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Review

Building Resilient Cities: A Comprehensive Review of Climate Change Adaptation Indicators for Urban Design

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Abstract: Urban areas generate more than 70% of the world's climate change emissions, mainly CO_2, produced by the combustion of fossil fuels. Climate change is increasing cities' exposure to climate hazards, such as heat waves or floods. Therefore, there is a need to improve risk management with the inclusion of climate resilience in urban policy design. Despite improved urban climate monitoring, there are still relatively few scientific publications on climate change adaptation in urban areas. Adaptation to climate change is not achieved through specific action, but rather through the adoption and continuous implementation of adaptation actions such as housing rehabilitation, green space management and protection measures for vulnerable groups. This variety of actions makes it difficult not only to identify different indicators, but also to use common benchmarks. Considering the role of municipalities in adapting to climate change, it is crucial to identify adaptation indicators that serve as a basis for decision making, as well as evaluation methods that allow the effectiveness of planned and implemented measures in municipalities. It can be used to determine which measures increase the level of adaptation or lead to poor adaptation. Therefore, monitoring indicators makes it possible to evaluate the effectiveness of the measures, in addition to formulating new ones. This paper includes a literature review of existing index designed to address climate hazards and mitigate their impacts in urban areas.

Keywords: climate change; climate change adaptation; urban areas; index; natural risk; indicators

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1. Introduction

Urban areas contain around 54% of the world's population, and by 2050, this percentage is expected to grow to 68% [1]. This makes population growth in urban areas a factor of global warming [2], significantly affecting society and making it likely that the most significant effects will be experienced in those areas. A city's adaptation capacity, understood as its potential to move to a more desirable position in the face of the impacts and risks of climate change, largely depends on the cultural, social, economic, and political contexts in which adaptation takes place [3]. Increasing adaptation capacity improves the opportunity for systems to manage the different ranges and magnitudes of climate impacts while allowing flexibility to rework approaches if they are later considered to be on an undesired trajectory [4].

Climate impacts are likely to affect many aspects of urban systems. Climate adaptation requires interventions which help cities to address many of their pressing problems. For example, the provision of social services and the maintenance of environmental resources, while mitigating the growing urban emissions of greenhouse gases and managing climate-related risks [3]. Research shows that initially, climate change researchers and institutions paid less attention to climate risks in urban areas, and more attention was paid to ecosystems and agriculture [2]. However, as the urban population grows and exposure to climate increases, more cities are introducing formal planning processes for their adaptation to climate change [5] considering also socioeconomic and human health vulnerabilities [2].

In a general context, indicator methodologies are usually used to understand the growing interest in climate adaptation. The Intergovernmental Panel on Climate Change (IPCC), who is the leading international body for the assessment of climate change, has exposed some of the challenges for these methodologies [6]. While it is easy to report on adaptation activity, the outcomes are more difficult to measure [5]. Thus, to effectively apply climate strategies, it is necessary to understand and measure how the climate is changing, the physical, environmental and social impacts of the changes, and if the adaptation and resilience policies and programs implemented in response are working [7].

In recent years, researchers have increasingly addressed the issue of climate change adaptation monitoring, in response to increasing demands for information about disasters, extreme events, or vulnerabilities. For example, "Laurien et al. (2022)" evaluate different assessments of approaches to climate and disaster resilience. They find a lack of clear standards and validated approaches in the measurement methodologies and the interaction between multiple hazards [8]. Other research evaluates resilience combining an index-based approach and principal components analysis [9]. A metric-based approach that uses free and open data sources so that the composite resilience indicator set could be simulated [10], or using another index such as the Socio-Climatic Vulnerability Index that uses free and open data too [3]. Furthermore, traditional approaches for collecting information on weather conditions and predicting risks, usually based on databases, can have different drawbacks such as the limitation of the sample scale or the frequency of data updates. This makes climate action plans developed on outdated information or using larger study scales.

A key challenge seen in this research lies in how to measure, monitor, and evaluate critical indicators of climate change. Thus, an urban climate indicators tracking system is an important tool for decision makers to help plan responses and timelines to climate change and communicate with the general public about the increasing risks and the need for such decisions [11]. Creating an effective indicator system involves not only defining key climate variables and impacts, but also monitoring adaptation and resilience measures [7]. These indicators should be designed to respond to the requirements of action against climate change in urban environments, and the demands of city-level climate risk managers and urban system operations specialists. Urban climate indicators will be required to encompass the tightly coupled structure of urban systems and the complex context of social, economic, and political conditions [7,12]. Furthermore, they should allow for tracking the evolution of climate change at a local level, documenting its vulnerability and interdependent impacts in the region by allowing for the evaluation of programs and policies designed to improve resilience.

Climate change has a negative impact in our systems, therefore, the European Commission has adopted a climate adaptation strategy (2021) [13] which establishes a method for preparing for the effects of climate change. However, some researchers highlights the difficulties to comparing the situation of different municipal entities and to linking adaptation impacts to local actions [11].

Nowadays, there is no standardized index that allows evaluating the adaptation capacity that a city has to face climate change, despite the existence of ISO 14092:2020 "Adaptation to climate change—Requirements and guidance on adaptation planning for local governments and communities" [14]. Therefore, it is useful to carry out a review of different databases to serve as a starting point to measure possible adaptation indicators and know the indexes used by researchers to measure the adaptation capacity. The challenge of comparing different local areas with similar hazards, the absence of a standardized index, and the selection of common indicators led the authors to investigate the existing studies.

Thus, the aim of this paper consists in carrying out a literature review on the use of indexes and tools to measure and monitor climate change adaptation in the context of urban areas. Firstly, the paper describes the methodology used for the review. Secondly, the most significant results, along with a discussion is presented. Finally, the last section exhibits the concluding points of the research.

2. Materials and Methods

With the aim to answer to the following question: *Are there common indices for assessing the adaptive capacity of cities?*, a series of databases were consulted, such as Scopus, Web of Science, and Google Scholar (Databases were consulted during the month of March) using the keywords climate adaptation index, indicators, cities, and urban. The search strategy was:

- ("Climate adaptation index") AND ("index" OR "indicators") AND ("cities" OR "urban")

The revision was limited to papers written in English, published in the last 10 years (2013–2022). The main intention was to obtain recent results in adaptation topics. Scopus and Web of Science include Open Access articles, so to complement the first revision, a second revision was required, including publications with open access. Finally, a third selection included papers classified as "Review" and "Articles". Following this initial review, a total of 524 articles were identified.

To include more relevant papers in this research, some inclusion/exclusion criteria were defined:

- **Phase 1. Duplicates revision**: The papers duplicated during the search process were removed.
- **Phase 2. Not related to the topic**: Papers not related to urban sector were discarded.
- **Phase 3. Index or indicators**: Publications which included index or indicators were selected.
- **Phase 4. Index selection**: Index related to the adaptation theme of vulnerability, thermal comfort, resilience, and adaptation were included.

In the literature review process, keyword filters were applied in three search engines: SCOPUS, Web of Science, and Google Scholar.

The results of the search for the word "Adaptation index" in combination with "Urban area" or "cities" in the Scopus database yielded a total of 240 articles, of which 205 were published in the last 10 years. Of these, 108 articles are available in open access, 7 are literature reviews, and 98 are research articles.

In the Web of Science database, a search for the keyword "Climate adaptation index" combined with "index" or "indicator" and "cities" or "urban" yielded a total of 676 articles, of which 654 were published in the last 10 years. Of these, 330 articles are available in open access, 13 are literature reviews, and 309 are research articles.

Finally, in Google Scholar, searching for the keyword "Adaptation index" in combination with "Urban area" or "cities" and "systematic review" yielded a total of 115 articles, of which 97 were published in the last 10 years.

These results indicate that there are a significant number of articles available in these databases that address the topic of adaptation indexes in urban areas or cities, and that most of them are research articles. In addition, a significant proportion of these articles are available in open access, which facilitates access to them for researchers and students.

The initial search resulted in 524 papers. Once the duplicates were removed, 493 papers were filtered to include only those that addressed topics related to the urban sector, cities, or risks in cities, which reduced the list to 196 papers.

In the next step, the list was filtered to include only documents that addressed indices, indicators or tools related to adaptation, which reduced the list to 124 documents. Figure 1 shows overview methodology applied.

Table 1 shows the number of reviewed papers per type of index. The revision included the index considered in the research studies. It can be seen that 39 papers related to vulnerability, 20 related to adaptation, 13 related to resilience, 15 related to thermal comfort, and 5 related to the universal thermal climate index were found.

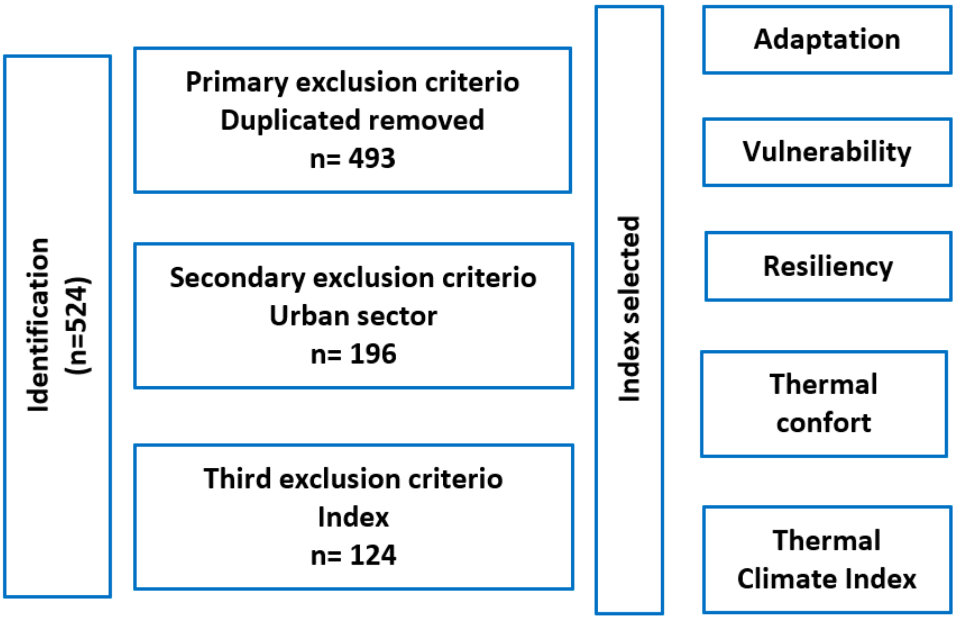

Figure 1. Overview of the methodology. Adapted from [15].

Table 1. Index collected in papers considered. Table created by the author.

Type of Index	Number of Papers	Type of Index	Number of Papers
Vulnerability	39	Adaptation	20
Resilience	13	Thermal comfort	15
Universal Thermal Climate Index (UTCI)	5	Blue city indicators	1
Exposition	1	Government	1
Habitability	2	City blueprint index	1
Cooling effect index	1	Area index	1
Comfort index	1	Sustainability index of collective centres	1
Bare soil index	1	Index WSC (Water Wise Cities)	1
Danger indicators	2	Risk indicators	2
Sensitivity indicators	1	Social indicators	1
Urban sustainability	1	Thermobioclimatic Index	1
Vegetation indicators	6	Index of discomfort	3
Precipitation index	1		

The articles that included indexes like vulnerability, adaptation, resilience, thermal comfort, and UTCI (*UTCI: It is an equivalent temperature (°C), a measure of the human physiological response to the thermal environment*) were selected (n = 91). The selected literature to review is presented in Table 2. The table shows the year of publication, the journal, and the type of risk considered.

Table 2. Literature to review considered. Table created by the author.

No.	Title	Authors	Year	Journal	Type of Risk	Citation
1	Indices of Coastal Vulnerability to Climate Change: A Review	Roukounis et al.	2022	Environmental Processes	Coastal Flood	[16]
2	Big Data in Criteria Selection and Identification in Managing Flood Disaster Events Based on Madro Domain PESTEL Analysis: Case Study of Malasya Adaptation Index	Abdullah et al.	2022	Big data and cognitive computing	Coastal Flood	[17]

Table 2. *Cont.*

No.	Title	Authors	Year	Journal	Type of Risk	Citation
3	A multilevel analysis to explain self-reported adverse health effects and adaptation to urban heat: a cross-sectorial survey in the deprived areas of 9 Canadian cities	Bélanger et al.	2016	BMC Public Health	Urban Heat	[18]
4	Review of studies on outdoor thermal comfort in warm humid climates: challenges of informal urban fabric	Bauriti et al.	2019	International Journal of Biometeorology	Urban Heat	[19]
5	A Literature Review of Cooling Center, Misting Station, Cool Pavement, and Cool Roof Intervention Evaluations	Black-Ingersoll et al.	2022	Atmosphere	Urban Heat	[20]
6	Accelerating Urban Heating Under Land-Cover and Climate Change Scenarios in Indonesia: Application of the Universal Thermal Climate Index	Setiawati et al.	2021	Frontiers in Built Environment	Urban Heat	[21]
7	Indicators for Monitoring Urban Climate Change Resilience and Adaptation	Feldmeyer et al.	2019	Sustainability	Climate Change	[22]
8	Are cities prepared for climate change? An analysis of adaptation readiness in 104 German cities	Otto et al.	2021	Mitigation and Adaptation Strategies for Global Change	Climate change	[23]
9	Index for climate change adaptation in China and its application	Lin et al.	2021	Climate Change Research	Climate change	[24]
10	Development and Validation of a Behavioural Index for Adaptation to High Summer Temperatures among Urban Dwellers	Valois et al.	2017	Environmental Research and Public Health	Urban Heat	[25]
11	Assessing current and future heat risk in Dublin city, Ireland	Paranunzio et al.	2021	Urban Climate	Urban Heat	[26]
12	Which are the factors influencing the integration of mitigation and adaptation in climate change plans in Latin American cities?	Kim et al.	2019	Environmental Research	Climate change	[27]
13	Development as adaptation: Framing and measuring urban resilience in Beijing	Yan et al.	2018	Climate change Research	Climate change	[28]
14	Development and validation of an index to measure progress in adaptation to climate change at the municipal level	Jacob et al.	2022	Ecological Indicators	Climate change	[11]
15	The climate and ocean risk vulnerability index: Measuring coastal city resilience to inform action	Rouleau et al.	2022	Sustainable Cities	Coastal Flood	[29]
16	Climate Adaptative Design Index for the Built Environment (CADI-BE): An Assessment System of the Adaptative Capacity to Urban Temperatures Increase	Bassolino et al.	2021	Energies	Urban Heat	[30]
17	Advancing index-based climate risk assessment to facilitate adaptation planning: Application in Shanghai and Shenzhen, China	Tian et al.	2022	Advances in climate change research	Climate change	[31]
18	An urban climate assessment and management tool for combined heat and air quality judgements at neighbourhood scales	Steeneveld, et al.	2018	Resources, Conservation and Recycling	Urban Heat	[32]

Table 2. *Cont.*

No.	Title	Authors	Year	Journal	Type of Risk	Citation
19	Multi-Risk Climate Mapping for the Adaptation of the Venice Metropolitan Area	Maragno, et al.	2021	Sustainability	Climate change	[33]
20	An Integrated Approach to Evaluate Urban Adaptative Capacity to Climate Change	Hu, et al.	2018	Sustainability	Climate Change	[34]
21	Assessment of urban resilience based on the transformation of resources-based cities: a case study of Panzhihua, China	Yang, et al.	2021	Ecology and Society	Climate Change	[35]
22	Assessment of urban flood vulnerability using the social-ecological-technological systems framework in six US cities	Chang, et al.	2021	Sustainable Cities and Society	River/coastal Flood	[36]
23	Measuring urban vulnerability to climate change using and integrated approach, assessing climate risks in Beijing	Zhang, et al.	2019	PeerJ	Climate change	[37]
24	Linkages between Typologies of Existing Urban Development Patterns and Human Vulnerability to Heat Stress in Lahore	Iqbal, et al.	2022	Sustainability	Urban Heat	[38]
25	Urban Ecosystem Vulnerability Assessment of Support Climate-Resilient City Development	Cai, et al.	2021	Urban Planning	Climate Change	[39]
26	An Index-Based Assessment of Perceived Climate Risk and Vulnerability for the Urban Cluster in the Yangtze River Delta Region of China	Sun, et al.	2019	Sustainability	Climate Change	[40]
27	Development and application of a Socioeconomic Vulnerability Indicator Framework (SVIF) for Local Climate Change Adaptation in Taiwan	Jhan, et al.	2020	Sustainability	Climate Change	[41]
28	Spatial Heterogeneity and Attribution Analysis of Urban Thermal Comfort in China from 2000 to 2020	Wu, et al.	2022	Environmental Research and Public Health	Urban Heat	[42]
29	Assessment of measured and perceived microclimates within a tropical urban forest	Chow, et al.	2016	Urban Forestry & Urban Greening	Urban Heat	[43]
30	Planning Resilient and Sustainable Cities: Identifying and Targeting Social Vulnerability to Climate Change	Ge, et al.	2017	Sustainability	Climate Change	[44]
31	Quantifying coastal flood vulnerability for climate adaptation policy using principal component analysis	Wu, Tao	2021	Ecological Indicators	Coastal Flood	[45]
32	An adaptation index to high summer heat associated with adverse health impacts in deprived neighbourhoods	Belanger, et al.	2015	Climatic Change	Urban Heat	[46]
33	Assessing Coastal Flood Risk in a Changing Climate for Dublin, Ireland	Paranunzio, et al.	2022	Marine Science and Engineering	Coastal Flood	[47]
34	Size does matter: City scale and the asymmetries of climate change adaptation in three coastal towns	Paterson, et al.	2017	Geoforum	Climate Change	[48]

Table 2. *Cont.*

No.	Title	Authors	Year	Journal	Type of Risk	Citation
35	A comprehensive assessment of urban vulnerability and its spatial differentiation in China	Chuanglin, et al.	2016	Geographical Sciences	Climate Change	[49]
36	Urban Resilience for Urban Sustainability: Concepts, Dimensions, and Perspectives	Zeng, et al.	2022	Sustainability	Climate Change	[50]
37	County-level heat vulnerability of urban and rural residents in Tibet, China	Bai, et al.	2016	Environmental Health	Urban Heat	[51]
38	Assessing urban adaptative capacity to climate change	Araya-Muñoz, et al.	2016	Journal of Environmental Management	Climate Change	[52]
39	Assessment of Urban Resilience to Natural Disasters with a System Dynamics Tool: Case Study of Latvian Municipality	Feofilovs, et al.	2020	Environmental and Climate Technologies	Climate Change	[53]
40	Passive activity observation (PAO) method to estimate outdoor thermal adaptation in public space: case studies in Australian cities	Sharifi, et al.	2020	International Journal of Biometeorology	Urban Heat	[54]
41	Evaluating the Role of Urban Drainage Flaws in Triggering Cascading Effects on Critical Infrastructure, Affecting Urban Resilience	Krishnamurti, et al.	2022	Infrastructures	Flood (drainage)	[55]
42	Spatial Assessment of Urban Climate change Vulnerability during Different Urbanization Phases	He, et al.	2019	Sustainability	Climate Change	[56]
43	Thermal perception in outdoor urban spaces under the Mediterranean climate of Annaba, Algeria	Labdaoui, et al.	2021	Urban Climate	Urban Heat	[57]
44	Urban Climate walk: A stop-and-go assessment of the dynamic thermal sensation and perception in two waterfront districts in Rome, Italy	Peng, et al.	2022	Building and Environment	Urban Heat	[58]
45	A Heat Vulnerability Index: Spatial Patterns of Exposure, Sensitivity and Adaptative Capacity for Santiago de Chile	Inostroza, et al.	2016	PLOS one	Urban Heat	[59]
46	Mapping Heat Vulnerability Index Based on Different Urbanization Levels in Nebraska, USA	Jalalzadeh, et al.	2021	GeoHealth	Urban Heat	[60]
47	Planning Nature Based Solutions against urban pluvial flooding in heritage cities: A spatial multi criteria approach for the city of Florence (Italy)	Pacetti, et al.	2022	Journal of Hydrology: Regional Studies	Flood (drainage)	[61]
48	Development of a heat vulnerability index for New York State	Nayak, et al.	2018	Public Health	Urban heat	[62]
49	Excess Heat Factor climatology, trends, and exposure across European Functional Urban Areas	Oliveira, et al.	2022	Weather and Climate Extremes	Urban Heat	[63]
50	Role of green roofs in reducing heat stress in vulnerable urban communities- a multidisciplinary approach	Sharma, et al.	2018	Environmental Research Letters	Urban Heat	[64]
51	A global analysis approach for investigating structural resilience in urban drainage systems	Mugume, et al.	2015	Water Research	Flood (drainage)	[65]

Table 2. *Cont.*

No.	Title	Authors	Year	Journal	Type of Risk	Citation
52	A New Framework for Understanding Urban Social Vulnerability from a Network Perspective	Ge, et al.	2017	Sustainability	Climate Change	[66]
53	How Can Climate Resilience Be Measured and Visualized? Assessing a Vague Concept Using GIS-Based Fuzzy Logic	Schaefer, et al.	2020	Sustainability	Climate Change	[67]
54	Adapting Cities to Pluvial Floding: The Case of Izmir (Türkiye)	Salata, et al.	2022	Sustainability	Pluvial Flood	[68]
55	Empirical Model of Human Thermal Comfort in Subtropical Climates: A First Approach to the Brazilian Subtropical Index (BSI)	Assis, et al.	2018	Atmosphere	Urban Heat	[69]
56	Investigation of Spatio-Temporal Changes in Land Use and Heat Stress Indices over Jaipur City Using Geospatial Techniques	Chandra, et al.	2022	Sustainability	Urban Heat	[70]
57	Finding key vulnerable areas by a climate change vulnerability assessment	Kim, et al.	2016	Natural Hazards	Climate change	[71]
58	The Influence of Socioeconomic Factors on Households' Vulnerability to Climate Change in Semiarid Towns of Mopani South Africa	Yusuf, et al.	2021	Climate	Climate Change	[72]
59	Effects of Orientations, Aspect Ratios, Pavement Materials and Vegetation Elements on Thermal Stress inside Typical Urban Canyons	Lobaccaro, et al.	2019	Environmental Research and Public Health	Urban Heat	[73]
60	Thermal comfort range and influence factor of urban pedestrian streets in severe cold regions	Jin, et al.	2019	Energy & Buildings	Urban Heat	[74]
61	Integration of earth observation and census data for mapping a multi-temporal flood vulnerability index: a case study on Northeast Italy	Cian, et al.	2021	Natural Hazards	Coastal Flood	[75]
62	Mapping Climate Vulnerability of River Basin Communities in Tanzania to Inform Resilience Interventions	Macharia, et al.	2020	Sustainability	Drought	[76]
63	Assessing urban vulnerability to flood hazards in Brazilian municipalities	Joan, R.	2016	Environmental & Urbanization	Flood	[77]
64	Climate change water vulnerability and adaptation mechanism in a Himalayan City, Nainital, India	Chauhan, et al.	2022	Environmental Science and Pollution Research	Drought	[78]
65	Urban Heat Island vulnerability mapping using advanced GIS data and tools	Sidiqui, et al.	2022	Journal of earth system science	Urban Heat	[79]
66	Coastal vulnerability to climate change in China´s Bohai Economic Rim	Zhang, et al.	2021	Environmental International	Climate change	[80]
67	Mapping Urban Heat Vulnerability of Extreme Heat in Hangzhou via Comparing Two Approaches	Liu, et al.	2020	Complexity	Urban Heat	[81]
68	Estimate of outdoor thermal comfort zones for different climatic regions of Iran	Roshan, et al.	2019	Urban Climate	Urban Heat	[82]

Table 2. *Cont.*

No.	Title	Authors	Year	Journal	Type of Risk	Citation
69	Conceptualizing and Measuring Megacity Resilience with and Integrated Approach: The Case of China	Yang, et al.	2022	Sustainability	Climate Change	[83]
70	Spatial Exposure and Livelihood Vulnerability to Climate-Related Disasters in The North Coast of Tegal City, Indonesia	Rudiarto, I.	2020	International review for spatial planning and sustainable development	Coastal Flood	[84]
71	Geophysical and social vulnerability to floods at municipal scale under climate change: The case of an inner-city suburb of Sydney	El-Zein, et al.	2021	Ecological Indicators	Floods	[85]
72	Summer Outdoor Thermal Perception for the Elderly in a Comprehensive Park of Changsha, China	Li, et al.	2022	Atmosphere	Urban Heat	[86]
73	Measuring Subjective Flood Resilience in Suburban Dakar: A Before-After Evaluation of the "Live with Water" Project	Bottazzi, et al.	2018	Sustainability	Flood	[87]
74	Outdoor thermal comfort conditions during summer in cold semi-arid climate. A transversal field survey in Central Anatolia (Turkey)	Canan, et al.	2019	Building and Environment	Urban Heat	[88]
75	Capturing the multifaceted phenomena of socioeconomic vulnerability	Sorg, et al.	2018	Natural Hazards	Climate change	[89]
76	A GIS-Based Approach for Flood Risk Zoning by Combining Social Vulnerability and Flood Susceptibility: A Case Study of Nanjing, China	Chen, et al.	2021	Environmental Research and Public Health	Flood	[90]
77	Thermal Environment Map in Street Canyon for Implementing Extreme High Temperature Measures	Takebayashi, et al.	2020	Atmosphere	Urban Heat	[91]
78	Assessing vulnerability and capacity of Bhubaneswar as a progressive smart-city: An empirical case study of Fani cyclone impact on the city	Kawyitri, N	2021	International Journal Disaster Risk Reduction	Cyclone	[92]
79	Assessing Urban Vulnerability to Flooding: A Framework to measure Resilience Using Remote Sensing Approaches	Cerbaro, et al.	2022	Sustainability	Flood	[93]
80	Adaptative capacity to extreme urban heat: The dynamics of differing narratives	Guardaro, et al.	2022	Climate Risk Management	Urban Heat	[94]
81	Global adaptation readiness and income mitigate sectorial climate change vulnerabilities	Asumadu, et al.	2022	Humanities & Social Sciences Communications	Climate change	[95]
82	Assessment of Cities´Adaptation to Climate Change and Its Relationship with Urbanization in China	Pei, et al.	2022	Sustainability	Climate change	[96]
83	The structural analysis of driving forces to adaptive capacity with climate change in Ahvaz City. Iran	Mohammadi, et al.	2022	Research Square	Climate Change	[97]
84	Mapping Transboundary Climate Risk: the case study of the Trinational Metropolitan Area Upper Rhine Area	Riach, et al.	2021	Natural Hazards	Climate change	[98]

Table 2. *Cont.*

No.	Title	Authors	Year	Journal	Type of Risk	Citation
85	Assessing hazards induced vulnerability in coastal districts of India using site-specific indicators: an integrated approach	Rehman, et al.	2020	GeoJournal	Climate change	[99]
86	Review of Current and Planned Adaptation Action in Pakistan	Parry, J.E.	2016	CARIAA Working papers	Climate change	[100]
87	Climate change adaptation for seaports and airports	Ching-Poo	2020	Liverpool John Moores University	Climate change	[101]
88	A framework for examining adaptation readiness	Ford, et al.	2015	Mitigation and Adaptation Strategies for Global Change	Climate change	[102]
89	The impact of adaptation on climate vulnerability: Is readiness relevant?	Amegavi, et al.	2021	Sustainable Cities and Society	Climate Change	[103]
90	Major principles and criteria for development of an urban resilience assessment index	Sharif, et al.	2014	International Conference and Utility Exhibition	Climate Change	[104]
91	Urban adaptation index: assessing cities readiness to deal with climate change	Alves, et al.	2021	Climatic Change	Climate Change	[3]

A total of 91 papers were considered. Figure 2 shows the trend of publications (by year) related to climate adaptation in urban environments in the last 10 years. It should be noted that most of these papers were conducted in 2020, 2021, and 2022.

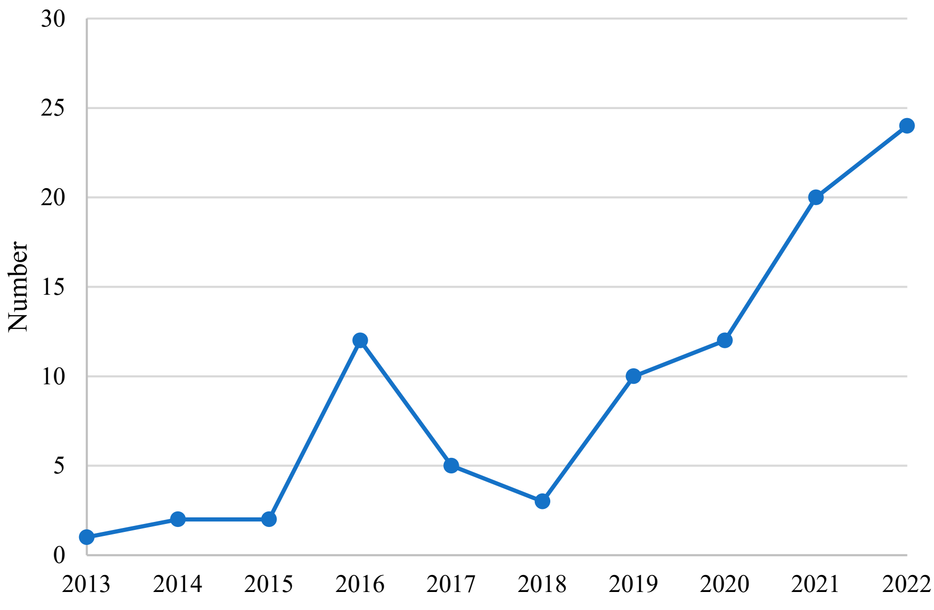

Figure 2. Year of publication of the 91 papers considered. Figure created by the author.

Figure 3 shows a classification by geographic region (origin of these articles) to know where the climate adaptation is a relevant topic. The majority (41%) were written in Asia, followed by Europe (32%), America (21%), Oceania (4%), and Africa (2%). These results suggest that research and publication on the topic of climate adaptation is more prevalent in Asia and Europe compared to other regions of the world. On the other hand, the publications selected studied the following topics: urban area (88%), costal area (10%), and suburban area (2%).

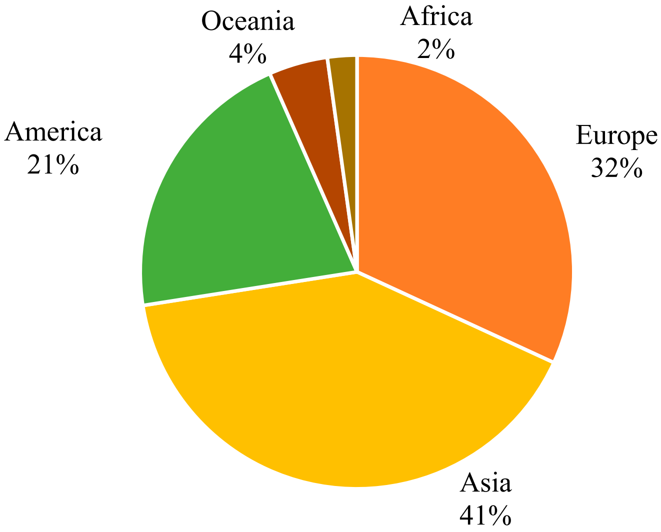

Figure 3. Classification by geographic region (origin of the reviewed articles). Figure created by the author.

3. Results and Discussion

Based on the literature review, two points were developed. On the one hand, natural risks identified and the methodologies that were used were analyzed to measure adaptation capacity, vulnerability, or urban exposition. Our analysis underscores three primary risks: climate change, urban heat, and floods. On the other hand, categories and indicators about climate change adaptation in urban areas were identified. Through the 91 papers identified, three categories which were frequently mentioned in the literature were considered (socio-economic, governance, and environmental). Based on these, we have listed different indicators.

3.1. Natural Risk Identified

Based on the literature review, the risks with more importance at urban level are (i) climate change (n = 39), (ii) urban heat (n = 32), and (iii) flood (n = 17). Therefore, municipal governments have regarded the enhancement of urban resilience as a crucial strategy [38].

Of the 91 references, 39 focus their efforts on the impacts of climate change. They develop indices based on secondary information. For instance, "Feldermeyer, D. et al. (2019)" involve stakeholders in defining the relevance of indicators [22]. They categorize the indicators into different categories (environment, infrastructure, economy, society, and governance), while "Kim, H. and Grafakos, S. (2019)" considered institutional, socioeconomic, and environmental categories to evaluate mitigation and adaptation in urban climate change plans [27].

Other studies have developed their index namely, the "*Adaptation readiness index*" [23]; "*Index for climate adaptation*" [24]; and "*Index for climate change adaptation*" [3]. The first study implemented their index at local level, the second at national level, and the third developed their index to assess the current potential capacity of cities to deal with climate change impacts at local level.

Heatwaves in urban areas were studied in 32 of 91. Studies on heatwaves focus the knowledge on two objectives. On the one hand, outdoor thermal comfort (n = 14), and on the other hand, social vulnerability to the heat island effect (n = 16). Two of the thirty-two studies have different objectives. "Valois, P. et al. (2017)" focus their study on the actions that citizens take during heatwaves [25]; and "Bassolino, E. and Cerreta, M. (2021)" verify the effectiveness of urban transformation climate-adaptative regeneration processes [30].

Other studies have focused on outdoor thermal perception; commonly used metrics include physiological equivalent temperature (PET) (*PET: The air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body* *is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed* [103]), universal thermal climate index (UTCI), standard effective temperature (SET) (SET: *A comfort index based on the transient modelling of the human metabolism, including the mechanisms of thermoregulation caused by the ambient conditions or the activity level* [105]), and predicted mean vote (PMV) (PMV: *A comfort index based on the transient modelling of the human metabolism, including the mechanisms of thermoregulation caused by the ambient conditions or the activity level* [105]) [74,86].

For the analysis of social vulnerability to the heat island effect, some scientists create maps to detect areas with higher vulnerability, considering climatic conditions, exposure, and population sensitivity [21,26,30,38,62].

Flood risk was studied in 17 of the 91 articles considered. These studies are categorized into coastal flooding ($n = 8$) [16,17,29,36,45,47,75,84], pluvial flooding ($n = 6$) [68,77,85,87,90], and urban drainage ($n = 3$) [55,61,65]. Flood reports concentrate the knowledge on the vulnerability (*Vulnerabilityy*: *predisposition to be adversely affected. Vulnerability comprises a number of elements including sensitivity, or susceptibility to harm, and lack of capacity to cope with or adapt to harm),* index of the area, considering exposition (*Exposition: The presence of people, livelihoods, species or ecosystems, environmental functions and services, or elements of economic, social or cultural heritage in places and sites that could be adversely affected*), sensitivity (*Sensitivity: The degree to which a system or species is affected, positively or negatively, by climate variability or change*), and adaptative capacity (*Adaptation capacity: The ability of systems, institutions, and people to adjust to potential harms, take advantage of opportunities, or respond to consequences*).

The 17 articles related with floods use secondary information to develop the index and define the indicators. Some of them employ multicriteria analysis in the process.

3.2. Key Indicators for Climate Change Adaptation

"Hansen and Macedo (2021)" consider the coupled relationship between humans and nature, defining the term Urban Ecology. "They characterize it as the study of ecosystems that include humans living in cities and urbanizing landscapes", connecting three systems: the natural environment, built environment, and social environment [106].

Our article includes three categories which are frequently mentioned in the literature, and very similar to the systems considered by Hansen and Macedo. Socio-economic categories include indicators include age, employment, education, population density, access to resources, and old buildings. Governance categories include strategies and plans, transparency, and civil protection plans. Finally, the environmental category includes indicators as climatic parameters, climate risk, and land use. Indicators selected in the table below (Table 3) are those most frequently repeated in the 91 articles considered in the review.

Table 3. Indicators reviewed. Table created by the authors.

Categories	Indicator	Description	Number of Articles
Socio-economic	Age	% of population over 65 and below 15	51
	Employment	% of employment/unemployment	33
	Education	% of population with low education level	51
	Population density	Number of populations exposed	32
	Access to resources	% of population without access to internet, air conditioning, water sources	15
Governance	Old building	Age of the building	11
	Strategies and plans	Plant and risk analysis considered	14
	Transparency	Public access to government	6
	Civil protection	Civil protection per climate risk	6
Environmental	Climatic parameters	Measuring weather conditions	16
	Climate risk	Determinate climate risk	34
	Land use	% of soil cover per green areas/grey areas	32

3.2.1. Socio-Economic

There are socio-economic factors which affect the adaptation capacity [107]. Social vulnerability should be examined to validate the adaptative capacity of the population for natural events. Adaptation measures under climatic conditions should promote socioeconomic well-being in vulnerable people. According to "Roukounis, C. and Tsihrintzis (2022)", most vulnerability indices consider socio-economic factors. These factors reflect the sensitivity and adaptative capacity of the population who suffer natural hazards. Therefore, the socioeconomic category includes six indicators: age, employment, education, population density, access to resources, and old buildings [15,16].

Age as an indicator is analyzed in 51 of the 91 articles considered. Vulnerability can vary according to the age of the population. People older than 65 or younger (<15 years) are more vulnerable to extreme events than people in other age ranges [108,109]. The influence of people´s level of education is the second indicator considered in the articles revised (51 to 91). It considers the impact of education on the adaptative capacity. Another important inter-relationship is the population density with climate change. Densely populated urban areas are particularly vulnerable to the effects of climate change.

In some cases, belonging to a vulnerable population group means that you are affected by more than one indicator at a time. For example, unemployed people have more difficulty accessing essential resources such as air conditioning. For instance, people with less resources have more problems to adapt to than rich people [110]. In addition, the poorer population tends to live in older dwellings, where access to basic resources (such as air conditioning) is more limited. In the literature review, 11 articles considered the building age construction [111]. Climate change can significantly impact residential buildings' energy consumption and greenhouse emissions. Therefore, climate change adaptation should consider building design and façade renovation.

3.2.2. Governance

Adaptation has become a policy emergency to face climate change [112]. Governance is the category with the lowest relevance in the revised articles. Only 15% of the articles consider strategies or municipal plans as relevant indicators, and just 6 of 91 papers consider government transparency and civil protection plans. Climate change sets out a challenge for governments, and open government can contribute to improving management of climate change issues [113]. "Sharifi, A. and Yamagata, Y. (2014)" include governance as one of the major criteria that can be used in a framework for the assessment of urban resiliency [104]. The authors "Davoudi, S. and Sturzaker, J. (2017)" provide valuable insights into the complexities of urban form and the challenges of achieving sustainable urban metabolism, which are relevant to understanding and addressing climate risk in urban areas. The article highlights the limited success of urban planning policies in Europe and North America in steering urban form towards a more sustainable path. Additionally, it discusses the complexities of urban development processes, the influence of planning regulations and cultural norms on urban form, and the diverse typologies of policy interventions aimed at shaping urban development. These insights are valuable for understanding the multifaceted nature of urban development and the need for more effective policy packages to address sustainability challenges in urban areas [12].

Strategies and climate plans as indicators have been studied in 15% of the articles studied. Government implications in these initiatives are interesting to reduce the barriers to climate change adaptation that have our cities. The lack of financial resources, unclear division of tasks and responsibilities, uncertain societal costs and future benefits, and fragmentation within and between scales of governance make cities lack these types of studies [114].

Finally, civil protection is another indicator with low relevance (6 of 91 articles considered); however, some articles, such as the report of "Groven, K. et al. (2012)", consider relevant in what form climate change adaptation policy has been integrated into civil protection, because preparing for extreme weather should be the protection system's central task [115].

3.2.3. Environmental

Environmental factors are directly associated with climate change. Environmental indicators are helpful to evaluate, monitor, and improve cities' environmental impact, life quality, and resilience [116].

Thirty-four of the ninety-one articles considered determinate climate risk such as heat waves, floods, and cyclones, not climate change globally.

Of the 91 revised articles, 32 include the soil type as an indicator to evaluate the adaptive capacity of urban areas. "García Sánchez, F.J. (2019)" consider how green infrastructure plays a key role in defining strategies for adapting cities to climate change [117]. Another report considers the importance of green infrastructure for municipalities' ecosystem services.

Climate parameters make it possible to monitor changes over time. Sixteen of the ninety-one articles measured climatic parameters. The main challenges they face when monitoring climate parameters are (i) identifying relevant resilience indicators at the appropriate scale, (ii) relating those to well-being indicators that can be tracked at different scales over the longer term, and (iii) using climate data to interpret well-being indicators in the context of climate changes and variations [118].

4. Conclusions

The literature review highlights the importance of climate adaptation indicators as an essential tool in mitigating the effects of climate change. The diversity of approaches and the need for standardization underscore the complexity of the field. After a selection process, 91 studies related to climate adaptation in urban environments and different areas (coastal, urban, and semi-urban) were reviewed. Some studies focus on physical variables and others on both physical and social factors. The diversity of approaches is interesting; the authors have used different scales of analysis, criteria for selecting variables, and natural phenomena as the main hazards for their research. The fact that there is a diversity of approaches and different selection criteria makes it difficult to compare the state of adaptation of cities.

Although standards such as ISO 14092:2020 exist, the absence of a specific framework for indicator selection was identified. In most case studies, indicators have been selected based on the availability of data and the aspirations of the researchers.

Most of the articles were published in recent years, with a significant increase in publications in 2021 and 2022. This trend suggests an increased interest and commitment to address climate adaptation challenges, mainly in Asian countries, particularly China.

Climate change, urban heat, and floods are the most-studied risks in the climate adaptation literature. On the other hand, drought and cyclones have received less attention in published research in this field, although they are sometimes a consequence of climate change. Climate change is considered, as a whole, as a general risk; however, the interconnectedness between risks is not assessed (e.g., an increase in temperature results in an increase in droughts). The literature creates an index based on secondary information and collaboration from citizens or expert panels. It does not focus on determining if cities are prepared to face heatwaves; instead, it concentrates on citizens' thermal comfort perception and social vulnerability, which are assessed using indexes like PET, UTCI, SET, and PMV.

Socio-economic and governance indicators have a direct impact on urban areas. These indicators can help urban planners and policymakers identify areas of vulnerability and develop effective adaptation and mitigation strategies to protect urban populations from the impacts of climate change. This is a relatively recent field of study with ample room for further research. Ongoing evaluation and standardization of climate adaptation indicators are essential to ensure their effectiveness and comparability. The exchange of best practices and collaboration among researchers, policymakers, and communities is crucial to addressing current and future climate challenges. The review identified the need for a specific framework for the selection of indicators, particularly in reports related to climate change and floods.

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References

1. World Meteorological Organization. United in Science 2023. In *Sustainable Development Edition-A Multi-organization High-level Compilation of the Latest Weather-, Climate and Water-Related Sciences and Services for Sustainable Development*; World Meteorological Organization: Geneva, Switzerland, 2023. [CrossRef]
2. Monteiro, A.; Ankrah, J.; Madureira, H.; Pacheco, M.O. Climate Risk Mitigation and Adaptation Concerns in Urban Areas: A Systematic Review of the Impact of IPCC Assessment Reports. *Climate* **2022**, *10*, 115. [CrossRef]
3. Neder, E.A.; Moreira, F.d.A.; Fontana, M.D.; Torres, R.R.; Lapola, D.M.; Vasconcellos, M.d.P.C.; Bedran-Martins, A.M.B.; Junior, A.P.; Lemos, M.C.; Di Giulio, G.M. Urban adaptation index: Assessing cities readiness to deal with climate change. *Clim. Chang.* **2021**, *166*, 16. [CrossRef]
4. Engle, N.L. Adaptive capacity and its assessment. *Glob. Environ. Chang.* **2011**, *21*, 647–656. [CrossRef]
5. Tyler, S.; Nugraha, E.; Nguyen, H.K.; Van Nguyen, N.; Sari, A.D.; Thinpanga, P.; Tran, T.T.; Verma, S.S. Indicators of urban climate resilience: A contextual approach. *Environ. Sci. Policy* **2016**, *66*, 420–426. [CrossRef]
6. IPCC. Climate Change 2014. In *Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects*; Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK, 2014; p. 1132.
7. Solecki, W.; Rosenzweig, C. Indicators and monitoring systems for urban climate resiliency. *Clim. Chang.* **2020**, *163*, 1815–1837. [CrossRef]
8. Laurien, F.; Martin, J.G.C.; Mehryar, S. Climate and disaster resilience measurement: Persistent gaps in multiple hazards, methods, and practicability. *Clim. Risk Manag.* **2022**, *37*, 100443. [CrossRef]
9. Medina, N.; Abebe, Y.A.; Sanchez, A.; Vojinovic, Z. Assessing socioeconomic vulnerability after a hurricane: A combined use of an index-based approach and principal components analysis. *Sustainability* **2020**, *12*, 1452. [CrossRef]
10. Sono, D.; Wei, Y.; Jin, Y. Assessing the climate resilience of sub-saharan africa (Ssa): A metric-based approach. *Land* **2021**, *10*, 1205. [CrossRef]
11. Jacob, J.; Valois, P.; Tessier, M. Development and validation of an index to measure progress in adaptation to climate change at the municipal level. *Ecol. Indic.* **2022**, *135*, 108537. [CrossRef]
12. Davoudi, S.; Sturzaker, J. Urban form, policy packaging and sustainable urban metabolism. *Resour. Conserv. Recycl.* **2017**, *120*, 55–64. [CrossRef]
13. European Commission. *Forging a Climate-Resilient Europe-the New EU Strategy on Adaptation to Climate Change*; European Commission: Brussels, Belgium, 2021; Volume 6, pp. 951–952.
14. *ISO 14092:2020*; Adaptation to Climate Change—Requirements and Guidance on Adaptation Planning for Local Governments and Communities. International Organization for Standardization: Geneva, Switzerland, 2020.
15. Li, F.; Yigitcanlar, T.; Nepal, M.; Thanh, K.N.; Dur, F. Understanding Urban Heat Vulnerability Assessment Methods: A PRISMA Review. *Energies* **2022**, *15*, 6998. [CrossRef]
16. Roukounis, C.N.; Tsihrintzis, V.A. Indices of Coastal Vulnerability to Climate Change: A Review. *Environ. Process.* **2022**, *9*, 29. [CrossRef]
17. Abdullah, M.F.; Zainol, Z.; Thian, S.Y.; Ghani, N.H.A.; Jusoh, A.M.; Amin, M.Z.M.; Mohamad, N.A. Big Data in Criteria Selection and Identification in Managing Flood Disaster Events Based on Macro Domain PESTEL Analysis: Case Study of Malaysia Adaptation Index. *Big Data Cogn. Comput.* **2022**, *6*, 25. [CrossRef]
18. Bélanger, D.; Abdous, B.; Valois, P.; Gosselin, P.; Sidi, E.A.L. A multilevel analysis to explain self-reported adverse health effects and adaptation to urban heat: A cross-sectional survey in the deprived areas of 9 Canadian cities Environmental health. *BMC Public Health* **2016**, *16*, 144. [CrossRef] [PubMed]

19. Baruti, M.M.; Johansson, E.; Åstrand, J. Review of studies on outdoor thermal comfort in warm humid climates: Challenges of informal urban fabric. *Int. J. Biometeorol.* **2019**, *63*, 1449–1462. [CrossRef]
20. Black-Ingersoll, F.; de Lange, J.; Heidari, L.; Negassa, A.; Botana, P.; Fabian, M.P.; Scammell, M.K. A Literature Review of Cooling Center, Misting Station, Cool Pavement, and Cool Roof Intervention Evaluations. *Atmosphere* **2022**, *13*, 1103. [CrossRef]
21. Setiawati, M.D.; Jarzebski, M.P.; Gomez-Garcia, M.; Fukushi, K. Accelerating Urban Heating Under Land-Cover and Climate Change Scenarios in Indonesia: Application of the Universal Thermal Climate Index. *Front. Built Environ.* **2021**, *7*, 622382. [CrossRef]
22. Feldmeyer, D.; Wilden, D.; Kind, C.; Kaiser, T.; Goldschmidt, R.; Diller, C.; Birkmann, J. Indicators for monitoring urban climate change resilience and adaptation. *Sustainability* **2019**, *11*, 2931. [CrossRef]
23. Otto, A.; Göpfert, C.; Thieken, A.H. Are cities prepared for climate change? An analysis of adaptation readiness in 104 German cities. *Mitig. Adapt. Strateg. Glob. Chang.* **2021**, *26*, 35. [CrossRef]
24. Fu, L.; Cao, Y.; Kuang, S.Y.; Guo, H. Index for climate change adaptation in China and its application. *Adv. Clim. Chang. Res.* **2021**, *12*, 723–733. [CrossRef]
25. Valois, P.; Talbot, D.; Caron, M.; Carrier, M.P.; Morin, A.J.S.; Renaud, J.S.; Jacob, J.; Gosselin, P. Development and validation of a behavioural index for adaptation to high summer temperatures among urban dwellers. *Int. J. Environ. Res. Public Health* **2017**, *14*, 820. [CrossRef] [PubMed]
26. Paranunzio, R.; Dwyer, E.; Fitton, J.M.; Alexander, P.J.; O'Dwyer, B. Assessing current and future heat risk in Dublin city, Ireland. *Urban Clim.* **2021**, *40*, 100983. [CrossRef]
27. Kim, H.; Grafakos, S. Which are the factors influencing the integration of mitigation and adaptation in climate change plans in Latin American cities? *Environ. Res. Lett.* **2019**, *14*, 105008. [CrossRef]
28. Zheng, Y.; Xie, X.L.; Lin, C.Z.; WanG, M.; He, X.J. Development as adaptation: Framing and measuring urban resilience in Beijing. *Adv. Clim. Chang. Res.* **2018**, *9*, 234–242. [CrossRef]
29. Rouleau, T.; Stuart, J.; Call, M.; Yozell, S.; Yoshioka, N.; Maekawa, M.; Fiertz, N. The climate and ocean risk vulnerability index: Measuring coastal city resilience to inform action. *Front. Sustain. Cities* **2022**, *4*, 127. [CrossRef]
30. Bassolino, E.; Cerreta, M. Climate adaptive design index for the built environment (CADI-BE): An assessment system of the adaptive capacity to urban temperatures increase. *Energies* **2021**, *14*, 4630. [CrossRef]
31. Tian, Z.; Lyu, X.Y.; Zou, H.; Yang, H.L.; Sun, L.; Pinya, M.S.; Chao, Q.C.; Feng, A.Q.; Smith, B. Advancing index-based climate risk assessment to facilitate adaptation planning: Application in Shanghai and Shenzhen, China. *Adv. Clim. Chang. Res.* **2022**, *13*, 432–442. [CrossRef]
32. Steeneveld, G.J.; Klompmaker, J.O.; Groen, R.J.A.; Holtslag, A.A.M. An urban climate assessment and management tool for combined heat and air quality judgements at neighbourhood scales. *Resour. Conserv. Recycl.* **2018**, *132*, 204–217. [CrossRef]
33. Maragno, D.; Dall'omo, C.F.; Pozzer, G.; Musco, F. Multi-risk climate mapping for the adaptation of the venice metropolitan area. *Sustainability* **2021**, *13*, 1334. [CrossRef]
34. Hu, Q.; He, X. An integrated approach to evaluate urban adaptive capacity to climate change. *Sustainability* **2018**, *10*, 1272. [CrossRef]
35. Yang, Y.; Fang, Y.P.; Xu, Y.; Zhang, Y. Assessment of urban resilience based on the transformation of resource-based cities: A case study of panzhihua, China. *Ecol. Soc.* **2021**, *26*, 20. [CrossRef]
36. Chang, H.; Pallathadka, A.; Sauer, J.; Grimm, N.B.; Zimmerman, R.; Cheng, C.; Iwaniec, D.M.; Kim, Y.; Lloyd, R.; McPhearson, T.; et al. Assessment of urban flood vulnerability using the social-ecological-technological systems framework in six US cities. *Sustain. Cities Soc.* **2021**, *68*, 102786. [CrossRef]
37. Zhang, M.; Liu, Z.; Van Dijk, M.P. Measuring urban vulnerability to climate change using an integrated approach, assessing climate risks in Beijing. *PeerJ* **2019**, *2019*, e7018. [CrossRef] [PubMed]
38. Iqbal, N.; Ravan, M.; Jamshed, A.; Birkmann, J.; Somarakis, G.; Mitraka, Z.; Chrysoulakis, N. Linkages between Typologies of Existing Urban Development Patterns and Human Vulnerability to Heat Stress in Lahore. *Sustainability* **2022**, *14*, 10561. [CrossRef]
39. Cai, Z.; Page, J.; Cvetkovic, V. Urban ecosystem vulnerability assessment of support climate-resilient city development. *Urban Plan.* **2021**, *6*, 227–239. [CrossRef]
40. Sun, L.; Tian, Z.; Zou, H.; Shao, L.; Sun, L.; Dong, G.; Fan, D.; Huang, X.; Frost, L.; James, L.-F. An Index-Based Assessment of Perceived Climate Risk and Vulnerability for the Urban Cluster in the Yangtze River Delta Region of China. *Sustainability* **2019**, *11*, 2099. [CrossRef]
41. Jhan, H.T.; Ballinger, R.; Jaleel, A.; Ting, K.H. Development and application of a socioeconomic vulnerability indicator framework (SVIF) for local climate change adaptation in Taiwan. *Sustainability* **2020**, *12*, 1585. [CrossRef]
42. Wu, J.; Li, X.; Li, S.; Liu, C.; Yi, T.; Zhao, Y. Spatial Heterogeneity and Attribution Analysis of Urban Thermal Comfort in China from 2000 to 2020. *Int. J. Environ. Res. Public Health* **2022**, *19*, 5683. [CrossRef] [PubMed]
43. Chow, W.T.L.; Akbar, S.N.A.B.A.; Heng, S.L.; Roth, M. Assessment of measured and perceived microclimates within a tropical urban forest. *Urban For. Urban Green.* **2016**, *16*, 62–75. [CrossRef]
44. Ge, Y.; Dou, W.; Liu, N. Planning resilient and sustainable cities: Identifying and targeting social vulnerability to climate change. *Sustainability* **2017**, *9*, 1394. [CrossRef]
45. Wu, T. Quantifying coastal flood vulnerability for climate adaptation policy using principal component analysis. *Ecol. Indic.* **2021**, *129*, 108006. [CrossRef]

46. Bélanger, D.; Abdous, B.; Gosselin, P.; Valois, P. An adaptation index to high summer heat associated with adverse health impacts in deprived neighborhoods. *Clim. Chang.* **2015**, *132*, 279–293. [CrossRef]
47. Paranunzio, R.; Guerrini, M.; Dwyer, E.; Alexander, P.J.; O'Dwyer, B. Assessing Coastal Flood Risk in a Changing Climate for Dublin, Ireland. *J. Mar. Sci. Eng.* **2022**, *10*, 1715. [CrossRef]
48. Paterson, S.K.; Pelling, M.; Nunes, L.H.; de Araújo Moreira, F.; Guida, K.; Marengo, J.A. Size does matter: City scale and the asymmetries of climate change adaptation in three coastal towns. *Geoforum* **2017**, *81*, 109–119. [CrossRef]
49. Fang, C.; Wang, Y.; Fang, J. A comprehensive assessment of urban vulnerability and its spatial differentiation in China. *J. Geogr. Sci.* **2016**, *26*, 153–170. [CrossRef]
50. Zeng, X.; Yu, Y.; Yang, S.; Lv, Y.; Sarker, M.N.I. Urban Resilience for Urban Sustainability: Concepts, Dimensions, and Perspectives. *Sustainability* **2022**, *14*, 2481. [CrossRef]
51. Bai, L.; Woodward, A.; Cirendunzhu; Liu, Q. County-level heat vulnerability of urban and rural residents in Tibet, China. *Environ. Health* **2016**, *15*, 3. [CrossRef]
52. Araya-Muñoz, D.; Metzger, M.J.; Stuart, N.; Wilson, A.M.W.; Alvarez, L. Assessing urban adaptive capacity to climate change. *J. Environ. Manag.* **2016**, *183*, 314–324. [CrossRef]
53. Feofilovs, M.; Romagnoli, F. Assessment of Urban Resilience to Natural Disasters with a System Dynamics Tool: Case Study of Latvian Municipality. *Environ. Clim. Technol.* **2020**, *24*, 249–264. [CrossRef]
54. Sharifi, E.; Boland, J. Passive activity observation (PAO) method to estimate outdoor thermal adaptation in public space: Case studies in Australian cities. *Int. J. Biometeorol.* **2020**, *64*, 231–242. [CrossRef]
55. de Oliveira, A.K.B.; Battemarco, B.P.; Barbaro, G.; Gomes, M.V.R.; Cabral, F.M.; de Oliveira Pereira Bezerra, R.; de Araújo Rutigliani, V.; Lourenço, I.B.; Machado, R.K.; Rezende, O.M.; et al. Evaluating the Role of Urban Drainage Flaws in Triggering Cascading Effects on Critical Infrastructure, Affecting Urban Resilience. *Infrastructures* **2022**, *7*, 153. [CrossRef]
56. He, C.; Zhou, L.; Ma, W.; Wang, Y. Spatial assessment of urban climate change vulnerability during different urbanization phases. *Sustainability* **2019**, *11*, 2406. [CrossRef]
57. Labdaoui, K.; Mazouz, S.; Reiter, S.; Teller, J. Thermal perception in outdoor urban spaces under the Mediterranean climate of Annaba, Algeria. *Urban Clim.* **2021**, *39*, 100970. [CrossRef]
58. Peng, Z.; Bardhan, R.; Ellard, C.; Steemers, K. Urban climate walk: A stop-and-go assessment of the dynamic thermal sensation and perception in two waterfront districts in Rome, Italy. *Build. Environ.* **2022**, *221*, 109267. [CrossRef]
59. Inostroza, L.; Palme, M.; De La Barrera, F. A heat vulnerability index: Spatial patterns of exposure, sensitivity and adaptive capacity for Santiago de Chile. *PLoS ONE* **2016**, *11*, e0162464. [CrossRef] [PubMed]
60. Jalalzadeh Fard, B.; Mahmood, R.; Hayes, M.; Rowe, C.; Abadi, A.M.; Shulski, M.; Medcalf, S.; Lookadoo, R.; Bell, J.E. Mapping Heat Vulnerability Index Based on Different Urbanization Levels in Nebraska, USA. *GeoHealth* **2021**, *5*, e2021GH000478. [CrossRef] [PubMed]
61. Pacetti, T.; Cioli, S.; Castelli, G.; Bresci, E.; Pampaloni, M.; Pileggi, T.; Caporali, E. Planning Nature Based Solutions against urban pluvial flooding in heritage cities: A spatial multi criteria approach for the city of Florence (Italy). *J. Hydrol. Reg. Stud.* **2022**, *41*, 101081. [CrossRef]
62. Nayak, S.G.; Shrestha, S.; Kinney, P.L.; Ross, Z.; Sheridan, S.C.; Pantea, C.I.; Hsu, W.H.; Muscatiello, N.; Hwang, S.A. Development of a heat vulnerability index for New York State. *Public Health* **2018**, *161*, 127–137. [CrossRef]
63. Oliveira, A.; Lopes, A.; Soares, A. Excess Heat Factor climatology, trends, and exposure across European Functional Urban Areas. *Weather. Clim. Extrem.* **2022**, *36*, 100455. [CrossRef]
64. Sharma, A.; Woodruff, S.; Budhathoki, M.; Hamlet, A.F.; Chen, F.; Fernando, H.J.S. Role of green roofs in reducing heat stress in vulnerable urban communities—A multidisciplinary approach. *Environ. Res. Lett.* **2018**, *13*, 94011. [CrossRef]
65. Mugume, S.N.; Gomez, D.E.; Fu, G.; Farmani, R.; Butler, D. A global analysis approach for investigating structural resilience in urban drainage systems. *Water Res.* **2015**, *81*, 15–26. [CrossRef] [PubMed]
66. Ge, Y.; Dou, W.; Zhang, H. A new framework for understanding urban social vulnerability from a network perspective. *Sustainability* **2017**, *9*, 1723. [CrossRef]
67. Schaefer, M.; Thinh, N.X.; Greiving, S. How can climate resilience be measured and visualized? Assessing a vague concept using GIS-Based fuzzy logic. *Sustainability* **2020**, *12*, 635. [CrossRef]
68. Salata, S.; Velibeyoğlu, K.; Baba, A.; Saygın, N.; Couch, V.T.; Uzelli, T. Adapting Cities to Pluvial Flooding: The Case of Izmir (Türkiye). *Sustainability* **2022**, *14*, 16418. [CrossRef]
69. Gobo, J.P.A.; Faria, M.R.; Galvani, E.; Goncalves, F.L.T.; Monteiro, L.M. Empirical model of human thermal comfort in subtropical climates: A first approach to the Brazilian Subtropical Index (BSI). *Atmosphere* **2018**, *9*, 391. [CrossRef]
70. Chandra, S.; Dubey, S.K.; Sharma, D.; Mitra, B.K.; Dasgupta, R. Investigation of Spatio–Temporal Changes in Land Use and Heat Stress Indices over Jaipur City Using Geospatial Techniques. *Sustainability* **2022**, *14*, 9095. [CrossRef]
71. Kim, H.G.; Lee, D.K.; Jung, H.; Kil, S.H.; Park, J.H.; Park, C.; Tanaka, R.; Seo, C.; Kim, H.; Kong, W.; et al. Finding key vulnerable areas by a climate change vulnerability assessment. *Nat. Hazards* **2016**, *81*, 1683–1732. [CrossRef]
72. Jimoh, M.Y.; Bikam, P.; Chikoore, H. The influence of socioeconomic factors on households' vulnerability to climate change in semiarid towns of Mopani, South Africa. *Climate* **2021**, *9*, 13. [CrossRef]

73. Lobaccaro, G.; Acero, J.A.; Martinez, G.S.; Padro, A.; Laburu, T.; Fernandez, G. Effects of orientations, aspect ratios, pavement materials and vegetation elements on thermal stress inside typical urban canyons. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3574. [CrossRef]
74. Jin, H.; Liu, S.; Kang, J. Thermal comfort range and influence factor of urban pedestrian streets in severe cold regions. *Energy Build.* **2019**, *198*, 197–206. [CrossRef]
75. Cian, F.; Giupponi, C.; Marconcini, M. Integration of earth observation and census data for mapping a multi-temporal flood vulnerability index: A case study on Northeast Italy. *Nat. Hazards* **2021**, *106*, 2163–2184. [CrossRef]
76. Macharia, D.; Kaijage, E.; Kindberg, L.; Koech, G.; Ndungu, L.; Wahome, A.; Mugo, R. Mapping climate vulnerability of river basin communities in Tanzania to inform resilience interventions. *Sustainability* **2020**, *12*, 4102. [CrossRef]
77. Rasch, R.J. Assessing urban vulnerability to flood hazard in Brazilian municipalities. *Environ. Urban.* **2016**, *28*, 145–168. [CrossRef]
78. Chauhan, D.; Thiyaharajan, M.; Pandey, A.; Singh, N.; Singh, V.; Sen, S.; Pandey, R. Climate change water vulnerability and adaptation mechanism in a Himalayan City, Nainital, India. *Environ. Sci. Pollut. Res.* **2022**, *29*, 85904–85921. [CrossRef]
79. Sidiqui, P.; Roös, P.B.; Herron, M.; Jones, D.S.; Duncan, E.; Jalali, A.; Allam, Z.; Roberts, B.J.; Schmidt, A.; Tariq, M.A.U.R.; et al. Urban Heat Island vulnerability mapping using advanced GIS data and tools. *J. Earth Syst. Sci.* **2022**, *131*, 266. [CrossRef]
80. Zhang, Y.; Wu, T.; Arkema, K.K.; Han, B.; Lu, F.; Ruckelshaus, M.; Ouyang, Z. Coastal vulnerability to climate change in China's Bohai Economic Rim. *Environ. Int.* **2021**, *147*, 106359. [CrossRef] [PubMed]
81. Liu, X.; Yue, W.; Yang, X.; Hu, K.; Zhang, W.; Huang, M. Mapping Urban Heat Vulnerability of Extreme Heat in Hangzhou via Comparing Two Approaches. *Complexity* **2020**, *2020*, 9717658. [CrossRef]
82. Roshan, G.R.; Saleh Almomenin, H.; da Silveira Hirashima, S.Q.; Attia, S. Estimate of outdoor thermal comfort zones for different climatic regions of Iran. *Urban Clim.* **2019**, *27*, 8–23. [CrossRef]
83. Yang, J.; Ding, Y.; Zhang, L. Conceptualizing and Measuring Megacity Resilience with an Integrated Approach: The Case of China. *Sustainability* **2022**, *14*, 11685. [CrossRef]
84. Rudiarto, I.; Pamungkas, D. Spatial exposure and livelihood vulnerability to climate-related disasters in the North Coast of Tegal City, Indonesia. *Int. Rev. Spat. Plan. Sustain. Dev.* **2020**, *8*, 34–53. [CrossRef]
85. El-Zein, A.; Ahmed, T.; Tonmoy, F. Geophysical and social vulnerability to floods at municipal scale under climate change: The case of an inner-city suburb of Sydney. *Ecol. Indic.* **2021**, *121*, 106988. [CrossRef]
86. Li, X.; Li, X.; Tang, N.; Chen, S.; Deng, Y.; Gan, D. Summer Outdoor Thermal Perception for the Elderly in a Comprehensive Park of Changsha, China. *Atmosphere* **2022**, *13*, 1853. [CrossRef]
87. Bottazzi, P.; Winkler, M.S.; Boillat, S.; Diagne, A.; Sika, M.M.C.; Kpangon, A.; Faye, S.; Speranza, C.I. Measuring subjective flood resilience in Suburban Dakar: A before-after evaluation of the "Live with Water" project. *Sustainability* **2018**, *10*, 2135. [CrossRef]
88. Canan, F.; Golasi, I.; Ciancio, V.; Coppi, M.; Salata, F. Outdoor thermal comfort conditions during summer in a cold semi-arid climate. A transversal field survey in Central Anatolia (Turkey). *Build. Environ.* **2019**, *148*, 212–224. [CrossRef]
89. Sorg, L.; Medina, N.; Feldmeyer, D.; Sanchez, A.; Vojinovic, Z.; Birkmann, J.; Marchese, A. Capturing the multifaceted phenomena of socioeconomic vulnerability. *Nat. Hazards* **2018**, *92*, 257–282. [CrossRef]
90. Chen, Y.; Ye, Z.; Liu, H.; Chen, R.; Liu, Z.; Liu, H. A GIS-based approach for flood risk zoning by combining social vulnerability and flood susceptibility: A case study of Nanjing, China. *Int. J. Environ. Res. Public Health* **2021**, *18*, 11597. [CrossRef]
91. Takebayashi, H.; Okubo, M.; Danno, H. Thermal environment map in street canyon for implementing extreme high temperature measures. *Atmosphere* **2020**, *11*, 550. [CrossRef]
92. Kawyitri, N.; Shekhar, A. Assessing vulnerability and capacity of Bhubaneswar as a progressive smart-city: An empirical case study of Fani cyclone impact on the city. *Int. J. Disaster Risk Reduct.* **2021**, *56*, 101986. [CrossRef]
93. Cerbaro, M.; Morse, S.; Murphy, R.; Middlemiss, S.; Michelakis, D. Assessing Urban Vulnerability to Flooding: A Framework to Measure Resilience Using Remote Sensing Approaches. *Sustainability* **2022**, *14*, 2276. [CrossRef]
94. Guardaro, M.; Hondula, D.M.; Ortiz, J.; Redman, C.L. Adaptive capacity to extreme urban heat: The dynamics of differing narratives. *Clim. Risk Manag.* **2022**, *35*, 100415. [CrossRef]
95. Sarkodie, S.A.; Ahmed, M.Y.; Owusu, P.A. Global adaptation readiness and income mitigate sectoral climate change vulnerabilities. *Humanit. Soc. Sci. Commun.* **2022**, *9*, 113. [CrossRef]
96. Pei, X.; Wu, J.; Xue, J.; Zhao, J.; Liu, C.; Tian, Y. Assessment of Cities' Adaptation to Climate Change and Its Relationship with Urbanization in China. *Sustainability* **2022**, *14*, 2184. [CrossRef]
97. Ghaedi, S.; Shanbehpour, F. The Structural Analysis of Driving Forces to Adaptive Capacity with Climate Change in Ahvaz City Iran. *ResearchSquare* **2022**, 1–19. [CrossRef]
98. Riach, N.; Scholze, N.; Glaser, R. Mapping Transboundary Climate Change Risk: The case study of the Trinational Metropolitan Area Upper Rhine Area. *Nat. Hazards Earth Syst. Sci. Discuss.* **2021**, 1–23. [CrossRef]
99. Rehman, S.; Sahana, M.; Kumar, P.; Ahmed, R.; Sajjad, H. Assessing hazards induced vulnerability in coastal districts of India using site-specific indicators: An integrated approach. *GeoJournal* **2021**, *86*, 2245–2266. [CrossRef]
100. Parry, J.-E. *Review of Current and Planned Adaptation Action in Pakistan*; IISD: Winnipeg, MB, Canada, 2011; pp. 1–92.
101. Poo, C.-P. Climate Change Adaptation for Seaports and Airports. Ph.D. Thesis, Liverpool John Moores University, Liverpool, UK, 2020.
102. Ford, J.D.; King, D. A framework for examining adaptation readiness. *Mitig. Adapt. Strateg. Glob. Chang.* **2015**, *20*, 505–526. [CrossRef]

103. Amegavi, G.B.; Langnel, Z.; Ofori, J.J.Y.; Ofori, D.R. The impact of adaptation on climate vulnerability: Is readiness relevant? *Sustain. Cities Soc.* **2021**, *75*, 103325. [CrossRef]
104. Sharifi, A.; Yamagata, Y. Major principles and criteria for development of an urban resilience assessment index. In Proceedings of the International Conference and Utility Exhibition 2014 on Green Energy for Sustainable Development (ICUE 2014), Pattaya City, Thailand, 19–21 March 2014.
105. Bogdan, M.; Walther, E. Comfort modelling in semi-outdoor spaces. *REHVA J.* **2017**, *54*, 23–25.
106. Hansen, G.; Macedo, J. *Urban Ecology for Citizens and Planners*; University of Florida Press: Gainesville, FL, USA, 2021.
107. Flanagan, B.E.; Gregory, E.W.; Hallisey, E.J.; Heitgerd, J.L.; Lewis, B. A Social Vulnerability Index for Disaster Management. *J. Homel. Secur. Emerg. Manag.* **2020**, *8*, 0000102202154773551792. [CrossRef]
108. Stafoggia, M.; Forastiere, F.; Agostini, D.; Caranci, N.; De'Donato, F.; Demaria, M.; Michelozzi, P.; Miglio, R.; Rognoni, M.; Russo, A.; et al. Factors affecting in-hospital heat-related mortality: A multi-city case-crossover analysis. *J. Epidemiol. Community Health* **2008**, *62*, 209–215. [CrossRef]
109. Lala, B.; Hagishima, A. Impact of Escalating Heat Waves on Students' Well-Being and Overall Health: A Survey of Primary School Teachers. *Climate* **2023**, *11*, 126. [CrossRef]
110. Ahammad, R. Constraints of pro-poor climate change adaptation in chittagong city. *Environ. Urban.* **2011**, *23*, 503–515. [CrossRef]
111. Ren, Z.; Chen, Z.; Wang, X. Climate change adaptation pathways for Australian residential buildings. *Build. Environ.* **2011**, *46*, 2398–2412. [CrossRef]
112. Hossen, M.A.; Netherton, C.; Benson, D.; Rahman, M.R.; Salehin, M. A governance perspective for climate change adaptation: Conceptualizing the policy-community interface in Bangladesh. *Environ. Sci. Policy* **2022**, *137*, 174–184. [CrossRef]
113. World Bank Group. *Open Government and Climate Change: Leveraging Transparency, Participation, and Accountability for Effective Climate Action*; Climate Governance Papers; World Bank: Washington, DC, USA, 2022.
114. Biesbroek, R.; Klostermann, J.; Termeer, C.; Kabat, P. Barriers to climate change adaptation in the Netherlands. *Clim. Law* **2011**, *2*, 181–199. [CrossRef]
115. Groven, K.; Aall, C.; van den Berg, M.; Carlsson-Kanyama, A.; Coenen, F. Integrating climate change adaptation into civil protection: Comparative lessons from Norway, Sweden and the Netherlands. *Local Environ.* **2012**, *17*, 679–694. [CrossRef]
116. Michalina, D.; Mederly, P.; Diefenbacher, H.; Held, B. Sustainable urban development: A review of urban sustainability indicator frameworks. *Sustainability* **2021**, *13*, 9348. [CrossRef]
117. Sánchez, G.F.J. Planeamiento urbanístico y cambio climático: La infraestructura verde como estrategia de adaptación. *Cuad. Investig. Urbanística* **2019**, *122*, 1–101. [CrossRef]
118. Mabalane, B. *Briefing*; International Institute for Environment and Development: London, UK, 2014; pp. 1–89.