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Mitigation and adaptation strategies for mass removals in arid zones: A theoretical model based on urban architecture projects in Antofagasta

Estrategias de mitigación y adaptación para remociones en masa en zonas áridas: Modelo teórico basado en proyectos de arquitectura urbana en Antofagasta

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ABSTRACT The Atacama Desert, particularly in the Antofagasta region, faces increasing risks of mass movement exacerbated by climate change. This article proposes a theoretical model that integrates mitigation and adaptation strategies within urban architecture projects at the neighbourhood scale, focusing on sloped desert areas. The methodological process includes an initial deductive classification stage followed by an inductive qualitative analysis. Within 13 academic projects from the School of Architecture at the Universidad Católica del Norte in the city of Antofagasta, two typologies are identified: one oriented toward mitigation through flood-control basins and retaining walls, and another mixed type that incorporates terrain adaptation, green barriers, floodable areas, ramps, and underground channelling. The model helps fill a gap in the literature on risk management in arid contexts, aligning with SDG 11 and SDG 13. It also offers a practical guide for architects and urban planners, promoting more resilient, sustainable, and safe urban policies and projects.

RESUMEN El desierto de Atacama, especialmente en la región de Antofagasta, enfrenta crecientes riesgos de remoción en masa agravados por el cambio climático. Este artículo propone un modelo teórico que integra estrategias de mitigación y adaptación en proyectos de arquitectura urbana a escala del barrio, enfocados en zonas desérticas en pendiente. El proceso metodológico contempla una etapa de clasificación deductiva seguida de otra de análisis cualitativo inductivo. Se identifican dentro de 13 proyectos académicos de la Escuela de Arquitectura de la Universidad Católica del Norte en la ciudad de Antofagasta dos tipologías: una orientada a la mitigación mediante piscinas aluviales y muros de contención, y otra mixta que incorpora adaptación al terreno, barreras verdes, zonas inundables, rampas y canalización subterránea. El modelo contribuye a llenar un vacío en la literatura sobre gestión de riesgos en contextos áridos, alineándose con el ODS 11 y ODS 13. Asimismo, ofrece una guía práctica para arquitectos y urbanistas, promoviendo políticas y proyectos urbanos más resilientes, sostenibles y seguros.

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PALABRAS CLAVE aluviones, adaptación climática, exposición al riesgo, arquitectura resiliente, desierto de Atacama



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1. Introduction

The Atacama Desert, with its extreme aridity and imposing landscapes, poses significant challenges for urban planning and disaster risk management. The city of Antofagasta, located in this region of northern Chile, has dramatically highlighted these geological challenges, especially following the devastating flash flood of 1991, which revealed the city's high vulnerability to mass-movement events.

Indeed, the heavy rainfall recorded on the night of June 18 triggered several ravines formed by the Cordillera de la Costa, causing flash floods throughout the city that resulted in a tragic toll of 91 deaths, 19 missing persons, and 70,000 people affected. This event marked a turning point in urban planning, spurring the adoption of special regulations for high-risk areas that were incorporated into the 2002 Municipal Zoning Plan. In addition, it was decided to construct risk-mitigation infrastructure for a total of 15 ravines, where settling basins—known as “flood channels”—were built to minimize damage from mass movements in future events.

Mass movement refers to the displacement of materials such as rock, soil, or debris down slopes under the influence of gravity (Cruden and Varnes, 1996; Hungr et al., 2014), triggered by rainfall or ground instability. Among these phenomena, flash floods are sudden flows of water and sediment

characteristic of arid zones (Crozier, 2010), whose frequency and intensity are expected to increase due to climate change (United Nations, 2022).

The city of Antofagasta has several land-use planning instruments, both indicative and binding. The most important of these is the Municipal Zoning Plan (PRC), which zones and regulates the city's various areas, along with the Sectional Plans (PS), which apply to a zone already defined by the zoning plan and provide greater detail regarding roadways, green spaces, and mixed land uses.

The current municipal zoning plan, in Article 44 of its local ordinance (Municipality of Antofagasta, 2002), designates all areas mapped in the plan as “natural disaster risk zones,” and these designations take precedence over the standards proposed by the plan for consolidated or urban expansion areas (Figure 1). Similarly, Article 63 designates “urban alluvial systems,” which become part of the city's road network and serve to transport and drain rainwater and sediment that may accumulate between the streams flowing into the city and the sea. The Plan identifies 14 streams as part of the alluvial system, excluding the La Chimba system because, at that time, it had not impacted the city's established urban areas, which did not yet exist.

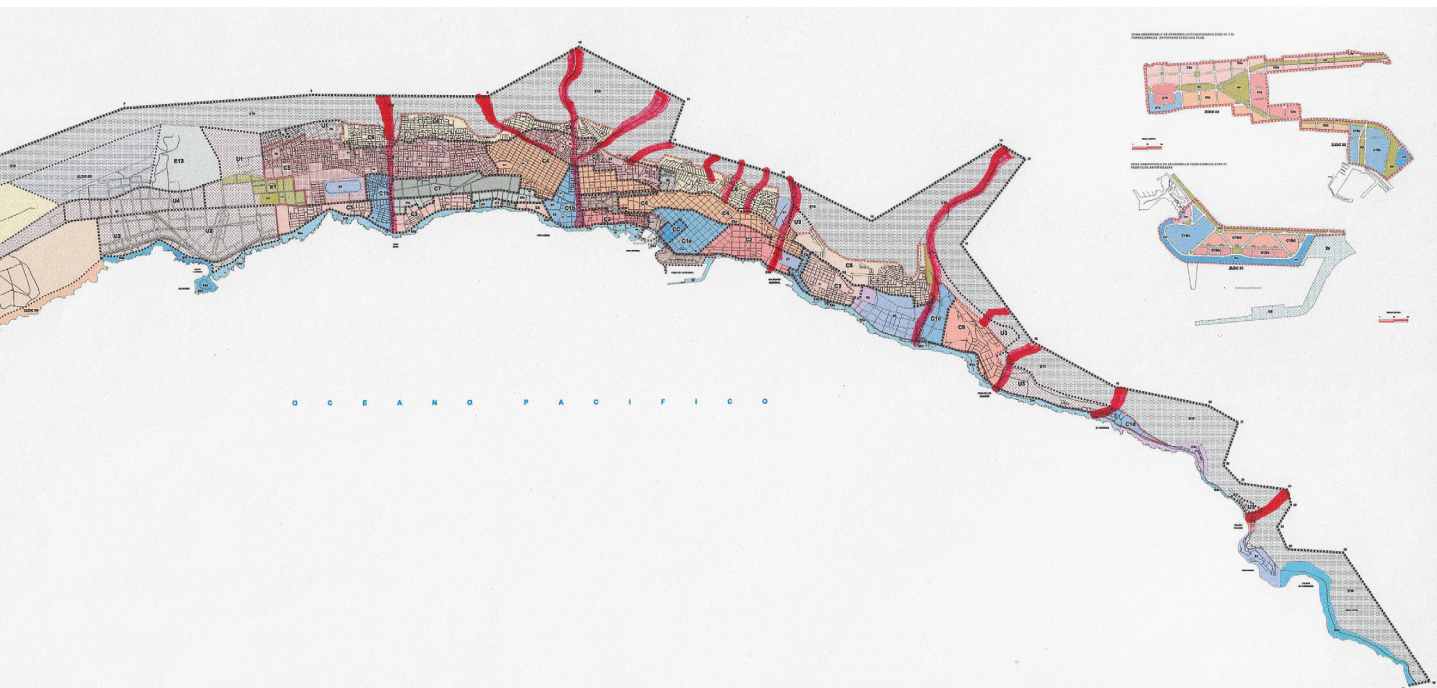


Figure 1: Map showing natural disaster risk zones. Municipal Zoning Plan (2002), Municipality of Antofagasta



Figure 2: Collage depicting the city of Antofagasta, Chile. (2025)

Between 2002 and 2016, under the framework of a “regulatory plan update,” the urban expansion areas in the northern sector of the city were incorporated, primarily due to rapid growth in housing and services. This led to the creation of the La Chimba Sectional Plan, which includes cross-city urban parks to mitigate the effects of future flood events.

Although the city currently has a land-use planning framework and municipal ordinances that regulate special areas related to mass-movement events, gaps remain in the integration of strategies at the neighborhood level, leaving local communities highly exposed and vulnerable. Globally, landslide risks are increasing due to urban expansion and climate change (United Nations, 2022), and between 1975 and 2016, landslides caused more than 600,000 deaths (Froude and Petley, 2018; Haque et al., 2019; Lacasse et al., 2005), underscoring the need for resilient urban approaches.

Urban planning strategies combine mitigation—interventions to reduce risks or greenhouse gas emissions—and adaptation—adjustments to current or expected climate conditions to prevent damage and capitalize on opportunities (Ledda et al., 2024; Perez-Lancellotti and Ziede, 2021; United Nations, 2022). Although they originate from different fields, their integration allows for maximizing effectiveness in risk management (Biesbroek et al., 2009; Klein et al., 2005).

In arid regions of the Global South, such as the Atacama Desert, the literature is limited (Nagendra et al., 2018; Pauleit et al., 2021) despite high exposure to hydrometeorological risks. These areas, defined according to the Köppen-Geiger climate classification as regions where annual precipitation is less than five times the aridity threshold (P_{th}) (Kottek et al., 2006; Peel et al., 2007), feature steep slopes, low soil infiltration, sparse vegetation, and informal settlements—conditions that facilitate the transformation of intense rainfall into flash floods. Studies in Tehran, Phoenix, and Amman highlight the importance of green and blue infrastructure in mitigating these impacts and underscore the need for further empirical research in arid regions (Jamali et al., 2021; Meerow et al., 2021; Okour and Shaweesh, 2024; Olgun et al., 2024).

Antofagasta, located between the Cordillera de la Costa mountain range and the Pacific Ocean, has an elongated urban structure with steep slopes (Figure 2) and an extremely arid climate with average annual precipitation of 3–4 mm (Garreaud and Rutllant, 1996; Vargas et al., 2000). These conditions underscore the need for urban projects that integrate mitigation and adaptation at the local scale, coordinating planning and architectural design to strengthen urban resilience.

In this context, the objective of this study is to develop a theoretical model that systematizes mitigation and adaptation strategies applicable to urban architectural projects in sloping desert areas exposed to mass movements intensified by climate change, with an emphasis on the neighborhood scale. The methodological design is mixed-methods, and the study's corpus consists of 416 academic thesis projects from the School of Architecture at the Catholic University of the North (UCN). The first stage is deductive, and the second is inductive and qualitative. This approach integrates knowledge, theoretical evidence, and practical application, promoting more resilient, safe, and sustainable cities.

In this regard, this research poses the following research questions: What are the typological characteristics of the mitigation and adaptation strategies that have been incorporated over the past 14 years into urban-architectural projects developed in a coastal desert context? To what extent are graduation projects from the UCN School of Architecture incorporating disaster risk management at the neighborhood level? And how can the strategies identified in the analyzed projects be systematized to generate a replicable theoretical model for other similar climatic contexts?

Hypothesis

Urban architectural typologies in steeply sloped coastal desert areas have the potential to form the basis of a replicable theoretical model for designing neighborhoods resilient to the risk of mass movements.

2. Methods

2.1. Study design

A mixed-methods design is employed, combining an initial deductive phase with a qualitative inductive phase to achieve the objective of developing a typology of urban architectural design strategies. Drawing on final-year architecture theses, the focus is on proposals located in high-risk areas, primarily on the hillsides of the city of Antofagasta. In the past, these areas have experienced mass landslides and flash floods, and forecasts indicate that such events will occur with greater frequency and intensity.

2.2. Corpus and data source

The study's corpus consists of 416 degree projects approved between 2010 and 2024 at the School of Architecture of the Catholic University of the North (Antofagasta). These thesis projects are available on CD, in digital format, or in print at the University's Central Library or the School of Architecture's library and adhere to standard presentation formats, primarily consisting of a thesis report and floor plans.

2.3. Stage 1 of deductive classification

The search begins among the 416 projects to identify those located in high-risk areas, then narrows them down to those situated on hillsides, and finally limits them to the city of Antofagasta. To apply these filters, the project reports are reviewed using the following keywords: risk zone, hazard zone, unsafe zone, vulnerable terrain, flooding, flash flood, rainfall, landslide, disasters, zone, or climate change. Once the number of projects containing these words has been reduced, their location is examined using the following keywords: hillside, hill, slope, foothill, ravine, watershed, incline, hillock, and gully.

These two sets of keywords from the deductive process reduce the corpus to 15 thesis projects. Finally, the geographic criterion is applied—requiring that the projects be carried out in the city of Antofagasta—resulting in thirteen projects.

2.4. Stage 2: qualitative inductive analysis

The thirteen retained projects are then studied inductively, without any a priori criteria, so that the freedom of the analysis can reveal specific features in the strategies. An open reading of the thirteen projects was conducted, and a descriptive form was completed containing the title, location, author, date, and program.

This was followed by a more in-depth analysis to identify how the risk problem was addressed at each location and what architectural design responses the program employed to make the project viable and sustainable. The forms were completed, and two researchers accumulated knowledge by comparing the proposals—both their similarities and differences—to identify patterns. The categories emerging from the forms and comparisons were compiled and submitted for review by a third researcher who, due to their professional background and experience in the discipline, refined the analysis and optimized the emerging categories.

This sequence of stages allows for the identification of six architectural design strategies for high-risk areas on the hillsides of Antofagasta that are not previously described in the literature and that uniquely address alternatives for adaptation to and mitigation of climate change—or a combination of both. The identification of these strategies represents the original methodological contribution of this research.

2.5. Validation and triangulation

The robustness of the process is achieved through triangulation among the three researchers, by obtaining feedback on the presentation of the findings at a Chilean conference in the field, and by maintaining a record of the project files for the thirteen projects to ensure their traceability, transparency, and future reviews.

2.6. Development of the typologies

The typologies are presented in a table that cross-references the three alternatives for responding to climate change with the six architectural design strategies identified during the inductive phase. Table 1 also contains a summarized visual representation of the main characteristics of each strategy. The typology table is accompanied by an operational description.

Finally, since these are thesis projects within the academic context of the Universidad Católica del Norte, there are no ethical restrictions on their dissemination within the framework of scientific research, and the students’ authorship is respected.

3. Results

Although the UCN School of Architecture has not formally incorporated the issue of climate change into its curriculum, a review of all graduation projects reveals themes related to territorial sustainability, energy strategies, and thermal comfort applied to architecture in arid zones of the Atacama Desert. This has been a distinctive feature since the school’s founding in 1981.

However, the research—analyzing the 2010–2024 period across a total of 416 graduation projects—found that only 3% of these address the issue of mass land clearing in Antofagasta, and it is only since 2021 that a slight increase in the incorporation of mitigation, adaptation, or both strategies has been observed.

		Strategies			
Year	Projects	Mitigation	Adaptation	Mitigation and Adaptation	
2011	Quebrada Baquedano Educational Recreation Complex, Antofagasta (Galleguillos Martínez 2011)				
2012	Making Use of the Slope: Integrating Public Space into Geographical Unevenness in Antofagasta—Promenade, Lookout, and Housing (Hurtado Duran, 2012)				
2012	Housing Complex and Public Terraces, Antofagasta (Aparicio Fernández, 2012)				
2015	Topography as a Resource in Shaping Architecture within the Landscape: Viewing Plaza and Sports and Community Facilities at Cerro la Cruz, Antofagasta (Cortés Riveros, 2015)				
2018	Urban Agricultural Park and Cultural Center for Desert Farming in the La Negra Ravine, Antofagasta (Méndez Pacheco, 2018)				
2019	Housing complex and university park (Rivera Alfaro, 2019)				
2021	Architecture and Biodiversity: Architecture as a Tool for the Restoration of the La Chimba Antofagasta National Reserve (Salazar Berroeta, 2021)				
2021	Lithium Technology Center, Quebrada la Negra, Antofagasta (Lagos Liebig, 2021)				
2022	Urban Rehabilitation: Construction of the Alluvial Channel in the Baquedano Ravine in the City of Antofagasta (Velásquez Escudero, 2022)				
2022	Quebrada el Toro Housing Complex, Antofagasta (Naveas Giovagnoli, 2022)				
2024	Micro-settlement and urban park typology (Miles Osorio, 2024)				
2024	Quebrada Baquedano Housing Complex, Antofagasta (Araya León, 2024)				
2024	Educational Facility as a Contemporary Response to Natural Disasters, Las Rocas Ravines and Equestrian Club, Chimba Alto Sector, Antofagasta (Rojas Riso, 2024)				

Table 1: Projects, architectural programs, and their respective strategies. (2025)

It is also observed that the total number of projects during the period under review is distributed irregularly over time, forming a sawtooth-shaped curve (Figure 3). Continuing with the results, a total of 15 title projects were identified, of which two were excluded because they were located in cities other than Antofagasta. Analysis of their location within the urban context shows that all cases are situated near alluvial ravines or on hillsides adjacent to them.

In terms of program, the proposals mainly consist of community-scale facilities combined with housing programs. These interventions are developed in accordance with current zoning regulations, particularly regarding occupancy restrictions in areas exposed to disaster risks. These limitations stem, to a large extent, from the city's geomorphological conditions, characterized by steep topography resulting from its proximity to the Coastal Range, which rises to over 1,000 meters above sea level.

3.1. Identified strategies

Six climate change strategies have been identified for hillsides in coastal desert areas exposed to mass movement hazards. In summary, six abstract symbols are used to represent them in Table 3, which are described below.

One of these strategies is "alluvial basins," which involves the use of barriers to control alluvial solids, equipped with deceleration platforms designed to drain and retain water flow. Other measures considered include blockers, alluvial containment structures, and channeling or deflecting devices, all intended to prevent water flow from heading toward the proposed residential buildings. An example of this strategy can be seen in the project "Housing Complex, Quebrada Baquedano, Antofagasta" (Araya León, 2024), which has a direct impact on the historic downtown area of the city of Antofagasta (Table 2, Project 1).

Another strategy we can identify is "adaptation and elevation" (open-plan typology). Under this strategy, several projects combine an open-plan layout as a way to rise above the terrain to avoid flooding and place the main architectural functions on the second or higher levels. An example of this strategy (Table 2, Project 2) is the project: "Architecture and Biodiversity: Architecture as a Support for the Recovery of La Chimba National Reserve, Antofagasta" (Salazar Berroeta, 2021).

The "retaining walls" strategy is characterized by combining retaining walls and strategically located reservoirs to reduce water flow and control accumulation during extreme rainfall events, thereby reducing the velocity of sediment flow resulting from mass movement.

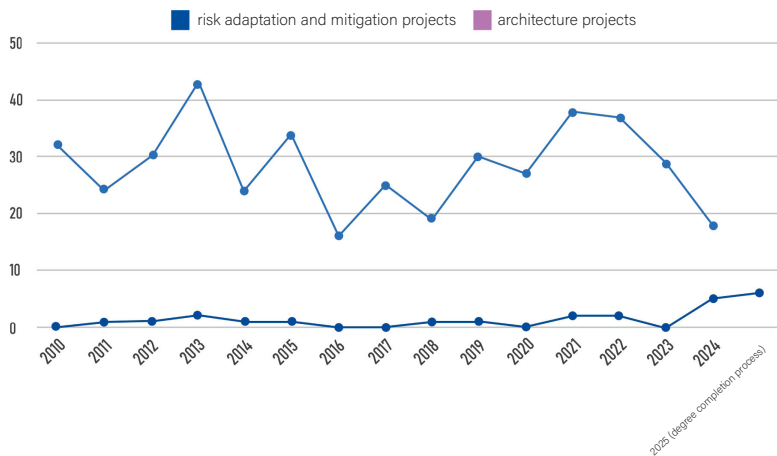


Figure 3: Distribution of the number of projects per year that incorporate adaptation and mitigation versus the number of projects focusing solely on architectural issues. (2025)

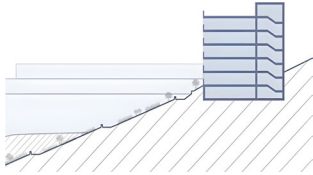
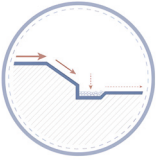
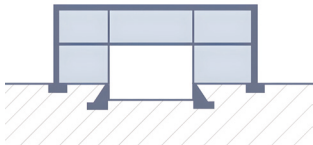
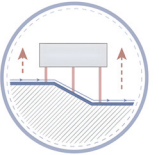
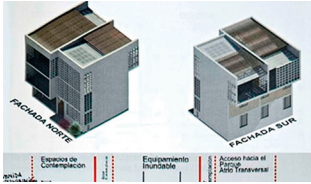
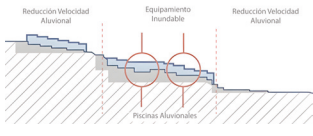
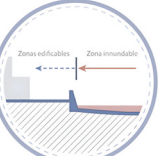
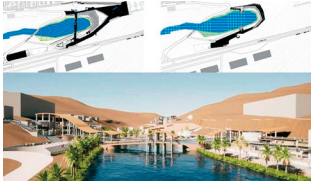
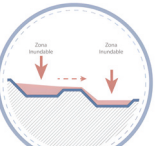
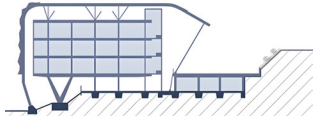
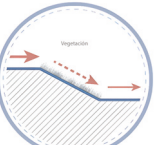
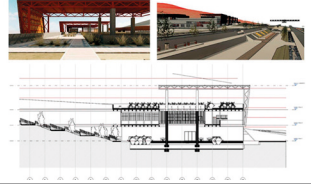
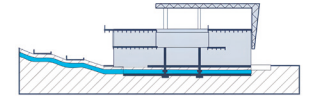
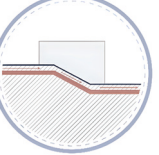
Projects	Architectural program	Strategies	Strategy overview
Project 1	Quebrada Baquedano Housing Complex, Antofagasta.	Project strategy	Alluvial pools
			
Project 2	Architecture as a Means to Support the Restoration of La Chimba National Reserve, Antofagasta	Project strategy	Adaptation and elevation
			
Project 3	Urban Rehabilitation: Construction of the Alluvial Channel in the Baquedano Ravine in the City of Antofagasta"	Project strategy	Retaining walls
			
Project 4	Urban Agricultural Park and Cultural Center for Desert Farming in the La Negra Ravine in the city of Antofagasta.	Project strategy	Flood zones
			
Project 5	Lithium Technology Center, La Negra Ravine, Antofagasta.	Project strategy	Green barriers
			
Project 6	"Educational Facilities as a Contemporary Response to Natural Disasters." Las Rocas Ravine and Equestrian Club, Chimba Alto Sector, Antofagasta.	Project strategy	Ramps and underground drainage
			

Table 2: Types of strategies. (2025)

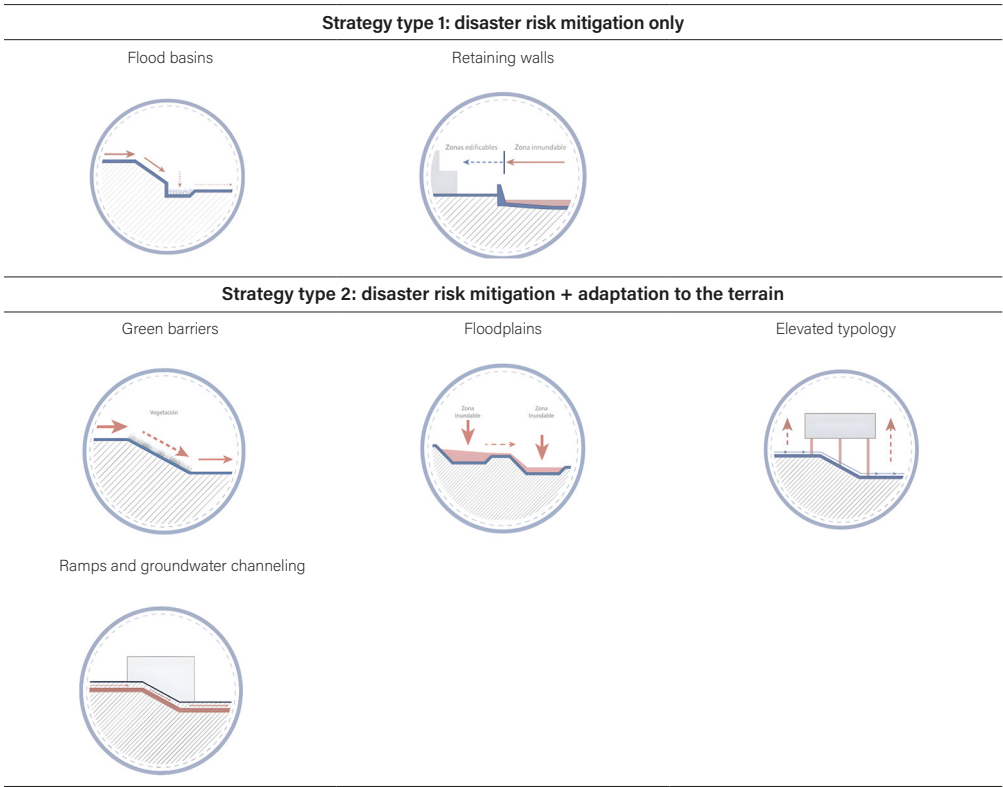


Table 3: Theoretical model of two types of strategies. (2025)

It is a strategy combined with controlled flooding conditions. An example of this strategy (Table 2, Project 3) can be found in the project “Urban Rehabilitation: Construction of the Alluvial Channel in the Baquedano Creek in the City of Antofagasta” (Velásquez Escudero, 2022).

One of the most interesting strategies, especially in arid areas such as the city of Antofagasta, involves “floodplains,” which are created by retaining water that flows down certain city ravines from the Coastal Range. We can identify two ravines with these characteristics: one is the La Chimba Ravine in the northern part of the city, and the other is the La Negra Ravine in the southern part. This strategy incorporates artificial pools into the architectural design that retain water while serving both ecological and landscape functions. This water can also be reused, after treatment, for urban farming. An example of this strategy (Table 2, Project 4) is the architectural project “Urban Agricultural Park and Cultural Center for Desert Farming in the La Negra Creek in the City of Antofagasta” (Méndez Pacheco, 2018).

The “green barriers” strategy is characterized by the use of plant species selected for their ability to contain and slow the flow of water from the La Negra ravine. These species act as natural barriers

that, together with small, strategically distributed retention ponds, reduce the speed of water flow, filter sediments, promote water infiltration and temporary storage, and create a microclimate capable of supporting certain species of lizards, birds, and arachnids, among others. This combination of green infrastructure and retention ponds helps mitigate the impact of flooding, optimizing water management in the area and reducing risks to nearby urban areas. An example of this strategy (Table 2, Project 5) is the “Lithium Technology Center, Quebrada La Negra, Antofagasta” project (Lagos Liebig, 2021).

Finally, there is the strategy that integrates “ramps and underground channels” designed to efficiently drain water during mass movement events or torrential rains. This is a solution focused on natural disaster management, which seeks to minimize the impact of these phenomena on urban areas. An example of this strategy (Table 2, Project 6) is the project “Educational Facilities as a Contemporary Response to Natural Disasters, Quebradas Las Rocas and Club Hípico, Chimba Alto Sector, Antofagasta” (Rojas Risso, 2024).

In turn, the six strategies described above can be grouped into two categories (Table 3). The first category is oriented toward disaster risk mitigation

and includes both flood detention basins and retaining walls. The second category, in addition to the aforementioned mitigation function, includes adaptation measures to address the effects of mass movement, such as terrain adaptation strategies, green barriers, floodplains, ramps, and groundwater channeling. In some cases, we find mixed strategies combining risk mitigation and adaptation.

The theoretical model (Table 3) conceptualizes the possibilities for implementation through the design of risk mitigation and climate change adaptation solutions and strategies, which are operationalized in urban projects at the neighborhood scale within the specific context of arid, sloped areas subject to a growing threat of mass movement due to the presence of alluvial ravines.

4. Discussion and Conclusions

The results reveal two types of neighborhood-scale urban architectural project strategies applicable to desert areas with slopes that may experience—as has been the case in the past—new catastrophic mass-movement events due to the intensification of the effects of climate change. The first type is focused on disaster risk mitigation and includes strategies such as alluvial basins and retaining walls. The second typology serves a dual purpose, aiming both at risk mitigation and at adapting the terrain to the effects of mass movement, revealing four strategies: terrain adaptation, green barriers, floodplains, ramps, and groundwater channeling. These findings enable the development of the theoretical model defined as the research objective and the research questions, consistent with the proposed hypothesis.

The theoretical model developed is the result of an inductive and flexible conceptualization based on a review of emerging final-year projects by architecture students addressing the issue of climate change in urban areas on slopes in Antofagasta, and, in turn, a deductive approach based on a review of the literature. Given the lack of studies addressing the neighborhood scale in the context of inhabited arid zones, the model takes into account the approaches at the city scale typically adopted by researchers—especially in arid regions—and fills the knowledge gap, particularly as it applies to a region of the Global South with desert-like characteristics. Unlike the approaches proposed to date, this research delves into the neighborhood scale through the lens of urban architecture to identify approaches for operationalizing the 2030 Agenda, with special emphasis on Sustainable Development Goals 11 and 13 (SDGs), which relate to quality of life in cities and climate action.

With the proposed model, practical guidelines for urban architecture projects can be addressed by referring to the two typologies and six strategies applicable to cities in desert regions on slopes at risk of mass movement. Given outdated territorial planning instruments such as Municipal Zoning Plans and Inter-municipal Zoning Plans (Pérez-Lancellotti and Ziede-Bize, 2024), urban planning that guides multiscale actions in the city is inefficient and out of step with emerging realities such as urban growth, the exacerbation of climate change effects, immigration, and informal settlements, among others. The theoretical model also serves as a guide for the training of architects themselves, so that when faced with urban contexts on slopes prone to landslides, they can leverage these practical strategies and integrate them into their proposals.

The identification of these six strategies based on an analysis of 13 final-year urban architecture projects at UCN may be perceived as limited; this could be addressed in the future by extending the analysis to other types of high-risk areas in arid regions and cities other than Antofagasta, and even by exploring cases that have been effectively designed and built.

It is anticipated that the model could be refined or subjected to empirical verification in other Chilean cities such as Iquique, Arica, Taltal, or Tocopilla, which share with Antofagasta a similar climate, urban settlement morphology, and exposure to mass movement risks. Within Chile, the research can be expanded to desert areas that do not meet the slope criteria but have watersheds within the cities, as is the case with Calama and Copiapó. Another line of research for desert cities is to examine settlements exposed to flooding as a result of rising sea levels. Furthermore, cities with arid deserts around the world could be included in a broader analysis, expanding the case studies

to include Lima (Peru), La Paz (Mexico), Eilat (Israel), Gwadar (Pakistan), Aqaba (Jordan), Muscat (Oman), Walvis Bay (Namibia), and Agadir (Morocco).

In conclusion, the article proposed developing a theoretical model to explain risk mitigation and adaptation strategies applicable to urban projects in sloping desert areas exposed to mass movements intensified by the effects of climate change, with an emphasis on the neighborhood scale. The theoretical model integrates two types of strategies: a first type focused solely on mitigating the risks of mass movement through strategies such as alluvial basins and retaining walls, and a second, mixed type combining mitigation and adaptation through strategies such as terrain adaptation, green barriers, floodplains, ramps, and groundwater channeling. The theoretical model addresses a gap in the literature regarding how to operationalize human interventions at the neighborhood scale through the design of urban architecture projects in desert areas on inhabited slopes.

The research reveals certain limitations in the methodological framework, which, after analyzing a corpus of 416 projects, conducts an in-depth analysis of thirteen projects. Additionally, there is a limitation in that the coded projects are of an academic nature; therefore, it is suggested that future research be supplemented with examples of built designs. The research could be enriched by validating the model as applied to the realities of desert cities in northern Chile—not necessarily on slopes—and by conducting a broader study of desert cities worldwide that are experiencing the effects of climate change due to precipitation.

The theoretical and practical contributions promote resilience and sustainability in highly vulnerable desert urban areas and anticipate the need to protect human lives, investments in livable environments, and infrastructure to ensure a better quality of life.

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Conflict of Interests. The authors declare no conflict of interests.

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