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Retrofit Design for Climate Resilient Housing: Strategies for Architectural Adaptation to Climate Change

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Abstract

This study examines design flaws in single-family homes in the UAE, worsened by climate change-triggered rainfall and escalating maintenance requirements. The research focuses on three objectives: identifying existing weaknesses, analyzing building materials and construction methods, and proposing enhanced retrofit design standards. The methodology comprises both secondary data, gathered through literature reviews, and primary data obtained via site visits, participatory observation, and case studies. Examining multiple UAE regions, particularly six case studies in affected housing in Dubai, Sharjah, and Ajman, underscores widespread concerns in resilient housing, revealing deficiencies in drainage, waterproofing, and protective detailing. Notable problems include inadequate drainage slopes, subpar sealing around structural penetrations, and insufficient moisture barriers. These issues compromise structural integrity, inflate maintenance costs, and pose health hazards from mold and poor indoor air quality. By assessing current conditions, the study suggests various retrofit solutions, such as improved water-resistant coatings, slope modifications, drip edges, and overhangs. Findings emphasize rigorous detailing, robust materials, and periodic inspections to mitigate impacts from intensifying rainfall. Additionally, broader urban planning strategies, such as flood risk assessments and upgraded infrastructure, are crucial in minimizing future water intrusion. Collectively, these insights advocate novelty in research and set a blueprint for a fundamental shift in UAE housing design, prioritizing climate resilience, structural longevity, and occupant well-being in an era of rapidly changing environmental conditions.

Keywords: Climate Change; Housing Design; Maintenance; Retrofit for Climate Resilient Design.

1. Introduction

Climate change represents a significant global challenge, profoundly affecting the environment, society, and economy. A particularly urgent issue is enhancing the resilience of affordable housing against the effects of climate change, including increased flooding. Affordable housing serves as a critical refuge for millions, yet its susceptibility to flood damage threatens the well-being of countless individuals. This issue arises from the necessity to adapt housing to withstand climate change effects while managing the constraints of cost and resource availability. Urban flooding occurs when intense and sudden rainfall events exceed the capacity of drainage systems, leading to inundated streets and basements. This phenomenon has been documented in various global regions and is a growing concern due to its frequent

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and widespread occurrence [1-3]. Such events, often referred to as pluvial floods, highlight the challenges that modern urban drainage infrastructures face under extreme weather conditions.

The United Arab Emirates, predominantly a dry region, receives limited annual rainfall, typically occurring on just 5 to 10 days each year, primarily from November to March. In response to this scarcity, UAE authorities have adopted cloud seeding, a method involving the dispersion of substances into the atmosphere to promote cloud formation and increase precipitation. This strategic initiative, aimed at boosting the nation's rainfall, seeks to decrease reliance on desalinated water resources [4].

Recent data from the National Center of Meteorology UAE (2022/23) [4] reveal an uptick in rainfall during the winter months, with a total annual precipitation of 56.2 mm in 2022. Notably, the summer month of July recorded an unprecedented 14.8 mm of rainfall, the highest for this period in over two decades, although March and May saw no rainfall. On July 27th, significant rainfall occurred, particularly in the Fujairah area, where Fujairah Port recorded 220.9 mm, Fujairah Airport 169.4 mm, and Masafi 123.3 mm. This event marked a shift in the long-term average, indicating a decrease in annual rainfall yet punctuated by intense, localized downpours. Sherif et al. [5] also discussed how climate change compounds the challenges of managing the UAE's water resources. Increasing global temperatures enhance evaporation rates, exacerbating water scarcity. As climatic conditions become less predictable, precipitation patterns fluctuate more widely, complicating the management of water resources. The heavy rains continued until July 28th, 2023, resulting in flash flooding across various locales in and around Fujairah. Further research by Daniel [6] predicts a significant increase in the UAE's rainfall due to climate change. The National Centre of Meteorology anticipates a potential rise in annual precipitation by up to 30% across much of the country during this century, reflecting a considerable adjustment to the regional climate paradigm.

A historic climatic event was recorded by WAM [7] between April 14–16, 2024, marking the heaviest rainfall since official record-keeping began in 1949. The intense storm affected various parts of the country, causing extensive damage. This extraordinary rainfall of over 250 mm within less than 24 hours in some areas of Dubai and Sharjah led to widespread flooding, uprooting of trees, and significant infrastructural damage, including in Dubai, where the impact was so severe that flights were canceled, vehicular traffic was disrupted, and schools were closed. This remarkable weather event underscores the evolving and unpredictable nature of climate-related phenomena in the region.

According to Ebrahim et al. [8], the intense and unexpected rainfall in the UAE on April 16, 2024, caused significant disruptions across multiple cities, rendering them almost immobile. In Dubai, the streets outside residences were so inundated that vehicles were immobilized, and residents did not anticipate any external assistance. In Sharjah, the situation was dire as residents of flooded apartment buildings, left without electricity, struggled to evacuate vulnerable individuals, including an elderly woman and young children from a high-rise. Moreover, in some areas, water flowed continuously into buildings from adjacent streets that were elevated above the building foundations. In Dubai's Green Community West, residents faced the challenge of wading through almost a meter of murky standing water to access their homes, with the added complication of non-functional plumbing systems due to the backflow from flooded drains. This extraordinary weather event effectively brought daily life to a halt in Dubai, Sharjah, and Al Ain, leading to the closure of educational institutions and a shift to remote working as recommended by authorities.

Further exacerbating the chaos, the floodwaters disrupted road traffic, grounded flights, and suspended operations of the Dubai Metro and Dubai Tram. Fortunately, early warnings from the National Center of Meteorology allowed for some preparatory measures, such as implementing distance learning for schools and encouraging remote work for both the public and many private sectors. This record-breaking rainfall, the most severe in 75 years, left many motorists stranded on flooded roads. However, the community response was remarkable, with residents coming together to assist those trapped in their vehicles and offering shelter to those displaced by the flood [9]. This collective spirit highlighted the resilience and solidarity of the UAE's population in facing such unprecedented natural challenges. These occurrences significantly impact the built environment, especially housing infrastructures and the communities dependent on them. In recent years, numerous research initiatives have focused on documenting the diverse impacts of climate change on human settlements and their living spaces.

Reporting the effects of climate change and heavy rains on housing, Chohan et al. [10] reported that adobe houses suffered extensively under flood conditions, with damage ranging from wall cracks to total collapses, revealing their vulnerability to such disasters. Soil erosion and defects in floors and roofs further weakened the structures. In various regions of Pakistan, the damages to housing were severe, including foundational and water tank damages and building failures. Landslides and the powerful wash-away effects of floodwater further aggravated the situation, underscoring the intense destructive potential of these natural events on less durable construction. Buchanan et al. [11] conducted a detailed study on the effects of flooding on residential buildings, underscoring the importance of proper planning and the selection of appropriate building materials to mitigate damage. The research detailed the detrimental impacts of floods on the foundations, walls, and overall structural integrity of the buildings involved, offering crucial information for builders, policymakers, and homeowners.

Adger et al. [12] provided an extensive analysis of how climate change impacts housing and human settlements. Their research outlines a detailed rationale connecting climate change to increased housing disasters. The study emphasizes that climate change intensifies the susceptibility of residential buildings to severe weather phenomena, including hurricanes, floods, heatwaves, and wildfires. This not only jeopardizes the safety and welfare of residents but also imposes considerable economic burdens on homeowners, tenants, and governmental bodies responsible for the restoration or reconstruction of affected properties. Additionally, climate change presents obstacles to the accessibility and affordability of housing. In addition, the research conducted by Anderson et al. [13] explored the complex relationship between climate change and affordable housing. Their findings indicate that in the United Kingdom, climate change is intensifying existing disparities in access to affordable housing, thereby heightening the risks of displacement and homelessness.

2. Literature Review

In previous section 1.0, this study has established that the frequency and intensity of heavy rainfall events have escalated due to global climate change, posing significant challenges to housing infrastructures worldwide. This review section examines the literature concerning low-resilient house designs under heavy rain conditions, focusing on structural vulnerabilities, mitigation strategies, and policy responses, as shown in Figure 1.

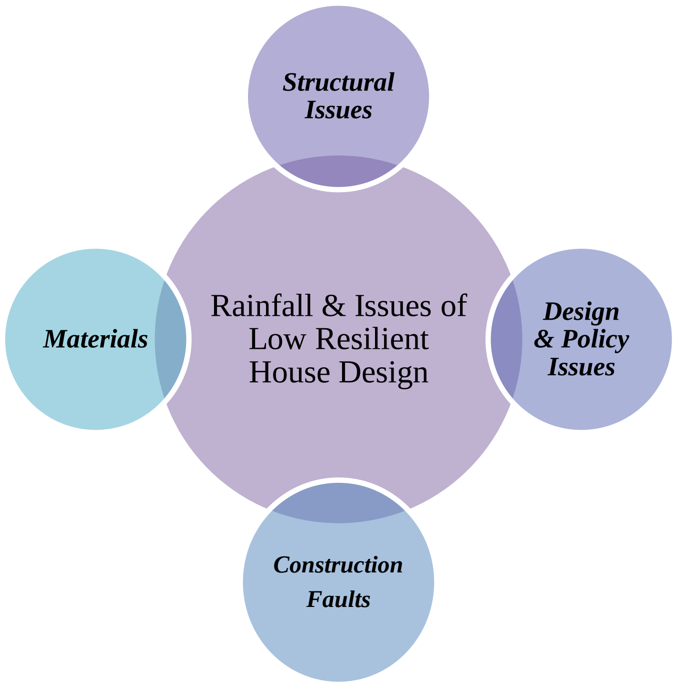


Figure 1. Rainfall and Low Resilient Housing

Further, this part of the study evaluates scholarly insights into five interconnected themes: damage caused by challenges encountered in coastal developments, conditions in locations hit by tsunamis, exposure risks in areas prone to wildfires, and the ramifications of extreme heat and prolonged drought. Researchers have consistently identified systemic shortcomings, indicating an urgent demand for design improvements that better align with a shifting climate.

2.1. Rainfall and Effects on Built Environment

Heavy rains expose critical structural vulnerabilities and their impact on house designs not built to withstand such conditions. Jordan & Rogers [14] and Sen [15] document the physical failures in housing structures such as foundation washouts and roof collapses in flood-prone areas. These vulnerabilities not only endanger the physical safety of inhabitants but also lead to substantial economic losses [16, 17]. Furthermore, studies by Taylor et al. [18] and Tingsanchali [19] discuss the inefficiencies in drainage systems and the long-term moisture damage to building materials.

Regarding resilience through design and materials, literature portrays a variety of design principles and materials that enhance housing resilience. Heibaum [20] and Bignami et al. [21] advocate for the use of elevated structures on stilts or piers, a method supported by Faircloth et al. [22] for its effectiveness in flood mitigation. Additionally, waterproofing solutions and materials that resist mold and moisture are crucial in regions experiencing heavy rainfall, as detailed by Shell [23] and Khartode et al. [24]. Another approach for climate-resilient house design is constructing homes in clusters and elevating the foundations above the floodplain, ensuring that residential enclosures stay dry during flooding events. This planning and architectural approach often involves using columns, docks, or raised earth mounds to lift the structure above potential water levels. While effective, this method can lead to increased construction expenses and may necessitate more frequent maintenance [25, 26].

Innovative technologies and green infrastructure play a critical role in enhancing resilience in house design in the face of climate change. Smart home systems that integrate real-time weather tracking and automated water resistance measures are explored by Sturiale & Scuderi [27] and Staddon et al. [28]. Green roofs and permeable pavements reduce surface runoff and mitigate flood risks, a point emphasized by Ercolani et al. [29] and Öztürk et al. [30]. The discussion above underscores the necessity of integrating resilience into house design to cope with the increasing threats posed by heavy rains. While numerous studies offer valuable insights and solutions, the need for practical implementations that bridge the gap between theory and practice remains critical. Continuous innovation, coupled with robust policy frameworks, will be essential to advancing the field of resilient housing design.

Given the high risk of damage from climate change, there is a need to improve and implement policy and design codes for resilient houses. This requires a multi-faceted approach that involves policy interventions, community engagement, and technological solutions. One strategy is to invest in green infrastructure that can mitigate the effects of climate change. Green infrastructure includes measures such as green roofs, rain gardens, and trees that can help to reduce the risk of flooding and erosion while providing other benefits such as improved air quality and enhanced biodiversity [30-33]. Policy interventions are essential for promoting resilient housing designs. The studies by Enker & Morrison [34] and Mitchell [35] highlight the role of updated building codes and regulations that mandate resilience features. Community engagement strategies, such as those discussed by Patel [36] and Chaurasia et al. [37], are also vital in raising awareness and ensuring compliance with new housing standards.

2.2. Effects of Tropical Storms and Tsunamis on Coastal Buildings

Besides the effects of climate change and unprecedented rainfall, there are other escalating climate disturbances, from tropical storms to intensifying heat waves, emphasizing the critical need to develop housing solutions capable of withstanding such environmental pressures. Investigations in various academic fields have repeatedly shown that existing residential structures often lack robustness in materials, structural detailing, and construction methods [38-40]. In the context of irregular rainfall patterns, studies highlight that poor drainage and inadequate water-resistant features can lead to significant water intrusion and flooding, with older properties particularly at risk due to obsolete designs and limited retrofit guidance [38]. Investigations further reveal that suboptimal roof gradients and outdated stormwater strategies often result in damage to structural components [39]. Although innovative hydrophobic coatings have drawn recent attention, there is still a shortage of standardized protocols for renewing older buildings to manage heavier rainfall [40, 41]. In addition, recent investigations by Zhu et al. [42] and Zhou et al. [43] underscore the performance enhancements achieved through hydrophobic coatings on residential exteriors exposed to intense rainfall. These specialized surface treatments exhibit strong water repellency, thus reducing moisture uptake by building materials. By minimizing prolonged contact between water and vulnerable substrates, hydrophobic layers prevent structural degradation, promote longevity, and limit mold growth. Scholars highlight their role in sustaining thermal insulation, even in saturated conditions, thereby optimizing energy efficiency. Additionally, advances in nanotechnology have resulted in improved durability and self-cleaning features, further minimizing maintenance needs. Overall, hydrophobic coatings represent a promising, cost-effective strategy to bolster housing resilience against severe precipitation events.

Along coastal zones, ongoing research indicates that foundations can deteriorate from encroaching saltwater, while high winds carry moisture into vulnerable structural interfaces [44, 45]. Proposed approaches, including flexible building codes and amphibious housing concepts, show promise but have yet to be rigorously assessed for feasibility in communities with lower financial resources [46, 47]. Housing exposed to tsunami events, on the other hand, demonstrates the need for specialized reinforcements and flood defenses, particularly as the focus on immediate rebuilding often overshadows long-term resilience measures [48, 49]. Elevated frameworks and breakaway panels can mitigate water-related damage, though socio-economic and legal constraints hinder widespread application [50, 51].

One of the major challenges in coastal settings prone to large earthquakes is the threat of a subsequent tsunami, placing the issue of tsunami and housing reconstruction at the forefront of concerns for policymakers, engineers, and local communities. Post-disaster housing reconstruction in these regions calls for a holistic strategy that balances immediate rebuilding needs with sustainable resilience [51, 52]. Scholars emphasize the significance of incorporating specialized tsunami engineering for housing, where architectural and structural designs are tailored to endure powerful water surges and the impact of drifting debris. Common measures include reinforced concrete components, raised living spaces, and breakaway wall elements that help redirect hydrodynamic forces away from core structural sections, thereby minimizing collapse risks [53, 54]. Moreover, case studies of previous disasters indicate that conventional building practices often fall short under extreme coastal inundation. Consequently, countries susceptible to seismic hazards are exploring revisions to their construction regulations, integrating explicit tsunami structural design provisions aimed at boosting performance and safety. Such amendments typically define performance objectives, set minimum criteria for structural integrity, and encourage the use of innovative materials capable of sustaining repeated stress loads. Drawing from computer-based fluid simulations and forensic examinations of damaged buildings, these improved guidelines are expected to fortify dwellings and enhance occupant protection in post-tsunami scenarios [55, 56].

In parallel, decision-makers and industry representatives are reassessing the economic feasibility of stricter codes to ensure that reconstruction is not only durable but also cost-efficient. Collaborative partnerships between government bodies, technical experts, and community groups have yielded forward-thinking methods that strengthen building performance while reflecting local cultural preferences and ecological constraints [57]. Notably, the literature confirms that solid tsunami planning goes beyond engineering; measures such as public awareness initiatives, effective evacuation routes, and active community participation play a vital role in safeguarding lives and property. Consequently, refining construction standards in accordance with evolving research stands as a pivotal step toward reducing vulnerabilities and accelerating recovery after tsunami events. Future research must continue to refine tsunami structural provisions, ensuring that future updates of building codes match evolving hazards [58, 59].

2.3. Effects of Climate Change & Wildfires on Buildings

Another aspect of climate change is wildfires and resilience of built form, zones prone to wildfires; the focus shifts to materials resistant to fire, planned vegetation clearance, and regional planning that incorporates safe buffer distances. Research points to promising innovations such as advanced composites and heat-shielding barriers [60]. Elevated wildfire activity in many regions has spurred research into retrofit solutions that strengthen houses against extreme heat and ember penetration. Recent studies emphasize that improving external cladding, reinforcing roof and window assemblies, and utilizing non-combustible materials can significantly reduce structural loss during wildfire events. However, the pursuit of a truly sustainable and fire-resilient built environment involves more than just reactive measures. Proactive design choices that balance minimal ecological impact with superior fire performance are increasingly central to this field. In addition, the emergence of fire-safe aerogels and foams for thermal insulation has highlighted new avenues for improving occupant safety [61, 62]. These advanced materials are celebrated for their low weight, excellent insulation capacity, and enhanced flame resistance. Yet, questions remain about their overall lifecycle impacts, cost, and scalability for large-scale architectural projects. Critics also point out the need for comprehensive policy frameworks that mandate rigorous testing and performance standards [63-66]. In general, the literature offers promising evidence that enhanced retrofitting techniques and fire-safe insulation can reduce the destructive potential of wildfires; further multidisciplinary research is essential. By integrating building science, environmental stewardship, and economic considerations, the goal of resilient, sustainable, and fire-safe housing can be effectively achieved. Such convergence remains vital.

2.4. Effects of Climate Change & Heat Waves

Lastly, persistent heatwaves and lack of rainfall strain the thermal efficiency of buildings, and accelerating climate change has pushed desert and tropical regions to confront unprecedented heat levels, raising concerns over occupant well-being and indoor air quality. This phenomenon places additional strain on the thermal efficiency of houses, prompting a surge in energy consumption for mechanical cooling [67, 68]. Traditional building techniques, such as thick walls, shaded courtyards, and carefully placed openings, have historically mitigated high temperatures and harsh sunlight. However, contemporary developments often overlook these climate-responsive methods in favor of standardized approaches, leaving residents vulnerable to extreme conditions and, consequently, elevated cooling costs [69, 70].

In response, researchers have turned to more adaptive strategies, particularly hybrid radiant-air cooling systems. These setups integrate radiant panels with supplemental air circulation to moderate indoor heat while optimizing occupant comfort. Unlike purely mechanical systems, hybrid configurations leverage the heat transfer advantages of radiation, reducing the reliance on high-capacity air conditioners [71, 72]. As desert climates intensify, this blend of radiant cooling and controlled airflow emerges as a viable approach to conserve energy and enhance resilience. Moreover, integrating local practices such as wind towers or vernacular roof designs into hybrid cooling frameworks might yield synergistic benefits, thereby amplifying thermal performance while honoring regional heritage [73-75].

However, current studies do not adequately explore how these indigenous methods can be combined with computational simulations to tackle the challenges of urban heat phenomena. While passive measures and systematic ventilation demonstrate notable energy savings, further empirical work is necessary to refine design strategies that match local climatic variations. The integration of computational fluid dynamics optimizes passive and hybrid cooling designs in hot climates. Comprehensive modeling of dynamic microclimatic parameters coupled with policy support can spur the adoption of innovative, contextually relevant solutions. Ultimately, prioritizing climate-sensitive design, exploring hybrid cooling techniques, and preserving time-tested construction methods will prove vital in achieving sustainable thermal comfort and long-term resilience in rapidly warming environments.

3. Material and Methods

3.1. Implementation of Retrofit Design in UAE

An analytical review of the literature reveals that government subsidies, incentives, and public-private partnerships (PPPs) play pivotal roles in advancing retrofitting measures for climate resilience in housing. In regions like the UAE, where climate change poses increasing threats, adopting such financial and structural frameworks is essential to encourage large-scale retrofitting efforts [76-78]. Studies highlight that government subsidies significantly reduce the financial burden on homeowners, making retrofitting more accessible. Subsidies targeting low-income households are particularly effective in promoting equity while enhancing overall community resilience [79]. Moreover, subsidies for energy-efficient materials and waterproofing solutions help mitigate upfront costs, which often hinder adoption [77]. Incentives in the form of tax credits, low-interest loans, or grants have been recognized as critical tools for stimulating retrofitting initiatives. Tax rebates for installing sustainable insulation or moisture-resistant materials motivate homeowners to invest in long-term solutions [80]. Similarly, utility rebates tied to energy savings from retrofits foster sustained homeowner participation [76]. Public-private partnerships provide a unique opportunity to bridge funding gaps and bring innovation into retrofitting projects. PPPs enable collaborations between government entities, private developers, and technology providers, fostering shared responsibility for implementing resilient housing solutions [78]. Successful models, such as those used internationally, can be adapted to meet the UAE's needs through innovative and localized approaches [80].

Additionally, regulatory frameworks, when combined with incentives, enhance retrofitting adoption. Combining legal mandates with financial assistance ensures compliance without overburdening homeowners [77]. Effective policies often include performance-based subsidies, wherein financial support is tied to achieving specified resilience benchmarks. Furthermore, technological advancements supported by government-backed research and private investments play a critical role in advancing resilient housing. Innovations in fire-safe insulation and waterproof materials, when subsidized or incentivized, accelerate market adoption and improve housing resilience [76].

3.2. Identified Gaps and Future Directions

Despite significant progress in climate-resilient housing, several gaps persist. First, the integration of occupant well-being (e.g., health and comfort) into engineering-centric solutions remains underrepresented [30-33]. Second, research frequently focuses on single hazards (e.g., floods or fires), while ignoring compound events that simultaneously expose multiple vulnerabilities [24-25]. Third, scaling innovative designs (like amphibious or elevated structures) to diverse socioeconomic contexts remains a challenge [6, 9]. Lastly, the literature calls for updated regulatory frameworks enforced through local codes and robust incentive structures to ensure widespread adoption of resilient designs [18-20]. Addressing these gaps necessitates interdisciplinary collaboration among architects, engineers, policymakers, and public health experts, ultimately leading to holistic and long-lasting solutions for climate-threatened housing.

3.3. Research Viability

Considering the discussions outlined above, this study recognizes that recent climatic trends in the United Arab Emirates, especially the notable increase in significant rainfall events, have exposed critical vulnerabilities in the current housing design practice. Traditional design and construction practices are proving insufficient to cope with these changes, resulting in severe disruptions. This prompts an urgent need to rethink housing designs in the UAE to better accommodate the ongoing impacts of climate change, especially increased rainfall.

Houses and apartments in the UAE have historically been designed for a dry, arid climate, largely ignoring the potential for heavy rainfall. Recent events have demonstrated how easily rainwater can penetrate doors and windows, causing damage within homes. This indicates a critical lack of weatherproofing elements, low architectural detailing, and inadequate use of suitable materials in current building designs. Furthermore, the existing drainage systems in many residential areas are not capable of handling heavy rainfall, leading to widespread waterlogging and flooding. Essential services such as plumbing and electricity have also failed under these extreme weather conditions, exacerbating the discomfort and risks for residents.

Moreover, many residential developments have been constructed without adequate consideration of topographical studies. This oversight means that buildings are often situated in unfavorable locations, such as low-lying areas that naturally accumulate runoff, without sufficient drainage solutions in place. Addressing these issues requires a comprehensive retrofit design of existing housing. Retrofit housing designs must incorporate features that respond to the climatic realities of the region, including better waterproofing, improved structural integrity to withstand heavy downpours, and the use of materials that are resistant to moisture and mold.

3.4. Research Aim and Objectives

The aim of this study has been set to investigate and improve the resilience of housing infrastructure in the United Arab Emirates against the increasing frequency and intensity of rainfall due to climate change.

To effectively meet the aim of this study, it is essential to outline specific objectives that are designed to comprehensively address the fundamental purpose of the research. These objectives serve as critical stepping stones in ensuring that the study's goals are systematically achieved through focused and detailed investigations.

- Assess the Current Vulnerabilities: Evaluate the existing vulnerabilities of UAE residential buildings to water damage during heavy rainfall events, focusing on issues such as water penetration through doors and windows, and the adequacy of current drainage systems.
- Analyze Building Materials and Construction Practices: Examine the materials and construction practices currently used in UAE housing to identify their weaknesses in terms of water resistance and structural integrity during adverse weather conditions.
- Develop Enhanced Retrofit Design Standards & Proposal: Propose retrofit design techniques and standards for residential buildings that incorporate advanced waterproofing elements, technologies, improved drainage systems, and materials suited for wetter climates.

3.5. Research Framework and Methods

This framework in Table 1 provides a structured approach for conducting the research, ensuring that each objective is methodically addressed through appropriate methodologies, with clear expected outcomes that contribute to the overall aim of enhancing housing infrastructure resilience in the UAE against the effects of increased rainfall.

Table 1. Research Framework

Objective	Methodology	Expected Outcomes
Assess the Current Vulnerabilities	• Case studies, Site inspections, participation and surveys, Interviews with residents and building managers, review of maintenance records and scale of damage to residential units.	Identification of common points of failure in building exteriors and infrastructure. Insight into the effectiveness of existing drainage systems.
Analyze Building Materials and Construction Practices	• Literature review on best practices and materials for water resistance; • Interviews with construction experts and architects; • Analysis of case studies floods and rain affected building.	Detailed assessment of the water resistance and structural integrity of materials used. Recommendations for material and practice improvements.
Develop Retrofit Design Standards and Proposal	• Literature review of comparative analysis of building issues in tropical or high rain and flooding regions; • Analysis of existing design in case studies and propose retrofit changes in existing residential buildings.	Development of new design standards and design guidelines incorporating advanced technologies, retrofit elements and materials as a practical blueprint for existing and future building projects.

In response to set objectives, this study implements a comprehensive approach to investigate and address these challenges, based on primary and secondary data, as shown in Figure 2. The study begins with phase one by exploring literature reviews in the realm of climate-resilient housing, climate change and housing maintenance, available retrofits, and policy. The second phase of research began with case studies at various locations by conducting detailed building surveys and inspections across a representative sample of residential buildings to pinpoint common vulnerabilities such as water penetration, deficient design, and resulting maintenance. Concurrently, this study engaged with residents, property managers, and maintenance staff through semi-structured interviews to collect qualitative data on the frequency and impact of water-related damage.

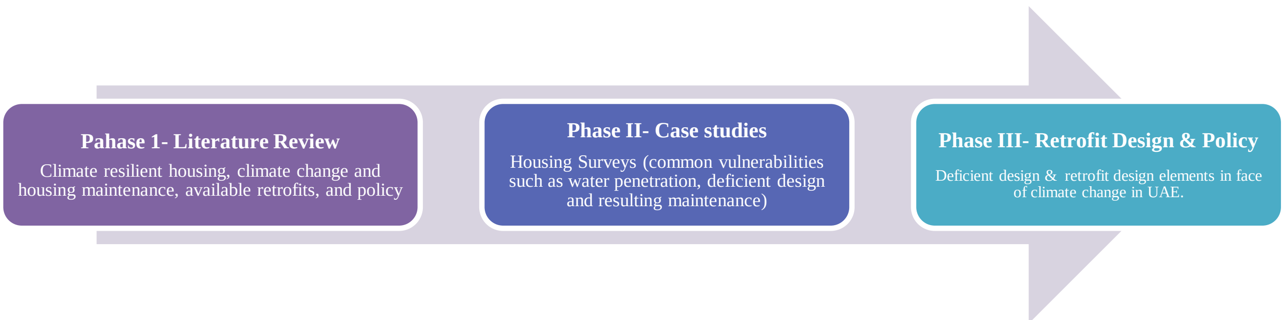


Figure 2. Research Phases

In the third phase, this study has analyzed the issues of deficient design and proposed and retrofitted design elements of existing buildings and a blueprint of policy guidelines for new housing design.

In the face of climate change in the UAE, this approach allows us to accumulate valuable insights, which we then analyze using statistical tools to discern trends and patterns in building vulnerabilities, echoing the methodologies used effectively by Tierolf et al. [81] and D'Ayala et al. [82] in their study of climate change, flooding, and building resilience in Southeast Asia.

Further, our study delves into the materials and construction practices currently utilized in UAE housing. Through a thorough literature review focused on water resistance and structural integrity, complemented by panel discussions with construction experts, architects, and engineers, we assess the effectiveness and identify weaknesses of these materials and practices. This phase involves a comparative analysis with global best practices, similar to the approach undertaken by Hashim & Sirajuddin [83] and Ali et al. [84], allowing us to spot discrepancies and areas ripe for improvement.

Building on the gathered data, the study has developed enhanced design standards and retrofit design proposals. This phase involves facilitating interviews with residents, owners, and building professionals, in addition to a comparative analysis of design practices in tropical and high-rainfall regions to suggest design standards and policies that better address the emerging climate challenges. The results of this study have developed a set of retrofit design elements and materials under simulated conditions of heavy rainfall to evaluate their practical efficacy. Parallel to these outcomes, this research has proposed a set of policies and design standards, including implementation strategies and compliance mechanisms. This part of our methodology is modeled on the successful process described by Tyler & Moench [85], who developed new urban planning guidelines to enhance resilience to climate change through expert workshops and prototype testing.

Through these interconnected activities, our research aims to provide actionable insights and solutions that significantly enhance the resilience of UAE housing against the increasingly severe impacts of climate change and heavy rainfall.

4. Case Studies

The investigation into the resilience of standalone houses in the UAE to heavy rainfall began with a rigorous preparatory phase designed to ensure the selection of representative case studies. This initial stage involved a strategic process to identify diverse standalone houses in Sharjah and Ajman, areas that have recently experienced significant rainfall events as reported by Daniel [6], WAM 2024 [7], and Ebrahim et al. [8]. The selection process was guided by specific criteria, including the severity of reported damage, ease of access to the property, and the level of cooperation from homeowners and tenants. These criteria ensured that the chosen properties not only exhibited various degrees of vulnerability but also provided a practical framework for data collection.

Collaboration with property owners was critical to this process. Prior to initiating field visits, the research team engaged with homeowners and tenants to secure consent and access, ensuring that all necessary preliminary data, such as historical maintenance records and structural assessments, were available. This partnership enabled the gathering of both qualitative and quantitative data during subsequent site evaluations.

The study was deliberately confined to low-density urban housing, focusing on standalone houses and townhouses in areas of Ajman and Sharjah that had been highly affected by recent rainfall. This targeted approach allowed for a detailed analysis of urban residential structures under extreme weather conditions, providing insights into localized vulnerabilities. Additionally, the selection of case studies was influenced by local privacy regulations and logistical considerations, such as the ease of access and the feasibility of comprehensive data collection. Overall, this methodical approach ensured that the selected case studies reflected a broad spectrum of housing conditions and were well-suited for evaluating retrofit measures. The robust dataset derived from these cases serves as a foundational element for analyzing current structural weaknesses and developing tailored recommendations for enhancing the resilience of residential buildings in similar climatic environments. In this context this study has managed to reach sites (neighborhoods) such as Al Yasmin and Naumeia in Ajman and Qasmia and Al Suyoh suburb and Al Mijaz in Sharjah, as shown in the location map (Figures 3 to 6).

Figure 3. Al Yasmeen Ajman UAE

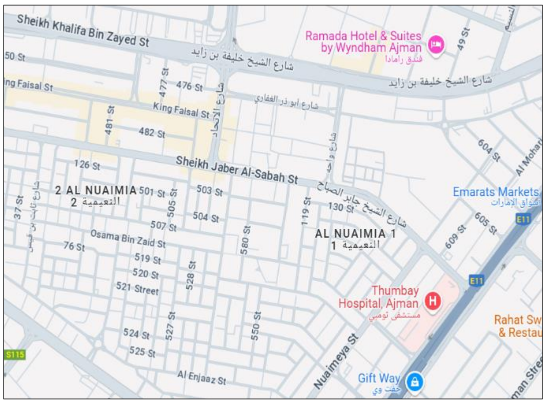


Figure 4. Al Naumia Ajman UAE

Figure 5. Mijaz Sharjah UAE

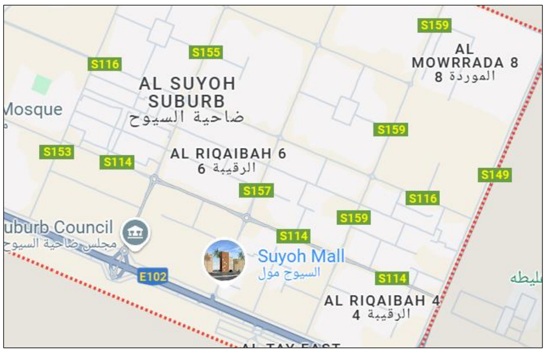


Figure 6. Al Suyoh Sharjah UAE

The research team undertook direct engagements with homeowners and tenants; these initial assessments were vital, involving thorough walkthroughs of each property to assess the general conditions. However, the exact location and sites and houses cannot be disclosed for the sake of privacy and regional rules. These interactions were instrumental in establishing an understanding with the residents, which further enabled open discussions about their experiences and the specific impacts of the rainfall on their properties. However, in the phase of detailed observations, the team meticulously documented visible damage to the properties. This included a thorough examination of the integrity of roofs, walls, foundations, and windows. Particular attention was directed towards identifying signs of water penetration, structural weakening, and any resultant erosion surrounding the properties. Detailed records of each defect were maintained, noting the location, dimensions, and perceived causes of the damage.

Simultaneously with participation and the survey, structured interviews were conducted with the homeowners. These discussions aimed to delve deeper into the personal experiences of the residents during the rainfall events. The interviews covered various aspects, such as the duration and intensity of the rain, the residents' immediate responses to water ingress, and any previous similar incidents. To complement the qualitative data, photographs of all noted damage were taken, meticulously tagged with relevant details including the causes of damage and impact at specific locations within the property for later analysis.

4.1. Case 1: Water penetration at Vertical and Curved Surfaces

Figures 7-a to 7-c depict a dome and wall significantly compromised by water penetration due to detailing design flaws and inadequate waterproofing, with visible moisture damage and fungal growth undermining both its structural integrity and aesthetic. The dome's waterproofing is insufficient, failing to prevent water from seeping through cracks or joints, a situation worsened in recent heavy rainfall environments in the UAE. The construction materials used are not moisture-resistant, evident from the rapid deterioration marked by peeling paint and discoloration from long-term moisture exposure. Additionally, the ceiling's poor drainage design does not effectively manage water runoff, resulting in pooling and seepage that exacerbate the damage over time. The persistent dampness has also encouraged mold and fungus, posed health risks, and further compromised the structure. This scenario underscores the urgent need for robust waterproofing, durable materials, and effective drainage systems in architectural design to prevent such issues.

(a) (b) (c)

Figure 7. (a) Water leaks at ring beam, (b) Dampness and Fungus, (c) Dampness in wall

4.2. Case 2: Water Ponding on Horizontal Surfaces

Figures 8-a to 8-c showcase a significant architectural and construction defect characterized by water ponding on a flat surface, likely an exterior and interior of a building. This issue stems from insufficient sloping or leveling during construction, hindering effective rainwater drainage and leading to various structural complications. The lack of a proper incline impedes water runoff, essential in architectural design to prevent water accumulation. Persistent standing water can penetrate material pores and cracks, weakening the structural integrity through moisture damage, which accelerates the decay of wooden elements, rusting of metal components, and deterioration of protective coatings. Additionally, water trapped on the surface can seep underneath, compromising substructures and potentially destabilizing the foundation, posing long-term safety risks. This environment also cultivates mold and algae growth, negatively impacting appearance and possibly health if inside or material lifespan if outside. Addressing these issues requires integrating effective water management strategies in design and construction phases, including appropriate grading, drainage channels, or using porous materials. Regular maintenance to keep drainage systems clear, especially in rain-prone areas, is crucial.

(a) (b) (c)

Figure 8. (a) Rainwater drains leaks, (b) Water ponding at overhang, (c) Poor slopes & water ponding

4.3. Case 3: Flash Flood Inside

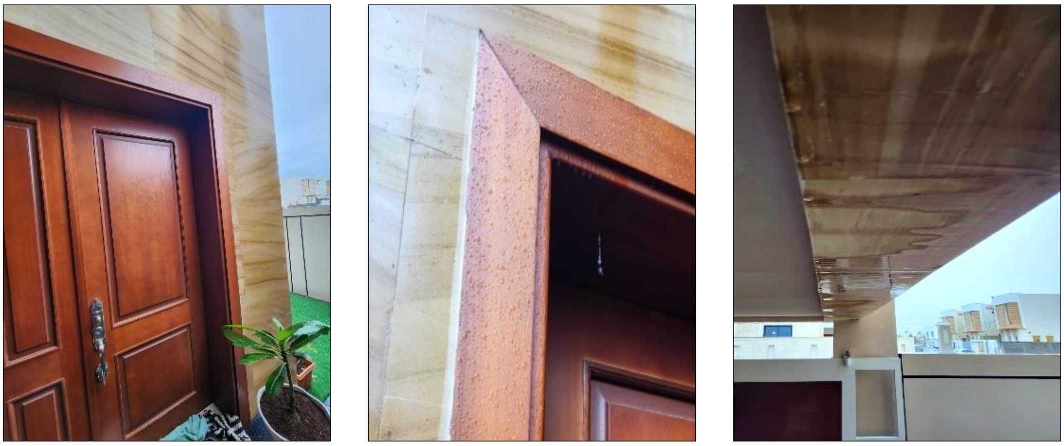
Figures 9-a to 9-c depict a serious case of indoor flooding, highlighting a significant design flaw in a residential setting overwhelmed by flash flooding. This likely stems from inadequate architectural planning for flood mitigation, especially in regions of the UAE susceptible to high water levels. Primary oversights include insufficient plinth level of the building, poor drainage systems, and lack of effective barriers to prevent water entry into living spaces. In designing homes in flood-prone areas, it is essential to implement measures to prevent water ingress. Strategies should involve elevating the building's foundation, installing robust drainage systems capable of managing sudden, heavy flows, and placing flood barriers at critical entry points like doors and windows. Neglecting these preventive measures can result in water easily penetrating the structure, rendering the dwelling uninhabitable, and causing substantial property damage and safety hazards for residents.

(a) (b) (c)

Figure 9. (a) Water ponding inside house, (b) Water ponding inside house boundary, (c) Water ponding at lobby

4.4. Case 4: Water Runoff and Penetration on Wall and Soffit Surface

Figures 10-a to 10-c illustrate design flaws where rainwater runoff is impacting the building's exterior, evident around the wall surface and the architrave of a door, leading to wood damage and water penetration. This points to a lack of effective architectural measures, such as inadequate drip, overhangs, or improperly installed flashing, which fail to divert water away from vulnerable wood frames and joints. Furthermore, the architrave’s treatment and positioning might not sufficiently resist water entry, likely due to poor sealing or non-weather-resistant materials. This architectural oversight not only detracts from the building's visual appeal but also poses a risk to its structural integrity by permitting water to seep in. Such moisture penetration can degrade building materials, especially wooden elements, making them susceptible to rot and mold. Additionally, damp conditions may foster pest infestations, compounding the damage. To safeguard the building's functionality and longevity, it is crucial to enhance its water management strategies and ensure regular maintenance to address these vulnerabilities effectively.



(a) (b) (c)

Figure 10. (a) At wall rainwater run-off, (b) Rainwater penetration, (c) At soffit rainwater dispersion

4.5. Case 5: Water penetration through Oriels & Curtain Walls

Figures 11-a to 11-f clearly illustrate an architectural design flaw resulting from the absence of a protective canopy or sufficient window projection, leading to rainwater penetration as evidenced by water stains cascading down the interior wall. This originates from large flush windows or curtain walls lacking adequate protection against the elements. Architecturally, the design and installation of such large window panels, especially in curtain wall systems, should include robust weatherproofing measures like canopies, eaves, or extended sills to channel rainwater away from the building's façade. The visible streaks on the wall suggest a failure to implement these protective measures effectively, allowing rainwater to infiltrate the window frames or glass panels and seep directly into the building. This oversight not only causes cosmetic damage, marked by unsightly water stains, but also jeopardizes the structural integrity of the wall, potentially leading to more severe internal damage such as mold growth and material deterioration. Moreover, the water ingress can escalate maintenance costs and reduce the space's functionality and comfort for occupants. This situation highlights the critical need for integrating comprehensive weatherproofing in the initial design phase to enhance the longevity and durability of architectural structures, particularly in areas frequently exposed to heavy rainfall.

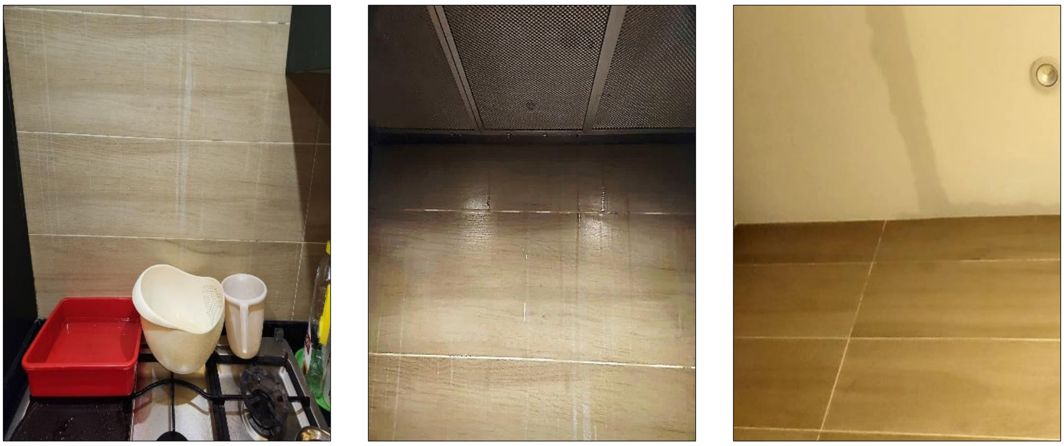
(a) (b) (c)

(d) (e) (f)

Figure 11. (a) At door rainwater penetration, (b) At window rainwater penetration, (c) Rainwater penetration curtain wall, (d) Sill sloping retrofit, (e) Paint peel off, (f) At wall rainwater marks

4.6. Case 6: Water Penetration through AC and Exhaust Vents

Figures 12-a to 12-c display visible signs of water running off on a kitchen wall, characterized by streaks that suggest a significant design detailing defect associated with water runoff. This issue likely stems from rainwater penetration through exterior penetrations such as cooking exhaust and air conditioning (AC) vents. Such vulnerabilities occur when the poor detailing, sealing, and waterproofing around these installations are inadequate or improperly executed, failing to prevent water ingress during rainfall. In the context of architectural design, ensuring that all penetrations through the building envelope, like vents, are meticulously detailed and sealed is critical. The failure depicted in the image typically happens when either the initial design did not adequately account for water sealing at these junctions, or the construction did not adhere to the required specifications for waterproofing. Over time, such oversights can lead to the deterioration of adjacent building materials, further exacerbating the damage and potentially leading to more severe structural issues.



(a) (b) (c)

Figure 12. (a) Rainwater penetration, (b) At exhaust rainwater penetration, (c) Rainwater leak & ceiling dampness

5. Analysis and Discussion

In the UAE, recent extraordinary rainfall events have starkly exposed significant vulnerabilities in residential design, underscoring the critical need for improved architectural planning and construction to effectively address the challenges posed by climate change.

Case 1 details the damage inflicted on the dome and wall due to water ingress, stemming from design flaws and inadequate waterproofing. The lack of moisture-resistant materials and improper drainage slopes has led to evident moisture damage, fungal growth, and structural compromise, highlighting the urgent need for durable waterproofing and robust materials to mitigate such issues.

Case 2 observes significant water accumulation on both external and internal surfaces, resulting from improper construction sloping and leveling. This deficiency hampers effective rainwater drainage, leading to structural weakening, decay of wooden elements, and potential foundation instability. The presence of mold and algae exacerbates the degradation of the building's aesthetic and structural integrity, emphasizing the necessity for comprehensive water management strategies and regular maintenance of drainage systems.

Case 3 recounts a scenario of indoor flooding caused by inadequate flood mitigation design, particularly in areas known for high water levels. The insufficient elevation of the building's foundation, coupled with ineffective drainage systems and the absence of strong water barriers, results in extensive property damage and renders the space uninhabitable. Implementing strategic foundation elevation and robust drainage systems is crucial to prevent water ingress.

Case 4 exposes how rainwater runoff adversely affects a building's exterior, damaging wood and facilitating water penetration around an architrave. The lack of effective architectural measures such as adequate drip edges, overhangs, or proper flashing highlights the need for precise water management and regular maintenance to maintain the building's functionality and longevity.

Case 5 depicts water intrusion through large flush windows or curtain walls, caused by the absence of a protective canopy or sufficient window projections. This design oversight leads to water stains, potential mold growth, and material deterioration, stressing the importance of comprehensive weatherproofing measures in the design and installation of expansive window systems to maintain structural integrity.

Case 6 illustrates water damage on a kitchen wall from moisture penetration through inadequately sealed and detailed external penetrations like vents. This highlights the importance of meticulous detailing and sealing of all building envelope penetrations to prevent water ingress and protect the materials and structural integrity.

Concurrently, these cases reveal a widespread deficiency in architectural resilience to increased rainfall and flooding in the UAE. They underscore an urgent need for advancements in weatherproofing, climate-adaptive building techniques, and proactive architectural design to enhance the durability and safety of structures amidst evolving environmental conditions. Based on findings in cases discussed above, the following matrix (Table 2) has been developed to ascertain the nature of defects raised from the adverse effects of climate change in the UAE.

Table 2. Issues of Low Resilience and Building Damage

Case	Building Issue(s) Identified	Root Causes	Possible Interventions for Resolution
1	• Dome and wall damage from water ingress; • Moisture damage, fungal growth, and structural compromise.	• Inadequate waterproofing and drainage • Use of non-moisture-resistant materials	• Upgrade to high-quality waterproof membranes; • Install proper drainage channels for dome and walls; • Use moisture-resistant materials (e.g., treated wood, water-repellent coatings); • Periodic inspections and maintenance.
2	• Water accumulation on external and internal surfaces; • Structural weakening, decay of wooden elements, potential foundation instability; • Mold and algae growth.	• Improper sloping and leveling of surfaces • Ineffective rainwater management	• Redesign sloping and leveling to ensure proper runoff; • Install comprehensive gutter and downspout systems; • Integrate foundation drainage solutions (French drains, sump pumps); • Regular cleaning and maintenance of drainage components.
3	• Indoor flooding; • High water levels causing property damage; • Uninhabitable spaces.	• Low foundation elevation • Inadequate flood mitigation measures • Ineffective drainage systems	• Elevate building foundations and critical areas above flood level; • Incorporate flood barriers and water-tight doors; • Install robust, strategically placed drainage systems; • Consider flood-adaptive design (wet-proofing or dry-proofing).
4	• Exterior damage from rainwater runoff. • Wood deterioration and water penetration around architrave.	• Lack of proper water management elements (drip edges, overhangs, flashing) • Insufficient protective detailing in exterior finishes	• Install drip edges, overhangs, and proper flashing around openings; • Use durable, rot-resistant wood or composite materials; • Regular inspection and maintenance of exterior finishes.
5	• Water intrusion through large flush windows/curtain walls; • Water stains, mold growth, material deterioration.	• Absence of protective canopies or sufficient window projections • Inadequate weatherproofing of large window systems	• Integrate canopies, overhangs, or window ledges to direct water away; • Use high-performance curtain wall systems with proper seals and gaskets; • Apply water-repellent coatings on glazing edges and frames; • Conduct thorough detailing and testing during installation.
6	• Water damage on kitchen wall; • Moisture penetration through poorly sealed external penetrations (e.g., vents).	• Inadequate sealing of building envelope penetrations • Poor detailing around external fixtures and openings	• Improve detailing and sealing at all penetrations (vents, ducts, pipes); • Use high-quality sealants, flashing tapes, and gaskets; • Regularly inspect and re-seal penetrations as necessary; • Employ moisture sensors or early detection systems.

6. Climate Change and Retrofit Design for UAE Housing

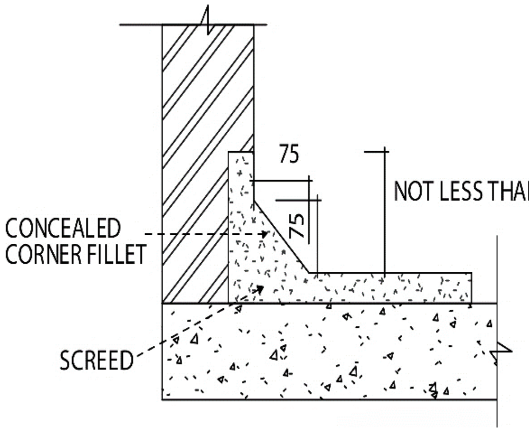
This study has established that recent extreme rainfall events (2024) in the UAE have revealed significant shortcomings in residential design and construction, particularly regarding the absence of critical detailing, protective features, and adequate waterproofing measures. In many instances, inadequately designed water slopes and insufficient drainage mechanisms have heightened building vulnerabilities, leading to persistent issues such as leaks, damp interiors, and overall structural compromise. These deficiencies not only result in physical damage but also contribute to a deterioration in indoor air quality by promoting mold growth, thereby posing significant health risks to occupants. Furthermore, the cumulative effect of these issues has led to escalating repair and maintenance costs, casting doubts on the long-term viability of the current housing stock.

Considering these challenges, there is a growing consensus on the necessity to retrofit existing buildings with climate-resilient strategies. The effectiveness of these retrofit measures was evaluated using a set of criteria, focusing on measurable improvements in structural integrity, water penetration, water ponding, and overall water resistance. In addition to these performance indicators, the assessment also incorporated factors such as cost efficiency and ease of implementation. These criteria were derived from both quantitative metrics and qualitative insights provided by expert reviews, ensuring that the proposed solutions are both effective and practical. The integration of durable construction materials with advanced waterproofing and moisture control methods is essential for mitigating the adverse impacts of intensified rainfall and other climate-related stresses. Such an approach is expected to enhance the resilience of residential structures, ensuring they remain functional and safe under extreme weather conditions. By addressing both the physical and economic aspects of retrofitting, this strategy aims to safeguard public health and secure long-term investment in housing infrastructure, ultimately contributing to the creation of more sustainable and resilient urban communities.

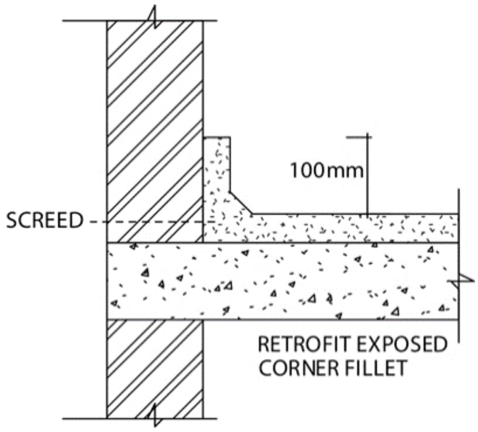
This section focuses on a series of six case studies that illustrate the gravity of these issues and highlight effective solutions to address them. Each case underscores specific shortcomings ranging from inadequate drainage slopes to insufficient detailing around structural penetrations and demonstrates how targeted interventions can dramatically improve resilience. The proposed retrofits encompass a broad spectrum of measures, including enhanced waterproof membranes, strategic elevation of foundations, robust gutter and drainage configurations, and the use of moisture-resistant materials. Moreover, the incorporation of protective overhangs, drip edges, and precise detailing around window and door openings can substantially reduce water ingress.

By illustrating the technical considerations involved and the potential benefits of each intervention, these case studies collectively advocate for a paradigm shift in the UAE's residential construction approaches. The insights gleaned from these retrofits underscore the pressing necessity for more rigorous design principles, regulatory policies, and maintenance practices that together will help fortify UAE housing against the challenges posed by an evolving climate.

In the ***first case study***, a critical focus is placed on enhancing the waterproofing of ceiling constructions. This is possible through the application of new waterproof coatings or the retrofitting of C.C. screeding and fillet details at the edges of the parapet wall of the installation of more effective moisture barriers, as shown in Figures 13-a and 13-b.



(a)

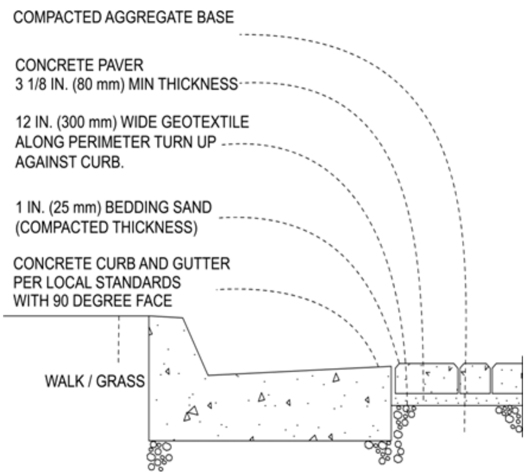


(b)

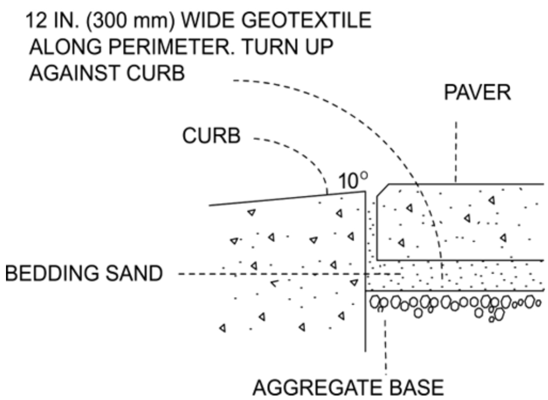
Figure 13. (a) Concealed Fillet Retrofit, (b) Exposed Fillet Retrofit

Additionally, improving ventilation in affected areas can significantly decrease moisture buildup, thus reducing the risk of fungal growth and structural damage. Regular inspections and maintenance are imperative for the early detection and prevention of potential leaks or moisture issues, crucial for maintaining the building's structural integrity and environmental health.

The second case highlights the need to adjust the slope of affected areas or retrofit drainage solutions to more effectively manage water. Retrofitting slopes at the edges of the outer surface, reworking visible cracks, and maintaining proper floor slopes are essential steps to mitigate water ingress, as shown in the retrofit detail section, Figures 14-a and 14-b.



(a)



(b)

Figure 14. (a) Retrofit for Gully Floor, (b) Retrofit for Gully Floor 2

The ***third case*** calls for a re-evaluation of architectural and urban planning norms, particularly regarding flood risk assessment and the integration of appropriate flood defense mechanisms into building designs. Retrofitting of existing structures with flood-resistant materials and features and ensuring compliance with local building codes that mandate flood mitigation are vital to prevent catastrophic outcomes. Based on site visits (flooded areas) in Dubai, Sharjah, and Ajman, it is evident that flooding risks in these areas are shaped by a combination of environmental and infrastructural factors. Specifically, sewer backflow flooding often stems from the sewer network, such as the condition of lateral sewer connections and local drainage systems. At one location in Sharjah, infiltration flooding is significantly affected by the prevailing groundwater conditions, the properties of the soil, and how individual plots manage drainage. The situation of overland flooding was most commonly noticed at various sites, resulting from ineffective or non-availability of regional stormwater management infrastructures and neglected local topographical features such as elevation. Given these observations, it is crucial to conduct comprehensive research to further consolidate these varied pragmatic factors. This approach will enable a more precise evaluation of site-specific flood vulnerabilities in urban settings like Sharjah and Ajman, enhancing our understanding and management of urban flooding scenarios.

In the ***fourth case***, it is noted that existing water management strategies require reassessment to enhance the building's design, including improving architectural details such as sealants around openings, adding or extending overhangs, and using more durable materials for exposed areas. Regular maintenance checks are crucial to identify and rectify any early signs of water damage, ensuring the building's safety and functionality. In this context, the following retrofit has been suggested in Figure 15 to address the situation of excess rain penetration.

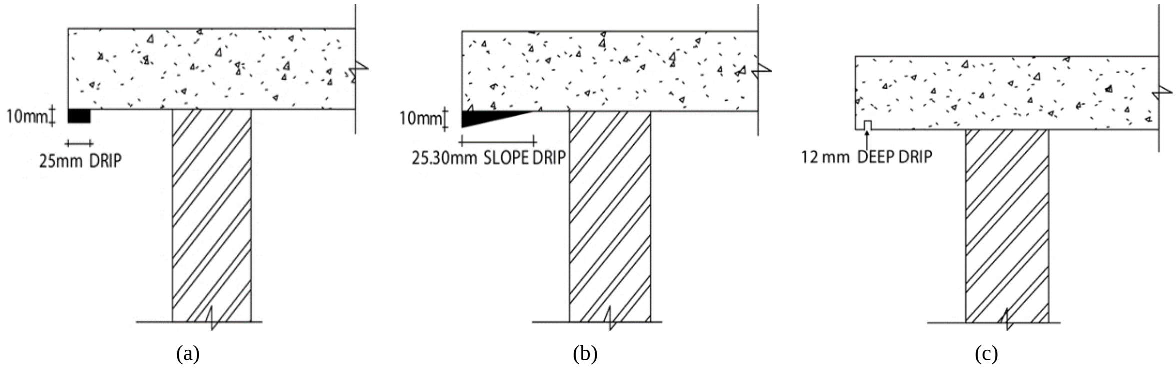


Figure 15. (a) Rainwater Drip 1, (b) Rainwater Drip 2, (c) Rainwater Drip 3

The ***fifth case*** suggests that the building's façade may need redesigning to include adequate weather protection. Retrofitting might involve adding architectural features like a slope in the outer sill, awnings, or extended ledges to provide better coverage over vulnerable areas. Ensuring that all window installations are complemented with high-quality weather stripping and water-resistant sealants is essential for enhancing the building's resistance to water penetration, as shown in Figures 16-a and 16-b.

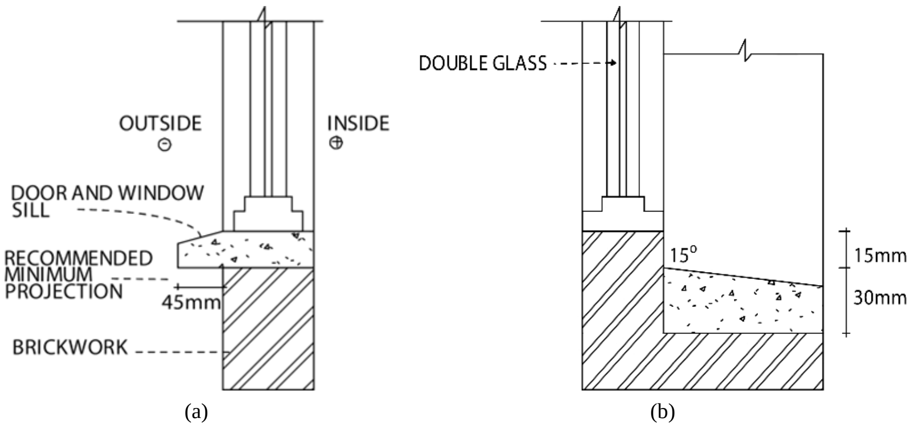
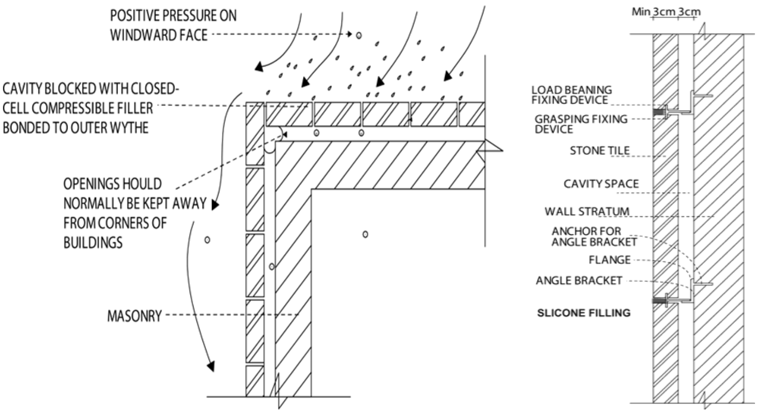


Figure 16. (a) Windowsill Detail, (b)Windowsill Detail 2

Finally, the ***sixth case*** indicates that a thorough inspection of all exterior penetrations exposed to the elements is necessary. Remedial measures should include sealing any gaps with durable sealants and adding protective features like drip edges or flashings to direct water away from vulnerable points. Implementing these solutions will help address current water ingress issues and prevent future occurrences, preserving the building's integrity and longevity, as shown in Figures 17-a and 17-b. This emphasizes the importance of precise architectural detailing and the necessity for strict quality control throughout the construction process to ensure the building's resilience against water-related damages.



(a) (b)

Figure 17. (a) Wall Cladding Water Seal, (b) Wall Cladding Water Seal 2

In general, the estimated costs and potential savings associated with retrofit design are highly variable, depending on factors such as property/unit size, construction complexity, material choices, and implementation methods. While initial costs may range widely, from waterproofing measures to drainage improvements, these investments offer significant long-term benefits. Potential savings from reduced maintenance, extended building lifespans, and improved occupant health highlight the economic viability of retrofitting efforts in addressing the challenges posed by climate change and extreme rainfall. However, this study has interviewed the maintenance contractors in the UAE to provide the tentative cost for the retrofit design proposed by the study, as shown in Table 3.

Table 3. Estimate of associated costs and potential savings

Retrofit Measures	Cost Estimate	Notes
A- Waterproof Coatings and Moisture Barriers		
Installation of waterproof membranes and coatings	AED 120-160/m²	Protects building envelopes from water penetration.
Retrofitting C.C. screeding and fillet details	AED 70-100/m²	Enhance water drainage and prevents water stagnation.
Moisture-resistant sealants for parapet walls	AED 15-30/m	Provides an extra layer of protection against moisture ingress.
B- Drainage Enhancements		
Retrofitting drainage slopes and fixing cracks	AED 150-250/m²	Corrects inadequate slopes and minimizes water pooling.
Integration of new gutter systems and drainage	AED 200-350/unit	Prevents water accumulation and structural flooding.
C- Architectural and Façade Improvements		
Overhang extensions, drip edges, and weather protection	AED 250-400/unit	Shields building from direct rainfall and water splash-back.
Windowsill adjustments with weather stripping	AED 100-200 per window	Reduces water ingress through windows and increases air tightness.
D- Flood Mitigation Measures		
Installation of flood-resistant materials	AED 300-500/m²	Protects structures from groundwater and surface flooding.
	Maintenance Saving	
Potential Savings	***Estimated Range***	***References***
Reduced repair and maintenance costs	30-50% annually	Well-implemented waterproofing can significantly reduce maintenance needs [1, 2].
Extended building lifespan	Up to 10-15 years	Retrofitting structural components extends durability and reduces early deterioration [3].
Health-related cost reductions	10-20% reduction in medical expenses	Improvements in air quality and mold prevention directly benefit occupants' health, lowering healthcare costs [4].

7. Conclusion

In the context of climate change and its impact on housing design in the UAE, this study has clearly highlighted the crucial role that retrofit interventions play in fortifying existing homes against increasing environmental challenges, particularly rainwater penetration. As the region experiences more frequent and intense rainfall events due to shifting climate patterns, homes that were originally designed for an arid climate are now vulnerable to water-related damage. The six cases analyzed in the study offer a range of targeted solutions, addressing the need for enhanced detailing, improved waterproofing, effective moisture management, and key structural adjustments aimed at preventing water ingress.

The importance of these retrofit interventions mentioned in Section 8.0 of this study cannot be overstated, as they provide vital protection to maintain the architectural design and structural integrity of homes in the UAE, where traditional construction methods may not have accounted for the escalating threat of heavy rains. Inadequate waterproofing or poor architectural detailing can lead to moisture infiltration, compromising the building envelope and triggering a cascade of problems. The study demonstrates how modern interventions, such as advanced waterproofing systems and enhanced drainage solutions, can significantly mitigate these risks. Moreover, the study emphasizes the broader implications of rainwater penetration, particularly in moisture-prone environments. Without the necessary safeguards, homes are susceptible to fungal growth and mold, both of which can degrade building materials and pose significant health risks to residents. This issue is particularly pressing in the UAE, where the combination of high temperatures and moisture can accelerate the deterioration of building materials, further weakening structures. The effective management of moisture, through improved ventilation and insulation, is therefore critical in ensuring both the longevity of the building and the health of its occupants.

The research outcomes reveal crucial solutions for mitigating the impacts of extreme rainfall and poor water management on UAE housing. It underscores how inadequate waterproofing, insufficient drainage, and poor architectural detailing expose homes to severe structural and environmental hazards. A series of retrofitting measures are presented through six case studies, each targeting specific weaknesses to improve building resilience and longevity.

One key outcome is the improvement of waterproofing systems in ceilings and parapet walls through the application of new waterproof coatings, C.C. screeding, and moisture barriers, as shown in Figures 13-a and 13-b. Enhancing ventilation further reduces the risk of mold and structural damage. Another significant recommendation involves retrofitting floor slopes and drainage systems to better manage water flow, as depicted in Figures 14-a and 14-b.

The research highlights flood-resistant materials and compliance with flood mitigation codes as essential components for addressing flood risks, particularly in vulnerable areas like Dubai, Sharjah, and Ajman. Additionally, enhancing sealants around openings, extending overhangs, and using durable materials (Figures 15-a to 15-c) are shown to minimize rain penetration.

Façade retrofitting, including installing weatherproof features such as awnings and ledges and applying weather-resistant sealants, improves water resistance (Figures 16-a and 16-b). Proper inspections and sealing gaps with durable materials, supported by drip edges and flashings (Figures 17-a and 17-b), further prevent water ingress. These outcomes collectively advocate for a paradigm shift in UAE housing construction, emphasizing strict quality control, regular maintenance, and the integration of resilient design principles to combat future climate risks.

Beyond just preventing immediate damage, these retrofits also offer long-term benefits in terms of sustainability and cost efficiency. By investing in retrofitting solutions that are tailored to the specific climatic challenges posed by the UAE's changing weather patterns, homeowners can reduce the need for costly repairs in the future. Furthermore, these interventions support the goal of creating more climate-resilient urban environments, where homes are better equipped to handle the inevitable fluctuations in weather patterns caused by climate change.

Besides, there is also a need for continued research into new materials and technologies that provide better resistance to environmental stresses, with a focus on developing cost-effective solutions. Despite the availability of resilient housing designs, their widespread adoption is hampered by high costs, a lack of awareness, and resistance to altering traditional building practices [86, 87]. Future research should thus concentrate on devising cost-effective resilience strategies and policies that motivate homeowners and builders to embrace these measures [88, 89]. Additionally, in the context of the UAE, research can be considered for improving education and awareness about resilient building practices through workshops and training, which is critical. Establishing regular maintenance and inspection routines and involving the community in housing design and retrofit projects will also contribute significantly to enhancing the structural durability and safety of buildings. These collective efforts support sustainable development and create a resilient built environment in the UAE.

8. Declarations

8.1. Author Contributions

Conceptualization, A.H.C., J.A. A.I.C., and A.A.; methodology, A.H.C.; investigation, A.H.C.; resources, J.A.; writing—original draft, A.H.C.; writing—review & editing, J.A. and A.I.C.; figures and drawings, A.A. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.3. Funding and Acknowledgements

The authors would like to thank Ajman University and the Healthy and Sustainable Built Environment Research Center (HSBRC) Ajman University for their support and providing the research facilities used in this study.

8.4. Conflicts of Interest

The authors declare no conflict of interest.

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