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Local urban risk assessment of dry and hot hazards for planning mitigation measures

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ABSTRACT

With the change of global climate and increased urbanisation, urban dry and hot hazards is becoming a more urgent problem that may affect sustainable city development. In the case of pronounced increase of air temperature and duration of dry periods, cities may experience long-lasting heat waves, soil dryness, and water shortages that concern the urban population, ecosystems, and socio-economic sectors. The research investigates urban vulnerability towards compound dry and hot hazards in one of the largest Polish cities - Wrocław. The aim of the paper was the development of multi-hazard framework to establish a set of metrics for a hot and dry hazards monitoring system that would provide insights into better management and sustainable development of the city in the long run. The developed indicators and thresholds system for hazard assessment covers meteorological and hydrological drought indices, heat waves, long lasting dry spells, extremely hot days, cooling degree days and low flows identification procedures. Analysis of long-term variability of the indicators values including frequency and trend analysis were the basis for the estimation of hazard levels. The main socio-economic sectors were examined in terms of their vulnerabilities to dry and hot hazards with regard to the spatial variation of sensitive city components. A combination of the estimated hazard levels and the vulnerability of the respective city sectors supported with expert judgments provided a local multi-risks urban assessment matrix. Reducing risks of dry and hot hazards requires coherent actions including educational, organisational, and technical solutions.

1. Introduction

The agglomeration of people, assets, and economic activity make cities particularly vulnerable to natural hazards. Urban centres are at risk from the impact of increased temperatures, heat islands, and other hazards that climate change is expected to exacerbate (IPCC, 2014). It may have a range of interrelated short- and long-term consequences for cities, including human health, social systems, and economic activities depending on the city's preparedness and resilience. Observed and projected changes in climate may also affect cities indirectly via reduced agricultural production and disturbed food security as well as reduced snowpack accumulation limiting river network reinforcement (Guide, 2011).

Guerreiro et al. (2018), using all climate model runs from CMIP5 for the RCP 8.5 scenario, revealed an increase in the number of heat wave days and the maximum temperature of heat waves for all 571 analysed European cities. The highest increase in maximum temperature of heat waves was found for the cities located in Central Europe. In the warming climate it is expected that also

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precipitation extremes will become more intense. According to the high-impact scenario, most of the European cities will suffer from the increase of both drought and river flood risk (Guerreiro et al., 2018).

An increase in the population of both cities and urban areas results in increased demand for products and services with greater water footprints. The sustainable growth of cities depends on reliable water supply systems that are able to meet water demands and are robust enough to cope with drought (Buurman et al., 2017). In cities scarcity of water resources can be associated not only with low precipitation, but also with poor water management. Systematic growth of impervious areas increases the surface runoff, reduces water storage in soils, and leads to disturbance in the natural water cycle. The impact of climate change on cities is therefore likely to become a tension that will be at its highest during periods of drought.

Drought is defined as sustained and regionally extensive occurrence of below average natural water availability (Tallaksen and Van Lanen, 2004) resulting from a range of phenomena, which start from a precipitation deficit propagating over time and affecting the successive components of the hydrological cycle (Wilhite, 2000). The onset of drought is caused by the persistent anticyclonic patterns that lead to low relative humidity, high air temperature, and reduced cloudiness and more sunshine. The impacts of drought vary between different city sectors and drought phases. In the first stage of drought, a high atmospheric demand for water may incentivize soil evaporation and plant water consumption through transpiration (Miralles et al., 2019). In combination with excessive heating driven by urban development, dry hazards can intensify and promote the formation of unfavourable urban climates that become a threat to human health and services for urban dwellers. Further drought evolution causes soil moisture depletion that can threaten urban green areas. Drought persistence is likely to alter water availability and trigger water resources scarcity due to an imbalance between water supply and water demand.

The same high-pressure systems that largely suppresses ascending motions, reduces water vapor condensation and precipitation formation, are also recognized during the onset of heat waves extreme high temperatures events (Ionita et al., 2021).

Common precursors: persistent below normal precipitation and elevated temperature makes these dry and hot hazards likely to occur simultaneously (concurrent or compound hazards) (Sutanto et al., 2020). After Sutanto et al. (2020), following the definitions from Leonard et al. (2014) and Liu and Huang (2015) compound hazards are two or more extreme events occurring simultaneously, i.e. on the same day and in the same region.

Compound hazards potentially trigger more significant impacts relative to single hazards (Sutanto et al., 2020). Recent research proves that combination of compound climatic events are responsible for the largest negative impacts due to cumulation of negative impacts (IPCC, 2014; Liu et al., 2016). Over the last years (e.g., 2015, 2018, 2019) severe heatwaves and droughts have struck Europe that affected society and caused significant economic losses as well as environmental damages (Ionita et al., 2017; Buras et al., 2020). Moreover, the probability of dry hazards to simultaneously occur is expected to rise in the future due to an increase in air temperature (Zscheischler and Seneviratne, 2017).

With the observed increasing trend of positive association between the occurrences of heat waves and droughts (Zscheischler et al., 2018; Kong et al., 2020) magnitude of individual hazards can be intensified through soil moisture-atmosphere coupling (Shukla et al., 2015). Drought severity can be aggravated in accordance with high temperatures that substantially enhance evaporation (Dai, 2013; Dai et al., 2004). Increase in the atmospheric demand for evaporation exacerbates high temperatures leading to a heatwave (Miralles et al., 2014).

In the same time many practices for climate change adaptation in urban areas concentrate around green spaces, water infrastructures and the use of air-conditioning. That are highly depend on water availability. In local urban environment it is therefore crucial to evaluate compound dry and hot hazards through multi-risk approach. To establish a ranking of different types of risk, taking into account possible conjoint and cascade effects. In most common approach to risk evaluation, risk levels should reflect two main components: the chance that a hazard of given intensity will occur (hazard probability/frequency) and the magnitude of the associated impacts (Blaikie et al., 1994; Wisner et al., 2004; Sayers et al., 2016) that represent probable stresses to the human-environment-economy system (vulnerability to hazard). Indices and indicators became one of the most important and useful methods for monitoring and assessing different types of hazard especially for drought hazard assessment. Over the years, various researchers have proposed different indices to identify onset, and to characterise and quantify the attributes of different drought phases (Palmer, 1965; McKee et al., 1993; Byun and Wilhite, 1999; Tsakiris, 2007; Nalbantis and Tsakiris, 2009). The decision to apply the particular indicator usually depends on the aim of the application, the ability to reproduce spatial and temporal features of drought occurrence, as well as the availability of the data required for its calculation (Tokarczyk and Szalińska, 2010).

In the same time, many research was dedicated to define and assess urban vulnerability to different types of hazard (Fang et al., 2016; Swart et al., 2012; Romero-Lankao et al., 2012; Füssel, 2007). For example Wang et al. (2020) defined urban vulnerability to drought as the extent to which the balance of urban water demand and supply is disrupted and the city is unable to cope with. Levels of urban vulnerability depends on exposure to climate hazards, sensitivity of urban infrastructures, populations, or activities, and the resulting or potential impacts (Romero Lankao and Qin, 2011). Exposure designate the extent to which an urban system is subjected to the hazards. It can be assessed with the use of factors such as the spatial and age distribution of the population, dwelling type and quality, access to social networks and health services, and the city's resources of freshwater. The sensitivity is characterised by the degree to which distinctive city components (the population of elderly residents, city transportation, energy production, etc.) are susceptible to the hazard.

To reduce the recognised risks the recommended method is the approach based on risk management (Rossi, 2000; Wilhite, 2011; Buurman et al., 2017) that aims to suppress the probability of hazard occurrence, reduce exposure, mitigate consequences, or increase the resilience of the relevant city sectors and components (Kallis, 2008). In the same time identification of factors that influence vulnerability to drought is essential in developing coping strategies to reduce hazard impacts. The identification of vulnerable groups acts as an entry point to both understand and address the processes that cause and exacerbate vulnerability (Brooks et al., 2005). In

order to reduce societal vulnerability and increase resilience to drought (UNISDR, 2003) it is necessary to shift from re-active crisis management to pro-active preparedness (Sivakumar et al., 2014). Following this approach Crossman (2018) developed a framework for Drought Resilience, Adaptation and Management Policy (DRAMP) that documented six goals for actions to be taken for managing and adapting to drought, which reduce exposure to drought and vulnerability, increase resilience, transform and prepare, and respond and recover from drought.

The purpose of this study is to provide framework methodology for assessment of compound dry and hot hazards associated with drought formation, evolution, and persistence for the urban population, environment, and economy sectors based on the multi-risk approach.

The study was undertaken for the one of the largest Polish cities – Wrocław. The work delivers updates of the preliminary results presented in Szalińska et al. (2018). It provides development for spatially based assessment of local drought risks for the planning of mitigation and adaptation measures. The presented measures are a synthesis of the actions proposed by the authors to be included in the “Development of Urban Adaptation Plans for cities with more than 100,000 inhabitants in Poland” (<http://www.44mpa.pl>) for the city of Wrocław. Selected measures specify those actions that corresponds to mitigation of compound dry and hot hazards.

2. City components vulnerable to dry and hot hazards

Slow-onset nature of drought and compound hot phenomena as well as their extensive areal coverage trigger cumulative and nonstructural impacts. In urban context the assessment of vulnerability to dry and hot hazards requires to explore the influencing factors with the main focus on societal vulnerability (Ward & Shively, 2017; Zarafshani et al., 2012).

Long-lasting periods of high air temperature (heat waves) have a strong impact on human health. The effects of long-term periods with high temperatures is particularly felt by people living or staying in the central districts of the city (due to building density, high proportion of impermeable surfaces, and poor ventilation). Moreover, a mosaic of building materials with different parameters of the ability to reflect and absorb thermal radiation lead to the development of urban heat islands that augment the thermal stress of city dwellers (Kozłowska-Szczęśna et al., 2004; McGregor et al., 2006). The most vulnerable group are small children, the elderly, and chronically ill persons, especially those suffering from cardiovascular and respiratory diseases. The increase in the maximum air temperature in cities is particularly troublesome in the summer season. In the case of particularly prolonged heat waves, an increased burden on health and social care facilities can be expected. During heat waves, mortality associated with cardiovascular and respiratory diseases increases, and the number of accidents on roads and at workplaces rises as well (Kuchcik, 2013). Increases in air temperature are likely to raise energy demand, caused by air conditioning used for cooling buildings. Droughts can be particularly stressful for sensitive groups and those with increased water demand (infirm people) during a synergy effect of scarcity of water and thermal discomfort. For older people in case of problems with water supply abstraction it may be too heavy to carry water e.g. from cisterns temporarily supplying the city.

In the case of road infrastructure and public urban transport, an increase of temperature and heat wave events influences the susceptibility of bituminous surfaces, increasing the impact of vehicles and, consequently, limiting the movement of heavy vehicles and causing higher maintenance costs. In the rail subsystem, high temperatures may additionally cause overheating of trackways and track infrastructure, causing reduced speed limits as well as interruptions in power supply in traction due to possible overloading of power grids (Adaptation, 2014). Moreover, high temperatures promote overheating of vehicle engines and other technical devices. Heat waves reduce the comfort of journeys and increase demand for air-conditioning of public transport vehicles, resulting in higher fuel consumption.

In cities rainless periods and meteorological droughts cause decreased moisture in the air and an increase in the concentration of allergens, dustiness and pollution including particulate matter. This lead to worsening symptoms of allergies and respiratory diseases. This phenomenon is compounded by weak airing of the city, especially its central parts. This can be tackled by a temporary decrease of sources of particulate matter in the city (e.g. transport regulation) or by increasing moisture in the city (e.g. by water spraying or increased water cleaning of streets). Increased water consumption during meteorological drought can however aggravate the situation and trigger other types of drought (Swart et al., 2012).

Further drought development (soil-moisture drought) have a direct impact on urban green spaces and green infrastructure. Drought impacts the city's green areas with increased water stress and endangers water-sensitive plant and animal species. Green spaces and green infrastructure, if managed and watered, increase consumption of water and therefore make cities more vulnerable in case of water scarcity and drought events. This vulnerability can be lessened by the selection of drought-resilient species and by the design of green spaces (e.g. by including rainwater reservoirs in them) (Swart et al., 2012).

Drought conditions are likely to impact city water supply systems. In urban areas water consumption falls into five main categories: municipal use, which includes domestic water usage for drinking and bathing; industrial use, which includes electricity production from power plants; and providing ecosystem benefits, which includes irrigation water and supporting the water needs of animals and recreational uses. Periods of lack of precipitation and high air temperature may affect the quality and quantity of the raw material introduced to the system. High temperatures increase the number of bacteria in the network and in reservoirs, causing the need to intensify water disinfection methods. During heat waves, also the pH of water tends to increase. High temperatures and long-lasting dry periods lead to increased water demand including irrigation of home gardens. This may also pose a threat to the water supply system related to the reduction of water pressure in taps in peripheral housing estates. In sewage and wastewater management high temperature contributes to the increase of odour nuisance of sewage management facilities (collectors, sewage treatment plants, landfill sites, composting plants).

Low flows and hydrological droughts are the biggest threats to water supply systems and consequently to industry and energy

production. The availability of water is crucial for many technological and cooling processes. Changes in precipitation and increases in low flow events may therefore highly influence patterns of energy and water use and supply. In particular, it may cause a reduction in the efficiency of traditional power plants with open-circuit cooling and hence a reduction in the amount of energy produced by these plants. Challenges to production from power plants is posed also by restrictions on the temperature of cooling water returned to water bodies. Cities are usually in a position to regulate the rate of water abstraction through soft and hard measures. To mitigate these impacts building artificial water reservoirs or diversify their supply is a common practice. Failure to regulate water abstraction during hydrological drought can lead to socioeconomic drought, which is sometimes the last link in the causality chain, starting with unusually long periods of dry weather and ending with insufficient supply of drinking water in the public supply system (Swart et al., 2012).

Low flows and hydrological droughts also limit open-water-related recreational activities like sailing, fishing, and swimming.

3. Materials and methods

3.1. Study area and database

Wrocław is located in the south-west part of Poland (Fig. 1). With an area of 293 km² and a population close to 640,000 inhabitants, it is one of the largest Polish cities. The location in the temperate climate zone with oceanic and continental influences causes large variability of weather conditions. The city area is cut by the River Odra and its tributaries (Bystrzyca, Widawa, Oława, and Ślęza) and an extensive system of drainage and irrigation ditches.

A primary water source for Wrocław comes from surface water. Resources are secured by two retention and flood-prevention reservoirs on the Nysa Kłodzka river (Odra tributary): the Nysa and the Otmuchów reservoirs. The storage capacity covers the entire current-use requirement of Wrocław water company (24.15 million m³) with a 92-day reserve.

Current climatological and hydrological conditions were investigated based on daily data observed within the period 1981–2015 at monitoring stations operated by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB): meteorological station Wrocław-Strachowice (51°06'N; 16°54'E) and five water-gauge stations (Fig. 1).

3.2. Conceptual framework

The assessment of compound dry and hot hazards associated with drought formation, evolution, and persistence including extremely hot days, heat waves, prolonged period of cooling degree days, long lasting dry spells and low flows was done in a multistage process (Fig. 2). Estimated risks levels were a function of the following components (i) hazard assessment representing probability of perturbations and stresses to the urban system; (ii) exposure representing the extent to which elements of the urban system are subjected to hazards; (iii) sensitivity – the degree to which distinctive city components are susceptible to the hazard, and (iv) coping capacity, representing the ability to avoid or lessen the negative consequences of dry and hot hazards based on access to resources, assets, and options to cope with the consequences.

Risk estimation evolved analysis of long term measurements of meteorological and hydrological parameters in order to assess frequency of the analysed extreme events, investigation of climate change projections to infer on their future tendencies, building inventory of socioeconomic and environmental data along with the press and media reports and literature review on consequences of historical events to capture the sensitivity of distinctive city components, performing spatial analysis of urban land cover, population, economic activity, transportation etc. to delineate exposure units as well as analysing local policies, plans and strategies to evaluate city vulnerabilities.

The applied methodology assumed utilising additionally expert judgement at each stage of the risk assessment process. The



Fig. 1. River network and location of water gauge stations in the vicinity of Wrocław area.

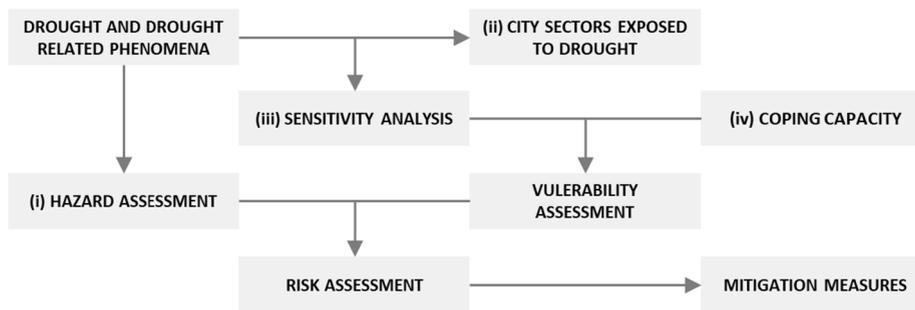


Fig. 2. A conceptual framework of an urban dry and hot risk assessment scheme.

contributions from the risk analyses were combined with considerations of subjective perceptions of risk and value judgements in the decision making process. This involved organizing a multidisciplinary group of experts from City Council and stakeholders representing different city sectors including governmental and non-governmental institutions. Experts opinions were elicited through a series of collaboration workshops to characterize their collective knowledge. During the workshops background information, results from analysis were communicated to obtain the judgments of groups of experts and final findings were synthesized.

3.3. Hazard assessment

Climate change in Poland is mainly expressed in a significant increase in air temperature and changes in the structure of precipitation. In 1951–2008, the highest increase was observed in winter and spring, over 0.35 °C/10 years (Marosz et al., 2011), and an increasing trend in heat wave frequency and intensity is observed (Wibig, 2018). According to climate projections for the RCP4.5 scenario, the average annual air temperature in Poland is likely to increase by 1.1 °C before 2050 and by 2 °C within the period 2071–2100 (Kundzewicz et al., 2017). Projections of Standardised Precipitation Index (SPI) values for Poland indicate a decrease of dryness intensity during the winter months and an increase in the summer period within the 21st century (Osuch et al., 2016).

Effective drought monitoring promotes indices that can be estimated from standard collection of hydrometeorological data and easily transferred and applied in different regions. Identification of hot and dry hazards including extremely hot days, heat waves, high number of cooling degree days, long lasting dry spells and low flows, meteorological drought and hydrological drought was done with the use of the following indices that represented stresses to the urban human-environment-economy system:

- *Extremely hot days (EHD)* - defines days with the daily maximum temperature higher than the 98th percentile of long-term observations;
- *Heat waves (HW)* - are identified by using a threshold-based method (Perkins and Alexander, 2013). HW is defined as an event of at least three consecutive days during which daily maximum air temperatures exceed the 90th percentile. For each calendar day d , the climatological 90th percentile for maximum air temperatures has been calculated from the daily air maximum temperatures in a 5-day moving window centered on the day d (the 90th percentile is computed over the reference period 1981–2010). The heatwaves have been calculated for warm season (April–September). Heat waves were analysed both in terms of their frequency and duration;
- *Cooling degree days (CDD)* – represents accumulated deviation of the air temperature over the days with the air temperature exceeding the assumed threshold value (Christenson et al., 2006). The threshold value was assumed locally as 27 °C to provide information on the cooling energy demand.
- *Dry spells (DS)* - defines a series of consecutive days without precipitation or with daily totals ≤ 1 mm. The longest dry periods and periods lasting ≥ 10 days were determined for each year.
- *Standardised Precipitation Index (SPI)*, (McKee et al., 1993) is an indicator of drought, recommended by the World Meteorological Organisation (WMO, 2012). The SPI is a standardised value of the totals of precipitation in a given time interval (1 month, 3 months, 6 months, 12 months, 24 months). The values of the SPI allow the identification of periods of drought for different time scales.
- *Standardised Runoff Index (SRI)* - was used as an indicator of hydrological drought (Shukla and Wood, 2008). Analogously to SPI index, SRI is a standardised value of the runoff characteristics in a given time interval (1 month, 3 months, 6 months, 12 months, 24 months). The values of SRI allow the identification of the hydrological conditions in the catchment.
- *Low flow (LS)* [Nizowka] - represents the period of river flow below the assumed threshold value (Ozga-Zielińska and Brzeziński, 1997; Tallaksen and Van Lanen, 2004). The threshold value depends on different criteria, i.e. hydrological or economical (Tokarczyk, 2013). The low flows periods can be characterised and classified according to different criteria, i.e. low flow deficit volume (D_i [m^3]) and low flow duration (T_i [days]) (Jakubowski and Radczuk, 2004).

The long-term series of values of each indicator (EHD, HW, CDD, DS, LF, SPI, SRI) was developed for the period 1981–2015. Variability and trends in patterns of each the analysed dry and hot hazards was examined individually.

In the same time analysis of co-occurrence of extreme dry and hot events were performed in order to estimate the frequency and

Table 1
Parameters and sensitivity factors for quantifying vulnerability to dry and hot hazards.

sector	Sensitivity factors	Unit	References	Relevance
population	population density	[no./km ²]	Wang et al., 2020; Zhang et al., 2019; Yuan et al., 2015; Swart et al., 2012	The higher the population density, the higher the density of the built environment and the higher the potential of thermic stress
	children under 6 years old	[no./km ²]	Swart et al., 2012	The higher the proportion of potentially state-dependent, or family-dependent people, the lower the response capacity
	people over 65 years old	[no./km ²]	Dong et al., 2020; Zhang et al., 2019; Swart et al., 2012	
economy	main economy sectors	list of sectors	Wang et al., 2020	The larger the number of water-intensive industries the higher the sensitivity
	budget structure	[%]	Wang et al., 2020	
	gross domestic product	<i>per capita</i>	Wang et al., 2020	The richer the society, the higher the response capacity
land cover	green space and protected areas	[%]	Wang et al., 2020; He et al., 2019; Meza et al., 2019	The higher the share of green space the lower the potential of thermic stress. Large share of green spaces and protected areas increases sensitivity to drought due to the need for watering;
	impermeable area	[%]	Swart et al., 2012	Lower the share of impermeable areas the higher infiltration and retention capacity and lower impacts
	biologically active area	[%]	Swart et al., 2012; Wang et al., 2020; He et al., 2019	
energy	energy supply structure (fossil, renewable)	[%]	Dong et al., 2020; Meza et al., 2019	The higher the cooling water demand, the higher the sensitivity of the urban power supply
water management	electrical energy consumption per sector	TWh	Meza et al., 2019	The change in density is an indicator of the periodic loss of the water network (rivers, small natural and artificial watercourses) and an increase in susceptibility to the effects of drought
	water channel density	km/km ²	Dong et al., 2020	
	municipal water supply	[%]	Wang et al., 2020; Swart et al., 2012	
transportation	water consumption structure (total, industry, agriculture and forestry, domestic water consumption,)	m ³ /year water consumption per capita	Dong et al., 2020; Swart et al., 2012; Yuan et al., 2015	The efficiency of a water supply system decreases its sensitivity to drought The higher the water use per sector/per capita, the higher sensitivity to drought and low flows events
	rail tracks	[km]		The increase in track length increases the risk of problems in rail transport due to high temperatures
	road density (total length of main roads per square meter)	[km/km ²]	He et al., 2019	High density road areas reduce infiltration and retention. High temperatures cause deformation of bituminous surfaces.
	public transport vehicles without air conditioning	[%]		Reduced thermal comfort of passengers during hot weather
healthcare	hospital emergency wards hospital beds	<i>per capita</i> <i>per capita</i>	Wang et al. 2020; He et al., 2019; Swart et al., 2012	The more emergency wards/ hospital beds, the higher city's response capacity

trends of compound dry and hot hazards. This was done based on identification and investigation of heatwaves and drought episodes. Drought condition was identified with the use of the effective drought index (EDI) developed by Byun and Wilhite (1999) on a daily basis. Heatwave events are identified by using HW threshold method. The compound dry and hot event (CDH) was then defined as a combined index when a heatwave event occurs during a period under drought conditions ($EDI < -0.7$). Similar approach was applied at the pan-European scale by Bezak and Mikoš (2020). The analysis were made for the warm season (April–September) within 1981–2020 period.

3.4. Vulnerability assessment

Anthropogenic factors are the primary drivers of induced environmental degradation (Chen and Sun, 2017; Mahmoud and Gan, 2018). Wang et al. (2020) emphasized the importance of socio-economic factors elaborated from urban characteristics (including water infrastructure, etc.) to estimate the level of risk that the hazard poses to people. For urban vulnerability assessment anthropogenic factors becomes essential.

The first step for quantifying urban vulnerability is to identify the relevant factors that address sensitivity to dry and hot hazards. Population, economy, and water infrastructure are dominant factors for index selection to assess drought exposure, sensitivity and coping capacity (Yuan et al., 2015). In the study, social, economic, and environmental parameters were analysed as factors contributing to the level of vulnerability to dry and hot hazards. Selection of factors refers to the indicators widely used in the relevant literature to evaluate climate change vulnerability (Zhang et al., 2019; Sarkodie and Strezov, 2019; Tapia et al., 2017; Swart et al. 2012), heat wave vulnerability (Sandholz et al., 2021; He et al., 2019), drought vulnerability (Meza et al., 2019), urban water shortage (Dong et al., 2020; Boruff et al., 2018; Koutroulis et al., 2019; Srinivasan et al., 2013), urban drought vulnerability (Wang et al., 2020). The applied set of indicators is resultant of their relevance (message), feasibility (availability of data) and credibility (reliability of data source).

Based on information obtained from the Polish Database of Topographic Objects (<https://www.geoportal.gov.pl>), ortophotomaps, the Wrocław Spatial Information System (<https://www.geoportal.Wroclaw.pl>), the Polish Statistical Office Database (<http://www.stat.gov.pl>), as well as the city master plans, strategies, regulations, and local policies, the respective sensitivity factors were expressed in qualitative and quantitative measures (Table 1).

Analysis of spatial distribution of the selected sensitivity factors was performed in order to delineate spatial city units representing areas of similar exposure to dry and hot hazards. These areas were divided into nine categories based on socio-economic and environmental spatial data:

- *old town* – clearly distinguished area of multifunctional, high-density housing, mainly services and housing with possible enclaves of buildings of a different nature or greenery (e.g. moat and green belts accompanying them);
- *downtown* – area of dominant residential and service buildings with the presence of industrial buildings, covering historic urban quarters, possibly with scattered enclaves of buildings of a different function or morphology (e.g. a single contemporary block, warehouse, factory) or greenery (squares, small parks). The total area of the “other” land should not exceed 20% of the delineated area;
- *residential housing* – area with domination of block housing with the presence of basic services (elementary schools, high schools, kindergartens, nurseries, clinics, cultural service centres, small shopping centres - supermarkets - up to 15 ha) and distributed enclaves of buildings of a different nature (e.g. industrial) or green areas (e.g. parks). The total area of the “other” land should not exceed 20% of the delineated area;
- *intensive single-family housing* – area with dominant housing development in the form of terraced, atrium, semi-detached, or detached houses located on small plots (up to 500 m²) and distributed enclaves of buildings of a different nature (functional or morphological) and green areas (e.g. squares, parks, sports and recreation areas). The total area of the “other” land should not exceed 20% of the delineated area, and the proportion of the biologically active area should not exceed 40%;
- *extensive single-family housing* – area with dominant housing development in the form of terraced, atrium, semi-detached, or detached houses located on large plots (more than 500 m²), farmhouses and distributed enclaves of buildings of a different nature (functional or morphological), and green areas (e.g. squares, parks, sports and recreation areas). The proportion of the biologically active area should exceed 40%;
- *public services* – large complexes for public services of area exceeding 10 ha with a significant participation of greenery - universities (campuses), hospitals, museums, etc.;

Table 2

Risk categories pending on the probability of dry and hot hazards and vulnerability levels.

Vulnerability level	Probability of hazard event occurrence				
	Low (1)	Occasional (2)	Medium (3)	High (4)	very high (5)
catastrophic (5)	medium risk	medium risk	high risk	high risk	very high risk
critical (4)	low risk	medium risk	medium risk	high risk	very high risk
serious (3)	low risk	low risk	medium risk	high risk	high risk
marginal (2)	low risk	low risk	medium risk	medium risk	high risk
negligible (1)	low risk	low risk	low risk	medium risk	medium risk

- **industrial zone** – highly industrialised areas with the majority of plots exceeding 10 ha with distributed enclaves of buildings of a different nature (e.g. residential) or green areas (e.g. parks). The total area of the “other” land should not exceed 20%;
- **commercial zone** – area composed of large commercial buildings on plots exceeding 10 ha with distributed enclaves of buildings of a different nature (e.g. residential) or green areas (e.g. parks). The total area of the “other” land should not exceed 20%;
- **greenspace** - open city areas including parks, protected areas, and areas of undeveloped landscape with enclaves of isolated buildings.

The information on sensitivity factors combined with delineated spatial city units was used to list the city components (sectors, areas) most vulnerable to dry and hot hazards. For the identified city components, the level of vulnerability was assessed based on reports on the consequences of historical heat waves and drought events together with press and literature reports combined with expert judgments. Integral element of vulnerability assessment was experts’ opinion on coping capacity in terms of financial possibilities - city budget (the ability to mobilize external funds and private partners); preparation of civil services (training of engineering and medical services), social capital (functioning of social organizations, the level of social awareness of local groups), mechanisms for informing and warning residents, network and equipment of municipal institutions and facilities in the health and education sector, organization of cooperation with neighbouring communes in the field of crisis management, systems of protection and shaping of urban ecosystems, innovation potential (research institutes, universities, eco-innovative companies).

3.5. Risk estimation

To assess risks related to compound dry and hot hazard a multi-risk approach was applied. This approach considered both hazards and vulnerability interactions in order to present a cause-effect matrix of hazard probability and vulnerability correlations. This analysis allowed for direct comparison and aggregation among different kinds of risks to establish their ranking. In the study, the semi-quantitative analysis were performed to obtain a five-level classification of the hazard and vulnerability assessment individually and, while combining this information, to assess respective risk levels.

The hazard probability classification was based on the analysis of the observed frequency and trends in the selected dry and hot hazard indicator values (SPI, SRI, EHD, HW, CDD, DS, LF) supported with the investigations of the projected future changes. Investigated scenarios were based on regional climate models according to RCP 4.5 and RCP 8.5 concentration pathways for the 2050 time horizon developed from the Euro-CORDEX simulations. within the framework of the MPA project.

Based on this findings, a level of probability of occurrence for each type of dry and hot hazards was assigned as follows:

- low (1): in the historical period (1981–2015) a hazard did not occur, and the climate change predictions indicate a low probability of occurrence;
- occasional (2): in the historical period the phenomenon occurred at least once, and the climate change predictions indicate that the intensity or frequency of hazard event occurrence will not become critical within the next 10–30 years;
- medium (3): in the historical period the phenomenon occurred more than once, but not more than once every five years, and climate change predictions indicate that the intensity or frequency of occurrence may become critical within the next 10–30 years;
- high (4): in the historical period the phenomenon occurred more than once every five years, but not more often than once a year, and the climate change predictions indicate that the intensity or frequency of occurrence may become critical within the next 10 years;
- very high (5): in the historical period the phenomenon occurred more than once a year, and the climate change predictions indicate that the intensity or frequency of the occurrence may become critical over the next few years.

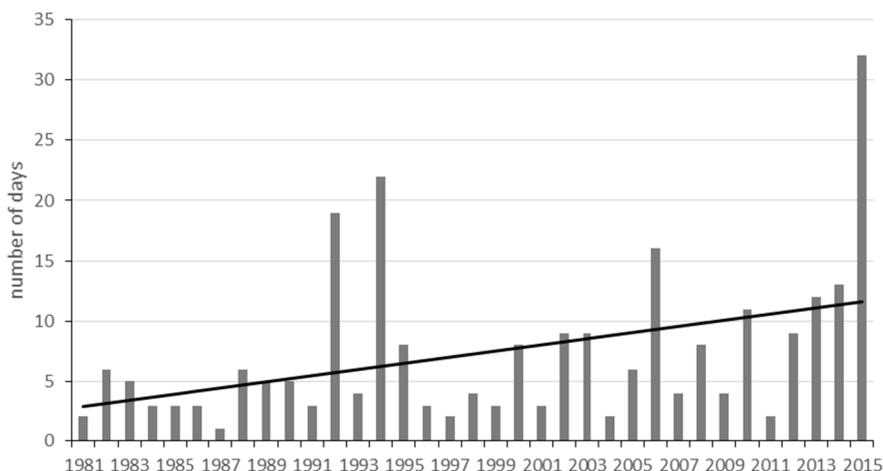


Fig. 3. Annual number of extremely hot days in the period 1981–2015 in the area of Wrocław.

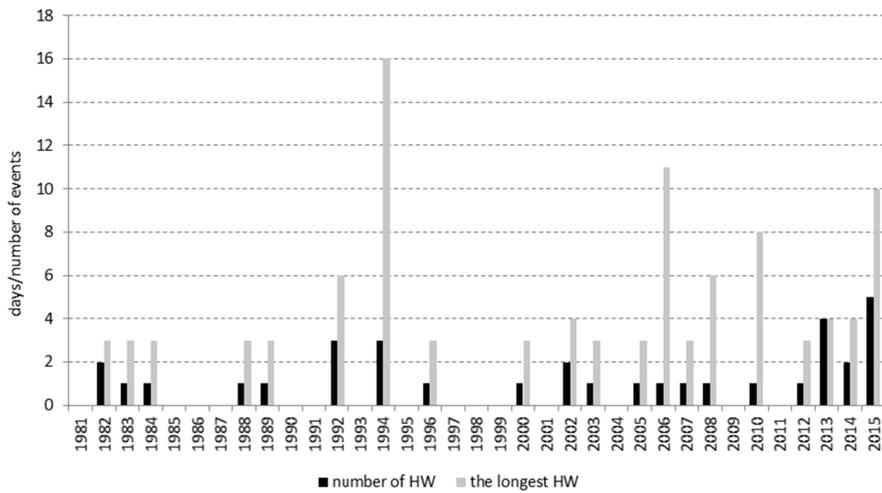


Fig. 4. Annual number of heat waves (HW) and duration of the longest HW (in days) in the period 1981–2015 in the area of Wrocław.

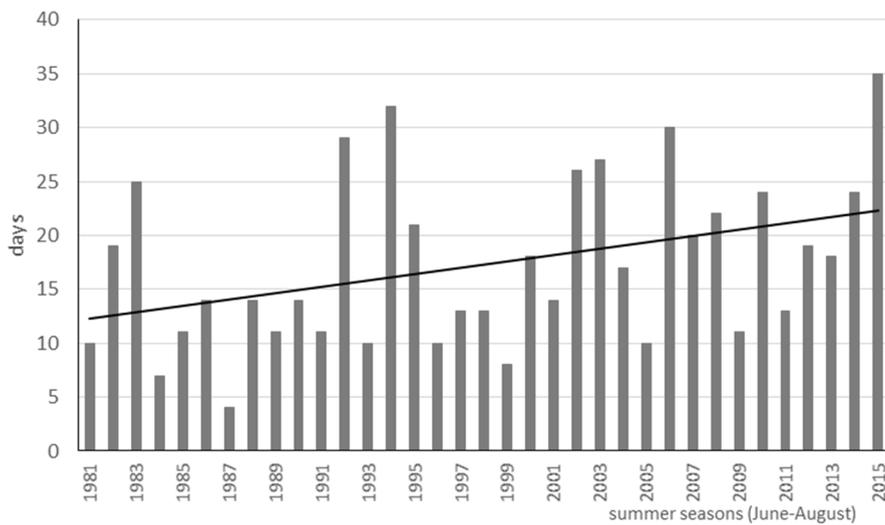


Fig. 5. Number of cooling days observed in summer seasons (June-August) in the period 1981–2015 in the area of Wrocław.

For identifying sectors of the city of Wrocław, which are potentially vulnerable to dry and hot hazards a one-day workshop was organized with the group of experts. Based on the selection of each participant, the final list of city vulnerable sectors was accepted. The level of vulnerability was classified with the reference to the results from sensitivity, exposure and coping capacity evaluation. A preliminary findings and collected evidence were communicated to the group of experts and final levels were agreed. Respective categories of vulnerability were obtained from expert elicitation and weights that described experienced or potential impacts of analysed hazards in terms of the time and resources required to return to normal conditions and the size of losses:

- negligible (1): no damage to the infrastructure; no adverse effect on human health; lack or minimal impact on the environment; minimal financial losses;
- marginal (2): disruption of operations or services for less than one day; local damage to the infrastructure; slight adverse impact on human health; minimal impact on species; moderate financial losses felt by a small group of residents, owners;
- serious (3): disruption of operations or services for one or two days; extensive damage to infrastructure, requiring maintenance and repair; adverse impact on human health; the need to displace residents from homes; adverse impact on the environment; large financial losses incurred by many residents, owners;
- critical (4): long-term disruption in the functioning of activities and services; damage to existing infrastructure or losses requiring costly repairs; permanent physical injury among people; significant impact on the environment; large financial losses incurred by many residents, owners, companies;

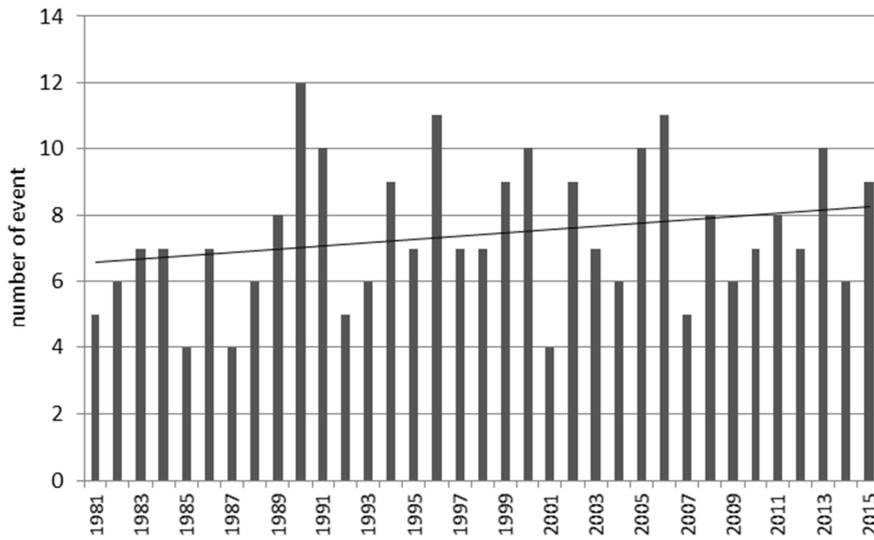


Fig. 6. Annual number of 10-day and longer dry periods in the period 1981–2015 in the area of Wrocław observed at the Wrocław-Strachowice station.

Table 3

Low-flow period characteristics in the years 1981–2015.

Water gauge	River	Low-flow period characteristics			
		$D_i < D_{50\%} \ \& \ T_i < T_{30}$	$D_i < D_{80\%} \ \& \ T_i < T_{90}$	$D_i < D_{90\%} \ \& \ T_i < T_{120}$	$D_i < D_{95\%} \ \& \ T_i < T_{180}$
Jarnołtów	Bystrzyca	95	18	8	5
Krzyżanowice	Widawa	57	17	9	6
Oława	Oława	101	25	8	4
Borów	Ślęza	33	21	4	6
Malczyce	Odra	76	25	3	7
Oława (Most)	Odra	69	22	5	4

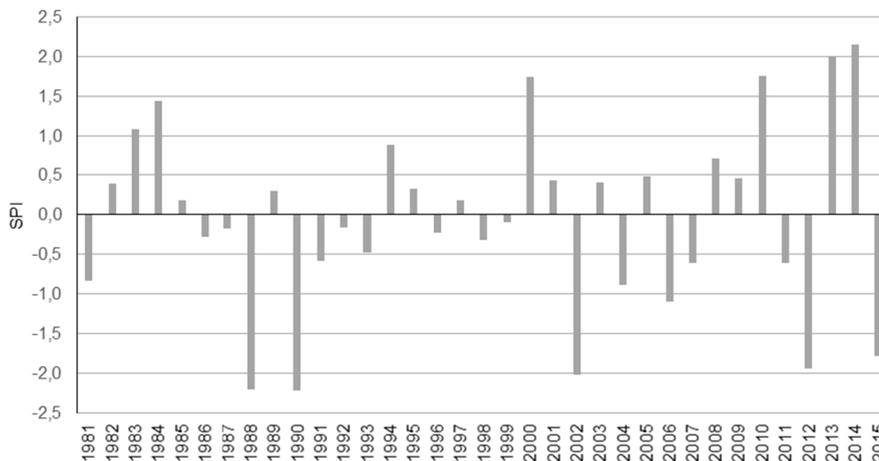


Fig. 7. Time series of SPI3 values (calculated for 3-month window) obtained at the end of May for the period 1981–2015 in the area of Wrocław.

- catastrophic (5): permanent infrastructure damage or loss of infrastructure services in the whole region; large financial losses related to the need to carry out corrective actions or reconstruction of environmental resources; adverse effects on human health, requiring immediate response, including cases of disability or death as a result of the incident; permanent loss of environmental resources; huge financial losses incurred by many residents, businesses, and the city.

Risk levels were grouped into four categories: low (L), medium (M), high (H), and very high (V) with regard to the interactions

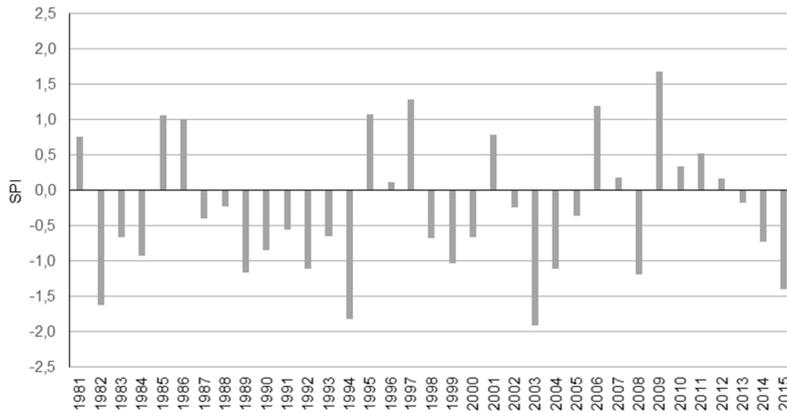


Fig. 8. Time series of SPI3 values (calculated for 3-month window) obtained at the end of August for the period 1981–2015 in the area of Wrocław.

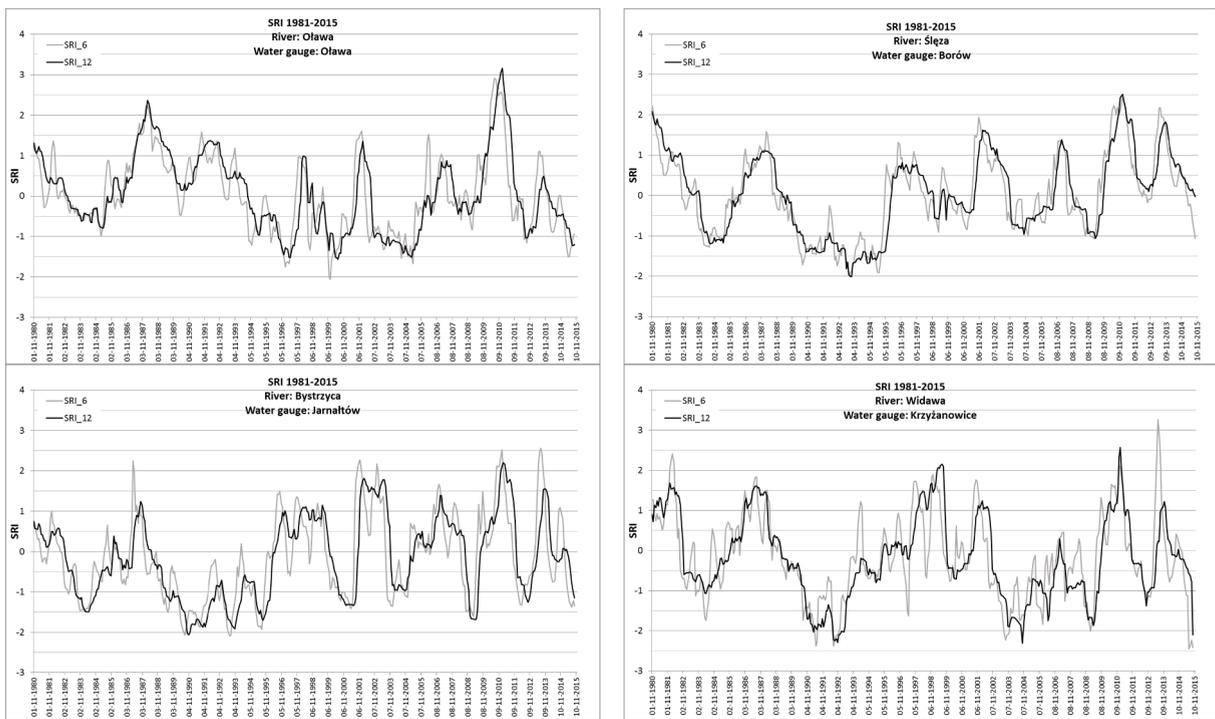


Fig. 9. Variability of the SRI index in the period 1981–2015 for the Olawa, Śleza, Bystrzyca, and Widawa rivers.

between hazard and vulnerabilities according to the scheme presented in Table 2.

4. Results

4.1. Local dry and hot hazards

4.1.1. Extremely hot days (EHD)

In the area of Wrocław, the mean annual air temperature has increased by 0.49 °C per 10 years within the period 1981–2015. The increase of temperature was noted for all seasons (winter, spring, summer, and autumn); however, the highest was observed in summer (June–August). A rising trend was also detected for daily maximum air temperature. Consequently, this implies an increase in the frequency of extremely hot days (Fig. 3).

Predictions of climate change indicate a further increase in the annual air temperature by the middle of the 21st century. The average annual air temperature may increase by 1.2 °C (RCP8.5 scenario), and by 0.8 °C for the RCP4.5 scenario. Predictions also indicate a further increase in the maximum air temperature and annual number of EHDs.

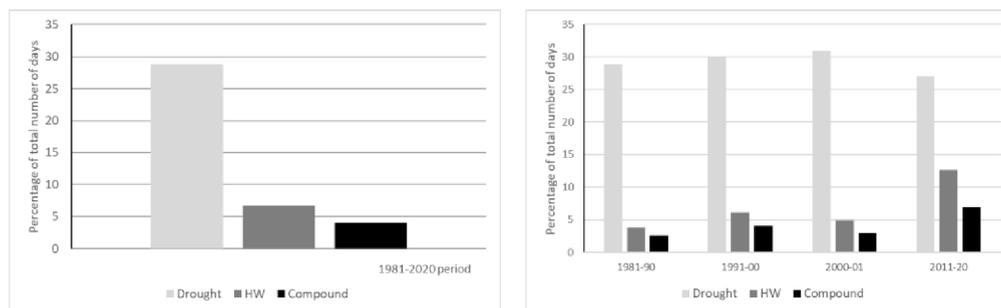


Fig. 10. Total occurrence of single (drought, heat waves) and compound hazards over the period 1981–2020 in the area of Wrocław (left) and on decadal time scales (right).

4.1.2. Heat waves (HW)

In Wrocław heatwaves occur on average two times a year. Heatwaves lasting three days were the most common (45% of all events), 4-day heatwaves occurred with frequency of almost 27%. The greatest number of heatwaves (six) was observed in the warm season of 2012. The longest heatwave lasted for 11 days (from 1st to 11th August 1992 and from 18st to 28th July 2006). During the 10-day heatwave from 6th to 15th August 2015, the maximum daily temperature exceeded the previously recorded value and reached 37.9 °C on 8th August 2015. After 2001 the frequency of heatwaves increased and occurred every year (Fig. 4).

Projections of climate change indicate increasing frequency of heatwaves by up to 3.8 events on average per year. Both climate scenarios (RCP 4.5 and RCP 8.5) show similar tendencies.

4.1.3. Cooling degree days (CDD)

In Wrocław the observed number of cooling degree days (CDD) in the summer seasons significantly increased by 2.9 days per 10 years within the 1981–2015 period (Fig. 5). A further increase is predicted in climate-change scenarios (RCP 4.5 and RCP 8.5).

4.1.4. Long-lasting dry spells (LLDS)

During the analysed period (1981–2015) the longest dry period in Wrocław lasted for 52 days, from 22nd January 22 to 14th March 2014. 35-day and longer dry periods were also recorded in 1984, 1989, 1996, 2005, 2011, and 2014. Analysing the frequency of long-lasting dry periods (with at least 10 consecutive rainless days) revealed high variability; however, a modest increase in the number of these periods can be noted (Fig. 6). This tendency is confirmed for both climate-change scenarios (RCP 4.5 and RCP 8.5).

4.1.5. Low flows (LF)

River flows observed at the gauging stations located in the vicinity of Wrocław during the 1981–2015 period were analysed in terms of low-flow period identifications and characterisation. Characterisation was done in terms of low-flow duration (T) and low-flow deficit volume (D) (Table 3). Low-flow deficit volume (Di) was expressed as a probability of non-exceedance of the given deficit volume: D_{50%}, D_{80%}, D_{90%}, D_{95%}. The obtained results proved that the most frequent are short-term low-flow periods with small deficit volume. The greatest number of such events (101) were noted for Oława station (Oława river). The smallest number (33) was noted for Borów station (Ślęza river). Number of events of long-lasting low-flow periods with small volume deficit ranged from 17 to 25. Extremely-low-flow periods lasting more than 180 days and with 95% probability of non-exceedance of the their deficit volume were

Table 4

Risk assessment matrix: P denotes estimated hazard probability level, V denotes estimated vulnerability level.

Hazard City component / area	EHD		CDD		HV		LLDS		LF		MD		HD	
	P = 5		P = 5		P = 5		P = 4		P = 4		P = 3		P = 3	
	V	R	V	R	V	R	V	R	V	R	V	R	V	R
Population	3	H	3	H	4	V	2	M	2	H	3	M	4	M
Sensitive population	4	V	4	V	5	V	3	M	4	H	3	M	4	M
Healthcare infrastructure	1	M	2	H	2	H	1	M	2	M	1	L	2	M
Water supply	1	M	2	H	3	H	4	H	4	H	4	M	5	H
Sewage and wastewater management	2	H	2	H	3	H	3	H	3	H	2	M	3	M
Rainwater management	1	M	1	M	2	H	1	M	1	M	1	L	2	M
Transportation	4	V	3	H	4	V	1	M	2	M	1	L	1	L
Energy	4	V	4	V	4	V	1	M	2	M	4	M	5	H
High-density residential zone	3	H	3	H	5	V	2	M	3	H	2	M	4	M
Low-density residential zone	2	H	2	H	2	H	1	M	2	M	3	M	4	M
Public services and commercial zone	3	H	3	H	3	H	1	M	2	M	3	M	4	M
Industrial zone	3	H	3	H	3	H	2	M	3	H	4	M	5	H
Greenspace	1	M	1	M	2	H	3	H	3	H	4	M	5	H

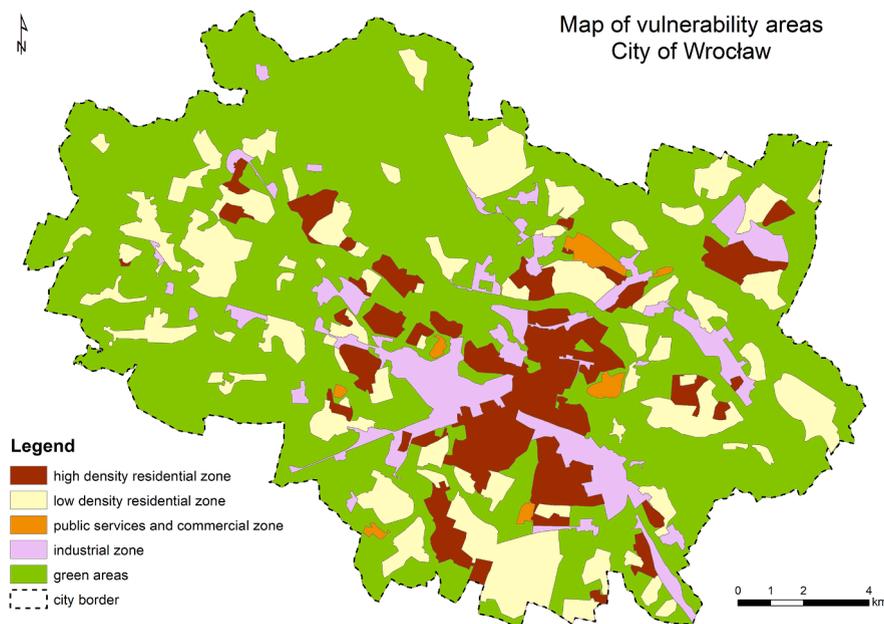


Fig. 11. Vulnerability areas of dry and hot hazards for the City of Wrocław (in colour).

observed four times on the Olawa River, five times on the Bystrzyca and Widawa rivers, and seven times on the Odra River.

4.1.6. Meteorological drought (MD)

Meteorological drought events were identified with the use of three-month SPI values obtained for each month during the 1981–2015 period. Drought conditions during the spring season (March–May) were observed for 31% of the time. The most extreme drought events were in the spring seasons in the years 1988, 1990, and 2002. SPI values were lower or equal to -2 (extreme drought), Fig. 7. Drought conditions for the summer season (June–August) were observed for 48% of the cases. Series of six consecutive dry summer seasons ($SPI \leq -0.5$) were observed from the end of the 1980s to the mid-1990s (Fig. 8). The most intense drought occurred in the summer seasons in the years 1982, 1994, and 2003 (very dry conditions), while extreme drought ($SPI \leq -2$) was not recorded.

4.1.7. Hydrological drought (HD)

The SRI index allows the identification of hydrological drought occurrence while analysing the runoff from a given basin. SRI classification was used to evaluate moisture conditions in the river catchments within the area of the City of Wrocław. Catchment conditions were classified as dry when the SRI was equal to or below -1.0 . Analysis of the temporal course of SRI values indicate that dry conditions occur every 4–8 years depending on the catchment (Fig. 9). In the Odra River catchment, up to the Olawa–Most station, these conditions were observed for 12.5% of the time, for the Olawa river for 14%, for the Ślęza river 18%, for the Bystrzyca river 26%,

Table 5

Criteria applied in MCA method and corresponding weights obtained through AHP process.

Criteria category	criteria	description	assigned weight
Adaptivity	Effectiveness	Does the option enable the achievement of the goal that was sat?	0.11
	Reliability	Does the given solution be reliable in view of the currently observed and future hazards?	0.09
	Flexibility	Does the given measure allow for the implementation of adjustments during its implementation?	0.06
	Synergy	Does the given measure, apart from reducing the dry and hot risks contribute to the achievement of other city goals?	0.07
Society and environment	Side effect	Does the measure not adversely affect other areas or weaker social groups?	0.06
	Acceptability	Does the measure politically and socially acceptable?	0.1
	Sustainability	Does the measure comply with the principles of sustainable development?	0.13
Time	Time / period of implementation	In what time frame can the measure be implemented?	0.05
	Time for achieving results	In what time period the effects of the implementation of the given measure can be expected?	0.08
Economy	Costs	The total value of the estimated costs of measure implementation	0.09
	Benefits	Estimated value of benefits resulting from the obtained results	0.16

and for the Widawa river 21% of the time.

4.2. Compound dry and hot hazards (CDH)

The total occurrence of single (drought, heatwaves) and compound hazard (CDH) in the period 1981–2020 in area of Wrocław calculated as the number of days per hazard and compound hazard divided by the total number of April–September days is presented in Fig. 10. The frequency of CDH days was also calculated on decadal time scales. Compared with the previous decades, the period 2011–2020 is characterized by an increase in the number of CDH days/decade (app. 22 days/decade). The increase in number of CDH days is mainly due to an increase in duration and frequency of heatwaves.

4.3. Multi-risk assessment

Multi-risk assessment was done while analysing the combination of probabilities and consequences according to the adopted risk categories (see Table 2). The highest risk values were attributed to the events of very high probability of occurrence and catastrophic or critical consequences.

Dry and hot hazards were estimated on the basis of the observed variabilities of the respective indices within the period 1981–2015 as well as projected changes according to climate-change scenarios. The resulting category of probability of hazard event occurrence values were developed on the grounds of accepted classification (see Section 3.5). Due to the observed and projected increase of air temperature, the highest probability of event occurrence was attributed to the events of extremely hot days, cooling degree days, and heat waves. Probabilities of occurrence of long-lasting dry spells, dry spells with high temperature, and meteorological drought as their consequence were estimated as a high. According to the accepted probability categorisation, low flows and hydrological droughts were assessed on the level of medium probability of occurrence.

The list of recognised main sectors of the city of Wrocław, which are potentially vulnerable to dry and hot hazards included: population, sensitive population, healthcare infrastructure, water supply, sewage and wastewater management, rainwater management, transportation, and energy. Vulnerability represents the propensity or predisposition of a community, system, area, or asset to be adversely affected by a certain hazard. City key component vulnerabilities were quantified according to the adopted vulnerability scale while analysing exposure to hazard, reported losses, and consequences as well as coping capacity to reduce these impacts. The resulting estimates of city vulnerabilities were verified with the expert judgments of the City Council members and stakeholders representing different city sectors. In the City of Wrocław the highest vulnerability values were assigned to the following city components: water supply, energy, transportation, and sensitive population (Table 4)

In order to address drought mitigation measures to the most vulnerable areas to dry and hot hazards, distinctive spatial city units were attributed according to vulnerability assessment. Featured categories were grouped into five types differentiating with the degree of vulnerability to dry and hot hazards: high-density residential zone (old town, city centre, residential housing), low-density residential zone (intensive and extensive single-family housing), public services and commercial zone, industrial zones, and greenspace (Fig. 11). As the most vulnerable city areas, the high-density residential zone, the industrial zone, and greenspace were identified (Table 4).

Corresponding risk assessment depended on the probability of the analysed hazard. According to risk assessment matrix, very high risks (V) were estimated for sensitive population, transportation, and energy due to extremely high temperatures. These risks are the greatest in the high-density residential zone (old town, city centre, residential housing) during heat wave episodes. Low flows and hydrological drought triggers a high risk (H) to water supply, sewage and wastewater management and energy. The biggest exposure to this risk was found for industrial zone and greenspace areas.

The resulting matrix presents the main hotspots that require appropriate measures to mitigate the effect of dry and hot hazards in the City of Wrocław area.

4.4. Mitigation and adaptation measures

Integrating drought preparedness into local land use planning is increasingly recognised as a key to reducing drought risk (Burby et al., 2000; Fu and Tang, 2013). The obtained risk matrix was used to deliver a set of recommended measures targeting the recognized hotspots. An inventory of potential measures supportive to water management and town planning strategies that should contribute to local comprehensive plans was prepared. The activities included educational, organisational, and technical actions that comply with the recognised risks (very high and high) and fulfil goals established in pursuit of reduce societal vulnerability and increased resilience to drought (Crossman, 2018).

The inventory was a starting point for the selection of measures that would constitute an optimum option for mitigating potential dry and hot hazards consequences. The process of selection was done through multi-criteria analysis (MCA) that is the tool widely recommended for adaptation options evaluation (Van Ierland et al., 2013). With the use of MCA proposed measures were assessed in terms of the performance against adopted set of criteria. In MCA process the group of experts and stakeholders was employed to frame their preference. The introduced set of criteria including are presented in the Table 5. Prior to measures evaluation the list of criteria was weighed with the use of Analytical Hierarchy Process (AHP) in the procedure of pair-wise rankings to reflect relative importance of each criteria. This was done while questioning group of experts and final weighs are summarized (see Table 5).

A list of measures was then prioritized according to the criteria and preferences identified above. The resulting list of the selected mitigation and adaptation options included measures that could be organised on the city level as well as operations that should be

implemented locally in the selected vulnerability area. The ranking results are presented in brackets:

(a) Sustainable city development (III)

The activity is focused on creating the principles for the city development process so as to minimise the potential negative consequences of climate change. Urban heat island effects and heat waves can be mitigated while using town planning solutions that protect ecological corridors and aeration wedges to secure airing and cooling of the city. It is also crucial to ensure a sustainable city design to guarantee a percentage of surface that is permeable and biologically active to decrease the heating of the city and improve the urban water budget.

(b) Rainwater management system (II)

Mitigation of dry and hot hazards in urban areas requires an effective water management system with emphasis on rainwater collection, storage, and treatment. The activity includes development of guidelines on ways and solutions for retaining rainwater and slowing its outflow after rainstorms while maintaining ecosystem services. It includes development of a holistic rainwater management strategy taking into account the predicted change in rainfall patterns, and an inventory of all system elements and the potential of water retention in reservoirs and green areas. This should be done in close connection with the spatial composition of the city, in order to obtain added value in its visual and functional form, social acceptance, and increased ecological awareness of the inhabitants.

(c) Upgrading water supply safety (VI)

This measure is aimed at increasing the security of water supply systems in periods of high temperature and water shortage. As part of the activity, a search for new freshwater resources for the City of Wrocław is planned as well as optimisation of the existing intake system. As a part of the optimisation, the existing infrastructure will be modernised and the water loss management system will be developed. Due to the identified risks related to the impact of climate phenomena on water quality, the measure also includes development of a water quality monitoring system in the network and carrying out appropriate disinfection activities in the case of exceedances in the range of the acceptable bacteria levels.

(d) Managing energy system reliability and peak demand (VII)

This measure is aimed at improving the city's energy security during increased demand for electricity in periods of high temperatures, for the needs of air-conditioning equipment and cooling systems. This action requires investments in new energy generation from renewable energy sources and distribution infrastructure as well as investments to reduce this demand, including better insulation of buildings. The action includes also a verification of the existing procedures for power blackout and water scarcity situations valid for local industry entities with regard to projected climate changes.

(e) Improving outdoor human thermal comfort (IV)

This activity is focused on building the appropriate infrastructure to ensure thermal and moisture comfort of residents and tourists during heat waves and days with extremely high temperatures. It is planned to achieve this through the introduction of natural and artificial forms of shading, providing water for drinking (street spas) and cooling purposes (drinking-water fountains, water spray curtains, water playgrounds). An important element is the adaptation of the recreational space to the needs of groups particularly sensitive to compound dry and hot hazards: the elderly and small children. These actions should focus on supplying groups of people particularly vulnerable to the risk of heat stroke with drinking water, providing air-conditioned public spaces in periods of heat waves, and shading playground areas as well as the use of permeable surfaces and materials with limited heat accumulation for their construction.

(f) Adaptation of the urban transportation system to climate change (V)

This activity is focused on the integrated development of the urban transportation system, including communication roads, pathways, infrastructure to provide additional ecological functions, and ecosystem services such as local climate regulation, mitigation of the impact of extreme weather events, sustaining an urban hydrological cycle, absorbing waste and pollution, and raising the visual value of urban space. These services for users depend on the type of transportation facility, its location relative to waterways, green areas, dominant wind direction, and the types of materials and design used. Measures are therefore concentrated on development and renovation of the existing rail and road routes to form the system of ventilation corridors that allows air from non-urban areas to enter the city centre, on supplementing routes and parking places with effective drainage and retention systems, introducing permeable surfaces and street greenery, building green roundabouts, and screening greenery of trees and shrubs along the communication tracks. Within the framework of the measure, it is also planned to adopt the existing public transport infrastructure and create advanced transit shelters that additionally bring cooling and thermal comfort for city dwellers or replacement of existing fleets with more fuel-efficient vehicles.

(g) Development of the green–blue infrastructure system (I)

The measure is focused on improving the urban water cycle, controlling urban air temperature, humidity, or moisture retention in the soil by development of blue (water-retention objects) and green (green space) infrastructure. Blue-green infrastructure (BGI) provides a mechanism for the management of rainwater discharged into rainwater drainage systems, retaining water in the urban landscape through storm-water harvesting and reuse while also reducing urban air temperatures through enhanced evapotranspiration and surface cooling. It is planned that BGI is implemented strategically targeting areas of high heat exposure and high degree of impervious area, with a special emphasis on system approach. The system approach implies linking already existing urban green areas (parks, forests, squares, green spaces, etc.) while introducing linear forms of greenery between these areas in combination with micro-retention objects that gather water from surface runoff and contribute to maintaining and developing urban biodiversity.

(h) Development of the system of information on dry and hot hazards (VIII)

This measure is aimed at ensuring an appropriate level of information and alerting the city residents about the risks related to the occurrence of dry and hot hazards and its possible consequences. Effective implementation of these tasks is possible through constant monitoring of threats and an efficient warning system. The main tasks of the system include: i) collection and distribution of dry and hot hazards information from various monitoring and alerting systems operated by different institutions; ii) assessment, analysis, and forecasting of dry and hot hazards in the city; and iii) warning and alerting the population about dry and hot hazards and providing information on response alternatives.

Resulting set of actions comply with the principles of the DRAMP. Conserved and sustainably managed water resources are planned within the actions (b), (c), and (g). These actions include increased water supply options through investment in sustainable approaches to water harvesting, locating new potential resources, and building new storage systems (Crossman, 2018). It is also planned to use data from future climate-change modelling to support a long-term strategy that reflects the estimated transformations caused by climate change with emphasis on precipitation characteristics. Actions (e) and (g) take advantage of the ability of the natural system to reduce drought risk through increased provision of ecosystem services as well as ecological restoration and biodiversity conservation (Tadesse, 2016).

Recognised within the framework of this work, spatial heterogeneity of local biophysical and socio-economic drought vulnerability characteristics (McNeeley et al., 2016) helps to implement land use planning at the landscape scale to encourage sustainable land use in drought-prone areas. This is a key aspect of the activity (a) that incorporates drought risk assessment into land use development planning. Actions (d) and (f) promotes an integrated approach to technological, policy, and institutional options that increase drought resilience (Shiferaw et al., 2014) including energy providers, local industry, and transportation.

To anticipate and communicate drought risk it is necessary to design participatory, tailored, and comprehensive drought monitoring and early warning systems, integrating multi-scale climate, soil, water, and socioeconomic indicators (UNISDR, 2015) along with real-time drought assessment products (UNCCD, FAO, and WMO, 2013; Tadesse, 2016). Within the framework of activity (h) it is planned to collect and disseminate better drought indicators (WMO and GWP, 2016), including indicators on impact, damage, loss (Tsegai et al. 2015; Bachmair et al., 2016), and vulnerability (Naumann et al., 2014) based on high spatial and temporal resolution baseline data on climate, soil, water availability/demand, and socioeconomics. It is foreseen to produce consistent drought risk assessment maps, data on impact and loss, and provide the public with free and open access to data and provide key and timely information to support decisions (UNISDR, 2015; Tadesse, 2016).

5. Discussion

Understanding the magnitude and pattern of impacts and of the factors increasing (or decreasing) susceptibility and coping abilities is vital to modifying current policies and to implementing new policies and programs to increase resilience to extreme events (Ebi and Bowen, 2016).

Observed and projected climate changes may have an explicate effect on drought and heat hazards co-occurrence. The results obtain by Mukherjee and Mishra (2021) suggest significant increases in drought-related heatwaves and affected global land area in recent periods. The Central Europe, the region where is located city of Wrocław, is becoming dryer due to an increase in the potential evapotranspiration and mean air temperature. The frequency analysis of compound events (e.g., high temperatures and droughts), done by Ionita and Nagavciuc (2021) shows that the potential evapotranspiration and the mean air temperature are becoming essential components for drought occurrence over Central Europe.

The vulnerability of cities to drought and heat is increasing in many world regions (Wang et al., 2020; Elmqvist et al., 2019; Cremades et al., 2021). Recent drought and heatwave events in Europe (García-Herrera et al., 2019; de Brito et al., 2020) highlighted the relevance of drought risk management. However, understanding and managing drought in urban areas requires a more comprehensive approach. Managing drought in a local, urban context relies on a complex relationship among water utility decision makers, officials, organized civic groups, residential customers, commercial and industrial users and regulating legal institutions (Dilling et al., 2019). In case of drought, the main issue is to adoption of proactive risk management strategies (WMO and GWP, 2014; Wilhite et al., 2014). This approach includes the analysis of the past trends and future projections, as well as the analysis of the societal and environmental exposure and vulnerability. These actions determine the drought risk, which can be managed by developing drought policies and drought management plans that are adapted to the regional, national and local context (WMO and GWP, 2014; GWP-CEE, 2015). However in relation to urban drought, there is a lack of proactive drought planning by cities (Buurman et al., 2017).

The most of the measures concerned to deal with droughts in cities are implemented by the time the drought is already ongoing. Policy responses from cities to droughts mainly focus on short-term emergency actions that disregard sustainability in the connected regional and river basin systems (Cremades et al., 2021). Therefore, Cremades et al., 2021 conclude that urban planners need to institutionalize transparency and cross-sectoral integration in multi-sector partnerships, to consider long-term land use planning together with water and energy, and to apply integrated climate services to cities.

The presented techniques employing a multi-risk matrix take a multi-hazard approach to drought, which helps to align drought policy with other disaster risk management policies (Grobicki et al., 2015; UNISDR, 2015). It also attempts to deepen the understanding of community drought and heat risk and vulnerability by developing risk profiles that consider vulnerable groups, including children, the elderly, and the sensitive population.

The developed set of measures prepare for response, and recovery from drought and heat, as well as supporting the transition towards a water-secure and drought-resilient city through a systematic approach comprising sustainable urban planning and water management. They employ mix of hard infrastructure and soft solutions, such as capacity building, green infrastructure, and nature-based solutions to absorb and recover from the effects of drought (Coates and Smith, 2012). Local comprehensive plans developed through experts' analysis and public consensus serve as a policy document building towards future development (Berke and Smith, 2009). This creates the basis for a preventive, long-term risk management culture supported by drought prevention, mitigation, and adaptation strategies (Logar and van den Bergh, 2013; UNCCD, FAO, and WMO, 2013; Tsegai et al., 2015).

Dissemination of knowledge and deepening the community's understanding of existing drought and heat adaptation practices (Milgroom and Giller, 2013) is scheduled in all planned activities. Dissemination of information by creating dialogues, educating, and informing citizens of drought risk (Tadesse, 2016) will help to increase human adaptive capacity (Lemos et al., 2016), especially social capital (Chen et al., 2014).

6. Conclusions

The proposed framework methodology for multi-hazard risk assessment combines a system of indicators for hazards investigation with vulnerability assessment components (exposure, sensitivity, and impacts). The selection of indicators attempted to describe dry and hot hazards that may co-occur with different drought phases (heat waves, long lasting dry spells, extremely hot days, prolonged cooling degree days, low flows) and impact the vulnerable city components. The main socio-economic sectors were examined in terms of their vulnerabilities to dry and hot hazards with regard to the spatial variation of sensitive city components according to systematized method for expert judgment elicitation and integration including MCA and AHP procedures. Estimated risk levels were used to propose a set of measures including educational, organisational, and technical solutions that addressed recognized goals to adapt to drought and cope with impacts in pursuit of avoiding potential water shortage summarized in DRAMP program.

The innovations of this study is to provide a roadmap for compound various types of hazard assessment through combined multi-risk approach. The potential application of this framework at the city level facilitate a city to set up adaptation and mitigation plan while implying targeted and prioritised measures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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