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Original Article

Predictive Assessment of the Performance of the Huancayo Rainwater System (Junín) in the Face of Climate Change: An Approach Using Digital Hydraulic Models

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Abstract *- Climate change, together with rapid and frequently unplanned urban expansion, is placing increasing pressure on stormwater drainage systems in inter-Andean cities such as Huancayo (Junín, Peru). This study uses the Storm Water Management Model (SWMM) to make a prediction about how Huancayo's stormwater network will work now and in the future based on climate models. Local hydrometeorological records and stormwater infrastructure data are combined and collected to model runoff response, peak discharge, ponded volume, and network overload. Simulations show that under normal conditions for 10 and 100-year return periods, the system has limited capacity. Peak outflows reach about 78 to 121 m³/s, ponded volumes rise to about 62,000 to 145,000 m³, and node surcharge is widespread. In a 2070 projection using RCP 8.5, peak discharge and ponded volume rise by about 21% and 37%, respectively, compared to the baseline. A hybrid green–gray adaptation package that includes detention tanks, Low-Impact Development (LID) practices, collector enlargement, and monitoring support cuts peak flows and ponded volumes by 30% to 46% in baseline conditions and by about 29% to 33% in the future scenario. The findings underscore that predictive hydraulic modeling can facilitate pragmatic adaptation planning and enhance flood resilience in elevated urban catchments subject to climatic variability.*

Keywords *- SWMM, LID, RCP, Flood*

1. Introduction

Over recent decades, climate variability combined with rapid urban expansion has significantly affected both the availability and quality of water resources, particularly in developing regions. These pressures have forced researchers and planners to increasingly rely on geospatial analysis and digital hydraulic tools to identify recharge zones, evaluate drainage performance, and anticipate system failures. In urban drainage planning, advanced models such as SWMM and MIKE FLOOD are now commonly required to represent complex hydrological responses. However, their application has also revealed structural weaknesses in areas with fragile soils, suggesting that conventional infrastructure design often underestimates safety margins and long-term risk [1, 2].

Several studies in Europe report that Ultraviolet (UV) filtration and disinfection technologies are effective in reducing the microbial contamination in harvested rainwater. Nevertheless, these systems show a limited performance for removing dissolved chemical pollutants, which point to the need for stricter quality controls within integrated water management frameworks [3]. Rooftop rainwater harvesting has been widely recognized as a relatively low-cost, technically feasible option to mitigate water scarcity, offering a supplementary supply, energy savings, and compliance with international drinking water standards when properly managed [4]. In Sub-Saharan Africa, simpler rainwater collection systems-often based on storage tanks, basic filtration units, and low-cost mobile sensors-have also been implemented. Although their efficiency is lower, these solutions remain valuable due to their adaptability to local economic and social conditions [5].

Flooding in cities is not a new problem, but it has become worse and more complicated in many urban areas over time. Numerous research employing the MIKE FLOOD model have focused on evaluating the real efficacy of urban drainage systems under practical scenarios, rather than only under theoretical design parameters; these evaluations usually identify key areas by using spatial susceptibility methods and suggest possible improvements based on local conditions. The findings suggest that an integration of green infrastructure with conventional gray solutions, together with evaluations of ponding depth and surface topography, can establish a robust technological framework for the improvement of flood control measures [6].

However, the fact that these solutions function well on paper does not always imply that people will actually use them. In the last few years, there has been a growing concern about how much flood mitigation initiatives can cost, especially when they are applied at large scale, for instance, studies carried out in European tourist areas reveal that combined solar and stormwater systems often require a high initial investment and may not begin to generate economic returns for a long period of time, usually between 7 and 15 years. This situation highlights how important it is to perform a complete cost–benefit analysis before starting the implementation of such measures [7]. Efforts for managing water are now becoming more closely related to efforts for saving electricity.

The use of Pumps as Turbines (PaT) in water distribution networks has been shown to be an effective way to improve hydraulic efficiency and reduce leakage losses, especially in areas with sloping terrain or changing elevation profiles [11]. Experiences reported from Pamplona, Colombia, demonstrate that the digitalization of local water networks does not always require large financial investments. In fact, it has been possible to build basic digital-twin environments under modest budgets by using drone-based topographic surveys, demand estimations, and hydraulic modeling at the same time [12]. The cultural and historical perspectives can also provide useful contributions, together with the technical developments. For example, in some regions of China, traditional rural architecture has long incorporated stormwater control practices that were adapted to local climate and landscape conditions.

This situation demonstrates that water management strategies have often evolved over time through practical experience rather than through formal engineering design processes. [13]. From a more technical point of view, micro-scale hydraulic models based on RSPD formulations show that controlled pumping and temporary storage can significantly reduce peak runoff. These measures are particularly important in cities where the sewer system is not able to handle high rainfall volumes and where intense precipitation events are more likely to occur [14]. Other fields of engineering also support the idea that predictive modeling methods are valuable. Thermo-hydraulic simulations of supercritical fluids have improved numerical accuracy and lowered computing costs [15]. Eco-hydrological studies of beaver dam systems illustrate the impact of structural configuration on flood mitigation [16]. Uncertainty evaluations from the nuclear sector demonstrate that linked modeling frameworks can improve the reliability of complex systems. These scientific approaches are appropriately adapted to urban hydrologic situations [17].

Research objectives (as guiding questions/hypotheses). The study seeks to answer the following questions:

1. How does the existing stormwater network in Huancayo perform under design storms of different return periods in terms of surcharge ponding and peak discharge?
2. To what extent do projected climate scenarios for RCP 8.5 for 2070 intensify hydraulic stress and flooding indicators compared with baseline conditions?
3. Can a hybrid green–gray adaptation strategy achieve meaningful reductions in peak discharge and ponded volumes, thereby improving system resilience under both current and future climates?

The working hypothesis posits that climate-induced intensification of rainfall results in non-linear escalation of network surcharge and surface ponding, while integrated green-gray interventions can generate quantifiable reductions in flooding indicators and in overload duration, even under unfavorable projected climate conditions.

2. Materials and Methods

2.1. Study Area

The research was carried out in Huancayo, the capital city of the Junín region, located in the central highlands of Peru. The study area is situated within the upper Mantaro River basin, which forms part of a complex system of inter-Andean valleys. Huancayo is located at an average altitude of approximately 3,259 meters above sea level, and during recent decades the city has experienced one of the most rapid urban growth rates in the Peruvian Andes. According to the national census conducted in 2017, the metropolitan area had a population exceeding 545,000 inhabitants. As an important economic, cultural, and administrative center, Huancayo has undergone fast land-use changes driven by commercial expansion, academic activities, and public-sector developments.

The regional climate is generally classified as moderate and sub-humid, showing a marked seasonal variability. The mean annual precipitation ranges between 1,600 and 1,700 mm, with more than 70% of the rainfall occurring during the rainy season, mainly from November to April (SENAMHI, 2023). During this period, intense convective rainfall events are frequent and often intensified during El Niño–Southern Oscillation (ENSO) events, resulting in recurrent flash floods in specific zones and widespread urban flooding. The mean annual air temperature varies from 11 °C to 13 °C, while daily thermal amplitudes are relatively high due to the city's altitude.

From a geomorphological perspective, Huancayo is located on an alluvial plain surrounded by elevated hills, a condition that favors rapid surface runoff. The interaction between irregular topography, soils with low infiltration capacity—mainly silty-clayey deposits—and the continuous increase of surface sealing caused by unregulated urban growth increases the likelihood of surface water accumulation after heavy rainfall events. At present, approximately 65% of the consolidated urban area is covered by impermeable surfaces, which reduce natural groundwater recharge and accelerate the catchment's hydrological response.

The existing stormwater drainage infrastructure is considered old and limited in capacity, and the system was originally designed for lower population densities and less intense rainfall conditions. It is mainly composed of open channels and underground collectors, with typical widths ranging from 0.30 to 0.80 m. During intense storm events, these conduits frequently exceed their hydraulic capacity, causing manhole surcharging, surface ponding, and overflow to adjacent streets. Areas that are repeatedly affected include El Tambo, Chilca, and the historic city center. In addition, several peri-urban zones continue to expand without adequate drainage planning, which further intensifies flood-related impacts. These conditions affect urban mobility, cause damage to residential and commercial properties, and place essential services such as water supply, sanitation, and electricity at risk.

Figure 1 depicts the geographical distribution of flood-prone regions in Huancayo; the areas marked in red indicate the sectors with the highest susceptibility, which are defined by low-lying topography, increased runoff generation, and an inadequate collection capacity. This spatial evidence highlights the necessity to evaluate the efficacy of the city's stormwater drainage system under the existing conditions as well as under anticipated future climatic scenarios.

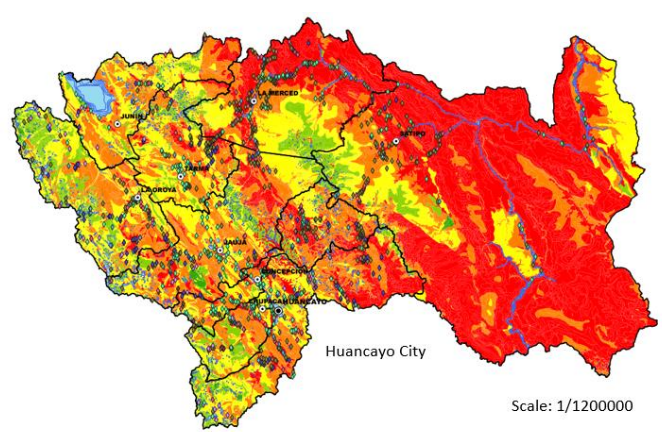

Fig. 1 Susceptibility zoning in the city of Huancayo

2.2. Climate Data and IDF Curves (Improved and Expanded)

Hydrometeorological records for Huancayo (Junín, Peru) indicate a clearly seasonal rainfall regime, along with moderate but persistent thermal variability, characteristic of the central Andean highlands. Mean annual precipitation is approximately 1,660 mm, with more than 70 % concentrated during the wet season, typically from November to March. Rainfall reaches its peak in February, when monthly totals often exceed 270 mm and the number of rainy days surpasses twenty. In contrast, June is consistently the driest month, with precipitation generally remaining below 35 mm.

Temperature patterns are strongly influenced by elevation. The mean annual temperature in Huancayo is close to 9 °C, with minimum values around 5 °C and maximum temperatures reaching approximately 17 °C. The city's high altitude and the fact that it is often clear during the dry season are two main reasons why the temperature range changes so much over the day. These weather conditions are important for hydrological studies because they affect how runoff is made, how soil moisture changes, and how the stormwater drainage system works, as shown in Table 1.

Table 1. Hydrometeorological data

Variable / Month	Average value	Additional details
Annual precipitation	1,660 mm	Highest during rainy season (Nov–Mar); June ≈ 5 mm
Annual mean temperature	9 °C	Ranges from 5 °C (min) to 17 °C (max)
June temperature	Max: 14 °C / Min: 4 °C / Avg: 9 °C	Around 1 mm of rainfall over 5 rainy days
February (wettest month)	~271 mm	Up to 22 rainy days per month
June (driest month)	~33 mm	2–5 rainy days per month

2.3. Stormwater Infrastructure

Huancayo's stormwater system has pumping stations, underground collectors, open channels, and a mix of these types of drainage. A lot of these parts were made and built decades ago, when cities were different, it did not rain as much, and there were not as many hard surfaces as there are now. Table 2 shows that when it rains a lot, the underground collectors, which are about 300 to 800 meters wide, often have to work harder than they were meant to. This situation often causes surcharging and repeated surface overflows in many parts of the city.

The open channels that lead to the Mantaro River system also seem to have limits on how well they work; the solid waste and sediments that wash down from nearby slopes often block these channels. Many street inlets and grates along major roads also look like they have not been properly cared for; this makes them less effective at catching surface runoff and lowers their overall performance, the city does not have many pumping stations, and most of them were not made to work well when it rains a lot, because of this, people have found some places that are likely to flood, especially in the old cities of Chilca and El Tambo, where heavy rains often cause small areas to flood. These conditions show that we need to use predictive hydraulic modeling and targeted reinforcement of the infrastructure we already have to make the whole system stormwater work better.

Table 2. Characteristics of the stormwater system in Huancayo

Infrastructure element	Main characteristics	Current limitations
Underground collectors	Diameters ranging from 300 to 800 mm	Insufficient for extreme rainfall; frequent overflows
Open channels	Connected to the Mantaro River	Frequent blockage by solid waste; slope erosion
Inlets and grates	Distributed along main roads	Poor maintenance; low capture capacity
Pumping stations	Limited coverage; only in specific areas	Not designed for extreme scenarios
Critical flood zones	Historic center, Chilca, El Tambo	Recurrent flooding during heavy rainfall events

Table 3 shows a summary of the performance of the stormwater drainage system in Huancayo, considering two design return periods (T = 10 and T = 100 years), a future climate scenario projected for the year 2070 (S3 – RCP 8.5), and several mitigation strategies that were simulated using the SWMM model. Under the baseline conditions (S0), the rainfall event with a return period of 10 years generated peak outflows of around 78 m³/s. Also, the ponded volume was close to 62,000 m³, while 31 nodes of the drainage network were operating beyond their hydraulic capacity, accumulating a total duration of surcharge of about 18.2 hours.

When the return period was increased to 100 years, the stress on the system became more evident. The peak discharge increases up to approximately 121 m³/s, and the ponded volumes reach values near 145,000 m³. At the same time, the number of overloaded nodes increased to 57, which indicates that a larger portion of the network was affected. In general terms, these results reflect the limited capacity of the existing drainage infrastructure to properly cope with extreme rainfall events, especially under more severe hydrological conditions. The implementation of mitigation measures resulted in noticeable performance improvements, the combined application of detention tanks, low impact development practices, and collector enlargement (M1 + M2 + M3) reduced peak discharge by approximately 32 %, decreased volumes and by around 40 %, and lowered the number of overloaded nodes by more than 50 % under the 100-year storm scenario; the inclusion of additional pumping capacity (M4) further enhanced system behavior, achieving total reductions of roughly 37 % in peak discharge and 46 % in ponded volume.
Future simulations for the year 2070 under the RCP 8.5 scenario indicate an increase of about 21 % in peak flows and nearly 37 % in ponded volume when compared with the baseline conditions. Despite this increase in hydraulic demand, the combined mitigation package (M1 + M2 + M3) continued to provide significant benefits, reducing the peak discharge and the ponded volume by approximately 29% and 33%, respectively. Overall, the results confirm that integrated adaptation strategies can notably improve the resilience of the Huancayo stormwater drainage system under both present-day and projected climate conditions.

Table 3. Performance at nodes/outfalls (aggregated volumes)

Scenario	Measures	Peak at outflows (m³/s)	Ponded volume (m³)	Overloaded nodes (N)	Overload hours (sum)
S0 Base T=10	–	78	62,000	31	18.2
S0 Base T=100	–	121	145,000	57	42.7
S0 T=10	M1	69 (-12%)	48,800 (-21%)	24	12.6
S0 T=10	M2	72 (-8%)	52,900 (-15%)	26	14.1
S0 T=10	M3	64 (-18%)	44,500 (-28%)	19	10.5
S0 T=10	M1+M2+M3	53 (-32%)	36,900 (-40%)	14	8.3
S0 T=10	M1+M2+M3+M4	49 (-37%)	33,500 (-46%)	12	7.6
S3 2070 T=10	–	94 (+21%)	85,200 (+37%)	39	26.5
S3 2070 T=10	M1+M2+M3	67 (-29% vs S3)	57,400 (-33% vs S3)	25	15.4

3. Results and Discussion

The hydraulic assessment of Huancayo's stormwater drainage network under the baseline conditions (S0) identified important structural limitations when the system is subjected to intense rainfall events. For the storm associated with a return period of 10 years, the peak discharges reached approximately 78 m³/s, generating an estimated ponded volume of around 62,000 m³.

Under these conditions, 31 nodes within the network become surcharged, accumulating a total operational overload duration of nearly 18.2 hours. When the return period was increased to 100 years, the limitations of the system became much more evident. Peak discharges rise to roughly 121 m³/s, ponded volumes expand to almost 145,000 m³, and 57 nodes experienced conditions of hydraulic overloading.

In this scenario, the total surcharge durations exceed 42 hours, as illustrated in Figure 2. These results indicate that the existing stormwater drainage infrastructure lacks the hydraulic capacity required to withstand extreme precipitation events; consequently, recurrent flooding is concentrated in highly vulnerable sectors, particularly the historic city center, Chilca, and El Tambo and beyond localized water accumulation, such flooding events pose risks to public safety, disrupt commercial activities, and compromise the continuous operation of essential urban services.

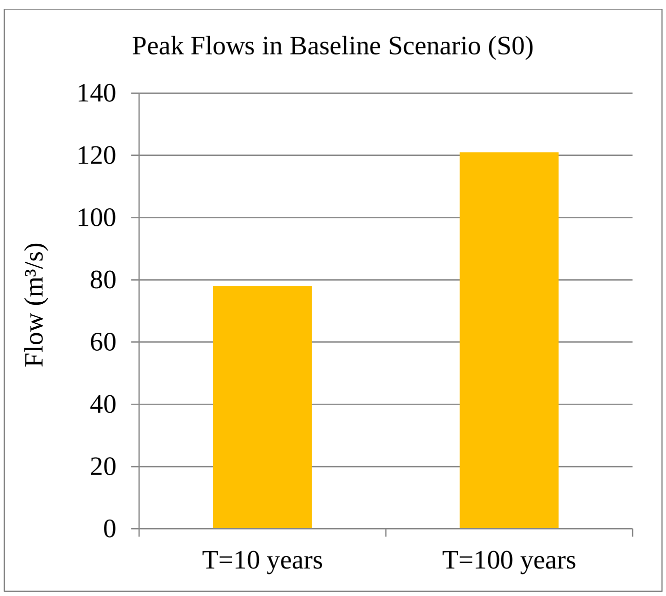

Fig. 2 Results of the base scenario

Figure 3 illustrates the spatial distribution of flood susceptibility across the city of Huancayo. The areas highlighted in red and orange represent zones with the highest vulnerability and are mainly concentrated in the eastern sectors and in peripheral areas of the urban zone. Regions shown in yellow indicate a moderate susceptibility, while green and blue areas correspond to zones with relatively low flood exposure, this spatial pattern indicate that a considerable portion of the city is subject to critical flood conditions, which can be attributed both to the limited capacity of the existing storm water drainage network and to the rapid urban expansion that is occurring in areas that are prone to hydrological risk.

The figure also shows the location of Intelligent IoT Sensors deployed across the drainage system and connected through 5G and satellite communication. These devices enable continuous monitoring of water levels and flow conditions, providing timely information for the early detection of critical events. In this sense, the monitoring system represents a valuable technological tool for improving emergency response and for supporting adaptive flood management strategies under future climate change pressures.

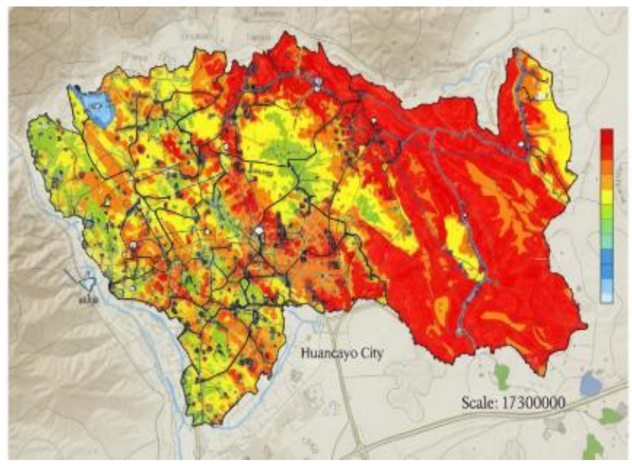

Fig. 3 Flood susceptibility zoning in the city of Huancayo

Figure 4 illustrates the variation in urban ponding volume (%) under different climate scenarios and storm return periods, as well as the effect of mitigation measures on overall system performance. Under current conditions, represented by a 10-year return period, the ponding volume is approximately 30 %. When future climate scenarios are considered, particularly RCP 4.5 and RCP 8.5, this value increases progressively and exceeds 120% under the most critical conditions, corresponding to RCP 8.5 with a 100-year return period.

The implementation of mitigation measures, including detention tanks, permeable pavements, and collector enlargement, leads to a substantial reduction in flood-related impacts. For return periods of 10 years, these interventions achieve reductions in ponding volume of up to 60 %. Even under the most severe climate projections, the reduction remains close to 30 %, indicating a sustained mitigation effect. Overall, the results confirm that hybrid green–gray adaptation strategies represent an effective and feasible approach for enhancing the resilience of the Huancayo storm water drainage network under projected climate change conditions.

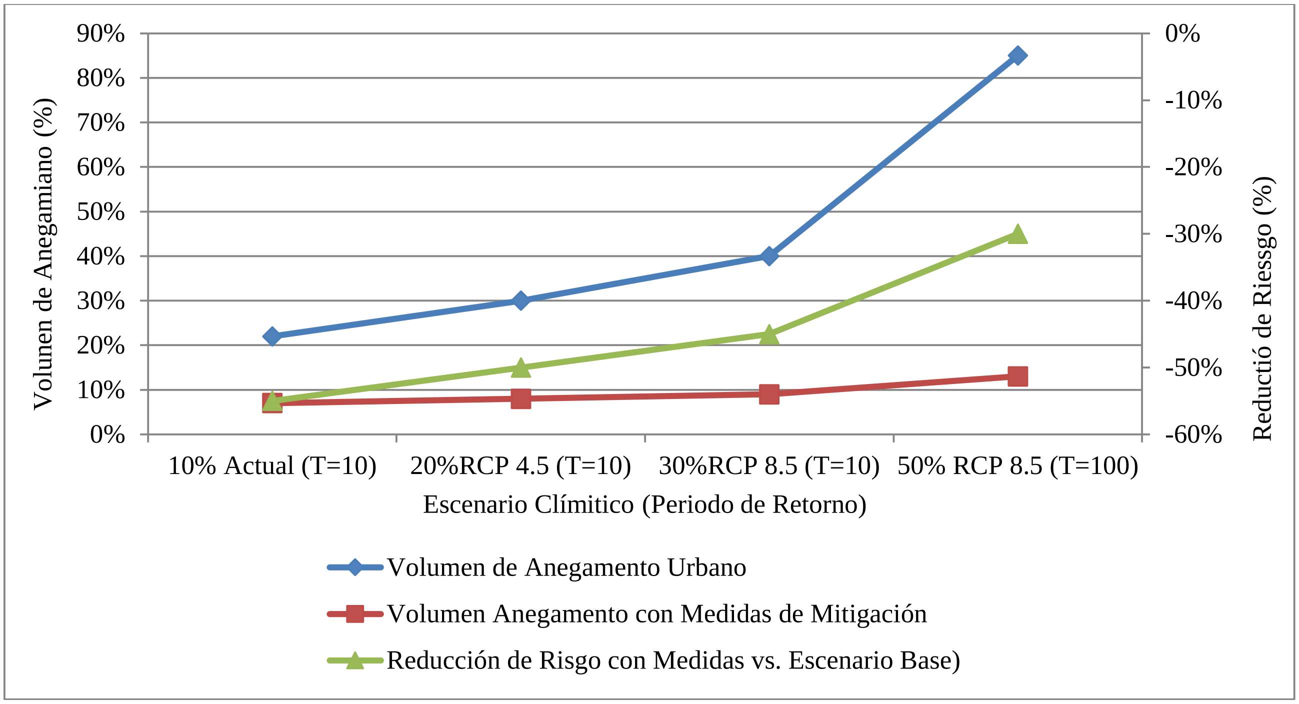

Fig. 4 Variation in urban flooding volume and risk reduction under different climate scenarios.

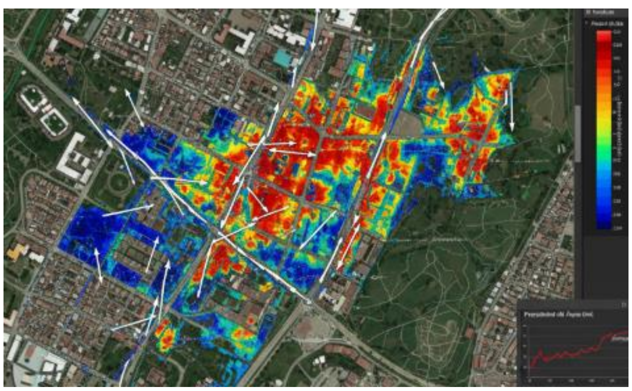
Fig. 5 Spatial distribution of flood depth and surface runoff directions in an urban area of Huancayo

Figure 5 presents a spatial simulation of surface water depth for a representative urban sector of Huancayo, which was generated using the hydraulic model developed in this study. The color scale depicts the distribution of accumulated surface water, where red and orange tones indicate higher water depths and, as a consequence, a greater flood susceptibility. On the other hand, blue areas represent zones with shallow ponding or almost negligible water accumulation; the directional arrows illustrate the main surface flow paths, outlining corridors where runoff tends to converge toward the principal accumulation areas within the city. In the lower-right part of the figure, the rainfall–persistence curve shows the temporal evolution of discharge during the simulated storm event, reflecting the rapid hydrological response of the urban catchment to intense precipitation. Taken together, these spatial and temporal patterns reveal a limited capacity of the existing drainage network, particularly in sectors that are densely built up. This evidence reinforces the relevance of mitigation measures such as detention tanks, permeable pavements, and intelligent monitoring systems, in order to reduce flood risk under both present conditions and future projected climate scenarios.

Fig. 6 Comparative visualization of urban flooding

Simulation outcomes show that an increase in precipitation intensity under future climate scenarios leads to a non-linear amplification of flood-related vulnerability within the stormwater drainage system of Huancayo. For the RCP 4.5 scenario associated with a return period of 10 years, the total ponded volume increases by approximately 20 % when compared to the current conditions. Under the RCP 8.5 scenario for the same return period, this increase becomes more evident, reaching values close to 37 %. The system response intensifies even more during extreme rainfall events. For a return period of 100 years under the RCP 8.5 scenario, the simulated ponded volumes rise up to about 120 % relative to the baseline conditions. This strong escalation highlights the high sensitivity of Huancayo's drainage infrastructure to the projected climatic variability, as illustrated in Figure 6.

4. Conclusion

This study evaluates the performance of the stormwater drainage network of Huancayo under present conditions and also under projected future climate scenarios, using the SWMM modeling platform. The obtained results suggest that climate change will place a much higher hydraulic pressure on the system than it currently experiences. For the RCP 8.5 scenario in the year 2070, considering a return period of 100 years, both peak discharges and ponded volumes increase to values that are more than twice those observed under present-day conditions.

Even so, the application of hybrid adaptation measures shows an important capacity to reduce these negative impacts. The combined use of detention tanks, Low-Impact Development (LID) practices, collector enlargement, and pumping stations resulted in reductions of up to 46 % in peak discharge and surface ponding. When the strategies are analyzed separately, detention tanks and LID measures tend to produce the strongest reductions; however, the integrated application of all measures provides the greatest improvement at the overall system level.

The findings highlight the need for more comprehensive and forward-looking planning strategies in inter-Andean cities, where steep topography and strong hydrological variability usually amplify flood-related risks. Although the hydraulic model was calibrated and validated with acceptable results, some limitations still remain. These limitations are mainly associated with the coarse spatial resolution of the climate projections that are currently available and with the simplified way in which soil infiltration processes were represented within the modeling framework.

Future research efforts should focus on incorporating climate datasets with higher spatial resolution, along with more detailed evaluations of socio-economic impacts and a complete cost–benefit analysis of the proposed adaptation options. Additionally, the development and testing of real-time control and monitoring mechanisms for stormwater systems represent a promising path to improve adaptive capacity and operational resilience under increasingly variable climatic conditions.

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