Climate risk assessment in urban environments.

Chaymae Benballa[1*], *Faycal* Fatah[1], and *Thami* Daiboun[1]

[1]Territoire, Environnement Et Developpement,Faculty of Letters and Human Sciences of Kenitra, IbnTofail UniversityKenitra,B.P 401, Kénitra, Morocco.

Abstract. The majority of climate change vulnerability and health concerns are concentrated in informal settlements. Hazardous locations can be found in many communities, including low-lying ground along exposed riverbanks and ocean coasts, degraded slopes, and buildings that don't adhere to building rules. A complex network of interrelated social, ecological, and technical processes makes up the urban environment. Global warming is expected to have a wide range of repercussions on ecosystems and society, which naturally increases complexity, in addition to other environmental, economic, and political concerns.By integrating satellite, environmental, and socioeconomic data using an integrated method that included remote sensing, statistical modeling (PCA), and geographical analysis, this work created a spatially explicit diagnosis of urban climate risks in Rabat. Three primary risk factors were investigated: air pollution (PM2.5 and NO_2), urban heat (heat island), and related socioeconomic vulnerability.

1 Introduction

As drivers of socio-economic development, cities inevitably become areas of concentrated risk and greenhouse gas emissions, fueling climate change and its impacts[1]. However, according to estimates by the Intergovernmental Panel on Climate Change, some cities and people are more vulnerable than others (**Figure 1**)[2].Most health risks and climate change vulnerability are concentrated in informal settlements. Many towns have hazardous sites such as eroded slopes, low-lying land close to unprotected riverbanks and ocean shores, and structures that do not meet building codes[3], [4], [5]. The urban environment comprises a complex structure of interconnected social, ecological, and technical processes [6].In addition to other environmental, economic, and political challenges, global warming is predicted to have a wide range of effects on ecosystems and society, which naturally increases complexity[7], [8].As governments recognize the value of urban forests in enhancing quality of life and reducing climate change, cities around the world are preparing for resilience through urban greening projects[9].

* Corresponding author: author@email.org

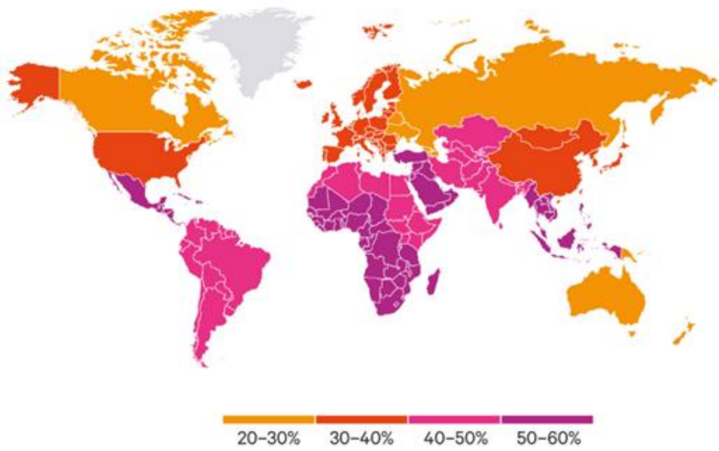

Fig. 1. Impacts on the region, 2040: percentage of the population that experiences significant heat waves annually.

However, rigorous evaluations of the factors that contribute to tree dieback and mortality in urban settings are uncommon, and climate change poses a threat to the survival of urban forests and the ecosystem services they offer [1], [10]. To detect and stop failures and deaths brought on by climate change, long-term monitoring studies and adaptive management are required. According to a global study, over 50% of all plant species found in urban forests are already climatically tolerant of mean annual temperatures, and this percentage is expected to rise by 2050, thus endangering the health of urban ecosystems even more[11].Urban woods are also at risk from extreme weather events like heatwaves, severe droughts, and floods, which are becoming more often and severe due to climate change[12].Adapting their cities to the unavoidable consequences of climate change is starting to receive more attention from local governments[13]. This is because there is a delay between when greenhouse gas emissions are reduced and when the climate system will experience those effects[13].Climate change and heightened climate variability will modify the environmental baselines of metropolitan areas, including temperature regimes and precipitation patterns[14]. Climate shifts and the heightened occurrence of extreme events directly affect water supply and quality, the frequency of flooding and drought, and water demand, among various other factors[15], [16]. These dynamic changes will impact system operations across several urban sectors interactively, heightening the uncertainty faced by urban managers and decision-makers[17], [18].Like other developing nations, Morocco will bear the consequences of the greenhouse gas emissions from developed nations, which in 2004 accounted for 46% of global emissions despite having 20% of the world's population[19]. The most likely sectors to be negatively impacted by climate change in Morocco are agriculture and water resources[20].Morocco's climate is generally defined by hot, dry summers with little precipitation and significant evapotranspiration; winters are mild along the coast and cold elsewhere[21]. Morocco's geographic location and the topography of the Atlas Mountain ranges, however, result in a variety of climate combinations[22].

This study develops a paradigm for urban risk assessment, highlighting the effects of climate change on cities rather than the contribution of cities to climate change via greenhouse gas emissions. The aim is to identify the areas most exposed to urban climate risks in the city of Rabat, particularly in relation to the urban heat island (UHI) and air pollution.

2 Literature

The results of the studies exposing the socioeconomic effects of climate change in cities were not all the same. The majority of studies brought up issues with how the climate affects poverty, food security, agriculture, and urban regions' ability to adapt.For example, **Nakyai et al**. [23]examined the connections between air pollution levels, weather conditions, and health risk evaluations in Chonburi Province, Thailand's urban and industrial districts. Automatic air pollution monitoring stations run by the Thai Meteorological Department and the Thailand Pollution Control Department provided data on air pollutant concentrations and meteorological variables over ten years (2012–2021).The results showed that wintertime saw the highest quantities of air pollutants in urban and industrial locations.The findings are essential for organizing and creating practical plans to reduce the health hazards that air pollution exposure poses to both the general public and employees[23]. **Ma et al.** [24], too, propose a comprehensive assessment framework for assessing climate justice in shelters during extremety phoons. The maximum storm surge flooding area of Xiamen is very small, according to the results, but it poses a threat to disaster prevention on remote islands like Xiaodeng. The socioeconomic characteristics of shelter service locations differ greatly. While medium-service areas demonstrate considerable interactions between income and other metrics, low-service areas display similar influential elements[24]. Rapid urbanization and climate change have increased the frequency and intensity of flooding, causing significant harm to infrastructure and populations. However, **Tabasi et al**. present the Integrated Risk Linkages (IRL) Framework. Furthermore, the authorsevaluate existing flood risk assessment methods, emphasizing their characteristics and practical applicability, and address challenges in data quality and integration by promoting flexibility and adaptability in applying the IRL framework along with the proposed hierarchical structures across diverse contexts[25].**Maglia's** study is based on an innovative analytical and probabilistic approach to assessing the operation of rainwater reservoirs in stormwater management, with the possibility of using the collected water for non-drinking purposes.A new iteration of an analytical probabilistic approach was used to assess the rainwater tank's performance in fulfilling irrigation, and its validation showed that it is promising and provides good perspectives in the field of stormwater management [26].A framework for evaluating outdoor thermal comfort was created by **Jia et al**. To create the model, 668 onsite observations from field experiments conducted during the day on normal summer days were gathered. Approximately 74.8% of locations had severe to extreme heat stress during extreme hot circumstances, with thermal sensations rated as hot or very hot. The remaining 25.3% of places experienced moderate heat stress, according to the results[27].**Mekkaoui et al.** investigated the urban flood vulnerability of Tetouan, Northern Morocco, by mapping and identifying flood-prone areas using four machine learning models: Factorial Discriminant Analysis (FDA), Support Vector Machine (SVM), Logistic Regression (LR), and Classification and Regression Tree (CART). By identifying the most vulnerable areas, the main objective is to improve flood prevention efforts and reduce losses. The results provide useful information for flood risk management decision-makers and urban planners, enabling better resource allocation in Tetouan-Martil and maybe directing equivalent tactics in similar areas around the world [28].The methodology used in the extensive breadth of this study in Nador by **Lambarki, R. et al.** is carefully planned to evaluate the viability of implementing green roofs in the urban context using a complete approach. The study's results, which show which roofs are most suited for implementing green roofs, are combined with the roofs' attribute database and financial data to form the basis for the green cadastre, which offers a plethora of data. This method also enables you to use Geographic Information System (GIS) technologies to produce detailed maps of green roofs. Making informed selections regarding the ideal sites for green roofs is made simpler with the help of these maps [29].The primary goal of the work of **Afif. H. et al.** is to measure retention basin efficacy by adapting to the natural morphology of watersheds while also being consistent with flood hazard assessment. The flood hazards results identify three levels of runoff intensity during rainstorm events or river floods: high, medium, and low. The retention basins' findings have a positive impact, which motivates the pursuit of greener options [30].**Table 1** summarizes the studies discussed on the socio-economic effects of climate change.

Table1. An overview of studies on the socioeconomic effects of climate change.

Authors	Focus Area	Location	Key Findings	Implications
Nakyai et al. [23]	Air pollution, weather, and health risks	Chonburi Province, Thailand	High pollutant levels in winter; 10-year data used.	Aids planning to mitigate health risks due to air pollution.
Ma et al. [24]	Climate justice in shelters during typhoons	Xiamen, China	Small flood areas can threaten remote islands; service area disparities in socioeconomic characteristics.	Improves shelter planning for vulnerable populations.
Tabasi et al. [25]	Flood risk assessment – IRL Framework	General (unspecified)	Promotes flexible, adaptable flood risk assessment with hierarchical structures.	Enhances flood resilience and method adaptability.
Maglia[26]	Rainwater harvesting and stormwater management	General (unspecified)	Analytical-probabilistic method shows good performance for irrigation.	Promotes sustainable water reuse in stormwater management.
Jia et al. [27]	Outdoor thermal comfortmodeling	General (668 field observations)	74.8% of sites experienced extreme heat stress.	Provides basis for urban design for thermal comfort.
Mekkaoui et al. [28]	Urban flood vulnerability using ML models	Tetouan, Morocco	FDA, SVM, LR, CART used to map flood-prone areas.	Informs better flood management and planning in urban areas.

Lambarki et al. [29]	Green roof viability and GIS mapping	Nador, Morocco	Developed green cadastre combining roof and financial data.	Enables informed implementation of green roofs.
Afif et al. [30]	Retention basin effectiveness for flood control	General (naturalwatersheds)	Identified three runoff intensity levels; basins reduce flood impact.	Encourages greener flood mitigation strategies aligned with watershed morphology.

Socioeconomic factors, air quality, severe temperatures, flooding, sea level rise, health, and water supply/drought are some of the urban issues[5]. The detrimental effects of air pollution and extremely high temperatures on health were highlighted in this review. Given the critical role that health plays in urban development, particularly in the current era where urban risk mitigation and adaptation are at the forefront, this emphasis was placed. It should be noted that certain nations and their cities already have policies in place for both adaptation and mitigation. Nonetheless, the emphasis should be on the widespread acceptance and implementation of these policies in all global urbanized areas[31], [32].

Fig. 1. Caption of the Figure 1. Below the figure.

3 Methodology

3.1 Study area

The capital of Morocco is part of the Rabat-Salé-Kénitra region(34.013 N, 6.49 W, 46 m.a.s.l)(**Figure 2**), which was created in 2015 as one of the country's 12 regions[33]. The previous areas of Rabat-Salé-Zemmour-Zaer and Gharb-Chrarda-Beni-Hssen merged to form one region. Geographically, it is bordered to the north by Tanger-Tetouan-Al Hoceima, to the east by Fès-Meknès, to the south by Casablanca-Settat, to the southeast by Beni-Mellal-Khénifra, and to the west by the Atlantic Ocean[34]. With a total area of 17,570 km^2, the region makes up 2.5 percent of Morocco.Rabat-Salé-Kénitra has a Mediterranean climate, which is marked by cold and rainy winters with average nighttime temperatures between 0 and 5 degrees Celsius and daytime highs of up to 17 degrees Celsius. Summers are characterized by an oceanic environment, with daytime highs of about 30 degrees Celsius and evenings cooled by ocean dampness. The "Chergui" desert winds can occasionally cause temperatures to reach 40 degrees Celsius for a few days throughout the spring and summer.

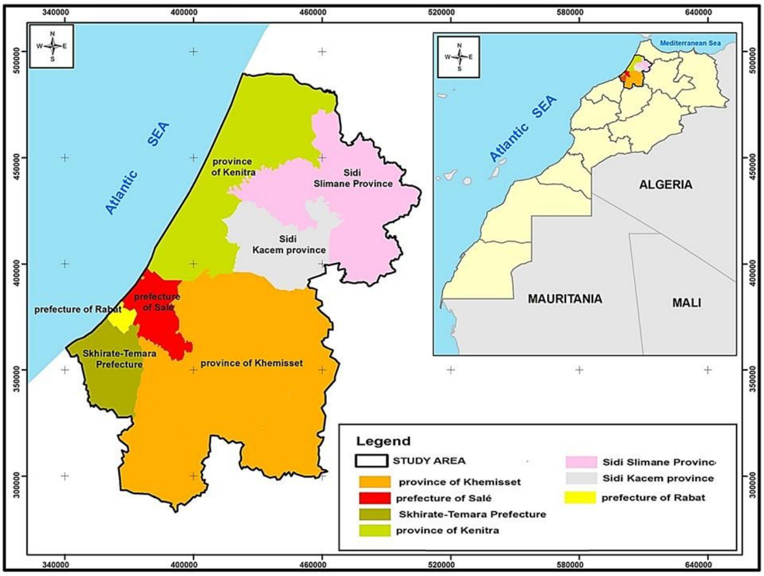

Fig. 2. Detailed map of the study area showing key geographical and administrative boundaries.

Has a temperate climate with average temperatures between 12°C and 23°C, minimum temperatures between 0°C and 5°C, and maximum temperatures between 30°C and 38°C. It receives 500 to 600 mm of rainfall annually on average, winds that are typically from the north and west, and a close proximity to the sea. The city of Rabat has a large, uniform area and has developed steadily thanks to its Urban Planning Plans (**Figure 3**). There are five districts of Rabat, each with its own urban tissue. The traditional tissue is the Medina. With residences, businesses, services, and even tiny public areas, it is extremely congested.

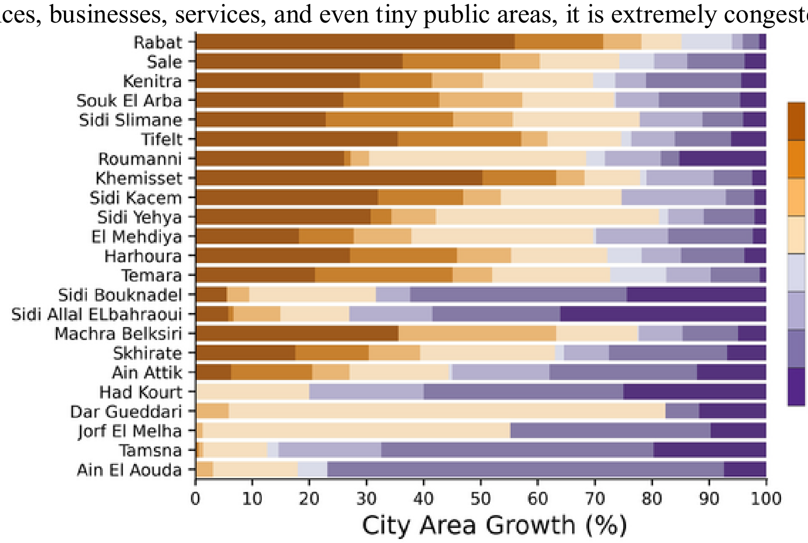

Fig. 3. Urban expansion intensity in three different cities of the RSK region, Morocco from 1972 to 2020.

There are two main aquifers of particular significance in the Rabat-Salé-Kénitra region, which is known for having substantial groundwater reserves[34]:

- The 390 km² Gharb Aquifer provides 126 million cubic meters (Mm³) of renewable water supplies per year. Due to significant recharge from precipitation and infiltration from the Gharb basin's edges, this aquifer maintains a typically healthy water balance, underscoring its regional hydrogeological significance[35].

- The Maâmora Aquifer is an unconfined aquifer that is mostly replenished by rainfall infiltration. It covers an area of around 4,000 km². With 134 Mm3 of renewable water resources every year, it acts as a sizable reservoir[35]

The Acknowledgements, Fundings, Data availability statement, Author contribution statement, should be typed in 9-point Times, without title.

3.2 Data acquisition and processing

The Geographic Information System (GIS) is a powerful tool for spatializing and analyzing a multitude of data[35]. In the coastal zone, GIS is increasingly used as an aid tool for homogenizing and integrating all the information in a geographic database to access the data, generate thematic cartography, and carry out spatial and geostatistical analysis; in this case, modelling and cartography of a possible rise in sea level on the one hand, and quantification of the areas at risk on the other[36].
The data used came from satellite and institutional sources. Landsat 8 satellite images (OLI and TIRS sensors) were used to map surface temperatures[37], focusing on July and August, when the heat island phenomenon is most pronounced[38]. The thermal bands (bands 10 and 11) were extracted and processed in QGIS software[39], applying an atmospheric correction using the Semi-Automatic Classification plugin[40]. This step made it possible to estimate the surface temperature (LST) at the city scale, then to classify it by temperature intervals[41].

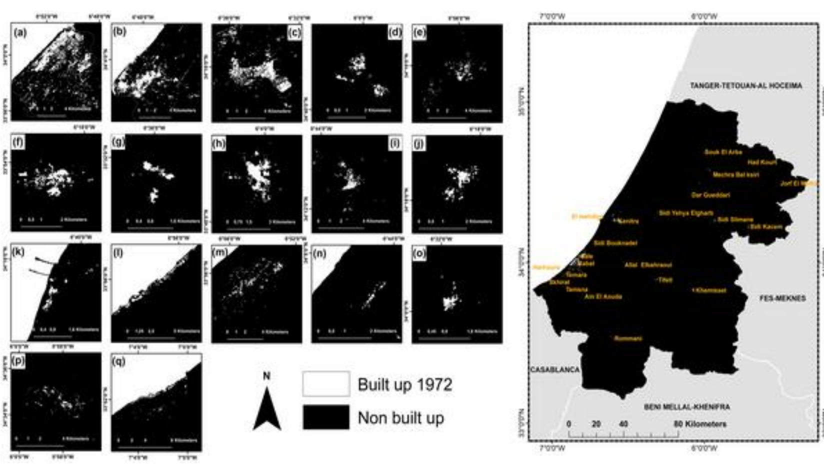

Fig. 4. Evolution of the urban fabric in the RSK region, Morocco from 1972 to 2020[42].

Concerning air pollution, NO_2 and PM2.5 concentrations were integrated from two sources: measurements from local stations of the National Centre for Air Quality (INH)[43], and data from the Copernicus Atmosphere Monitoring Service (CAMS)[44], which provides daily estimates of air pollution on a regional scale[45]. The data was interpolated using the IDW (Inverse Distance Weighting) method to generate a continuous layer over the city[46].

4 Assessment of climate risks in urban areas: case study of Rabat

4.1 Urban heat (UHI)

Higher temperatures in densely populated areas relative to nearby rural areas are known as the urban heat island (UHI). In Rabat, surface temperatures at various times of the year were mapped using Landsat 8 satellite photos (TIRS, or Thermal Infrared Sensor)[47].

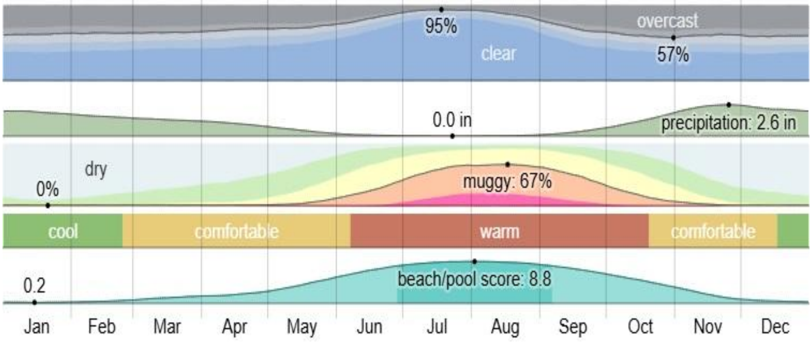

Fig. 5. Climate and Average Weather Year-Round in Rabat-Morocco [48].

Table 2. Criticalenvironmentalcharacteristics in three Rabat neighbourhoodsexposed to high climaticrisks (surface temperature, NO_2, PM2.5)[49], [50].

Quartier	Température de surface (°C)	NO_2 (µg/m³)	PM2.5 (µg/m³)
Yacoub El Mansour	>45	Jusqu'à 65	Jusqu'à 38
Akkari	>45	Jusqu'à 65	Jusqu'à 38
Agdal Centre	>45	Jusqu'à 65	Jusqu'à 38

Table 2 indicate that surface temperatures in heavily populated regions, including Agdal, and Yacoub El Mansourcan be up to 6°C higher than those in more vegetated outlying locations, like the Hilton Forest and the vicinity of OuedBouregreg[51]. The concentration of transportation infrastructures, the low density of green spaces, and the impermeability of the soil are the primary causes of this overheating[52].

4.2 Pollution

At the same time, the city of Rabat is under increasing pressure from air pollution, particularly from road traffic[53], industrial emissions, and district heating[44]. Monitoring data from the National Air Quality Centre, coupled with Copernicus satellite models (CAMS), indicate high concentrations of nitrogen dioxide (NO_2) and fine particles (PM2.5) in the central areas of the city[54]. These pollutants regularly exceed the thresholds recommended by the WHO, particularly during periods of high heat when atmospheric stagnation phenomena accentuate their concentration[55].

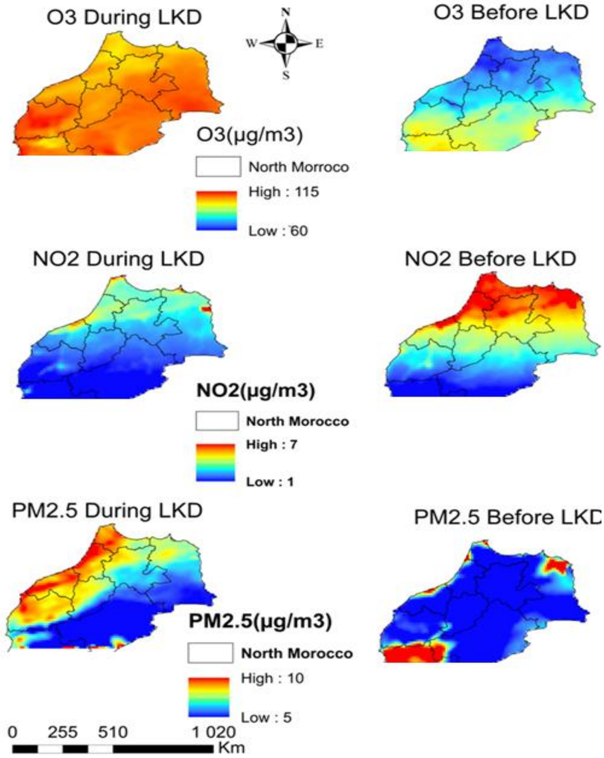

Fig. 6. Spatial patterns for O3, NO2, and PM2.5 before and during the COVID-19 pandemic lockdown over the north of Morocco [56].

The spatial distribution of NO2 mass concentrations before and during LCD is depicted in Figure 6. It is evident that the north and center (in our instance, Rabat) have the highest NO2 concentrations; nevertheless, we also demonstrate that the level of NO2 does not surpass the maximum value (40 µg/m3). NO2 drastically decreased throughout the LCD, which is consistent with all the findings of other European trials [56].

We discovered that during LCD, PM2.5 levels rise in the north and east of the study area, based on the literature. Two explanations for this result include the rise in ozone over the Atlantic and Mediterranean Seas in the north and northwest, which encourages the oxidation of OH radicals or O_3, which forms sea salt particles like iodine [56].

4.3 Statistical analysis

A principal component analysis (PCA) was used to examine a dataset that included socioeconomic (population density, access to green spaces, and housing quality), environmental (air pollution, vegetation cover), and climatic (surface temperature) variables to determine the primary gradients causing climate vulnerability in Rabat. The dimensionality of the dataset can be decreased while maintaining the crucial information, thanks to this multivariate technique.

Table 3: Axis 1: Climate Density Pollution Gradient.

Variable	Description	Direction on Axis 1
Land Surface Temperature (LST)	Retrieved from Landsat 8; proxy for urban heat island effect	Strong positive
Population Density	Number of inhabitants per km²	Strong positive
NO_2 concentration	Data from CAMS and local stations (µg/m³)	Strong positive
Impervious Surface Ratio	% of land covered by artificial surfaces (roads, rooftops)	Positive

Table 4: Axis 2: Green Space and Adaptation Capacity Gradient.

Variable	Description	Direction on Axis 2
Green space per capita	m² of vegetation per person (NDVI or municipal GIS data)	Strong positive
HousingQuality Index	Composite score from census (materials, age, size of dwellings)	Moderate positive
Access to public services	Water, sanitation, public transport proximity	Moderate positive
PM2.5 concentrations	Ambient fine particulatematter (µg/m³)	Moderatenegative

The PCA results show that the two main axes explain 78.4% of the total variance:

- Table 3 represents the intensity of climatic and environmental stress in urban areas.The first axis (51.2%) is strongly correlated with mean surface temperature (LST), population density (inhab/km²), and NO_2 concentrations. This factor can be interpreted as a gradient of intensity of climatic and anthropogenic stresses, where the combination of demographic pressure and soil sealing reinforces the urban heat island (UHI) and the stagnation of atmospheric pollutants.
- Table 4captures adaptive capacity and urban ecology. The second axis (27.2%) is structured around indicators of access to green spaces (m²/inhabitant) and the quality of residential buildings (composite indicator based on the HCP national census). This factor reflects the adaptive capacity of populations in the face of climate risks.

According to Ouali's research [57], the influence of the urban fabric's shape on wind speed in urban areas is extremely complex, taking into account multiple factors simultaneously. These include the streets' orientation concerning the direction of the wind, the urban area's roughness, which is determined by the height and dispersion of buildings, and the quantity of high-rise structures. The pattern with the highest wind speed is the compact high-rise, followed by the mixed zone, open low-rise, compact midrise, and open midrise [57].

The ability to generate suitable LUR models using PM2.5 information from small-n monitoring networks significantly enhances the cost-effectiveness of LUR approaches [58]. During study design or pilot investigations, it is especially crucial to use data from a small number of sites, either from monitoring networks that are already in place or those that have been purposefully created [59].

One drawback of PCA is that its primary components may have complicated physical implications, making it difficult to physically evaluate the models that are produced [60]. The primary limitation in this respect relates to the model's transferability [61]. However, if only principal components with logical physical interpretation are selected, and if PCA is applied independently to variables with similar physical meanings and for buffers of the same size, as was done here, the component interpretation and the resulting models can still be improved [62].

5 Conclusion

The long-term survival and expansion of urban environments with significant environmental and socioeconomic benefits can be achieved by improving planting results through the capacity to measure rates of death and decline brought on by climate change.This study established a spatially explicit diagnosis of urban climate risks in Rabat by combining satellite, environmental and socio-economic data through an integrated approach mobilising remote sensing, statistical modelling (PCA) and geographical analysis. Three main dimensions of risk were explored: urban heat (heat island), air pollution (NO_2 and PM2.5), and associated social vulnerabilities.The climate risk assessment carried out in the city of Rabat highlights the marked vulnerability of certain neighbourhoods to the intensification of environmental stresses, particularly those linked to urban heat and atmospheric pollution. By cross-referencing remote sensing data (surface temperatures, vegetation indices), pollution measurements (NO_2, PM2.5) and socio-demographic indicators, this study has made it possible to identify the areas combining the main risk factors.Principal component analysis has enabled us to distinguish two major axes structuring this vulnerability: the first is linked to heat and pollution intensity, the second to the adaptive capacity of neighbourhoods (access to green spaces, quality of buildings, infrastructure).

References

1. M. Esperon-Rodriguez et al., « Assessing the vulnerability of Australia's urban forests to climate extremes », PLANTS PEOPLE PLANET, vol. 1, no 4, p. 387-397, oct. 2019, doi: 10.1002/ppp3.10064.
2. M. Esperon-Rodriguez et al., « Assessing climate risk to support urban forests in a changing climate », PLANTS PEOPLE PLANET, vol. 4, no 3, p. 201-213, 2022, doi: 10.1002/ppp3.10240.
3. A. Monteiro, J. Ankrah, H. Madureira, et M. O. Pacheco, « Climate Risk Mitigation and Adaptation Concerns in Urban Areas: A Systematic Review of the Impact of IPCC Assessment Reports », Climate, vol. 10, no 8, Art. no 8, août 2022, doi: 10.3390/cli10080115.
4. R. D. Stewart et al., « An analytical approach to ascertain saturation-excess versus infiltration-excess overland flow in urban and reference landscapes », Hydrol. Process., vol. 33, no 26, Art. no 26, 2019, doi: 10.1002/hyp.13562.
5. W. Yue, K. Meng, K. Hou, R. Zuo, B.-T. Zhang, et G. Wang, « Evaluating climate and irrigation effects on spatiotemporal variabilities of regional groundwater in an arid area using EOFs », Sci. Total Environ., vol. 709, p. 136147, 2020, Consulté le: 26 janvier 2025. [En ligne]. Disponible sur: https://www.sciencedirect.com/science/article/pii/S0048969719361431
6. P. Metzger et R. D'Ercole, « Les risques en milieu urbain : éléments de réflexion », EchoGéo, no 18, Art. no 18, déc. 2011, doi: 10.4000/echogeo.12640.
7. R. V. Gallagher, S. Allen, et I. J. Wright, « Safety margins and adaptive capacity of vegetation to climate change », Sci. Rep., vol. 9, no 1, p. 8241, 2019, Consulté le: 4

mai 2025. [En ligne]. Disponible sur: https://www.nature.com/articles/s41598-019-44483-x

8. Y. Andersson-Sköld et al., « An integrated method for assessing climate-related risks and adaptation alternatives in urban areas », Clim. Risk Manag., vol. 7, p. 31-50, janv. 2015, doi: 10.1016/j.crm.2015.01.003.
9. H. Ritchie et M. Roser, « Urbanization. Published online at OurWorldInData. org. 2018 ».
10. B. S. Breger, T. S. Eisenman, M. E. Kremer, L. A. Roman, D. G. Martin, et J. Rogan, « Urban tree survival and stewardship in a state-managed planting initiative: A case study in Holyoke, Massachusetts », Urban For. Urban Green., vol. 43, p. 126382, 2019, Consulté le: 4 mai 2025. [En ligne]. Disponible sur: https://www.sciencedirect.com/science/article/pii/S1618866718308069
11. M. Esperon-Rodriguez et al., « Climate-change risk analysis for global urban forests », 10 mai 2021, bioRxiv. doi: 10.1101/2021.05.09.443030.
12. S. Fox et T. Goodfellow, Cities and Development, 2e éd. London: Routledge, 2016. doi: 10.4324/9781315815527.
13. W. A. E.-H. Mehanna et W. A. E.-H. Mehanna, « Urban renewal for traditional commercial streets at the historical centers of cities », Alex. Eng. J., vol. 58, no 4, p. 1127-1143, déc. 2019, doi: 10.1016/j.aej.2019.09.015.
14. K. C. Seto et al., « Human Settlements, Infrastructure, and Spatial Planning », Hum. Settl..
15. W.-Z. Wang, L.-C. Liu, H. Liao, et Y.-M. Wei, « Impacts of urbanization on carbon emissions: An empirical analysis from OECD countries », Energy Policy, vol. 151, p. 112171, avr. 2021, doi: 10.1016/j.enpol.2021.112171.
16. S. Zhang, Z. Li, X. Ning, et L. Li, « Gauging the impacts of urbanization on CO2 emissions from the construction industry: Evidence from China », J. Environ. Manage., vol. 288, p. 112440, juin 2021, doi: 10.1016/j.jenvman.2021.112440.
17. M. Brune, « Urban trees under climate change: potential impacts of dry spells and heat waves in three German regions in the 2050s », PhD Thesis, Climate Service Center Germany (GERICS), 2016.
18. H. Burley et al., « Substantial declines in urban tree habitat predicted under climate change », Sci. Total Environ., vol. 685, p. 451-462, 2019, Consulté le: 4 mai 2025. [En ligne]. Disponible sur: https://www.sciencedirect.com/science/article/pii/S0048969719323289
19. K. Agharroud, M. Puddu, A. Ivčević, A. Satta, A. S. Kolker, et M. Snoussi, « Climate risk assessment of the Tangier-Tetouan-Al Hoceima coastal region (Morocco) », Front. Mar. Sci., vol. 10, p. 1176350, 2023, Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://www.frontiersin.org/articles/10.3389/fmars.2023.1176350/full
20. H. A. Kacem, Fal ,Said, Karim ,Mounir, Alaoui ,Hicham Mharzi, Rhinane ,Hassan, et M. and Maanan, « Application of fuzzy analytical hierarchy process for assessment of desertification sensitive areas in North West of Morocco », Geocarto Int., vol. 36, no 5, p. 563-580, mars 2021, doi: 10.1080/10106049.2019.1611949.
21. « Bouregreg_volet agriculture_urbaine_2016.pdf ». Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://agritrop.cirad.fr/590901/1/Bouregreg_volet%20agriculture_urbaine_2016.pdf
22. F. Assali, H. M. Alaoui, H. Hajji, M. Lahlou, T. Aadel, et S. Taberkant, « Machine learning:: modeling the risk of forest fires ignition in the mediterranean region (North-

West Morocco) », Biodiversidade Bras., vol. 9, no 1, p. 184-184, 2019, Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://revistaeletronica.icmbio.gov.br/index.php/BioBR/article/view/1111

23. T. Nakyai, M. Santasnachok, A. Thetkathuek, et N. Phatrabuddha, « Influence of meteorological factors on air pollution and health risks: A comparative analysis of industrial and urban areas in Chonburi Province, Thailand », Environ. Adv., vol. 19, p. 100608, avr. 2025, doi: 10.1016/j.envadv.2024.100608.
24. C. Ma et C. Wen, « Is coastal urban environment for disaster prevention equitable? Assessing climate justice of shelters in Xiamen, China », Ocean Coast. Manag., vol. 261, p. 107546, févr. 2025, doi: 10.1016/j.ocecoaman.2025.107546.
25. N. Tabasi, M. Fereshtehpour, et B. Roghani, « A review of flood risk assessment frameworks and the development of hierarchical structures for risk components », Discov. Water, vol. 5, no 1, p. 10, févr. 2025, doi: 10.1007/s43832-025-00193-2.
26. N. Maglia et A. Raimondi, « A new approach on design and verification of integrated sustainable urban drainage systems for stormwater management in urban areas », J. Environ. Manage., vol. 373, p. 123882, janv. 2025, doi: 10.1016/j.jenvman.2024.123882.
27. S. Jia, Y. Wang, N. H. Wong, et Q. Weng, « A hybrid framework for assessing outdoor thermal comfort in large-scale urban environments », Landsc. Urban Plan., vol. 256, p. 105281, avr. 2025, doi: 10.1016/j.landurbplan.2024.105281.
28. O. Mekkaoui et al., « Unveiling Urban Flood Vulnerability: A Machine Learning Approach for Mapping High Risk Zones in Tetouan City, Northern Morocco », Urban Sci., vol. 9, no 3, Art. no 3, mars 2025, doi: 10.3390/urbansci9030070.
29. R. Lambarki, A. Elmostafa, M. Maanan, et H. Rhinane, « Assessing the potential of green roofs in urban areas: A multicriteria Boolean analysis utilizing GIS and remote sensing data in the city of Nador, Morocco », Green Technol. Sustain., vol. 3, no 2, p. 100171, avr. 2025, doi: 10.1016/j.grets.2025.100171.
30. H. Afif, M. Oujidi, M. Chourak, I. Amar, et S. Ramdani, « Assessment of flood hazards in Greater Berkane for the selection of nature-based solutions, Oriental region, Morocco », Model. Earth Syst. Environ., vol. 11, no 2, p. 139, févr. 2025, doi: 10.1007/s40808-025-02332-z.
31. R. L. Wilby, « A global hydrology research agenda fit for the 2030s », Hydrol. Res., vol. 50, no 6, p. 1464-1480, 2019, Consulté le: 19 janvier 2025. [En ligne]. Disponible sur: https://iwaponline.com/hr/article-abstract/50/6/1464/70340
32. X. Wang et L. Liu, « The Impacts of climate change on the hydrological cycle and water resource management », Water, vol. 15, no 13. MDPI, p. 2342, 2023. Consulté le: 19 janvier 2025. [En ligne]. Disponible sur: https://www.mdpi.com/2073-4441/15/13/2342
33. N. Salhi, A. Bouyahya, S. Fettach, A. Zellou, et Y. Cherrah, « Ethnopharmacological study of medicinal plants used in the treatment of skin burns in occidental Morocco (area of Rabat) », South Afr. J. Bot., vol. 121, p. 128-142, 2019, Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://www.sciencedirect.com/science/article/pii/S0254629918319021
34. [34] A. Atillah et al., « Tsunami vulnerability and damage assessment in the coastal area of Rabat and Salé, Morocco », Nat. Hazards Earth Syst. Sci., vol. 11, no 12, p. 3397-3414, déc. 2011, doi: 10.5194/nhess-11-3397-2011.
35. A. Elmotawakkil, A. Sadiki, et N. Enneya, « Predicting groundwater level based on remote sensing and machine learning: a case study in the Rabat-Kénitra region », J.

Hydroinformatics, vol. 26, no 10, p. 2639-2667, sept. 2024, doi: 10.2166/hydro.2024.494.

36. K. Benaomar et A. Outzourhit, « Exploring the Complexities of Urban Forms and Urban Heat Islands: Insights from the Literature, Methodologies, and Current Status in Morocco », Atmosphere, vol. 15, no 7, p. 822, 2024, Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://search.proquest.com/openview/1bf3f47065324e5ec74ccb80290649bc/1?pq-origsite=gscholar&cbl=2032431&casa_token=UgtbOFWXyncAAAAA:eICXsIHP1P70el2H9tRaAOlgp8-Xonpr5COlj2HG44SD7arJdfjeHcJOBmtsCJtdOYpTgbz9uG93
37. T. R. Oke, « The energetic basis of the urban heat island », Q. J. R. Meteorol. Soc., vol. 108, no 455, p. 1-24, 1982, doi: 10.1002/qj.49710845502.
38. S. Boulmani et A. Saadane, « Land Use and Urban Sprawl in the Case of the City of Rabat in Morocco: An Integrated Approach Using Remote Sensing, Geospatial Modeling, and Machine Learning », in E3S Web of Conferences, EDP Sciences, 2023, p. 03006. Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://www.e3s-conferences.org/articles/e3sconf/abs/2023/55/e3sconf_acc2023_03006/e3sconf_acc2023_03006.html
39. M. Santamouris, « Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions », Sci. Total Environ., vol. 512-513, p. 582-598, avr. 2015, doi: 10.1016/j.scitotenv.2015.01.060.
40. D. Zhou, S. Zhao, S. Liu, L. Zhang, et C. Zhu, « Surface urban heat island in China's 32 major cities: Spatial patterns and drivers », Remote Sens. Environ., vol. 152, p. 51-61, sept. 2014, doi: 10.1016/j.rse.2014.05.017.
41. J. A. Voogt et T. R. Oke, « Thermal remote sensing of urban climates », Remote Sens. Environ., vol. 86, no 3, p. 370-384, août 2003, doi: 10.1016/S0034-4257(03)00079-8.
42. « Monitoring rural-urban transformation in the coastal region of Rabat-Sale-Kenitra, Morocco », PLOS ONE, vol. 18, no 8, p. e0290829, août 2023, doi: 10.1371/journal.pone.0290829.
43. « Institut National d'Hygiène ». Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://inh.ma/
44. H. El Fadili, M. B. Ali, M. El Mahi, A. T. Cooray, et E. M. Lotfi, « A comprehensive health risk assessment and groundwater quality for irrigation and drinking purposes around municipal solid waste sanitary landfill: A case study in Morocco », Environ. Nanotechnol. Monit. Manag., vol. 18, p. 100698, 2022, Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://www.sciencedirect.com/science/article/pii/S2215153222000587
45. Y. Bounakhla et al., « Overview of PM10, PM2.5 and BC and Their Dependent Relationships with Meteorological Variables in an Urban Area in Northwestern Morocco », Atmosphere, vol. 14, no 1, Art. no 1, janv. 2023, doi: 10.3390/atmos14010162.
46. E. H. Ouharba, Z. el abidine Triqui, et R. Moussadek, « Impact of Climate Change on Cereal farming in Morocco Case study: Rommani (Rabat-region), Bouregreg watershed centre. | EBSCOhost ». Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://openurl.ebsco.com/contentitem/gcd:161811972?sid=ebsco:plink:crawler&id=ebsco:gcd:161811972
47. L. El Ghazouani, L. Bounoua, J. Nigro, M. Mansour, H. Radoine, et H. Souidi, « Combining Satellite Data and Spatial Analysis to Assess the UHI Amplitude and

Structure within Urban Areas: The Case of Moroccan Cities », Urban Sci., vol. 5, no 3, Art. no 3, sept. 2021, doi: 10.3390/urbansci5030067.

48. « Rabat Climate, Weather By Month, Average Temperature (Morocco) - Weather Spark ». Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://weatherspark.com/y/33170/Average-Weather-in-Rabat-Morocco-Year-Round
49. « Cadastre des émissions atmosphériques - MINISTERE DE LA TRANSITION ENERGETIQUE ET DU DEVELOPPEMENT DURABLE وزارة الانتقال الطاقي والتنمية المستدامة ». Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://www.environnement.gov.ma/fr/cadastre-des-emissions-atmospheriques/118-theme/air?utm_source=chatgpt.com
50. « LNESP - Laboratoire National des Etudes et Surveillance de la Pollution ». Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://labo.environnement.gov.ma/?utm_source=chatgpt.com
51. K. Ouali, K. El Harrouni, M. L. Abidi, et Y. Diab, « Analysis of Open Urban Design as a tool for pedestrian thermal comfort enhancement in Moroccan climate », J. Build. Eng., vol. 28, p. 101042, mars 2020, doi: 10.1016/j.jobe.2019.101042.
52. N. Fathi, Bounoua ,Lahouari, et M. and Messouli, « A Satellite Assessment of the Urban Heat Island in Morocco », Can. J. Remote Sens., vol. 45, no 1, p. 26-41, janv. 2019, doi: 10.1080/07038992.2019.1601007.
53. M. E. A. Chbani, K. El Harrouni, et A. Lamzah, « Urban Heat Islands impacts on architecture and urban planning: Rabat case study », Afr. Mediterr. J. Archit. Urban., 2024, Consulté le: 6 mai 2025. [En ligne]. Disponible sur: https://revues.imist.ma/index.php/AMJAU/article/view/53205
54. M. Mourjane, N. E. Hammouch, F. E. Hassani, F. E. Hammichi, M. Benabdelhadi, et H. Tabyaoui, « Assessment of tropospheric nitrogen dioxide (NO2) levels on the COVID-19 pandemic in Morocco », BIO Web Conf., vol. 115, p. 01004, 2024, doi: 10.1051/bioconf/202411501004.
55. « RAPPORT-GESTION-RISQUES_0.pdf ». Consulté le: 6 mai 2025. [En ligne]. Disponible sur: http://87.98.152.231:8091/sites/default/files/docs_publications/RAPPORT-GESTION-RISQUES_0.pdf
56. S. E. Sbai, F. Bentayeb, et H. Yin, « Atmospheric pollutants response to the emission reduction and meteorology during the COVID-19 lockdown in the north of Africa (Morocco) », Stoch. Environ. Res. Risk Assess., vol. 36, no 11, p. 3769-3784, nov. 2022, doi: 10.1007/s00477-022-02224-z.
57. K. Ouali, « Assessment of the mixed local climate zones as the best design for future eco-districts in sub-humid climate: A case of rabat », Int. J. Sustain. Build. Technol. Urban Dev., vol. 14, no 1, p. 3-17, mars 2023, doi: 10.22712/susb.20230002.
58. H. A. Olvera et al., « Principal component analysis optimization of a PM2.5 land use regression model with small monitoring network », Sci. Total Environ., vol. 425, p. 27-34, mai 2012, doi: 10.1016/j.scitotenv.2012.02.068.
59. V. Isakov, M. Johnson, J. Touma, et H. Özkaynak, « Development and Evaluation of Land-Use Regression Models Using Modeled Air Quality Concentrations », in Air Pollution Modeling and its Application XXI, D. G. Steyn et S. Trini Castelli, Éd., Dordrecht: Springer Netherlands, 2012, p. 717-722. doi: 10.1007/978-94-007-1359-8_117.

60. G. Hoek et al., « A review of land-use regression models to assess spatial variation of outdoor air pollution », Atmos. Environ., vol. 42, no 33, p. 7561-7578, oct. 2008, doi: 10.1016/j.atmosenv.2008.05.057.
61. M. Gonzales, C. Qualls, E. Hudgens, et L. Neas, « Characterization of a spatial gradient of nitrogen dioxide across a United States–Mexico border city during winter », Sci. Total Environ., vol. 337, no 1, p. 163-173, janv. 2005, doi: 10.1016/j.scitotenv.2004.07.010.
62. D. Carr et al., « Modeling Annual Benzene, Toluene, NO2, and Soot Concentrations on the Basis of Road Traffic Characteristics », Environ. Res., vol. 90, no 2, p. 111-118, oct. 2002, doi: 10.1006/enrs.2002.4393.