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New methods for local vulnerability scenarios to heat stress to inform urban planning—case study City of Ludwigsburg/Germany

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Abstract
Adaptation strategies to climate change need information about present and future climatic conditions. However, next to scenarios about the future climate, scenarios about future vulnerability are essential, since also changing societal conditions fundamentally determine adaptation needs. At the international and national level, first initiatives for developing vulnerability scenarios and so-called shared socioeconomic pathways (SSPs) have been undertaken. Most of these scenarios, however, do not provide sufficient information for local scenarios and local climate risk management. There is an urgent need to develop scenarios for vulnerability at the local scale in order to complement climate change scenarios. Heat stress is seen as a key challenge in cities in the context of climate change and further urban growth. Based on the research project ZURES (ZURES 2020 website), the paper presents a new method for human vulnerability scenarios to heat stress at the very local scale for growing medium-sized cities. In contrast to global models that outline future scenarios mostly with a country-level resolution, we show a new method on how to develop spatially specific scenario information for different districts within cities, starting from the planned urban development and expansion. The method provides a new opportunity to explore how different urban development strategies and housing policies influence future human exposure and vulnerability. Opportunities and constraints of the approach are revealed. Finally, we discuss how these scenarios can inform future urban development and risk management strategies and how these could complement more global or national approaches.

Keywords Vulnerability scenarios · Adaptation to climate change · Heat stress · Urban areas

1 Introduction

Adaptation strategies towards climate change and heat stress oftentimes focus on present and future climatic conditions, without considering sufficiently human vulnerability and changing future socio-economic or demographic conditions. Vulnerability is understood, in the climate

This article is part of a topical collection on Risk & Vulnerability to Extreme Events: Dynamics and Future Scenarios change community, as "the propensity or predisposition to be adversely affected." (IPCC 2014: 1775; 2012: 560). In addition, UNDRR (2016) defines vulnerability as "conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards." That means vulnerability encompasses different dimensions (physical, social, economic, etc.) and causal factors (susceptibility, capacities to cope, etc.) that shape the ability of a society or system to deal with climate change and extreme events and to recover from such impacts (see Wisner et al. 2004; Birkmann 2006; Birkmann et al. 2013). Scenarios for vulnerability should ideally consider these multi-dimensional phenomena. However, at the same time scenario data is often limited and therefore has to be based on selected indicators that capture selected characteristics and aspects of the broader phenomena of vulnerability.

Adaptation needs and options are not only determined by changing climatic conditions (e.g. heat stress in 2030, 2050, 2100) but also significantly influenced by future exposure and human vulnerability (Birkmann et al. 2015; Garschagen and Kraas 2010). Enhancing methods and approaches to develop scenarios for human vulnerability at the local level is therefore key. This requires, among other issues, the identification of relevant data and a parallel modelling approach (Greiving et al. 2017). Against this background, the paper examines the following questions:

- What are scenarios of human vulnerability to climate change?
- Why do local vulnerability scenarios have to differ from downscaled global scenarios to inform urban planning and local risk management?
- How to develop human vulnerability scenarios for the very local scale for medium-sized cities?
- Which data is available for measuring future human vulnerability?
- What is the additional value of combining local climate (heat stress) scenarios with human vulnerability?
- How can such scenarios inform decision making in the case study city, but also in growing medium-sized cities in other countries?

The first part of the paper deals with core characteristics and fundaments of vulnerability scenarios focusing on local versus global approaches and specific challenges for local scenarios of vulnerability linked to questions of urban planning. Based on this discussion, we introduce the importance of medium-sized cities and the case study of Ludwigsburg as a representative case for a growing medium-sized city in Germany and Europe. In addition, we discuss specific local indicators to assess human vulnerability at the very local scale to heat stress considering the discussion within the scientific literature and specific results of a household survey conducted within the City of Ludwigsburg. Thereafter, we outline our own methodology to assess human vulnerability at ward and city-district scale focusing on selected indicators and the urban growth potential of the city. The results section shows selected vulnerability scenarios also combined with local heat stress scenarios with reference points to the RCP 2.6 and 8.5 (regarding RCP's see van Vuuren et al. 2011). Finally, conclusions outline how such local approaches linked to urban planning issues can complement global or national scenarios and allow informing local decision-makers. The paper is based on a research project called ZURES (future-oriented vulnerability and risk assessment as a tool to support urban resilience; see ZURES-website 2020) funded by the Federal Ministry of Education and Research (BMBF), focusing on the City of Ludwigsburg which is a representative growing medium-sized city in Germany.

2 State of the art: approaches and gaps in current research

2.1 Vulnerability scenarios

Vulnerability scenarios are methods and ways to characterize hypothetical states of vulnerability of a system in the future using selected quantitative indicators or qualitative approaches (van Ruijven et al. 2013; Birkmann et al. 2015, 2019). In this regard, vulnerability is a multi-dimensional and multi-faceted phenomenon (Birkmann et al. 2013); however, vulnerability scenarios often have to simplify the reality, since only few and selected indicators or criteria are going to be used to describe a hypothetical state or process in the future. A vulnerability scenario in climate change and risk research characterizes a hypothetical state of an exposed and potentially vulnerable human system (society, community), social-ecological system (e.g. farming system) or physical system (building, infrastructure) in the future. That means scenarios are a mechanism for describing future trends and/or conditions for a specific point in time, despite some degree of irreducible uncertainty with respect to the future (see e.g. Kok et al. 2011, 2015). Scenarios allow us to illustrate and discuss various potential directions that development processes might take, drawing attention to the consequences for decision making and management strategies (see e.g. Glenn and the futures group international 2009; van Vuuren et al. 2012a, b). Scenarios developed for the IPCC encompass the former emissions scenarios (SRES) as well as the recent scenarios that aim to also inform adaptation policies, such as the shared socioeconomic pathways (SSPs). Scenarios have been developed particularly to illustrate different futures for decision-makers and to show different potential development pathways and therewith to underscore what might be possible and impossible development directions (see Glenn and the futures group international 2009; van Vuuren et al. 2012b; Hallegatte et al. 2011). Scenarios often encompass an analytic and a normative dimension. The analytic dimension explores how future development could look like, while the normative element of scenarios also aims to explore how the future should look like (Börjeson et al. 2006).

Present scenarios used in risk management and adaptation can be systematized in terms of their underlying concept, characteristics, focus and context (see UBA 2019; O'Neill et al. 2014, 2017; Kok et al. 2015, 2019). In contrast to quantitative climate change scenarios, such as the SRES and RCPs (representative concentration pathways) (IPCC 2014), scenarios that inform vulnerability and adaptation planning can encompass both tangible and intangible aspects due to the multi-faceted nature of social or physical vulnerability (see Birkmann et al. 2013, 2017; Garschagen and Kraas 2010). Tangible aspects of vulnerability include e.g. parameters such as the percentage of people living in extreme poverty, income distribution, or the percentage of elderly—used as proxies for assessing population groups susceptible to climatic hazards. Also, the access to infrastructure and social vulnerabilities towards disaster-related infrastructure failures (Garschagen and Sandholz 2018) are indicators used in present assessments. In contrast, intangible aspects of vulnerability are linked to aspects of governance (e.g. issues of corruption) or the strength of social networks, which can only be quantified in part and indirectly. In general semi-quantitative and qualitative vulnerability scenarios allow capturing intangible aspects more comprehensively compared to quantitative approaches.

2.2 Local versus downscaled global scenarios

While the shared socioeconomic pathways (SSPs) focus primarily at larger scales of nations or global developments (O'Neill et al. 2017), the construction of human vulnerability scenarios at the local level requires additional information about specific configurations of future states of human vulnerability at the city-district or neighbourhood scale. Broader trends such as urbanization, population growth or ageing at international or national scale cannot simply be downscaled to the local scale due to the large variations at the local level. A single value for a city downscaled from a global or national approach would be too broad to be able to characterize differential developments within the city. For example, global approaches, such as the shared socioeconomic pathways, encompass scenarios that assume high population growth, economic growth, and intensive fossil-fuel use (O'Neill et al. 2017). While economic growth could be downscaled for one city (but not usefully for different city districts), downscaling population growth from these models to individual wards or districts in a medium-sized city is in many cases not appropriate, since locally specific conditions influence these growth patterns significantly. Consequently, local vulnerability scenarios require methods that account for specific local trends and patterns that influence future exposure and vulnerability. For example, for growing medium-sized cities, such as Ludwigsburg, it is the (limited) available space for urban expansion and housing that significantly determines the overall population growth and its distribution within different districts. Hence, a pure extrapolation of existing structural differences between city districts without considering potential changes due to future urban development is not useful.

2.3 Local projections and existing data gaps

For various cities in Germany and Europe—but also in North America—projections and scenarios in terms of the future population exist at city scale and with regard to different time scales (see e.g. Landeshauptstadt München 2017; Bertelsmann Stiftung 2019). Information about future population is often a pre-requisite for urban planning.

In the state of Baden Wuerttemberg, where this paper's case study city Ludwigsburg is located, the official Statistical Office (StaLaBW) provides different population scenarios for cities in order to illustrate different development corridors (see e.g. Waldherr 2016). In this regard, three population scenarios exist from StaLaBW for the City of Ludwigsburg (source StaLaBW 2015) (see Fig. 1). While the "low growth" scenario assumes a rather low population increase in the city of about 3% between 2015 and 2030, the "high growth" scenario assumes a population increase by more than 21% over the same period (see Hochstetter and Brachat-Schwarz 2016; Brachat-Schwarz 2016). In terms of the planning of new housing space, these scenarios imply very different necessities for urban extension and densification. The scenarios contain different assumptions about sub-national and international migration and changes in life expectancy of male and female population.

The StaLaBW also provides information on the ageing trend within the society. However, the data is solely provided for the entire city. According to StaLaBW, the percentage of elderly—i.e. people over 60 years of age—will increase from about 24.5% in 2020 to 28.1% in 2030 and 29.4% in 2035 (StaLaBW 2015). That means, even though the city is growing in the future, ageing is a significant overall trend with a growth rate of about 22.7% between 2020 and 2035. The percentage of elderly with about 28% in 2030 according to StaLaBW is higher compared to the shared socioeconomic pathway no. 4 and no. 3 for example which include ageing and assume that in 2030 about 25–27% of the population will be 65 years and older (Wittgenstein Centre 2020). This difference might also be linked to the fact that the category of StaLaBW deviates about 5 years from the classification used in our analysis (> 60 years). Consequently, it is fair to assume that ageing is an important overall trend and that this trend is also affecting human

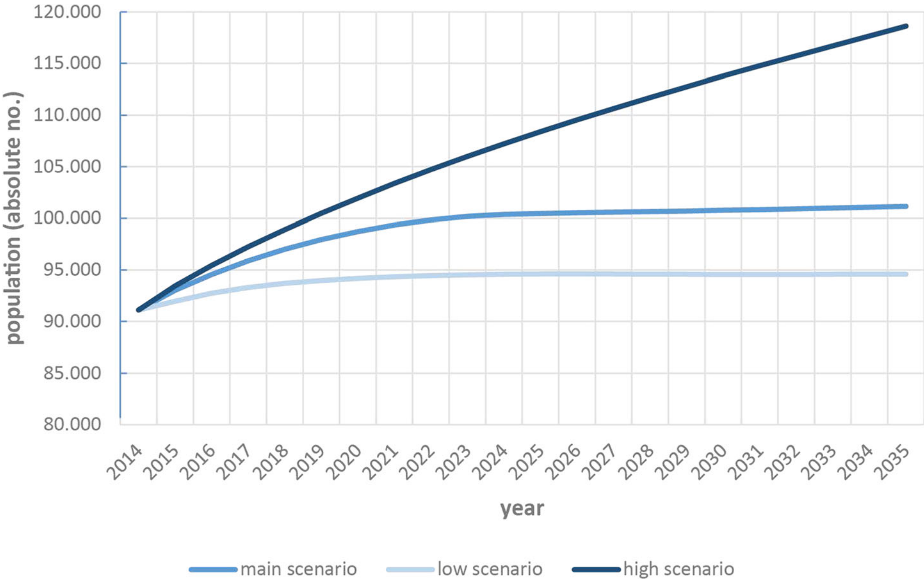

Fig. 1 Population scenarios for Ludwigsburg 2014–2035 (own figure based on data of StaLaBW 2015)

vulnerability to heat stress. However, neither the SSPs nor the StaLaBW data do provide sufficient information on how this trend might materialize in different parts of the city.

Restrictions in terms of the non-availability of land for new housing areas in cities are not considered even though the land availability is a major restriction for population growth in growing medium-sized cities especially in the region of Stuttgart (City of Stuttgart 2019), but also in other regions in Germany. Only very few or no data exist in terms of projections or scenarios for the future development of poverty, employment, and migration at the very local scale. Even though these issues are of high importance for local authorities and urban planning, most cities hence do not have forecasts or scenarios regarding these themes.

2.4 Drivers and indicators of vulnerability to heat stress at the local scale

In the scientific literature (see Johnson et al. 2009; Laverdière et al. 2015; Reid et al. 2009; Sandholz et al. 2018), high age, chronic disease prevalence, poverty, and other socio-economic factors are discussed as key indicators for human vulnerability to heat stress. These findings are confirmed by previous research, including an extended stakeholder workshop and participatory scenario workshop, also for the case study city Ludwigsburg (Garschagen et al. 2018). Furthermore, a previous household survey conducted in that city also confirmed that the elderly and people with chronic diseases are particularly vulnerable and face severe problems during a heat wave or thereafter (Laranjeira et al. 2021). The survey revealed a positive and significant correlation between age and cardiovascular health issues, thus showing that elderly (people aged 65 years and older) experience more cardiovascular problems during heat stress compared to younger respondents (Laranjeira et al. 2021). In addition, elderly people also have lower coping and adaptive capacities; for example, the household survey found that elderly have a stronger tendency to stay in their present living location and do not consider the option of relocation into a cooler neighbourhood in the future (ibid.). Furthermore, persons without an own garden often live in multi-family houses and therefore depend on the provision of green space by the city.

The household survey revealed that households belonging to the lower income group have a significantly higher percentage of household members with pre-existing health problems compared to persons that belong to the middle- and high-income groups (Laranjeira et al. 2021). About 19% of households within the low-income group (up to 2000 Euros per month) stated that at least one person in the household is considered to be sick or in need of medical care. The same category accounts for only 9% in the middle-income group and for 2% in the high-income group (6000 Euros and more) (ibid.). Hence, it can be concluded that income plays an important role in terms of the level of susceptibility and coping capacities of different people exposed to heat stress.

Since income data at a high spatial resolution is very scarce, assessments in the German context, such as ours presented here, oftentimes refer to the recipients of social welfare support. Even though the number of people that receive social welfare support is not equal to the number of poor people, the indicator social-welfare recipients is an option for us to integrate socio-economic disadvantaged households in our local assessment and scenario development. Payments of social-welfare are processed at the local level and thus data is available at the very local scale.

In many cases, present national scenarios—in the German context and elsewhere—only focus on GDP per capita or national poverty trends, without providing sufficient information for the local scale. Downscaled data from global SSP-scenarios exist for population development at GRID-cell level for urban areas worldwide (see Jones and O'Neil 2016); however, these scenarios are based on global modelling approaches that do not account sufficiently for the local specific context conditions and trends within growing medium-sized cities. Therefore, information on how poverty and ageing developed in the past and might develop under different scenarios in the future has to be based on existing local statistics for assessing present conditions and on methods that allow for a locally specific scenario development for the future situation.

3 Case study: medium-sized cities and the City of Ludwigsburg

Compared to megacities, research has not given sufficient attention to growing medium-sized cities in the context of climate risk management. However, growing medium-sized cities are critical. Medium-sized cities need special attention, since adaptation to climate change and heat stress in particular can be integrated into the ongoing development process. They often have to deal with both: the necessity to adapt to increasing heat thus preserving open green spaces for cooling and, and at the same time, to provide new space and land for housing due to population and economic growth. The City of Ludwigsburg—with about 93,000 inhabitants and more than 50,000 jobs—is an appropriate representative case for a growing medium-sized city in Germany and Europe. The city is part of the larger urban metropolitan area of the region of Stuttgart with about 2.8 million inhabitants (VRS 2019). The region is economically booming with world-leading companies, such as Bosch, Porsche, and Daimler. At the same time the region of Stuttgart and the City of Ludwigsburg face a high—above German average—exposure to heat stress in summer (VRS 2008). In the future, the entire urban region of Stuttgart, including Ludwigsburg, is very likely to experience more intense heat stress and especially in city centre's the urban heat island effects will further aggravate this situation.

Consequently, the protection of open green space (support of cold air streams) is an important goal for urban and spatial development. At the same time the city and the region are characterized by an ever-increasing population and a severe lack of affordable housing (see e.g. City of Stuttgart 2019). This leads to tensions between the general goal of preserving open green space and the need for future urban growth (Garschagen et al. 2018). Therefore, adaptation to heat stress is a particularly hot topic in growing medium-sized cities.

4 Methodology: assessing future human vulnerability to heat stress at the local scale

Since the StaLaBW scenarios for the City of Ludwigsburg do not offer information on the inner-city distribution of the future population, we had to gather additional data and develop new methods for assessing future vulnerability for the city district (Stadtteile) and ward (Stadtviertel) scale (see Figs. 2, 3). The method should provide information about dynamics within future urban development, rather than just extrapolating existing structural differences between city districts into the future. Consequently, we used an approach that focuses on the actual and future space for new housing areas and urban renewal as an entry point in order to estimate growth potentials and potential shifts in the socio-economic and socio-demographic composition of districts and wards. That means a core component of the local scenario method

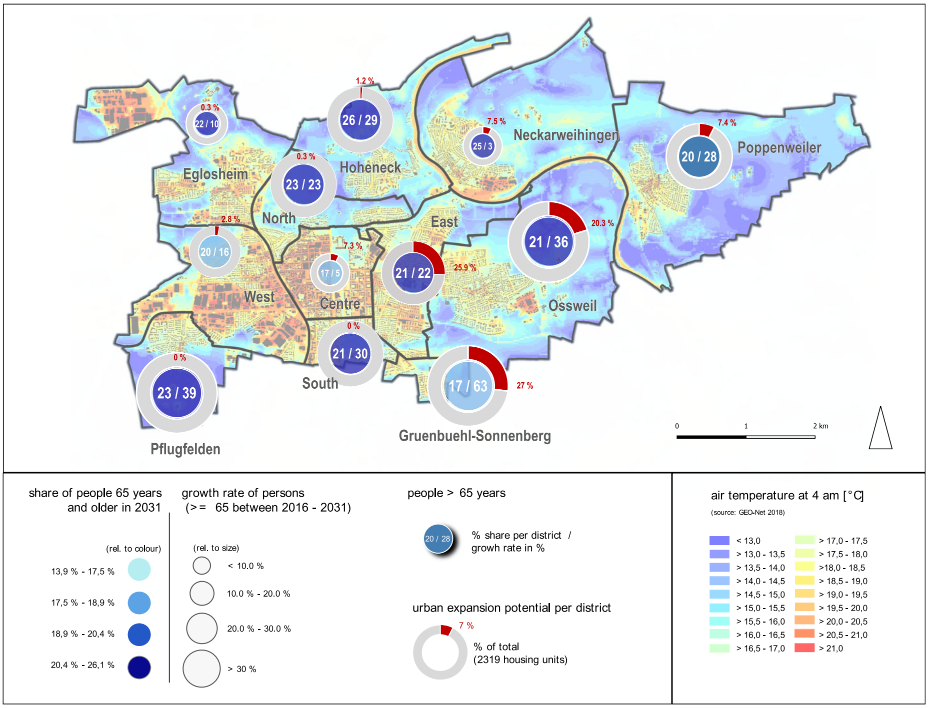

Fig. 2 Overlay—scenario of human vulnerability 2031 (proxy elderly), temperature levels at night and urban development potentials at city district scale in Ludwigsburg (own map based on data of Birkmann et al. 2019; Biregio and City of Ludwigsburg 2017 and own calculations of heat stress by GEO-Net within the project)

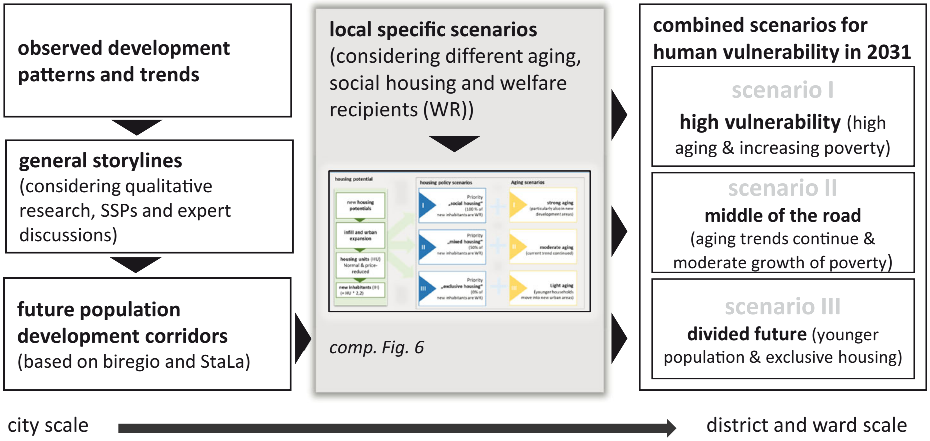

Fig. 3 Development of spatial specific vulnerability scenarios for the City of Ludwigsburg; source: own figure

is based on the analysis and calculation of land that can be made available within the next 30 years for new housing and urban renewal. With this approach, the inner-city distribution and future dynamics according to different scenarios can be examined. In addition, local specific trends were examined and used to develop specific scenarios for future increases of the elderly population and for poverty.

4.1 Data and scenario information regarding future ageing

Interestingly, the City of Ludwigsburg has developed—together with a research and consultancy firm (Biregio)—a projection of the future population in different districts of Ludwigsburg for the year 2031 including differentiating various age groups. The scenario approach of Biregio and the City of Ludwigsburg (2017) estimates an overall population growth of about 11% between 2016 and 2031 thus staying in the medium development range (main scenario) calculated by StaLaBW. Biregio and the City of Ludwigsburg (2017) provide data regarding the development of the urban population for specific city districts and for different age groups even for the year 2031. This scenario data also encompasses the number and share of elderly people (population 65 years and older) at district scale and therewith can inform vulnerability scenarios to heat stress in our case.

The exposure scenario 2031 of Biregio and the City of Ludwigsburg shows an increase of people (absolute number) particularly in the city districts Ossweil, East and Gruenbuehl-Sonnenberg, while the city centre continues to have a high population density. The highest growth rate between 2017 and 2031 is foreseen in Gruenbuehl-Sonnenberg, Oßweil and Poppenweiler and East (comp. Fig. 2). However, next to the process of ageing as an important characteristic of human vulnerability to heat stress, we also aimed to include poverty aspects in our assessment method in order to capture at least two core dimensions of human vulnerability. After a longer research and consultation phase with city departments, the quantitative scenario development focused on the development of the number and percentage of elderly and of low-income households using the proxy of households that receive social-welfare support (SGB II). The number and amount of recipients of SGB II (social welfare) are important indicators for socioeconomic problems and households that are depending on governmental assistance (see e.g. City of Wuerzburg 2017: 11).

4.2 Data and scenarios regarding climate change and heat stress

In terms of heat stress, an analysis from our research consortium was conducted that focuses on present and future local climatic conditions (Bueter et al. 2019; GEO-Net) assessing local climate change and heat stress under RCP 2.6 and RCP 8.5, based on EURO-CORDEX data for the region and the consideration of land use changes in the city due to planned urban growth. In this regard, RCP 2.6 and RCP 8.5 represent extreme upper and lower bounds of possible futures, rather than likely scenarios (see Raftery et al. 2017; Hausfather and Peters 2020). The methodology used for downscaling climate data is based on guidelines of an expert commission of federal and state institutions in Germany.

4.3 Linking local vulnerability scenarios with future urban development

Growing medium-sized cities are characterized by a future expansion or densification of urban areas. We used this important fact as an entry point for modelling different socio-economic and demographic futures at district and ward level. We gathered relevant data of the newly planned urban extension and urban renewal areas that are likely to be realized within the next 14 years—thus until 2031 (in line with the end of the Biregio scenario). The number and size of these housing projects are quite different in various districts. However, all planned housing projects encompass already information about the size, the number of housing units to be built, the type of housing (multi-family homes versus single-family homes), and the percentage of low-income housing provided. Consequently, the project descriptions and the overall planning documents provide a solid information base for developing scenarios about the future population growth due to these housing projects.

We used and further enhanced this information with scenarios for the development of the share of elderly and the share of welfare recipients in these newly planned areas based on the type of housing and planned percentage of low-income houses (see Fig. 3). The geographic distribution of these urban extension areas and infill development areas reveals that projects are planned in various districts and wards and, therefore, the data and information can be used as an important methodological input for the local scenario development and future transformation processes. However, the impact of the planned housing projects on various districts is also determined by the size of the housing project and the underlying housing policies that result for example in specific housing types and the number of price reduced and/or social housing units.

Next to the analysis of future shifts in population due to new housing projects, we also developed and tested different storylines about the future demographic and socio-economic development of households in the city that particularly consider the potential impacts of the new urban expansion (housing projects) on age structure and low-income households. These storylines include different assumptions about the provision of housing particularly for low-income households depending on whether social housing is seen as a policy priority or a purely market-driven development. For a better communication, however, we reduced the number of potential scenario combinations to 3 core scenarios also presented in this paper. The following section outlines the different assumptions and calculations behind these three scenarios for human vulnerability.

4.4 Development of quantitative local scenarios for human vulnerability

The first phase of the scenario development encompassed the analysis of past and present trends and the discussion of different storylines that could inform quantitative scenarios. The discussion also encompassed the topic of future growth and population development. The storyline discussion benefited from participatory scenario development conducted within the city and focusing on the development trends of the city at large (Garschagen et al. 2018).

In a second phase, a quantitative assessment of potential development corridors of the core indicators (e.g. future population development and amount of elderly) was undertaken, based for example on projections and data of the State statistical office (StaLaBW) and the data for the shared socioeconomic pathways (e.g. SSP4) for Germany as well as own studies of the city. This phase allowed us to gain additional knowledge about the variance of the future development of ageing and poverty. For example, various scenarios and estimates about the future population conclude that the city will face future ageing in terms of the growth of the number of people that are 65 years and older. However, most of this data does not sufficiently provide information for the very local scale.

In a third phase, we applied baseline scenarios for the development of different age groups and SGB II recipients and added a scenario approach—that particularly accounted for changes induced by the planned new housing areas within the city. In this regard, we focused on different trends and policies in terms of the provision of housing for elderly and social-welfare recipients in the newly planned areas. In doing this, significant differences are modelled and calculated assuming that for example housing for elderly and SGB II recipients should be an absolute priority in the new urban areas (housing projects) in one scenario, while another scenario assumed that housing is mainly provided for wealthier people with respective gentrification effects for non-wealthy households.

4.5 Resulting vulnerability scenarios

In the following, the underlying assumptions and calculation methods used for the three resulting scenarios are outlined.

4.5.1 The first scenario—high vulnerability

In the first local vulnerability scenario, a significant increase in the number of SGB II recipients and elderly people is assumed. In terms of the storyline, we defined that social housing is a key priority for the new urban areas. In addition, we assumed that the general ageing trend is intensifying in the city and also in the new urban areas the provision of housing for elderly is an important goal. More precisely, we assumed in this scenario that all people in SGB II in 2017 are also accounted as SGB II recipients in 2031; however, the population size in 2031 has changed. Here we were able to use the estimated growth rates of Biregio (Biregio 2017) for different districts for the next 15 years and applied it to the current population in 2017 at city ward scale in order to estimate the population in 2031 at ward scale. Moreover, we defined that all new housing units in the new urban areas will be occupied by SGB II recipients only. That means the number of SGB II recipients will increase particularly in the new urban areas.

In addition, we calculated the percentage and growth of elderly based on an own forecast of the development of elderly (baseline scenario) and the influence of different housing policies in terms of the planned urban areas. Based on the official data from 2017 received from the city (June 2017) that classifies the population into seven different age groups, we were able to calculate the number of people that are very likely to be over 65 years in 2031. We assumed that all people (100%) of today's population classes between 51 and 80 years will be over 65 years old in 2031. Within the age class of 81–90 years, we assumed that 50% of this population group can be considered. While for the age group of people 91 years and older today (2017), we assumed that only 25% is considered for the ageing scenario in 2031. Thereafter, the percentage of elderly on the population was calculated based on the overall downscaled population data of Biregio for the year 2031. The baseline scenario estimates that the percentage of elderly—people 65 years and older—in 2031 will account for about 30% of the entire population of Ludwigsburg. This is a bit higher compared to the figures of the StaLaBW that estimated a share of 28% in 2030 and for 29.4% in 2035 (StaLaBW 2015). The shared socioeconomic pathway no. 4—which includes ageing—assumes that in Germany overall the percentage of people 65 years and older will account for about 25% of the total population (see KC and Lutz 2014; O'Neill et al. 2017). Also the Biregio ageing scenario for different city districts assumes that the percentage of people 65 years and older will account for about 21% in 2031. However, our analysis justified using a stronger ageing scenario, since the percentage of people 65 years and older has been already accounted for 20% in June 2017. Next to the calculation of the baseline scenario, we developed different assumptions about the housing policies (see Fig. 4) to calculate the additional influence of the new urban areas on the demographic composition of the wards. The scenario I assumes that within the new urban areas 50% of the housing units will be occupied by persons 65 years and older in 2031. Thus, in this scenario, the new urban areas intensify the ageing process particularly within specific wards.

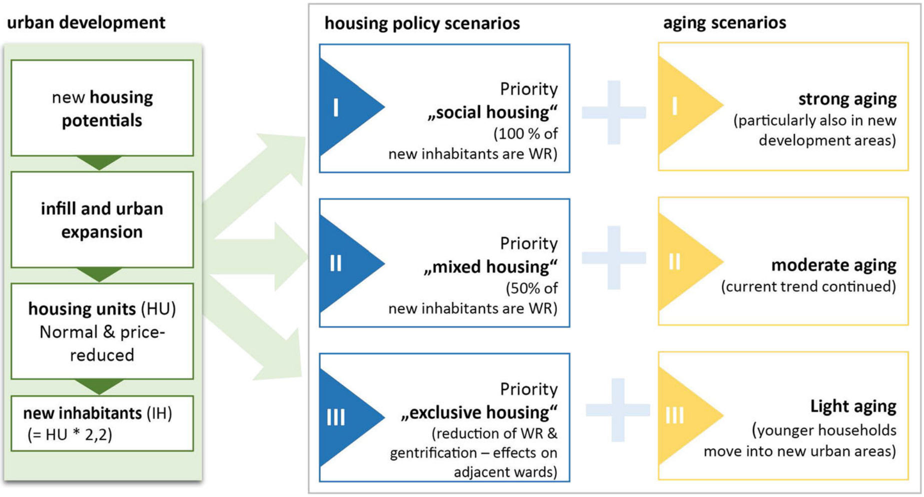

Fig. 4 Calculation of the influence of different housing policy scenarios for new urban areas to assess components of human vulnerability in Ludwigsburg; own figure

4.5.2 The second scenario—middle-of-the-road

The second scenario is a middle-of-the-road scenario. We assumed that the number of SGB II recipients will grow moderately. In this regard, we calculated that the planned social housing units in the new urban areas will be occupied by SGB II recipients and therewith the scenario includes a moderate increase of SGB II recipients in these districts. The price-reduced or social housing units often account for 10 to 20% of the planned housing stock in the new urban areas. Regarding the ageing component, we applied the baseline scenario calculation and assumed that the new housing areas do not modify the baseline scenario and respective trends embedded in the present ageing structure. This middle-of-the-road scenario therefore implies a stronger continuity of present trends and structures, even though the new housing projects can modify some wards significantly.

4.5.3 The third scenario—divided future

The third scenario assumes a high price of urban development and the provision of housing space particularly for wealthier households. In this regard, housing policies would lead to gentrification effects in the respective wards and the city, especially in terms of SGB II recipients. To operationalize this scenario, we calculated that the wealthier households would lead to an outmigration of poorer households in terms of two to one—thus, two new wealthier households would force one low-income household to leave the ward. We calculated that this effect also has an impact on the neighbouring wards for example in terms of increasing housing and rental prices. Hence, it might lead to additional forced outmigration of SGB II recipients. This is particularly the case if the number of SGB II recipients in the respective ward is lower than 50% in terms of the new incoming inhabitants. That means a new housing project and urban area with a large number of new inhabitants in a relatively small ward leads to additional forced migration of poorer households in surrounding wards in the same district. The third scenario also encompassed a younger population in the new urban area meaning that we applied the baseline scenario and calculated that within the new urban areas only households will settle down that are under 65 years old in 2031. This scenario would mean that the city mainly attracts wealthy and young families to the new urban areas. However, in terms of the present shortage of affordable housing, this policy would not be very appropriate.

While in some city districts and wards the socio-demographic and socio-economic condition will not change significantly due to the new housing projects and therewith existing trends will be dominant, the situation in other districts and wards changes significantly due to urban expansion or densification, such as in the districts city centre and district East.

4.6 Linking climate change and human vulnerability futures

The climate scenarios calculated by GEO-Net within our consortium considered the future intensification of heat stress due to climate change and land-use changes within the city (Bueter et al. 2019). The calculated heat stress values were provided in five ordinal levels based on the range of standardized (z-transformed) heat average for the district level from very low to very high. The combination of heat and both dimensions of human vulnerability (age and poverty/SGB II) was performed by using the min-max normalization of the respective value ranges. Based on the understanding that climate risks are a product of the interaction of human vulnerability and climatic hazards (IPCC 2014), we aggregated both human vulnerability dimensions by building the sum of the normalized values and multiplied them with the climate heat stress values (h) for the different scenarios and different spatial scales. In line with other risk definitions (see e.g. IPCC 2014) that account for both—the hazard and the human vulnerability—we assume that once climate heat stress is zero or vice versa human vulnerability to heat stress is zero, there is no risk. In contrast, high risk can be seen in areas where climate heat stress and human vulnerability is high at present and/or in the future. In the following, we present selected results of the combination of the worst case and middle-of-the-road/moderate vulnerability scenarios with a moderate and strong climate change scenario.

5 Results: combined scenarios of climate change and human vulnerability

5.1 Heat stress, future ageing, and urban expansion

The analysis of the present heat stress conditions juxtaposed with the ageing trends (see Fig. 2) shows that the central district and the inner city can be seen as hotspots today (see Fig. 2).

The combination of climate data and the "ageing" scenario at district scale already indicates that the city centre is highly exposed to heat stress (present condition). However, the combined map also underscores that the elderly population in this area is significantly lower compared to the neighbouring districts East and South. The highest share of elderly in relation to the total population in 2031 is estimated in Hoheneck with about 26% in 2031. However, this district does not rank among the districts that are severely heat-exposed. The juxtaposition of the present heat stress map with a local scenario of the development of the elderly at district scale already reveals significant differences in terms of the relevant hotspots and priority areas for adaptation. However, the Biregio scenario is only one scenario and operates solely at the district scale. In addition, Fig. 2 also shows the urban expansion potentials within each city district. This information underscores that significant change of the local population due to urban expansion projects can be expected in the future particularly in the districts Gruenbuehl-Sonnenberg, East and Ossweil.

Against this background, we also calculated the very local vulnerability scenarios and also combined these results with the future temperature and heat stress information to identify priority areas for adaptation.

5.2 Local vulnerability scenarios combined with heat stress information at district and ward scale

The results of the combination of different climate and vulnerability scenarios clearly reveal the influence of vulnerability even under high emission scenarios. Figure 5 shows the spatial distribution of selected results of the scenario combination for a relatively moderate heat stress scenario (RCP 2.6) with a moderate (scenario II) and a high vulnerability scenario (scenario I) (Fig. 5—upper two maps). The lower left scenario encompasses a heat stress scenario under an RCP 8.5 and a moderate vulnerability scenario, while the lower right map shows the results of a combined high heat stress scenario (RCP 8.5) with a high vulnerability scenario (scenario I).

The combined scenarios underscore that the City of Ludwigsburg would face significant challenges in a high vulnerability scenario combined with a temperature increase of the RCP

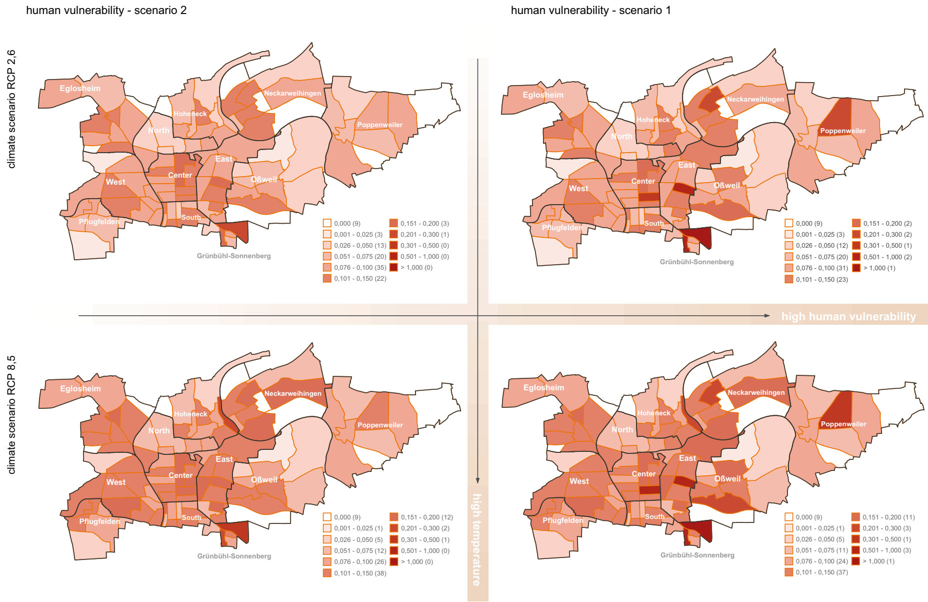

Fig. 5 Integrated scenarios—climate and human vulnerability 2030 (own figure)

8.5. Moreover, the combined scenario reveals important spatial differences at ward scale. Next towards in the city centre and the east part of the city (district East), also southern wards around Gruenbuehl-Sonnenberg, emerge as hotspots for adaptation and risk reduction. These specific areas, where human vulnerability adds significantly to the overall risks, might require additional attention in terms of adaptation to heat stress due to the non-favourable socio-economic and demographic conditions in this area. However, in some areas the absolute number of inhabitants exposed to heat stress is limited. Therefore, a further assessment of the specific hotspots and their profile is needed when designing specific adaptation strategies and measures.

Overall, the integrated scenarios and spatial analysis (maps) underscore that next to the inner city—which is often a heat hotspot—and also areas outside of the centre have to be monitored in terms of heat-related vulnerability and risks. This is particularly the case for areas and wards where planned urban development projects are very likely to modify the socio-demographic fabric in the near future and might transform in terms of the age and income structure of the households. The two vulnerability scenarios and their combination with the climate change scenario underscore the impact of the new housing projects and show that respective housing policies are also entry points for adaptation and risk reduction. Even under a strong climate change effect, the socio-economic and demographic indicators still influence the risk patterns.

A further zoom into specific districts is interesting and provides additional information (Fig. 6) about present and future heat stress and human vulnerability. The analysis of climatic conditions at present reveals that the inner city faces high challenges and a higher average temperature compared to the wards in the eastern district (see e.g. ward no. 43, 44, 45 and 46 in Fig. 6a/b/c). Particularly ward 45 contains better local climatic conditions compared to ward number 43 or 46 and also better conditions compared to the red coloured wards within

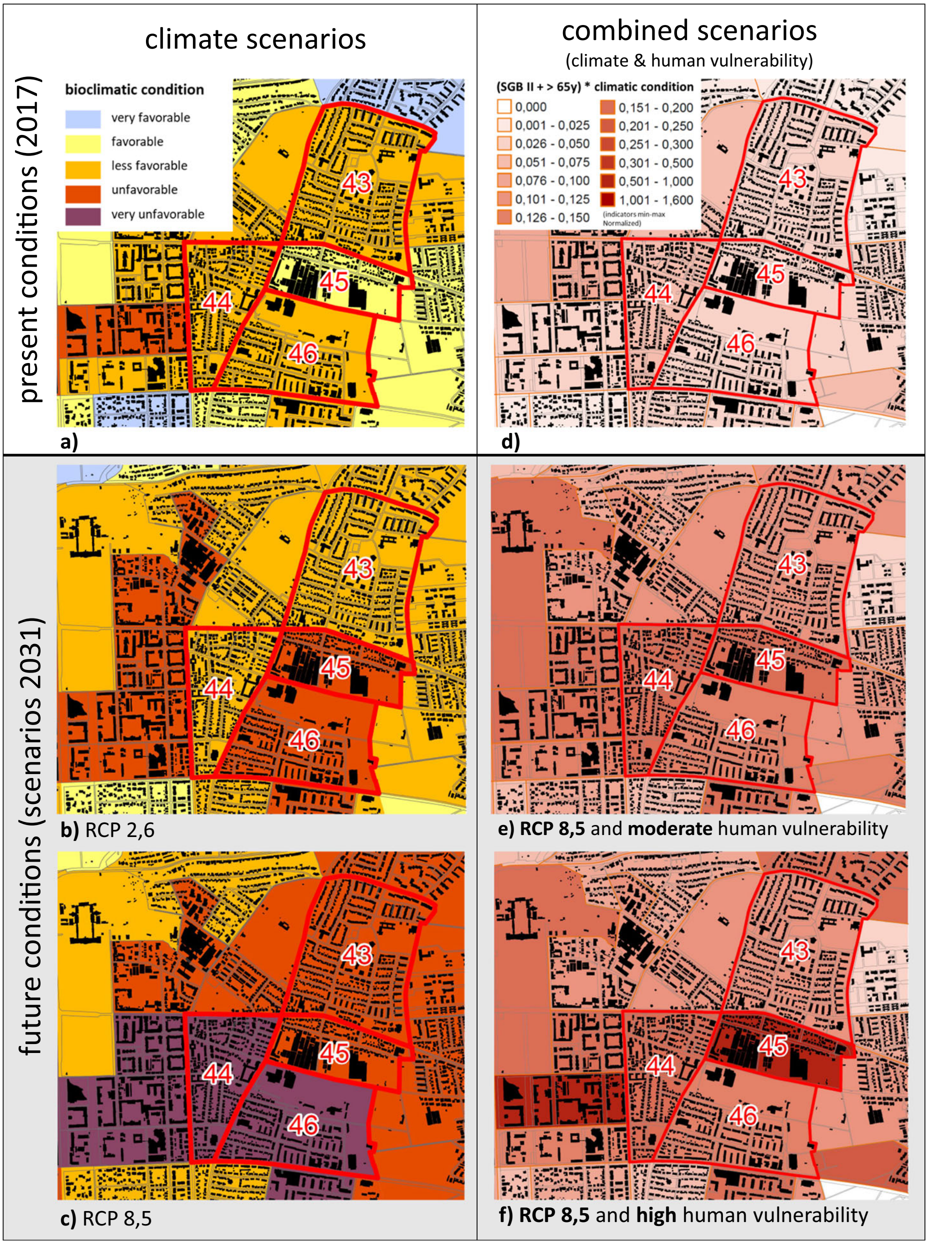

Fig. 6 Climate and human vulnerability scenarios. **a** Climatic conditions 2017. **b** Climate scenario 2031 (RCP 2.6). **c** Climate scenario 2031 (RCP 8.5). **d** Present climatic and human vulnerability conditions 2017. **e** Climate scenario (RCP 2.6) and moderate human vulnerability scenario 2031. **f** Climate scenario (RCP 8.5) and high human vulnerability scenario 2031. Source: own figure based on the climate and human vulnerability scenarios calculated within the ZURES project; data basis City of Ludwigsburg and GEO-Net; **a**–**c** Geo-Net only

the inner city. In contrast, the scenarios of the future climatic conditions and the scenarios of future human vulnerability show that e.g. ward no. 45 might change significantly due to the planned new housing areas and the urban renewal project.

In addition, in terms of the socio-economic conditions today (base year 2017), the northern wards in the eastern district—particularly ward no. 43 (with a rate of 5% SGB II recipients)—are better off regarding social-welfare recipients compared to ward number 46 (SGB II rate of about 11%). Also, the ageing structure is different in these wards. For example at present ward number 43 and 44 encompass more elderly (about 20–22%) compared to ward number 45 and 46 (16–18%) based on the local statistical data (City of Ludwigsburg 2017). The combined climate and human vulnerability map (Fig. 6d) for the present situation shows solely minor differences between the wards, also due to the fact that the bioclimatic conditions are somehow similar (43, 44 and 46) (see Fig. 6a). Significant differences emerge in the future especially when a higher increase of elderly and SGB II recipients is assumed also within the newly planned housing units of the district. Particularly, ward no. 45 changes significantly under different vulnerability scenarios. In terms of climatic conditions under an RCP 8.5, ward no. 44 and no. 46 are classified as areas with “very unfavourable” bio-climatic conditions, while ward no. 45 is classified within the same climate scenario as an area with “unfavourable” bio-climatic conditions. However, the socio-economic and demographic changes within the two different vulnerability scenarios imply additional changes and therefore ward no. 45 might face higher challenges in terms of adaptation compared to wards no. 44 and no. 46 especially if the new urban development does not support a balanced development (see Fig. 6d/e/f). Even though hotspots and spatial patterns of the combined maps are also significantly influenced by changes in local climatic conditions (see Fig. 6a/b/c), important differences between the local climate assessment and the climate scenarios on the one hand and the different scenarios of human vulnerability are revealed (see Fig. 6d/e/f).

The assessment results of the integrated climate and vulnerability scenario maps for the year 2031 at ward scale underscore that even under an RCP 8.5 scenario, human vulnerability still plays a role and makes a difference (see Fig. 6e, f). Our assessment focusing on climatic and physical changes as well as on changes of human vulnerability shows very precisely that this integrated perspective has an added value. While the heat stress and local climate scenario in a RCP 8.5 world shows that ward 44 and 46 face severe challenges and ward 45 and 43 are better off, the integrated maps underscore that ward no. 45 can be seen as an additional priority area where the decisions about the housing projects today influence future human vulnerability significantly. The changes of ward no. 45 under different vulnerability scenarios point towards the fact that the city has the ability to influence future demographic and socio-economic structures. Hence, urban planning today has a significant influence on human vulnerability in the future.

6 Conclusions

Even though methodological challenges remain, the paper demonstrates that scenario information for assessing future human vulnerability at the very local scale can be developed and can complement existing heat stress or climate change assessment and maps. In the following, we discuss how the methods might determine the results and how specific recommendations can be formulated from the findings of the different scenarios for practical urban planning and development.

The method and the selected indicators used capture future climate change, population growth, ageing and poverty. Compared to global downscaled approaches, the specific local approach presented in this paper links the local scenarios of vulnerability (population growth, ageing and poverty) with various strategies of urban expansion. Even though the data used for the City of Ludwigsburg is based on specific statistics within Germany, a similar approach can likely be conducted in other (European) cities. Some indicators and measures might need to be modified, but the overall approach linking future vulnerability to spatially defined urban growth and development scenarios is transferable. While the selection of indicators influences the results, the findings, however, represent important characteristics of human vulnerability to heat stress agreed in the scientific literature, such as the relevance of ageing. The method also puts emphasis on the planned urban expansion spaces as modifiers of urban vulnerability to heat stress in the future. In this regard, the method and respective scenarios show that future decisions about land-use and the specific housing types have an impact on human vulnerability and thus future vulnerability and exposure is dynamic and can be influenced through the decisions taken today.

6.1 The relevance for urban planning and other cities

Mapping the potential impacts of future climatic change on local climatic conditions (heat stress) and the influence of societal change and urban development on future human vulnerability in specific districts and wards can hint towards new priority areas for adaptation compared to a climate change assessment. The integrated scenario maps consider particularly future urban developments (urban expansion and densification) and their potential impacts on socio-demographic and socioeconomic structures within various districts or wards. The scenarios show how present urban development and housing policies influence future vulnerability. The districts city centre and East for example show within different wards rather high human vulnerability in different scenarios; therefore, attention needs to be given to ensure that new housing projects also improve the socioeconomic and demographic structure. In addition, urban renewal projects might need to target existing structures. The amendment of the federal building code in Germany allows defining priority areas for urban renewal that receive funding from national level also through the identification of areas where climate change risks might pose a challenge to sustainable urban development. Thus, the approaches presented can inform future funding requests for urban renewal. Considering that future urban growth strategies in these growing cities encompass more compact housing types in order to reduce the consumption of open space, it is also evident that low-income or elderly households in these housing types are to have access to green space in the neighbourhood, because they will not have an own garden. Thus, the local maps can help to show where the most vulnerable population groups are located today and in the future. The maps and findings also provide important arguments for mixed housing and further development of green infrastructure in specific districts and wards.

Overall, we believe that the methods and the links to practical decision-making in urban development are highly relevant to other growing medium-sized or big cities that prepare adaptation and risk reduction strategies to heat stress.

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