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Social vulnerability assessment of the Cologne urban area (Germany) to heat waves: links to ecosystem services

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ABSTRACT

More than three-quarters of the European population live in urban areas and this proportion is increasing, leading, in some cases, to increased vulnerability of cities to environmental hazards. The health impacts of heat waves are aggravated in cities due to the high density of buildings, the fragmentation of green areas and the higher concentrations of air pollutants. Ecosystems can provide important benefits that mitigate the impacts of heat waves but at the same time can themselves be affected by the hazard, thus limiting their services. The objective of this study was to assess the vulnerability of the Cologne urban population to heat waves, taking into consideration a range of social and ecological variables. Based on the MOVE framework, indicators were developed and GIS applications were used to spatially assess the relative vulnerability of the 85 districts of Cologne to heat waves. The insights gained were integrated and corroborated with the outcomes of stakeholders' interviews. As environmental factors play a major role in this assessment, it is suggested that ecosystem management in Cologne and its surroundings be improved. In addition, though vulnerability is higher in central districts, attention needs to be paid to the periphery where the most susceptible groups reside.

1. Introduction

In Europe, 75% of the population live in urban areas and the proportion is increasing [1]. However, absolute population growth is not the major contributor to the increase of the disaster potential in cities [2]. Rather, the shift in the location of industries and homes, driven by economic factors and lifestyles plays a significant role in the conversion of rural lands near European cities [3] which in turn alters ecosystems, affecting their services through e.g. the compaction of soil and the impairment of its functions. These changes increase the loss of water permeability (soil sealing), compromise the availability of water supply in terms of groundwater recharge and fragment green cover which is accompanied by an increase in resources and energy consumption [1]. In addition, under scenarios of climate change, geographical areas that were less affected by heat spells are likely to become at higher risk of extreme hydro-meteorological events [4]. The vulnerability of urban populations to hazards is in this way further exacerbated.

The impacts of heat waves on the ageing segment of the population that lives in the highly modified ecosystem of urban areas are of increasing concern for European cities. In fact, urbanization affects climate locally, as cities tend to be warmer than their surroundings, producing the

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so-called Urban Heat Island (UHI) effect. This manifests itself especially at night and principally as a consequence of the properties and density of built infrastructures, low albedo, low green cover and low moisture availability in cities. Air quality is also degraded in cities, mainly due to the higher concentration of road traffic and industrial activities which require fuel combustion leading to the emission of air pollutants dangerous for human health. As a result, during heat waves, the rates of heat-related morbidity and mortality are often higher in cities than in their surroundings [5]. This is especially true for densely populated areas, where heat-retaining buildings, few and fragmented green areas with a lower cooling capacity, and higher levels of air pollution due to higher road traffic, amplify the impacts of the hazard [6–11]. It is therefore suggested that excess deaths occurring in urban areas during periods of extreme heat can be significantly reduced through appropriate urban land cover planning [12]. Land use patterns are in fact related to the capacity of urban ecosystems to provide regulating services which can be assessed through landscape functions (i.e. the capacities of a landscape to provide goods and services to the society) [13,14]. It should however be emphasized that social and institutional considerations (e.g. early warning systems, the adoption of appropriate behaviours, facilitating tighter social networks) remain paramount while dealing with this type of vulnerability.

The objective of this study is to assess the social vulnerability of the 85 districts of the Cologne urban area as part of the Methods for the improvement of Vulnerability Assessment in Europe (MOVE) project funded by the European Commission. In the following introductory sections, vulnerability assessment, social vulnerability to heat waves, the role of ecosystem services in mitigating the impacts of heat waves, as well as the assessment of ecosystem services as landscape functions are briefly reviewed and defined. Section 2 presents the methodology developed, Section 3 presents the results, which are then discussed in Section 4.

1.1. Vulnerability assessment

An extensive review of the vulnerability terminology was carried out by Thywissen [15] and includes a comprehensive list of definitions that primarily differ according to the school of thought in which these are developed and in use. According to these different schools, which can mainly be clustered into "political economy", "social-ecology", "holistic vulnerability and disaster reduction assessment" and "climate change science" [16], various approaches and frameworks have been developed to assess vulnerability. The MOVE project was intended to overcome these differences by producing a generic Framework (Fig. 1) that would bring together and be applicable both in the domain of disaster risk reduction and climate change adaptation. The MOVE framework is intended to be a guiding tool more than a close representation of reality. By assembling the main elements of the vulnerable social–ecological system (i.e. a coupled system of biophysical and social components that interact and evolve according to complex dynamics) at multiple scales, and representing the risk factors, the framework closes the loop through the adaptation section. Adaptation is actually considered as a central element in shaping vulnerability in the long term

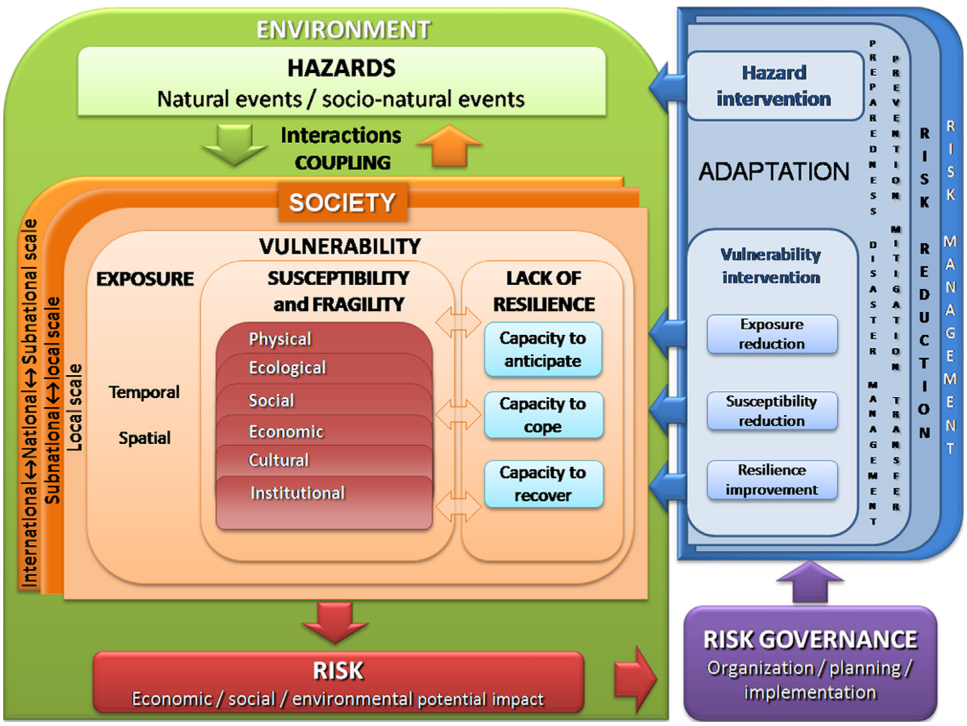

Fig. 1. The MOVE Generic Framework.

within the risk governance frame. The framework is also intended to facilitate the integration of different indices and methodologies to contribute to a more integrated assessment. To respond to the need of holistic approaches, using quantitative, qualitative and participatory methods at different scales, it is in effect a challenge to combine different methodologies [17].

The present study also applies the multidimensional concepts of vulnerability assessment developed within the MOVE project. Vulnerability is defined as "the propensity of exposed elements such as physical or capital assets, human beings and their livelihoods to experience harm and suffer damage and loss when impacted by single or compound hazard events" [16]. In the Framework, vulnerability is considered to be the result of the contributions and interactions of three components: exposure, susceptibility (or fragility) and lack of resilience. Exposure defines "the extent to which a unit of assessment falls within the geographical range of a hazard event"; susceptibility "describes the predisposition of elements at risk to suffer harm"; while lack of resilience is defined by the "limitation in access to and mobilization of the resources of a community or a social–ecological system in responding to an identified hazard", compromising the capacity to anticipate, to cope and to recover of the system [16]. Six dimensions of vulnerability are considered within MOVE to characterize the susceptibility and the lack of resilience of the system: physical, ecological, social, economic, cultural and institutional. While socio-economic and institutional aspects of vulnerability are well explored in the literature, other dimensions of vulnerability, such as the ecological or the cultural ones, are currently not well integrated in vulnerability assessments.

The present study, through the application of the MOVE generic framework and definitions, aims at illustrating the operationalization of these theoretical concepts for practical use in the decision-making context. The assessment presented in this work focuses on the core part of the framework, which considers the main interactions between the three components of vulnerability, and this from the social as well as the ecological dimensions.

1.2. Heat waves and social vulnerability

A heat wave is considered to be a continued and intensive period of heat stress, which may be accompanied by high humidity, and that directly affects human health [18]. Various morbidity and mortality impacts on the human population have been assessed for past events [19–24]. It is estimated that during the heat wave which affected Europe in 2003, more than 70,000 people died [25]. Similarly, the 2010 heat wave that affected Russia claimed the lives of ca. 55,000 people [26]. Also, extreme heat events are expected to increase in number, length and intensity in the future [4].

Koppe et al. [18] note that "skin eruptions, heat fatigue, heat cramps, heat syncope, heat exhaustion and heat stroke are traditionally considered as heat related illnesses". Those most likely to die or be affected by heat are the elderly people, the chronically ill and the isolated [27]. In Chicago, people older than 65 accounted for 72% of the heat-related deaths due to the mid-July 1995 heat wave [28] and in the 1999 Chicago heat wave, the strongest risk factor for heat-related death was living in isolation [29]. In the elderly people, physiological responses to changes in the environment are less acute and medications may interact with thermoregulation and risk perception, further increasing their vulnerability to heat [30]. Fouillet et al. [21] found excess mortality during the 2003 heat wave in France to be higher for people living at home and in retirement institutions than for those in hospitals, and that the mortality of widowed, single and divorced individuals was greater than that of married people. In a review article, Bouchama et al. [31] found that being confined to bed, not leaving home on a daily basis, and being unable to care for oneself were associated with the highest risk of death during heat waves. Additionally, pre-existing psychiatric illness tripled the risk of death, followed by cardiovascular and pulmonary illness, while using home air-conditioning, visiting cool environments, and increasing social contact were strongly associated with reduced mortality [31]. A further increase in losses in central European regions was due to a higher vulnerability of the population as this was located where hot spells are relatively infrequent [32]. The presence of strong social networks may increase the resilience of the system when the hazard strikes. Although, direct positive relationship between tight social networks and resilience for elderly people exposed to heat waves in two UK cities was not found [33], Yardley et al. [5], reviewing both environmental and socio-economic factors that may determine the health and mortality impacts of heat waves, found in several studies that lack of social contact is a major risk factor, as people might only become aware of their condition and seek help when it is already too late [5,34]. Ethnicity is also considered in studies, especially in the US where non-white[1] people had a higher death rate (sometime double) than white people. This was linked to poverty rates, showing that socio-economic factors (i.e. income, education), more than ethnicity, play an important role in heat related mortality [5]. The researchers concluded that a socio-ecological approach, able to take into account the multiple factors that play a role in heat mortality risk and the different local circumstances, is required.

1.3. Heat waves and ecosystem services

Mortality risk increases by between 0.2% and 5.5% for every 1 °C rise in temperature above a location-specific threshold [35], though it is unlikely to be a truly linear trend. Therefore, zones of the city where the UHI effect is stronger are those where the risk of illness or death during a heat wave is generally higher.

Green cover and trees in streets make important contributions to the improvement of urban climate, especially during summer months and periods of heat stress [36–42]. Various studies have analyzed how vegetation influences

[1] "White" is one of the race categories used in the US census, which includes both racial and national-origin groups.

the thermal microclimate of urban areas and mitigates the UHI effect. Depietri et al. [43] reviewed some of these studies, reporting data taken from measurements in different cities and showing how the cooling potential of green areas, while being considerable, varies from one urban area to another depending on the local conditions. On average, an urban green area is 1–2 °C cooler if compared with a non-vegetated zone [40,44] and a 0.8 °C reduction in ambient air temperature should follow a 10% increase in the ratio green/built up area in a city [39]. Studies also stress the importance of placing vegetation (e.g. street trees) within the urban fabric and consider visits to green areas as a good coping strategy in case of heat stress [43]. Vegetation structure for improving the microclimate is a significant factor: maximum benefits seem to be obtained by planting two or three rows of trees with a relatively high density and adequate ventilation [45,46].

Higher concentrations of air pollutants during heat waves can lead to an increase of excess death [7,8,47,48]. There is increasing evidence for a synergic effect on mortality between high temperatures and ozone (O_3) concentrations [49]. Similar, but less pronounced differences, have been found for other pollutants such as particulate matter less than 10 μm (PM_{10}), black smoke, nitrogen dioxide (NO_2), and sulphur dioxide (SO_2) [49]. The mortality increase due to the combined effect of heat and air pollution can be reduced by decreasing exposure to O_3 and PM_{10} on hot days [35]. Interestingly, ground level O_3 and PM_{10} are the pollutants whose concentrations declined the least in Europe between 1990 and 2009 and that directly affect human health [50]. European ecosystems are also most affected by substances that cause acidification, eutrophication and vegetation damage (i.e. resulting from O_3 exposure) [50].

As reviewed in Depietri et al. [43], urban trees can improve air quality in different ways such as by intercepting atmospheric particles and absorbing various gaseous pollutants. Additional information is provided by Nowak et al. [51] who estimate, for instance, that the total annual air pollution removal by US urban trees amounts to 711,000 metric tons[2] ($3.8 billion value). To contribute to better air quality in cities it is important to plant appropriately selected tree species which are more tolerant to air pollutants and more effective in their removal.

On the other hand, heat waves may have a series of impacts on cities' ecosystems and services that would amplify the vulnerability of the urban population. For instance, sources of water supply (i.e. surface and groundwater) for agriculture, drinking water, water treatment plants and cooling of hydropower plants may experience shortages or may fail due to a sudden increase in demand [52]. Food production and distribution, as well as forestry, may be affected when peri-urban agricultural land sees its productivity diminished. This in turn can have implications for employment in the rural sector [52]. More broadly, the well-being of the urban population may diminish when recreational services are affected by heat stress: vegetation in parks may be damaged by heat and the higher concentration of air pollutants; the use of small watercourses, ponds and lakes may be interrupted when high levels of eutrophication leads to algal blooms and hypoxia. At the wildland-urban interface, the risk of forest fires may also increase. Some of these impacts have been described in detail in Depietri et al. [43]. However, most of the information available from the literature concerns the role of ecosystems in mitigating the impacts of the hazard, and much less refers to indirect impacts, namely those that, affecting the urban and peri-urban ecosystems, could increase the magnitude of the impact on the human population.

[2] The pollutants considered in the study are carbon monoxide (CO), NO_2, O_3, PM_{10} and SO_2.

1.4. Measuring landscape functions

Flows of ecosystem services remain poorly characterized at local-to-regional scales mainly because there is no direct relation between land cover and functionality of ecosystems [53,54]. Verburg et al. [55] state that, “a proper representation of land function will always require additional data beyond land cover observations”: information on the spatial distribution of landscape functions generally needs additional intensive field observations or cartographic work [54]. Also, according to Burkhard et al. [56], using quantitative and qualitative assessment data in combination with Land Use (LU) and Land Cover (LC) information originating from remote sensing and GIS, the state of ecosystem services can be evaluated.

Some studies have assessed the state of ecosystem services through land use and land cover features at different scales, from the global to the national/regional scales and to the local e.g. [57–62]. Most of them make use of additional quantitative biophysical information to build proxies for landscape functions for a wide range of services at different scales. The advantage of this approach is that, besides providing an estimate of the ecosystem services considered, it conveys information which has a spatial component and facilitates the presentation of the results to policy and decision makers. In this study, we contribute to this field focusing on the local level to assess the potential use of land cover and land use as a proxy for regulating services.

2. Methods

2.1. Case study: the Cologne urban area

The case study is the Cologne urban area (50°57′N and 6°58′E), situated within a floodplain along the river Rhine, in central-western Germany and in the Federal State of North Rhine Westphalia (NRW). Cologne is the fourth largest city in Germany and the largest one both in NRW and within the Rhine-Ruhr Metropolitan Area, with around 1 million inhabitants. It is also considered to be the warmest city in the country with a sub-Atlantic climate with traits of mild oceanic to mild continental climate due to the surrounding relief and its position in the landscape [63]. On a daily basis, the winds that enter the city at night prior to the onset of the Rhine Valley Wind (from 01:00 CET), namely the country breeze and the down-slope wind, are insufficient to adequately ventilate the city centre [64]. Heat wave events have affected the region in the past and elevated temperatures have characterized the recent summers. The highest temperature ever reached in the Cologne-Bonn Metropolitan Area since 1957 was recorded on the 12th August 2003 and was about 38.8 °C.[3] The health department of Cologne reported an increase of 16.5% of deaths in the month of August 2003 compared to the mean values in August for the previous three years (i.e. 775 deaths per month) [65].

From a geographical point of view, the urban area includes industrial sites, inner harbours, historic city centres and residential areas with different vegetation portions and fallow land [66]. In the environs of Cologne and along the river Rhine, the land use pattern is composed mainly of agricultural land with maize, sugar beet and forests as well as several artificial lakes [66]. Hills to the northeast and southwest comprise mixed cultivations of both meadows and maize fields. Historically, the spatial structure of Cologne was significantly influenced by perpendicular alignments dating back to the Roman occupation of the area [67]. It developed radially from the centre around rings arranged in a semicircle along the Roman city wall. At the beginning of the 20th century, while the city was expanding outwards, certain spaces were protected to ensure environmental quality [67]. In fact, during the term of office of Konrad Adenauer (Cologne City Mayor between 1917 and 1933), the city's former fortifications were converted into a greenbelt. The initial plan of the outer greenbelt by the German urbanist Fritz Schumacher (who collaborated with Konrad Adenauer) was put in place in the early 1920s and was further developed throughout the century. The external green ring was planned to act as a buffer between the urbanized city and its peripheral industrial areas [68]. At present, the main green areas of the city are composed of an outer ring and inner ring connected radially by green axes. A plan to develop open green spaces along the River Rhine was initiated in 1978. Overall, Cologne has abundant natural land: some 230 km^2 covering 57% of the urban area [69].

From a socio-economic point of view, the vast majority of the lowest wealth neighbourhoods are clustered in two parts of the city: the larger one is located east of the river Rhine and the second one is located in the north-western part of the city [70]. Compact suburbs with subsidized housing settlements and public transport systems for low-income groups were built during the baby boom in the 1960s after 60% of the city was destroyed during the Second World War [71]. The city districts with the highest social status are more dispersed, though most of them are located at the border of the city [70]. In the surrounding "green peripheral areas", wealthier families developed larger, individual plots during the 1980s [71].

2.2. Data used

For the quantitative part of the study, four main datasets were used: socio-economic data regarding the population of the city of Cologne (i.e. statistical values), remote sensing data in the form of thermal infrared imagery, land use (LU) and land cover (LC) classification maps, and a map of the forest cover. All of the socio-economic data for each of the city districts were obtained from the Statistical Department of Cologne for the year 2001. Data about elderly people living alone per district were available only for the year 2005. The Environmental Department of Cologne provided the thermal imagery. The dataset was captured using a thermal infrared camera airborne at 3000 m altitude which delivered an image with a resolution of 7.5 m. The thermal scans were conducted on 30th June 1993 at 9 p.m. (reflecting the heat accumulated during the day; Fig. 2) and on 1st July 1995 at 4 a.m. (reflecting night temperature; Fig. 3). The LU and LC data were obtained from the Centre for Remote Sensing of Land Surfaces (ZFL) of the University of Bonn (Germany). Based on the Landsat TM satellite image of 2001, the LU and LC class information were categorized with a resolution of 30 m. The classes defined include both sealed (i.e. low, middle, high and other areas) and unsealed (i.e. grassland, coniferous forest, deciduous forest, mixed forest, agricultural land and water bodies) surfaces (Fig. 4). The shape file of the Cologne urban forest measured in 2003 and provided by the Office of Landscaping and Green Spaces of Cologne was used. For the administrative subdivision of Cologne the 85 districts were used, see Fig. 5.

We considered as negligible the chronological mismatch between the datasets used. Based on the LU and LC maps for the years 1984, 2001 and 2005, also provided by ZFL, most of the major land use changes in Cologne that took place between 1993 and 2005 involved the marked decrease in grassland and a symmetrical increase of urbanized areas characterized by low fractions of impervious surfaces ($<40\%$) (ZFL, Univ. Bonn). The maximal Leaf Area Indexes (LAI) (providing information on evapotranspiration capacity) for the two CORINE classes, discontinuous urban fabric and natural grasslands, do not differ significantly [72]. In addition, city areas occupied by high impervious surfaces and forests, which most influence the intensity of the UHI, have changed little during the same period. Therefore, the thermal images of 1993 and 1995 can be considered as representative of the environmental conditions in which the people of Cologne lived between 2001 and 2005.

Stakeholders' interviews were carried out between December 2011 and January 2012 to investigate the perception of relevant local authorities regarding the capacity of a range of ecosystems to mitigate the impacts of heat waves, and to gather their opinion on past or potential indirect impacts of the hazard on the urban and peri-urban ecosystem. Interviewees were identified at the city level amongst those institutions in charge or contributing to the planning and management of urban ecosystems and those responsible or active in the sector of human health at the city level. In particular, a list of 25 institutions and organization working in a field

[3] ⟨http://www.dwd.de/bvbw/generator/DWDWWW/Content/Oeffentlichkeit/KU/KUPK/Wetterrekorde/absolute__hoechsttemperaturen__brd__en,templateId=raw,property=publicationFile.pdf/absolute_hoechsttemperaturen_brd_en.pdf⟩.

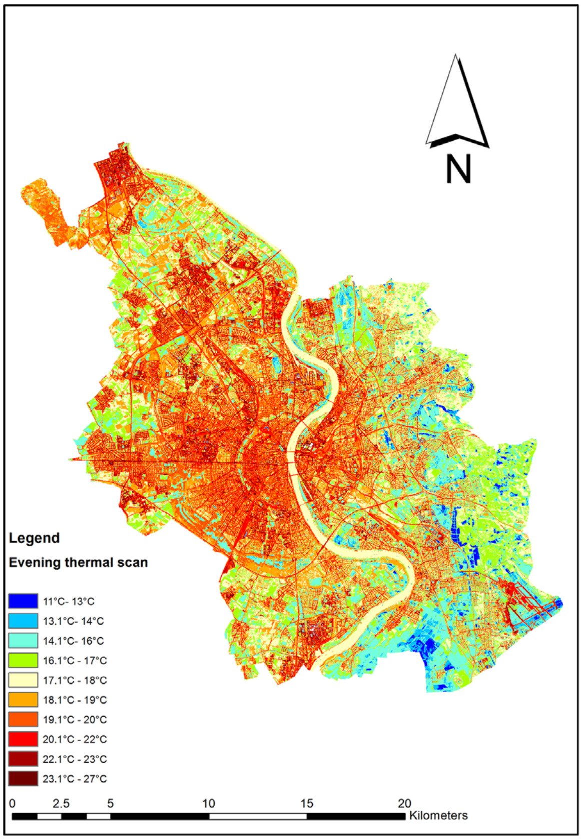

Fig. 2. Evening thermal scan of Cologne (June 30th 1993 at 9 p.m.). *Source*: Environmental Department of Cologne.

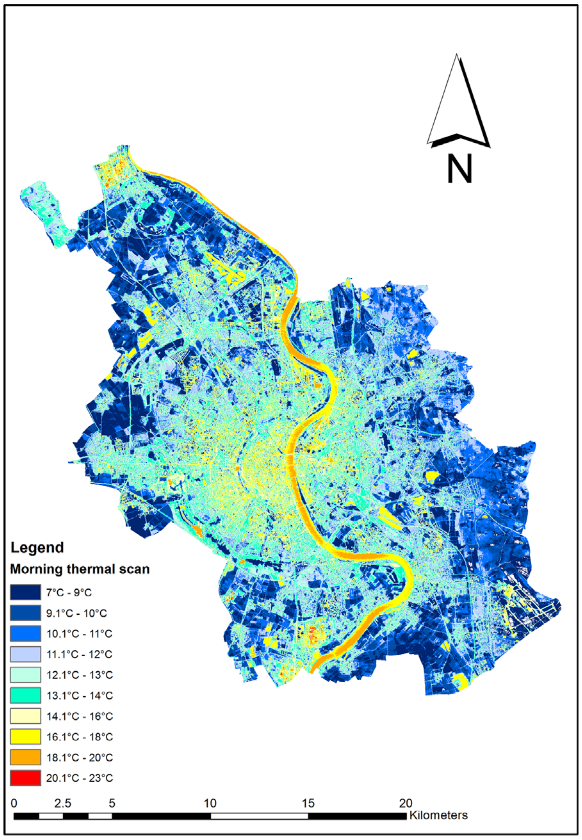

Fig. 3. Morning thermal scan of Cologne (July 1st 1995 at 4 a.m.). *Source*: Environmental Department of Cologne.

relevant to our focus at the city level was drawn up. The list was discussed internally, benefiting from our previous experience of working on disaster risk in Cologne. We then contacted each one of the institutions via mail and/or phone to find out about their interest in participating in an interview. Some of them refused as they did not consider their daily work to be strictly relevant for our study, but, nevertheless, some of these pointed out other local authorities that they thought would be more appropriate to be involved in our analysis. We finally ended up with a list of seven institutions willing to be interviewed which covered exactly the set of dimensions we considered in our study (see Table 1).

The interviews were carried out based on a questionnaire composed of open questions. Following the above-mentioned aim of the qualitative assessment, the questionnaires were divided into two sections: the first set of questions focused on the perceptions of the interviewees with respect to the role of the Cologne urban and peri-urban green and blue areas in regulating city climate and air quality; while the second focused on past and potential impacts of heat waves on the local ecosystem and its services (e.g., water supply, recreational activities and peri-urban agriculture and gardening) and thus, indirectly on the urban population. Each interview lasted from 40 to 60 min, was recorded and then transcribed. The transcribed text was analyzed making use of the Atlas.ti (ATLAS.ti Scientific Software Development GmbH, Berlin) software which supports qualitative data analysis. By allowing coding of the text and insertion of quotations, the software facilitates the cross comparison of the information contained in the transcripts and the generation of knowledge, while avoiding reducing the complexity contained in the data.

2.3. *Indicators selection and development*

Based on the MOVE framework and the definitions presented in Section 1.1, an extensive literature review, stakeholders' involvement and data availability, relevant indicators were identified to characterize the three components of vulnerability (i.e. exposure, susceptibility and lack of resilience). The indicators used and the composite indicators developed were then assessed and spatially represented through the application of the GIS ArcMap 10 software (ESRI, Redlands, CA).

The exposure component (E) was defined in time and space as the social and material context, represented by persons, resources, infrastructure, goods, services and ecosystems that may be affected by the hazard. In this study, it was measured as the number of people per city district differently exposed to heat waves due to the UHI effect which aggravates the intensity of the hazard. For Cologne it was not possible to investigate the effect of the spatial

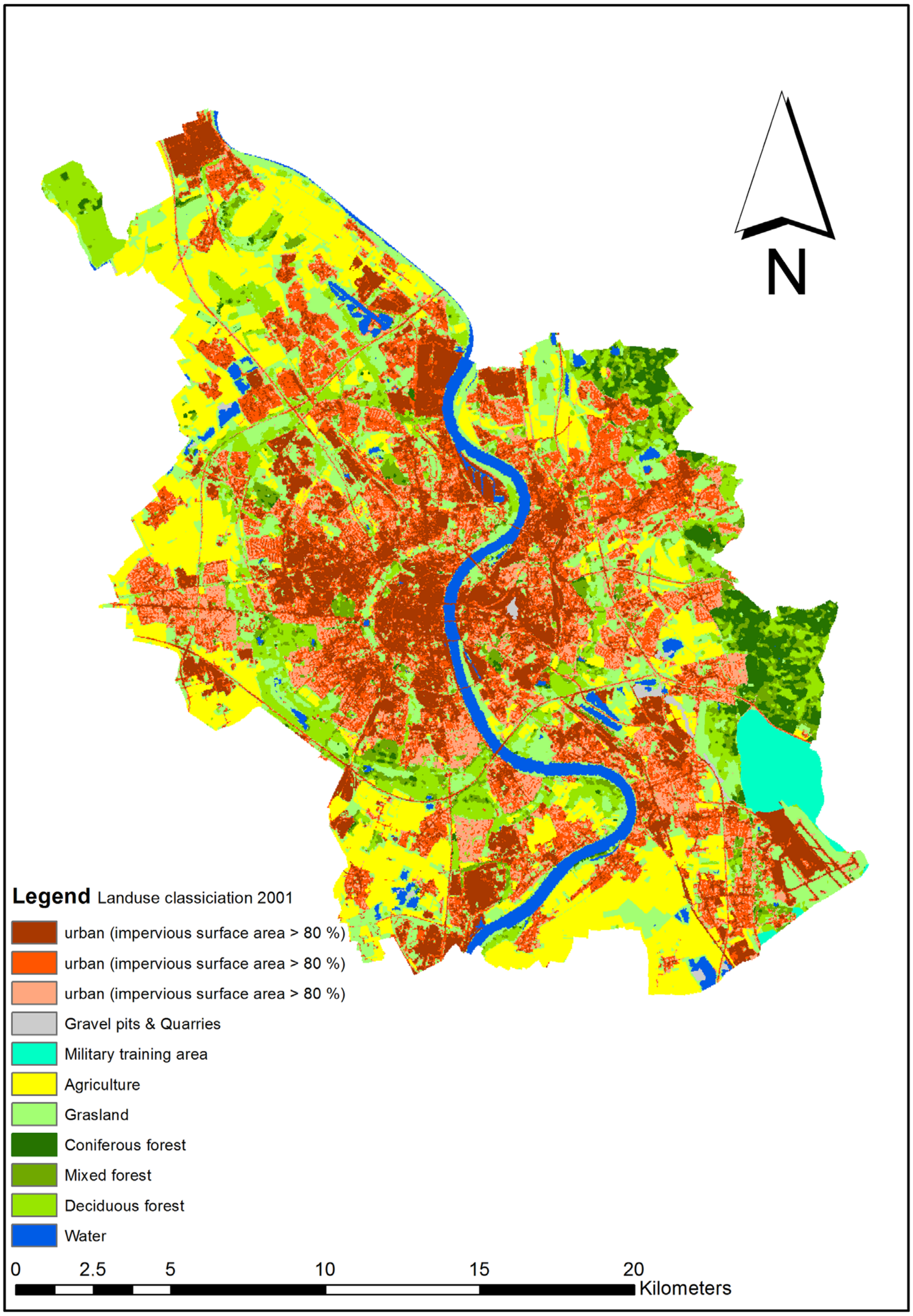

Fig. 4. Land use and land cover map of Cologne.
Source: Centre for Remote Sensing of Land Surfaces (ZFL), University of Bonn (Germany).

distribution of air pollutants and the role of air purification capacity of urban green areas on the exposure: while data on emissions for road traffic, households and industries are abundant and spatially detailed, few measurement points were available for the concentration of pollutants in the air.

With the objective of exploring different methods and assessing the opportunity to use each one of them according to the data availability, exposure is calculated in two ways named respectively E_1 and E_2: E_1 is obtained by multiplying the number of inhabitants per city district (I) with the normalized mean surface temperature (normalized using the Min–Max Normalization method) per city district (T) derived from the thermal infrared satellite images (see Eq. (1)); while E_2 is obtained by multiplying I

Fig. 5. Districts of Cologne.

with one minus the percentages of different LU/LC types per city district (L_n where n goes from 1 to 8 as listed in Table 2) weighted by specific coefficients (c_n) (see Table 2) which indicate the capacity of the LU/LC cover types to provide climate regulating services (Eq. (2)). Following the literature presented in Section 1.4, c_n were calculated as the average between the values presented in Burkhard et al. [56], who assign, through expert judgment, coefficients from 0 to 5 to the capacity of CORINE land cover types to provide ecosystem services (0 = no relevant capacity, 1 = low relevant capacity, 2 = relevant capacity, 3 = medium relevant capacity, 4 = high relevant capacity and 5 = very high relevant capacity), and the values obtained through the stakeholder interviews of the local authorities (see Table 2). The CORINE land cover classes were homogenized and translated into the classes used by

Table 1
Characterization of the stakeholders interviewed.

Interviewee	Male (M)/Female (F)	Position	Type of institution	Sector
1	M	Project manager	Municipal	Environment
2	M	Head of department	Municipal	Landscape and urban green areas
3	M	Head of department	Municipal	Public health
4	F	Head of department	Municipal	Urban planning
5	M	Head of department	Municipal	Water management
6	M	Professor	University Institute	Public health
7	M	Project manager	Local branch of a national NGO	Forest management

Table 2
Matrix of the coefficients (c_n) which estimate the capacities of different LU/LC types to provide climate regulation services, as derived in Burkhard et al. [56] and local stakeholders (SHs) interviews.

ES coefficients		c_n		
LU/LC type				
n	Name	Burkhard et al. [56]	SHs interviews	Average
1	Continuous urban fabric	0.00	0.00	0.00
2	Discontinuous urban fabric	0.00	1.60	0.80
3	Agricultural land	2.00	3.10	2.55
4	Deciduous forest	5.00	4.40	4.70
5	Coniferous forest	5.00	4.00	4.50
6	Mixed forest	5.00	4.40	4.70
7	Natural grassland	2.00	3.70	2.85
8	Water bodies	2.00	4.30	3.15

ZFL, Univ. Bonn.

$$E_1 = IT \tag{1}$$

$$E_2 = I\left(1 - \sum_{n=1}^{8} L_n c_n\right) \tag{2}$$

Indicators measuring susceptibility translate the predisposition of a society (and ecosystems) to suffer harm resulting from the levels of fragilities of settlements, disadvantageous conditions and relative weaknesses. As shown in the literature reviewed in Section 1.2, which mainly reflects on the extreme heat events in Chicago of 1995 and in Europe of 2003 (thus on the features of vulnerability to heat waves in richer countries as relevant to the location of our case study), the age and health conditions of the population, followed by socio-economic and socio-cultural factors, are the main drivers that shape susceptibility to heat waves. The elderly, the unemployed and the immigrant are considered to be the most susceptible groups to suffer harm in the case of extreme heat events. Based on these findings and on the discussions held during expert workshops, the following indicators were chosen as representative: the percentage of the population per city district older than 65 years (*El*); and the percentage of unemployed per city district (*U*) as a proxy for low income. Initially, the number of immigrants per city district was also considered as a proxy for low income and of disadvantageous conditions due to difficulties in understanding warning messages. However, it proved to be highly correlated with the number of unemployed per city district (r=0.979) and *U* was kept as it facilitates the comparison with relevant and related studies. *El* and *U* are both derived from census data on the population of Cologne and percentages are calculated with respect to the total population of each city district. The composite indicator of susceptibility (*S*) is obtained, according to Eq. (3), by normalizing and by equally weighting the two single indicators.

$$S = \frac{1}{2}El + \frac{1}{2}U \tag{3}$$

Lack of resilience (*LoR*) describes the limitations in access to and mobilization of resources of the social–ecological system and its incapacity to respond by absorbing the impact. This component of vulnerability includes the capacity to anticipate, cope and recover in the short term. In our assessment, it is calculated as a composite indicator of two single indicators. During a heat wave, the majority of deaths generally occur amongst the elderly who live alone as they are less able to promptly recognize, seek help and be assisted in case of malaise (see literature presented in Section 1.2). It is therefore assumed that the percentage of elderly living alone per city district (El_a) is a proxy for the lack of coping capacity of the population. Second, the vicinity of a household to urban parks and forests encourages and facilitates visits. The most susceptible groups can gain relief in case of extreme heat, benefiting from the cooler microclimate and cleaner air. The percentage of the surface of Cologne covered by urban forest per city district (*Cf*) is used as a proxy, thus city districts with a low percentage of or no urban forest indicate a lack of coping capacity. The composite indicator for *LoR* is then calculated by normalizing, giving equal weights, and aggregating these two indicators according to Eq. (4).

$$LoR = \frac{1}{2}El_a + \frac{1}{2}(1 - Cf) \tag{4}$$

For all three components equal weightings were given to provide, as a first step, a more generalized approach that can be applicable in a wide range of situations. On another occasion, the weightings can be allocated with local experts to tailor the analysis to specific conditions.

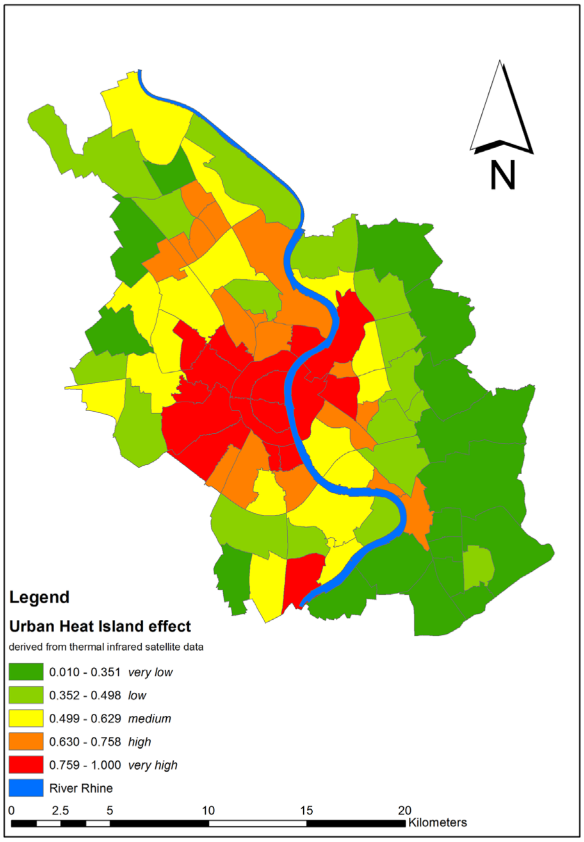

Fig. 6. Degree to which each district is exposed to heat waves, based on mean surface temperatures derived from thermal infrared satellite data.

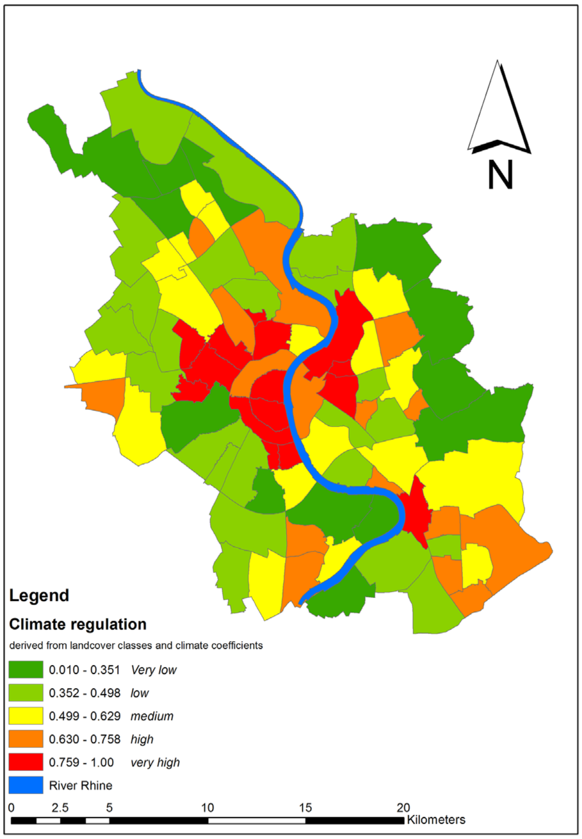

Fig. 7. Degree to which Cologne districts are exposed to heat waves based on the capacity of different land covers to regulate the urban microclimate.

Finally, the vulnerability (V) of the city of Cologne to heat waves is calculated by normalizing and aggregating the composite indicators of the three components through Eq. (5).

$$V = E[(S + LoR)/2] \tag{5}$$

This formulation takes into account that with no elements exposed, there would be no vulnerability.

For the spatial representation and mapping of the single and composite indicators shown in Figs. 6–19 (see Section 3), the values obtained were grouped into five classes using the quantile method, which is a predefined function of the ArcGIS 10 software (ESRI, Redlands, CA). With this method, each class contains an equal number of features, thus all classes differ in their values ranges. To facilitate comparison, the qualitative labels "very high, high, medium, low, very low" are used in the legends.

3. Results

3.1. Vulnerability assessment to heat waves

In this section, we present and describe the results obtained through the spatial analysis for all single and composite indicators used for the calculation of the final map of vulnerability.

First, the spatial distribution of the UHI effect on exposure is calculated through two methods (E_1 and E_2) and presented in Figs. 6 and 7. Fig. 6 is based on the thermal infrared images and shows the mean surface temperature per city district while Fig. 7 is based on the capacity of different land cover types to cool the environment. The first map clearly shows that the stronger effect of the UHI is concentrated in the central districts, where building density is higher and it then diminishes departing from the city centre towards less densely populated and more green/rural areas. Fig. 7 shows a less clear pattern in the UHI effect. While reflecting the fact that more densely built districts are affected by higher temperatures, the presence of forest areas and parks appears to counterbalance this effect and takes an excessively high weight in the equation. In fact, the almost central districts on the western side of Cologne, although crossed by the green belt, actually present high average surface temperatures possibly due to their vicinity to the dense centre and the still significantly elevated percentage of high sealed areas. On the other hand, in the southeast, the local and peripheral concentration of sealed surfaces does not seem to significantly affect the surface temperature (Fig. 6). The discrepancies in the results between the two methods are shown in Fig. 8 which compares Figs. 6 and 7. These differences appear to be significant throughout all the urban area, with relatively higher values of UHI measured

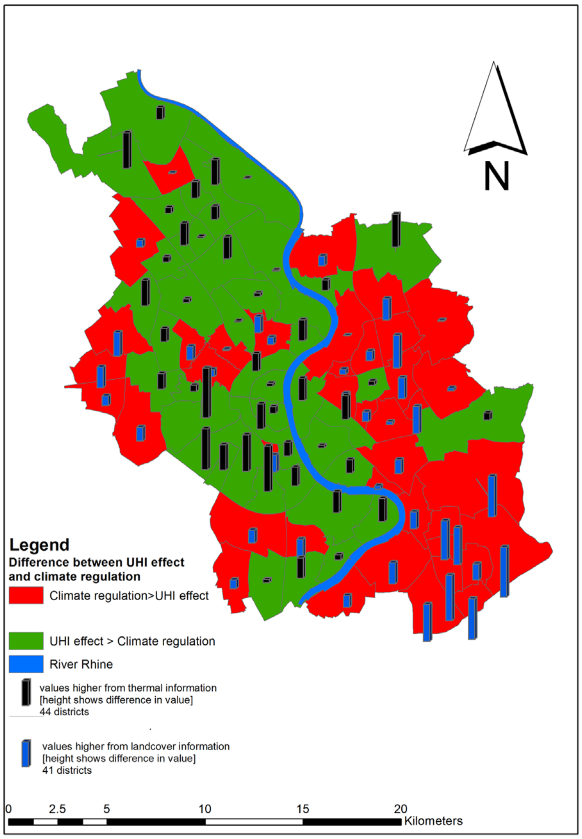

Fig. 8. Difference between the UHI effect calculated through the mean surface temperatures per city district (Fig. 6) and through the land cover capacity to cool the environment (Fig. 7).

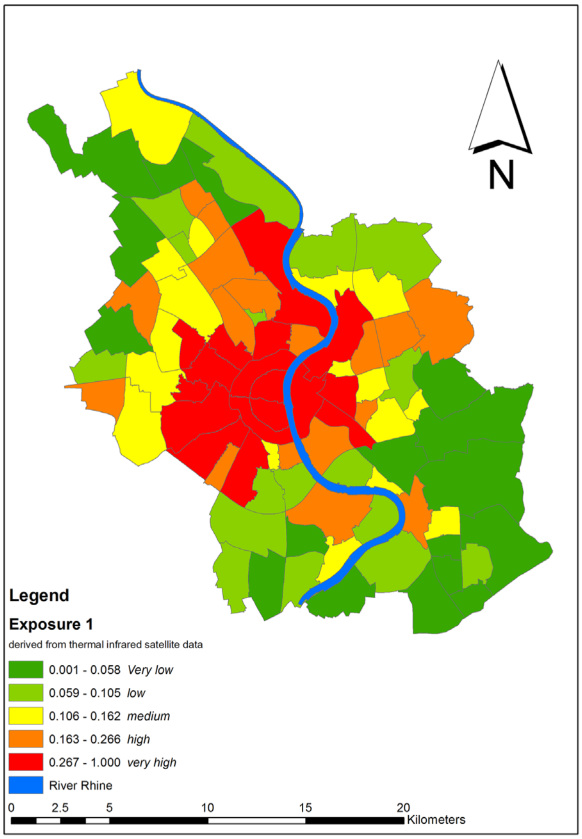

Fig. 10. Exposure of the Cologne population to heat waves based on surface temperatures distribution (E_1).

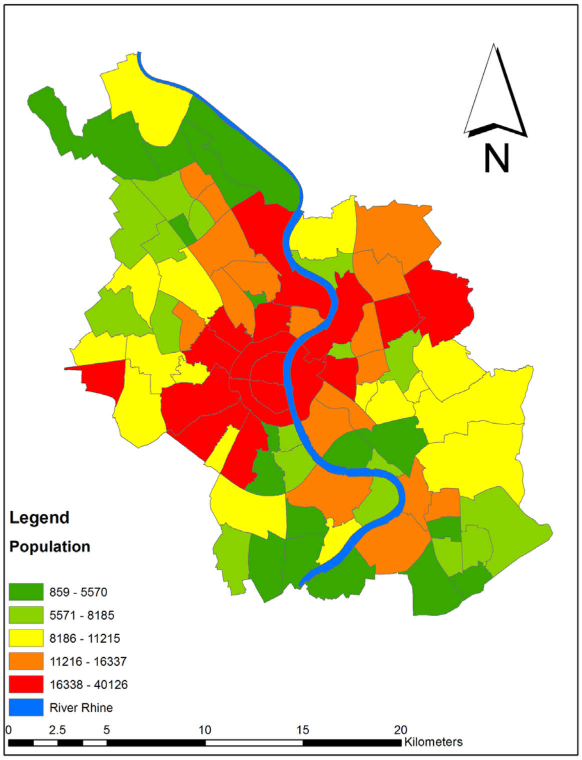

Fig. 9. Population per city district.

through the thermal scans compared with the land cover classification, the opposite being true for the more peripheral districts.

The one million inhabitants of Cologne are principally distributed in the western-central districts and along the river Rhine (see Fig. 9). Multiplying separately the spatial values obtained with the two methods to calculate the UHI with the spatial distribution of the population we obtain respectively E_1 (Fig. 10) and E_2 (Fig. 11). Both show a higher degree of exposure for the districts at the city core which hosts most of the population and for which the UHI is higher. The differences between the results obtained with the two methods are also mitigated when calculating the composite indicators (Fig. 12) but still remain high for highly populated districts such as Lindental and Sülz. Some additional considerations and quantitative data are needed to derive an adequate estimation of the UHI based on the land cover types. The vicinity to and the concentration of districts with high or low sealed surfaces need, for instance, to be integrated into the calculation. Consequently, and given the reliability of the data input for the two methods, E_1 is used in the final calculation of vulnerability.

For the calculation of susceptibility, two indicators, elderly per city district and unemployed, were measured and spatially represented. The elderly are sparsely distributed in often isolated districts, all around the city centre

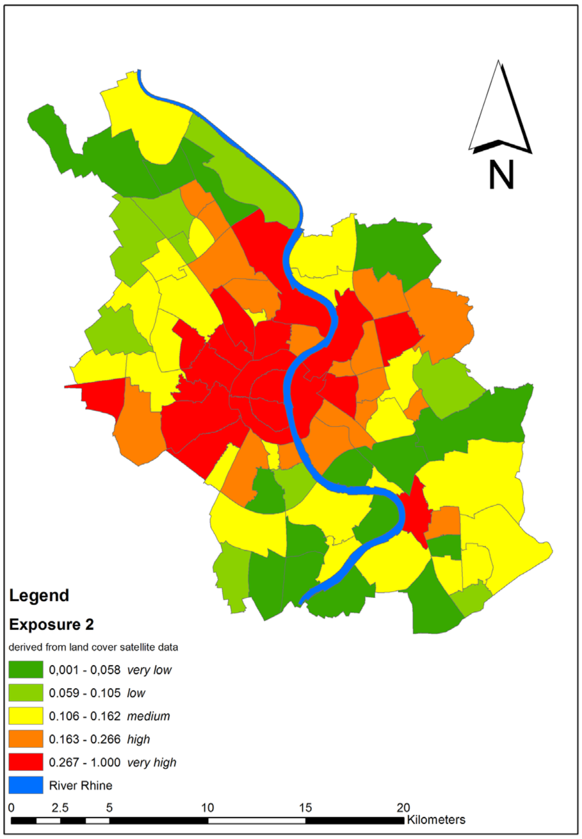

Fig. 11. Exposure of the Cologne population to heat waves based on the capacity of different land cover types to regulate microclimate (E_2).

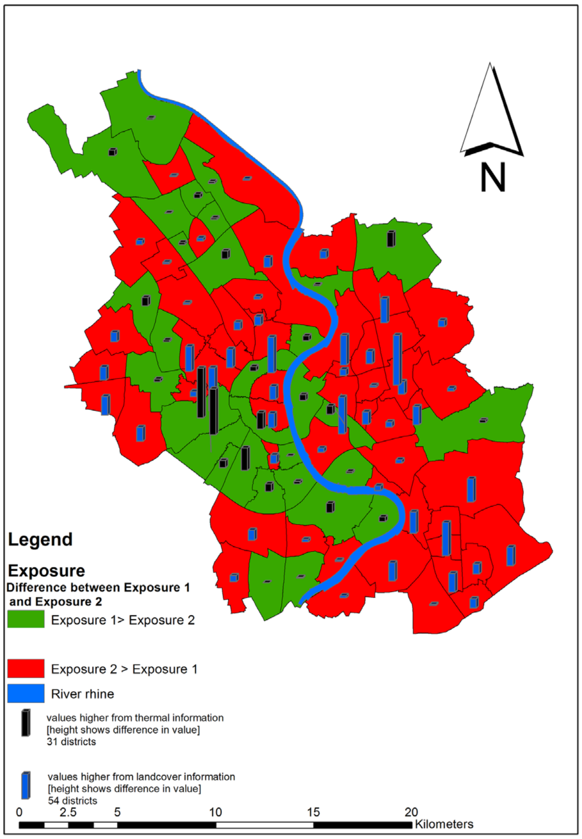

Fig. 12. Difference between the exposure based on temperature distribution (E_1) and exposure based on the capacity of different land covers to regulate microclimate (E_2).

(Fig. 13). The unemployed are mainly concentrated in two zones of the city: one towards the north-west around Ossendorf and one close to centre but on the eastern side of the river Rhine (Fig. 14), as also described in Wolf [70]. As a result of the combination of these two indicators, Cologne presents hotspots of susceptibility in districts situated all around the city centre (e.g. Zollstock and Raderthal, Bocklemünd/Mengenich and Vogelsang, Rodenkirchen, Longerich, Flittard) with a concentration of susceptible areas on the eastern side of the river Rhine, around Ostheim (Fig. 15). The most exposed central districts are thus not densely inhabited by the most susceptible groups.

For the calculation of the lack of resilience we used two indicators: elderly people living alone and green cover per city district. Elderly people living alone, who form the group with least capacity to be promptly assisted in case the hazard becomes an event, are principally distributed in the central areas of the city on the western side of the Rhine (Fig.16). High percentages of elderly people living alone are also located north to the city centre, on both sides of the river. Green cover per city district links the lack of resilience to environmental components as it gives a measure of the capacity to cope with the event by having access to nearby cooler areas. As mentioned, urban parks are in fact at least 1–2 °C cooler then surrounding built up areas [40,44], thus this might not significantly affect the thermal condition of the surrounding areas [43]. Interestingly, some of the districts with very high percentages of elderly people living alone are crossed by the outer green ring of the Cologne urban forest which provides an opportunity to benefit from cooler places and a healthier environment (Fig. 17). As a result, the lack of resilience is higher in very central districts of Cologne and with high values for some single districts such as Lövenich in the west, Porz, Ensen and Libur in the south (Fig. 18). The distribution of the Cologne forest seems to play an important role in this component.

As a result of the combination of the three composite indicators, the highest vulnerability of Cologne to heat waves affects the central districts on the western side of the river. In the assessment, exposure has a strong influence as illustrated by the sensitivity analysis below. This explains the high degrees of vulnerability which affect also the wealthy districts crossed by the external green belt. The vulnerability map is presented in Fig. 19.

3.2. Validation of the results using a sensitivity analysis

A sensitivity analysis was performed with "IBM SPSS Statistics" (IBM, New York) in order to assess the impact of each indicator on the model output. This analysis examines the sources of variation in a model and can therefore be used to determine input variables largely

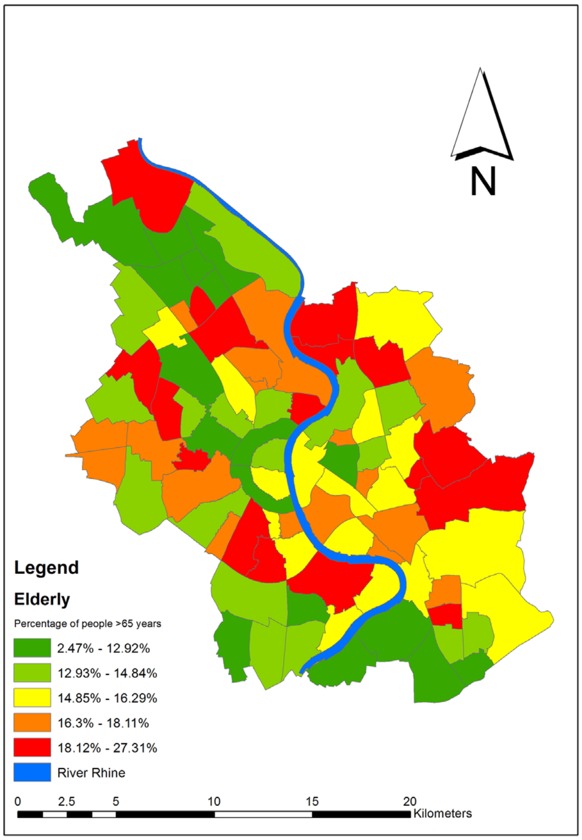

Fig. 13. Percentage of elderly (older than 65 years) per city district.

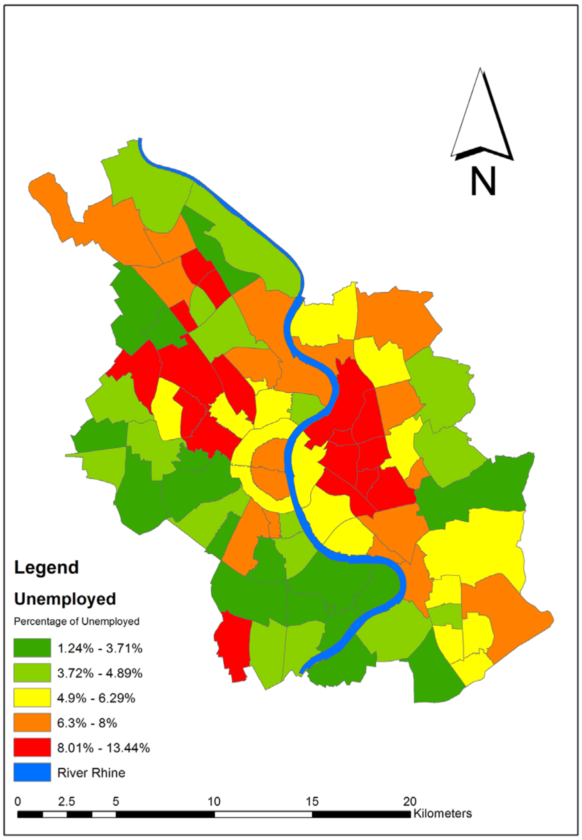

Fig. 14. Percentage of unemployed per city district.

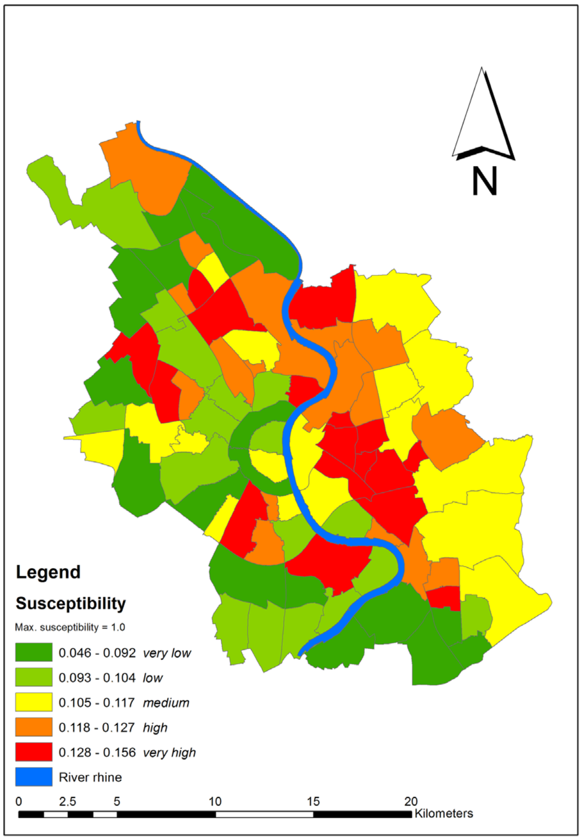

Fig. 15. Susceptibility of the population of Cologne to heat waves.

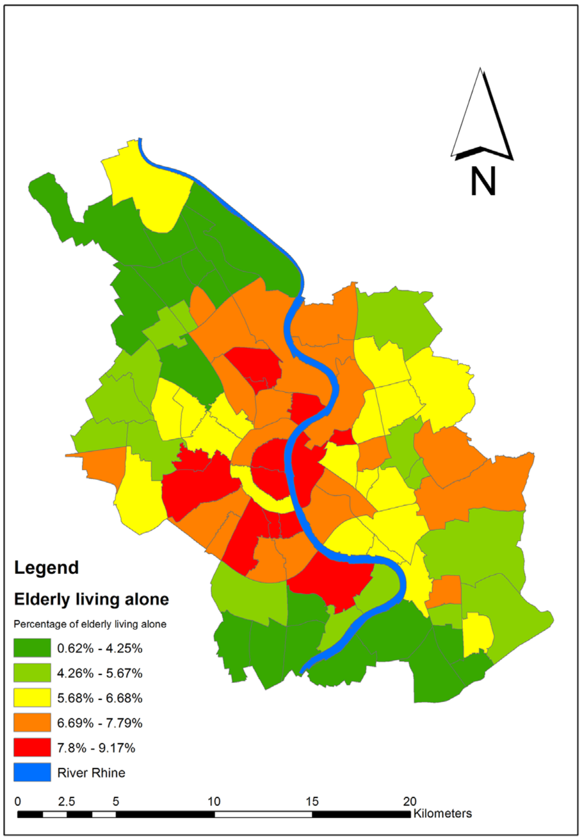

Fig. 16. Percentage of elderly living alone per city district.

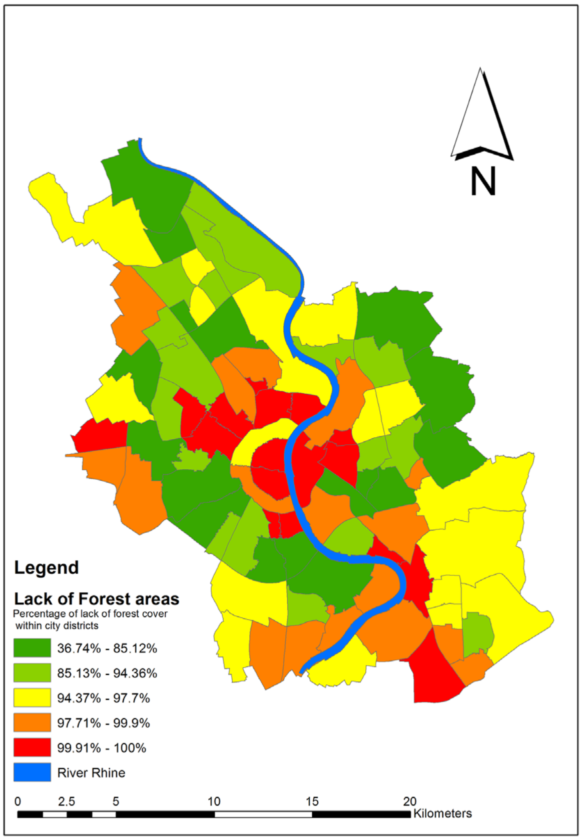

Fig. 17. Percentage of forest cover per city district.

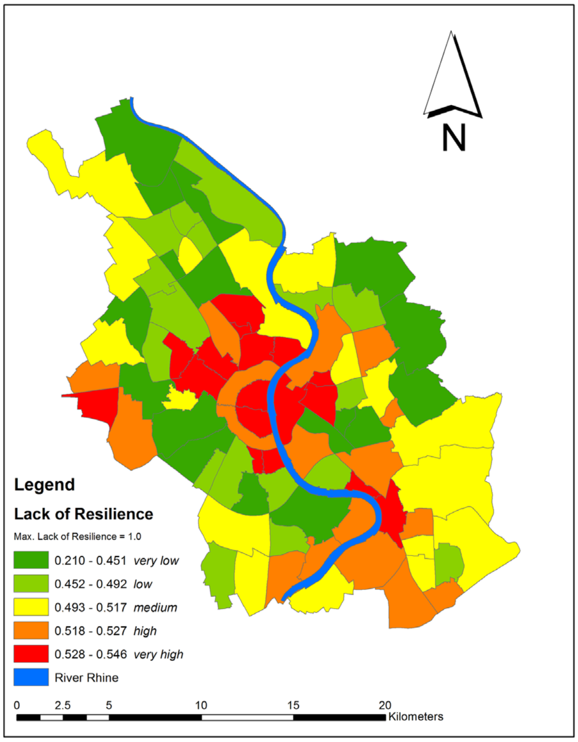

Fig. 18. Spatial distribution of the lack of resilience of the population of Cologne to heat waves per city district.

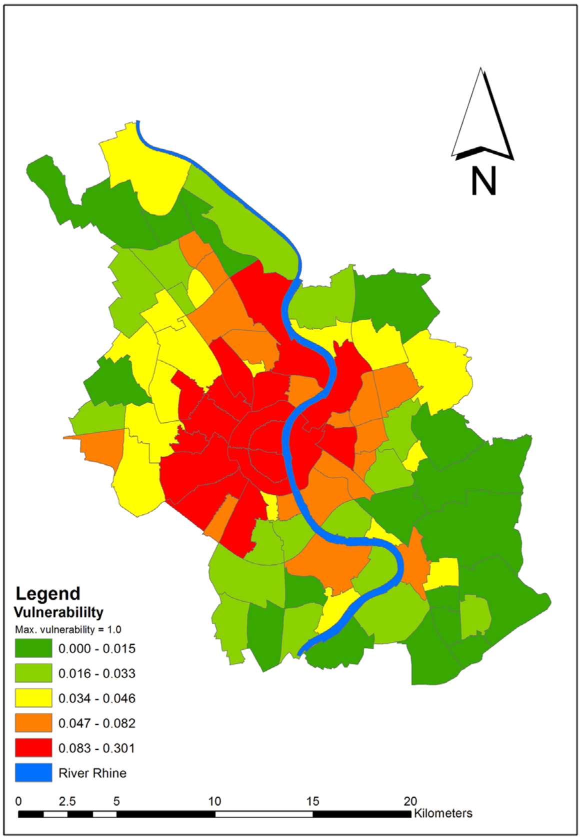

Fig. 19. Map of the vulnerability of the population of Cologne to heat waves.

contributing to the variation and those with low influence on the outputs [73]. The results of the analysis are shown in Fig. 20. The figure consists of three parts (a, b and c). Fig. 20(a) shows the effect of each indicator as a curve. On the x-axis is the original input data for each indicator scaled between -0.5 and $+0.5$, and the y-axis shows the variance of these indicators scaled between 0 and 1 in terms of overall response on the final index of vulnerability. The stronger the influence, the steeper is the curve. Fig. 20(b) shows a boxplot with the different indicators on the x-axis and the sensitivity on the y-axis. On the x-axis, the indicator names are in the same order as they are ranked in Fig. 20(a). The size of the box explains the degree of dispersion of the value of each indicator in influencing the index. The smaller the box, the more distinct is the influence on the index. The bold line in each box describes the median, whereas high values on the y-axis explain the strength of the influence of each indicator to the overall index. Fig. 20(c) shows the influence and interaction of each indicator with the other in the case of changes of one indicator. This could lead to the following effects e.g. the total sensitivity index of one indicator would be $y=0$ meaning that this indicator has no influence on the model output and thus could be neglected whereas a high median represents a non-substitutable and meaningful indicator.

Overall Fig. 20 shows that the exposure has the highest impact on the model output, followed by the percentage of

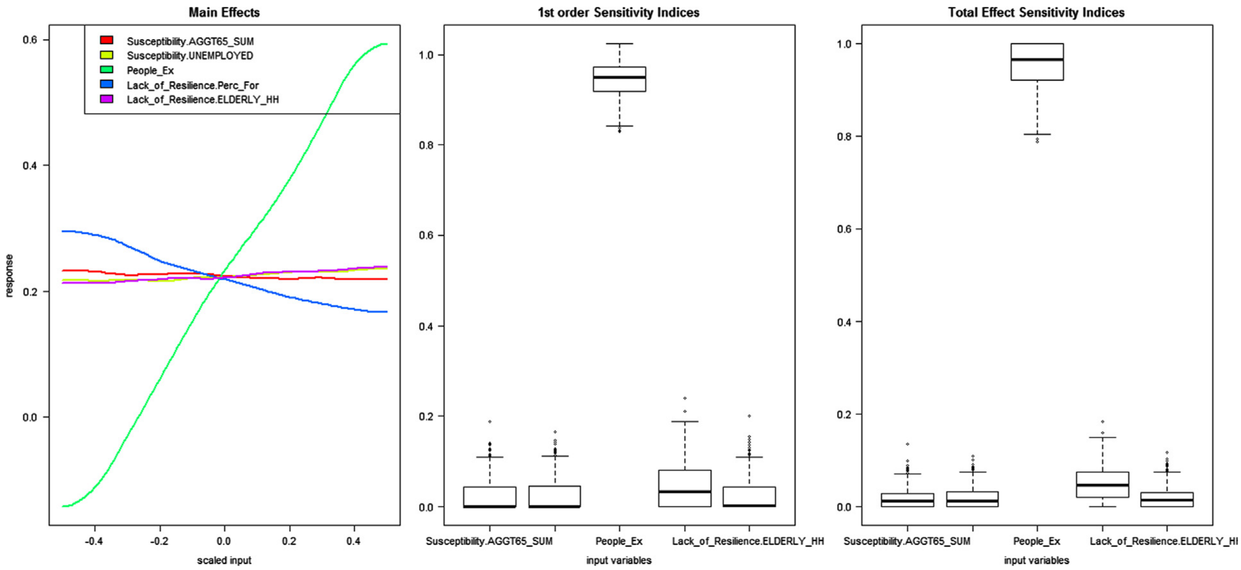

Fig. 20. (a), (b) and (c) Sensitivity analysis.

forest cover as a measure of the coping capacity of the population.

3.3. Experts' interviews

The results of the stakeholders' interviews are summarized in Tables 3 and 4. The first table presents the gathered opinions on the role urban and peri-urban ecosystems may have in mitigating the impacts of heat waves in Cologne. Most of the respondents agreed on the need to conserve and have well managed green and blue areas in the city as these can contribute to mitigating the impacts of extreme heat. In particular, this is due to the cooling functions performed by the urban vegetation of Cologne. A mix of indigenous species, resistant to droughts but also presenting adequate levels of evapotranspiration is thought to be suitable for this purpose. A smaller emphasis was put on the effectiveness of green areas to remove pollutants and thus reduce the impact on health of extreme heat. To mitigate this impact a reduction in emissions is primarily necessary. It is recommended that the full range of services provided by urban ecosystems is taken into account in planning and management. Decisions on the allocation of green areas and street trees should not be based only on their aesthetic value. An additional expectation and suggestion made was to have ecosystems as much connected as possible through the urban fabric to form corridors that would bring fresh air into the city centre from the surrounding cooler areas. In this way, obstacles encountered in the process of reconversion of built-up areas into green and blue spaces can be partially overcome.

The second table, Table 4, presents the perceptions and previous experience of stakeholders regarding the impacts of heat waves on urban/peri-urban ecosystems and their services in and around Cologne which would indirectly further increase the vulnerability of the city. Negative impacts of heat waves would mainly hit agricultural land and gardening, diminishing their productivity. In this regard, strategies to adapt to increasing warm conditions (such as the selection of more resistant crops) are already being taken by farmers. Recreational activities can also be affected by the hazard due to the deterioration of small water bodies and of the vegetation in urban parks and forests distributed in the surrounding areas. The risk of forest fire should be monitored, especially in periods of extreme heat. Local mixed forests have shown to be the most appropriate to cope with these impacts. All respondents agreed that the provision of drinking water is not affected at present by the impacts of extreme heat, thanks to the high quantity of groundwater available in the region.

4. Discussion and conclusions

The assessment of the vulnerability of Cologne to heat waves presented in this paper is based on the MOVE project generic framework and integrates both quantitative and qualitative data as well as the social and ecological dimensions of vulnerability. This allowed consideration of a broader set of drivers and elements that come into play in determining morbidity and mortality from heat waves in the urban environment. In fact, though the vulnerability of Cologne to heat waves is expected to be low compared to that of other municipalities in NRW due to the relatively low percentage of elderly population [74], it represents a relevant case to investigate the role of the extended set of variables that shape urban vulnerability to heat waves, particularly the environmental ones.

From the spatial quantitative analysis, vulnerability was higher overall in the central and western districts where most of the population resides and where the percentage of sealed surfaces is high and contributes to the UHI. This is further accentuated by the fact that most of the elderly people living alone live in these central districts. On the other hand, the measurement and representation of each

Table 3
Stakeholders perceptions on the capacity of the Cologne ecosystem to regulate climate and air quality and thus mitigate the impacts of heat waves.

Ecosystem	Negative opinion	Positive opinion	What cannot/should not be done	What could/should be done
Green areas		Important for their cooling capacity, especially for the high evapotranspiration rates of plants. Broad woodlands are the most effective in this sense.	To broaden urban green areas is thought to be unrealistic as it would imply the reconversion of buildings and streets over large areas and would be in contrast with the spreading concept of compact city.	Appropriate management of existing green spaces and increase of the number of trees along streets.
				Green roofing. To date there are no shared guidelines, only ad-hoc projects. The cooling function of peri-urban grasslands and agricultural areas should also be taken into account Opening wind corridors (both green corridors and large streets) to build connections between green areas. This would bring cooler air into the city centre from the surrounding woodand agricultural lands.
			It is often problematic to reserve space for street trees as these compete for space mainly with parking for cars.	Street tress should be considered in urban planning for their cooling function in addition to their aesthetic value. This is valid also for parks and urban forests.
			While planting Mediterranean species has become a trend in the last years because they consume less water, these also evapotranspirate less reducing their cooling functions.	Selected species should be able to cope with 2–3 °C increase in temperature. Indigenous beech forests and oak trees are considered to be the appropriate species to cope with the condition of projected climates.
	Visits to parks are generally not considered as a relevant coping strategy in periods of heat waves.			Parks should however be well distributed amongst the city to allow easy access of the most vulnerable (i.e. elderly, poor, ill).
	Green areas have minor positive effects on the reduction of air pollutants. Urban parks and street trees are thought to be the less effective in delivering this service and can themselves be affected by high concentrations of air contaminants in inner parts of the city.	Urban and peri-urban forests are the most effective in purifying the air.	Trees positioned along streets with narrow spacing can form a dense canopy that traps pollutants paradoxically worsening air quality.	A reduction of air pollutants at the source is needed. Zones at the centre of the city restricted to traffic should be delineated.
Blue areas	The cooling effect of water bodies is noticeable on a seasonal rather than on a daily basis. This constrains their effect in mitigating the impacts of heat waves in urban areas.		Most of urban water bodies have been buried under streets and their conversion is complicated.	Small water bodies should be restored throughout the city. Fountains should also be reactivated through the city.

Table 4
Stakeholders' perceptions on the potential impacts of heat waves on the urban ecosystem and its services to the inhabitants of Cologne.

Ecosystem/system	Direct impacts	Indirect impacts	Potential/undertaken actions	Notes
Surrounding agricultural land/gardening	Negative impacts on crops growth and gardening.	Decrease in local agricultural productivity.	Farmers are already aware of these impacts and are starting to select and grow alternative, more resistant crops.	Dry periods occurring in spring times preceding a heat wave are the main responsible for the reduction in productivity rather than the heat waves itself. It can become an even more important issue in the future due to climate warming.
Sources of drinking water	Generally not relevant. In some cases, when the water table is low, the flow of water can change and get exposed to chemical compounds.			It is mainly due to the high rate of infiltration in the region which allows the city to rely on sufficient groundwater resources. In future climates drinking water might also be affected due to an increase in surface runoff which leads to the decrease in groundwater recharge.
Small water bodies	The quality can be deteriorated due to eutrophication and consequent decrease in the concentration of oxygen. Some smaller ponds may even dry-up.	On recreational activities around the city.		
Water treatment plants	Not relevant.		In case of low levels of the river Rhine due to dry spells the concentration of effluents should be kept under control.	
Power plants	Not relevant. These are not much present along the river Rhine so there is no risk of increase in temperature of the cooling water.			
Vegetation	Negative. These have also occurred in the past: trees lose their leaves, photosynthesis is reduced which leads to a reduction in the production of oxygen. Grasslands are the most affected while mixed forest and indigenous vegetation have shown to be the most resistant to droughts. There might also be a risk of forest fires, especially in the future with the increase of heat extremes.	On recreational activities in and around the city.	A good mixture of native plants, avoiding monoculture or grassland, increases the resilience of the forest system to fires and should be preferred.	The risk of forest fires also depends on the type of trees. Beech, oak, ash and lime trees are thought to be quite resistant while coniferous forests are considered to be more at risk.

single indicator allowed highlighting a different geography in which the most susceptible groups are sparsely distributed towards the periphery of Cologne and on the eastern side of the Rhine. The urban forest also plays a relevant role in our assessment. Distributed along circular green belts, it contributes to reducing the vulnerability of susceptible groups (mainly the elderly people) in some of the more peripheral areas.

These results are directly linked to the historical dimension of the vulnerability of Cologne. Its present distribution clearly appears to be the result of processes that occurred through the centuries but that culminated in the last century when planning decisions more strongly influenced the assessed patterns of vulnerability. Two of these urban developments should be underscored: the allocation of space for the greenbelts in and around the city at the beginning of the century, along which the wealthiest segments of the population are located; and the intense sub-urbanization which took place during the reconstruction period following World War II and associated with the baby boom of the 60s. In these latter parts of the city, low income, more susceptible groups are still concentrated (see Section 2.1).

The results of the quantitative assessment, suggest that, to effectively tackle the vulnerability of Cologne to heat waves, local city authorities in charge of urban planning, environmental management and health should collaborate to implement strategies which improve the social–environmental conditions of the city centre due to the higher levels of exposure and lack of resilience, but also need to consider the fate of susceptible groups which are located in its surrounding areas. The development of social services should be prioritized to cope with heat waves in Cologne, but, as shown in the sensitivity analysis, the environmental factors have a strong influence on the assessment and are integrated in exposure (i.e. the UHI) and in the lack of resilience (i.e. the distribution of the forest cover) in our analysis. This result indicates that the ecological dimension is an important factor and needs to be taken into account in tackling vulnerability to hydro-meteorological hazards.

The qualitative assessment provided additional and complementary information to the quantitative analysis especially regarding the links between ecosystem services from the surrounding areas and the vulnerability of Cologne to heat waves. It stressed how in Cologne it is necessary to acknowledge the cooling functions of urban trees and green areas in urban planning as well as those of grasslands and peri-urban agricultural land, and draw better links between the city core and its surrounding areas, as it is also suggested for Stuttgart [75] or Freiburg [76]. This consideration supports the more sustainable model of the compact city [77]. Well designed green corridors could improve microclimate in the inner parts of the city bringing fresh air from the outskirts and bettering the living condition of the high density city centre. Furthermore, even if the urban forest of Cologne covers a relatively high area compared to other German cities, the type of species planted should also be carefully thought through, preferring, a mix of indigenous species, according to our respondents. In this regard, a debate is ongoing as to whether climate change might favour invasive species, thus caution needs to be taken when selecting species for adequate green areas management.

Furthermore, the qualitative data gathered provided insights into additional sources of vulnerability that could originate by the failure of certain ecosystems to provide services to the urban population. It emerged that most of the impacts of extreme heat affect peri-urban ecosystems such as forests and small water bodies while compromising agricultural production and gardening. The benefits derived from recreational activities in these periods can thus be hindered, especially around the city, while water supply seems not to be at risk. This adds to the quantitative assessment and further prompts consideration of the wider urban/rural interface dynamics, moving the focus partly outside the urban core.

Within the set of actions taken from the local government to adapt to climate change, plans and strategies are developed in collaboration with the regional or federal authorities and awareness is rising in Cologne with respect to the impact of weather-related hazards such as heat waves.[4] At the Federal level, guiding documents are prepared by the Ministry in charge of the environment and nature conservation which set the strategic framework for cities situated in the region to plan and adapt to climate change, including to the increase of heat related stress.[5] A broad list of measures is here suggested but some seem to be specifically relevant for the Cologne urban area. According to our research, a reduction of the exposure, especially through green infrastructure and an increase of the connectedness between the city and its green and surrounding areas, are urgent measures to be implemented. This overall calls for a broader collaboration between sectors in charge of health, environment as well of urban green and urban planning at the city level. This field based study therefore demonstrates the context specificity of the choice of strategies to cope or adapt to increasing frequency and impacts of heat waves and that resources should be allocated at the local level to conduct such studies to select and prioritize strategies.

Additional guidance and frameworks come from the European level. Several projects, such as the EuroHEAT project, contributed to the implementation of the EC Environment and Health Action Plan. The final report of this project concluded that, although coordination between institutions for timely and appropriate response actions and early warning systems should be priority actions of the health plan to mitigate vulnerability to heat waves, the reduction of exposure through improved urban planning should also be prioritized [78].

In summary, our analysis showed that, while the higher vulnerability of the population of Cologne to heat waves is concentrated in the city centre, policies that aim to tackling it should also take into account the connections and interactions between the city centre, the surrounding districts and its hinterland, reducing the susceptibility of

[4] ⟨http://www.stadt-koeln.de/3/umwelt/klima/klimawandel/07145/⟩.

[5] ⟨http://www.umwelt.nrw.de/klima/klimawandel/anpassungspolitik/anpassungsstrategie/index.php⟩.

lower status social groups and enhancing ecosystem management.

Acknowledgements

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