, Atlas Risk of Mexico City information reported 1,790 stormwater ponding events (see Supplementary Information, Table S1). The year 2016 was atypically high, with 714 events. Ponding depths concentrated between 24 cm and 36 cm but reached a maximum depth of 2.5 m. Information on whether depth is recorded in roads or residential areas is unavailable. Figure 1 shows the location of these stormwater ponding events; specific patterns can be observed regarding recurrence and depth. Many events were recorded in the central area of the city. Flood events near natural or cultivated soil (green areas) were also high, with a few acute events.

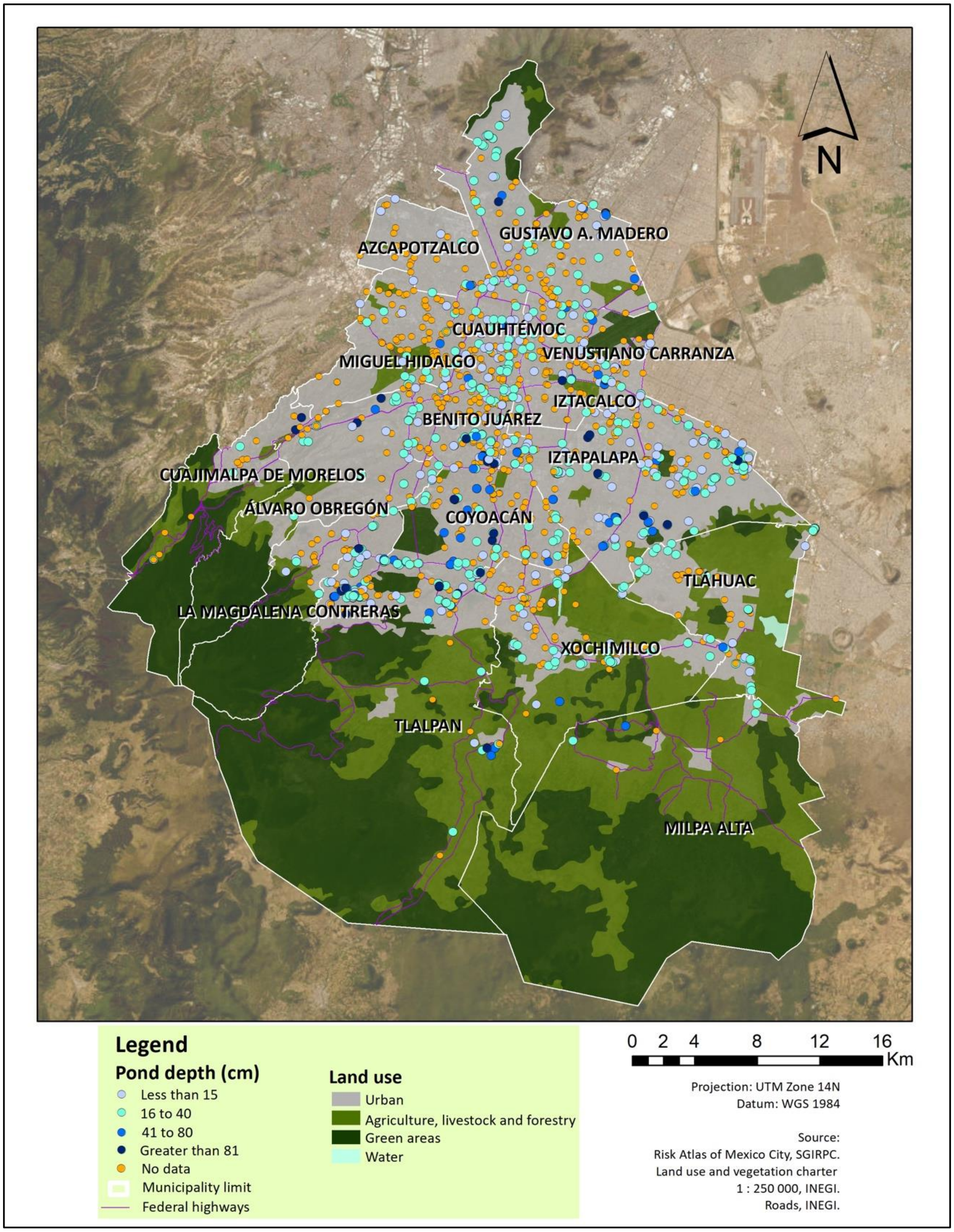

Figure 1. Municipality stormwater ponding events in Mexico City (2016 – 2020)

The stormwater ponding events listed by municipality in Table 1 show recurrent events in Iztapalapa (356) and Tlalpan (243) with lower recurrence in the other municipalities such as Gustavo A. Madero (164), Benito Juárez (137), or Cuauhtémoc (136). The average pond depth was 32 cm. Seven municipalities have more than 25% of their area as natural land, with the potential to retain rainfall water in upstream areas.

Table 1. Stormwater ponding events by municipality (2016 – 2020)

		Pond depth (cm)				
Municipality	Total ponding events	No information available	Minimum	Maximum	Average	% of natural land
Álvaro Obregón	67	37	10	140	34	36
Azcapotzalco	29	22	10	25	16	1
Benito Juárez	137	83	10	250	47	0
Coyoacán	128	77	5	120	41	14
Cuajimalpa	27	22	20	120	60	77
Cuautemoc	136	79	10	80	22	0
Gustavo A. Madero.	164	105	5	150	31	17
Iztacalco	70	49	10	70	27	8
Iztapalapa	356	167	2	200	31	14
Magdalena Contreras	28	21	5	90	33	76
Miguel Hidalgo	101	83	10	50	24	15
Milpa Alta	6	3	30	45	38	98
Tláhuac	71	34	10	100	33	73
Tlalpan	243	109	8	200	40	84
Venustiano Carranza	114	75	5	110	23	25
Xochimilco	111	60	10	50	24	78

The second flood-prone indicator utilises data from insurance claims. Figure 2 shows the neighbourhoods impacted by each event (mapped with a different color). We can observe how a single event can flood multiple neighbourhoods, which might not be contiguous or even located in the same municipality. In this period, 51 neighbourhoods were flooded at least twice, and one, in Iztalapalapa, was flooded nine times. Events might not impact the whole neighbourhood, but more exact information is lacking.

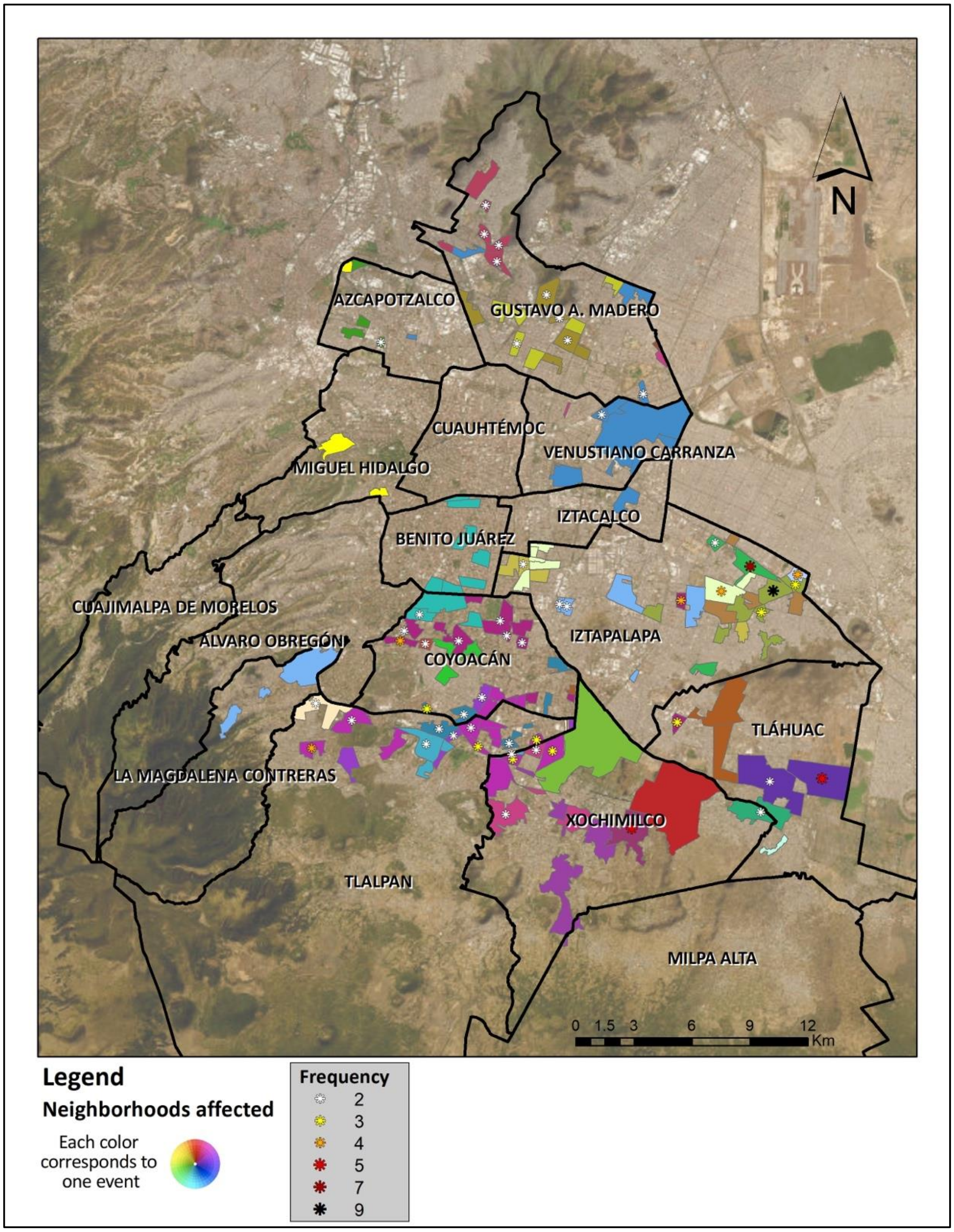

Figure 2. Location of neighbourhood flood events compensated by Mexico City's insurance scheme (2017-2018)

3.1.2 Flood cost indicators

The lack of official information complicates the estimation of the economic impact of flood events; therefore, we use proxy data from a public flood insurance scheme (GCM, 2022). It provides a reference for the magnitude of recent flood events. From 2017 to 2020, 45 flood events were covered by the insurance scheme, with about 6,700 affected households (see Supplementary Information, Table S2). This information is displayed in Figure 3. The most expensive event was on May 29, 2017, costing MX$16.09 million (US$793,710[4]), while the event with the largest number of affected units (973) was on September 6, 2017. The average payment is MX$10,198 (US$503), with a maximum payment of MX$19,870 per household (US$ 979).

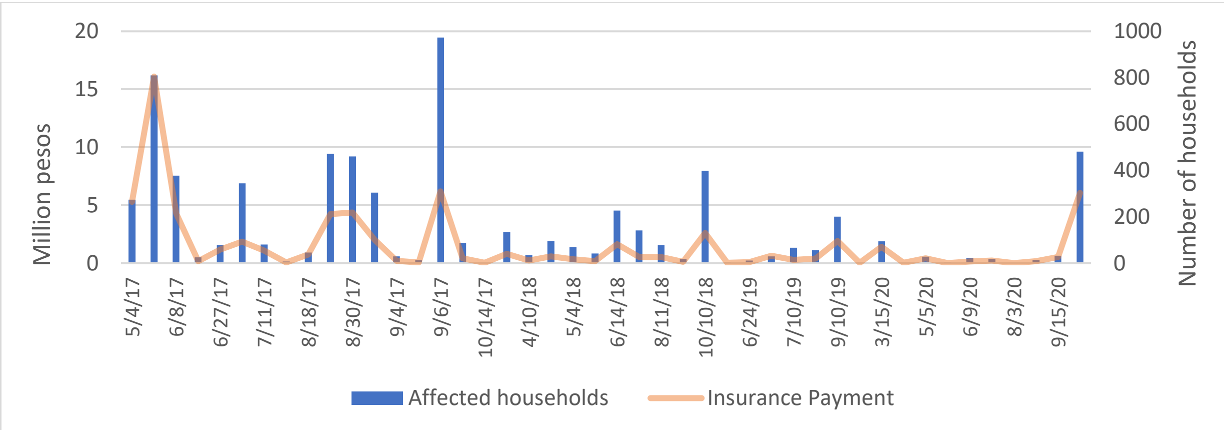

Figure 3. Affected units and average household insurance payment by flood event

Figure 4 shows municipalities' cost and affected units of different events – note that the information is not disaggregated by neighbourhood. The height of the orange cost bars shows that costly events have been recorded in southern areas close to peri-urban areas (Tlalpan and Xochimilco). The height of the blue bars for affected units shows significant impacts in Tlalpan, Gustavo A. Madero, and Miguel Hidalgo. In certain cases, we observe many affected units with low costs, irrespective of their social development index. Only in one case, in Xochimilco, is the cost significantly higher than the number of affected units.

[4] Exchange rate 1USD=20.27 MXN, 2.7.2022

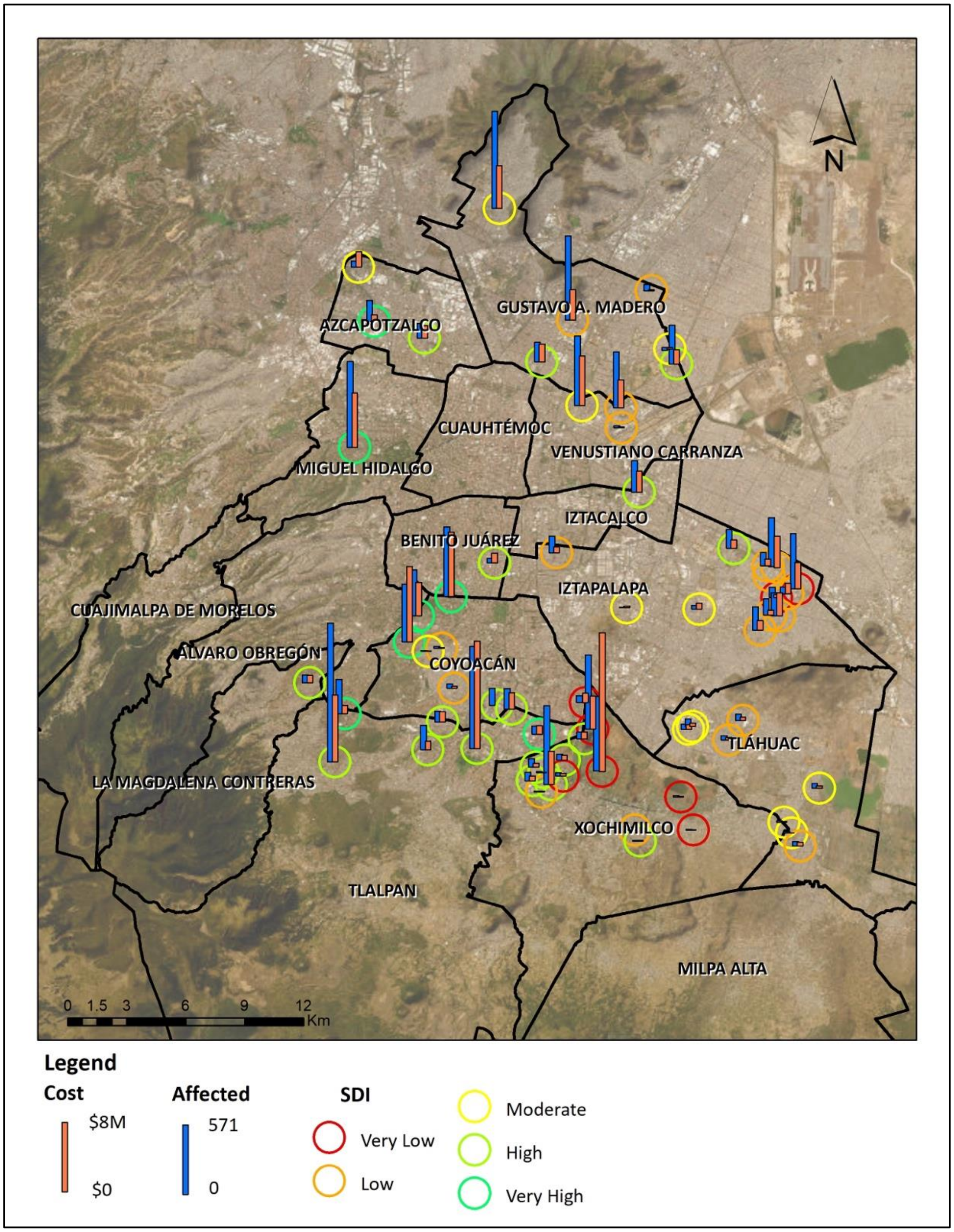

Figure 4. Cost and number of affected units (households) by municipality and social development index (SDI) (2017-2018)

Next, we compare the costs of flood events observed in 2017-2020 as proxied by payments made under Mexico City's insurance scheme, where the highest average cost was 19,870 pesos (US$975) (see Figure 3 and Table S1) with estimated costs based on parametric functions calculated by Baró-Suárez et al. (2011). Using the functions, the costs of flooding for a household with a high marginality index (very low SDI) that is flooded to a depth of 32 cm is estimated at MX$64,895 pesos (US$3,201). The estimated costs rise to MX$97,463 (US$4,808) for a household with a medium marginality index (medium development index)[5]. This comparison suggests that insurance payments provide a low estimate of the costs for affected households. It might indicate that the scheme is not working well or that the insurer only compensates a percentage of the total costs incurred. According to personal communication, some affected households only report their most significant losses, omitting damage to clothing, food, etc., and some households in areas with recurrent floods opt out as they do not wish to have repeated visits from loss adjusters.

3.2 Supply-side indicators

3.2.1: NbS restoration scenario

During a significant rainfall event, water retention in peri-urban soil depends on the intensity of rainfall and the natural characteristics of the areas. Runoff coefficient values calculated in peri-urban areas ranged from 0.06 to 0.78 (draining between 6% and 78% of the rainfall that precipitates), with higher runoff levels in the southern zone, in Tlalpan and Xochimilco municipalities (Soto et al., 2018). Figure 5 shows four ranges of runoff coefficients; a large proportion of the peri-urban area presents coefficients in the first and second ranges (0.15-0.30 and 0.30-0.45) and, to a lesser extent, in the third range (0.45-0.60). Almost four-fifths (79%) of the Protected Areas are in the lowest runoff coefficient range, with around 8% in the second and third ranges.

[5] This is considering the minimum salary of 141.7 pesos in 2021.
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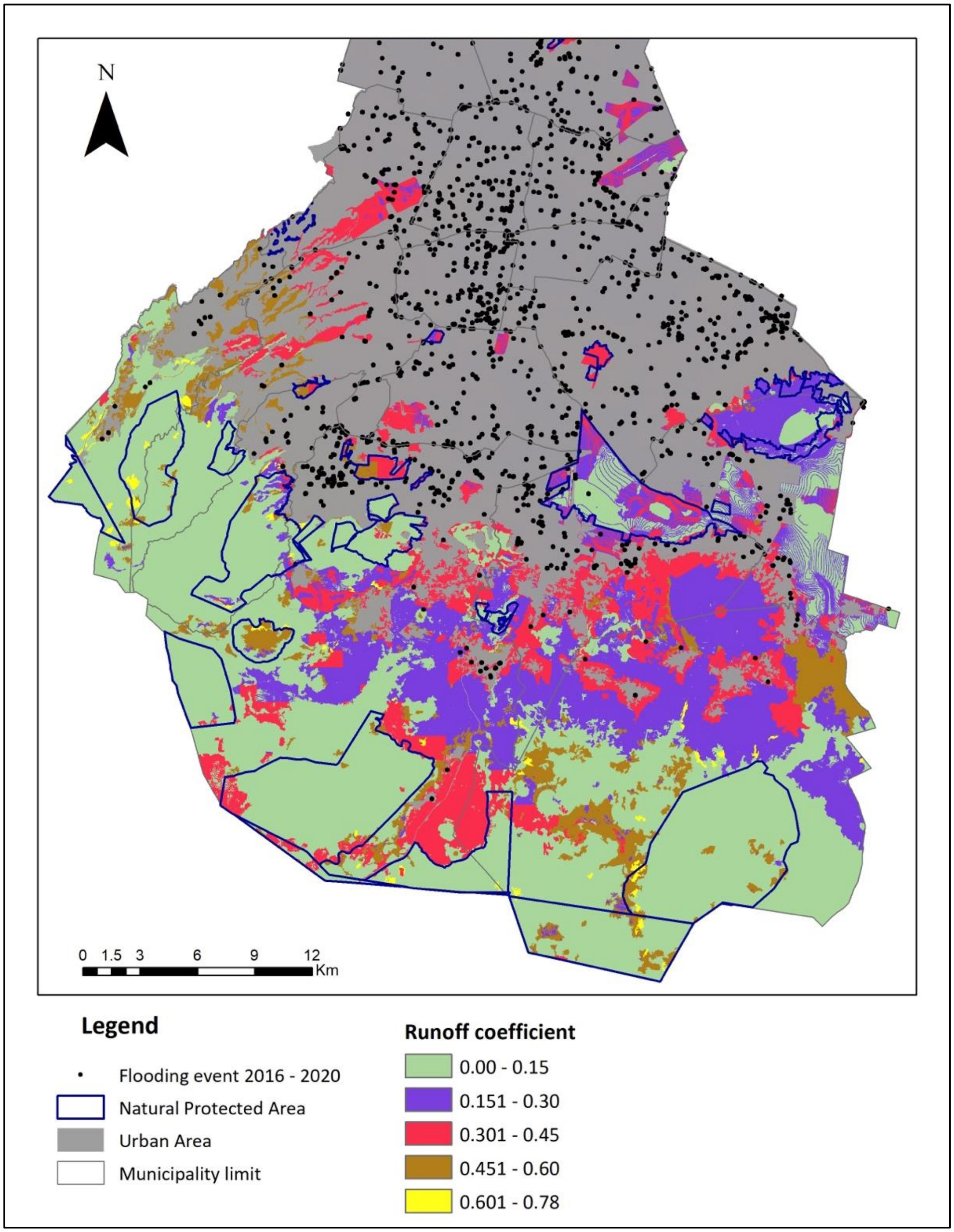

Figure 5. Runoff coefficients in Mexico City's peri-urban interface and natural protected areas with flooding events (2016-2020)

Results from SWAT calculate that if 20 hectares were reforested (18.1 hectares of agricultural land and 1.9 hectares of barren land) in a micro watershed of 148 hectares (Figure 6), this would reduce runoff by 2.6 mm / 6.3 mm for an extreme daily rainfall event of 60 mm / 100 mm, respectively. This corresponds to a reduction in rainwater flowing towards lower urban areas of 3,863.1 m^3/day and 9,360.7 m^3/day, respectively. Figure 5 shows potential areas that have recorded flood events during the study period that could benefit from the NbS intervention.

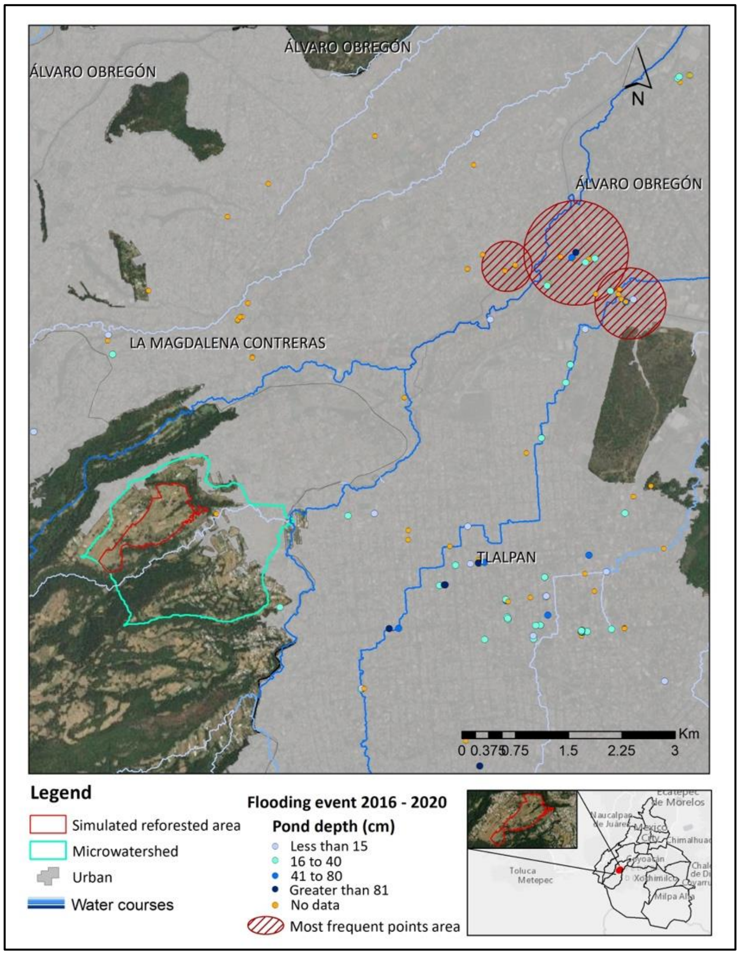

Figure 6. Simulated reforestation intervention in a peri-urban micro watershed near the urban zone.

3.2.2 Replacement cost estimate

A market price reference was obtained from a Mexican company operating nationwide that drew on expertise from more than 200 projects. Estimates of the cost of installing a stormwater regulation system range between MX$4,640 and MX$9,280 per m^3 (US$226-453), with an average of MX$6,980 per m^3 (US$341). Using the average grey infrastructure cost estimate, for the 20 hectares considered before, the replacement cost of installing stormwater regulation systems to control the 3,863 m^3 that could be retained in a 60 mm/day event would be MX$26.9 million (US$ 1.3 million).

3.2.3 Avoided cost estimates

The second pricing approach uses avoided costs, i.e., an estimate of flood property damage (that could be avoided with an intervention). Using Baró- Suárez et al. (2011) parametric functions, if 50 households are flooded to a depth of 32 cm in areas with medium marginality, the flood damage costs are estimated at MX$4.8 million (US$240,412). This estimate is lower at MX$3.2 (US$160,077) in areas with a high marginality. If restoration were to improve retention by 3,863 m^3 and thereby reduce pond depth by 5 cm, this would reduce the losses in a neighbourhood with medium marginality / high marginality by about MX$ 0.63 million (US$31,378) / MX$0.33 million (US$16,658).

If Mexico City's insurance scheme covers these 50 households, the average insurance payment is 10,000 pesos (US$503) per household or a total of 500,000 pesos (US$24,666). If the retention of the 3,863 m^3 reduces the pond depth by 5 cm, then insurance payments could be reduced by 10%, saving 50,000 pesos (US$2,467).

3.3 Integrating demand and supply side indicators

Priority areas for intervention can be identified by combining information on high runoff areas (in Figure 7, yellow, brown, pink, and purple areas closer to urban infrastructure), the flow of water courses, and the location of previous flood events. Policy instruments aimed could target these priority areas and fund future research on the water retention potential of vegetation restoration approaches under different peri-urban landscapes such as agricultural soil, protected areas, or community land.

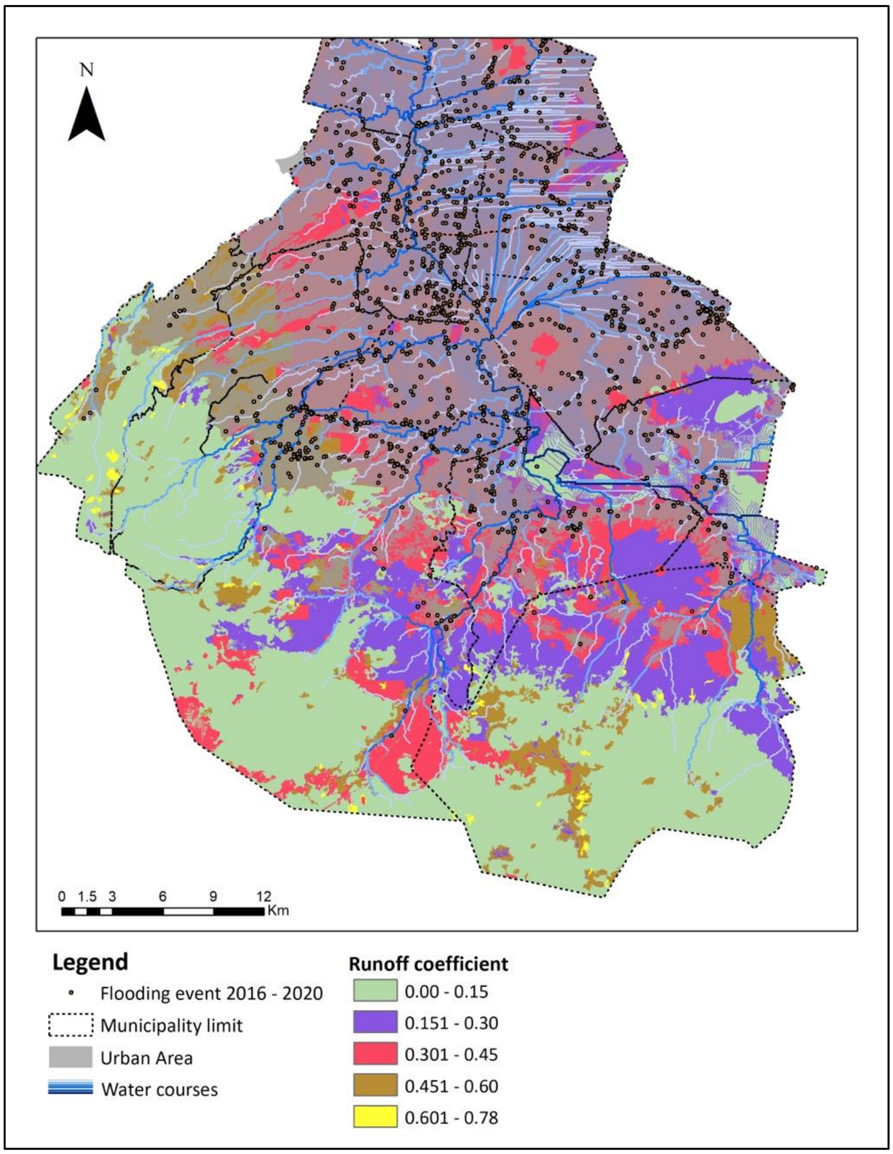

Figure 7: Ponding events 2016-2020, peri-urban area runoff coefficient, and the surface hydrographic network

Mexico City has several policy instruments designed to foster the sustainable management of conservation land and the ecosystem services it provisions that forbid land-use change, promote management of protected areas, and subsidise sustainable agriculture, forest conservation, and fire prevention activities. This study finds that runoff coefficients are lowest in Protected Areas, providing an economic rationale for protecting such areas as an efficient policy instrument to regulate rainwater flows in the peri-urban interface. The National Commission of Natural Protected Areas has recognized this potential to reduce disaster risks in a few sites (CONANP, 2021), and this research provides evidence of the monetary value of these areas.

The direct cost of restoring one hectare is approximately MX$30,000 (US$1,480), including reforestation and maintenance (DOF, 2014), excluding land opportunity costs (the incentive to maintain forest areas instead of other land uses). This restored hectare of peri-urban land could reduce runoff by 193.2 $m^{3,}$ which, if delivered through grey infrastructure, would cost around MX$1.3 million (US$66,513). This suggests that a restoration program would not only be able to cover the direct costs of reforestation but also compensate landowners for the opportunity cost.

4. Discussion

Information on the spatial context of ecosystem service provision in peri-urban areas and areas vulnerable to floods is essential to assess the benefits of an NbS approach to improving flood resilience of cities. Here, we present a series of indicators based on reliable and accessible information that considers the spatial context of water flow regulation supply and demand areas in a complex megacity with a topographic risk condition.

The NbS benefit estimates confirm that restoring upstream peri-urban areas is cost-effective when compared to the replacement costs of alternative grey flood management infrastructure and avoided costs to affected households. The avoided cost benefits range from US$ 979 per household under the public insurance scheme payments to US$ 4,808 per household in an area with a medium marginality index under an parametric function. Whereas, restoring one hectare of peri-urban land at US$1,480, including reforestation and maintenance, but excluding the opportunity cost of landowners (DOF, 2014), could reduce 193 m^3 runoff during an extreme event under a 60 mm/day event. Delivering this same reduction with an engineered solution (replacement cost) would cost US$66,513. There is clarity in the simplicity of these NbS supply and demand indicators that connect the water flow regulation ecosystem service provisioned by peri-urban areas with at-risk urban neighbourhoods.

Our analysis shows that settlements in megacities, such as Mexico City, depend on peri-urban natural ecosystems to regulate rainwater flows and reduce flood events. This confirms previous research where the combination of runoff coefficients with the location of vulnerable areas can identify urban areas that need greater intervention, such as in a municipality in Venice where high-resolution maps indicated areas where green infrastructure had greater potential to mitigate urban flooding (Maragno et al., 2018). Also, a study in northern Iran found that slope, distance to stream, and land use/land cover explained flood occurrence (Arabameri et al., 2019). Thus, runoff coefficients pinpoint upstream peri-urban ecosystems that add to or mitigate flood risk.

Evidence of the relationship between runoff coefficients in peri-urban soil and areas with recurrent and costly events may improve stakeholder attention on NbS and foster restoration activities where there is a potential to increase this water flow regulation with likely benefits. In our case study, the urban fringe closest to peri-urban areas is a target for restoring disturbed ecosystems as they likely have contributed to historic flood events. Such an approach could support long-term decision-making around strategic land use planning and targeted conservation and restoration projects designed to maintain or improve the provision of regulating ecosystem services. The effectiveness of Protected Areas as a flood management policy instrument (due to low runoff coefficients) is significant, as Gunnell et al. (2019) suggested for other metropolitan areas. Of note is that three-quarters of the Protected Areas are social property (communal and ejidos lands)[6], which implies that effective flood managers will need to work with social property landowners and might consider targeting partners in areas that require urgent intervention.

The analysis of water flow regulation provision shows the potential of NbS in peri-urban ecosystems in Mexico City to mitigate urban flooding problems in flood-prone areas, confirming results from studies in other large urban areas around the world. In the case of London in the UK and Chennai in India, the storage capacity for runoff volumes increased the flood hazard (Gunnell et al., 2019). Also, in Mexico City, Sao Paulo in Brazil, and Buenos Aires in Argentina, certain areas of natural soil in watersheds are associated with water availability and flood risk (Zambrano et al., 2017).

Only in a few contexts has the value of this ecosystem service been estimated using different approaches. For instance, farmers' willingness to accept the flooding of their agricultural land to protect a Danish municipality was estimated at an annual payment of 290 Euro/ha for farmers with no prior experience of flood-related crop losses and 469 Euro/ha for farmers with such experience (Zandersen et al., 2021). Willingness to pay estimates have also been used to estimate the benefits of reducing flood and avalanche protection of natural ecosystems (see Brander et al. (2013) for wetlands, Petrolia et al. (2014) for coastal restoration programs and Unterberger and Olschewski (2021) for avalanche protection).

It is further evidence that urban authorities and stakeholders could add NbS interventions to their portfolios of risk reduction measures when existing conventional infrastructure is insufficient for managing extreme events (Maragno et al., 2018) and because, in specific contexts, nature requires less maintenance and is more effective (Keesstra et al., 2018; Bradbury, et al., 2021). Overcoming the inertia of conventional engineering solutions to incorporate new policy innovations such as NbS and non-structural basin runoff controls has been reported in megacities, for instance, in Guangzhou, China, where efforts are still ad hoc (Meng et al., 2022).

Reviewing planning and other policy instruments to integrate NbS in megacities requires an evidence-based approach acknowledging that the peri-urban interface mediates the interaction between nature and economic systems. Current evidence suggests that Mexico City's Urban Development Plan might promote irregular human settlements and road infrastructure development (Heider et al., 2018) rather than preserving peri-urban ecosystems. Other studies have also found a lack of protection for natural storage in upstream basins, partly because they are remote high-elevation areas at a considerable distance from the beneficiaries of the service that provides the protection (Gunell et al., 2019).

The active participation and involvement of local communities, decision-makers, beneficiaries of ecosystem services, and other stakeholders to inform the design of a new approach to target restoration in peri-urban areas are essential for governance success because the policy schemes used by previous local authorities have been criticized due to lack of policy coherence and coordination (Cetina et al., 2022). Potential buyers (cities, insurers) and potential sellers (ejidos, private landowners) should be included in the design of policy schemes. Directing new and existing funding and obtaining the support of NGOs with similar goals will also improve such opportunities.

[6] The remainder is federal land (7.6%), private land (5.9%) and designated as urban soil (11.6%).

Communities of Practice (CoP) can be used as a platform to foster social learning to drive a paradigm shift towards integrating NbS in governance instruments, for example, for Natural Flood Management (NFM) in Yorkshire, UK (King et al., 2023). CoP may help to foster a participative process of different stakeholders to recognise the insurance value of NbS and underpin the development of governance instruments and legal frameworks (Anderson et al., 2017; Sellberg et al., 2018). Since much of the flow regulation ecosystem service is provided by communal and ejido-lands, local knowledge could be pivotal to designing and targeting restoration efforts (Cetina et al., 2022). For example, in Bangkok, Thailand, the importance of consulting peri-urban communities was found to be an essential step for the policy design process to mitigate urban flood risk (Irvine et al., 2023).

Policy options include compensation for flood water storage, payment for ecosystem services or the declaration of new natural protected areas to incentivise the provision of flow regulation in communal and ejido lands. Alternatively, charges to disincentivise risk-increasing management could be introduced, such as a "vulnerable natural area tax" of up to 2% of building construction costs, imposed on developers, as used in France, or a mitigation banking system like that in the United States, where a developer compensates for water storage losses by purchasing credits from a mitigation banker who preserves and restores wetlands at another site (Sohn et al., 2020). The least desirable scenario is the status quo, where targeted instruments are lacking to compensate landholders for peri-urban insurance values.

5. Conclusions

Assessing flood risk management policies through NbS in a mega city of medium and low-income country has the challenge of producing reasonable indicators that connect the peri-urban interface and the at-risk urban areas when hydrological modelling data is patchy or unavailable. Our analysis contributes to the literature by proposing how to develop spatial supply and demand indicators that support specific interventions in peri-urban areas to mitigate urban flood risk. We used simple runoff coefficients in peri-urban areas and mapped flood areas utilising official data on the magnitude of flood events, flood insurance claims, and parametric cost functions. Integrating indicators of urban and peri-urban landscapes provides information to manage flood risk in an alternative or additive way. We confirmed that some areas in the peri-urban interface have high runoff coefficients that increase the flood risk of nearby urban areas and that the Protected Areas provide significant insurance value. In addition, our analysis furthers the research of the insurance value provided by peri-urban areas against floods. Using pricing approaches, we estimated that restoration actions in peri-urban areas could provide important cost savings compared to grey infrastructure solutions and reduce damage costs that flooded households face.

Ejido and communal land predominate in the peri-urban areas of Mexico City. Therefore, the challenge is to develop policy instruments that directly reach communities, ejidos, and private landowners. Another challenge is coordinating authorities in different sectors (water, environment, risk management, and urban development) to develop specific instruments, such as conservation incentives to maintain or improve natural ecosystems or compensation for development. This can be done in collaboration with NGOs and other stakeholders working in these areas.

The experience of Mexico City might be comparable to other complex megacities in developing countries with similar topographic conditions with the objective of reducing flood risk and adapting to climate change through NbS. This research shows that it is essential to systematically observe the conditions of peri-urban ecosystems and their connection with urban floods. City governments should improve their capacity to integrate NbS to reduce flood disasters in collaboration with peri-urban communities that acquire new relevance for megacities.

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