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Analysis Of Housing Vulnerability And Local Adaptation Strategies To Climate Risks In The City Of Bol, Lake Province, Chad, Central Africa

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Abstract

Climate change poses a major challenge for Sahelian cities such as Bol, located in the Lac province of Chad, a region classified as one of the world's climate change hotspots. In this city, the vulnerability of the built environment remains insufficiently documented. Against this backdrop, this study analyses the main climate risks, their impact on housing types and local adaptation strategies in the city of Bol. The methodology adopted is based on a mixed approach combining the analysis of long-term climate data (1982–2022), surveys of 385 households, interviews, field observations and statistical analyses (χ^2), supported by GIS tools. Three types of housing (traditional, semi-modern and modern) were analysed. The results show strong seasonality in climate risks, with flooding and erosion predominating in the wet season and heat waves, fires, and strong winds in the dry season. All types of housing are vulnerable, although in different ways. Local adaptation strategies are mainly structural, autonomous and reactive. This research makes an original contribution by offering a holistic view of the physical vulnerability of housing, integrating climate, social perceptions and construction types, and providing key elements to guide adaptation policies in Sahelian cities.

Keywords: *Climate change, climate risks, housing typologies, housing vulnerability, adaptation strategies, Bol (Lake Chad)*

Introduction

Climate change is a complex phenomenon with multiple causes and effects [1]. To better understand it, we must first define it, referring to the first formal definition of the term given in the United Nations Framework Convention on Climate Change (UNFCCC) [2], Article 1 of which states the following: "Climate change" means a change attributed directly or indirectly to human activity that alters the composition of the global atmosphere and is in addition to natural climate variability observed over comparable time periods. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) provides scientific evidence that the current rate of global warming will increase [3], resulting in more intense and frequent extreme weather events such as floods, rising temperatures, strong winds and droughts [4,5]. These events will endanger the lives and livelihoods of billions of people [3], affecting all spheres of human activity, from the socio-political and economic to cultural, urban planning, and architecture [6]. These events have a direct impact on infrastructure, road

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networks, sewerage systems, energy supply systems, and buildings [3,7–9]. Global climate change projections clearly show that climatic conditions affecting the built environment are becoming increasingly variable and extreme, thereby increasing its vulnerability [10].

Vulnerability to climate change is defined as the degree to which a system is susceptible to, or unable to withstand, the adverse effects of climate change, including climate variability and extreme events, taking into account exposure, sensitivity, and adaptive capacity [11,12]. The work of Gemeda et al. [13] and Allarané et al. [14] shows that vulnerability assessment is a prerequisite for developing effective adaptation strategies. Thus, this vulnerability analysis integrates socio-economic, physical and local climatic conditions. Unfortunately, in the literature on mitigation and adaptation, studies on architectural design aimed at assessing the risks and impacts of climate change on housing are not yet at a sufficient level [15], as illustrated by a bibliometric analysis of articles published between 1990 and 2021 carried out by Aydın and Sarı (2022) [16]. However, research conducted during this period focused on sustainability and energy efficiency, while research on climate change and adaptation increased after 2015 [15]. In addition to this, it has been observed that the few studies carried out on the assessment of the impacts of climate change on housing in the discipline of architecture have focused on a specific building issue with a view to mitigating risks, and that the assessment is carried out using indicators related to these issues [15]. In order to carry out a comprehensive assessment of building vulnerability, these assessments, approached from different angles, must be brought together in a holistic perspective [15]. This shortcoming highlights the urgent need to develop holistic approaches that integrate architectural choices and the population's perceptions of their impacts into vulnerability analyses to strengthen the resilience and adaptation of housing to climate change.

However, while climate change remains a global phenomenon, not all regions of the world are affected (vulnerable) in the same way by its effects [17], as Africa is particularly vulnerable to climate change [3] and extreme temperature increases have been recorded across most of the continent, with an increased likelihood and magnitude of extreme events such as floods, heatwaves, droughts and storms [7]. These climate change-related events will affect buildings and infrastructure [9], causing damage such as torn-off roofs, destroyed walls and dampened interiors, quickly stripped paint, posts knocked over, and compromised technical networks [18]. Countries such as Senegal, Gambia, Mauritania, Mali, Burkina Faso, Niger, and Chad are located in areas with among the most extreme climate risks [17], making it important to understand the frequency and scale of extreme weather events affecting housing in Chad to inform policy. Despite numerous studies, government initiatives and development agencies that have attempted to reduce the catastrophic effects of climate change on infrastructure, buildings and the environment, the results remain insufficient.

Located at the crossroads of Saharan Africa, West Africa, and Central Africa [19,20], Chad is considered the most vulnerable country to climate change [21]. This has led the international scientific community to consider it one of the world's climate change hotspots [19,22,23]. Indeed, Chad has been ranked the most at-risk country among 186 countries assessed in a study on climate vulnerability [24]. Increased rainfall variability and the resurgence of extreme weather events, such as droughts, floods, heat waves, and violent winds, are the current manifestations of climate change [19,25]. According to the country's updated Nationally Determined Contribution (NDC) [25], consultations with stakeholders have shown that infrastructure, housing and land use planning, etc. are among the priority sectors for climate change adaptation [26]. Information contained in the third national communication on climate change [27] shows that the building sector is subject to serious climate threats such as floods, high winds and extremely high temperatures, making housing and populations vulnerable. And according to Allarané et al. [14], extreme weather events such as floods, heat waves and high winds have affected not only infrastructure but also housing.

Recognising its extreme social and climatic vulnerability, Chad has signed and ratified the United Nations Framework Convention on Climate Change (UNFCCC), protocols and agreements, including the Kyoto Protocol and the Paris Climate Agreement, and actively participates in intergovernmental climate debates [19]. In this context, in accordance with its commitments to the UNFCCC, Chad has developed policy documents to combat climate change (National Communications, Nationally Determined Contribution, National Adaptation Plan of Action (NAPA), National Strategy to Combat Climate Change, etc.). Despite the development of these various documents, Chad remains vulnerable to climate change. In 2019, approximately 18% of the country's buildings (61% of which were in urban areas) and 13% of the population were exposed to extreme flooding with a return period of 1 in 100 years [28]. Since June 2022, Chad has been affected by floods, affecting nearly 1.9 million people and destroying more than 217,000 homes. These floods have affected all 23 provinces, so if we consider the proportion of people affected in relation to the population, the most affected provinces are Lac (38%), Ennedi-Est (31.6%), Borkou (27.6%), Mandoul (25.2%), Moyen-Chari (24.4%) and Batha (21.9%) [29]. These provinces fall into the priority 1 category established by the national flood management committee.

The city of Bol is located in Lake Province, 153 km north of the capital [30], in a context where Lake Chad is considered emblematic of the threat posed by climate change [22]. IPCC reports indicate that the Lake Chad region is among the areas most affected by climate change [31]. The National Adaptation Plan of Action (NAPA) and the various national communications submitted to the United Nations Framework Convention on Climate Change (UNFCCC) by the country highlight the many climate risks in Lake Province that threaten the well-being of populations the built environment, such as the 2024 floods that affected 102,145 households, left 71,070 people homeless and destroyed 72,586 homes [32]. However, flooding is not the only threat to the city. It is also exposed to other risks, including high winds, fires, soil erosion and desertification [22,25,33]. Despite climate change exacerbating the vulnerability of housing in the Lake Province, particularly in the city of Bol, studies conducted to date on climate change in the area have neglected the housing sector. For example, the work of Daiba et al. [34], Ngaryamngaye et al. [20,30] focused on climate variability and its impact on agriculture, fisheries and health. Budnukaeku [35] and Mahmood et al. [36] analysed the vulnerability of the Lake Chad basin to climate change, highlighting the impact on the population. Ogunmakin [37] and Kitoko [38] worked on global warming and migration, emphasising the need for regional cooperation and appropriate policies to mitigate the effects of climate change and limit forced migration in the Lake Chad region. Gali et al. [39] examined the effects of climate change on the Bol population, with a focus on gender disparities. Griffin [40], Tope Shola and Ogunbodede [41], and Singh [42] examined the links among climate change, natural resource instability, and pastoral conflicts in the Lake region, highlighting how these factors have contributed to violence and insecurity in the area. The housing sector has not received much attention from the scientific community and professionals involved in the fight against climate change. It is essential to fill the gap in scientific knowledge on the impact of climate change on housing through this original contribution, which combines long-term climate data, social perceptions of risk and a typological analysis of housing, thus offering an integrated view of urban vulnerability in Sahelian cities.

The objective of this study is to analyse climate risks and their impacts on housing to support the development of effective adaptation strategies in Bol, Lac province. Specifically, our study aims to:

i. Analyse the main climate risks in the city of Bol.

ii. Assess the physical impacts of climate risks perceived by the local population on different types of housing in the city of Bol.

iii. Identify the adaptation strategies implemented by households to strengthen the resilience of housing in Bol.

Materials and Methods

Study area

Location of the study area

The town of Bol is located on the shores of Lake Chad, 153 km north of the capital, in the Sahelian zone of Chad, between 13° 27' 31'' north latitude and 14° 42' 53'' east longitude [30]. Bol is the capital of Lake Province, which borders Nigeria, Niger and Cameroon. Administratively, the town of Bol was established as a commune by Decree No. 564/PR/87 of 28 October 1996 [39]. The city of Bol enjoys an arid climate and a large surface water basin known as the "arm of Lake Chad". The average annual temperature is 28°C, and the average annual rainfall is around 234 mm. This temperature regime and rainfall distribution give rise to two seasons: the dry season (with cool weather from November to February and hot weather from March to mid-June) and the rainy season (from mid-June to early November) [39]. It is a very active commercial hub due to its large-scale production from the Lake Chad polders, becoming a real magnet for migrants with a population growth rate of 3.6% per year, higher than the national average [39,43,44]. Figure 1 below shows the location of the city of Bol.

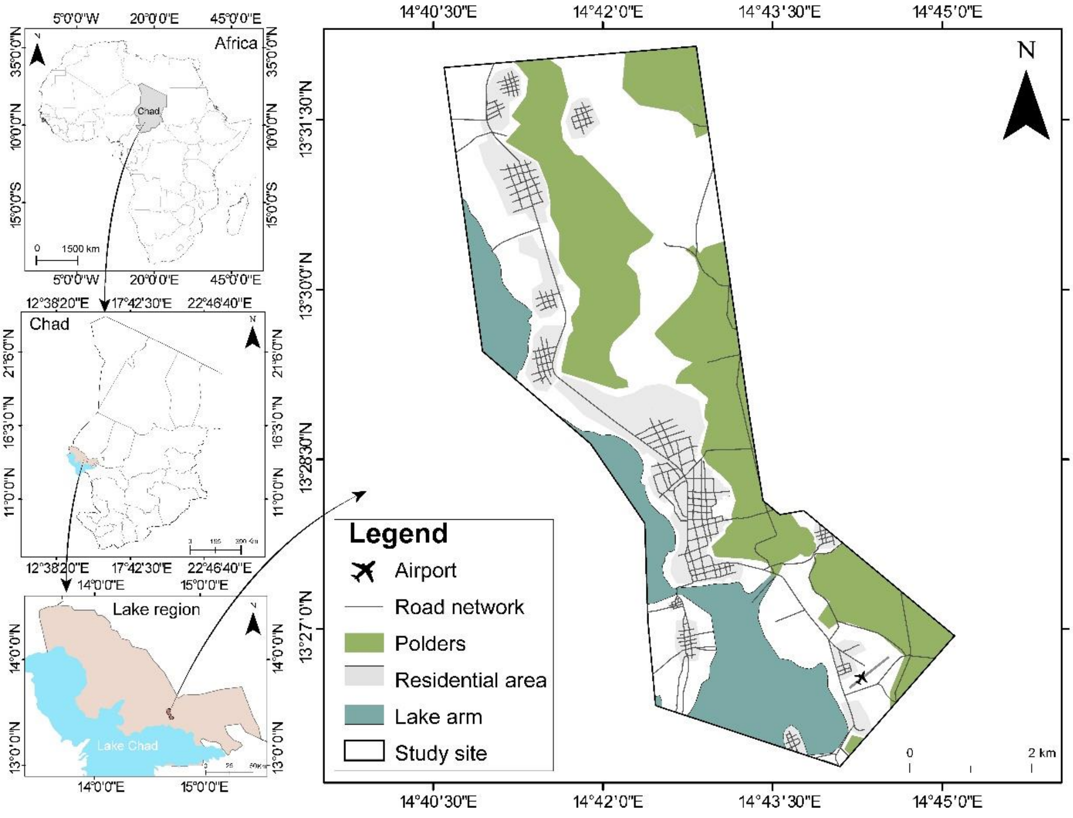
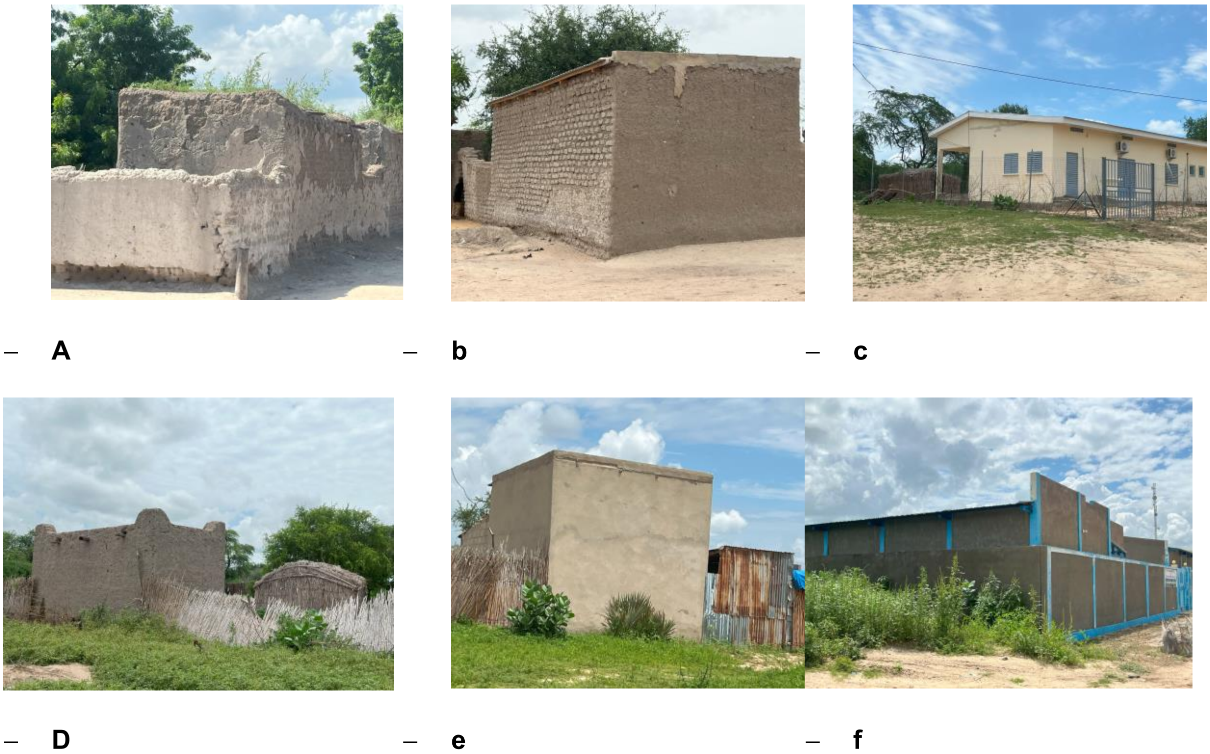


Figure 1: Geographical location of the town of Bol.

Identification of housing types in the study area

The town of Bol is characterised by three categories of housing (Figure 2), distinguished by the materials used and construction techniques: modern housing (c, f), semi-modern housing (b, e), and traditional housing (a, d) [45]. Modern dwellings are rectangular in shape and built with contemporary materials such as hollow bricks, cement, concrete, sheet metal and steel. They are characterised by sloping or gabled roofs, large glass or metal windows, plastered and painted walls, and cement or tiled floors. Semi-modern dwellings represent a compromise, combining both traditional and modern materials: they are also rectangular, with a single-sloped roof, cement, cinder block or fired brick walls, earthen or cement floors, and sheet metal or locally sourced roofing materials. Finally, traditional dwellings, which are the most common in Bol, are built entirely from local materials such as earth and straw. They have thick walls, small openings and a flat earthen roof, often covered with grass during the rainy season. Thus, in the context of this study, the analysis of the impact of climate risks will focus on these three types of housing.



– A – b – c

– D – e – f

Figure 2: Different types of housing in Bol. (**a,d**) traditional housing, (**b,e**) semi-modern housing, (**c,f**) modern housing

Sampling and data collection

This study used a methodological approach based on documentary research, meteorological data collection, individual interviews, household surveys, observations, and photographs, as used by Allarané et al. [24] and Teadoum Naringué et al. [46]. The documentary research enabled us to review similar work carried out in other geographical areas addressing the same issue.

Weather data collection

The monthly meteorological data used in this study mainly concern precipitation, maximum and minimum temperatures, relative humidity and wind speed. These monthly data, covering the period from 1982 to 2022, were obtained from the National Meteorological Agency (ANAM) of Chad. This dataset complies with the latest World Meteorological Organisation (WMO) standard and is used to highlight the intensity and recurrence of extreme weather events observed in the city of Bol.

Individual interviews and household surveys

Interviews were conducted with technicians from the provincial delegation for the environment and sustainable development, the provincial delegation for land use planning, urban planning and housing, the municipality of Bol, local authorities, leaders of non-governmental organisations (NGOs) and stakeholders in the construction sector who were able to provide a historical perspective on climate change and its impact on housing.

The household surveys covered a sample of 385 households: each selected at random to avoid duplication. The questionnaires were created using KoboToolbox [47,48] and administered via the Kobocollect application, version 2024.2.4. Verbal consent was systematically obtained before each interview or survey. To ensure proper understanding, surveys were conducted in the local language, when necessary, with the support of translators and local informants trained for this purpose [49]. The main categories of data collected for this purpose were as follows:

- Socio-economic and demographic characteristics (gender, age, activities and level of education);
- Type of housing occupied;

- Perceived impacts of climate risks on housing and the number of buildings lost;
- Housing adaptation and resilience strategies used by the population to cope with climate risks.

To determine the sample size, the inverse of the margin-of-error formula proposed by Daniel Schwartz was used. Let n be the sample size for a rounding factor q, and we have the following:

$$n_q = \frac{[(z_a)^2 \; x \; P(1-P)]}{d^2}$$

With Za: Fixed margin or margin reduced to a 5% risk (1.96), which corresponds to a 95% confidence interval; d: margin of error set at 3% and P: proportion of the population of the city of Bol in the Lake Chad region (8.29%, or 0.0829 rounded to 0.1).

Applying the figures:

$$n_q = \frac{[(1{,}96)^2 \; x \; 0{,}1(1-0{,}1)]}{(3\%)^2}$$

n_q =385

Direct observations and photography

Direct observation is a tool that allows immediate perception through the human senses, particularly sight, providing an overview (synoptic view) of a given phenomenon [17]. As defined, direct observation allowed us to see and understand the impact of risks on different types of housing in the city of Bol directly. Photography, as a material object, medium or record, allowed us to take photos of the manifestations of risks on housing for illustrative purposes. Thus, direct observations and photographs were used in this study to make the phenomenon visible [51].

Data analysis and processing

Monthly climate data (precipitation, temperatures, winds, humidity) were analysed to identify extreme values and intra-annual variability using monthly box plots that show the median, quartiles, and extreme values. Values beyond the whiskers were considered potential extreme events, allowing the most exposed months to be identified. Data from field surveys conducted with Kobocollect using the KoboToolbox platform were organised and formatted in Excel (Microsoft Office 365). These survey data were analysed to assess perceptions of climate impacts based on risks, seasons and intensity levels. A χ^2 (chi-square) independence test was applied to the survey data to examine the significance of the differences observed between categories. The significance threshold was set at $p < 0.05$, and the results showed highly significant differences ($p < 0.001$). This combined approach makes it possible to link the observed climate extremes to the perceptions of the populations surveyed. The data processing and statistical tests were performed using version 4.4.0 of the R software and its associated software. The town of Bol's geographical location map was produced using ArcGIS 10.4 and Illustrator 2024, based on shapefiles obtained from the town's Geographic Information System (GIS) department.

Results

Analysis of the main climate risks

Analysis of precipitation

Figure 3 illustrates, using box plots, the interannual distribution of monthly precipitation recorded at Bol from 1982 to 2022. This figure shows that the first rainfall appears tentatively in April (median zero, but maximum 21.1 mm), then increases slightly in May (Q3 = 10.6 mm). The rainy season really sets in from June onwards, when 50% of values exceed 15.8 mm and 75% reach 36.9 mm. The maximum rainfall is observed in July (median = 84.4 mm, Q3 = 127 mm, maximum = 274 mm) and August (median = 127 mm, Q3 = 174 mm, maximum = 290 mm), confirming the peak of the main rainy season. A sharp decline is then observed in September (median = 42.2 mm, Q3 = 63.3 mm), followed by low rainfall in October (median = 0 mm, Q3 = 10.6 mm). Precipitation (Figure 3) shows that July and August have the highest rainfall (median > 120 mm), corresponding to the period of highest flood risk. These results show that Bol's rainfall pattern is characterised by a high seasonal concentration of precipitation, creating conditions conducive to sudden and difficult-to-predict flooding events for urban buildings.

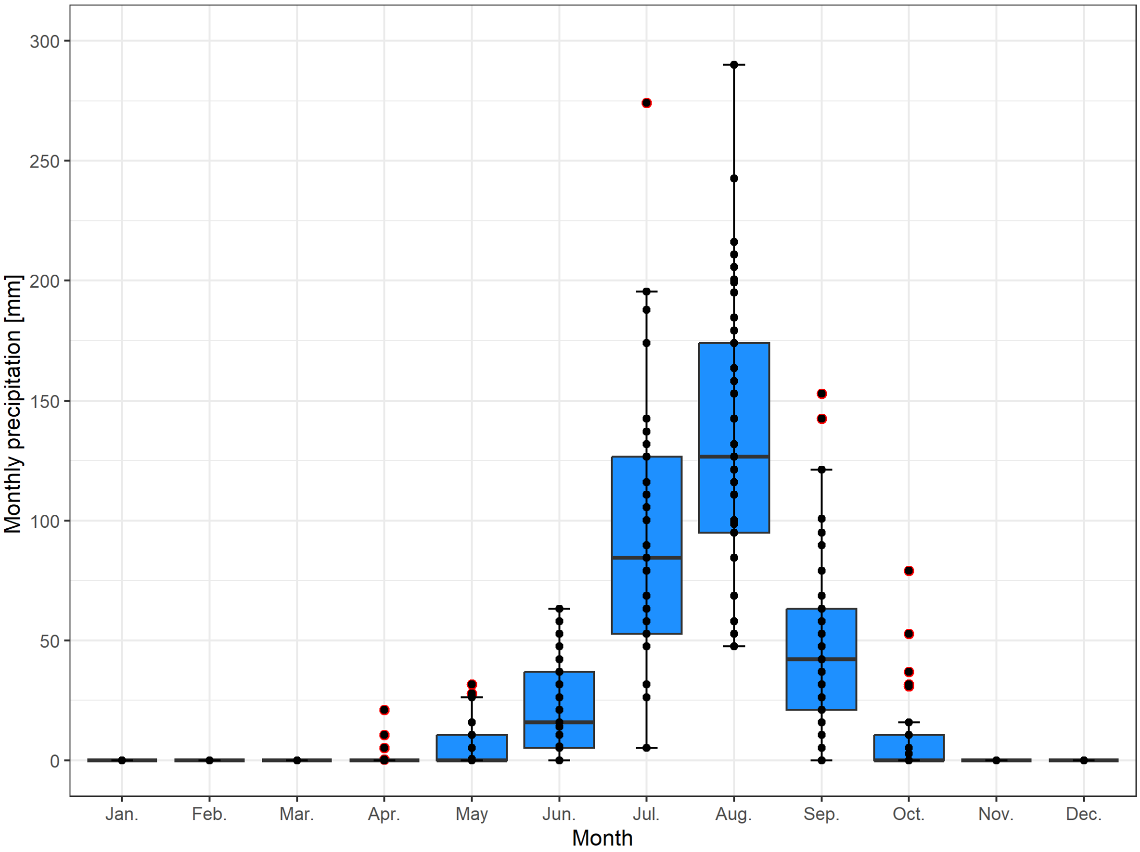


Figure 3: Monthly precipitation trends in Bol from 1982 to 2022

Temperature analysis

Changes in monthly minimum temperatures

Minimum temperatures show marked seasonal variability (Figure 4). During the coolest period of the year, the lowest values are observed in December (median = 11.5 °C, Q3 = 13.2 °C) and January (median = 10.4 °C, Q3 = 11.5 °C), with absolute minimums dropping to 6.6 °C. A gradual rise is observed from February (median = 12.4 °C) to April (median = 21.2 °C), reflecting the transition to the warm season. The maximum Tmin values are reached between May and June, with respective medians of 24.0 °C and 25.5 °C, and Q3s reaching 24.9 °C and 25.8 °C, confirming the onset of the hottest season of the year. Subsequently, Tmin stabilises around 23°C in July, August and September (medians between 22.5°C and 23.6°C), indicating relative thermal homogeneity during the rainy season. In October, a significant drop began (median = 19.4°C, Q3 = 20.2°C), which continued in November (median = 15.9°C, Q3 = 16.5°C) to reach cool conditions again in December.

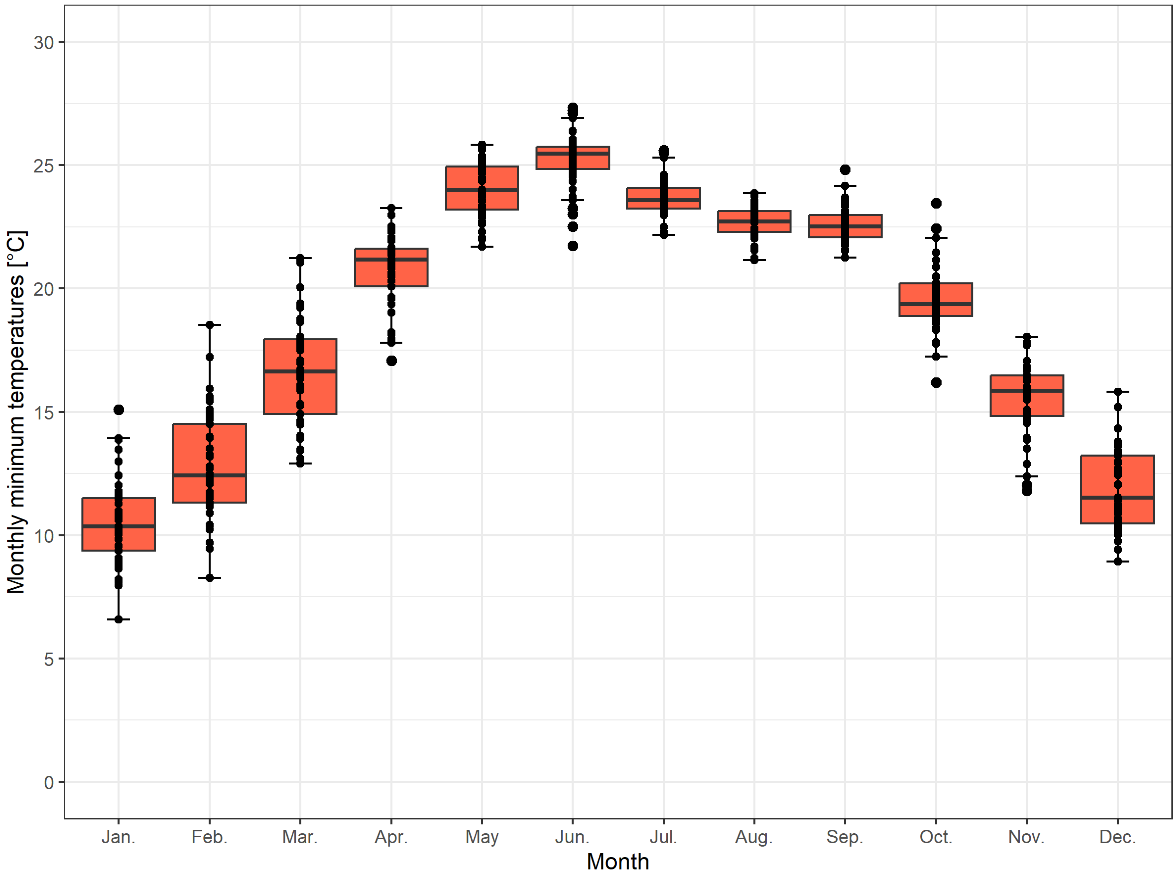


Figure 4: Monthly changes in minimum temperatures in Bol from 1982 to 2022

Changes in monthly maximum temperatures

Figure 5 shows the box plot of monthly temperature changes. Maximum temperatures vary greatly throughout the year. In January and December, maximum temperatures are relatively moderate, with half of the values around 36°C and the remaining three-quarters below 38°C. The highest temperatures occur between March and May, when half of the Tmax values reach 42-45 °C and 75% exceed 44 °C, marking the hottest period of the year. A relative cooling is observed in July-August (median = 38-41 °C, three-quarters < 40 °C), corresponding to the rainy season. The months of September-October see a rise (half ≈ 40 °C), followed by a gradual decline towards November-December. Maximum temperatures (Figure 5) peak between March and May (median > 42 °C), identifying the period of severe heat waves. This thermal dynamic highlights the prolonged exposure of the habitat to extreme temperatures, which is likely to increase the stress on building materials and indoor thermal comfort.

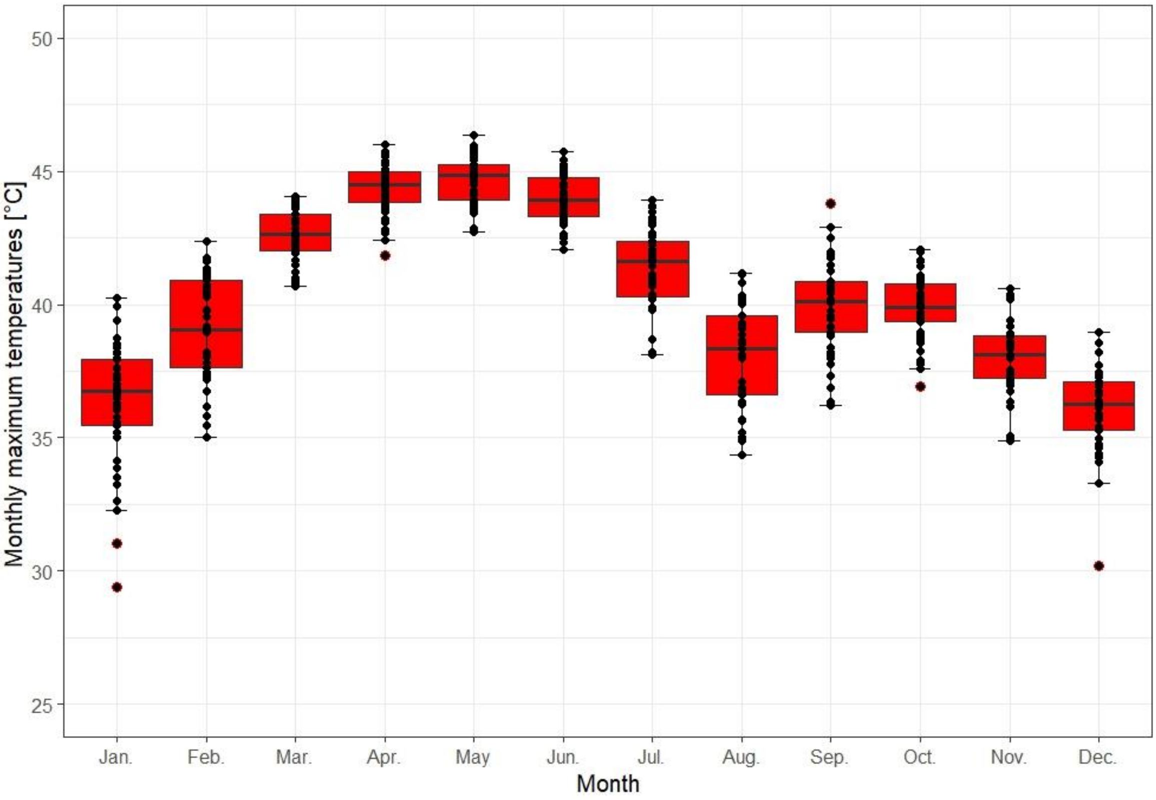


Figure 5: Monthly changes in maximum temperatures in Bol from 1982 to 2022

Wind speed dynamics

Figure 6 highlights marked seasonal variability in the average monthly wind speed in Bol. The highest speeds are recorded in January-March and November-December, when half of the speeds are between 4.2 and 4.4 m/s and 75% reach 4.6 m/s. A gradual decrease is observed from April (median = 3.6 m/s) to September, when half of the values fall to 2.2 m/s, and three-quarters remain below 2.3 m/s, indicating the calmest period of the year. From October onwards, speeds start to rise again (median ≈ 2.8 m/s, Q3 = 3.2 m/s), heralding the transition to the windier season. Wind speed (Figure 6) is highest from January to March and from November to December (median > 4.2 m/s), coinciding with the period of strong winds. These trends indicate that periods of strong winds coincide with dry seasons, increasing the risk of mechanical damage to roofs and lightweight structures.

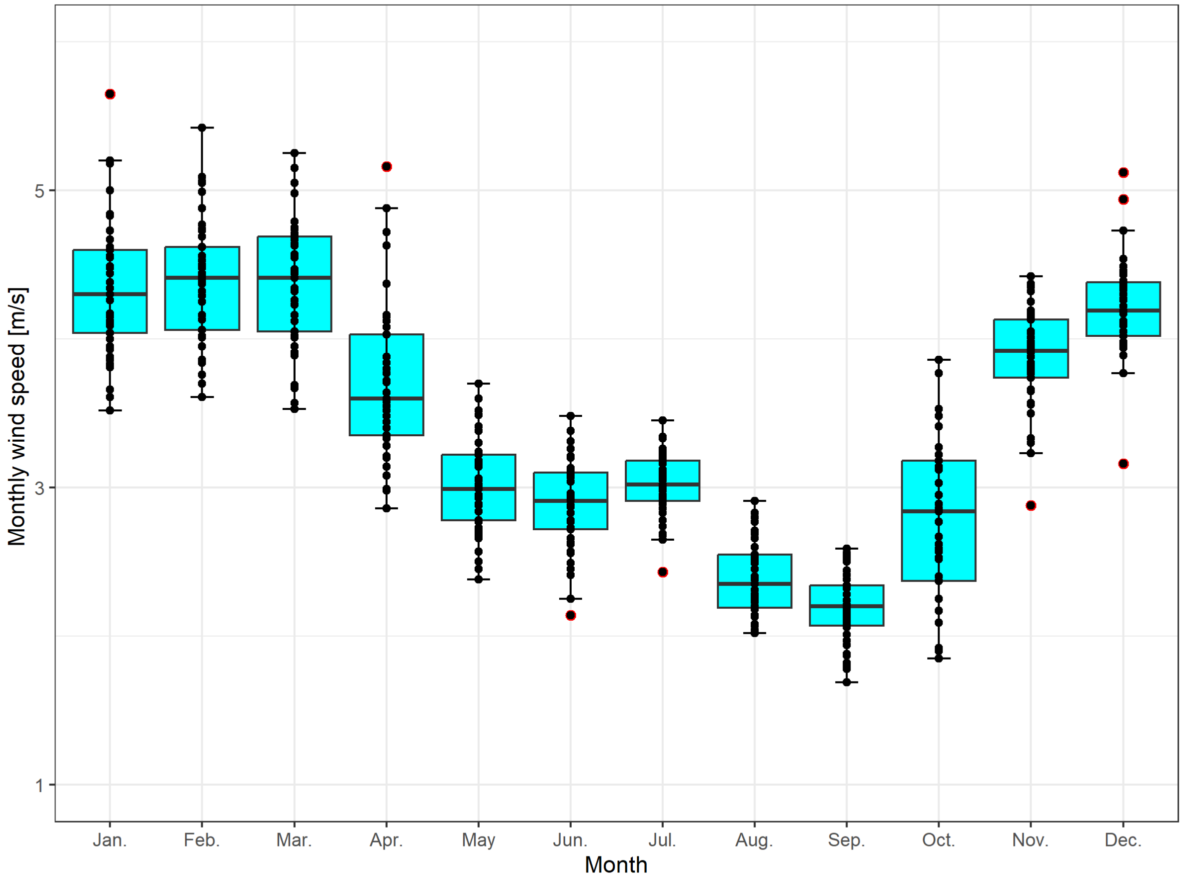


Figure 6: Monthly changes in wind speed in Bol from 1982 to 2022

Analysis of relative humidity trends

Figure 7 shows the box plot of monthly humidity in Bol from 1982 to 2022. This figure shows that relative humidity varies significantly across seasons. The driest period is February-March, when half of the values are between 11-15% and three-quarters remain below 16%. A gradual increase begins in May (median ≈ 23%) and intensifies in June (50% of values ≥ 35%). Maximum values are reached in July-August, when half of the values are between 52-64% and three-quarters exceed 55-70%, corresponding to the peak of the rainy season. Thereafter, a decline begins in September-October (median ≈ 33-58%), before returning to lower levels in November-December (median ≈ 21%). Relative humidity (Figure 7) is lowest in February-March (median ≈ 11–15%), increasing the risk of fire during the dry season. The high seasonal variability in relative humidity accentuates the combined risks of fire during the dry season and of material degradation during the wet season.

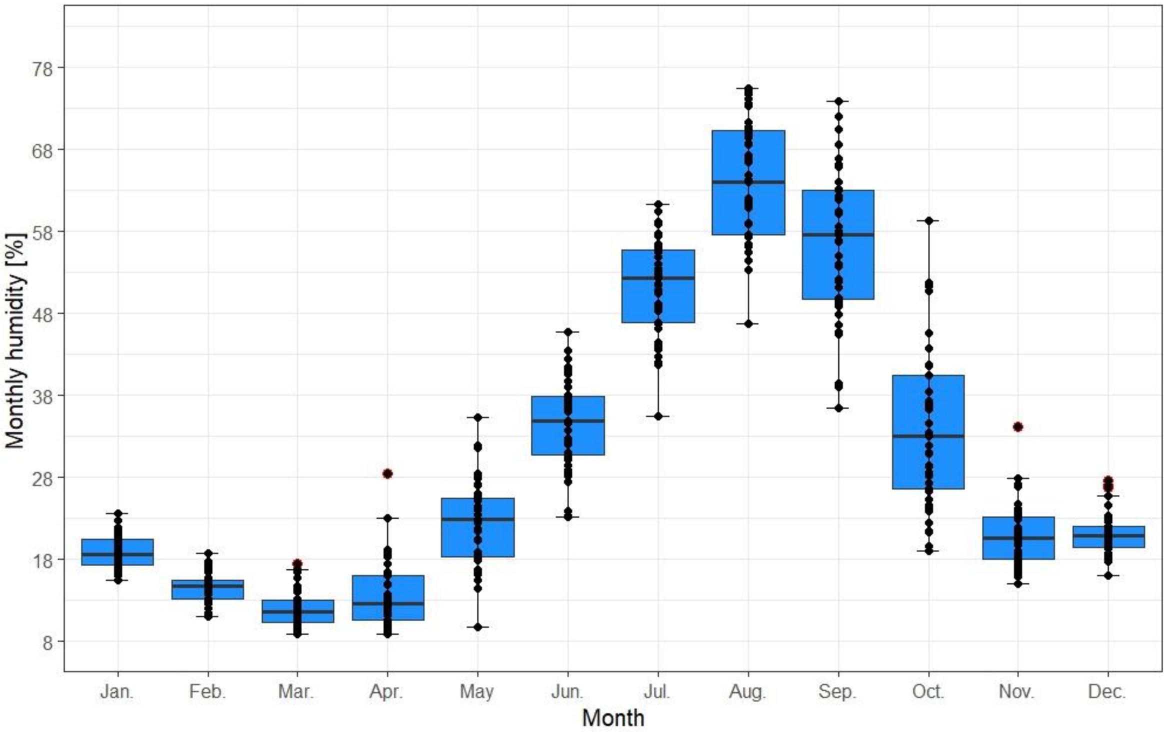


Figure 7: Monthly relative humidity trends in Bol from 1982 to 2022

Perception of the intensity of risk impacts according to season.

The survey results (Figure 8) reveal a strong seasonal perception of climate risks, with a highly significant association among risk type, season, and impact intensity ($p < 0.001$). Flooding and erosion are perceived exclusively in the wet season, with a predominance of strong impacts for flooding (11.25%), reflecting destructive effects on housing. Conversely, heat waves and fires are perceived only in the dry season, highlighting the central role of high temperatures and the drying out of materials and vegetation. They are associated with low to medium impacts (up to 15.25% for heat waves). Strong winds are the only risk perceived during both seasons, with varying intensities. These results reflect respondents' perception of strong seasonal control of climate impacts, with each season associated with a specific profile of risks and intensities. This seasonal differentiation of hazards highlights the importance of adapting vulnerability-reduction and habitat-adaptation strategies to climatic seasons rather than adopting uniform approaches year-round.

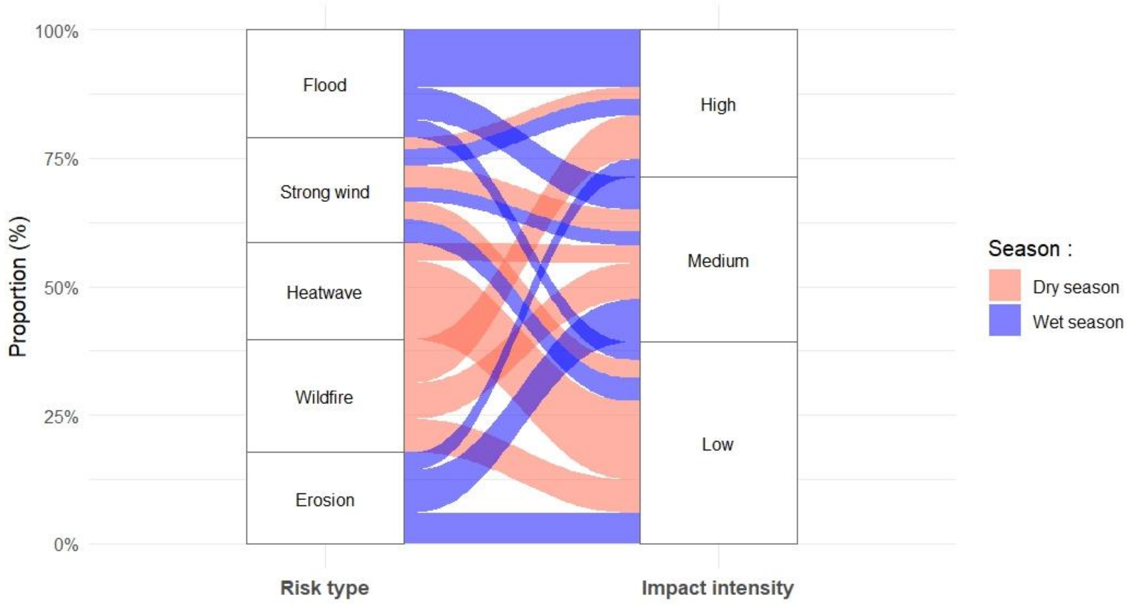


Figure 8: Perception of the intensity of risk impacts according to season

Assessment of the physical impacts of climate risks on housing types in Bol

Impacts of heavy rainfall (flooding) on housing

Figure 9 highlights significant differences in the nature and extent of flood damage across house types.

In modern houses, the majority of residents report cracks (≈ 28.7%), followed by damage to parts of the house or partial or total loss (Des_elts_House: DWRPC, ≈ 25.9%). These figures reflect significant structural damage in the event of flooding. Other impacts such as rising/seepage of water into the house (MWIH, ≈ 7.7%), corrosion of metal elements (CME, ≈ 13.4%), deterioration of foundations (Des. FB, ≈ 14.5%), unpleasant odours (UO, ≈ 3.4%) and insect infestation (PIH, ≈ 2%) are less frequent but still significant.

For semi-modern houses, the most frequently cited impact is MWIH (≈ 20%), followed by wall cracking (≈ 19%) and destruction of structural elements (Des_elts_House: DWRPC, ≈ 18%). This distribution highlights serious damage, even in partially protected dwellings.

In traditional houses, water elevation/infiltration (MWIH, ≈ 17.9%) is the main impact. Breaks in structural elements, UO and damage to furniture (PIH) also account for high proportions (≈ 11-13%), highlighting the high vulnerability of the most precarious constructions to flooding. The high frequency of cracks and structural damage shows that flooding directly threatens housing, not just crops. This has important implications for the safety, well-being and resilience of households. Overall, these results reveal that although impacts differ depending on the materials and construction techniques used, no type of dwelling provides effective protection against flooding, highlighting a widespread structural vulnerability.

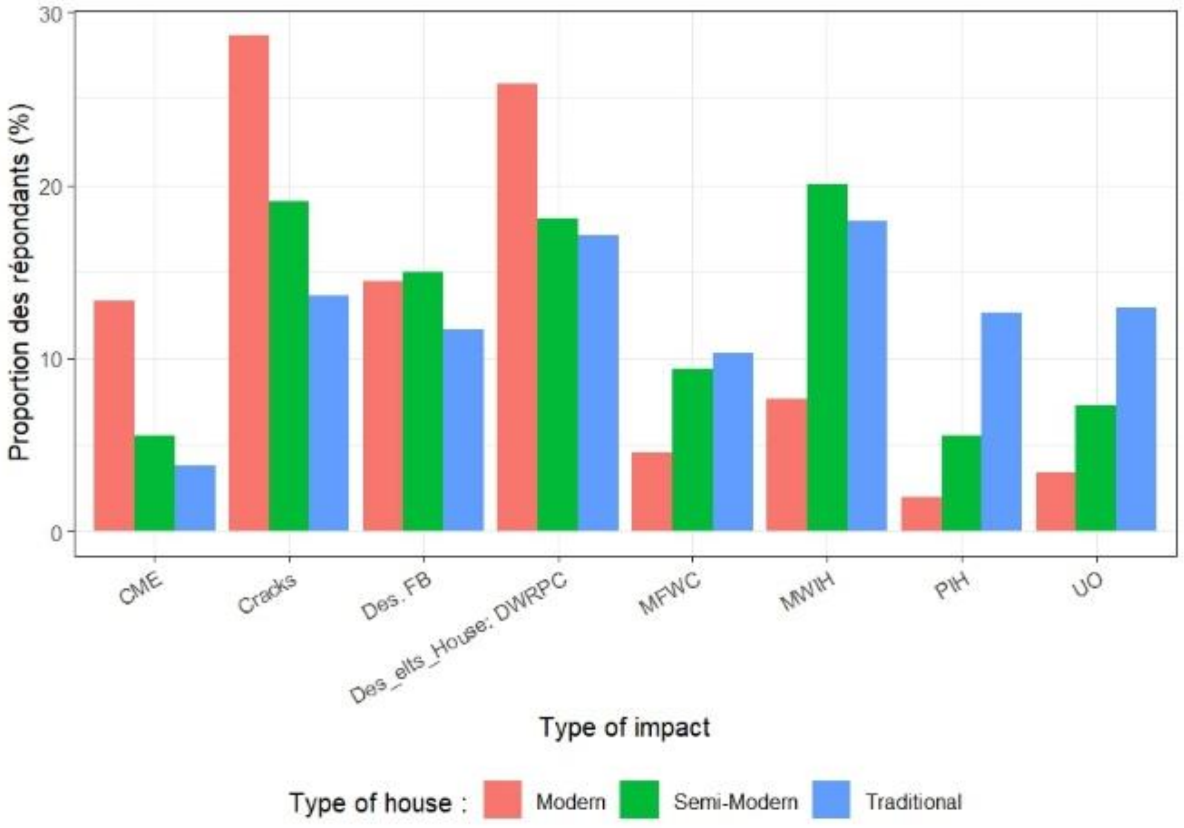


Figure 9: Impact of flooding on different types of housing in Bol. CME: Corrosion of metal components; Des. FB: Destruction of foundations or buildings; Des_elts_House: DWRPC: Destruction of house components: doors, windows, roofs, paintwork, cladding, etc.; MWIH: Damp and water infiltration in the house; MFWC: Mould and fungi on walls and ceilings; UO: Unpleasant odours; PIH: Proliferation of insects in the house.

Impacts of strong winds on housing

Strong winds are perceived as causing significant structural and material damage to all types of housing (Figure 10). In modern houses, the most frequently reported impacts concern the detachment of roofs (DR, ≈ 27.6%) and the partial destruction of doors, windows and structures (Des. DWSC, ≈ 20.3%), followed by the collapse of walls (CW, ≈ 14%) and the destruction of foundations (Des. F, 10%). Electrical problems (EP, ≈ 14.3%), cracks (≈ 7.8%) and fire risk (≈ 5.9%) are also reported, but to a lesser extent.

In semi-modern houses, detached roofs (DR, ≈ 26.1%) and destruction of structural elements (Des. DWSC, ≈ 20.6%) remain dominant, while collapse of walls (CW, ≈ 14.9%), destruction of foundations (Des. F, ≈ 11.7%) and electrical problems (EP, ≈ 12.6%) indicate significant structural vulnerability. Cracks (≈ 6.3%) and fire risk (≈ 7.7%) appear to be secondary impacts.

For traditional houses, the highest proportions concern roof detachment (DR, ≈ 26.7%), partial destruction of structures (Des. DWSC, ≈ 22.2%), and wall collapse (CW, ≈ 12.1%), followed by destruction of foundations (Des. F, ≈ 11.2%), electrical problems (EP, ≈ 10.1%), cracks (≈ 7.3%), and fires (≈ 10.3%). Roofs and fragile structures are the elements most affected by high winds, regardless of the type of dwelling. This highlights the need to strengthen the resilience of urban dwellings to extreme weather events, particularly through the use of more durable materials and appropriate construction techniques. Roof detachment is the main factor contributing to vulnerability to high winds, regardless of dwelling type, indicating widespread weakness in anchoring systems.

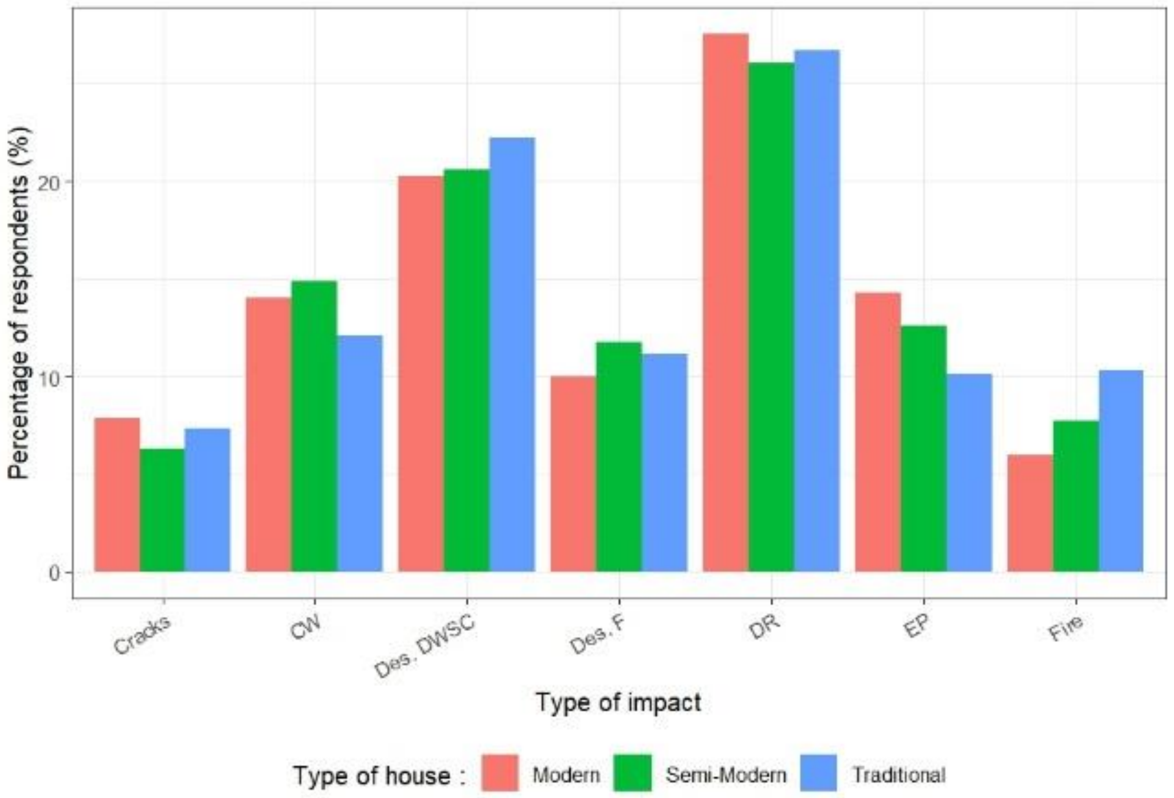


Figure 10: Impact of strong winds on different types of housing in Bol. Des. F: Destruction of foundations; Des. DWSC: Destruction of doors, windows, structures, cladding, etc.; DR: Detachment of roofs; CW: Collapse of walls; EP: Electrical problems.

Impacts of erosion on housing

Erosion is mainly associated (Figure 11) with weakening foundations (WF) and stability issues (SI), reflecting its impact on the overall structure of homes. In modern houses, weakening of foundations (WF, ≈ 27.3%) and stability issues (SI, ≈ 20.7%) are the most frequently reported impacts, followed by cracks in walls (≈ 18.7%) and materials degradation (MD, ≈ 16.7%). Water infiltration (WI, ≈ 10%) and damage to doors, windows and cladding (Dam. DWC, ≈ 6.7%) are less frequent but still present. For semi-modern houses, the proportions are similar: weakened foundations (WF, ≈ 25%), stability issues (SI, ≈ 21.3%), cracks (≈ 20%), materials degradation (DM, ≈ 12.5%) and IE (≈ 13.8%). Damage to doors, windows and cladding (Dam. DWC, ≈ 7.5%) remains low.

In traditional houses, weak foundations (WF, ≈ 23.7%), stability issues (SI, ≈ 20.5%) and cracks (≈ 19.2%) are the most common, while water infiltration (WI, ≈ 16%) and material degradation (MD, ≈ 12.2%) are moderate. Damage to cladding (Dam. DWC, ≈ 8.3%) is less common. The data show that erosion mainly affects stability and foundations, posing a major structural threat to all types of dwellings, with a slightly higher risk in modern and traditional houses. These results confirm that erosion is a progressive structural risk, often underestimated, whose cumulative effects weaken dwellings over the long term.

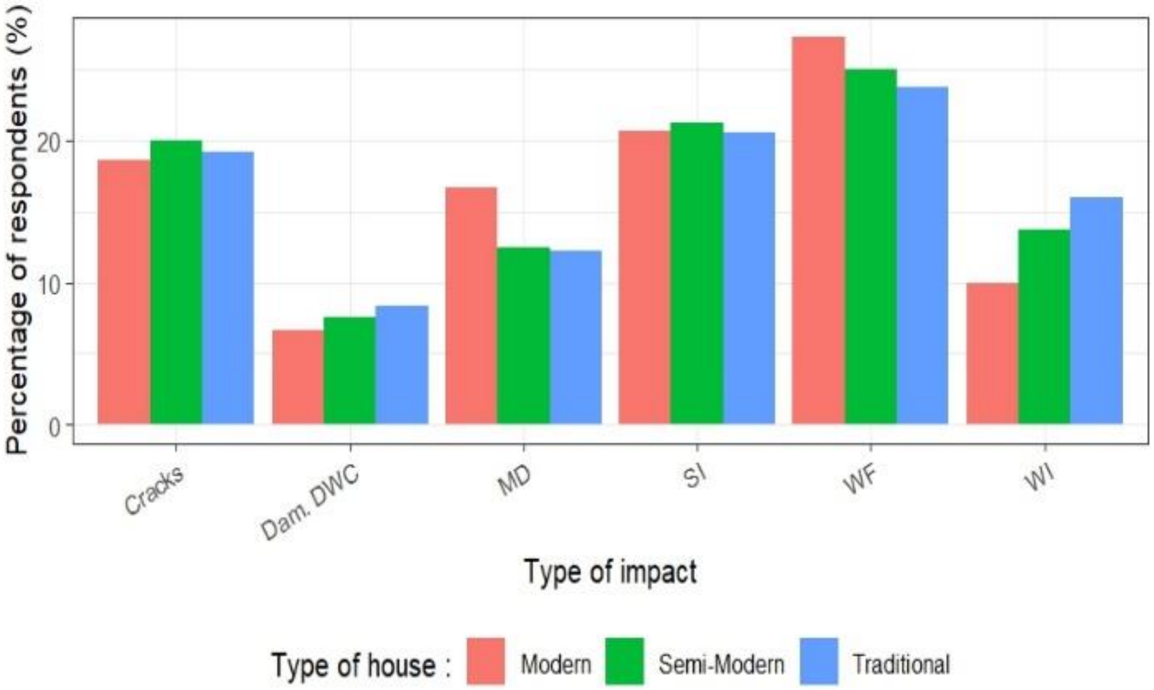


Figure 11: Impact of erosion on different types of housing in Bol. WF: Weakened foundations; MD: Materials degradation; Dam. DWC: Damage to doors, windows, cladding, etc.; Cracks in walls; WI: Water infiltration; SI: Stability issues.

Impact of fires on housing

Fires (Figure 12) are perceived as events with a significant impact on housing, mainly affecting structures and cladding. In modern houses, complete destruction (Des. C, ≈ 44%) is the most common outcome, followed by roof destruction (Des. R, ≈ 23.8%) and cladding damage (Dam. R, ≈ 22.2%). Structural weakening (WS, ≈ 9.5%) is less common but still significant. For semi-modern houses, the trend is similar: complete destruction (Des. C, ≈ 42%) and damage to cladding (Dam. C, ≈ 24.6%) are the most reported impacts, followed by destruction of the roof (Des. R, ≈ 20.3%) and structural weakening (WS, ≈ 13%). In traditional houses, complete destruction (Des. C, ≈ 41.9%) and damage to cladding (Dam. C, ≈ 25.7%) remain predominant, accompanied by roof destruction (Des. T, ≈ 25.7%), while structural weakening (WS, ≈ 6.7%) is less common. Fires mainly result in the total or partial loss of dwellings, affecting both building materials and structures, highlighting the high vulnerability of houses, particularly in urban contexts where the density and proximity of buildings can amplify the risks.

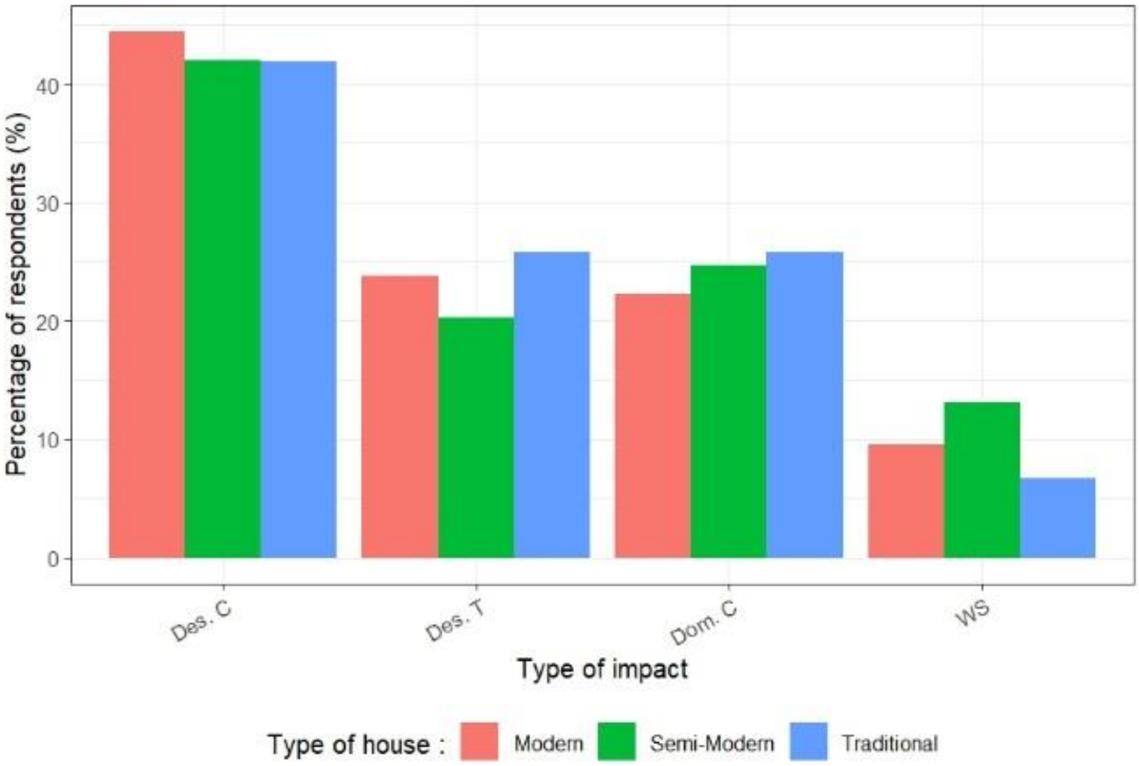


Figure 12: Impact of fires on different types of housing in Bol. WS: Weakening of the Structure; Des. C: Complete destruction; Des. R: Destruction of the roof; Dam. C: Damage to cladding.

Impacts of heat waves on housing

The results (Figure 13) indicate that, regardless of the type of housing, heat waves are perceived as being mainly associated with an increased risk of internal fire (IFR) and a deterioration in indoor air quality and ventilation (Pro. IAWV). These two impacts have the highest rates in all housing categories: ≈ 45-46% for deterioration in air quality in modern and semi-modern houses, and ≈ 41% in traditional dwellings. This convergence indicates that indoor air heating is the main problem experienced by households, regardless of the quality of construction. Modern dwellings have a slightly higher proportion of ventilation problems (Pro. IAWV, ≈ 45.3%) than traditional houses (≈ 41.2%), which may reflect reduced air circulation due to more insulating materials and a more closed configuration. On the other hand, traditional houses have higher proportions of damage to doors, windows, walls, materials and roofing (Des. DWWMR) and building destruction (Des. B) (≈ 19.1% compared to 12-16% in modern houses), suggesting increased structural vulnerability to thermal shocks.

Cracks due to thermal expansion (Cracks) remain in the minority (≈ 5.8-11.5%), but nevertheless reflect the stresses placed on structures during heat waves. Destruction of building (Des. B) follows a similar trend, with slightly higher vulnerability in traditional houses (≈ 10.5%). The high prevalence of ventilation problems and material damage shows that heatwaves not only affect thermal comfort but also impact the structural integrity and safety of homes. These results suggest that heat waves affect thermal comfort and indoor air quality more than structural integrity, revealing a functional vulnerability of the home rather than immediate physical damage.

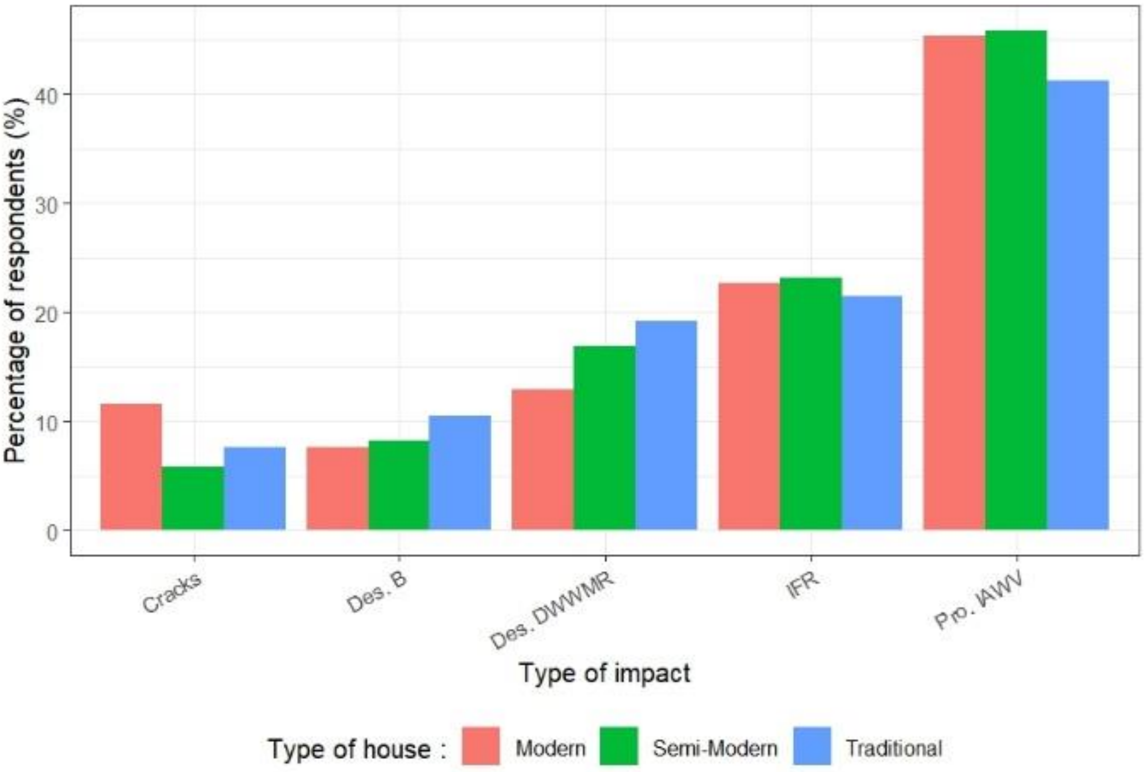


Figure 13: Impact of heat waves on different types of housing in Bol. IFR: Increased risk of fire; Des. DWWMR: Destruction of doors, windows, walls, materials, roofing, etc.; Pro. IAWV: Problems with indoor air quality, ventilation, etc.; Des. B: Destruction of buildings.

Proportion of buildings lost by Class, Type of housing and Risk

The results (Figure 14) show that, across all the risks studied, the most frequent structural losses involve minor to moderate damage (1 to 2 buildings lost), regardless of housing type. For flooding, the most recurrent risk, modern (79.3%), semi-modern (59.1%), and traditional (61.0%) dwellings mainly record limited losses (1-2 buildings), while more significant destruction (≥3 buildings) remains less frequent.

For other climate risks-high winds, erosion, and fires-the same trend holds: low-intensity losses dominate across all types of housing (between 66% and 100% of cases, depending on the risk). Major damage (≥4 buildings destroyed) remains rare but is proportionally more frequent in traditional areas in the case of fire (16.7%) and high winds (6.06%). It should be noted that no heat-wave-related losses were reported, regardless of construction type. This result indicates a virtually zero structural impact for this hazard in the context studied. On the other hand, no structural damage was reported during heat waves, regardless of dwelling type.

The results of the dependency tests between the type of dwelling and the level of damage reveal that none of the risks analysed show a statistically significant association. For floods, Fisher's test indicates that the distribution of damage (1-2, 3-4, more than 4 buildings lost) does not differ significantly between modern, semi-modern and traditional houses ($p = 0.47$). Similarly, for high winds ($p = 0.16$), erosion ($p = 1.00$), and fire ($p = 0.28$), the levels of loss observed do not vary significantly by dwelling type.

These results suggest that, in the context studied, the type of dwelling is not a statistically significant determinant of the extent of damage caused by the climate risks considered.

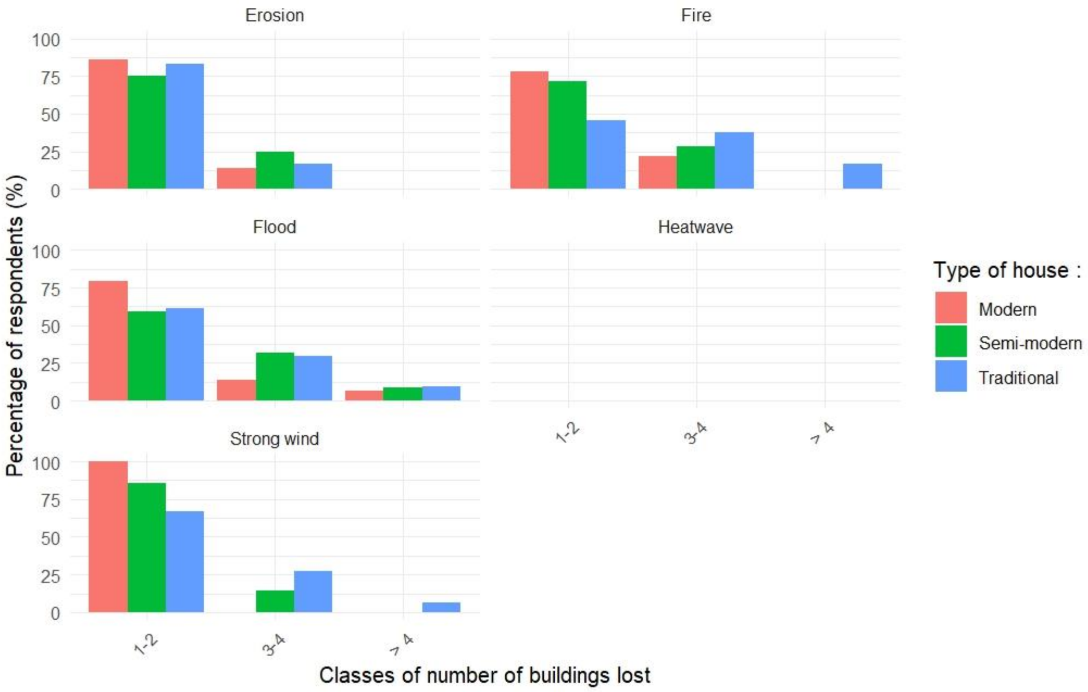


Figure 14: Proportion of buildings lost by Class, Type of Housing and Risk in Bol

Identification of household adaptation and resilience strategies

Analysis of proportions reveals significant differences in the adaptation strategies households implement depending on the nature of the climate risks they face (Figure 15). This heterogeneity reflects both the specific nature of the hazards and the technical and material adjustment capacities of local populations.

Faced with the risk of erosion, the preferred strategies are mainly structural measures aimed at strengthening building stability. Deep foundations (DF, 22.8%) are the most commonly used solution, followed by structural reinforcement (RS, 17.1%) and the installation of barriers (IB, 17.1%). Households also resort to retaining wall construction (Cons.RW, 10.6%) and drainage trench construction (Cons.DT, 10.6%), while plant vegetation (PV, 6.5%) remains marginal.

Regarding fires, adaptation strategies are dominated by immediate, reactive responses. The use of water (UW, 46.1%) is by far the most common measure, highlighting its central role in quickly extinguishing fires. This strategy is followed by clearing dry grass around homes (CDGAH, 21.6%) and choosing less flammable building materials, such as earth rather than straw and vegetation (Cons.WISV, 19.4%). The use of sand (US, 12.9%) appears to be a secondary alternative.

For floods, strategies are more diverse, as households adopt a wider range of measures, combining preventive, structural and temporary adaptation measures. The most common are foundation elevation (Elev.F, 24.3%), construction of building dykes and dams (Cons.DD, 22.1%), followed by the use of water-resistant materials (UWRM, 14.8%) and construction of gutters (Cons.G, 18.6%). The use of tarpaulins indoors (UTIR, 11.7%) and the use of vegetation (UV, 7.9%) is also implemented, while the absence of measures (Nothing, 0.6%) remains very marginal.

Finally, in response to strong winds, the implemented strategies primarily focus on strengthening buildings' mechanical resistance. Households favour deep foundations (DF, 25.1%), resistant materials (RM, 16.3%) and structural reinforcement (SR, 15.6%). Other important strategies include thick walls (TW, 12.4%), protection of openings (PO, 13.9%) and low-slope roofs (LSR, 10.2%). Planting trees around the building (windbreak) (PTB(WB), 6.6%) remains more limited.

Overall, the results show that households' adaptation strategies are strongly influenced by the type of climate risk, favouring structural solutions for hazards with high physical impact (erosion, flooding, strong winds) and more immediate responses for rapid, localised risks such as fires. Overall, the adaptation strategies implemented in Bol are predominantly autonomous, reactive and focused on ad hoc structural solutions, reflecting a strong capacity for individual adjustment but weak collective planning at the urban level.

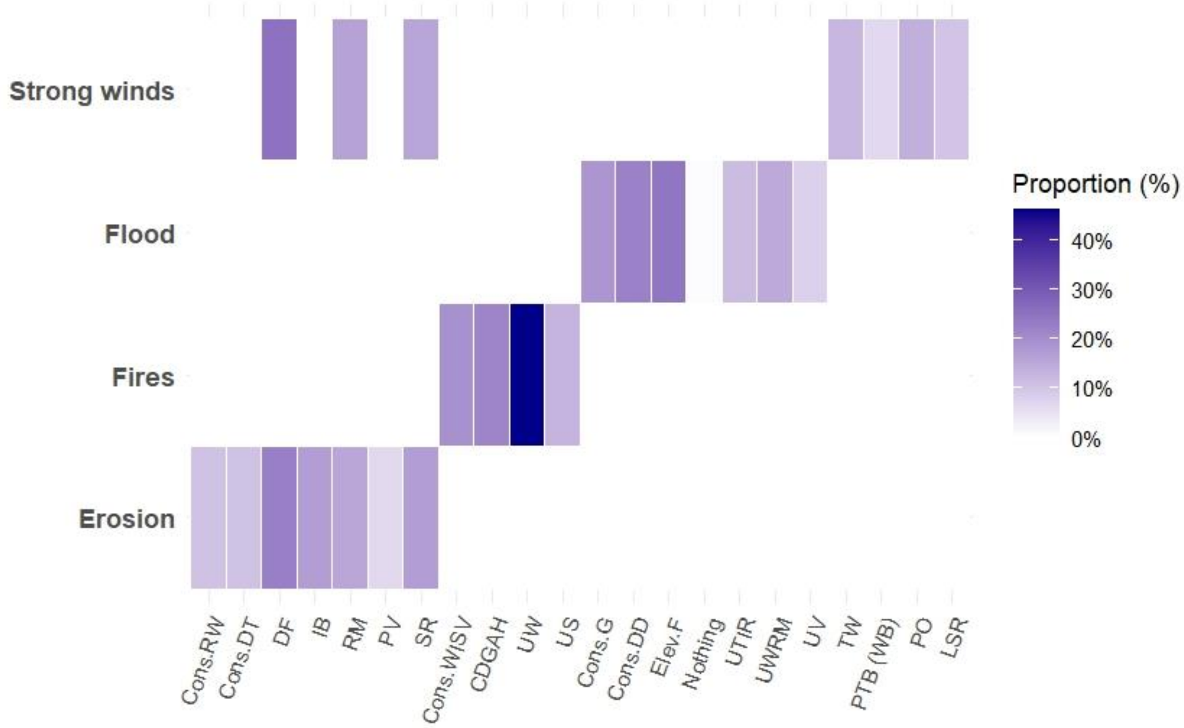


Figure 15: Adaptation and resilience strategies adopted by the population in response to various risks in Bol. Cons.RW: Construction of retaining walls; Cons.DT: Construction of drainage trenches; DF: Deep foundations; IB: Installation of barriers; RS: Resistant materials; PV: Planting vegetation; RS: Reinforcing structures; Cons.WISV: Building with earth instead of straw and vegetation; CDGAH: Cleaning dry grass around the house; UW: Using water; US: Using sand; Cons.G: Construction of gutters; Cons.DD: Building dykes and dams; Elev.F: foundation elevation; UTIR: Use of tarpaulins inside rooms; UWRM: Use of water-resistant materials; UV: Use of vegetation; ME: Thick walls; PTB (WB): Planting trees around the building (windbreaks); PO: Protection of openings; LSR: Low-slope roofs.

Discussions

This study aimed to analyse climate risks, their impacts on different types of housing, and local adaptation strategies in Bol, a particularly vulnerable town in Lake Chad province. The results provide empirical and contextualised insights into a field of research that remains underexplored in Central Africa, particularly regarding the systemic vulnerability of the built environment. The following discussion interprets these results, considering the existing literature.

Intensification of climate risks in Bol

Climate results highlight strong seasonality in precipitation, temperatures, relative humidity and wind speed, with extremes concentrated during specific periods. Temperature, precipitation and wind speed patterns are being altered by climate change [52], increasing the likelihood and intensity of extreme events such as floods, heat waves, droughts, erosion, fires and storms. This dynamic is fully consistent with recent observations that variations in annual temperature and precipitation patterns are nuanced and variable [53] and are now a major feature of climate change [1,20,30].

More specifically, the intensity of rainfall observed between July and August in the city of Bol, with maximums exceeding 270 mm, confirms the trend towards more concentrated and violent rainfall, already documented in West and Central Africa [1,5]. These results are consistent with the conclusions of IPCC AR6, which highlight that Sahelian areas are experiencing a simultaneous increase in heavy rainfall events and prolonged drought, thereby increasing the risk of urban flooding [54]. This study provides crucial local validation of these global trends, confirming that Bol, as a lakeside city, is bearing the brunt of this new hydroclimatic dynamic.

Furthermore, the extreme maximum temperatures recorded between March and May (42–45 °C) are in line with the intensification of heat waves in sub-Saharan Africa highlighted by [24,55]. This overlap of hydrological and thermal hazards confirms that Bol is fully in line with global climate hotspots, as highlighted by work on the Lake Chad basin [20,31]. Our analysis goes beyond simple trend observation; it establishes a precise calendar of high-intensity periods for each risk, thereby addressing a gap in local adaptation policies, which often lack detailed temporal data.

Differentiated vulnerability of housing: the decisive role of building types

Analysis of physical impacts shows that all types of housing are affected, but in different ways. Modern and semi-modern houses appear to be more prone to cracks, corrosion, and structural damage during floods, while traditional dwellings are more prone to water infiltration, structural failure, and material loss.

These results confirm the work of Papathoma-Köhle et al. [8] and Binz et al. [9], which shows that the vulnerability of buildings depends not only on their level of modernity, but above all on the compatibility between materials, construction techniques and the local climate. In the case of Bol, the use of modern materials (cement, concrete, metal) that are not adapted to hydromorphic soils and humidity conditions promotes structural damage, a phenomenon also observed in other African cities [18]. This highlights a paradox: materials such as concrete, perceived as solid [56], can lead to increased fragility in the face of specific climatic stresses when their use does not correspond to climatic requirements [57].

Conversely, while traditional dwellings are often perceived as more vulnerable, their relative thermal performance in the face of heat waves (thick walls, small openings) is consistent with the conclusions of Tossim et al. [58], Berardi and Jafarpur [10] and Çal and Ciravoğlu [15], who highlight the value of vernacular architecture and bio-based materials in optimising thermal comfort, and therefore climate adaptation strategies. Our study expands on this notion by quantifying this relative performance and revealing the dual role of these constructions: a certain thermal resilience, but extreme vulnerability to water and mechanical hazards. This argues in favour of hybrid approaches, where the bioclimatic principles of vernacular architecture are combined with targeted technical reinforcements.

Combined effects of strong winds, erosion and fires on building stability

Strong winds appear to be a cross-cutting hazard affecting all types of housing, with a predominance of roof detachments and structural damage. This observation is consistent with studies conducted in Sahelian cities, where poor anchoring and the absence of appropriate building standards amplify the damage caused by extreme gusts [12,59]. The almost identical vulnerability of the three types of housing to this risk is a striking result, suggesting that neither traditional techniques nor modern practices commonly used in Bol offer adequate solutions against strong winds.

Erosion acts as a silent aggravating factor, gradually weakening the foundations and overall stability of buildings. This process, which is well documented in the lake and river areas of the Sahel [11,12], results from the interaction between intense runoff and loose soils. Our study confirms that its impact is perceived as significant, regardless of the type of housing, making it a fundamental threat to the very foundations of buildings. The necessary interventions, therefore, go beyond the scale of the individual building, which is not sufficient to encompass the site and the neighbourhood.

Furthermore, local factors can exacerbate these effects. The work of Zahinda Mugisho et al. [60] highlights, in the case of Bukavu (DRC), the influence of construction defects and planning errors that amplify erosion-related damage. Such synergy between anthropogenic vulnerabilities and natural hazards could well be found in the urban context of Bol, highlighting the need for a holistic diagnostic approach.

Although less frequent, fires are notable for their high destructive potential, with a high proportion of complete destruction, particularly in traditional dwellings. These results are consistent with the analyses of Daraz et al. [4], which show that rising temperatures and drying materials significantly increase the risk of fire in informal urban areas in Africa. The perceived link between heat waves and fire risk in our study highlights the interconnected nature of risks in the dry season, creating a "cocktail" of mutually reinforcing threats.

Seasonality of impacts, a key determinant of urban vulnerability

One of the major contributions of this study is its clear perception of the seasonality of climate risks. The exclusive association of flooding and erosion with the wet season, and heat waves and fires with the dry season, confirms the existence of seasonal vulnerability profiles, already highlighted in the work of Gemeda et al. [13] and Atchadé et al. [49]. This detailed perception, aligned with objective climate data, reflects the inhabitants' in-depth empirical knowledge of the environment.

This seasonal differentiation reinforces the idea, developed by the IPCC [61] and by Allarané et al. [14], that adaptation strategies must be dynamic and seasonalised, rather than static. In Bol, this approach appears all the more relevant, as the hazards do not overlap temporally but follow one another, each with distinct impact mechanisms. An effective adaptation policy should therefore promote a "resilience calendar", with specific preparatory actions carried out before each risky season.

Local adaptation strategies

The adaptation strategies implemented by households reflect a remarkable capacity for autonomous adaptation, based mainly on structural solutions (deep foundations, dykes, thick walls, resistant materials) and immediate responses to rapid risks (water and sand for fires). This repertoire of actions, although fragmented, constitutes a wealth of essential know-how that should be harnessed.

These results confirm observations made in Chad and Central Africa, indicating that adaptation is mainly reactive, incremental, and self-financed in the absence of effective institutional mechanisms [24,26]. However, several strategies remain constrained by economic, technical, and land constraints, which limit their long-term effectiveness. For example, artisanal dykes can shift the problem to neighbours, and deep foundations are inaccessible to the poorest. The lack of mastery of certain adaptation techniques, such as raising, amphibious and floating techniques [62] in the event of flooding, is also a hindrance.

The almost total absence of planned solutions at the urban level (structured drainage, climate-compatible building standards, zoning of flood-prone areas) highlights a persistent gap between national adaptation policies and their local implementation, already highlighted in Chad's Third National Communication [27] and in work on urban planning in Chad [46]. The strategies documented here are primarily individual or community-based, revealing a failure of urban governance in protecting the built environment. This study makes an original contribution to the literature by combining long-term climate data, local perceptions and a typological analysis of housing, an approach that is still underdeveloped in research on climate change in Sahelian Africa [16].

Conclusion

This research highlighted the exposure of housing to climate risks in the town of Bol, in the Lac province of Chad, one of the regions most affected by climate change. By combining the analysis of long-term climate data, risk perception, assessment of physical impacts on housing types and identification of local adaptation strategies, the study provides an integrated and contextualised reading of a field that has not yet been sufficiently explored in Sahelian cities. The results show that climate risks in Bol are highly seasonal, with flooding and erosion predominating in the wet season, and heat waves, fires and strong winds in the dry season. This seasonal pattern of risks has varied impacts, but affects all types of housing, whether traditional, semi-modern or modern. Contrary to some common perceptions, the modernity of materials does not constitute a systematic factor of protection and can even create new forms of vulnerability when construction techniques are not adapted to local climatic constraints. Conversely, traditional dwellings are relatively thermally efficient during heat waves but remain extremely vulnerable to water and mechanical hazards. Analysis of adaptation strategies reveals a strong capacity for individual adjustment among households, primarily through structural and reactive solutions. However, these strategies remain largely fragmented, unevenly accessible, and constrained by economic, technical, and institutional constraints. The absence of urban-scale structural measures, such as planned drainage systems, climate-compatible building standards or zoning of risk areas, highlights a persistent gap between national adaptation frameworks and their effective implementation at the local level. This study thus makes an original contribution to the literature on climate change and housing in Central Africa by proposing a holistic approach that links climate, architecture, social vulnerability and adaptation. It demonstrates that assessing the vulnerability of the built environment cannot be reduced to a technical analysis of buildings, but must integrate social dynamics, local perceptions and adaptive practices, from a territorial and seasonal perspective. Ultimately, this research suggests a renewed approach to climate adaptation in Sahelian cities, based on recognising local knowledge, adapting architectural practices to climatic realities, and implementing integrated urban policies. Such an approach is essential to strengthen housing resilience and ensure the sustainability of cities facing intensifying climate risks.

Author Contributions

Conceptualization, P.A.T.; methodology, P.A.T., F.T.N., A.K.D. and K.K.; software, P.A.T. and V.V.A.A.; validation, K.K. and J.M.T.; formal analysis, P.A.T and J.M.T.; investigation, P.A.T. and F.T.N.; resources, P.A.T, V.V.A.A. and J.M.T.; data curation, P.A.T., V.V.A.A., F.T.N. and JMT.; writing-original draft preparation, P.A.T.; writing-review and editing, A.K.D., K.K., F.T.N. and J.M.T.; visualization, K.K., A.K.D. and K.S.K.; supervision, K.K., A.K.D. and K.S.K.; project administration, K.S.K.; funding acquisition, P.A.T. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

In accordance with the scientific ethics governing activities at CERViDA-DOUNEDON, this study obtained prior approval from an ethics committee of the thesis jury, and the data collected from households have been anonymised and do not allow for any direct or indirect identification of respondents. The use of this data is strictly limited to scientific research purposes.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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