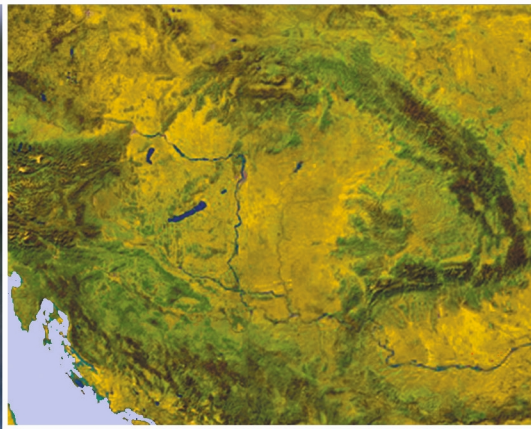


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The WRF model as a new tool for investigating climate change in the Carpathian region – Near-future projections of temperature and precipitation

ÁKOS JÁNOS VARGA¹, ZSUZSANNA ZEMPLÉNI² and HAJNALKA BREUER¹

Abstract

This study presents the first application of the Weather Research and Forecasting (WRF) model for regional climate modelling in Hungary, specifically adapted for the Carpathian Basin. Simulations for the historical (1985–2010) and future (2020–2045) periods were conducted using WRF with a 10 km grid spacing, downscaling the MPI-ESM1-2-LR global climate model from the sixth phase of the Coupled Model Intercomparison Project (CMIP6). The future simulation employs the high-emission SSP5-8.5 scenario. The CARPATCLIM observational dataset was used for model evaluation and bias correction. Expected changes in mean temperature and precipitation between the future and historical periods are assessed based on the bias-corrected WRF simulations. WRF projects a spatially averaged temperature increase of 1 °C in winter, 0.7 °C in summer, and 0.6 °C in spring and autumn over Hungary. Precipitation is projected to increase by 12 percent in winter, 31 percent in spring, and 21 percent in autumn, with no significant change in summer. While future climate change assessments should always be based on multiple model simulations, this study demonstrates the utility of WRF as a regional climate model for the Carpathian region.

Keywords: climate change, regional climate model, WRF model, temperature, precipitation

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Introduction

Regional climate models (RCMs) are widely used to study climate processes and analyse climate change at a fine-scale regional level (GIORGI, F. 2019). A wide range of RCM simulations is now available from internationally coordinated projects like the Coordinated Regional Climate Downscaling Experiment (CORDEX) for various regions, including Europe (VAUTARD, R. *et al.* 2021). However, adapting RCMs for specific countries is also justified. It allows for greater flexibility in model tuning and evaluation over the re-

gion of interest and enables adjustments to the model output based on its intended use (e.g., output frequency and variables). Internationally available RCM simulations, along with targeted national model runs, are essential for obtaining future climate information. They support adaptation and mitigation strategies and facilitate uncertainty assessment (RUMMUKAINEN, M. 2016; GUTOWSKI, W.J. *et al.* 2020).

In Hungary, four models have been adapted for regional climate modelling: REMO and ALADIN-Climate at the Hungarian Meteorological Service (HungaroMet) (Csima,

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G. and HORÁNYI, A. 2008; SZÉPSZÓ, G. and HORÁNYI, A. 2008; BÁN, B. *et al.* 2021; SUGA, R. *et al.* 2021; MEGYERI-KOROTAI, O.A. *et al.* 2023), and PRECIS and RegCM at the Department of Meteorology at Eötvös Loránd University (ELTE) (BARTHOLY, J. *et al.* 2009; TORMA, Cs.Zs. *et al.* 2011; PIECZKA, I. *et al.* 2017; KALMÁR, T. *et al.* 2021). These models have been extensively evaluated and applied to study various aspects of climate change. In addition to general assessments of temperature and precipitation changes (e.g. KRÜZSELYI, I. *et al.* 2011), they have been used to investigate specific phenomena such as heatwaves (GÖNDÖCS, J. *et al.* 2018), air quality (PIECZKA, I. *et al.* 2019), river runoff (KIS, A. *et al.* 2020), and urban climate (ALLAGA-ZSEBEHÁZI, G. 2021).

The Weather Research and Forecasting (WRF) model (SKAMAROCK, W.C. *et al.* 2019) has been widely used as a regional climate model globally (e.g. CALDWELL, P. *et al.* 2009; HEIKKILÄ, U. *et al.* 2011; MARTA-ALMEIDA, M. *et al.* 2016; SRIVASTAVA, A.K. *et al.* 2023). In Hungary, WRF has long been used for numerical weather prediction (HORVÁTH, Á. *et al.* 2015), but its application as an RCM is a novel approach in the country. We began the adaptation of WRF by conducting short-term sensitivity studies to evaluate the performance of different physical and dynamical settings (VARGA, Á.J. and BREUER, H. 2020). We then conducted an evaluation run for the 1985–2010 period, driven by the ERA5 reanalysis (HERSBACH, H. *et al.* 2020). The validation results, previously published for various meteorological variables such as convective environmental parameters, temperature, precipitation, global radiation, and snow depth, are available in VARGA, Á.J. and BREUER, H. (2022, 2023, 2024a).

This study presents results from WRF regional climate simulations for a historical period (1985–2010) and a future period (2020–2045). The simulations are driven by a general circulation model from the sixth phase of the Coupled Model Intercomparison Project (CMIP6), marking the first time a CMIP6 model has been downscaled specifically for

the Carpathian region. The model is evaluated and bias-corrected using observational data from the CARPATCLIM dataset. Expected changes in monthly and seasonal mean temperature and precipitation are presented. The main goal is to demonstrate the suitability and initial applications of WRF as a regional climate model for the Carpathian region.

Data and methods

CARPATCLIM observations

Observational temperature and precipitation data were obtained from the CARPATCLIM dataset (SZALAI, S. *et al.* 2013; SPINONI, J. *et al.* 2015). CARPATCLIM consists of quality-controlled, homogenized daily weather station observations interpolated to a 0.1° grid. It covers the period 1961–2010 and the region 44°–50°N, 17°–27°E, which also defines our study area. In this study, CARPATCLIM is used to evaluate the historical WRF simulation for the 1985–2010 period and serves as a reference for bias correction.

WRF model configuration

The Weather Research and Forecasting (WRF) model, originally developed in the United States, is a highly flexible, open-source meteorological model. It is particularly well-suited for mesoscale applications due to its non-hydrostatic dynamical core.

For the regional climate simulations in this study, the Advanced Research WRF (ARW) version 4.2 (SKAMAROCK, W.C. *et al.* 2019) was configured on a Lambert conformal conic projection with two one-way nested domains (Figure 1). The outer domain, covering the Med-CORDEX region (RUTI, P.M. *et al.* 2016), has a horizontal grid spacing of 50 km with 110×69 grid points. The inner domain has a 10 km grid spacing with 226×131 grid points. This study presents results only for the 10 km

runs, while the 50 km runs served as an intermediate step to downscale the relatively coarse (~200 km) general circulation model data. The 10 km grid spacing was selected as a compromise between regional-scale detail and the computational cost of multi-decadal climate simulations. At this resolution, deep convection is still parameterized, and the simulation is therefore not a convection-permitting simulation (PREIN, A.F. *et al.* 2015). Vertically, the model employs 61 hybrid sigma-pressure levels, with the top at 50 hPa.

The initial and boundary conditions for the WRF RCM were derived from the low-resolution (~200 km) version of the Max Planck Institute for Meteorology Earth System Model version 1.2 (MPI-ESM1-2-LR) (MAURITSSEN, T. *et al.* 2019), a participant in the sixth phase of the Coupled Model Intercomparison Project (CMIP6) (EYRING, V. *et al.* 2016). Lateral boundary conditions were updated every

six hours. The historical CMIP6 simulations reflect climate change conditions consistent with observed data. For the future period, the global model forcing is based on the high-emission SSP5-8.5 scenario, which represents a worst-case fossil-fuel-based development pathway for the 21st century (MEINSHAUSEN, M. *et al.* 2020).

The regional climate simulations for the historical period were initiated on 1 July 1984 at 00 UTC and ended on 1 January 2011 at 00 UTC. For the future period, the model integration started on 1 July 2019 at 00 UTC and ended on 1 January 2046 at 00 UTC. The future period was selected to focus on near-term climate change impacts, as extending the simulations to the end of the century would have substantially increased the computational requirements. The first six months of both periods served as a spin-up period and were excluded from the analysis.

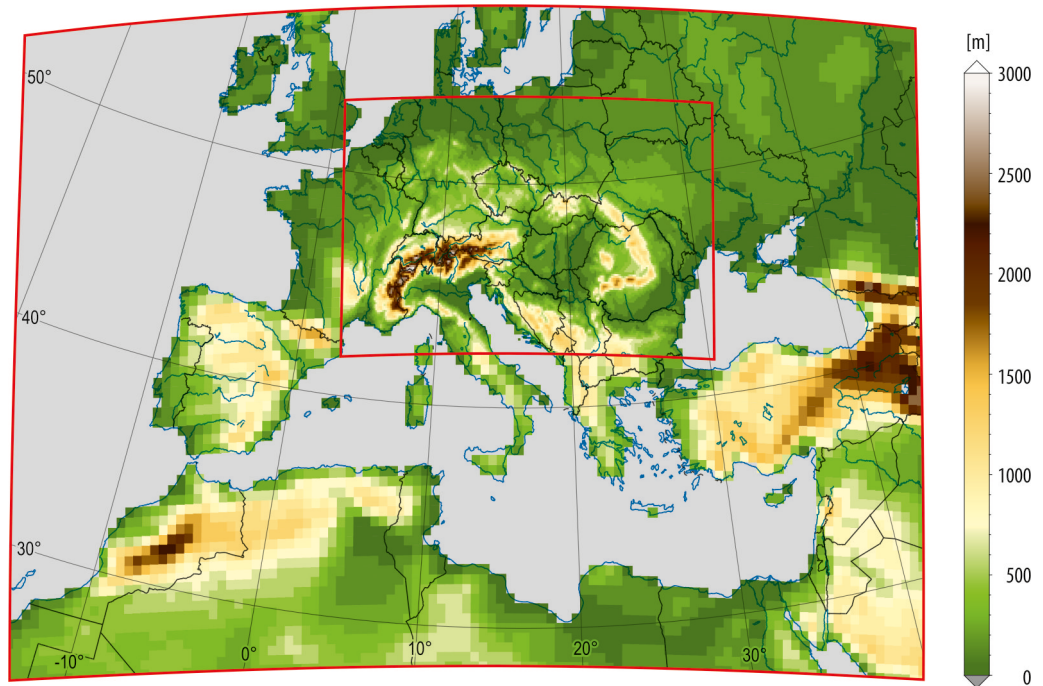


Fig. 1. Geographical coverage and topography of the WRF regional climate model domains.

Source: Authors' own elaboration.

The WRF physical parameterizations include the Rapid Radiative Transfer Model for General Circulation Models (RRTMG) for radiative transfer (IACONO, M.J. *et al.* 2008), the Kain-Fritsch scheme for deep convection (KAIN, J.S. 2004), the Thompson scheme for microphysics (THOMPSON, G. *et al.* 2008), and the Mellor-Yamada-Janjić (MYJ) parameterization for the planetary boundary layer (JANJIĆ, Z.I. 1994). The surface layer uses the Eta model's similarity scheme, while the Noah-Multiparameterization Land Surface Model (Noah-MP) is employed for land surface processes (Niu, G.Y. *et al.* 2011). The model configuration was informed by previous sensitivity experiments conducted during the adaptation of WRF for the Carpathian region, including those presented by VARGA, Á.J. and BREUER, H. (2020). These experiments showed that model performance depends strongly on the selected physics schemes and that no single configuration performed best for all evaluated variables and seasons. Therefore, the final configuration was selected based on the broader experience gained during the adaptation process rather than by directly adopting a single best-performing setup from the sensitivity experiments.

Three-hourly temperature and precipitation values from WRF were interpolated from the native Lambert conformal projection to a regular 0.1° grid using bilinear interpolation ("remapbil" in Climate Data Operators (CDO); SCHULZWEIDA, U. 2023) to facilitate comparison with CARPATCLIM observations and the bias correction procedure. Daily mean surface (2 m) temperature and total daily precipitation were then calculated from the three-hourly output.

Bias correction and climate change assessment

Bias correction was applied to daily temperature and precipitation fields using quantile mapping (the "QuantileMapping" function in the *ibicus* Python package; SPULER, F.R. *et al.* 2024). Quantile mapping adjusts

the distribution of model-simulated data to better match observed data by aligning the cumulative distribution function (CDF) of the model with that of the observations (CANNON, A.J. *et al.* 2015), thereby correcting systematic biases. However, the method assumes that model biases remain constant over time. To account for seasonality, a 31-day running window was used during the correction process. The correction function was calibrated using CARPATCLIM observations and the historical WRF simulation (1985–2010) and subsequently applied to both the historical and future WRF simulations. In the following, WRF_RAW refers to the WRF output before bias correction, while WRF_BC refers to the corresponding bias-corrected WRF output. Finally, monthly and seasonal climate averages were computed from the bias-corrected data for the historical (1985–2010) and future (2020–2045) periods.

Climate change is assessed using bias-corrected data by comparing mean temperature change (°C) and relative precipitation change (%) between the historical and future periods. The study area corresponds to the CARPATCLIM region. Spatial distributions of model errors and temperature and precipitation changes are shown for the entire region, while spatially averaged monthly means are presented for Hungary.

Results and discussion

Evaluation of the historical (1985–2010) simulation

Figure 2 shows the observed and WRF-simulated annual cycles of temperature and precipitation for the historical (1985–2010) period, highlighting both the raw model biases and the effects of bias correction. The raw WRF simulation underestimates the spatially averaged monthly mean temperature over Hungary by 1.9–2.1 °C in winter and by 0.9–1.4 °C in spring, compared to the CARPATCLIM observations. This cold bias

is attributed to the inadequate treatment of snow cover, specifically the overestimation of snow depth and snow albedo in winter and early spring (GARCÍA-DÍEZ, M. *et al.* 2015; VARGA, Á.J. and BREUER, H. 2024b). In summer, slight warm biases ($< 1\text{ }^{\circ}\text{C}$) are observed. Precipitation is overestimated by 33–50 per-

cent in spring, and by 68 percent in January, while dry biases of 12–36 percent appear in summer and September. The figure also demonstrates that biases in the mean and median values are effectively corrected by the quantile mapping method for both temperature and precipitation.

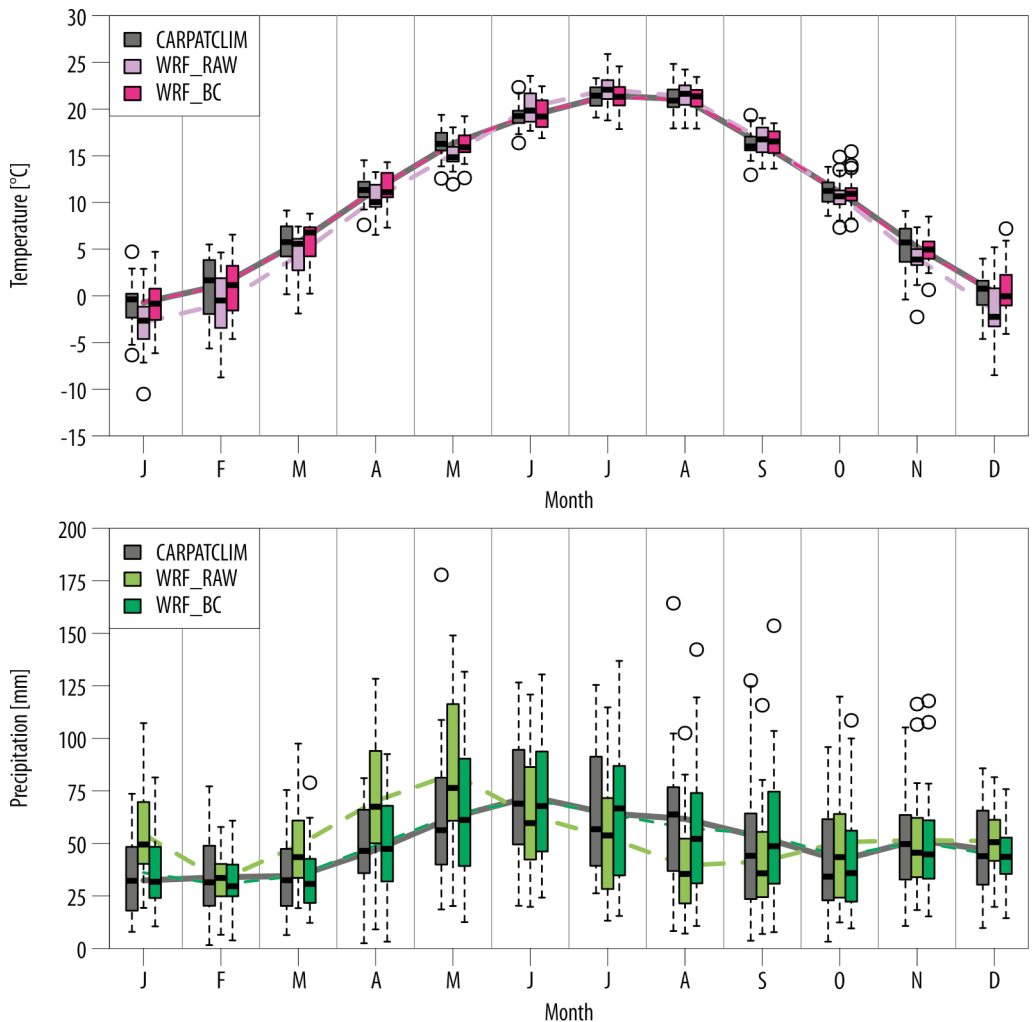


Fig. 2. Annual cycle of monthly mean temperature (top) and precipitation (bottom) from the CARPATCLIM observations, as well as the raw (WRF_RAW) and bias-corrected (WRF_BC) WRF simulations for the 1985–2010 period, spatially averaged over Hungary. The solid line represents mean values for observations, while the dashed lines represent the mean values for the raw and bias-corrected WRF simulations.

Source: Authors' own elaboration.

The spatial distribution of seasonal mean biases in the raw WRF model also reflects the extensive precipitation overestimation in winter and spring, and the underestimation in summer (Figure 3). Errors are smallest in autumn. Precipitation overestimation is most pronounced on the windward side of the Carpathian Mountains. However, the bias correction effectively reduces model errors across all seasons and the entire study area. Accordingly, although the assumption that model biases remain constant over time must be acknowledged, the bias-corrected model is expected to provide an improved representation of future climate conditions. Based on the good performance of the bias adjustment, as demonstrated in Figure 2 and 3, temperature and precipitation projections for the future period are presented only for the bias-corrected fields.

Future (2020–2045) projections of temperature and precipitation

The bias-corrected WRF model projects a spatially averaged temperature increase of

0.7 °C in Hungary between the near-future (2020–2045) and historical (1985–2010) periods. The largest seasonal increase is projected in winter (1 °C), followed by summer (0.7 °C), and spring and autumn (0.6 °C) (Figure 4). This projected warming is lower than the approximately 1.4 °C annual increase reported by Torma, Cs.Zs. and Kis, A. (2022) for the Carpathian region in 2021–2050 relative to 1976–2005. Part of this difference can be explained by the different reference and projection periods used in the two studies. Over Hungary, the mean temperature difference between the 1976–2005 and 1985–2010 reference periods in the CARPATCLIM dataset is 0.3 °C. Additional factors may include differences in the analysed domain (Hungary versus the entire Carpathian region) and the use of a single simulation rather than a multi-model ensemble. Since Torma, Cs.Zs. and Kis, A. (2022) identified CCLM4 as one of the best-performing regional climate models in their evaluation, we additionally analysed a bias-corrected EURO-CORDEX CCLM4 simulation driven by MPI-ESM-LR (Vautard, R. et al. 2013; Jacob, D. et al. 2014). This yielded a mean annual warming of 0.73 °C in Hungary

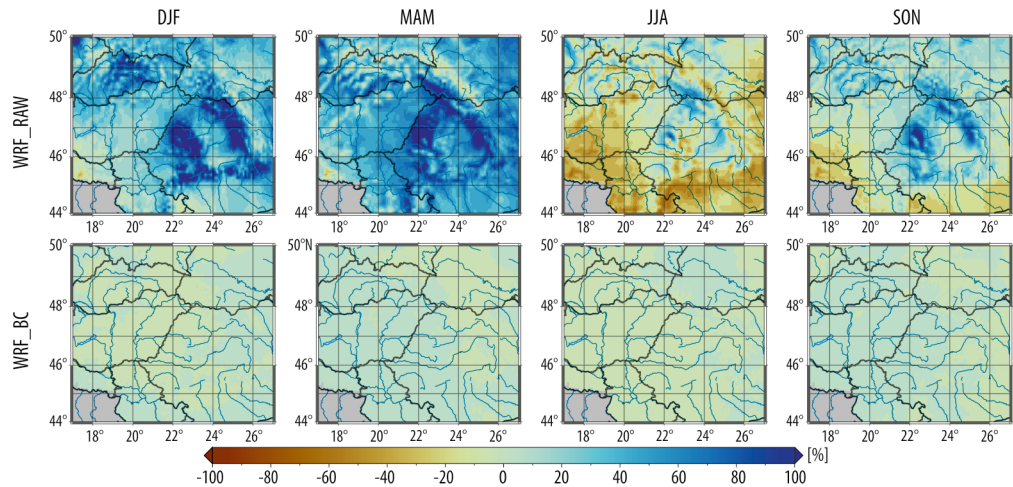


Fig. 3. Relative error of seasonal mean precipitation from the raw (WRF_RAW) and bias-corrected (WRF_BC) WRF simulations during the 1985–2010 period, with respect to the CARPATCLIM observations (DJF = winter, MAM = spring, JJA = summer, SON = autumn). Source: Authors’ own elaboration.

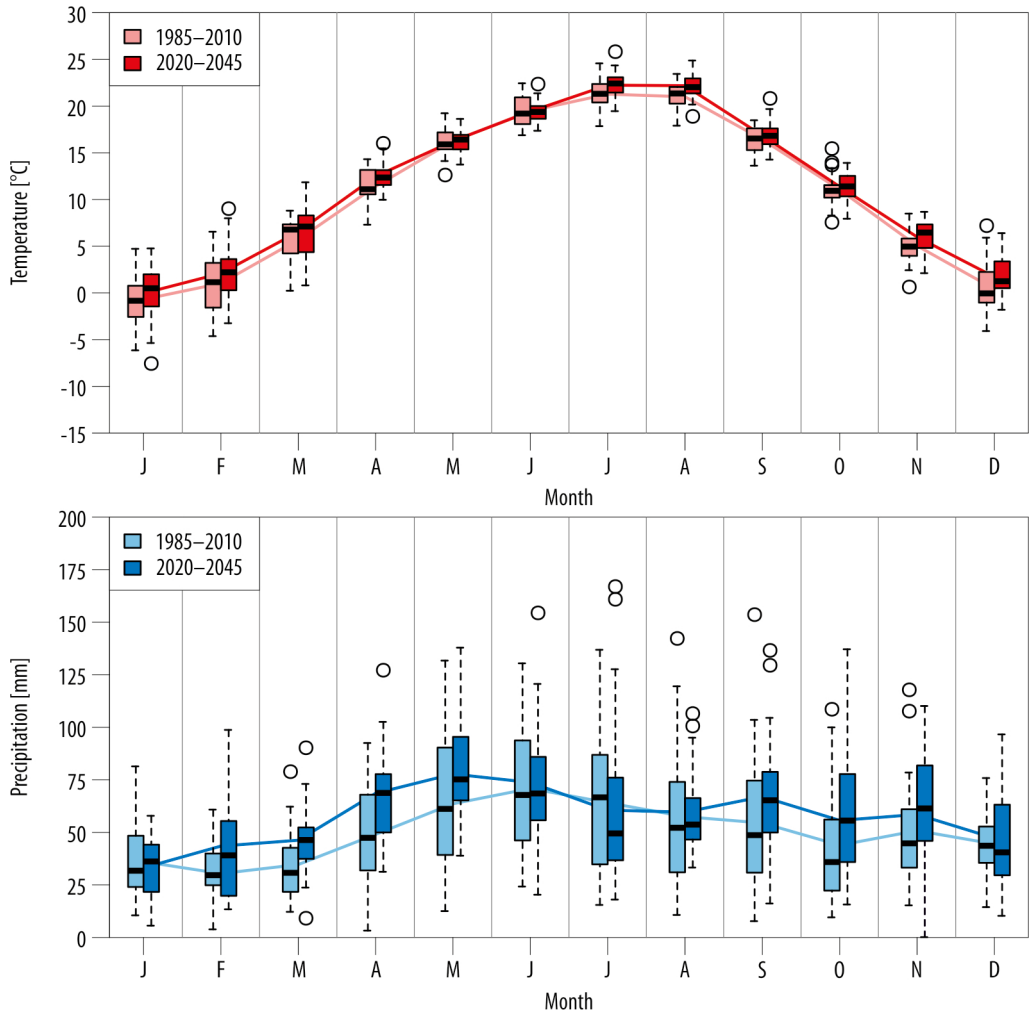


Fig. 4. Annual cycle of monthly mean temperature (top) and precipitation (bottom) from the bias-corrected WRF simulations for the historical (1985–2010) and future (2020–2045) periods, spatially averaged over Hungary. The lines represent the mean values. Source: Authors' own elaboration.

between 1985–2010 and 2021–2045, which is consistent with the 0.7 °C warming projected by our WRF simulation.

For precipitation, the WRF model projects a spatially averaged increase of 16 percent over Hungary for the entire 26-year period. However, this change is not evenly distributed across the seasons: winter precipitation is expected to increase by 12 percent, spring by 31 percent, and autumn by 21 percent, while

summer precipitation is projected to remain nearly unchanged, with only a 1 percent increase. A preliminary analysis of the number of days with daily precipitation exceeding specific thresholds indicates that changes between future and historical periods are negligible below the 5 mm/day threshold but exceed 30 percent for thresholds above 15 mm/day (not shown). This suggests an increase in the occurrence of extreme pre-

cipitation. This finding is consistent with previous studies for the Carpathian region and Europe, which project increasing heavy precipitation intensity and frequency under climate change (RAJCZAK, J. and SCHÄR, C. 2017; TORMA, Cs.Zs. et al. 2020). However, a more comprehensive analysis of extremes will be conducted in future research.

The spatial distribution of seasonal mean temperature changes in the near future, relative to the historical period, shows positive values across the study area, with the greatest warming occurring in winter (Figure 5). Winter warming is most pronounced in the northern and eastern parts of the region, exceeding 1.5 °C east of the Carpathian Mountains. This southwest-northeast gradient in projected winter warming, also observed in

spring, is consistent with previous studies using the ensemble mean of eight CORDEX regional climate simulations for the Carpathian region (TORMA, Cs.Zs. and KÍS, A. 2022), as well as the large EURO-CORDEX ensemble (COPPOLA, E. et al. 2021). The amplified winter and spring warming in northern and eastern Europe is attributed to reduced snow cover, which leads to greater solar radiation absorption and enhances warming via the snow albedo feedback. In summer and autumn, no significant spatial patterns of temperature change are observed, except for slight increases over the mountain ranges of the Southern Carpathians. This contrasts with CORDEX simulations, which show a more marked north–south gradient in summer, with stronger warming in the southern

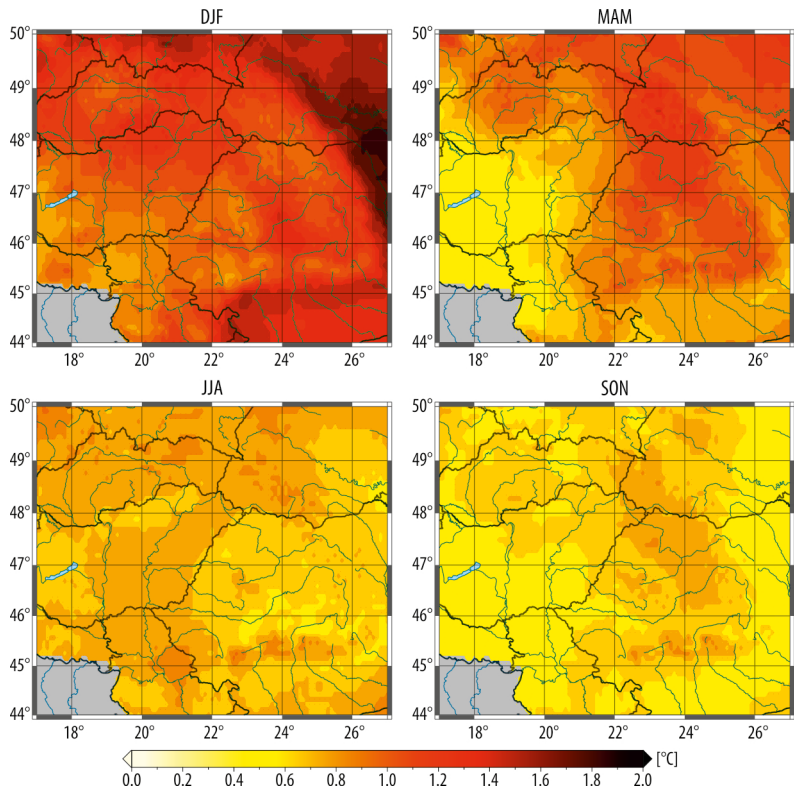


Fig.5. Projected seasonal mean temperature change (2020–2045 relative to 1985–2010) based on the bias-corrected WRF simulations (DJF = winter, MAM = spring, JJA = summer, SON = autumn). Source: Authors' own elaboration.

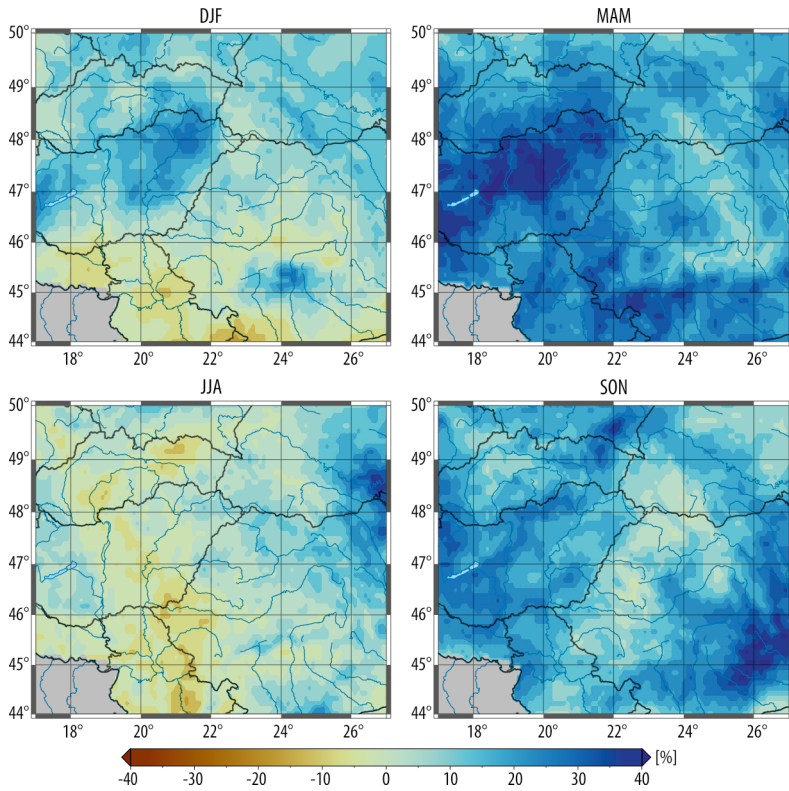


Fig. 6. Projected seasonal mean precipitation change (2020–2045 relative to 1985–2010) based on the bias-corrected WRF simulations (DJF = winter, MAM = spring, JJA = summer, SON = autumn). Source: Authors' own elaboration.

parts (COPPOLA, E. *et al.* 2021; TORMA, Cs.Zs. and KIS, A. 2022). Additionally, the ensemble mean of eight CORDEX models analysed by TORMA, Cs.Zs. and KIS, A. (2022) projects the largest warming in summer (2021–2050 relative to 1976–2005) for the Carpathian region, whereas our WRF simulations project stronger winter warming. These discrepancies may arise from the specific features of the MPI-ESM1-2-LR model used to drive our WRF simulations. Additionally, while the CORDEX models were run at similar grid spacing (~ 10 km or 0.11°) and applied a high-end emission scenario (RCP8.5), their boundary conditions were derived from general circulation models based on the CMIP5 protocol, the predecessor of CMIP6, which

was used in our WRF simulations. COPPOLA, E. *et al.* (2021) demonstrated that the CMIP6 ensemble projects stronger warming over Europe in both winter and summer compared to CMIP5, indicating that differences in forcing data may influence the climate change signals of the RCMs. Variations in the temporal coverage and bias correction methods across the studies prevent direct quantitative comparison.

The analysis of the spatial distribution of seasonal mean precipitation change between the near-future and historical periods (Figure 6) shows the largest increases in spring and autumn. The most significant relative increases across the Carpathian region occur over Hungary in both winter

and spring. Precipitation change also exhibits an orographic effect, with larger increases on the eastern (leeward) side of the Carpathian Mountains compared to the western (windward) side. Our results align well with the ensemble mean of six bias-corrected RCMs analysed for the Carpathian region, which also project increasing precipitation in winter, spring, and autumn during the near-future period (TORMA, Cs.Zs. et al. 2020). However, while their ensemble projects decreasing summer precipitation, our WRF simulations indicate a more heterogeneous summer response, with both drying and wetting regions and only a 1 percent increase in the spatially averaged precipitation. Furthermore, the pronounced differences across the Carpathian Mountains are consistent with the strong influence of orography on precipitation change identified by TORMA, Cs.Zs. et al. (2020). However, it should be noted that summer precipitation is primarily convective in nature, making it highly variable spatially and temporally. Its simulation is strongly influenced by model physics and dynamics, leading to high uncertainty in future projections of mean summer precipitation (RAJCZAK, J. and SCHÄR, C. 2017).

Conclusions

The adaptation and application of the WRF model as a regional climate model for the Carpathian region are demonstrated through near-future (2020–2045) projections of temperature and precipitation. WRF was run with a 10 km horizontal grid spacing, driven by the MPI-ESM1-2-LR model from the CMIP6 protocol at the outer boundaries, using the SSP5-8.5 emission scenario. The model was validated and bias-corrected against the CARPATCLIM observational dataset for the historical period (1985–2010). The bias-corrected model was then used to estimate future changes in monthly and seasonal mean temperature and precipitation in the region.

According to the bias-corrected projections, the spatially averaged seasonal mean temperature over Hungary is expected to increase by 1 °C in winter, 0.7 °C in summer, and 0.6 °C in both spring and autumn, relative to the historical period. Precipitation is projected to increase by 12 percent in winter, 31 percent in spring, and 21 percent in autumn, with no noticeable change in summer.

While similarities with previous studies on projected temperature and precipitation changes, based on the state-of-the-art ensemble of CORDEX regional climate simulations, were found, a few discrepancies also emerged. This highlights the importance of using an ensemble framework to obtain robust and reliable climate projections. Individual simulations, such as the one presented here, should be interpreted with caution. Nevertheless, the utility of WRF as a regional climate model for the Carpathian region has been demonstrated, providing a basis for further WRF-based applications in the region, including future kilometre-scale, convection-permitting simulations.

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Progressive lake warming in Central Europe: six decades of trends in lake heat waves in Poland

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Abstract

Against the backdrop of observed climate changes, there is growing interest in the extreme course of processes and phenomena in the natural environment. This trend is also being explored in relation to various components of the hydrosphere, in which one fundamental characteristic is water temperature. The aim of this study was to assess the temporal and spatial variability of heat waves occurring in lakes. The research material included daily water temperatures from 1964 to 2023 for nine temperate-zone lakes with diverse morphometric parameters. The study found that the duration, cumulative intensity, and maximum intensity of heat waves increased over the last six decades. In general, the first half of the analysed period was relatively stable in the context of the study, whereas the most recent three decades showed an increase in various heat wave characteristics. A sharp increase in the duration and cumulative intensity of heat waves was observed, along with greater variability in these parameters across years and among the studied lakes. The average rate of change in heat wave duration, maximum intensity, and cumulative intensity increased by 15 days per decade, 0.5 °C per decade, and 50 °C per decade, respectively. Additionally, the changes in average heat wave duration and cumulative intensity more than doubled between 1996 and 2023. These findings should be considered unfavourable in both natural processes and the economic aspects of lake utilization. This situation creates a new reality that should be taken into account when considering potential restoration efforts to improve water quality.

Keywords: extreme hydrological events, global warming, inland water, Poland

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Introduction

The response of natural environment components to observed climate changes varies due to the complexity of their interactions with the atmosphere. A clear reaction is observed in the surface water layer of lakes, where air temperature determines the thermal conditions of these ecosystems. Lake temperature is widely recognized as a fundamental property of water, influencing the frequency

and intensity of numerous processes. As a result, the study of thermal regimes attracts significant interest and holds an interdisciplinary dimension, mainly addressing two key aspects: biotic and abiotic conditions. The increase in water temperature in Lake Iseo (Italy) has been linked to higher nutrient concentrations (DORY, F. *et al.* 2024). Studies on *Escherichia coli* in lakes have revealed significant interactions affecting *E. coli* survival, particularly between temperature and to-

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tal dissolved solids, as well as temperature and coexisting microbes (YONEDA, I. *et al.* 2024). Temperature has been positively correlated with methane (CH_4) concentration in the water column, bubble emissions, and diffusion, as confirmed by studies of two polymictic lakes in Brazil (PALMA-SILVA, C. *et al.* 2013). The low abundance of large cladocera in shallow urban lakes (Lingan) has been attributed to high water temperatures, food limitations, and predator pressure (CHEN, G. 2021). The way lakes function is undergoing a gradual transformation due to climate warming and the associated rise in water temperature. Lake warming has been well documented in many regions worldwide. The surface water temperature of Lake Nam Co (Tibetan Plateau) increased significantly ($p < 0.05$) between 1963 and 2019, at a rate of 0.41°C per decade (GUO, L. *et al.* 2023). In Lake Balaton (Hungary), water temperature has been rising by 0.7°C per decade, with a more pronounced warming trend in annual minimum and winter temperatures (LI, H. *et al.* 2024). Based on data from over 500 lakes in north-western Canada, the average increase in water temperature during the open-water season has been recorded at 0.03°C per year (ATTIAH, G. *et al.* 2023).

However, increasing attention is being given to extreme events, whose occurrence may have negative environmental consequences. Unlike the rise in average annual temperature, heat waves are considered more significant for natural populations (MAMERI, D. *et al.* 2020), including those in inland waters. Regarding temperature, the greatest impact may result from increased climate variability and the number of extremely hot days and heat waves (HANDISYDE, N. *et al.* 2006). CHEN, W. *et al.* (2020) highlight the steady rise in the frequency of extreme climate events, which could have harmful consequences for lake ecosystems. Exceeding certain thermal thresholds can affect lake functioning. Changes in water mixing patterns may occur once a specific temperature threshold is surpassed (SCHMID, M. *et al.* 2014). Prolonged

above-average temperatures are linked to warming of water bodies, limiting lake overturning and potentially leading to anoxic conditions at the lake bottom (SMOYER-TOMIC, K.E. *et al.* 2003).

An analysis of physio-chemical thresholds in French lakes found that maximum water temperature plays a crucial role in fish species distribution (ROUBEIX, V. *et al.* 2017). The impact of high temperatures, alongside changes in the N:P ratio, contributed to declines in zooplankton density over time and a reduction in cladocerans relative to copepods (KELLY, P.T. *et al.* 2024). Internal loading in the shallow Littoistenjärvi lake (Finland) showed a significant positive correlation with maximum water temperature and pH (SARVALA, J. *et al.* 2020). Many salmonid fish species are at risk of thermal stress and habitat loss due to rising temperatures during summer heat waves (ADAMEK, M. *et al.* 2023). From a climate perspective, even a short-term heat wave can have widespread hydrological effects within a given year (WHITFIELD, P.H. *et al.* 2024). Therefore, in the context of existing knowledge on lake thermal regimes, a significant research trend has emerged in recent years, focusing on extreme events – specifically, lake heat waves (ZHANG, K.X. and YAO, Y.L. 2023; DUAN, Z. *et al.* 2024; WU, Y. *et al.* 2024). In Poland, lakes represent a crucial element of the natural environment, influencing not only ecological conditions but also the national economy (NOWAK, B. and DUMIŃSKI, G. 2020). Polish lakes have been studied in relation to thermal conditions, a fundamental characteristic of the hydrosphere (ZHU, S. *et al.* 2020). To date, research on heat waves in Polish lakes has analysed the 2018 event against data from 1987–2020 (SUN, J. *et al.* 2025).

Results indicate that the European heat wave of 2018 increased the mean and maximum lake surface water temperatures (LSWTs) by 2.35°C and 3.38°C , respectively, relative to the multi-year average. These findings encourage further analysis and a deeper understanding of heat wave occurrences in

Polish lakes. Detailed monitoring of water temperatures in selected Polish lakes enables the realization of such research objectives. More broadly, this study, based on sixty years of daily field measurements from nine lakes with diverse morphometric characteristics, contributes to the global understanding of lake ecosystem functioning. Against this background, the study aimed to determine the frequency and duration of lake heat waves and to identify trends in their occurrence over the past six decades. It should be emphasised that this approach aligns with the current direction of hydrological research, which increasingly focuses on extreme events. As highlighted by JAMALI, M. and ESLAMIAN, S. (2023), in the case of extreme hydrological events, trend analysis is an appropriate method for obtaining the essential practical information required for regional water resource management and planning.

Materials and methods

Study area and materials

The study uses surface water temperature data from nine lakes (Table 1) located in the lake districts of northern Poland (Figure 1).

The measurements were systematically collected by the Institute of Meteorology and Water Management (IMGW). The dataset comprises detailed daily water temperature records spanning six decades (1964–2023). Measurements were taken at a fixed location in each lake, at a depth of 0.4 m, every morning at 6:00 UTC. The study also uses daily air temperature data collected by the same institute over the same period in accordance with standard meteorological measurement procedures.

Methods

The methodology proposed by HOBDDAY, A.J. et al. (2016) was used to identify lake water heat waves (LHW). An anomalously warm event lasting at least five consecutive days, during which water temperature exceeded the threshold, was classified as an LHW. Threshold values for each lake for each day of the year were defined based on the 90th percentile values from a 30-year historical baseline period. In this study, 1964–1993 was adopted as the baseline period. Events separated by gaps of two days or fewer and subsequent heat wave events of five days or more were treated as a single continuous heat wave event. For each LHW, the start date, end

Table 1. Lakes morphometric parameters

No.	Lake	Latitude North (Lake)	Longitude East (Lake)	Depth*		Area,* ha	Altitude,* m a.s.l.	Volume,* m ³
				max, m	mean, m			
1	Ślowskie	51.89	16.02	12.3	5.2	822.5	56.9	42,664.80
2	Gardno	54.71	17.39	2.6	1.3	2337.5	0.3	30,950.50
3	Łebsko	54.65	17.10	6.3	1.6	7020.0	0.3	117,521.00
4	Charzykowskie	53.77	17.50	30.5	9.8	1336.0	120.0	134,533.20
5	Jeziorak	53.72	19.62	12.9	4.1	3152.5	99.2	141,594.20
6	Mikołajskie	53.77	21.60	25.9	11.2	424.0	115.7	55,739.70
7	Hańcza	54.27	22.81	106.1	38.7	291.5	227.3	120,364.10
8	Białe Augustowskie	53.86	23.03	30.0	8.7	476.6	122.0	41,700.00
9	Studzieniczne	53.87	23.12	30.5	8.7	244.0	123.4	22,073.60

*After CHOŃSKI, A. 2006.

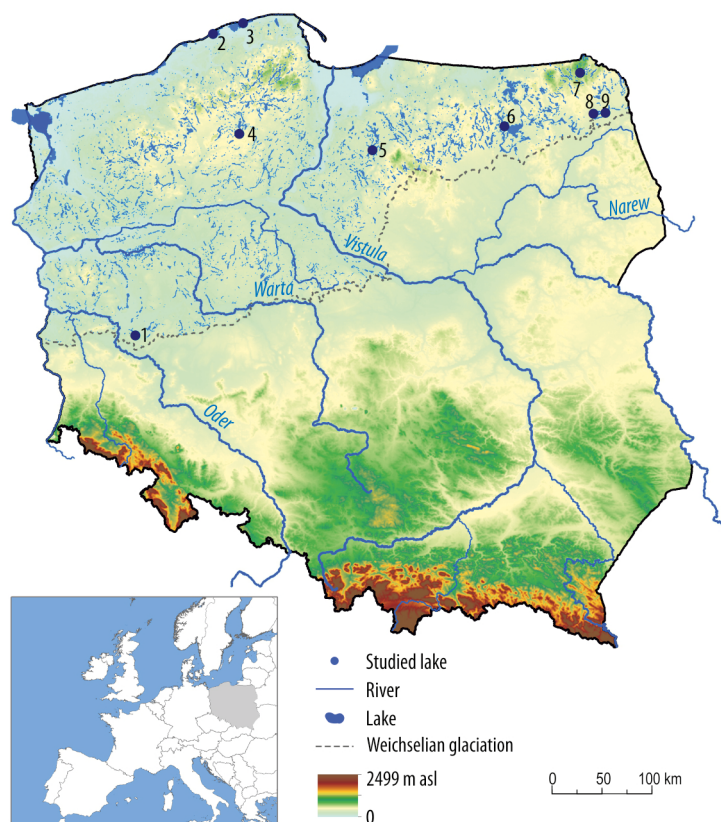


Fig. 1. Location of studied lake inside the territory of Poland. Lakes: 1 = Sławskie; 2 = Gardno; 3 = Łebsko; 4 = Charzykowski; 5 = Jeziorak; 6 = Mikołajskie; 7 = Hańcza; 8 = Białe Augustowskie; 9 = Studzienne. Source: Authors' own elaboration.

date, duration (DT), mean intensity (IMean), maximum intensity (IMax), and cumulative intensity (CI) were determined. Annual statistical summaries of these parameters were subsequently prepared. Where an LHW spanned two consecutive calendar years, it was divided into two separate episodes to enable the preparation of annual summaries. In addition, LHW were classified into four categories – moderate, strong, severe, and extreme – according to their maximum intensity, following the methodology of HOBDA, A.J. *et al.* (2018). Statistical summaries for each heat wave category were prepared for six decadal periods: 1964–1973, 1974–1983, 1984–1993, 1994–2003, 2004–2013, and 2014–2023.

The resulting values were further analysed to identify long-term changes in lake water heat wave parameters between 1964 and 2023. In the first stage of the analysis, the non-parametric Pettitt test (PETTITT, A.N. 1979) was used to identify break points in the annual DT, IMean, IMax, and CT series from the period 1964–2023. The non-parametric Mann-Kendall test (KENDALL, M.G. and STUART, A. 1968), and Sen test (GILBERT, R.O. 1987) were then used to analyse long-term changes in DT, IMean, IMax, and CI values in the study lakes. Two hypotheses were formulated for the Mann-Kendall trend analysis: the null hypothesis (H_0) that no trend is present in the time series, and the

alternative hypothesis (H1) that a trend is present. The magnitude of the identified trends in annual DT, IMean, IMax and CI values was estimated using Sen's non-parametric test. Before the trend analysis, the time series were tested for autocorrelation and, where necessary, its influence was removed (YUE, S. *et al.* 2002). The R package RmarineHeat waves, developed by SMIT, A.J. and co-authors (2018), was used to identify lake-water heat waves. The Mann-Kendall's and Sen's tests were applied using the modified R package mk developed by PATAKAMURI, S.K. and O'BRIEN, N. (2022). Finally, principal component analysis (PCA) was performed to identify the location and lake morphometric variables associated with changes in DT, IMean, IMax, and CI. The PCA analysis was conducted using Statistica 13.1 software.

Results

The results showed that lake heat waves occurred in nearly every year of the analysed 60-year period. In Lake Ślaskie (#1), heat waves were recorded in 54 years, whereas in Lake Gardno (#2), in 58 years. In 46 years of the 60 years, lake heat waves occurred in all nine lakes (Figure 2).

Across the nine lakes, the mean cumulative duration of lake heat waves was ranging from 1,927 days (8.8%) in Lake Łebsko (#3) to 3,510 days (16.0%) in Lake Charzykowskie (#4). Among individual years, 2020 was characterised by the greatest lake heat wave activity across all nine lakes (Figure 3). In that year, the mean cumulative heat wave duration was 176 days per lake, ranging from 79 to 269 days in Lake Łebs-

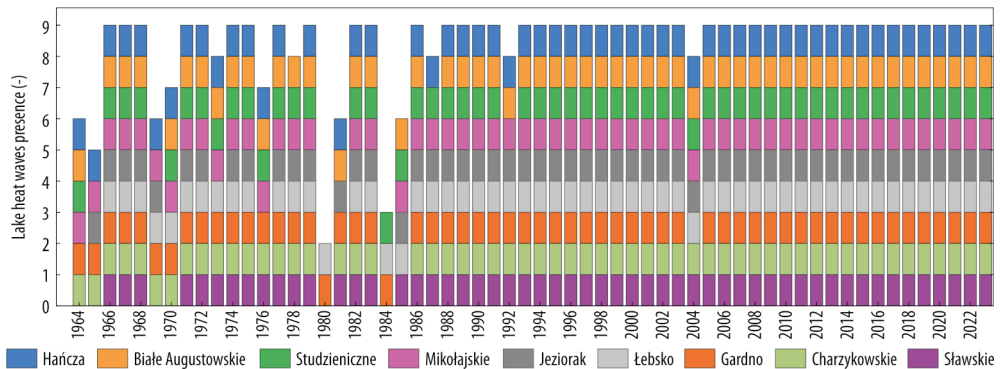


Fig. 2. Heat waves occurrence in the studied lakes. Source: Authors' own elaboration.

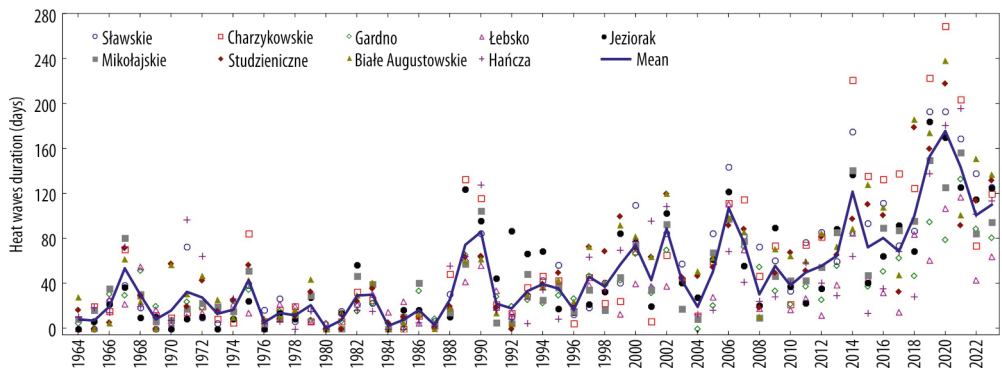


Fig. 3. Duration of lake water heat waves in the period 1964–2023. Source: Authors' own elaboration.

sko (#3) and Lake Charzykowskie (#4), respectively.

The mean annual cumulative LHW intensity across all the analysed lakes was 159 °C per year, ranging from 126 °C to 180 °C per year among individual lakes. Notably, cumulative LHW intensity generally reached its highest values during the final three decades of the study period, which were also characterized by the greatest variability (Figure 4). Annual IMax reached its highest values in 2000 and its lowest values in 1980 (Figure 5, a). Variability in annual IMax among the analysed lakes was greater during the first three decades of the study period, from 1964 to 1993. IMean exhibited lower inter-annual variability than IMax (Figure 5, b). As with IMax, variability in IMean among the lakes was greater during the first three decades of the analysed period.

Another important characteristic of lake heat waves is their severity. Across all the analysed lakes, moderate heat waves accounted for approximately 86 percent of all events, while strong and severe heat waves represented about 13 percent and just over 1 percent, respectively (Figure 6). In the coastal lakes (Gardno #2, and Łebsko #3), moderate LHWs accounted for 92.6 and 91.3 percent,

respectively. Strong LHWs accounted for 7.3 and 8.7 percent of events, respectively, while no severe and extreme events were recorded in either lake. In the remaining lakes, the proportion of moderate LHWs ranged from 83.0 to 86.8 percent, that of strong LHWs ranged from 11.7 to 15.5 percent, and that of severe LHWs ranged from 0.4 to 2.3 percent. Short extreme LHW events were also recorded, particularly in lakes located in eastern Poland (Hańcza #7, Białe Augustowskie #8, and Studzieniczne #9), 0.1, 0.1 and 0.2 percent, respectively.

Analysis of the variability of heat wave categories across the six decadal periods 1964–1973, 1974–1983, 1984–1993, 1994–2003, 2004–2013, and 2014–2023 showed that strong and severe LHWs were already present during the first decade, accounting for 7.3 and 2.3 percent of all events, respectively (Figure 7). In the period 1974–1983, LHWs were the least severe, with 97 percent of moderate category LHWs and about 3 percent of strong category LHWs. Over the following four decades, the proportion of strong LHWs increased progressively to 6.9, 10.4, 11.8, and 17.9 percent respectively, while the proportion of moderate LHWs decreased from 93.0 to 80.8 percent. The proportion of

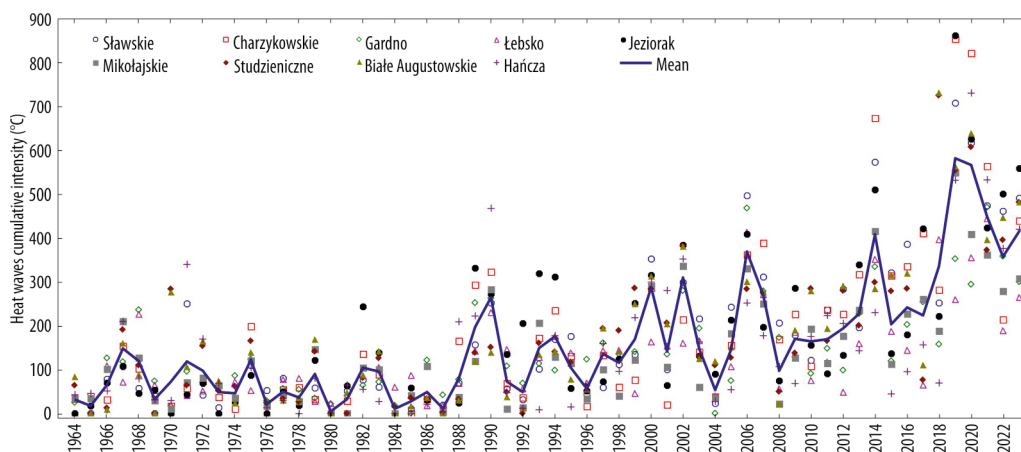


Fig. 4. Variability of cumulative intensities of lake water heat waves from 1964 to 2023. Source: Authors' own elaboration.

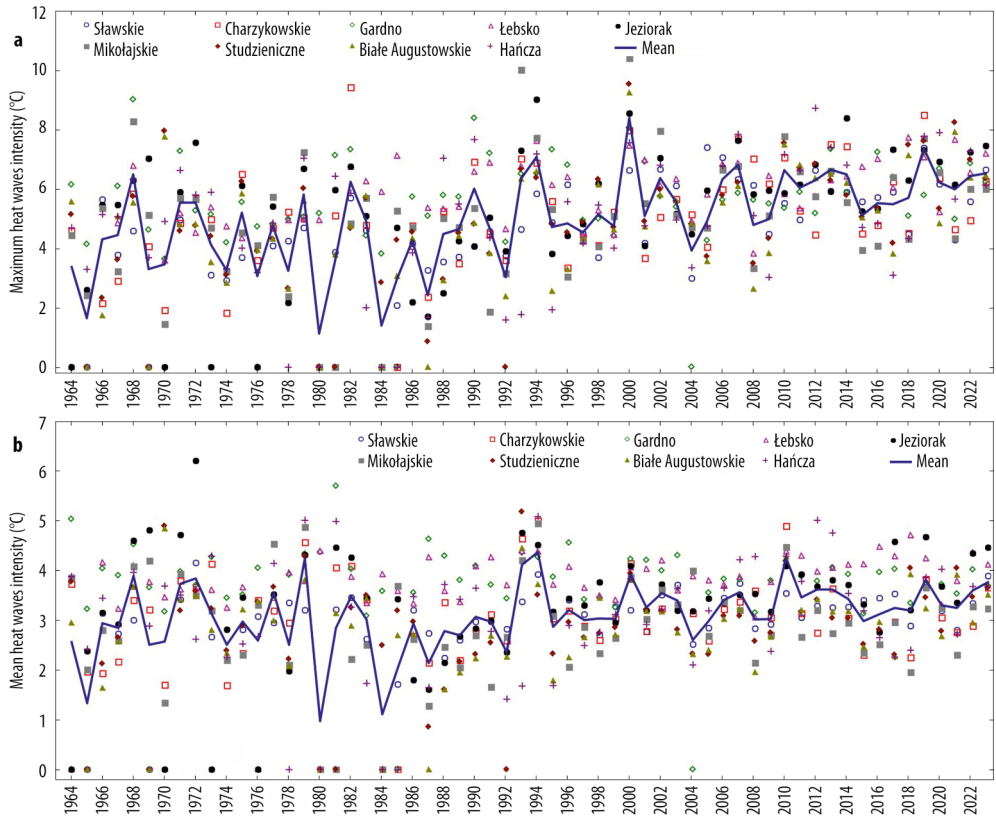


Fig. 5. Variability of maximum (a), and mean (b) annual lake water heat waves intensities from 1964 to 2023. Source: Authors' own elaboration.

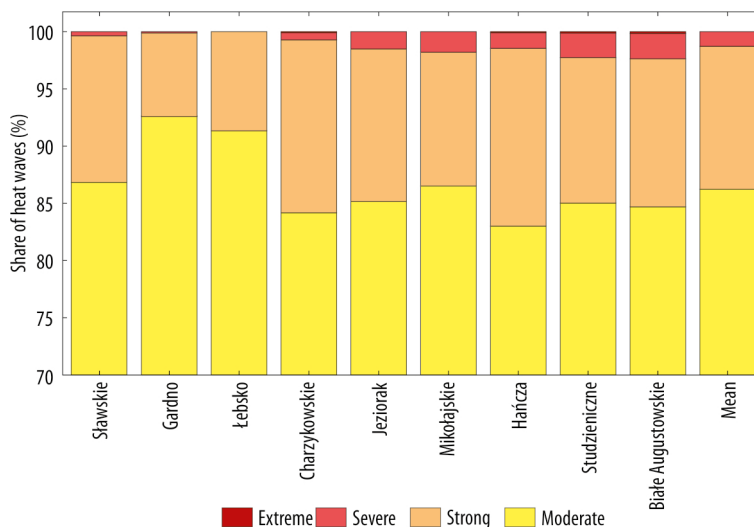


Fig. 6. Shares of different lake water heat wave categories. Source: Authors' own elaboration.

severe LHWs during the final four decades ranged from 0.1 to 2.3 percent, reaching its highest value in the period 2004–2013, while extreme LHWs occurred only sporadically (see Figure 7).

The decadal variability of heat-wave category events in individual lakes was spatially represented using pie charts. The diameter of each chart represents the mean annual number of LHW days, while the colours indicate the proportions of the individual LHW categories (Figure 8).

The analysis of lake heat wave characteristics over the past six decades revealed significant upward trends in both total DT and CI at the 0.01 significance level for all the lakes (Table 2). The smallest increases in DT were observed in the two coastal

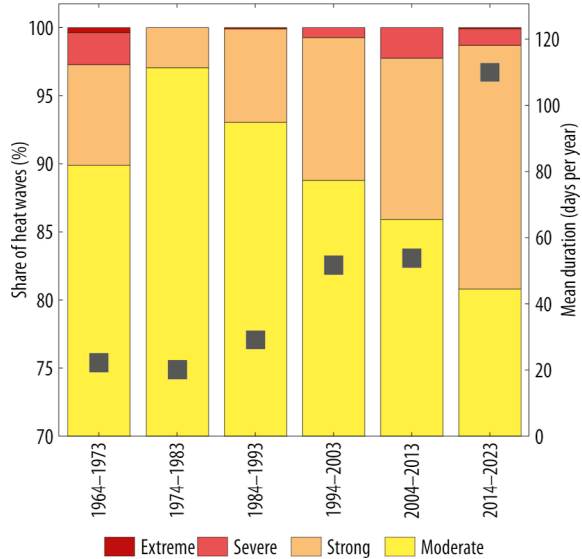


Fig. 7. Share of each category of lake water heat waves in the six decadal periods (1964–1973, 1974–1983, 1984–1993, 1994–2003, 2004–2013 and 2014–2023). Source: Authors’ own elaboration.

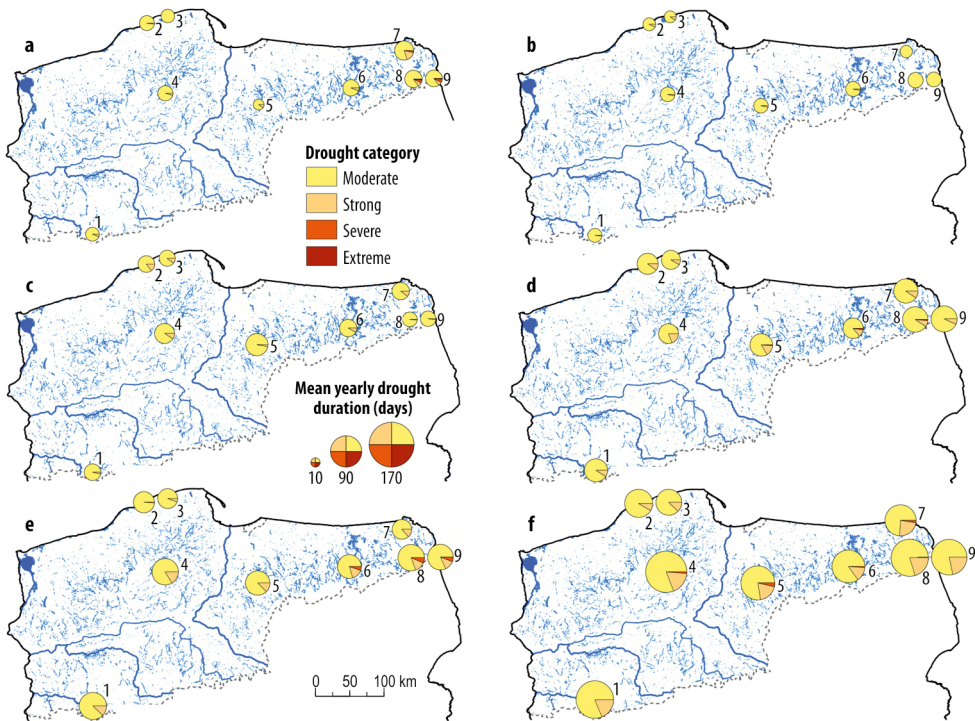


Fig. 8. Share of lake heat wave categories for the six decadal periods: 1964–1973 (a), 1974–1983 (b), 1984–1993 (c), 1994–2003 (d), 2004–2013 (e), and 2014–2023 (f). Source: Authors’ own elaboration.

Table 2. Long-term changes of the parameters describing the lake heat waves

Lake	Parameter	S-value	Tau	Z-value	p-value	Sen's slope value
Sławskie	DT	993	0.580	6.49	0.000	19.2
	IMax	719	0.420	4.70	0.000	0.5
	IMean	451	0.264	2.94	0.003	0.1
	CI	1027	0.600	6.71	0.000	63.5
Gardno	DT	853	0.499	5.57	0.000	9.6
	IMax	259	0.151	1.69	0.092	–
	IMean	–109	–0.064	–0.71	0.480	–
	CI	839	0.490	5.48	0.000	36.1
Łebsko	DT	735	0.430	4.80	0.000	7.9
	IMax	627	0.366	4.09	0.000	0.4
	IMean	481	0.281	3.14	0.002	0.1
	CI	781	0.456	5.10	0.000	33.3
Charzykowskie	DT	913	0.534	5.96	0.000	20.6
	IMax	499	0.292	3.26	0.001	0.4
	IMean	107	0.063	0.69	0.488	–
	CI	911	0.532	5.95	0.000	58.4
Jeziorak	DT	917	0.536	5.99	0.000	15.8
	IMax	571	0.334	3.73	0.000	0.7
	IMean	407	0.238	2.66	0.008	0.3
	CI	903	0.528	5.90	0.000	58.8
Mikołajskie	DT	775	0.453	5.06	0.000	14.3
	IMax	335	0.196	2.18	0.029	0.3
	IMean	143	0.084	0.93	0.353	–
	CI	703	0.411	4.59	0.000	40.3
Hańcza	DT	631	0.369	4.12	0.000	9.6
	IMax	363	0.212	2.37	0.018	0.4
	IMean	237	0.139	1.54	0.123	–
	CI	667	0.390	4.36	0.000	34.7
Białe Augustowskie	DT	971	0.568	6.34	0.000	19.1
	IMax	561	0.328	3.66	0.000	0.6
	IMean	247	0.144	1.61	0.108	–
	CI	977	0.571	6.38	0.000	63.9
Studzieniczne	DT	935	0.546	6.11	0.000	18.1
	IMax	635	0.371	4.15	0.000	0.6
	IMean	245	0.143	1.60	0.111	–
	CI	919	0.537	6.00	0.000	57.3
Mean	DT	987	0.577	6.45	0.000	14.9
	IMax	709	0.414	4.63	0.000	0.5
	IMean	498	0.291	3.25	0.001	0.1
	CI	995	0.582	6.50	0.000	49.5

Source: Authors' own elaboration.

lakes and Lake Hańcza. In the remaining six lakes, DT increased by an average of 15 days per decade. This increase was accompanied by a corresponding rise in cumulative intensity, with CI increasing at rates ranging from 33 °C to 64 °C per decade. The smallest increases were again recorded in the two coastal lakes and Lake Hańcza, whereas the remaining six lakes exhibited higher rates of increase, averaging 49 °C per decade. Maximum heat wave intensity (IMax) also increased in all studied lakes, at an average rate of 0.5 °C per decade.

Principal component statistical analysis showed that the mean duration and average cumulative intensity of heat waves increased with distance from the Baltic Sea (*Figure 9*). Furthermore, both maximum and average intensity of heat waves were higher in larger lakes and increased with latitude.

Discussion

The occurrence and impacts of extreme natural events and processes are an increasingly prominent topic in environmental sciences, as evidenced, among others, by hydrologi-

cal research (REICH, P. and LAKE, S. 2015; DE LUCA, P. *et al.* 2020; ASHRAF, M.S. *et al.* 2023). In line with this trend, a study was conducted on lake heat waves in Central Europe over the past six decades. In general, the first half of the analysed period was relatively stable in the context of the research, while the second thirty-year period showed an increase in various characteristics of heat waves. This period is associated with a shift in the climate regime, which, in lakes, has been confirmed by rising water temperatures in Central Europe since the late 1980s (WOOLWAY, R.I. *et al.* 2017).

The characteristics of heat waves varied between individual lakes. As shown by statistical analysis, their average duration and cumulative intensity increased with greater distance from the Baltic Sea (see *Figure 9*). The moderating influence of the sea was also evident in long-term changes in heat wave duration, with the smallest increases observed in coastal lakes such as Łebsko (#3) and Gardno (#2), as well as in Lake Hańcza (#7) (8 and 10 days per decade). The first two lakes not only experience maritime influences on atmospheric conditions but also have a hydraulic connection to the sea, where marine intrusions affect the physical and chemical properties of lake water. Lake Hańcza (#7), on the other hand, is the deepest lake in the Central European Plain, and as previous studies have shown (PTAK, M. and SOJKA, M. 2021), its morphometric characteristics significantly modify the impact of overarching factors such as climate conditions. This is evident in the lake's thermal behaviour, where noticeable changes in surface water temperature occurred about a decade later than in other lakes in this part of Europe. Further results indicate that the share of intense heat waves is highest among lakes in eastern Poland (the Masurian Lake District). Due to the dominant influence of the continental climate, this area historically retained ice cover the longest, effectively isolating the water from external factors. However, this state is clearly changing, and

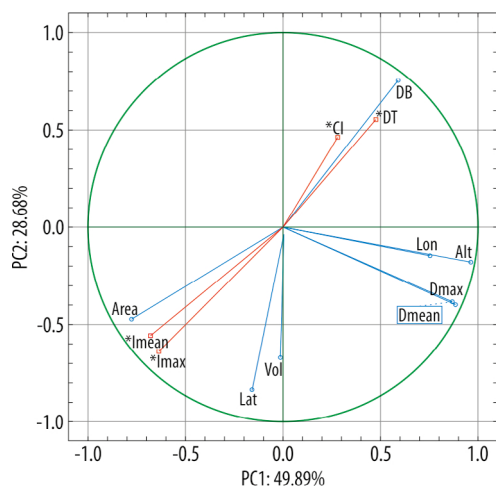


Fig. 9. Results of principal component analysis between heat waves parameters and location/morphometric lakes. Source: Authors' own elaboration.

the ice season has become significantly shorter, especially in recent decades (PTAK, M. and SOJKA, M. 2021). In extreme cases, ice cover did not form at all, for instance, in 2020. Therefore, the lakes undergoing the greatest transformation in their functioning are those that, due to the presence of ice for several months each year, were previously well insulated from atmospheric influences, but this period of insulation is now decreasing significantly.

The increase in heat waves in Europe may impact water quality and the ecological functioning of aquatic systems (FREE, G. *et al.* 2021). In terms of water quality, according to the classification of uniform bodies of surface water in line with the Water Framework Directive guidelines, all lakes (for which relevant data are available) are characterized by a poor overall status (isok.gov.pl/hydroportal.html). Moreover, the catchments of all these lakes (for which data have been compiled) are sensitive to eutrophication, which accelerates the growth of algae and higher forms of aquatic vegetation. This leads to undesirable disturbances in the biological balance of aquatic environments and a deterioration in water quality.

Among the most harmful effects of eutrophication are toxic cyanobacterial algae blooms (TOPOROWSKA, M. and PAWLIK-SKOWROŃSKA, B. 2011), and such events have been observed in the lakes analysed. The massive growth of cyanobacteria is dependent on anthropogenic pressures and rising water temperatures.

The observed increase in the frequency and duration of heat waves requires that this information be taken into account in lake restoration strategies and the pursuit of specific water quality standards. The selection of a potential restoration method should account for extreme conditions that may significantly compromise the intended outcomes of the interventions. Beyond technical solutions, water possesses natural properties that influence its self-purification ability.

One of the key parameters for the functioning of lake ecosystems is the amount of dissolved oxygen, which will decrease as the water temperature rises (PTAK, M. and NOWAK, B. 2016). Based on monitoring studies conducted in Poland by the Chief Inspectorate of Environmental Protection (wody.gios.gov.pl/pjwp), it can be stated that for selected lakes analysed in this study, oxygen saturation in the surface water layer is high. This reflects processes such as photosynthesis occurring in these waters. In deep lakes, however, the occurrence of heat waves intensifies thermal stratification, which has further consequences. Research by STETLER, J.T. *et al.* (2021) revealed a shallowing of the stratification depth in Crater Lake, which may have significant ecological implications, particularly for stationary primary producers and by reducing nutrient upwelling. For the studied lakes, oxygen levels drop rapidly below the epilimnion, reaching very low values. For example, in the summer season (August), oxygen saturation in Lake Charzykowskie (#4) was 2 percent (at a depth of 6 m), in Lake Mikołajskie (#6) 2.3 percent (depth 8 m), and in Lake Studzieniczne (#9) 3 percent (depth 7 m).

Conclusions

Water temperature is a fundamental characteristic of lake ecosystems that influences both their biotic and abiotic functioning. In addition to understanding typical temperature patterns, it is essential to investigate extreme events, whose frequency is increasing as climate change progresses. The results of this study revealed increases in the duration, maximum intensity, and cumulative intensity of lake heat waves at rates of 15 days per decade, 0.5 °C per decade, and 50 °C per decade, respectively. Moreover, the pattern of lake heat waves has changed, with an increase in the proportion of strong events. The intensification of extreme thermal condi-

tions may affect stratification stability, oxygen conditions, the rates of biogeochemical processes, and the functioning of aquatic organisms, thereby altering the functioning of entire lake ecosystems. This is therefore a complex mechanism that requires an interdisciplinary approach, including in practical management and conservation measures. These emerging conditions should be considered when planning and evaluating the effectiveness of future protection and restoration measures aimed at stabilising and improving the functioning of lake environments.

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Evaluating flood frequency analysis of the rivers in the Skopje Basin, North Macedonia – Statistical distribution fitting and hydrological insights

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Abstract

This study examines the flood frequency analysis (FFA) of four rivers in North Macedonia: Vardar, Treska, Lepenac, and Serava. The aim is to contribute to water resource management, flood risk mitigation, and resilience to climate change through detailed seasonal analysis. The most appropriate probability distributions were determined for each river: Pearson Type III (PIII) for the summer and winter seasons in the Vardar, PIII for summer, and Gamma for winter in the Treska, PIII for both seasons in the Lepenac, and PIII for summer and Log-Normal for winter in the Serava. For each distribution, discharge estimates were calculated for different return periods. The results show significant seasonal variations in discharge, especially for the Treska and Lepenac rivers. For the Treska, winter discharges are significantly higher than summer discharges in all return periods, indicating that winter conditions mainly determine the annual flood risk. The Lepenac shows a similar pattern with significantly higher discharges in winter. In contrast, the Vardar shows relatively constant discharges between summer and winter, suggesting a balanced seasonal contribution to the annual flood risk. The Serava shows less seasonal variation, indicating a less variable hydrological system. These results emphasise the importance of considering both annual and seasonal variability in the FFA to improve the accuracy of flood risk assessments and support effective water resource management. This research highlights the need for customised flood frequency models that account for seasonal runoff patterns to improve prediction accuracy and provide information for strategic planning in the face of climate change.

Keywords: flood frequency analysis, hydrological extremes, river discharge variability, hydrological data analysis, Vardar, Treska, Lepenac, and Serava rivers, North Macedonia

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Introduction

Floods are among the most widespread and devastating natural disasters, posing a serious threat to human lives and causing substantial damage to property, agriculture, and infrastructure worldwide (BLÖSCHL, G. 2022; HEINRICH, P. *et al.* 2023). The last few decades have recorded the increasing impact of floods,

a trend that will continue primarily due to the joint effects of socioeconomic progress and climate change (NGUYEN, V.D. *et al.* 2020). Floods account for more than 44 percent of all recorded natural disasters and occur at an alarming rate, with over 160 events annually. These disasters arise from a combination of natural and human-induced factors and are widespread environmental hazards impact-

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ing communities globally (CRED & UNDRR, 2020). Across Europe, recent studies have revealed substantial changes in flood occurrence, seasonality, and spatial distribution, reflecting the growing influence of changing hydro-climatic conditions and human pressures on river systems (e.g. FANG, B. *et al.* 2025). These changes are also evident in Southeast Europe and the Western Balkan region, where complex topography, increasing rainfall extremes, land-use changes, and expanding urban areas have contributed to heightened flood hazard and hydrological variability (e.g. PETROVIĆ, A. 2015; SABLJIĆ, L. *et al.* 2025). Within this regional context, the Republic of North Macedonia is also vulnerable because of its hilly-mountainous terrain, and pronounced hydro-climatic variability, which frequently generate floods and high-flow events with considerable environmental and socioeconomic consequences (RADEVSKI, I. *et al.* 2016; RADEVSKI, I. and GORIN, S. 2017). Rapid development within river catchments has further intensified flood problems by increasing surface runoff, reducing natural water retention, and altering river channel capacity (PETROVIĆ, A. 2015; FANG, G. *et al.* 2022; ADDIS, A. 2023). These regional characteristics underscore the importance of robust flood frequency analyses to improve flood hazard assessment and support sustainable water resources management in North Macedonia.

Flood frequency analysis (FFA), extreme river flood trends, and their relationship with global climate change have been the subject of extensive research that has been conducted worldwide (PETROW, T. and MERZ, B. 2009; BLÖSCHL, G. *et al.* 2017, 2019; BORMANN, H. and PINTER, N. 2017; BERTOLA, M. *et al.* 2019; CASSALHO, F. *et al.* 2019; LEŠČEŠEN, I. and DOLINAJ, D. 2019; LEŠČEŠEN, I. *et al.* 2019, 2022; ENGELAND, K. *et al.* 2020; LUDWIG, P. *et al.* 2023; PETROVIĆ, A.M. *et al.* 2024). The main aim of these studies is to develop practical and reliable tools for flood management and civil engineering design, while also enhancing the understanding of flood characteristics

(WILCOX, C. *et al.* 2018). So far, no uniform changes have been recognized worldwide despite extensive research on the global and regional spatial-temporal patterns of hydrological extremes. When historical data is evaluated, both a decrease and an increase in extreme discharges are observed in different parts of the world (CONDON, L.E. *et al.* 2015). The standard FFA method is based on fitting mathematical functions to available datasets and extrapolating the distribution tails for the purpose of estimating the probability and magnitude of extreme events (St. GEORGE, S. and MUDELSEE, M. 2019). When sufficient data is available at a single gauging station, an extreme value distribution is typically fitted to the observed data, resulting in an at-site FFA or local model (ARNAUD, P. *et al.* 2016). A suitable data length (>30) is essential for identifying the best-fit distribution function accurately, as the length of observed data plays a significant role in determining the best-fit probability distribution (AMIN, M.T. *et al.* 2016). Observational data from Europe over the past century have not shown a consistent trend in flood occurrence rates (PAPROTNY, D. *et al.* 2018). Despite this, almost every year new record-breaking hydrological extremes affect various regions of Europe, causing the debate between the effects of climate change and natural climate variability to intensify. The identification of the clear and statistically significant anthropogenic changes in atmospheric and climate variables, especially CO₂ concentration and air temperature are now clearly noticeable due to the increasing availability of high-quality hydrological and meteorological data (LEŠČEŠEN, I. *et al.* 2024). The Clausius-Clapeyron (CC) equation indicates that higher air temperatures are associated with increased atmospheric water vapour content, which influences the total precipitable water (ALFIERI, L. *et al.* 2015). Consequently, this CC relationship implies that the frequency of flooding could rise due to climate change (TABARI, H. 2020; PAPADOPOULOS-ZACHOS, A. and ANAGNOSTOPOULOU, C. 2023).

Despite extensive studies on flood frequency, a significant research gap remains, particularly in the Western Balkan region. This area has experienced an increase in flood frequency (LEŠČEŠEN, I. *et al.* 2023), yet comprehensive studies on peak discharge frequency analysis are sparse. The return period is a crucial hydrological tool as it estimates the interval between events of similar size or intensity (VOLPI, E. *et al.* 2019). This is why the FFA is most commonly used to estimate these return periods, which is essential for designing infrastructure like dams, bridges, culverts, storm drainage systems as well as for agricultural planning and flood prediction (TEMIME, G.S. 2024).

This paper presents a flood frequency analysis carried out on a 30-year period (1991–2020) series of maximum monthly discharge data for the Vardar, Treska, Lepenac, and Serava rivers. The motivation for this study stems from the lack of comprehensive studies related to the frequency analysis of peak discharge in the Republic of North Macedonia. Therefore, the purpose of this

study is to compare the results obtained by applying various frequency analysis methods to identical sets of discharge data and to identify the best-fitting distribution through visual analysis and statistical testing. This research aims to fill the existing knowledge gap in flood frequency analysis for this part of Southeast Europe and to provide valuable insights for flood risk management and infrastructure planning in the region.

Study area

North Macedonia, located in the Balkan Peninsula of Southeast Europe, is a landlocked country bordered by Serbia to the north and northeast, Bulgaria to the east, Greece to the south, and Albania to the west (Figure 1). The country has a relatively small geographical area, covering approximately 25,713 km². The study area includes four major rivers in the north-western parts of the country: Vardar, Treska, Lepenac, and Serava, which cover 18.2 percent of the coun-

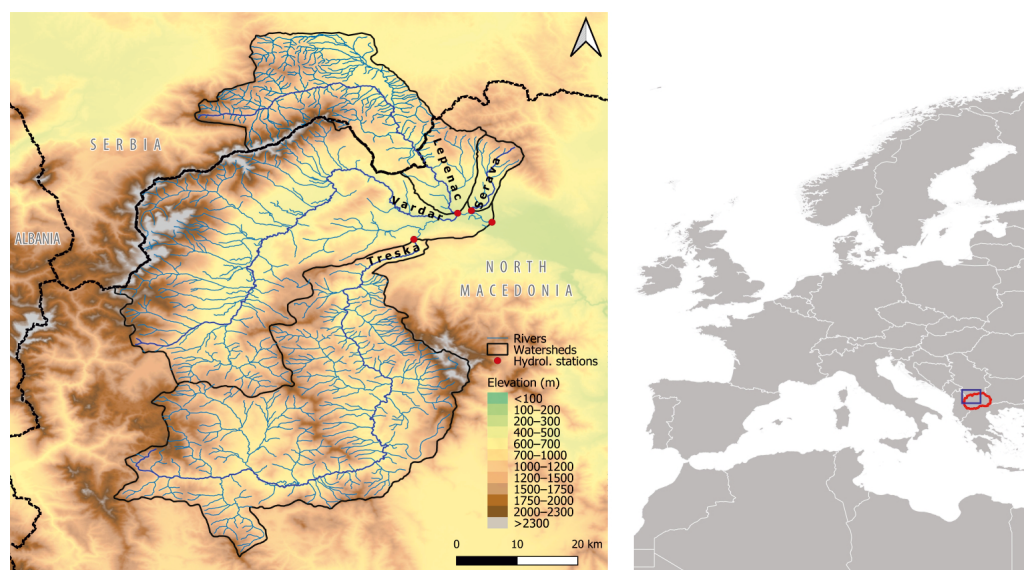


Fig. 1. Geographical location of the hydrological stations. Source: Authors' own elaboration.

try’s area. The Vardar is the longest and most significant river in North Macedonia, running through the central part of the country. It originates from the Gostivar area (Vrutok karst spring) in the western part of the country and flows southeast, eventually emptying into the Aegean Sea in Greece. The Treska is another important river in the study area, located in western North Macedonia. It is a tributary of the Vardar, joining it near the city of Skopje (PETROVSKA, I. and DIMOV, L. 2020). The Lepenac is situated in northern North Macedonia, flowing through the Polog Valley and joining the Vardar near Tetovo (SIMIĆ, S. *et al.* 2023). Lastly, the Serava is located in the northern part of the Skopje Basin before joining the Vardar.

These four rivers play a crucial role in the hydrological system of the Skopje Basin, providing water resources for irrigation, municipal use, and hydropower generation in the region. The Lepenac, flowing through the Kosovo Basin and Kachanik gauge, is influenced by the mountainous terrain of Shar Mountain and can experience rapid fluctuations in water levels during heavy rainfall events. The Serava, located in the northern part of the Skopje Basin, is influenced by both natural factors and human activities, such as agriculture and industrial development along its course. In

the present study, the focus is on analysing the flood frequency of these four rivers in North Macedonia. Skopje Basin with the mentioned four gauges belongs to the R2b stable pattern without a secondary winter maximum in the river regime. It has a spring maximum in April with around 15 percent of the total annual streamflow (RADEVSKI, I. *et al.* 2023).

Materials and methods

For the flood frequency analysis, crucial data were obtained from the National Hydrometeorological Service of the Republic of North Macedonia. This dataset includes the monthly maximum discharges recorded at four gauging stations located along four rivers in the northern part of North Macedonia. The analysis utilized data from the 1991–2020 period, which is detailed in Table 1, and visually represented in Figure 2.

Figure 2 presents the monthly maximum discharge time series (1993–2020) for the four investigated rivers. All these rivers show strong inter-annual and seasonal variability, with recurrent high-magnitude peaks superimposed on generally lower baseline flows. The Vardar and Treska rivers exhibit the largest discharges, reaching maxima of

Table 1. Geographical characteristics of the observed stations

River	Gauge	Latitude	Longitude	Height, m a.s.l.	Area, km ²
Vardar	Železnički Most	41.994630°	21.449720°	242	4,650
Treska	Sveta Bogorodica	41.960038°	21.296059°	286	1,880
Lepenac	Vliv	42.012906°	21.382173°	255	770
Serava	Momin Potok	42.018114°	21.409201°	257	67

Source: Compiled by the authors.

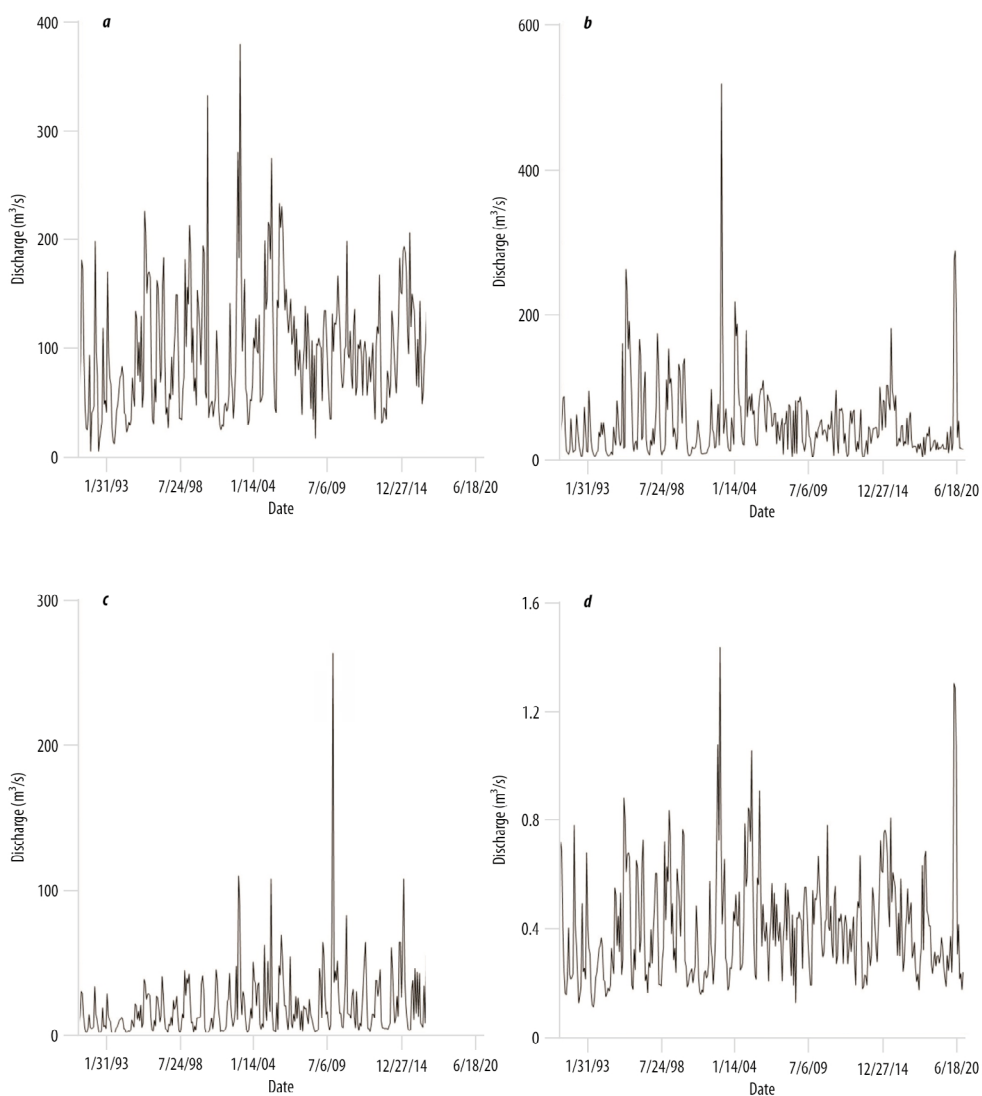


Fig. 2. The monthly maximum discharges of the investigated rivers: Vardar (a), Treska (b), Lepenac (c), and Serava (d). Source: Authors' own elaboration.

approximately $345 \text{ m}^3/\text{s}$ and $510 \text{ m}^3/\text{s}$, respectively, while the Lepenac and Serava rivers show comparatively lower magnitudes, peaking at around $260 \text{ m}^3/\text{s}$ and $1.4 \text{ m}^3/\text{s}$. Notable extreme events are visible around 2004 and 2020 across most rivers.

The time series data were plotted on probability paper, with points determined according to the Weibull formula. Subsequently, eight widely used probability distributions: Log-Normal (LN), Gamma (G), Pearson Type III (PIII), Log-Pearson Type III (LPIII), Gumbel

(GUM), Weibull (W), Generalized Extreme Value (GEV), and Pareto (Pr) (Table 2) were computed and employed for frequency analysis (VASILESKI, D. and RADEVSKI, I. 2014). The corresponding distribution lines were also plotted on probability paper for comparative analysis.

Furthermore, two statistical tests were applied to evaluate whether the empirical data followed the proposed theoretical distributions. The chi-squared (χ^2) test was utilized to determine if a sample originates from a specific distribution. However, it is important to recognize that the chi-squared test is not considered a high-power statistical test and has limited utility (TURHAN, N.S. 2020). This test depends on binned data, with the number of bins (k) determined by the following formula:

$$\chi^2 = \sum_{i=1}^n \frac{O_i - E_i}{E_i}, \tag{1}$$

where χ^2 represents Pearson’s parameter, O_i is the observed frequency of type i , n is the total number of observations, and E_i is the expected theoretical frequency of type i . To obtain the critical value for the χ^2 test, the degrees of freedom ($d = k - 1$), must be calculated, where k is the number of bins. The critical value is then referenced from the Pearson table. If the χ^2 statistic exceeds the critical value, the null hypothesis is rejected, indicating that the theoretical distribution does not adequately fit the empirical data (RADEVSKI, I. et al. 2016).

The Kolmogorov-Smirnov (K-S) test was employed to determine the best-fitting distribution, using the key parameter, maximum difference (D_{max}), between Weibull data points and each probability distribution (LEŠČEŠEN, I. et al. 2019, 2022; PETROVIĆ, A.M. et al. 2024). The K-S statistic for a given cumulative distribution function $F(x)$ is defined as

Table 2. Probability density and quantiles functions of the probability distributions

Distribution	Probability density function $f_{(y)}$	Quantile function $y(F)$
Log-Normal	$f_{(y)} = \frac{1}{y\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln y - \mu)^2}{2\sigma^2}\right)$	$y(F) = \exp(\mu + \sigma\Phi^{-1}(F))$
Gamma	$\frac{1}{\beta^\alpha \Gamma(\alpha)} (y - \mu)^{\alpha-1} \exp\left\{-\frac{(y - \mu)}{\beta}\right\}$	$y(f) = \Gamma^{-1}(k, F)$
Pearson III	$\frac{1}{\beta^\alpha \Gamma(\alpha)} (y - \mu)^{\alpha-1} \exp\left\{-\frac{(y - \mu)}{\beta}\right\}$	Explicit analytical form is not available
Log-Pearson III	$f(y) = \frac{1}{\sigma(y)\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{y - \mu(y)}{\sigma(y)}\right)^2\right]$	$y(f) = \mu(y) + \sigma(y)x\left[Z + \frac{1}{2}\left(\frac{Z^2 - 1}{3}\right)\right]$
Gumbel	$\frac{1}{\alpha} \exp\left[-\frac{y - \mu}{\alpha} - \exp\left(-\frac{y - \mu}{\alpha}\right)\right]$	$\mu - \alpha \log(-\log F)$
Weibull	$f(y) = \frac{k}{\lambda} \left(\frac{y}{\lambda}\right)^{k-1} \exp\left(-\left(\frac{y}{\lambda}\right)^k\right)$	$y(F) = \lambda(-\ln(1 - F))^{1/k}$
Generalized Extreme Value (GEV)	$\frac{1}{\alpha} = \left[1 - k\left(\frac{y - \mu}{\alpha}\right)\right]^{\frac{1}{k}-1} \exp\left\{-\left[1 - k\left(\frac{y - \mu}{\alpha}\right)\right]^{\frac{1}{k}}\right\}$	$\mu + \frac{\alpha}{k} [1 - (-\log F)^k]$
Pareto	$f(y) = \frac{\alpha y_m^\alpha}{y^{\alpha+1}}$	$y(F) = y_m \left(\frac{1}{1 - F}\right)^{1/\alpha}$

Source: Compiled by the authors.

$$D_{max} = \max |F_s(xi) - F_t(xi)|, \quad (2)$$

where D_{max} represents the maximum difference between the empirical distribution function $F_s(xi)$ and the theoretical cumulative distribution function $F_t(xi)$. The K-S test evaluates the goodness of fit by comparing the maximum difference. If the observed D_{max} is greater than the critical value from the K-S distribution, the null hypothesis that the data follows the proposed distribution is rejected. This test is advantageous because it is non-parametric and does not depend on

binning the data, providing a more direct comparison of the empirical and theoretical distributions.

For the frequency analysis, we used Hydromon, a free software for analysing and processing hydrological data, mainly in the form of time series (KOZANIS, S. *et al.* 2005; RADEVSKI, I. *et al.* 2016). This software includes the Pythia module, which enables frequency analysis and generates probability papers with cumulative frequency distributions (Figure 3a, b) and testing with K-S and χ^2 tests, with calculating of possibil-

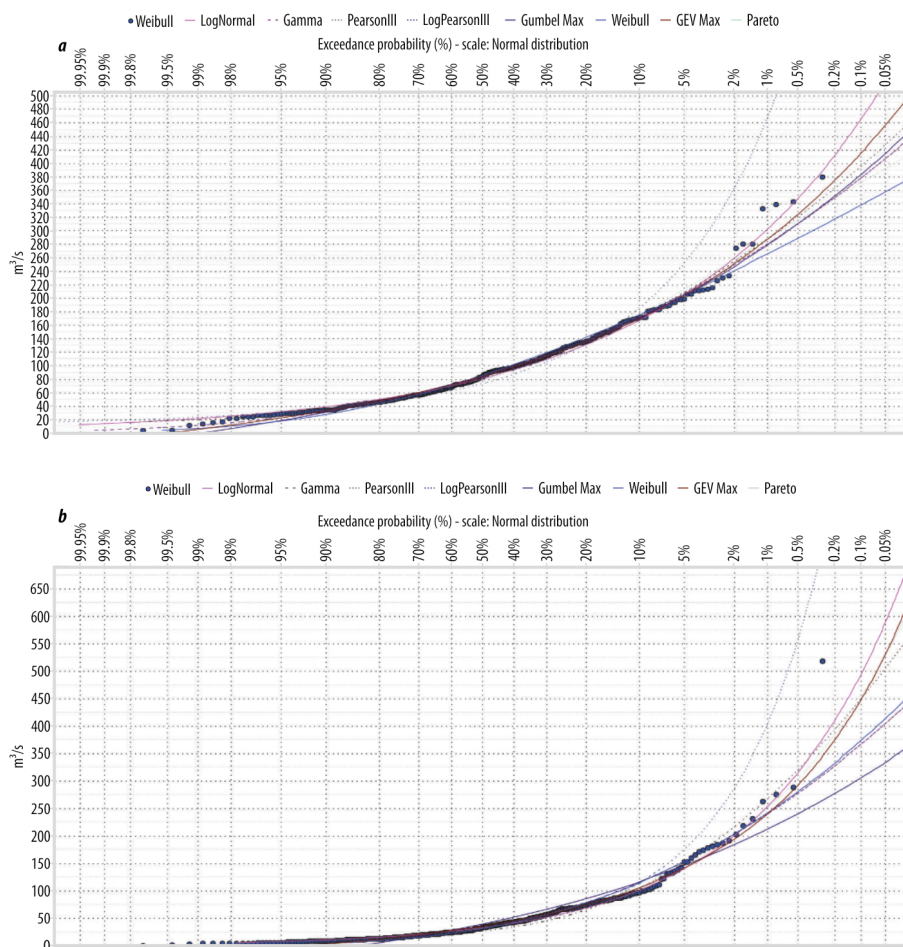


Fig. 3a. Probability paper with eight cumulative frequency distributions of monthly maximum discharge (m³/s) compared with Weibull plotted points at Vardar (a), and Treska (b) rivers. Source: Authors' own elaboration.

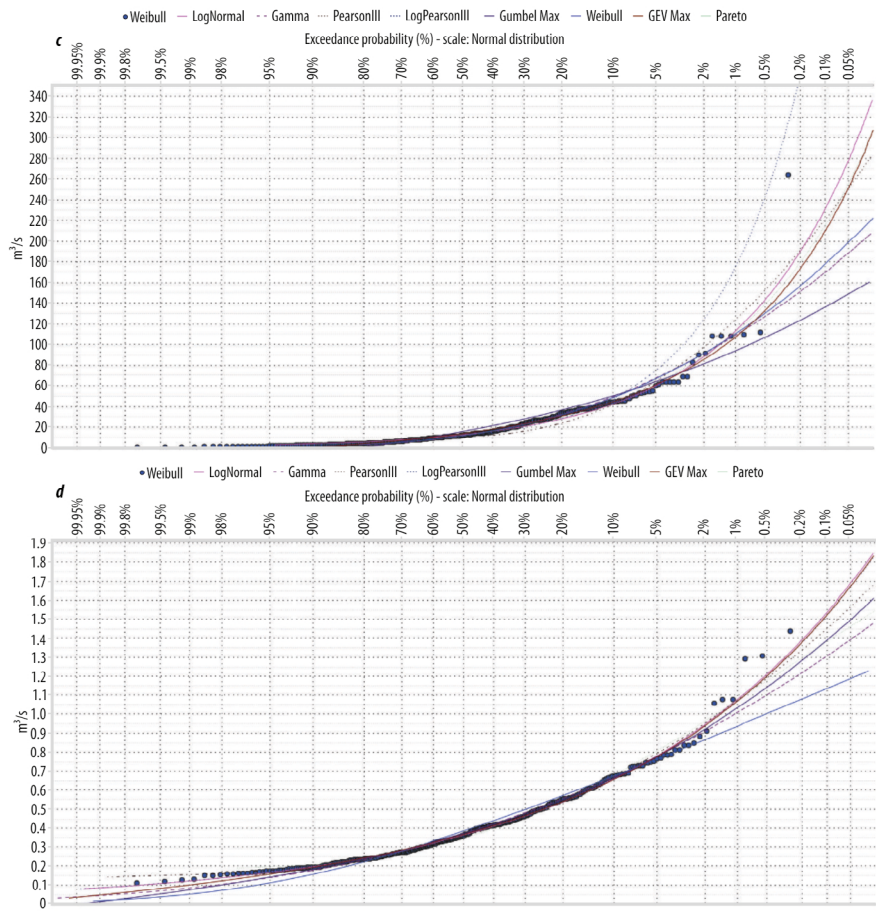


Fig. 3b. Probability paper with eight cumulative frequency distributions of monthly maximum discharge (m³/s) compared with Weibull plotted points at Lepenac (c), and Serava (d) rivers. Source: Authors' own elaboration.

ity discharges according to four probability distributions, for return periods of 10, 20, 50, 100, 200 and 500 years. Estimating discharge values for high return periods is significantly challenging due to uncertainties from both the length of the data series and the chosen distribution shape parameter (Leščešen, I. et al. 2019). Consequently, caution is crucial, especially when estimating discharges for extended return periods like 1000 years (Leščešen, I. et al. 2022). Therefore, our analysis is limited to return periods of up to 500 years.

Results and discussion

This study evaluated several frequency distribution functions to estimate the return periods of major flood events in northern North Macedonia using annual maximum monthly discharge data from four hydrological stations for the period 1991–2020. The monthly runoff maxima showed considerable variation between the stations. The discharges of the selected stations follow a similar trend. The highest discharges at Vardar (380.00 m³/s), Treska (518.87 m³/s)

and Serava ($1.44 \text{ m}^3/\text{s}$) were measured in January 2003, while at Lepenac the highest discharge was measured in February 2018 ($111.60 \text{ m}^3/\text{s}$).

The monthly maximum discharges of the Vardar show a high variability with several significant peaks of over $300 \text{ m}^3/\text{s}$. These events occur at irregular intervals, suggesting episodes of heavy rainfall or snowmelt and a complex response to climatic and hydrological factors (see *Figure 2*). Similarly, the hydrograph of the Treska shows variable discharge patterns with remarkable peaks of almost $500 \text{ m}^3/\text{s}$, indicating that the river responds to extreme hydrological conditions. The frequent high discharges indicate significant flood events as recorded in 2010 (HEERINGEN, K.J. and BEKIC, D. 2022). In contrast, according to the visual observation, the hydrograph of the Lepenac shows more moderate discharge values, with peaks around $200 \text{ m}^3/\text{s}$. Finally, the hydrograph of the Serava shows the lowest discharge values with a peak value of about $1.2 \text{ m}^3/\text{s}$. The variability of the discharge is present, but less pronounced than in the larger rivers, which is due to the smaller catchment area. The lower discharge values and less frequent flood events indicate a relatively stable hydrological regime with occasional peaks, probably due to localized precipitation events. Together, these hydrographs provide a comprehensive overview of the hydrological behaviour of these four rivers and reflect the diverse climatic and hydrological influences in the region.

The analysis of the ten highest monthly discharges for the rivers Vardar, Treska, Lepenac and Serava shows clear seasonal patterns and historical trends. For the Vardar, the highest discharges occurred mainly in the hydrological winter (October to March), with six of the ten highest discharges recorded during this period. Notable winter events include January 2003 ($380 \text{ m}^3/\text{s}$) and November 2022 ($280 \text{ m}^3/\text{s}$). However, 2020 showed significant summer discharges in April, May, and June, indicating an

unusual peak in summer floods. The data for the Treska also shows that winter discharges predominate, with seven of the top ten events occurring between October and March. The highest recorded discharge was in January 2003 ($518 \text{ m}^3/\text{s}$). Like the Vardar, the Treska also had notable summer peaks in 2020 (April, May, and June), highlighting the anomalous hydrological activity of the year. The highest discharges of the Lepenac are mainly concentrated in the winter months, with nine out of ten peak events occurring between October and March. The highest discharge was measured in December 2009 ($264 \text{ m}^3/\text{s}$). Only one significant summer discharge was observed in May 2005 ($108 \text{ m}^3/\text{s}$). The Serava showed a more balanced distribution with five winter and five summer peak discharges. The highest discharge occurred in January 2003 ($1.4 \text{ m}^3/\text{s}$), and the year 2020 also stands out with three significant summer discharges (April, May, and June). Historically, a higher percentage of these maximum discharges occurred in the 21st century, reflecting possible shifts in hydrological patterns likely influenced by climate change and increased precipitation variability. The data from the Vardar and Treska rivers in particular, point to 2020 as a period of increased flood activity, indicating the need for further investigation of the underlying climatic and hydrological patterns driving these changes.

Flood frequency analysis (FFA) is an important technique for understanding and predicting the frequency and magnitude of flood events, which is essential for effective water resource management and risk reduction strategies. The core requirements of FFA and the fitting of probability distributions include criteria such as randomness, independence, stationarity, and skewness of the data series. Therefore, the initial phase of the study involved calculating basic statistics for the monthly maximum data series, which included the mean value, median, standard error, standard deviation, skewness, and kurtosis for four gauging stations.

The results of these calculations are detailed in Table 3.

In subfigure (a) of Figure 4, which represents the Vardar, it can be seen that the Log-Normal, Gamma, Pearson III, and Log Pearson III distributions closely match the Weibull points, especially in the lower and middle range of discharge values. At higher discharge values, however, there is a clear deviation, especially for the Pareto and Gumbel distributions, which tend to overestimate

extreme discharges. This suggests that while multiple distributions can adequately model the central tendency of the data, accurately capturing the extreme values is a major challenge. Sub-figure (b), representing the Treska, shows a similar pattern, with the Log-Normal and Gamma distributions providing a reasonable fit for most discharge values. However, the Pareto distribution again overestimates the highest discharges, illustrating its tendency to predict more fre-

Table 3. Descriptive statistics of monthly maximum discharges of the four rivers in the North Macedonia

River	N	Mean, m ³ /s	Median, m ³ /s	Standard error	Standard deviation	Kurtosis	Skewness
Vardar	360	95.40	84.20	3.07	58.41	0.88	1.44
Treska	360	48.82	33.49	2.75	52.23	0.68	3.47
Lepenac	360	20.06	12.45	1.24	23.58	0.62	4.27
Serava	360	0.40	0.36	0.01	0.19	0.89	1.51

Source: Compiled by the authors.

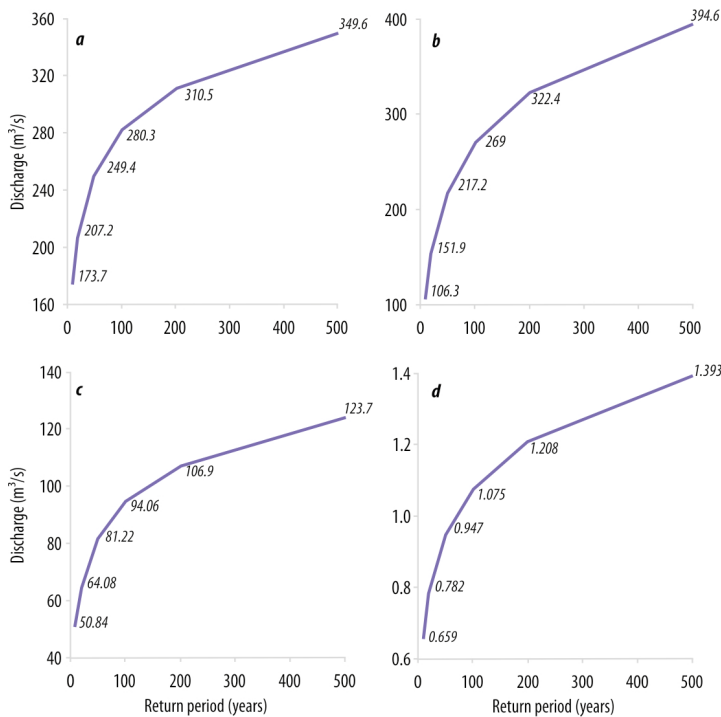


Fig. 4. Quantiles estimated for various return periods at the selected gauging stations. Source: Authors' own elaboration.

quent extreme events compared to empirical observations. The GEV and Log-Pearson III distributions provide a better fit for higher discharge values compared to the Pareto distribution. In subfigure (c) for the Lepenac, the discharge values are generally lower than for the Vardar and Treska rivers. The Log-Normal and gamma distributions show a good fit over the entire range of observed values. The discrepancies at higher discharge values are less pronounced, indicating a rela-

tively stable and less variable hydrological regime for the Lepenac. Finally, subfigure (d) for the Serava, which has the lowest discharge values, shows that the log-normal distribution has a good fit to the Weibull points over the entire range of discharges. This indicates that the log-normal distribution is particularly effective in modelling the hydrological behaviour of smaller rivers with less variability in discharge values (Table 4).

Table 4. χ^2 test and Kolmogorov-Smirnov test for eight theoretical functions

River	Distribution	χ^2 test		Kolmogorov-Smirnov (K-S) test	
		Attained α , %	Pearson parameter	Attained α , %	D_{max}
Vardar	Log-Normal	5.02	14.055	26.50	0.053
	Gamma	44.05	6.889	92.95	0.029
	Pearson III	60.93	4.500	60.09	0.040
	Log-Pearson III	0.00	32.667	0.20	0.098
	Gumbel	2.51	16.000	55.41	0.041
	Weibull	0.25	22.000	23.01	0.055
	GEV	24.22	7.944	63.34	0.039
	Pareto	3.88	13.278	25.00	0.419
Treska	Log-Normal	9.44	46.389	18.41	0.058
	Gamma	0.01	74.467	0.11	0.102
	Pearson III	100.00	1142.480	12.00	0.219
	Log-Pearson III	5.10	48.500	11.45	0.063
	Gumbel	1.08	191.633	11.60	0.172
	Weibull	0.19	64.122	0.31	0.095
	GEV	0.00	83.756	0.36	0.094
	Pareto	36.38	36.256	0.00	0.138
Lepenac	Log-Normal	0.01	75.522	2.72	0.077
	Gamma	0.00	85.233	0.02	0.113
	Pearson III	100.00	1824.160	6.86	0.278
	Log-Pearson III	0.29	61.167	25.81	0.053
	Gumbel	65.86	247.367	7.01	0.193
	Weibull	0.03	71.089	0.37	0.093
	GEV	10.00	103.178	0.06	0.106
	Pareto	26.25	38.789	5.97	0.069
Serava	Log-Normal	14.00	44.067	79.47	0.034
	Gamma	2.11	53.989	34.63	0.049
	Pearson III	48.12	33.722	51.07	0.043
	Log-Pearson III	10.36	44.700	73.75	0.036
	Gumbel	4.26	50.611	50.23	0.044
	Weibull	0.01	75.733	2.55	0.078
	GEV	11.57	44.067	62.23	0.039
	Pareto	0.00	89.878	0.00	0.349

Source: Compiled by the authors.

Selecting the most appropriate statistical distributions for hydrological data is crucial for accurate modelling and analysis. In this study, several distributions are evaluated using the χ^2 and Kolmogorov-Smirnov (K-S). In the following section, the best-fitting distributions for each river are discussed and supported by the statistical values of both tests. For the Vardar, the Gamma distribution is identified as the best fit. This conclusion is based on the achieved α -values and D_{max} values from the χ^2 and K-S tests. The Gamma distribution has an achieved α of 44.05 percent in the chi-square test, indicating a good fit. It also has the highest achieved α of 92.95 percent in the K-S test with a D_{max} value of 0.028, the lowest among all distributions tested. These results indicate that the Gamma distribution is closest to the empirical data and is the most reliable fit for the Vardar flow. These results are in contrast with previously published results which have shown that according to the both K-S and χ^2 tests, the best-fitting distribution for the Vardar is the Log-Normal distribution (RADEVSKI, I. and GORIN, S. 2017).

There are four possible reasons for this divergence; first, the length of the data series as the author of the earlier study is the 1971–2005 period compared to 1991–2020 used in the present one, second, the previous study used annual maximum discharge data while in this study monthly maximum discharge data was used, and thirdly, in the previous study, a total of five distribution functions were used (excluding the Gamma), while in this study eight distributions were used (including Gamma), and finally, the difference between two gauging stations on the Vardar used, with gauging station Demir Kapija (previous study) being located approximately 112 km to downriver from Skopje station that was used in this study.

In the case of the Treska flow, the Pearson III distribution stands out as the best fit. The χ^2 test shows an achieved α of 100.00 percent, indicating an excellent fit. Although the D_{max} value is not given in the K-S test, the perfect

result in the chi-square test strongly suggests the suitability of the Pearson III distribution for this data set. This distribution effectively reflects the statistical characteristics of the data and is, therefore, the optimal choice for modelling the first data set of the Treska flow.

For the Lepenac, the Gumbel distribution is considered the best fit. This distribution has an achieved α of 65.86 percent in the χ^2 test, which is a good fit. Although no specific α values are given for the K-S test, the balance between the chi-squared test results and the D_{max} value (0.193) suggests that the Gumbel distribution fits the data well. Its robust performance in the chi-squared test makes it a reliable model for the second data set of the Lepenac.

The log-normal distribution is the best-fitting distribution for the Serava. The results of the chi-square test show an achieved α of 14.00 percent, which is moderate but acceptable. However, the results of the K-S test provide strong support for this distribution, with an achieved α of 79.47 percent and the lowest D_{max} value of 0.034 among all distributions tested. These values indicate that the log-normal distribution closely matches the observed data and is therefore the best-fitting model for the Serava. Together, these results illustrate the importance of using multiple statistical tests to determine the best-fit distribution for hydrological data to ensure accurate and reliable modelling for each river.

The return period analysis reveals increasing discharge values for various return periods across the Vardar, Treska, Lepenac, and Serava rivers. These findings highlight the necessity of precise probability distributions in estimating extreme flood magnitudes, which are essential for effective risk management strategies in the northern regions of North Macedonia.

Analysing the seasonal flooding frequency of rivers is crucial for effective water resources management, flood risk mitigation and climate resilience (Yu, X. *et al.* 2015). As shown in Figure 2, significant seasonal fluctuations can be observed in these rivers as a result of seasonal variations in precipita-

tion and temperature, leading to differences in the frequency and magnitude of floods. Understanding these seasonal dynamics is crucial for the prediction of extreme hydrological events. Winter maximum discharges are often caused by snowmelt in combination with rainfall, while summer floods are caused by intense, short-duration rainfall.

This analysis identifies vulnerable periods, informs climate adaptation strategies, and helps in the design of hydraulic structures and land use planning to ensure socio-economic stability and environmental sustainability in North Macedonia. The comparative analysis of the best-fit distributions for these rivers shows significant seasonal variations, which underlines the need for a seasonal analysis of flood frequency for accurate hydrological modelling (see *Appendix*).

The seasons are defined as hydrological winter (from October to March) and hydrological summer (from April to September). For the Vardar, the Pearson III distribution is most appropriate for both winter and summer. In winter, it reaches an χ^2 significance level of 19.17 percent, with a Pearson parameter of 20.67 and a K-S test D_{max} of 0.05. In summer, it remains robust with an χ^2 test significance level of 36.38 percent, a Pearson parameter of 17.34, and a K-S test D_{max} of 0.04, confirming a high fit (98.23% for the K-S test). For the Treska, the Gamma distribution is the best fit for winter, as evidenced by a significance level of 88.17 percent in the χ^2 test, a Pearson parameter of 10.49, and a K-S test D_{max} of 0.05. In summer, the Pearson III distribution is more suitable, with an χ^2 test significance level of 28.62 percent, a Pearson parameter of 18.67, and a K-S test D_{max} of 0.04. In winter, the Lepenac flow shows a strong preference for the Pearson III distribution, which achieves an χ^2 test significance level of 100.00, a Pearson parameter of 397.56, and a K-S test D_{max} of 0.19. In summer, the Gamma distribution is more suitable, with an χ^2 test significance of 3.16 percent, a Pearson

parameter of 29.33, and a K-S test D_{max} of 0.06. For the Serava, the Log-Pearson III distribution performs excellently in the winter season, with a K-S test significance level of 44.60 percent and a D_{max} of 0.06. In summer, the log-normal distribution is the most suitable, with an χ^2 test significance of 37.50 percent, a Pearson parameter of 18.22, and a K-S test D_{max} of 0.04. *Table 5* presents the obtained results of the seasonal theoretical maximum discharges using of best-fit seasonal theoretical probability distributions.

Table 5 provides a comprehensive overview of the theoretical discharges for different return periods on these four rivers. In particular, seasonal and annual data are compared (see *Figure 4*), which highlights the importance of considering seasonal variations in

Table 5. Theoretical discharges for various return periods according to best-fit seasonal probability distributions

River		Vardar		Treska	
Season		Summer	Winter	Summer	Winter
Distribution		PIII	PIII	PIII	Gamma
Return period	10	171.89	174.53	99.84	128.82
	20	210.19	207.401	134.02	171.03
	50	259.66	249.03	180.51	227.42
	100	296.48	279.58	216.35	270.37
	200	332.92	309.54	252.60	313.52
	500	380.641	348.43	301.01	370.78

River		Lepenac		Serava	
Season		Summer	Winter	Summer	Winter
Distribution		PIII	PIII	PIII	Gamma
Return period	10	36.98	60.138	0.65	0.68
	20	47.61	82.12	0.78	0.79
	50	61.58	111.91	0.95	0.95
	100	72.11	134.83	1.09	1.06
	200	82.62	157.98	1.23	1.17
	500	96.48	188.85	1.43	1.31

Source: Compiled by the authors.

the FFA. Due to the hydrological regime of the rivers, the calculated discharges in the winter season are higher than the calculated discharges when the monthly maximum discharges for the whole year are used for the calculations, especially when the discharges of the 10-, 20- and 50-year return periods are observed. On the other hand, the calculated discharges for the 200- and 500-year return periods are larger if the entire data set is used and the seasonal values are disregarded. This statement applies to the rivers Vardar, Treska and Serava, while the results for the Lepenac show that the calculated discharges based on the winter season data are much larger than the data obtained from the entire data set. The reason for this can be found in the different climate types in the northern part of the Lepenac river basin, which is under the influence of the Sub-Mediterranean climate. In general, the results presented in *Table 5* underscore the imperative of incorporating seasonal variations into FFA methodologies as well. Doing so not only enhances the precision of flood risk assessments but also underpins the development of robust flood management strategies, crucial for fostering environmental sustainability and community resilience in the face of evolving climatic conditions. As the main goal of FFA is to determine discharge values with a larger return period, it can be concluded that, even though seasonal analysis provides valuable information, the data for the whole year should be used.

Looking at the seasonal variations, winter and spring are expected to be wetter as precipitation will increase by 20 mm due to higher temperatures, as shown by the CC equation. These results indicate that climate change is the primary factor influencing the observed changes in flood events, with statistically significant increasing trends in winter and summer precipitation over North Macedonia (GJEŠOVSKA, V. *et al.* 2022). The results of various global climate models (GCM) predict that North Macedonia will experience an increase in air temperature

in summer compared to the winter season by 2050 (MONEVSKA, S.A. 2011), which will likely lead to more intense precipitation as warmer air can hold more moisture (LIU, J. *et al.* 2019). The CC relationship shows that daily precipitation intensity increases by around 7 percent per °C increase in ambient temperature (BLÖSCHL, G. *et al.* 2019; TABARI, H. 2020). This correlation is supported by observational data and modelling experiments (WESTRA, S. *et al.* 2013; O'GORMAN, P.A. 2015), both of which have tested the CC scaling hypothesis at different spatial and temporal scales. An analysis of air temperature in North Macedonia from 1926–2020 found that the last decade of the 20th century and the beginning of the 2nd century were the warmest periods, with the last 14 consecutive years (2007–2020) showing the highest annual air temperatures (UHRM 2021). In North Macedonia, annual precipitation maxima have also increased over the last 65 years (GJEŠOVSKA, V. *et al.* 2022), while the analysis of seasonal precipitation indicates a negative trend in the winter and summer months (RADEVSKI, I. *et al.* 2024) and maximum discharges occur mainly in winter. Overall, the number of wet days has decreased in the Mediterranean region, including North Macedonia (ANDRÉ, J.C. *et al.* 2023), suggesting that a redistribution of precipitation has taken place, mainly the same or a lower monthly amount of rain in a shorter period of time.

Since the beginning of the 21st century, cyclonic activity in Europe has increased, leading to more frequent heavy rainfall (ARAGÃO, L. and PORCÙ, F. 2022; BERÉNYI, A. *et al.* 2023). An unusually high number of Mediterranean cyclones were observed in South Europe in the winter of 2012–2013 and spring of 2013 (KOUROUTZOGLOU, J. *et al.* 2011). These cyclonic events caused flooding in North Macedonia between 23 and 26 February 2013, damaging and breaching several dams, damaging agricultural fields, roads, railroad lines, and houses. Changes in these circulation patterns are likely to have an impact on rainfall totals

and significantly affect river flows and water levels. Further research is needed to investigate the relationship between circulation patterns, flood frequency, flood extent, and topography (NIED, M. *et al.* 2014). The results of this study underline the importance of a thorough analysis of changes in flood behaviour for flood planning and risk management (PETROW, T. and MERZ, B. 2009). Overall, North Macedonia faces increasing risks from climate change, including higher temperatures and changing precipitation patterns, which could further increase the likelihood of natural hazards such as flooding and forest fires (IMF 2024).

The study provides important insights to improve the resilience of energy infrastructure to flooding and supports better planning and design. Policymakers can use this information to develop strong flood protection policies to cope with increasing extreme flood events. The financial sector, including insurance companies and investors, can use these insights to manage evolving flood risks and guide investment strategies and risk assessments. In terms of environmental, social, and governance (ESG) policies, the study improves the understanding of the environmental impacts of climate change-induced flooding, helping to develop sustainable strategies. Overall, this research bridges the gap between scientific knowledge and practical applications and promotes informed decision-making and climate resilience.

While this study offers valuable insights into flood frequency analysis in the northern region of North Macedonia, it is important to acknowledge certain limitations. Firstly, the study's focus on the northern part of the country means that the results may not be applicable to other regions. Additionally, while the research provides an understanding of temporal and seasonal FFA, it does not explore the detailed mechanisms or causes behind the observed changes. Moreover, projections and implications for future flood events are not explicitly addressed, so caution should be exercised when generalizing

these findings to predict future hydrological scenarios. Despite these limitations, the study establishes a foundation for further research and highlights the need for a nuanced understanding of extreme flood dynamics in the context of climate change.

Conclusions

In this study, a comprehensive flood frequency analysis was conducted for the Vardar, Treska, Lepenac and Serava rivers in North Macedonia, using different probability distributions to estimate extreme flood heights. The analysis covered the period from 1991 to 2020 and the main objective was to identify the best-fitting distributions for each river in order to improve the accuracy of flood forecasts, which are crucial for effective water resource management and risk mitigation strategies.

The results showed that the Pearson III distribution provided the best fit for the Vardar, as evidenced by the better results of the chi-square and Kolmogorov-Smirnov tests. For the Treska, the Pareto distribution proved to be the best fit, while the Weibull distribution provided the best fit for the Lepenac. The discharge data of the Serava were best described by the log-normal distribution. These findings are crucial as they highlight the variability and complexity of hydrological responses across different rivers in the region, necessitating tailored approaches for flood risk assessment and management.

These results are of crucial importance as they highlight the variability and complexity of hydrological responses in the different rivers of the region, requiring tailored approaches to flood risk assessment and management. The analysis revealed significant discharge peaks in all rivers, with the Vardar and Treska rivers showing the most extreme variability, likely due to their larger watersheds and more dynamic hydrological systems. The Lepenac and Serava rivers had lower discharge values, but still showed

episodic high discharge events, emphasizing the importance of localized precipitation events and the dynamics of smaller catchments.

The seasonal FFA for the Vardar showed that the Pearson III distribution is most suitable for both winter and summer and achieves high significance levels in the χ^2 and K-S tests. The Treska requires the Gamma distribution for winter and Pearson III for summer, while the Lepenac shows a preference for Pearson III in winter and Gamma in summer. The best-fitting distribution for determining winter season discharges for the Serava is the Log-Pearson III distribution and Log-Normal in summer. Table 5 reveals that winter discharges are generally higher than annual discharges for shorter return periods, but for longer return periods, annual data yields higher discharges except for the Lepenac, influenced by its Mediterranean climate.

Results presented in this study underscore the necessity of accurate probability distributions in estimating extreme flood magnitudes. This information is crucial for designing effective flood mitigation infrastructure, helping stakeholders make well-informed decisions, and establishing and implementing emergency response strategies. As the frequency of extreme weather events is expected to increase due to climate change, the results of this study are particularly valuable for increasing the resilience of North Macedonia's water management systems.

Overall, the tailored FFA approach adopted in this study provides a robust framework for understanding and predicting flood risks in North Macedonia. The adoption of best-fitting probability distributions for each river not only improves the accuracy of flood forecasts but also supports the development of targeted risk management strategies. These contributions are vital for safeguarding communities, protecting infrastructure, and ensuring sustainable water resource management in the face of future climatic uncertainties.

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Appendix

Seasonal flood frequency analysis of the four rivers: Best-fit distributions according to χ^2 and Kolmogorov-Smirnov test

Vardar								
Distribution	Winter season				Summer season			
	χ^2 test for		Kolmogorov-Smirnov test		χ^2 test for		Kolmogorov-Smirnov test	
	Attained α , %	Pearson parameter	Attained α , %	D_{max}	Attained α , %	Pearson parameter	Attained α , %	D_{max}
Log-Normal	8.29	25.5556	26.17	0.07512	4.30	28.1713	50.68	0.06119
Gamma	1.82	31.3333	65.58	0.05464	77.02	12.4807	94.23	0.03932
Pearson III	19.17	20.6667	76.40	0.04977	36.38	17.3425	98.23	0.03452
Log-Pearson III	2.18	29.3333	2.00	0.11309	11.73	22.8674	16.16	0.08336
Gumbel	0.25	38.0000	35.82	0.0690	28.60	19.7735	62.56	0.05582
Weibull	0.20	38.6667	37.57	0.06801	0.81	34.1381	49.02	0.06198
GEV	2.47	28.8889	34.82	0.06958	42.14	16.4586	97.81	0.03525
Pareto	15.05	21.7778	–	0.47942	5.78	25.7403	0.37	–
Treska								
Log-Normal	34.79	18.6685	53.76	0.05976	0.04	43.8619	8.22	0.09390
Gamma	88.17	10.4917	85.66	0.04502	24.20	20.6575	83.82	0.04601
Pearson III	0.52	34.1381	21.04	0.07885	28.62	18.6685	97.33	0.03597
Log-Pearson III	1.83	29.9392	1.37	0.11736	0.18	37.4530	9.53	0.09170
Gumbel	5.71	27.0663	30.19	0.07221	0.06	42.5359	8.33	0.09370
Weibull	24.20	20.6575	70.15	0.05246	0.81	34.1381	51.97	0.06059
GEV	42.14	16.4586	99.58	0.03062	0.21	37.0110	49.67	0.06167
Pareto	1.72	30.1602	–	0.30591	13.00	22.4254	0.02	0.16069
Lepenac								
Log-Normal	1.94	31.1111	21.85	0.07840	–	86.0000	0.02	0.15900
Gamma	0.00	54.4444	0.02	0.16031	3.16	29.3333	48.52	0.06239
Pearson III	100.00	397.556	0.00	0.18622	2.32	29.1111	51.10	0.06116
Log-Pearson III	12.94	22.4444	49.99	0.06169	0.00	49.7778	5.60	0.09966
Gumbel	0.00	148.0000	–	0.22026	–	82.2222	1.34	0.11795
Weibull	0.05	42.6667	0.29	0.13463	6.31	26.6667	56.80	0.05855
GEV	10.00	72.8889	0.07	0.14823	0.00	61.5556	14.09	0.08583
Pareto	0.44	34.6667	18.07	0.08170	4.81	26.4444	57.15	0.05838
Serava								
Log-Normal	4.76	27.7778	44.58	0.06432	37.50	18.2222	94.07	0.03957
Gamma	0.06	42.4444	55.94	0.05893	1.32	32.4444	34.97	0.06949
Pearson III	4.27	26.8889	48.57	0.06237	14.32	22.0000	81.07	0.04754
Log-Pearson III	–	–	44.60	0.06431	–	–	92.58	0.04077
Gumbel	2.63	30.0000	40.45	0.06645	1.41	32.2222	40.63	0.06636
Weibull	0.01	48.4444	21.11	0.07901	0.11	40.4444	7.39	0.09572
GEV	0.76	32.8889	36.02	0.06889	6.06	25.5556	84.28	0.04589
Pareto	1.48	30.6667	–	0.25025	4.03	27.1111	–	0.27701

Source: Compiled by the authors.

Exploring the smart city agenda using knowledge networks – The emergence of a new global city landscape

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Abstract

In the era of digital transformation, cities increasingly adopt technology-based smart city (SC) agendas. However, implementation depends heavily on locally available scientific knowledge that is simultaneously embedded in global networks. To explore this paradoxical tension, this study provides a nuanced, global-scale analysis of the nexus between academic SC knowledge production and urban economic status. We used Web of Science (WoS) publication metadata (keywords and affiliations) across two distinct periods: 2010–2017 and 2018–2022. First, we employed network analysis (keyword-based thematic networks) to reveal academic SC knowledge segments. Then, we used affiliation data of publications for mapping SC knowledge hubs by scientific output globally. Finally, we derived SC knowledge ranking from collaboration data, adopting the Globalization and World Cities (GaWC) ranking methodology. We used the GaWC economic-related ranking for capturing economic status, based on the international corporate advanced producer services-related firms' data in 2016 and 2020. Our findings confirm that academic SC knowledge is highly interdisciplinary with a strong technological focus. While an increasing number of cities accumulate SC knowledge production, it becomes concentrated within a small subset of hubs. In addition, emerging economies such as China, India, South Korea, and Brazil as newly prominent regional hubs, are strengthening their position in the global knowledge landscape. Comparing SC knowledge ranking with GaWC ranking, focusing on change in time, our analysis reveals four distinct urban trajectories: *dynamic cities of economic and SC knowledge importance*; *SC knowledge accumulators*; *economic weight gainers*; and *potential laggards*. Although European cities dominate the top 100 in the rankings, a dynamic shift appears: European cities are mostly sliding into the economic weight gainer or potential laggard categories, while Asian (especially Chinese) cities dominate the dynamic category. These trajectories signal an emerging global urban paradigm where local SC knowledge increasingly complements traditional economic dimensions, particularly in less prominent cities.

Keywords: smart city, science mapping, knowledge network, global smart city knowledge space, global city network, city rankings

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Introduction

Cities are the primary engines of the global economy, acting as concentrated hubs of population, finance (BALLAND, P.A. *et al.* 2020), and knowledge. Several factors determine the global status of cities; among these, the economic role of the city is traditionally con-

sidered a significant one that influences urban development.

Knowledge has also been increasingly contributing to city status, along with the rising complexity of urban activities. Not only more people live in cities than in rural areas, but there are more devices connected in real-time than people, including smart-

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phones, public LCDs, or sensors deployed on trams, just to mention a few (TOWNSEND, A.M. 2014; UN 2022; BRIGLAUER, W. *et al.* 2024). Based on the connectedness of devices, cities have been increasingly adopting technology-based Smart City (SC) agendas (HAQUE, A.K.M.B. *et al.* 2022; TOH, C.K. 2022; SORRI, K. *et al.* 2024). This SC transformation is manifested in the growing output of SC-related knowledge and in emerging SC activities.

Furthermore, cities are both independent hubs and parts of a globally interconnected network. This network approach to determining cities' global rank is well captured in the concept of Globalization and World Cities (GaWC) network, based on economic and business-related linkages between cities. These change over time and the global city rankings reflect global influence correlated with economic growth (TAYLOR, P.J. 2001, 2004; TAYLOR, P.J. *et al.* 2002; DERUDDER, B. and TAYLOR, P.J. 2005, 2020; LIU, X. *et al.* 2013; BELDERBOS, R. *et al.* 2022).

Based on these considerations, this research aims to evaluate the thematic structure and spatial-temporal evolution of SC academic knowledge, and the relationship with SC activities, ultimately deploying a network approach to contrast these emerging knowledge-based urban structures against traditional economic configurations. To achieve this, the study first delineates the subfields of SC research (the SC knowledge segments), then maps the geographical footprint of its publication output over time. Finally adapts the GaWC framework to construct SC knowledge-based global city rankings based on scientific collaborations between cities. To grab the changes in time, we compare two time periods, which allows us to examine the changing patterns of SC knowledge segments, how SC knowledge hubs appear globally at the city levels, and, compared with GaWC rankings, what the differences are in time and in city development dimensions.

By contrasting this relational network with traditional economic-focused ones, the study seeks to isolate contemporary trends and possible new paths of global urban development. To guide the empirical investigation, the overarching aim is operationalised through the following specific research objectives and corresponding research questions:

RO1: To explore academic SC knowledge segments and the relation with SC activities.

RO2: To identify global SC knowledge hubs by mapping their geographical distribution based on publication output and city involvement.

RO3: To compare SC knowledge-based city rankings against GaWC economic-based rankings to identify emerging global SC knowledge hubs beyond established benchmarks.

The paper is structured as follows. Firstly, we review the literature, conceptualising SC transformations and arguing how this phenomenon is worth scrutinising more in depth as a global city phenomenon. We introduce the GaWC framework and propose to include academic SC knowledge in understanding global city status. At the end of this section, we highlight the importance of academic local and global knowledge in the case of adopting SC activities. Secondly, we describe our data and methods of mapping SC knowledge segments, visualising SC knowledge hubs and how GaWC ranking approach will adapt for SC knowledge ranking. Thirdly, we present the results, beginning with the thematic segmentation of SC knowledge, followed by its geographical and temporal distribution, and comparing the GaWC-derived global city SC knowledge rankings with the original economically focused GaWC ranking. The last section of the paper concludes with a discussion of findings and limitations. Our work advances the understanding of SCs and informs future research, encouraging extended global, local, social, and technological perspectives.

Literature review

Smart city transformations

The smart city (SC) literature highlights multiple interrelated dimensions, including technology, efficiency, citizenship, social organisation, and sustainability in urban development (TRANOS, E. and GERTNER, D. 2012; COCCIA, A. 2014; ALBINO, V. *et al.* 2015; ZUBIZARRETA, I. *et al.* 2016; EREMIA, M. *et al.* 2017; ANDREANI, S. *et al.* 2019; ZHAO, F. *et al.* 2021; MORTAHEB, R. and JANKOWSKI, P. 2023). In this study, we adopt the smart city as an urban system that supports economic and social activity through intelligent governance, technological and non-technological innovation, and efficient resource management, while reducing environmental impacts and improving quality of life for urban stakeholders (VAN DER HOOGEN, A. *et al.* 2019; KESHAVARZI, G. *et al.* 2021; KUENTZ-SIMONET, V. *et al.* 2023).

Cities are evolving, and many are currently engaged in processes of SC transformation (APPIO, F.P. *et al.* 2019; KUMAR, H. *et al.* 2020; DAI, Y. *et al.* 2024). This dynamism, reflected in the production of SC-related knowledge, provides a useful analytical entry point. To understand how SCs evolve in practice, it is necessary to examine the specific activities that constitute them. Accordingly, the literature has developed a range of frameworks that specify which urban functions are involved and how they are coordinated. A widely used framing is provided by APPIO, F.P. *et al.* (2019), who argue that SCs offer quality of life, business and innovation opportunities, and infrastructure and natural environments for citizens to *live-and-play* as well as dynamic spaces to *work-and-learn*. Building on this, we adopt the framework of KUMAR, H. *et al.* (2020), which maps SC solutions, aiming to structure the full spectrum of services capable of rendering a city smart, into four broad domains derived from large-scale crowdsourcing and expert validation:

information and communication technologies (ICT) infrastructure; environment protection and cleanliness; government planning, policy design and execution; smart services.

Integrating these frameworks allows the identification of the key combinations of activities that underpin SC development. For example, if a city authority deploys digital sensors and restricts combustion engine car circulation based on real-time smog data, this constitutes an SC project. Executing it requires the cross-coordinated management of sensor networks, pollution control, transportation, urban zoning, and citizen participation. Consequently, advancing SC transformations requires mobilising complex and diverse sets of related knowledge.

In *Figure 1* the two axes represent the social vs. physical, and live/play vs. work/learn components of the SC framework, as described by APPIO, F.P. *et al.* (2019), and the digital dimension – as offered by MORTAHEB, R. and JANKOWSKI, P. (2023) – is added. The three grey fields frame the aggregated combinations of these components, as in APPIO, F.P. *et al.* (2019). The coloured fields represent the major SC activities, originally described as SC solutions in KUMAR, H. *et al.* (2020), which are mapped onto the space defined by the axis components. Taken together, the figure offers a bird's-eye view of the main activities and activity fields of the SC.

Figure 1 provides an overview of SC activities. The axes distinguish social versus physical dimensions (vertical) and live/play versus work/learn functions (horizontal), following APPIO, F.P. *et al.* (2019). A digital dimension is added based on MORTAHEB, R. and JANKOWSKI, P. (2023). The resulting space defines combinations of urban functions, within which the major SC activity fields from KUMAR, H. *et al.* (2020) are positioned. The figure, thus, provides a bird's-eye view of the main activity domains and their inter-relations in smart city systems.

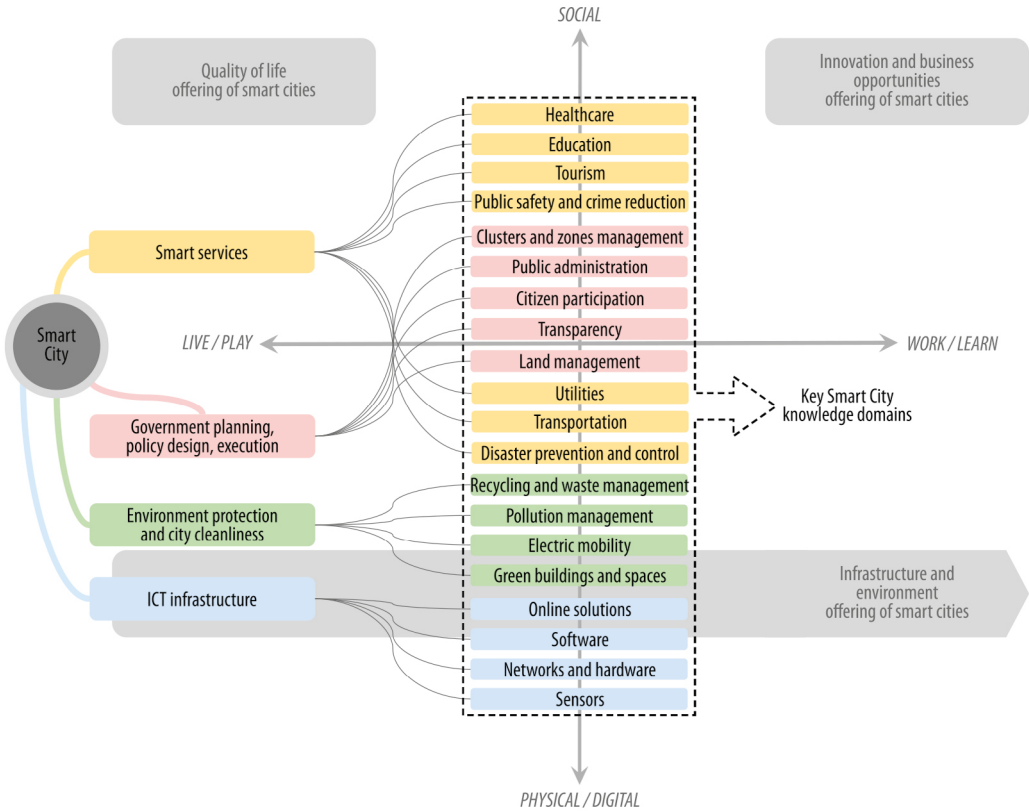


Fig. 1. Overview of SC activities. For detailed explanation see the text. Source: Combined from and simplified based on APPIO, F.P. *et al.* (2019), KUMAR, H. *et al.* (2020), and MORTAHEB, R. and JANKOWSKI, P. (2023).

As we can see, the SC agenda requires not only interconnected technologies, but also engaged citizens through public initiatives KESHAVARZI, G. *et al.* 2021; McLEAN, D. *et al.* 2021), a focus we term *the socio-technological duality*.

Given the interdisciplinary nature of SC development, it is necessary to understand how related knowledge domains are structured and evolve. Therefore, this study connects SC activities with the structure of academic knowledge as represented in WoS publications (ROI), enabling an analysis of how thematic research patterns align with urban transformation processes.

The global city landscape and the GaWC framework

While SC activities are implemented and appear locally, cities are not isolated islands, dynamics reinforce each other globally as well. Globalization has transformed the urban hierarchy, leading to the connection of not only countries but also cities (SASSEN, S. 1991; DERUDDER, B. *et al.* 2003; TAYLOR, P.J. 2004; DERUDDER, B. and TAYLOR, P.J. 2005; DERUDDER, B. and WITLOX, F. 2010; KRÄTKE, S. 2014; VAN DE VIJVER, E. *et al.* 2014; PERIS, A. *et al.* 2018; ACUTO, M. and LEFFEL, B. 2020; ACUTO, M. and LEFFEL, B. 2020. LEFFEL, B. *et*

al. 2023). The foundational work of SASSEN, S. (1991) introduced the concept of the “global city”, identifying strategic hubs like New York, London, and Tokyo as the primary command centres of the global economy. Within this framework, global cities serve as crucial geographic hubs that concentrate the advanced producer services necessary to manage and control geographically dispersed economic activities. Building on this concept, the Globalization and World Cities (GaWC) rankings are determined using an Interlocking Network Model (INM) that conceptualises the world city network through the locational strategies of advanced producer service firms (TAYLOR, P.J. 2001). Rather than assessing cities based on their internal economic attributes, this relational approach evaluates cities as nodes that are interconnected by the global office networks of transnational firms (as sub-nodes) in sectors like accountancy, advertising, banking, and law (TAYLOR, P.J. *et al.* 2002). This model assumes that the presence of offices of firms in two cities creates links, and a flow of information, capital, and labour (TAYLOR, P.J. 2011).

Through this relational lens, the GaWC framework maps a “world city network” characterized by hierarchical tendencies and complex regional patterns (TAYLOR, P.J. *et al.* 2002; DERUDDER, B. *et al.* 2003). This methodology has proven to be highly effective in yielding notable global city rankings that change over time, capturing the shifting geographies of corporate influence, economic growth, and global commodity chains (DERUDDER, B. *et al.* 2012; LIU, X. *et al.* 2013; DERUDDER, B. and TAYLOR, P.J. 2020; BELDERBOS, R. *et al.* 2022).

The role of academia and the knowledge-based global network

Since SC activities rely on diverse expertise, understanding how SC knowledge is structured is essential. SC knowledge em-

braces specific academic knowledge fields, where expertise, information, and understanding are organised, developed, and shared (ISRAILIDIS, J. *et al.* 2021).

Nevertheless, universities have already started acting as catalysts for locally applicable knowledge. First, academia serves as a bridge for managing knowledge within the city. For instance, universities can assist a city’s public health department by analysing data and research from local hospitals to enhance healthcare services. Second, researchers help filter external knowledge entering the city. Third, universities and research centres generate locally relevant new knowledge. Fourth, researchers evaluate external knowledge to ensure its effective application in the city. They might assess and pilot-test new educational technologies before integrating them into local schools (findings by ARDITO, L. *et al.* [2019] with own explanation and examples).

Crucially, this locally available academic knowledge is embedded in the global scientific knowledge networks. GHANBARI, H. *et al.* (2024) emphasise the important role of academic SC centres in connecting SC theories and actions. Furthermore, the growing adoption of technology, and local, knowledge-driven SC agendas in many urban areas indicates a shift in the global city landscape (WALL, R.S. and STAVROPOULOS, S. 2016; HAQUE, A.K.M.B. *et al.* 2022; TOH, C.K. 2022; BRIGLAUER, W. *et al.* 2024; SORRI, K. *et al.* 2024).

MATTHIESSEN, C.W. *et al.* (2010) inspired by the GaWC network approach, studied academic knowledge collaborations on the city level. Other studies on scientific co-authorship and academic networking also demonstrate that cities like Tokyo, New York, Paris, London, and Beijing operate as major knowledge hubs, reflecting hierarchies remarkably like the economic rankings observed in GaWC studies (MAISONOBE, M. *et al.* 2016a; CAO, Z. *et al.* 2023). Mapping this publication output and city-level involvement offers a robust foundation for iden-

tifying which urban nodes are developing into key administrative centres for smart city discourse globally (RO2).

The global connectivity of local knowledge is essential, as rapid technological advancements could otherwise render SC initiatives obsolete (ARPIO, F.P. *et al.* 2019). Therefore, we argue that the academic knowledge crucial to the emergence and development of SCs is globally connected in ways that the existing literature has not yet fully quantified. By adapting the GaWC framework to researcher collaborations and publication outputs, it becomes possible to map the geographical footprint of SC knowledge. Evaluating this novel, knowledge-based global city network directly against traditional, economic-focused GaWC rankings provides an opportunity to isolate contemporary trends, identify emerging knowledge hubs (RO3).

Data and research methodology

For revealing the SC academic knowledge segments, we use publications' metadata from the WoS database, with a document search based on SC definitions and smart urban phenomena (COCCHIA, A. 2014; ALBINO, V. *et al.* 2015; EREMIA, M. *et al.* 2017). Using the search profile in *Table S1* (in Supplement) and more precisely the terms from the literature in *Table S2* (in Supplement), metadata from over 28,000 journal articles were downloaded. Articles without a publication year and those published in 2023 were omitted. Only English-language articles and proceedings papers were retained. In *Figure 2* the number of articles by year is presented. We see the novelty of the field and the different trends of output over time. Articles published before the 2010–2022 period were excluded. This initial period, presumably the most diverse in terms of conceptual usage, contains only 802 articles. Based on the publication trends between 2010 and 2022 two periods were considered for longitudinal comparison: 2010–2017, when the number of articles

grew rapidly, and 2018–2022, when research output began to consolidate. This division makes it possible to compare SC knowledge segments, examine differences between the emerging and settled periods, and assess the global emergence of geographical hubs, as well as to observe differences when comparing these two periods with GaWC.

Number of publications from WoS over time, based on *Table S1* research profile. We included the articles between 2010–2022 and split the time span into two periods as there was a big difference in the trend of the number of articles. We distinguished an emerging period between 2010–2017, when the number of articles rose dynamically, and a consolidated period between 2018–2022, when the number of publications stagnated at a high level.

The authors and WoS-defined keywords in 25,782 articles were pre-processed through a systematic manual keyword standardization and restructuring (KSR) procedure (BORSI, B. *et al.* 2025). The KSR procedure improves the results of revealing SC segments, as instead of raw keywords, cleaned and systematically standardized ones are used during the thematic mapping process. Pre-processed keywords occurring fewer than 20 times were deleted, as they do not contribute significantly at this scale. Metadata from 22,190 articles, associated with 772 pre-processed keywords, were retained.

To explore academic SC knowledge segments (RO1), we used science mapping techniques, namely co-keyword analysis, which is highly effective for identifying conceptual contents in a field (ZUPIC, I. and ČATER, T. 2015). This method is a thematic-detection technique using network analyses as follows. First, a similarity matrix of the articles (nodes) was created, based on shared pre-processed keywords (edges). The cosine similarity of document vectors was applied as the similarity measure (SALTON, G. and MCGILL, M.J. 1983). Second, the similarity matrix was transformed into a proximity network of papers, with communities (clusters) detected using the Louvain method

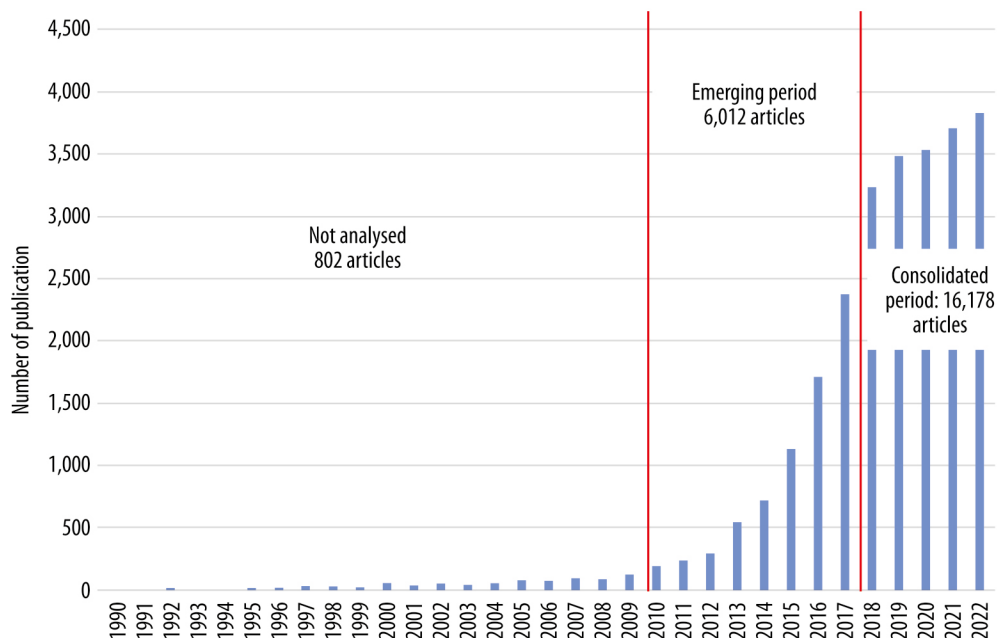


Fig. 2. Number of publications in SC field between 1990–2022. Source: Authors' own elaboration.

(BLONDEL, V.D. *et al.* 2008). The clusters with the Louvain method are non-overlapping, and within a cluster, the density of the co-keywords is high, while between them is low. The resulting two networks for the two periods, with 6,012 and 16,178 articles as nodes, are science maps that contain semantic linkages between the articles (Figure S1 in Supplement).

To identify potential global SC knowledge hubs (RO2), we associated articles with the cities where they were produced, based on authors' affiliations. If an article was a collaboration of multiple authors from the same city, that city was credited with one article. If an article had one author with multiple affiliations, each city was assigned a fraction of the article. The resulting data was projected onto a global map.

Next, for a comparison with GaWC economic-related ranking, we adapted the GaWC methodology for SC knowledge-based city ranking (RO3).

The concrete short methodology of the original Interlocking Network Model (INM) is the following: To quantify these relationships, the model assigns a service value (v) to the office of a specific firm (j) situated in a given city. Service value is a range between 0 and 5, based on the importance of the firm's office, e.g. no presence in a city: 0; headquarters: 5. The elemental connectivity between city a and city b generated by firm j is calculated as the product of their respective service values (TAYLOR, P.J. *et al.* 2002). A city's global connectivity (C_a) is subsequently modelled by aggregating these products across all firms and all other cities within the network:

$$C_a = \sum_{b, b \neq a} \sum_j v_{aj} v_{bj}$$

This measure, the city's proportional connectivity rank, is the proportion of a city's global connectivity score (C_a) shared with

the total connectivity score, which is the global sum of cities' global connectivity scores. The city's proportional connectivity rank value (GaWC rank) reflects its relative degree of integration into the global service economy. We use 2016 and 2020 (latest) ranking data which fit to our research periods.³

The GaWC INM model faces three main criticisms (DERUDDER, B. and PARNREITER, C. 2014). First, although critics argue that the model's undirected network structure ignores corporate hierarchies, this aligns well with our analysis of co-authorship, which is inherently undirected. Second, the model's assumption of a homogeneous space ignores geographical boundaries; however, since global scientific collaboration faces similar spatial constraints (HOEKMAN, J. *et al.* 2010; MAISONOBE, B. *et al.* 2016b; WUESTMAN, M.L. *et al.* 2019; Csomós, G. *et al.* 2020), these shared distortions justify the comparability of the rankings. Third, although critics note the model's narrow focus on advanced producer services, alternative frameworks like the Extended Interlocking Network Model (EINM), which incorporates sectors like media and NGOs, lack uniform global data. This narrower interpretation, however, allows us to make comparisons across the various dimensions that shape urban development. Consequently, the original INM remains the methodologically superior choice for this research.

In the case of a SC knowledge-based global network, sub-nodes are authors, nodes are cities and the networks are based on collaboration links. Our adaptation of the GaWC methodology for SC knowledge ranking for the two periods (2010–2017, 2018–2022) is based on three factors: article quantity, global linkages, and the diversity of aca-

dem SC knowledge (thematic segments) in each city. Specifically, we constructed an adjacency matrix to create a weighted network between cities based on co-authorships across different cities. We got a collaboration network at the city level, where cities are the nodes and the links between them are the co-published papers. The edge weights reflected the strength of collaboration between two cities counted on the number of shared articles. Intra-city collaborations and single-authored works were excluded, as they do not reflect the collaborative nature of global SC knowledge production (HALL, K.L. *et al.* 2018). For example, a link between Manchester and Warsaw would be established if authors from both cities contributed to the same article. We excluded cities that had fewer than two articles in each period or fewer than two connections to other cities, as these do not form the "triadic relationships" that are necessary for establishing lasting and meaningful links. Thus, a total of 673 cities in 2010–2017 and 1,724 cities in 2018–2022 was ranked.

In the SC knowledge-based ranking, the number of collaborated papers in a certain cluster corresponded to the service value in the GaWC ranking. The further counting of ranking follows the same way as in the GaWC ranking.

Finally, we compared the SC city rankings with the GaWC rankings for 2016 and 2020. This comparison allowed us to analyse the longitudinal dynamics of SC knowledge in 241 cities that appear in both the GaWC and the SC knowledge-based rankings. *Figure 3* shows the full research workflow.

In *Figure 3* the fields on the far left (green fields) show the work stages. The next section on the left presents the workflow for extracting SC knowledge themes, the geographical mapping of SC knowledge and the rankings. On the right side, the extraction of the GaWC ranking is shown. Fields with dotted borders represent logical and mathematical operations performed to extract content valuable for the analysis. Orange cells highlight ma-

³ The source of GaWC rank data was <https://www.lboro.ac.uk/microsites/geography/gawc/world2020.html>. (Accessed 11 March 2024.) As the webpage renewed the earlier one is available here: <https://web.archive.org/web/20240608095604/https://www.lboro.ac.uk/microsites/geography/gawc/world2020.html>

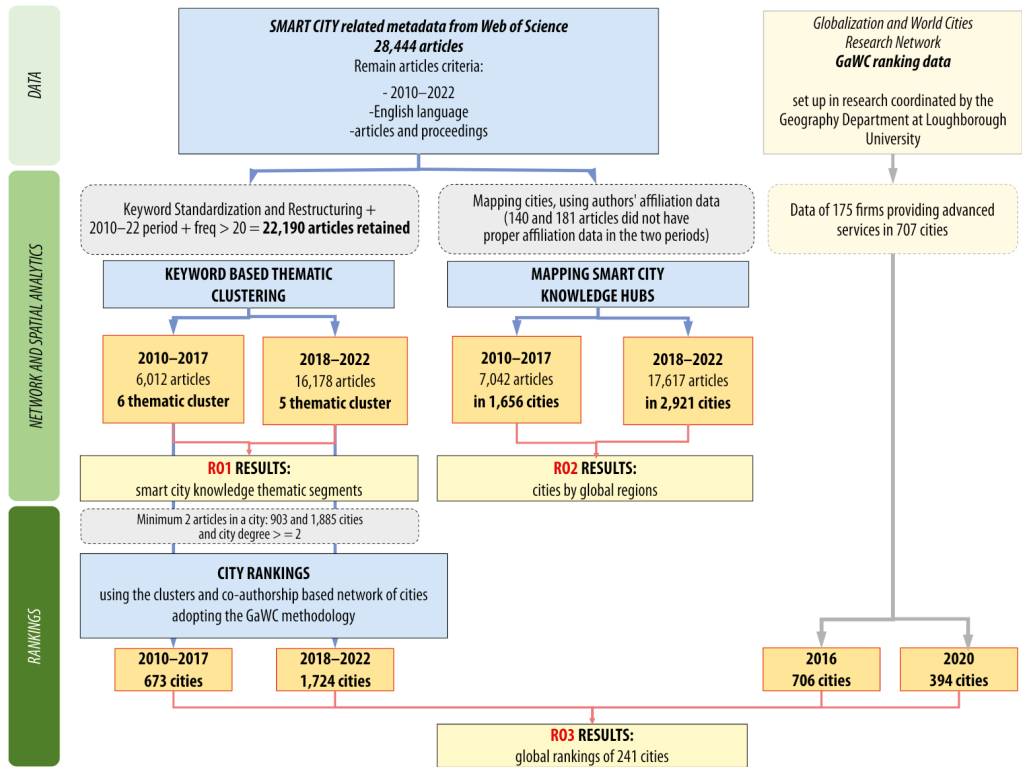


Fig. 3. Research workflow. For detailed explanation see the text. Source: Authors' own elaboration.

for steps directly supporting the research objectives, while yellow cells briefly outline these objectives. A detailed description of the workflow is provided in section “Data and research methodology”.

Results

RO1: The relationship between academic SC knowledge segments and SC activities

The network-based analysis of scientific articles, operationalised through keyword co-occurrence, reveals that SC knowledge segments are dominated by interdisciplinary approaches with a strong technological foundation. The clusters (segments) were named based on the most frequently connected key-

words across the articles (top of the Figure 4, and Figure S1 in Supplement). We studied the content of the clusters by word clouds representing the proportional frequency of keywords across the clusters, available in Figures S2a and S2b (in Supplement). In both periods, the largest cluster of articles – representing approximately one-third of the SC knowledge – focused on sustainable urban development, which encompasses not only technological considerations but also social, governance, and citizenship dimensions. The content of this cluster remained consistent across both periods, suggesting a robust, maturing sub-discipline. This persistence reflects the evolving intersection of sustainability and complex SC concepts, supported by increasingly interconnected technological knowledge bases.

An observable evolution in technological knowledge emerges across the two periods. In the first period, two application areas – transportation and energy systems – became prominent. Due to their shared technological challenges, such as optimization, traffic control, and grid integration, these areas merged into one thematic cluster in the second period. Emerging in the first period were data, sensor networks, and the Internet of Things (IoT), while Machine Learning, a “disruptor” technology relying heavily on Big Data, notably emerged in the second period. Additionally, the general notion of the “digital city” – initially distinct from sustainability – began to merge with sustainable urban development in the second period.

The SC activities (see *Figure 1*) are well-represented by the identified clusters, which visually capture the key themes of SC knowledge. In *Figure 4* we represented the connection between SC activities and the SC academic knowledge. The numbers in the table indicate the number of articles in which a term or word referring to a specific field of study appears among the keywords of SC’s scientific articles. If a term is crossed out, it was not found among the keywords. When only one part of a term is crossed out, the remaining part appeared among the keywords. For each SC activity that appeared notably frequently in a given cluster, we highlighted the number of occurrences (number of articles) in the table using the cluster’s colour. This made it possible to see which SC activities appear in which academic fields of knowledge through scientific publications. Most SC activities are concentrated within the *Sustainable urban development* cluster, with related engineering and technological domains also represented. Technological consolidation and an increasing focus on specific areas are observable between the two periods. This shift is reflected in the network data as a decrease in the number of clusters and an increasing concentration of articles around fewer, more focused topics (JAVED, A.R. *et al.* 2022).

On the left of *Figure 4*, the SC activities (see *Figure 1*) are repeated. At the top, in coloured rectangles, the SC thematic clusters are shown with the number of articles in each cluster. The numbers in the table represent the number of articles whose keywords contain the terms describing the SC activity category. Note: fully and partially strikethrough terms were not found. In case of partially strikethrough, only the remaining parts were found. Numbers highlighted with a coloured background are the highest in their row and/or decisive for the thematic clusters depicted at the top. For an overview of SC activities, see *Figure 1*.

Overall, global scientific SC knowledge predominantly focuses on technology, positioning it at the technological end of the socio-technological duality that shapes the contributions of universities and academia to the SC agenda.

RO2: Mapping global SC knowledge hubs

The number of cities involved in academic SC knowledge production increased rapidly until around 2017. Since then, consolidation has been observed, with approximately 1,600 cities globally contributing annually. While the volume of knowledge production continues to rise in cities in developing regions, cities in more developed regions are showing signs of consolidation (*Figure 5*).

Despite the growing number of cities, SC research is becoming increasingly concentrated in a smaller subset of cities. Occasionally, significant shifts at a more detailed level accompany this concentration. For example, cities such as Casablanca, Bucharest, Budapest, São Paulo, Rio de Janeiro, Montreal, Ottawa, Sydney, and Melbourne – previously less prominent in this domain – have emerged as regionally notable producers (*Figure S3a* and *S3b* in Supplement). Emerging economies are strengthening their positions in the SC knowledge landscape, with cities in China, India, South Korea, and Brazil making notable contributions (*Table S3* in Supplement).

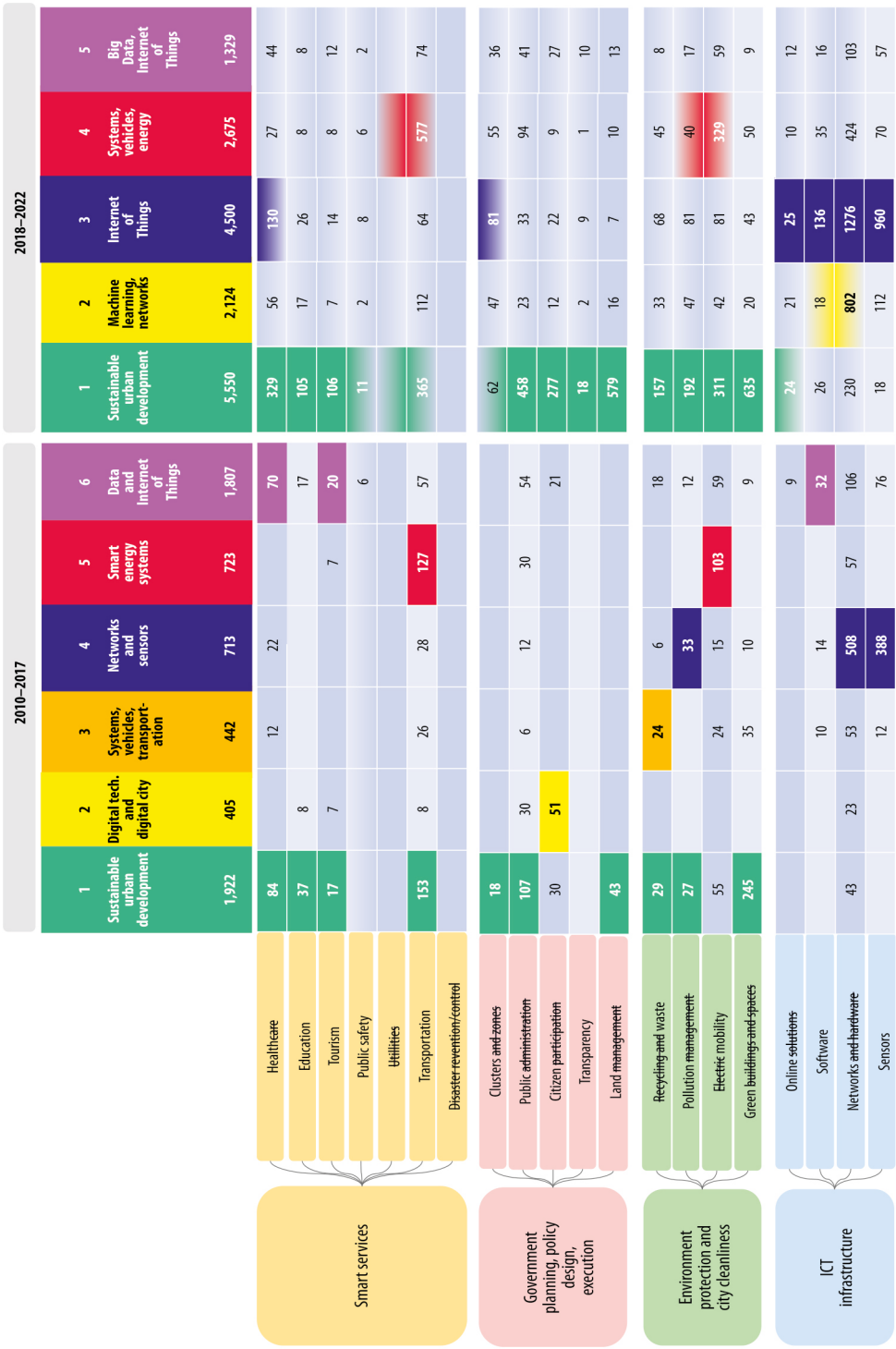


Fig. 4. Number of articles by thematic clusters with their keywords matching the SC activity categories. For detailed explanation see the text. Source: Authors' own elaboration.

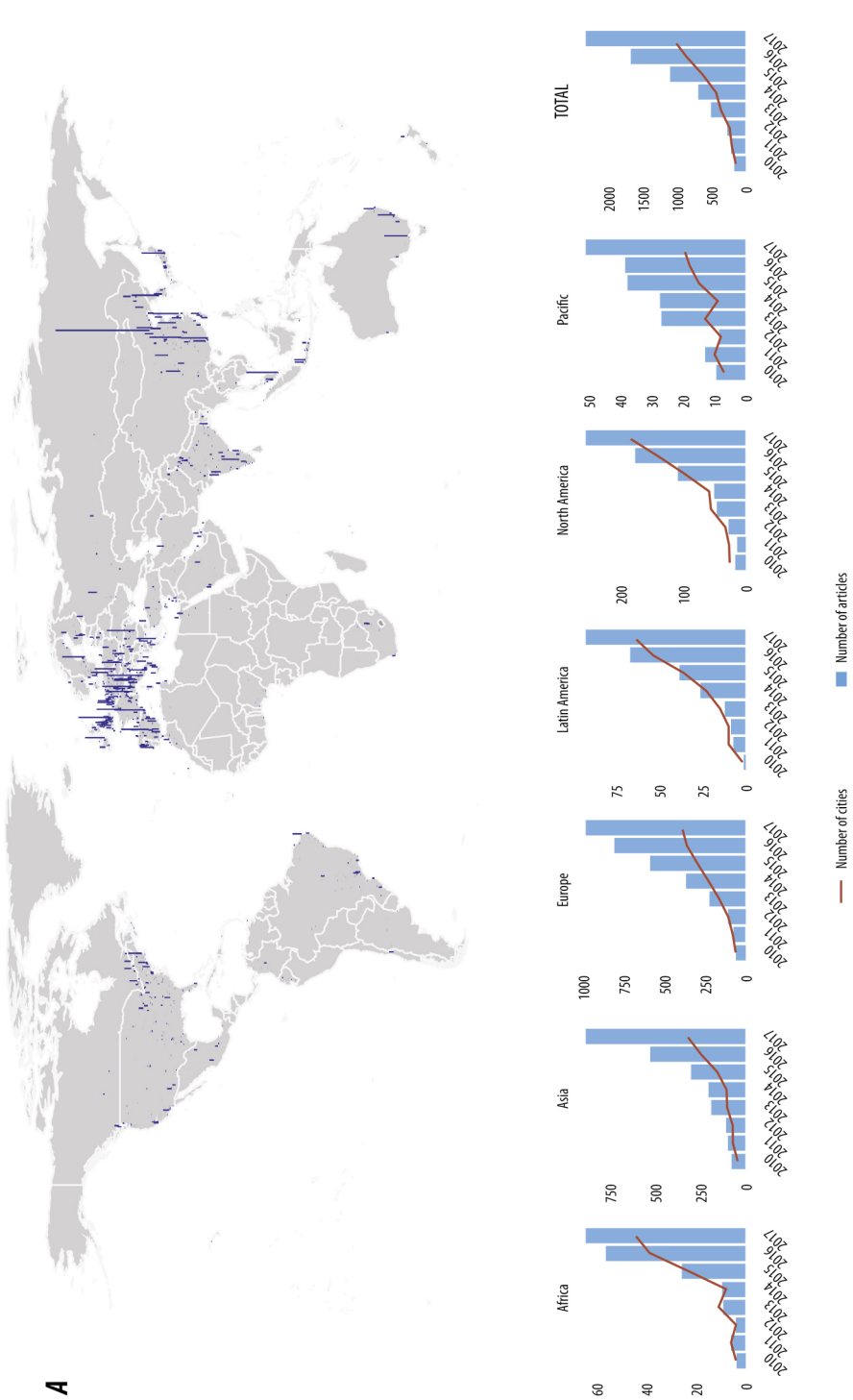


Fig. 5. Number of SC articles and SC knowledge producing cities in the two periods: 2010–2017 (A), and 2018–2022 (B). For detailed explanation see the text.
Source: Authors' own elaboration.



Fig. 5. Continued.

The bars on the maps represent the total number of articles produced at each city location, across two periods. Fractional counts were applied; for instance, if an article involved three cities, each city was assigned a count of 0.33. Below the map, the number of articles (bars) and cities involved in academic SC knowledge production (lines) are shown by major regions, with a summary provided in the Total chart. Note: The y-axes of the smaller graphs are scale-independent and not directly comparable.

As we will demonstrate through the network-based data used for the results, high publication output from a city is rarely achieved without substantial inter-city collaborations. Major article-producing cities are typically connected to many others, serving as hubs for scientific knowledge.

RO3: Comparing SC knowledge-based city ranking with GaWC ranking

Although we assumed that the two types of rankings represent different dimensions of urban development, the correlation between them suggests a weak-to-moderate relationship (0.506–0.620) (Table S4 in Supplement). This weak-to-moderate correlation justifies our initial selection of these two dimensions, as it demonstrates that traditional corporate economic weight does not automatically guarantee a central position in global SC knowledge production. However, high correlation is observed between the two periods within SC knowledge ranking (0.812) and GaWC ranking (0.933), pointing to deep structural path-dependencies within each respective network.

In analysing the rankings, first, we compared the top 50 cities separately in all four rankings, focusing on the changes between the two periods. Sixteen cities are consistently ranked among the top 50 in all four rankings. However, they differ in their significance and dynamic characteristics. Beijing leads in SC knowledge production through

cross-city collaboration and is the sixth most important global city. London, despite losing some of its SC knowledge edge, remains top-ranked in economic significance. Sydney, still in the top 10 global cities, excels in SC knowledge collaborations and significance. Among smaller cities, Prague is an important economic hub and local regional centre, but more populous cities have surpassed it in SC knowledge (Table 1).

Table 1 summarises the top 50 cities in the four city rankings used in the article, involving 241 cities which are equally found in all four rankings. (For methodological details of the rankings see section “Data and research methodology”.) Table 1 includes rank changes for cities appearing in both the SC rankings (left) and the GaWC rankings (right), indicated by arrows. In the middle, the 16 cities consistently featured in all four rankings are listed in descending order of their combined position.

Then we compared the changes in ranking places between the two rankings. This type of comparison allows us to determine which dimension of urban development (economic or academic) is more significant for each city. Based on this, we observed four categories: *dynamic cities of economic and SC knowledge importance*, when the rank change was positive in both rankings; *SC knowledge accumulators*, when SC knowledge rank changed positively but GaWC rank negatively; *economic weight gainers*, when GaWC rank changed positively but SC knowledge rank negatively; *potential laggards*, when the rank change was negative in both rankings. Figure 6 illustrates these dynamics focusing on the top of the rankings. 54 cities rank in the top 100 across all four rankings, with European cities dominating this combined list. Looking deeper, we can see notable differences. In the *dynamic cities of economic and SC knowledge importance* group many Chinese cities are significantly strengthening their positions as both global economic hubs and centres for SC knowledge, joined by a few cities from other emerging economies and even less from the de-

Table 1. Top 50 cities in the SC knowledge, and Global World City (GWC) rankings

Rank	SC knowledge ranking		Rank change		Rank change	GWC ranking		Rank
	2010–2017	2018–2022				2020	2016	
1	Beijing	Beijing	0	Cities in the top 50 on all rankings	0	London	London	1
2	London	Hong Kong	↑ 1		0	New York	New York	2
3	Hong Kong	Seoul	↑ 7		↑ 1	Hong Kong	Singapore	3
4	Rome	Shanghai	↑ 2		↓ -1	Singapore	Hong Kong	4
5	Wuhan	Sydney	↑ 16		↑ 4	Shanghai	Paris	5
6	Shanghai	Nanjing	↑ 14		0	Beijing	Beijing	6
7	Barcelona	Wuhan	↓ -2		↑ 1	Dubai	Tokyo	7
8	Milan	London	↓ -6		↓ -3	Paris	Dubai	8
9	Melbourne	Guangzhou	↑ 25		↓ -2	Tokyo	Shanghai	9
10	Seoul	Melbourne	↓ -1		0	Sydney	Sydney	10
11	Madrid	Riyadh	–	Hong Kong	↑ 17	Los Angeles	Sao Paulo	11
12	Bucharest	Shenzhen	↑ 21		↑ 9	Toronto	Milan	12
13	Singapore	Xi'an	↑ 10		↑ 2	Mumbai	Chicago	13
14	Paris	Singapore	↓ -1		↑ 12	Amsterdam	Mexico City	14
15	Turin	Madrid	↓ -4		↓ -3	Milan	Mumbai	15
16	Stockholm	Islamabad	–		↑ 1	Frankfurt	Moscow	16
17	Tokyo	Barcelona	↓ -10		↓ -3	Mexico City	Frankfurt	17
18	Athens	Chengdu	↑ 12		↓ -7	Sao Paulo	Madrid	18
19	Berlin	Hangzhou	↑ 21		↓ -6	Chicago	Warsaw	19
20	Nanjing	Bucharest	↓ -8		↑ 4	Kuala Lumpur	Johannesburg	20
21	Sydney	Rome	↓ -17	Lisbon	↓ -3	Madrid	Toronto	21
22	Dublin	Tokyo	↓ -5		↓ -6	Moscow	Seoul	22
23	Xi'an	Jeddah	–		↑ 2	Jakarta	Istanbul	23
24	Bologna	Montreal	–		↑ 3	Brussels	Kuala Lumpur	24
25	Vienna	Paris	↓ -11		↓ -6	Warsaw	Jakarta	25
26	Naples	Lisbon	↑ 1		↓ -4	Seoul	Amsterdam	26
27	Lisbon	Changsha	–		↓ -7	Johannesburg	Brussels	27
28	Prague	Brisbane	↑ 3		↑ 5	Zurich	Los Angeles	28
29	Bangalore	Chennai	–		↑ 1	Melbourne	Dublin	29
30	Chengdu	Bangalore	↓ -1		↓ -7	Istanbul	Melbourne	30
31	Brisbane	Athens	↓ -13	Prague	↑ 5	Stockholm	Washington	31
32	Amsterdam	Istanbul	–		↑ 2	Vienna	New Delhi	32
33	Shenzhen	Chongqing	–		↑ 4	Guangzhou	Zurich	33
34	Guangzhou	Berlin	↓ -15		↓ -5	Dublin	Vienna	34
35	Tianjin	Turin	↓ -20		0	Buenos Aires	Buenos Aires	35
36	Jinan	New Delhi	–		↑ 4	Luxembourg	Stockholm	36
37	Zurich	Milan	↓ -29		–	Montreal	Guangzhou	37
38	Ottawa	Budapest	–		↑ 11	Munich	Bogota	38
39	Birmingham	Doha	–		↓ -7	New Delhi	Miami	39
40	Hangzhou	Taichung	–		↑ 2	Santiago	Luxembourg	40
41	New York	Moscow	–		↑ 5	Boston	Riyadh	41
42	Cardiff	St. Petersburg	↑ 5		–	Shenzhen	Santiago	42
43	Bristol	Qingdao	–		↓ -2	Riyadh	Barcelona	43
44	Toronto	Warsaw	–		0	Lisbon	Lisbon	44
45	Manchester	Valencia	–		0	Prague	Prague	45
46	Harbin	Ottawa	↓ -8		–	Bangalore	Boston	46
47	St. Petersburg	Prague	↓ -19		↓ -16	Washington	Copenhagen	47
48	Pune	Stockholm	↓ -32		↓ -10	Bogota	Athens	48
49	Kolkata	Bologna	↓ -25		↓ -10	Miami	Munich	49
50	Florence	Naples	↓ -24		–	Rome	Atlanta	50

Sources: SC knowledge rankings computed by the authors. The source of Global World City rankings: <https://www.lboro.ac.uk/microsites/geography/gawc/world2020.html>. (Accessed 11 March 2024). As the webpage renewed the earlier one available here: <https://web.archive.org/web/20240608095604/https://www.lboro.ac.uk/microsites/geography/gawc/world2020t.html>.

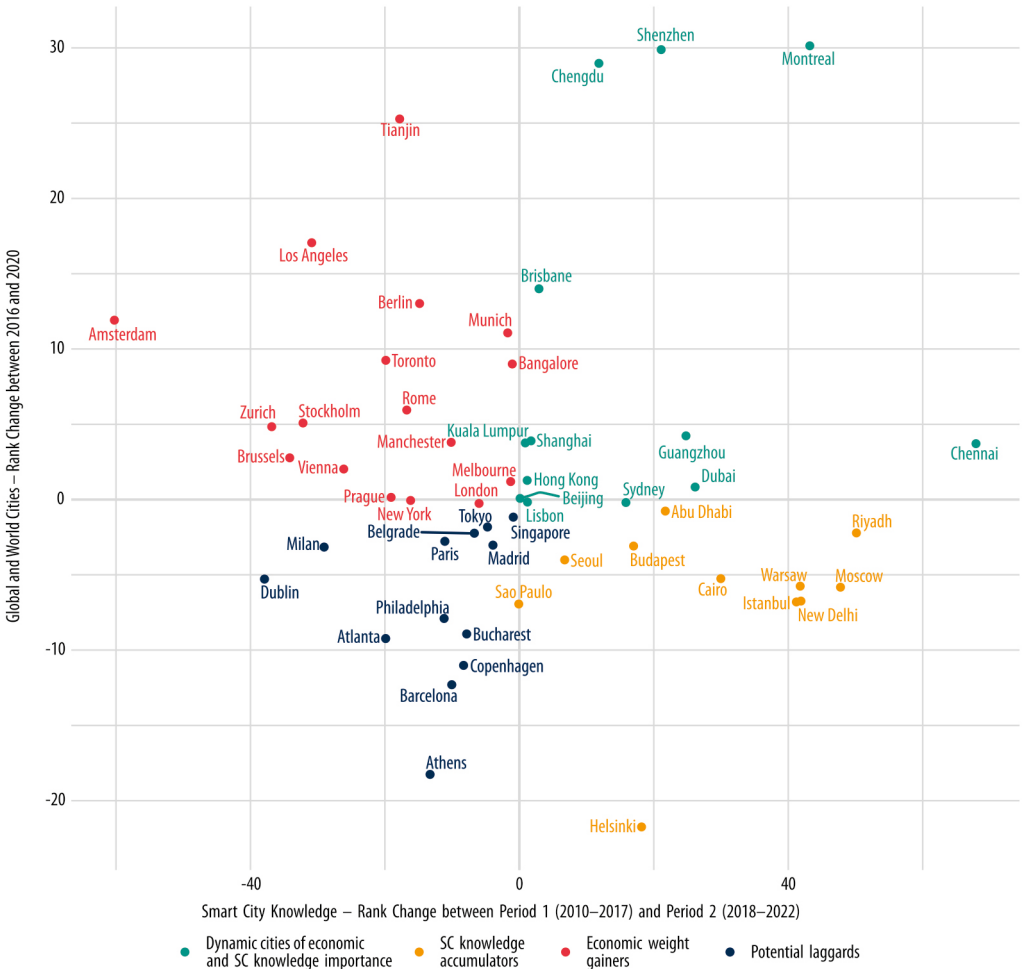


Fig. 6. Changes in the ranking of cities positioned in the top-100 in both networks and in both periods. For detailed explanation see the text. Source: Authors' own elaboration.

veloped nations. Montreal, for example, has made notable advancements in both areas. Europe is represented in this group only by one of the top 100 cities, Lisbon.

Conversely, in the *potential laggards* group, many European cities, such as Paris, Barcelona, Dublin, and Athens are indicated, showing a decline in both economic and SC knowledge importance.

In the *economic weight gainer* group, several European cities – such as Amsterdam, Berlin, Zurich, Rome, and Manchester – have

improved their economic positions but have seen a decline in their significance as SC knowledge hubs.

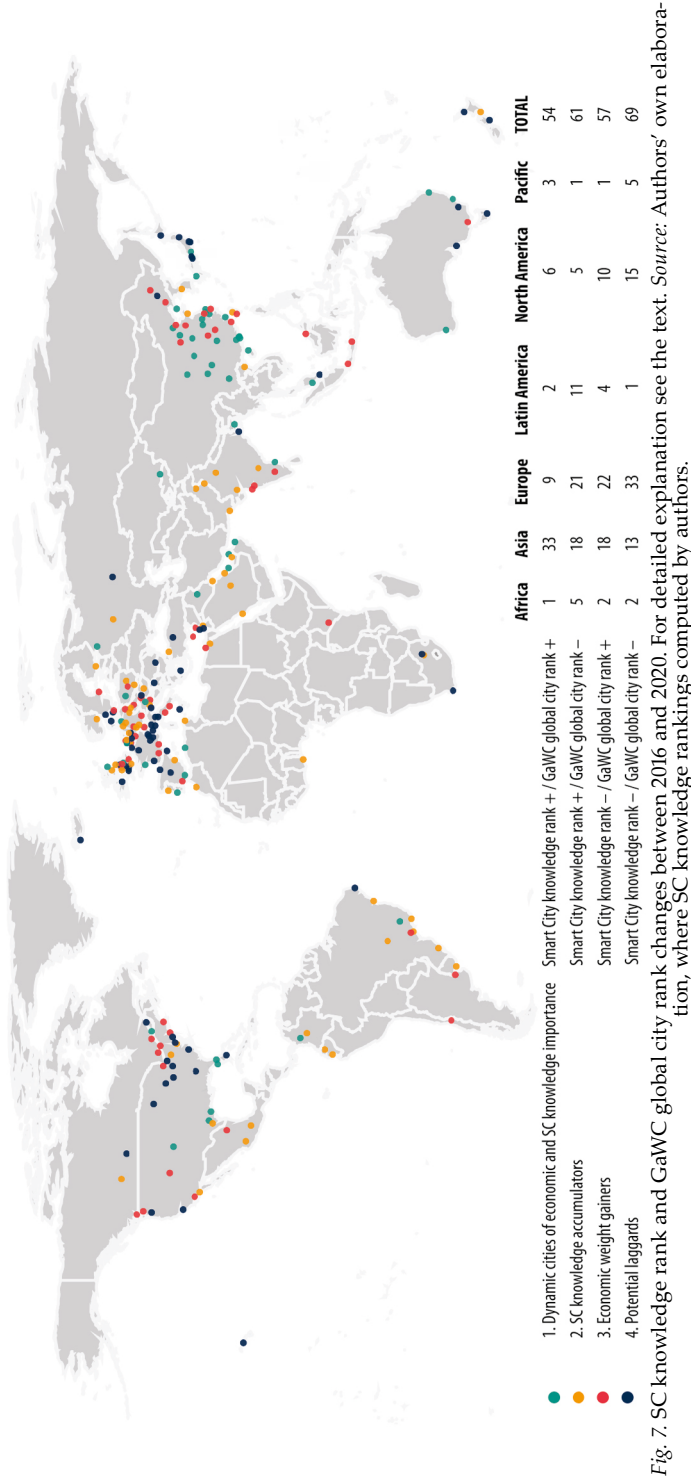
In the *SC knowledge accumulator* group cities like Budapest, Warsaw, and especially Helsinki appear to have experienced a decline in their global importance while improving their role in SC knowledge.

Figure 6 depicts the intersection of the top 100 cities from the four rankings. (For methodological details of the rankings see: Data and research methodology.) Cities are

positioned along two axes, indicating rank changes in the SC knowledge rankings (x-axis) and GaWC rankings (y-axis). Colours correspond to the four quadrants defined by these axes.

Finally, we applied the same approach globally to the 241 cities that appear in every ranking for both periods. From a more global perspective, we determined which cities and macro-regions are dominating each group. In the *dynamic cities of economic and SC knowledge importance* group, mostly cities of Asia, particularly China, have appeared, highlighting an increasing SC knowledge connectedness alongside economic connectedness. However, this group also has a regional character, including cities from other macro-regions, such as Australia, the Middle East, Europe, and the Gulf Coast region of Florida. Cities in the *SC knowledge accumulators* group are representing mostly India, the Middle East, Latin America, and Central and Eastern Europe.

In contrast, in the *economic weight gainer* group, in two developed macro-regions – Europe and North America – a notable number of cities have moved down the SC knowledge rankings, while a significant fraction of these cities has managed to enhance their global economic connectedness and influence (Figure 7). Most cities of the *potential laggards* group



are found in Europe, with a significant number in Asia and North America. The map shows 241 cities which are equally found in all four rankings. Below the map, the table summarises the number of cities in each category by major regions.⁴

Discussion

In our exploration of academic SC knowledge segments and their relationship with SC activities (RO1) we synthesized data from academic publications and we found that SC knowledge segments are dominated by interdisciplinary approaches with a strong technological foundation. The uncovered SC knowledge segments also represent the SC activities that shape SC transformations, directly reinforcing the findings of KUMAR, H. *et al.* (2020). The predominance of technology-oriented segments suggests that academic SC knowledge remains driven by the search for technical solutions to urban challenges. While governance, participation, and sustainability are visible components of the intellectual structure, they appear largely embedded within broader technologically-focused research agendas. This high technological density aligns with the framework of BIBRI, S.E. and KROGSTIE, J. (2017), where advanced ICT serves as the foundational engine for modern urbanism.

At a more granular level, we found that the intellectual structure of SC knowledge is divided between distinct technological-engineering domains – such as Big Data, smart energy systems, or machine learning – and sustainable urban development knowledge, which incorporates social and civil govern-

ance dimensions along with environmental sustainability. This finding matches the SC activity conceptualizations by experts; our findings also align with studies that focus on SC development (MORA, L. *et al.* 2019a) and on the practices cities adopt to foster the SC agenda (MORA, L. *et al.* 2019b).

However, the insight on the global divide of SC knowledge is accompanied by significant local variations. It remains uncertain whether emerging city hubs in developing countries, like European cities, and to lesser extent cities in Australia and Latin America, will embrace social and environmental sustainability in the same way. Regions like East Asia heavily prioritize technological infrastructure (CHEN, X. 2019; KONG, L. *et al.* 2020; JAVED, A.R. *et al.* 2022), and emerging urban environments in the Middle East, India, and Africa similarly employ context-driven technological frameworks. Nevertheless, these are increasingly adapted to local affordability and socio-economic planning (PARK, J. and Yoo, S. 2023). Whether or not developing city hubs will achieve a true convergence of sustainability and technological infrastructure is not self-evident. Emerging cities may not mimic Western trajectories; instead, they are likely to exhibit a hybrid model where technology serves as the primary mechanism to deliver basic needs.

By mapping global SC knowledge hubs and the geographical distribution of publication output (RO2), we showed that a growing number of cities contribute to and accumulate SC knowledge. Nevertheless, the majority of output comes from just a few cities, so concentration is evident in this sector as well, similar to what FLORIDA, R. *et al.* (2017) observed in other creative and intellectual sectors.

In the comparison of SC knowledge-based city ranking with GaWC ranking (RO3), a weak-to-moderate relationship was found. This correlation suggests that economic centrality and SC knowledge centrality represent related but distinct dimensions of global urban importance. Knowledge-intensive

⁴ The source of GaWC rankings: <https://www.lboro.ac.uk/microsites/geography/gawc/world2020.html> 3. (Accessed 11 March 2024). As the webpage renewed the earlier one available here: <https://web.archive.org/web/20240608095604/https://www.lboro.ac.uk/microsites/geography/gawc/world2020.html>

business service research also emphasizes the GaWC approach, which includes a knowledge dimension rather than just an economic one, as it uses advanced producer services data (MULLER, E. and ZENKER, A. 2001).

Cities topping these rankings show some European dominance; however, almost all Chinese cities are significant as both global economic hubs and centres for SC knowledge.

The temporal changes provided insights into four city categories: dynamic cities of economic and SC knowledge importance; SC knowledge accumulators; economic weight gainers; and potential laggards. Regional variance is notable among these groups, and from representing specialisation avenues across SC knowledge and economic hub dynamics. From a global perspective, the four identified city categories reveal that trajectories of urban development are becoming heterogeneous. Rather than following a single pathway towards global prominence, cities appear to specialise in different combinations of economic integration and SC knowledge accumulation. From this divergence, we can deduce a structural decoupling in the global urban hierarchy: while Asian hubs are using knowledge accumulation as a dynamic vanguard for growth, several legacy European hubs are experiencing a relative decline in SC related academic discourse despite maintaining corporate economic weight. The rise of several cities in the SC knowledge ranking without corresponding gains in the economic ranking suggests that scientific collaboration networks may act as an early indicator of emerging urban importance. Whether such knowledge advantages eventually translate into broader economic influence remains an open question. Conversely, cities that maintain strong economic positions while showing comparatively weaker performance in SC knowledge networks may face challenges in sustaining long-term competitiveness within increasingly knowledge-intensive urban environments.

Taken together, the results imply that global city status is becoming increasingly multidimensional. Economic connectivity remains a defining feature of urban prominence and SC knowledge networks reveal additional forms of centrality that are not fully captured by existing global city frameworks.

We have to acknowledge several limitations too.

First, the study relies on a single database of academic publications for SC knowledge. Although WoS provides extensive coverage and is widely used in similar studies, it does not capture all forms of SC-related knowledge production, such as local journal publications, policy reports, industrial research etc. We believe, however, that the scale of our study and the international coverage of the database provide a robust basis for the analysis and conclusions.

Second, the study conceptualizes SC knowledge through scientific publications and collaboration networks, reflecting the dynamics of codified academic knowledge rather than the practical implementations of SC agendas. Cities may differ substantially in their capacity to translate scientific knowledge into urban transformation.

Third, city-level knowledge hubs were identified through author affiliations. While this approach is common in spatial scientometrics, with the increasing prevalence of multi-institutional and internationally distributed research teams, geographical attribution of knowledge production might seem an oversimplification.

Fourth, the SC knowledge rankings and GaWC rankings capture fundamentally different forms of urban connectivity and the observed differences may arise both from genuine divergence between economic and knowledge dimensions and from differences in the underlying network structures. Future research should further investigate the relationship between these dimensions and the mechanisms through which they interact.

Finally, the analysis covers two broad time periods and therefore captures rather medium-term shifts. More detailed longitudinal analyses may reveal new patterns in the emergence, persistence, or decline of SC knowledge hubs.

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As the webpage renewed the earlier one available here: <https://web.archive.org>

Supplement

Table S1. SC research search profile

Search profile	Hits in Web of Science
TS = ("intelligent city" OR "knowledge city" OR "ubiquitous city" OR "sustainable city" OR "digital city" OR "smart city" OR "future city" OR "eco city" OR "eco-city" OR "compact city" OR "liveable city" OR "digital city" OR "innovative city" OR "green city"), OR TS = ("intelligent cities" OR "knowledge cities" OR "ubiquitous cities" OR "sustainable cities" OR "digital cities" OR "smart cities" OR "future cities" OR "eco cities" OR "eco-cities" OR "compact cities" OR "liveable cities" OR "digital cities" OR "innovative cities" OR "green cities"), OR TS = (urban OR city OR cities) AND ("smart econom*" OR "smart people" OR "smart govern*" OR "smart mobility" OR "smart environment*" OR "smart living"), AND DT = ("Article" OR "Proceedings paper") and English (Languages)	28,444

Note: Our search profile based on SC definitions and smart urban phenomena (COCCHIA, A. 2014; ALBINO, V. *et al.* 2015; EREMI, M. *et al.* 2017). Publications’ metadata were downloaded from the Web of Science (WoS) database on 18 May 2023. *Source:* Authors’ own elaboration.

Table S2. Search string construction and supporting literature for each term

COCCHIA, A. 2014	knowledge city knowledge cities; ubiquitous city ubiquitous cities
ALBINO, V. <i>et al.</i> 2015	urban + smart econom*; urban + smart people; urban + smart govern*; urban + smart mobility; urban + smart environment*; urban + smart living; city + smart econom*; city + smart people; city + smart govern*; city + smart mobility; city + smart environment*; city + smart living; cities + smart econom*; cities + smart people; cities + smart govern*; cities + smart mobility; cities + smart environment*; cities + smart living;
DUYGAN, M. <i>et al.</i> 2022	future city future cities; eco city eco-cities; smart city smart cities; intelligent city intelligent cities; sustainable city sustainable cities; compact city compact cities; liveable city liveable cities; digital city digital cities; innovative city innovative cities; green city green cities

Note: In the table and in the search strings, the asterisk (*) is used as a truncation (wildcard) operator to capture all word variants and derivatives complementing core smart city terms (e.g. ‘govern*’ captures ‘governance’, ‘government’, or ‘governing’; ‘environment*’ captures ‘environmental’ and ‘environment(s)’; and ‘econ*’ captures ‘economy’, ‘economies’, ‘economics’, etc.). *Source:* Authors’ own elaboration.

Table S3. The top ten countries by production of SC knowledge

2010–2017				2018–2022			
Country	Number of		Articles, %	Country	Number of		Articles, %
	cities	articles			cities	articles	
China	108	1037	14.5	China	203	2803	15.9
Italy	84	698	9.9	USA	428	1538	8.7
USA	253	581	8.2	India	260	1250	7.1
Spain	63	420	6.0	Italy	97	1025	5.8
India	123	406	5.8	United Kingdom	80	726	4.1
United Kingdom	57	359	5.0	Spain	85	703	4.0
Germany	81	237	3.4	Australia	35	524	3.0
Australia	26	196	2.8	Germany	130	494	2.8
France	69	183	2.6	South Korea	43	479	2.7
Japan	48	161	2.3	Brazil	135	467	2.6

Note: The table shows the total number of articles by cities within their respective countries (for details see: Data and research methodology) across two periods. It includes only the top 10 producer countries. Fractional counts were applied; for instance, if an article involved three cities, each city was assigned a count of 0.33. Articles published from 2010 to 2017 are summarized on the left, while those published from 2018 to 2022 are summarized on the right. The percent of articles is computed as share of the total number of articles. *Source:* Authors’ own elaboration.

Table S4. Spearman’s rank correlation coefficient between the four rankings

Rankings	Period	City rankings based on SC knowledge		Global and world cities ranking	
		2010–2017	2018–2022	2016	2020
City rankings based on SC knowledge	2010–2017	1.000	0.812	0.506	0.521
	2018–2022	–	1.000	0.579	0.620
Global and world cities ranking	2016	–	–	1.000	0.933
	2020	–	–	–	1.000

Note: The table summarizes the Spearman ranking correlations between the four city rankings used in the article, involving 241 cities (for details of deriving the rankings see: Data and research methodology). *Source:* Authors’ own elaboration.

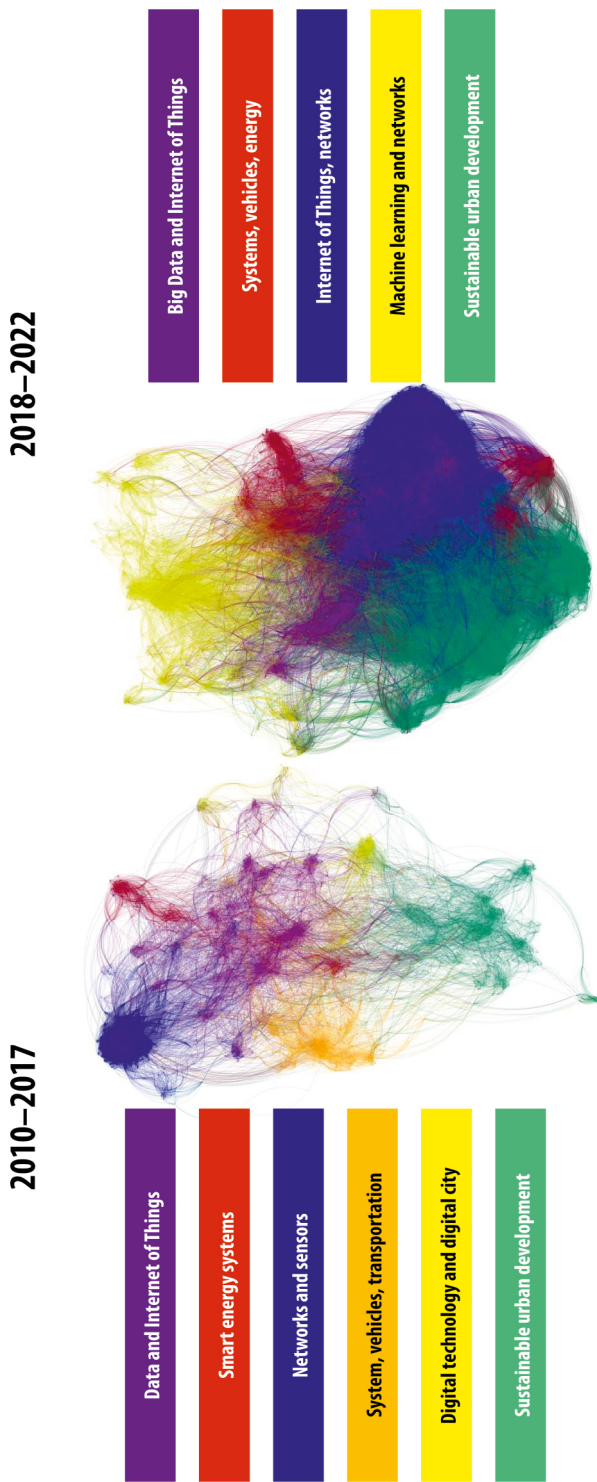


Fig. S1. Thematic clusters in the SC knowledge space. Note: The figure contains articles as nodes connected by shared keywords as edges, organized by the thematic clusters that emerged in the science mapping during two periods (for details see: Data and research methodology). The network of articles published from 2010 to 2017 is visualized on the left, while those published from 2018 to 2022 are shown on the right. The colours represent articles in different thematic clusters: nodes of the same colour belong to the same thematic cluster. For the cluster names and themes, see Figure 4 at the top. Similar colours were applied to clusters with comparable contents in the two periods. The detailed content, represented by word clouds, is depicted in Figures S2a and S2b. The following identical steps were sequentially performed in Gephi to facilitate visualization: Yifan-Hu network optimization was used (Hu, Y. 2005); edges below 0.4 edge weight were deleted, because low edge weights represent low cognitive similarity based on the shared keywords and there is no loss of influential content or influence on the community structure (YAN, X. *et al.* 2018); setting the minimum degree to 5 to further support visual clarity. Source: Authors' own elaboration.

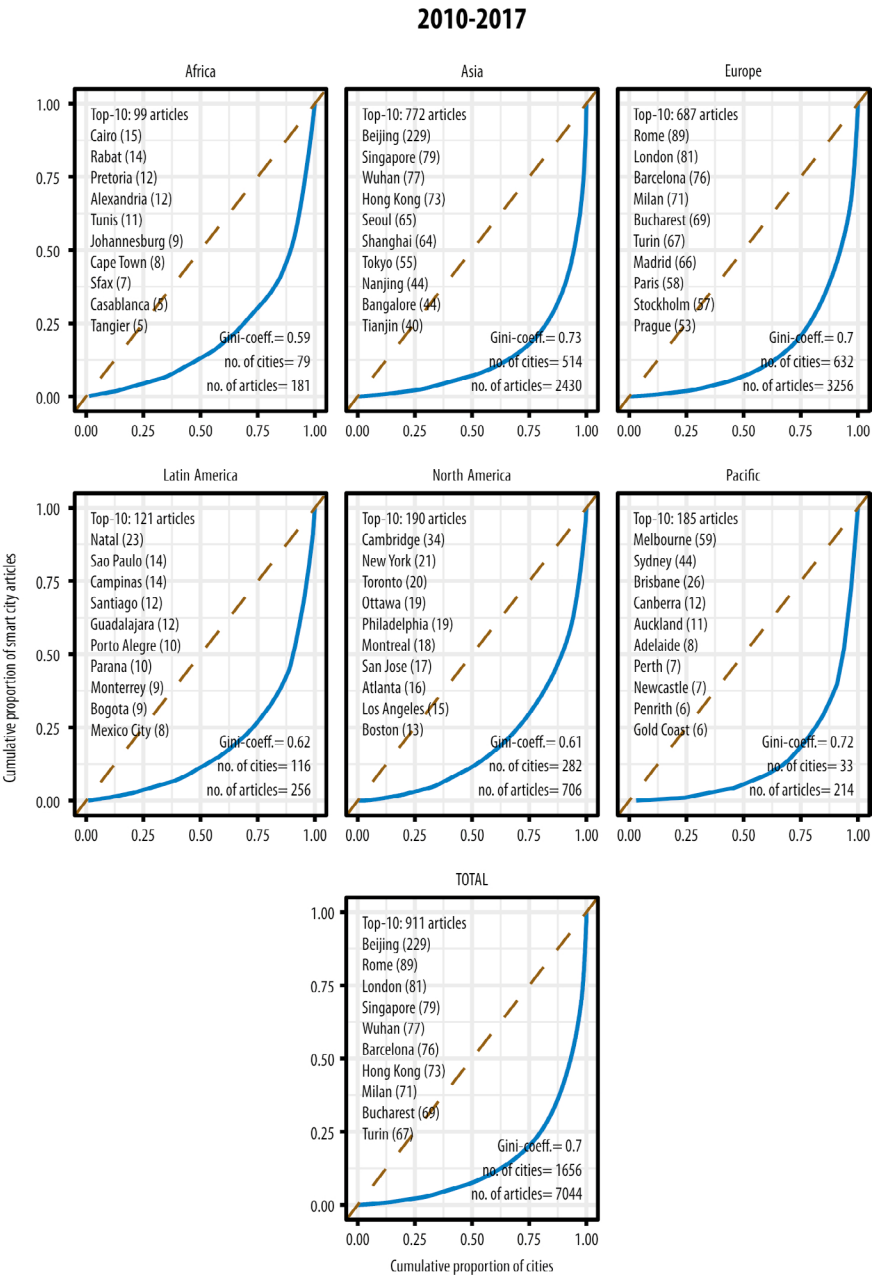


Fig. S3a. Concentration of SC knowledge in cities, 2010–2017. Note: Lorenz curves are shown for major regions and summarized in the TOTAL chart, across two periods. These curves plot the cumulative proportion of cities (x-axis) against the cumulative proportion of smart city articles produced (y-axis). Each regional chart includes the Gini coefficient, the total number of cities, and the total number of articles at the bottom-right. At the top-left, the top 10 cities and their respective article counts are listed. Fractional counts were applied; for instance, if an article involved three cities, each city was assigned a count of 0.33. Source: Authors' own elaboration.

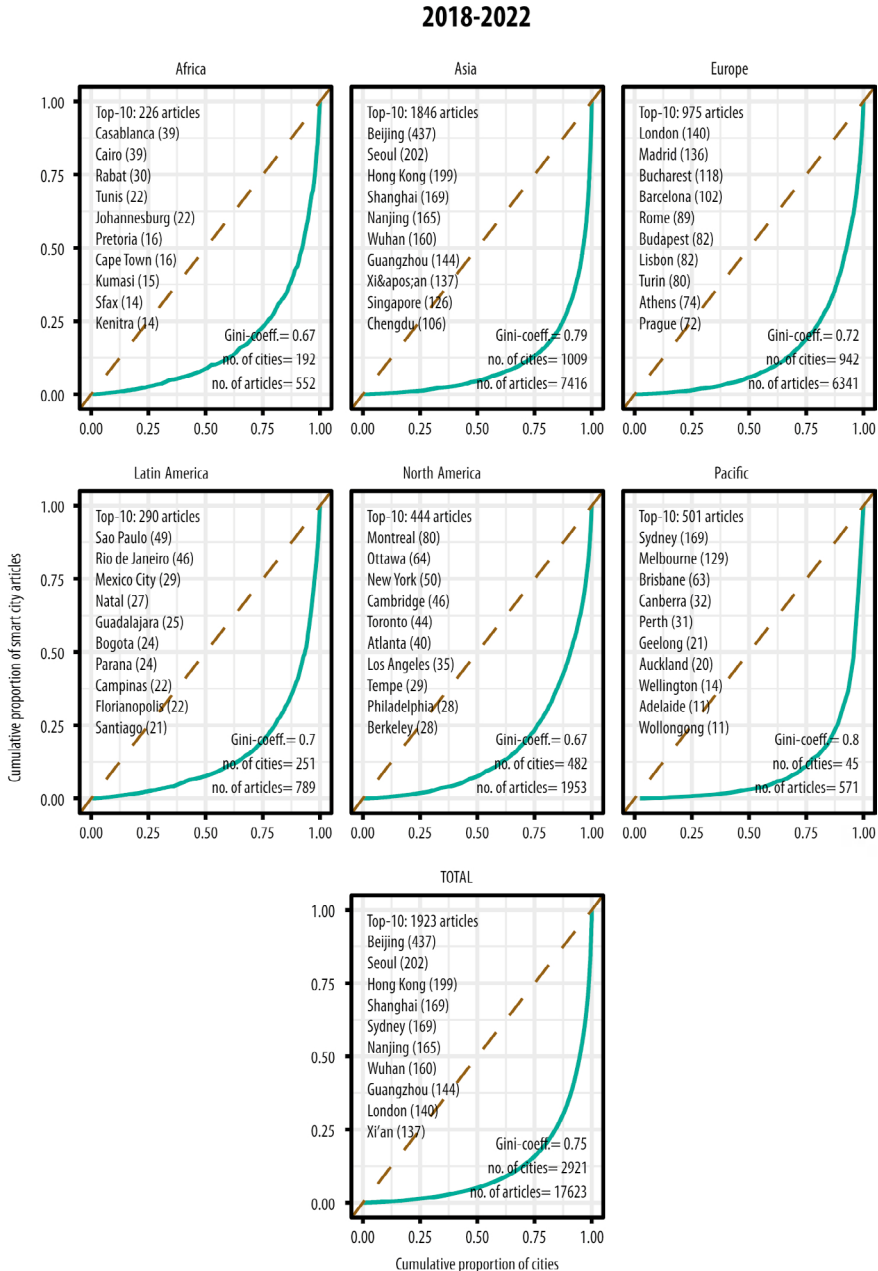


Fig. S3b. Concentration of SC knowledge in cities, 2018–2022. Note: Lorenz curves are shown for major regions and summarized in the TOTAL chart, across two periods. These curves plot the cumulative proportion of cities (x-axis) against the cumulative proportion of smart city articles produced (y-axis). Each regional chart includes the Gini coefficient, the total number of cities, and the total number of articles at the bottom-right. At the top-left, the top 10 cities and their respective article counts are listed. Fractional counts were applied; for instance, if an article involved three cities, each city was assigned a count of 0.33. Source: Authors' own elaboration.

Subcultural space through the adaptive cycle – Resistance and commodification in Berlin Kreuzberg SO36

DÁVID TILL¹ and DÁVID SÜMEGHY²

Abstract

Urban transformation is commonly interpreted through processes of capital accumulation, gentrification, and displacement, while less attention has been paid to the temporal trajectories of subcultural spaces and their changing relationship with commodification. This study examines whether Holling's adaptive cycle provides a useful analytical framework for interpreting these transformations in Berlin's Kreuzberg SO36. The research combines literature and document analysis with fieldwork conducted during four visits between 2023 and 2025, including systematic site observation and photographic documentation, supplemented by focused micro-interviews. Three symbolically significant sites – the Georg von Rauch Haus, M99, and Cuvrybrache – are examined as contrasting trajectories of subcultural spatial production. The findings show that these spaces can be interpreted through different phases of the adaptive cycle, characterized by changing configurations of potential, connectedness, and resilience. The cases further demonstrate that the accumulation of cultural and symbolic value can simultaneously strengthen subcultural spaces and increase their susceptibility to institutionalization and economic appropriation. However, these trajectories are not deterministic: legalization may constrain autonomy while supporting persistence, whereas displacement and redevelopment produce different outcomes. The study demonstrates the value of the adaptive cycle as a qualitative heuristic for interpreting the non-linear transformation of contested urban spaces.

Keywords: subculture, gentrification, production of space, adaptive cycle, Berlin

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Introduction

Berlin has undergone extensive socio-spatial transformation since German reunification, with gentrification particularly affecting its inner-city districts. Kreuzberg occupies a distinctive position within this process because its present transformation builds upon a history of political marginality, low-cost housing, migration, and alternative forms of urban space production.

During the division of Berlin, the eastern part of Kreuzberg occupied a peripheral po-

sition within West Berlin. The Berlin Wall enclosed the district on three sides, creating structural isolation that provided fertile ground for subcultural occupation during the 1970s and 1980s (LENNERT, L. 2014).

As HOCHMUTH shows, the wall generated lasting socio-spatial fragmentation (HOCHMUTH, H. 2017). Historically, Kreuzberg was commonly divided into the former postal districts SO36 and SW61. The abbreviations refer to *Südost* (southeast) and *Südwest* (southwest), while the numbers derive from Berlin's former postal districts. Although these des-

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ignations no longer have an administrative function, SO36 remains widely used to refer to the eastern part of Kreuzberg and its distinctive socio-cultural identity. The loss of green spaces, economic decline, industrial outmigration, and demographic restructuring reshaped the district. Guest workers – primarily Turkish and Southern European – settled due to low rents (HOCHMUTH, H. 2017), producing a culturally heterogeneous yet low-prestige social composition (BERNT, M. and HOLM, A. 2013). This configuration persisted after reunification.

Although gentrification in Berlin and Kreuzberg has been extensively studied, existing research has primarily examined processes such as displacement, housing-market restructuring, urban policy, and resistance. Less attention has been paid to whether the transformation of subculturally produced urban spaces can be understood as a cyclical process in which their emergence, consolidation, institutionalization, and commodification represent interconnected stages of transformation. This constitutes the central problem addressed by the present study.

Rather than reconstructing a linear trajectory of change, this article interprets SO36 as a site of cyclical socio-spatial transformation through HOLLING's adaptive cycle model (HOLLING, C.S. 2001). The study examines whether this model can provide an additional analytical framework for understanding the changing relationship between subcultural spatial production, intangible capital, institutionalization, and commodification. On this basis, the analysis proceeds from four interrelated hypotheses. Subcultural spaces in Kreuzberg SO36 are expected to correspond to distinct phases of the adaptive cycle, reflected in changing levels of capital, connectedness, and resilience. Their emergence and consolidation are hypothesized to coincide with the accumulation of intangible forms of capital, whereas increasing institutionalization and commodification are expected to strengthen connectedness and the realization of material capital while re-

ducing their transformative capacity. Finally, the analysis assumes that gentrification facilitates the incorporation of symbolic and cultural values produced within subcultural spaces into market-oriented urban development.

Space and its cyclical transformation

Building on LEFEBVRE and SOJA, urban space is approached as socially produced and inherently dynamic (LEFEBVRE, H. 1991; SOJA, E.W. 1996). LEFEBVRE's distinction between perceived, conceived, and lived space provides the basis for interpreting the built environment not merely as the physical setting of social conflict but as something continuously produced through social practices and representations. SOJA's spatial perspective extends this approach by emphasizing the simultaneous interaction of material, represented, and lived dimensions of space. In the Kreuzberg case, these concepts allow subcultural practices such as occupation, collective use, and symbolic appropriation to be interpreted as forms of spatial production rather than simply as reactions to urban change.

While LEFEBVRE and SOJA provide the framework for interpreting how urban space is socially produced and contested (SOJA, E. 1980; LEFEBVRE, H. 1991), NEIL SMITH and DAVID HARVEY locate these transformations within the political economy of capitalist urbanization (SMITH, N. 2002; HARVEY, D. 2006). Their approaches draw attention to the tension between use value and exchange value and to the role of capital reinvestment in restructuring urban space. This distinction is particularly relevant to Kreuzberg, where spaces appropriated for residential, cultural, or collective use increasingly acquired exchange value through their incorporation into the city's property and tourism markets.

Gentrification is therefore treated here not simply as demographic change but as a process through which locally produced spatial values become subject to economic

valorization. In Berlin, this process has been mediated by both market mechanisms and state policies, contributing to displacement and increasing pressure on lower-income residents and alternative spaces (BERNT, M. and HOLM, A. 2013; HELBRECHT, I. 2018). At the same time, these pressures have generated organized forms of resistance, particularly around housing and squatter-related spaces (DRISSEL, D. 2011).

The structure of Berlin's rental market is crucial for understanding how these broader processes materialize in Kreuzberg. Since reunification, restitution, modernization, tenant turnover and the expiration of housing subsidies have increasingly exposed previously inexpensive rental housing to market pressures (BERNT, M. 2022). These processes have been particularly consequential in inner-city neighbourhoods dominated by 19th-century tenement housing, where rents have risen substantially since the late 2000s (HÜBSCHER, M. and KALLERT, T. 2023; PETTAS, D. and SUWALA, L. 2023). In SO36, housing-market pressure is partly mediated through preservation regulations. Much of the study area is designated as a social preservation area (*Milieuschutzgebiet*), intended to protect the composition of the resident population from displacement, while parts are additionally subject to urban conservation regulations. Such institutional protections constrain particular forms of property transformation but do not remove the broader tension between the established use value of housing and its potential exchange value. This tension provides an important institutional context for the commodification processes examined in the three case studies.

Subculture and symbolic resistance

The concept of subculture has shifted from criminological to cultural and postmodern interpretations. Early Chicago School approaches framed subculture through territorialized deviance (BLACKMAN, S. 2005).

Later approaches increasingly shifted attention from deviance towards cultural practices and symbolic forms of resistance, most notably within the Birmingham Centre for Contemporary Cultural Studies (CCCS) (CONNELL, K. and HILTON, M. 2015).

At the CCCS, Phil COHEN reframed subculture as symbolic resistance (COHEN, P. 1972). Resistance Through Rituals conceptualized style and ritual as class-based semiotic practice (HALL, S. and JEFFERSON, T. 1976; JEFFERSON, T. 2002). This understanding is particularly relevant to the present study because it allows visible practices and symbols to be interpreted as expressions of collective opposition to dominant social and spatial arrangements. THORNTON's concept of subcultural capital provides a further analytical link between cultural distinction and the production of symbolic value (THORNTON, S. 1995). In the context of gentrification, this is important because values initially produced within subcultural communities may subsequently become recognizable, appropriable, and economically exploitable beyond those communities.

In this study, *subculture* is used as the broader analytical category, while *counterculture* refers more specifically to subcultural formations whose practices and values explicitly challenge dominant social, political, or economic norms. The term *subculture* therefore refers to socially and spatially embedded communities whose collective practices, symbolic expressions, and value systems distinguish them from dominant cultural and market-oriented forms of urban space production. It is used not primarily to describe a particular youth style or fixed social identity, but as an analytical category for communities that produce and maintain alternative meanings, practices, and forms of collective use within urban space. In SO36, squatting, anarcho-punk communities, and other autonomous cultural practices constitute the principal manifestations of this form of subcultural spatial production and, where explicitly oppositional, of counterculture.

Subcultural production of space

Building on the understanding of space as socially produced, subcultural spatial production is approached here as the appropriation and reinterpretation of urban space through collective practices, alternative forms of use, and symbolic meanings. In Kreuzberg SO36, these processes developed under the specific historical conditions created by Berlin's division and continued to shape urban space after reunification. Although the Berlin Wall disappeared as a physical boundary, its socio-spatial effects did not disappear simultaneously. Decades of peripheralization had altered the demographic composition, housing stock, and symbolic geography of Kreuzberg, and traces of this division remained after reunification (DRISSEL, D. 2011; HOCHMUTH, H. 2017). In LEFEBVRE's terms, the transformation of material space therefore did not immediately erase meanings accumulated within lived space. From this perspective, the alternative uses and meanings attached to buildings and neighbourhood spaces in SO36 can be understood as part of a historically embedded process of spatial production rather than merely as temporary reactions to gentrification.

The vacant and functionally uncertain spaces produced by this historical transformation can also be interpreted as liminal spaces: spaces characterized by transition and unsettled meanings (CZARNIAWSKA, B. and MAZZA, C. 2003). In SO36, some of these spaces became available for appropriation by autonomous groups, most visibly through the squatting movement. Their occupation involved not only physical control of buildings but also their symbolic reinterpretation through collective use, political practices, and movement-related representations. This process is referred to here as *subcultural spatial appropriation*. Symbolic appropriation has also been examined in Central and Eastern European urban contexts, where spatial markers can express collective identities and

claims to urban space (ERŐSS, Á. and TÁTRAI, P. 2010). Although examined primarily in the context of ethnic relations, this mechanism is also relevant to SO36, where graffiti, flags, banners, and other movement-related symbols contribute to the symbolic appropriation and differentiation of urban space.

Once appropriated, such sites may develop into what KOHN conceptualizes as *radical spaces*: places in which collective practices challenge dominant political and economic arrangements (KOHN, M. 2003). This concept is particularly relevant to squatter projects because their significance derives not only from occupying property but from establishing alternative forms of collective use and organization within it.

Squatter projects differ from commercial space through their emphasis on collective use, self-organization, and alternative value systems (LENNERT, L. 2014). Their significance therefore lies in producing forms of urban space in which use value and collective meaning may temporarily take precedence over exchange value. However, meanings attached to these places through subcultural spatial production may not be shared by wider society and can therefore become sources of social conflict.

The meanings produced within such spaces may conflict with market-oriented transformations of the surrounding neighbourhood. In SO36, opposition to gentrification is expressed not only through organized political action but also through the built environment, including graffiti, banners, flags, and other movement-related symbols. These visible markers contribute to the continued symbolic differentiation of subcultural spaces even where the surrounding neighbourhood has undergone substantial commercialization.

Subcultural spatial production can therefore be understood as an ongoing interaction between material appropriation, collective meaning, and resistance to the incorporation of urban space into dominant market logics.

The adaptive cycle and the fluidity of space

The adaptive cycle provides the principal analytical model used in this study to interpret the transformation of subcultural urban spaces. Originally developed by HOLLING from resilience research in ecological systems, the model conceptualizes change not as a linear progression towards equilibrium but as a recurring movement through four phases: exploitation (r), conservation (K), release (Ω), and reorganization (α) (HOLLING, C.S. 1973, 2001). These phases describe changing relationships between accumulated potential, connectedness, and resilience within a system. The adaptive cycle (Figure 1) should be distinguished from the broader concept of panarchy. While the adaptive cycle describes the dynamics of a system at a particular scale, panarchy conceptualizes how multiple adaptive cycles operating at different spatial and temporal scales interact with one another (GUNDERSON, L.H. and HOLLING, C.S. 2002). Panarchy therefore adds a cross-scale dimension to the adaptive cycle: processes occurring within one cycle may influence the persistence or transformation of systems operating at other scales. The empirical analysis in this study is primarily

based on the adaptive cycle model, while the broader implications of cross-scale interactions are considered in the Discussion.

This distinction builds on Holling's earlier separation of resilience from stability. Stability refers to a system's capacity to return towards an equilibrium following disturbance, whereas resilience concerns its capacity to absorb change while maintaining its fundamental relationships and functions (HOLLING, C.S. 1973). Later developments of resilience theory additionally emphasized *transformability*: the capacity to create a fundamentally new system when existing ecological, social, or economic conditions become untenable (WALKER, B. *et al.* 2004). These distinctions are particularly relevant to urban transformation, where persistence, adaptation, and transformation may represent different responses to external pressures rather than different degrees of the same process.

Although developed in ecology, the adaptive cycle has subsequently been applied to social and socio-ecological systems, including community resilience (BERKES, F. and ROSS, H. 2016), and complex patterns of social change (ROGERS, J.D. 2017). Its application to urban processes has included shrinking-city trajectories (HERMANN, D. *et al.* 2016),

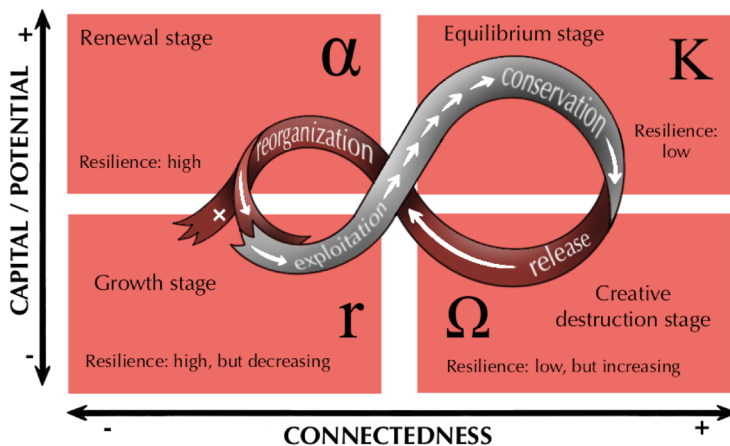


Fig. 1. The adaptive cycle model. Source: Authors' adaptation of TILL, D. (in press) based on HOLLING, C.S. (2001), and GUNDERSON, L.H. and HOLLING, C.S. (2002).

multilevel urban resilience (ROGOV, M. and ROZENBLAT, C. 2018), and community-based urban renewal (SAEZ UJAQUE, D. *et al.* 2021), and the transformation and institutionalization of countercultural spaces in Berlin SO36 (TILL, D., in press). These studies demonstrate the model's potential beyond ecological systems, while also highlighting the need to adapt its analytical dimensions carefully to the social and institutional characteristics of urban change. In this study, the adaptive cycle is applied to three subcultural sites in SO36, interpreting their transformation through changing configurations of potential, connectedness, and resilience.

The adaptive cycle distinguishes four phases – r , K , Ω , and α – through changing configurations of three central properties: potential, connectedness, and resilience (see *Figure 1*). Potential refers to the resources accumulated within the system, connectedness to the degree of internal control and interdependence among its components, and resilience to its capacity to absorb disturbance without shifting into a fundamentally different configuration (HOLLING, C.S. 2001). During the exploitation phase (r), resources are rapidly mobilized, connectedness remains relatively low, and the system retains considerable flexibility. In applying the model to subcultural urban space, this study interprets potential not only as material resources but also as accumulated intangible resources, including cultural, symbolic, and relational forms of capital. These forms of capital may subsequently acquire material or economic value as the system becomes increasingly consolidated.

The slow transition towards the conservation phase (K) marks a period of increasingly consolidated social structures. During this phase (K), accumulated potential and connectedness increase while flexibility and resilience tend to decline. Resources become increasingly bound within established structures, making the system more efficient but also potentially more vulnerable to disturbance. A sufficiently strong disturbance may trigger the release phase (Ω), during which

accumulated structures and resources are rapidly disrupted or released.

The subsequent reorganization phase (α) is characterized by low connectedness and increased opportunities for novelty and recombination. Resources released during Ω may be reorganized into new configurations, allowing either the renewal of the existing system or its transformation into a different one. The transition from α towards a new r phase therefore does not imply a return to an identical previous state but the emergence of a reorganized configuration shaped by the legacies and resources of the preceding cycle (HOLLING, C.S. 2001).

Study area and methods

The study focuses on SO36, the eastern part of Kreuzberg in the Friedrichshain-Kreuzberg borough of Berlin. The study area broadly corresponds to the historical Luisenstadt neighbourhood and adjacent Spree river-side areas, including Oranienplatz, Lausitzer Platz, Wrangelkiez, and the Reichenberger Straße area. During the division of Berlin, its peripheral location adjacent to the Berlin Wall, relatively low rents, deteriorating housing stock, and demographic transformation contributed to the concentration of migrant communities, alternative lifestyles, and autonomous movements (HOCHMUTH, H. 2017). Squatting became particularly significant from the 1970s onwards and developed into an enduring element of the area's political and cultural identity. Following reunification, SO36 shifted from a peripheral location to a more central position within Berlin, while rising property values and development pressure exposed these established communities and spaces to gentrification (BERNT, M. and HOLM, A. 2013).

The research combines a review of academic and historical literature with documentary sources and qualitative fieldwork. A database of occupied buildings was compiled primarily from the Berlin Besetzt archive

(Berlin Besetzt, 2025), and supplemented with information provided by Luisenstadt eG (Luisenstadt eG, 2026). This database provided the sampling framework for the field surveys: all identified formerly or currently occupied buildings within the study area were visited and documented.

Fieldwork was conducted during four approximately one-week research visits between 2023 and 2025: three in October and one in June 2025. It combined systematic site observation and photographic documentation with participant observation at selected local events.

The surveys documented the present condition and use of the identified buildings and systematically recorded predefined spatial markers of collective and political identity, including graffiti, posters, flags, and other movement-related symbols. Rather than being treated as independent evidence of resistance, these markers were interpreted in relation to the documented history, present use, and collective identity of each site.

Fieldwork was conducted as an external researcher rather than as a member of the autonomous communities examined. Participation in local events provided contextual familiarity, while this external position required reflexive interpretation of political and symbolic markers.

The field material was not subjected to a formal coding procedure. Instead, a predefined observational framework was used to identify movement-related visual markers, while their meanings were interpreted contextually and triangulated with documentary and historical sources. No separate intertextual analysis was conducted, as the study focused on the spatial manifestation and persistence of these markers rather than on textual relationships between individual messages. Three sites were selected purposively for detailed case analysis because of their symbolic significance within Berlin's countercultural history and their contrasting trajectories of transformation. The Georg von Rauch Haus represents the persistence of

squatting and autonomous spatial practices within SO36; the M99 functions as a long-standing symbolic node of Berlin's countercultural and anti-capitalist milieu; while the Cuvrybrache represents the opposite trajectory, in which an informally appropriated and contested space was ultimately cleared and incorporated into market-oriented redevelopment. The cases were therefore not selected as statistically representative examples, but as contrasting manifestations of subcultural spatial production that allow different configurations of the adaptive cycle to be examined.

The three cases were interpreted through the principal dimensions of the adaptive cycle: potential (capital), connectedness, and resilience, and their changing configurations across the r , K , Ω , and α phases. Material and intangible forms of capital, the degree of institutional and social connectedness, and the capacity of the respective spaces and communities to persist or reorganize under external pressure served as the main analytical dimensions. Assignment to particular phases was based on the combined interpretation of documented historical trajectories, observed material conditions, forms of social and institutional organization, and the transformation of the sites over time.

Findings: adaptive cycles and the transformation of space

For analytical purposes, the trajectories of the three case studies are traced from the release phase (Ω), characterized by the destabilization of established spatial arrangements and declining connectedness (HOLLING, C.S. 2001).

Contextualizing this phenomenon, based on the Berlin Besetzt map, such periods likely occurred between 1979–1982 and, following the fall of the Berlin Wall, in East Berlin between 1989–1990, when the number of squats surged dramatically (Berlin Besetzt, 2025). The latter can be clearly correlated with the collapse of the GDR. Additionally, the early

1980s in West Berlin as a whole – especially in Kreuzberg – were crisis years, exerting a significant impact on the real estate market conditions (HOCHMUTH, H. 2017). In the reorganization and renewal phase, due to low connectedness, new and innovative spatial combinations emerge that previously existed in isolation or in fixed forms (HOLLING, C.S. 2001). In our case, this is the period when the newly formed spatial pattern – the communities within occupied buildings – becomes self-aware and subsequently leverages the intangible capital concentrated within their possession through socially-oriented actions. In our view, the second avant-garde breaks into West Berlin at this time, concurrently with a new revolutionary class organizing itself. The bohemian anti-authoritarian communities demonstrate their high cultural capital through their events and communal life (DRISSEL, D. 2011). In the conventional representation of the adaptive cycle, the Ω - α backloop is characterized as comparatively rapid, whereas the r-K foreloop generally involves slower processes of accumulation and consolidation (HOLLING, C.S. 2001). The dismantling of obsolete, alienated struc-

tures and the process of renewal occur much more rapidly compared to the consolidation of a new hegemony (HOLLING, C.S. 2001). Autonomous small communities play a significant role in the transition between the Ω and α phases. Based on the central questions of the study, these groups, in this case, have subcultural backgrounds. However, unlike the r and K transition (which in this term represents institutionalization), the transition here is characterized by decentralization, weakening connections, and free flow. In this phase of the cycle, the transformation appears to gain new momentum.

Using the Georg von Rauch Haus as an example, the relationship between power and subculture in Kreuzberg during the 1970s, a period marked by housing shortages, can be clearly observed (VOLLMER, L. 2018). Housing issues began to emerge in the 1960s, a period during which previously established spatial and institutional arrangements became increasingly unstable, generating growing social tensions.

The placement shown in *Figure 2* reflects the current state of the site. The Rauch Haus is interpreted as remaining within the reor-

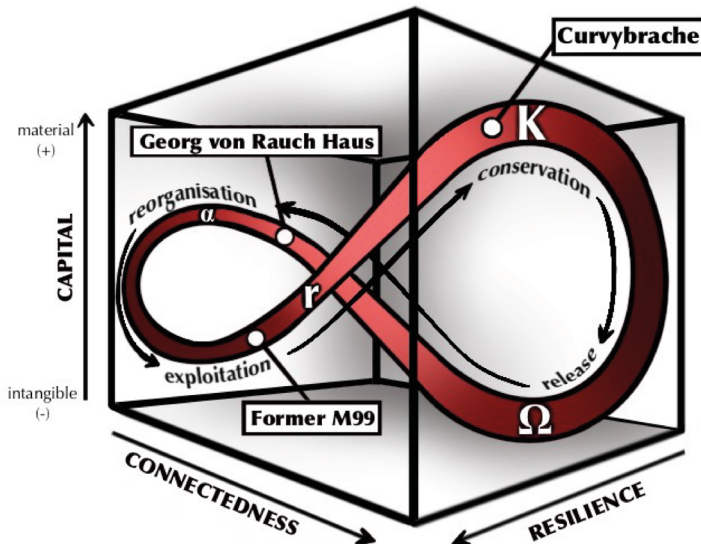


Fig. 2. Examined areas on the adaptive cycle. Source: Authors' own elaboration.

ganization phase, as its spatial persistence has not yet been accompanied by the degree of consolidation characteristic of the subsequent phases. Its present position in *Figure 2* represents an analytical interpretation of its relative persistence, connectedness, and institutionalization rather than a quantitatively measured position within the cycle.

The occupation of the Georg von Rauch Haus (hereinafter referred to as Rauch Haus) at Mariannenplatz 1/A in 1971 represents a crucial element in the symbolic release of this tension, which exhibited an exponentially rising trend over the following decade (*Photo 1*). “Friede den Hütten – Krieg den Palästen” (*Peace to the huts – war on the palaces*) – stands inscribed on the facade of the old building.

The symbolism of the Rauch Haus, which still exists today, is fulfilled in the breakthrough of the emerging revolutionary class

composed of young people. This is evidenced by earlier squats on 1 May, 3 July, and 13 July, 1970, in Reinickendorf, Steglitz, and the southeastern side of Mariannenplatz (Berlin Besetzt, 2025). Following the failure of the aforementioned attempts, the case of the Rauch Haus garnered significant media attention, and the efforts of the newly formed community (‘Die Trebegänger des Georg von Rauch Hauses’) also attracted the attention of the Berlin Senate (KAPPELER, M. and LIEBEL, M. 2022). A strong stance against the injustices of housing policy triggered an increase in the number of squats, leading to a rise in the resilience of Berlin’s autonomous communities and their residential spaces as interpreted in the urban context. Ironically, in the case under examination, the maximum of intangible capital can be understood in terms of the local value of material capital at its minimum, a concept recognized by



Photo 1. The Georg von Rauch Haus. Source: Photo taken by the authors.

literature interpreting HOLLING's theory from an economic perspective as a 'poverty trap.' As intangible capital, symbolic capital plays a crucial role, along with the cultural capital, which is notably overrepresented in Kreuzberg (BOURDRIEU, P. 2008; HUANG, X. 2019), which, in the case we are examining, is style-oriented and politically active, rather than being associated with ethnic groups that represent themselves in the area.

The r-K foreloop can be associated with the increasing incorporation of previously accumulated cultural and symbolic values into market-oriented urban development (HOLLING, C.S. 2001). In Berlin, this process is particularly visible in gentrifying inner-city districts such as Mitte, Prenzlauer Berg, and Kreuzberg, where pioneer gentrification has substantially transformed the built environment (BERNT, M. and HOLM, A. 2013; SIEMER, J. and MATTHEWS-HUNTER, K. 2017). Tourism and short-term rentals represent an additional dimension of this transformation: Airbnb has facilitated the integration of visitors into residential spaces while generating criticism concerning the effects of the sharing economy on urban neighbourhoods (STORS, N. 2022). Such practices extend tourist access into spaces otherwise unavailable to outsiders, potentially generating conflicts over local uses and meanings of space (KAPPELER, M. and LIEBEL, M. 2022).

The second case study is M99, a store operated by Hans-Georg "HG" Lindenau and a long-standing symbolic site of Berlin's countercultural milieu. Unlike the Rauch Haus, this location – and its proprietor – has been severely impacted by Berlin's gentrification activities. The M99 began its operations openly as a revolutionary leftist print shop and bookstore in 1985, located at Manteuffelstraße 99, just two blocks from the Rauch Haus. As a symbol of anti-capitalist resistance, it has endured numerous eviction attempts, police raids, and attacks. In 2015, the landlord unilaterally terminated the lease agreement, and after a prolonged struggle, the M99 was relocated to

Falckensteinstraße 46, with the intervention of the Umverteilen Foundation. The relevance of the placement of the earlier building (see *Figure 2*) is to highlight the spatial aspect of the exploitation of symbolic capital. The depicted moment in time is symbolic, referring to the building after eviction, which has since been absorbed by gentrification. The original location is now occupied by a restaurant. Gentrification commodifies symbolic places through the estrangement of urban spaces. In this case, we observe the triumph of such actions; however, the struggle itself and the presence and activity of the revolutionary class are noteworthy. As Henri LEBEVRE argues in his work "Right to the City", urban space should not be subjected to the control and oppression of market forces. Capitalism and commodification strip away the opportunity for city inhabitants to lead and shape their own living environments (KING, L. 2019).

We can observe that the local population, often reinforced by subcultural groups, actively resists all forms of exploitation in the r-K foreloop. Numerous demonstrations, protests, and various forms of civic resistance attest to Kreuzberg's radical character. Without striving for completeness, we will mention a few key events that illustrate the district's history of resistance since the 1980s: The riots that took place in December 1980 at Kottbusser Tor, along with the so-called Battle of Fraenkelufer on the same evening, and the street clashes on May 1, 1987, marked the awakening of the radical, autonomous creative class (Ω - α phases). However, the activist spirit of local subcultures is not merely a historical phenomenon – the last major resurgence occurred during the so-called "refugee crisis" of the past decade. The characteristic use of urban space for demonstrations evolved into the establishment of activist hotspots focused on aiding refugees and those abandoned by the state. Among these hotspots, we would highlight the Kotti&Co Protesthaus, which operated for years at the Kottbusser Tor intersection from 2012

onward, the civil refugee support center at Oranienplatz, and the house occupation on Ohlauer Straße, which pursued similar objectives. The mobilization of the district's residents remains ongoing; in October 2024, efforts to save Görlitzer Park became a focal point under the slogan “Der Görli bleibt” (Görli stays) (Berlin Besetzt, 2025).

The third and final case study of our research is located in the riverside area of Kreuzberg's SO36 district, at the intersection of Cuvrystraße and Schlesische Straße. Today, visitors to Schlesische Straße 34 are met with the sight of a massive newly built complex. However, looking back a decade, the history of this site has been problematic. Spanning 12,000 m², this plot was one of the last remaining open spaces in Kreuzberg among Berlin's underutilized sites. From the late 1990s, local residents primarily used the area for recreational purposes, as it became

an informal green space hosting subcultural activities. Between 2007 and 2008, numerous internationally renowned street artists created works here, turning the location into a globally recognized landmark (Photo 2). Their artworks adorned the firewalls surrounding the area for nearly a decade (LYDSSAN, Y. 2020; MERRILL, S. 2021).

The site, informally named Cuvrybrache (a fusion of *Cuvrystraße* and the German word *Brache*, meaning vacant land), attracted significant interest from investors. However, development plans repeatedly faced resistance from the local population. Neoliberal gentrification efforts – particularly the Media Spree project – sought to privatize the entire riverfront (SCHARENBERG, A. and BADER, I. 2009). This sparked a large-scale civic campaign titled “Mediaspree Versenken” (Sink Mediaspree), which led to the occupation of the Cuvrybrache site in June 2010 (Novy, J.



Photo 2. Cuvrybrache Wagenplatz. Source: <https://www.orte-der-einheit.de/en/cuvry-brache/>

and COLOMB, C. 2013). Despite decisive police interventions, the eviction attempts proved unsuccessful. By then, the site had evolved into a *Wagenplatz* (a self-organized community of mobile dwellings), where continuous demonstrations and acts of resistance prevented displacement. Eventually, in 2012, the property owner – an automotive corporation – announced plans to develop the site into a research laboratory focused on urbanization and future housing solutions. However, this initiative also faced resistance from residents, who, recognizing the real estate market impact of gentrification, successfully obstructed the investment. At this point, the population of Cuvrybrache surged. In response to an eviction notice issued in the summer of 2012, hundreds of people took to the streets, ultimately rendering the eviction order void. On 14 September 2014, a fire broke out in the *Wagenplatz*. Firefighters arrived on the scene, accompanied by the police. Using the chaos caused by the fire, law enforcement executed a surprise eviction of the Cuvrybrache site, rendering its residents homeless. Shortly after the clearance, redevelopment proposals emerged, culminating in the announcement of the Cuvryhöfe project – an exclusive residential complex featuring 250 luxury apartments. The construction has since been completed, aligning with Holling's adaptive cycle, where the phase of exploitation is distinctly identifiable (WOLFGANG, A.C. 2016; LYDSSAN, Y. 2020).

Analyzing the spatial transformation through the lens of system dynamics, the current state of Cuvrybrache corresponds to the conservation phase (K) of the adaptive cycle. The site has been integrated into a rigid urban structure, shaped by gentrification, reflecting the immobility of capitalism in the built environment. This phase represents the longest segment of the adaptive cycle, signifying the site's progression toward a high degree of accumulated potential and structural connectedness within the given urban framework.

Drawing on HOLLING' s theory (2001), we observe that the activities of these groups concentrate subversive forces that ultimately destabilize consolidated spatial arrangements. This destabilization enables rigid structures to regain flexibility, thus, opening pathways for change. Subcultural space production consistently exerts an effect on liminal spaces. Space that has lost its significance cannot remain without claim, whether it involves brownfield areas, vacant rental buildings, or green spaces relegated to the shadow of the wall, such as the Mariannenplatz. Based on this, we can trace the spatial manifestation of the concept of "meaning making."

At the same time, this form of social advocacy, along with the expression of independent cultural and artistic values, is often subjected to exploitation. Economically and productively inactive, nonconformist communities and subcultures – as well as the symbolic spaces and intangible assets they create – are pushed to the periphery of capitalism. As a result, they become subject to expropriation and exploitation (FRASER, N. 2022). Gentrification, as a driving force within the r-phase of the adaptive cycle, serves as a mechanism for this expropriation and exploitation. The homogeneous structure it creates not only displaces the original residents willing to engage in social participation of the area but also its unique character.

The adaptive cycle therefore provides a heuristic for interpreting how increasingly rigid spatial configurations may become vulnerable to disruption and subsequently open possibilities for reorganization.

Discussion

The findings demonstrate that subcultural spatial production and gentrification should not be understood as entirely separate or opposing processes. The three cases show that subcultural spatial appropriation involves not only the physical occupation of

space but also the production of cultural and symbolic meanings through collective practices. These meanings may persist beyond the initial act of occupation and accumulate precisely through practices that distinguish these spaces from market-oriented forms of urban development. Yet this accumulated value may subsequently become susceptible to commodification as these spaces gain wider recognition. The cases therefore reveal a tension between the production of alternative use values and their potential incorporation into exchange-oriented urban development. Viewed through the adaptive cycle, this tension is particularly visible in the transition from relatively flexible forms of spatial appropriation towards increasing consolidation. In the urban interpretation developed here, potential includes not only material resources but also cultural, symbolic, and relational forms of capital. The accumulation of such intangible resources can strengthen subcultural spaces and contribute to their persistence, while simultaneously increasing their visibility and potential economic appropriation. Institutionalization may therefore have an ambivalent role: legalization can protect autonomous projects from immediate displacement while also increasing connectedness and reducing some of the flexibility associated with their earlier forms, a process previously conceptualized in SO36 as selective resilience (TILL, D., in press).

In this process, different districts of Berlin are at varying stages (SIEMER, J. and MATTHEWS-HUNTER, K. 2017), additionally, the role of the local population varies in degree. Kreuzberg can be considered active in this regard, as the area's significant accumulation of intangible capital indicates strong, present communities who are currently grappling with the real estate market effects of gentrification (BERNT, M. and HOLM, A. 2013).

The comparison of the three cases indicates that transformations at individual sites are embedded within broader neighbourhood- and city-level processes. The processes

occurring in Kreuzberg can be associated with different phases of the adaptive cycle rather than with a single uniform trajectory. The occupied houses, and other autonomous spaces coexist with highly commercialized and redeveloped areas, demonstrating that different spatial configurations may persist simultaneously within the same neighbourhood. The diversity of the district's urban landscape becomes particularly striking as one moves away from the Spree riverside blocks toward the inner streets.

The three cases demonstrate that different spatial configurations may coexist within the same neighbourhood, while their trajectories remain embedded in broader processes of gentrification, housing policy, and institutional change. This also marks the analytical boundary between the adaptive cycle and panarchy. While the former is used here to interpret transformations within individual sites, panarchy draws attention to cross-scale interactions between site-, neighbourhood-, and city-level processes. The adaptive cycle, thus, provides a useful heuristic for interpreting non-linear urban transformation, although the qualitative application of potential, connectedness, and resilience allows analytical rather than quantitatively determined positioning within the cycle. These findings extend previous urban applications of the adaptive cycle to shrinking cities, multilevel urban resilience, and community-based renewal (HERRMANN, D. *et al.* 2016; ROGOV, M. and ROZENBLAT, C. 2018; SAEZ UJAQUE, D. *et al.* 2021). The SO36 cases demonstrate that the model can also illuminate transformations at the scale of contested subcultural sites, where spatial appropriation, institutionalization, displacement, and commodification interact over time.

The combination of SoJA and HOLLING provides complementary spatial and temporal perspectives on these transformations (SoJA, E.W. 1996; HOLLING, C.S. 2001). SoJA's framework explains how material conditions and accumulated social meanings contribute to the production of subcultural space, while

the adaptive cycle provides a temporal heuristic for interpreting its emergence, consolidation, disruption, and reorganization. In SO36, this combination demonstrates why physical transformation does not necessarily erase historically accumulated spatial meanings.

Conclusions

This study examined whether the transformation of subcultural spaces in Kreuzberg SO36 can be interpreted through HOLLING's adaptive cycle (HOLLING, C.S. 2001), and how these transformations relate to intangible capital, institutionalization, and commodification. The findings broadly support the four hypotheses. The contrasting trajectories of the Georg von Rauch Haus, M99, and Cuvrybrache demonstrate that subcultural spaces can be associated with different phases of the adaptive cycle, although their positions represent qualitative interpretations rather than quantitatively determined states.

The cases also support the proposed relationship between the accumulation of intangible capital and the emergence and consolidation of subcultural spaces. Increasing institutionalization and commodification are associated with stronger connectedness and the conversion of some accumulated symbolic and cultural value into material or economic value, while potentially constraining transformative capacity. However, these relationships are not deterministic: legalization and institutionalization may restrict autonomy while simultaneously enabling the long-term persistence of alternative spaces. Finally, the cases indicate that gentrification can incorporate cultural and symbolic values produced within subcultural spaces into market-oriented urban development, most clearly where formerly alternative spaces become economically exploitable through their accumulated meanings and recognition.

The adaptive cycle therefore provides a useful framework for interpreting the tem-

poral transformation of contested urban spaces without assuming a linear trajectory from resistance to commodification. In SO36, persistence, institutionalization, displacement, and redevelopment instead represent divergent outcomes of an ongoing process of socio-spatial transformation.

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BOOK REVIEW SECTION

Herb, G.H., Moorti, S. and Fuentes-George, K.: Middlebury Atlas of Globalization. Stuttgart, PONS Langenscheidt, 2024. 147 p.

A world atlas often creates the illusion that it merely shows where things are. Yet every map is the product of a series of choices: what is placed at the centre and what is pushed towards the margins, which boundaries are made visible, which categories are used, and ultimately what kind of world is brought into view. Critical cartography has long challenged the apparent neutrality of this process, drawing attention to the authority, selectivity and rhetoric embedded in cartographic representation (HARLEY, J.B. 1989). One of the strengths of the *Middlebury Atlas of Globalization* is that it makes this problem explicit.

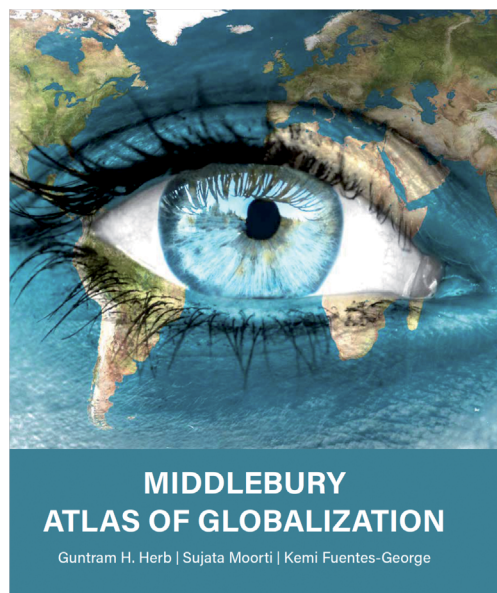
A particularly effective example appears in the *Maps and World Views* section of *Global Ideascapes*, where a Washington-centred world map is accompanied by an explanatory panel titled *The World from Washington, D.C.* The effect is striking. The surface of the Earth is reorganised in relation to Washington, while the familiar positions of the continents become strangely unfamiliar. The same planet is shown, but from an explicitly US-centred spatial perspective. The map therefore demonstrates considerably more than a technical feature of projection. It makes visible the extent to which a map of ‘the world’ depends

on the position from which that world is viewed. The accompanying text broadens the argument further: projection, scale, centring, naming and classification all shape what becomes visible, while cartographic representation itself carries a powerful aura of scientific authority. Here, the map functions as both representation and argument.

This question is central to an atlas of globalisation. The spatial logic of globalisation sits uneasily with the traditional atlas. Conventional political maps render territories and boundaries as fixed, relatively stable spatial units, whereas globalisation is commonly theorised through flows, networks, mobility, interdependence and rescaling. STEGER, M.B. (2003), for example, emphasises the multidimensional processes through which worldwide interdependencies and exchanges expand and intensify. Yet territory and place remain central to these processes. In CASTELLs’s terminology, the growing importance of the space of flows does not abolish the space of places (CASTELLs, M. 1996), while SWYNGEDOUW, E. (2004), and MURRAY, W.E. (2006) draw attention to the simultaneous processes of de-territorialisation, territorialisation and rescaling. An atlas of globalisation therefore faces an unusually demanding task: it must somehow represent territories and relations, places and flows, territorial distinctions and shifting scales at the same time.

Many of the thematic maps and double-page spreads in the *Middlebury Atlas of Globalization* rise impressively to this challenge. They juxtapose relations, flows, inequalities and perspectives whose combination alters how each is read. Paired maps are especially effective in allowing the same global process to be viewed from different angles. At its best, the atlas finds inventive ways of making visible precisely those connections and shifts of scale with which conventional atlases struggle. Elsewhere, inherited classifications and bounded territorial categories reassert themselves. The atlas’s own cartographic reflexivity therefore establishes a demanding standard against which its individual maps can also be read.

The volume’s remarkable thematic breadth is partly explained by the complementary backgrounds of its three authors. Guntram H. HERB’s work in political geography engages with nationalism, territory, borders, identity and scale, including in the co-edited volume *Scaling Identities: Nationalism and*



Territoriality, which treats territory and scale as dynamic processes rather than fixed spatial containers (HERB, G.H. and KAPLAN, D.H. 2018). Sujata MOORTI brings gender, sexuality, media, diaspora and transnational cultural circulation into the picture, while Kemi FUENTES-GEORGE works on global environmental politics, environmental justice and international governance. Together these perspectives help explain why political-territorial processes sit so naturally beside cultural, bodily and environmental dimensions of globalisation.

The book also moves beyond the conventional world atlas as a genre. With its interpretive texts and spreads organised around problems rather than geographical inventories, it often resembles a critical global studies textbook in atlas form. Maps and text form an integrated analytical apparatus, with arguments frequently emerging from their juxtaposition. The printed format matters, as facing pages let maps, indicators and commentary be viewed simultaneously. The companion website, *Mapping Globalization* (Middlebury College n.d.), supplements the volume with additional materials and classroom resources, while offering only a limited view of the atlas itself.

This volume belongs to a broader tradition of thematic atlases that represent the world through transnational relations and interdependencies rather than as a mosaic of states. It has affinities with DURAND, M.-F. *et al.*'s (2013) *Atlas de la mondialisation*, while SOLARZ's *The Global North-South Atlas* offers a different point of comparison. SOLARZ organises his atlas around the metageographical question of whether the inherited Global North–Global South divide remains meaningful (BARTA, G. 2020; SOLARZ, M.W. 2020). The *Middlebury Atlas of Globalization*, by contrast, places a much wider range of processes alongside one another to make the multidimensionality of globalisation visible.

Structurally, the volume moves from questions of representation and historical context towards thematic and regional perspectives. *Global Geography* and *Global History* provide the cartographic and historical framing, followed by the three thematic chapters: *Global Powerscapes – Politics and Economy*, *Global Ideascapes – Culture and Society* and *Global Bodyscapes – People and Experience*. The volume concludes with *Global Regions*, a series of continent-scale regional maps.

The distinctive labels *Powerscapes*, *Ideascapes* and *Bodyscapes* succinctly express the volume's relational and multidimensional understanding of globalisation. The terminology clearly resonates with APPADURAI's influential vocabulary of global 'scapes', devised to conceptualise overlapping and disjunctive transnational flows that resist simple territorial ordering (APPADURAI, A. 1996). In the Middlebury volume, the -scape suffix likewise evokes global spaces shaped by configurations of power, circulating ideas, cul-

tural patterns and embodied experience, rather than separate, neatly bounded domains. The terminology is therefore apt for an atlas concerned with the tension between relatively fixed territorial orders and relationships that cross and continually rework them.

The *Global Powerscapes* chapter works particularly well when it shows political and economic processes as relational rather than merely distributed across states. In *Climate Management*, total and per capita carbon footprints are combined with commitments under the Paris Agreement, while *Digital Connections* shows that the apparently deterritorialised digital world depends upon material infrastructures, cables, unequal access and spatially concentrated networks.

The *Global Ideascapes* chapter broadens the range of phenomena one might expect an atlas of globalisation to map. Gender, political power, beauty ideals, food cultures and film industries all become cartographically visible. The polycentric geography of film is a telling case: Bollywood and Nollywood make it difficult to sustain a model in which cultural globalisation radiates from a Western centre towards the rest of the world.

The *Global Bodyscapes* chapter makes perhaps the book's most conceptually inventive move by recasting globalisation as an embodied condition. It brings under a common heading subjects conventionally dispersed across population geography, migration studies, health geography, gender studies, development geography and environmental geography. Population change, migration, pandemics, inequality, hunger, pollution, women's bodies and water stress become manifestations of a common question: how are global relationships and inequalities experienced through human bodies and everyday conditions of life? The pairing of the *Water Stress* and *Virtual Water* maps demonstrates the value of this approach. Water scarcity initially appears to be a local environmental condition, yet virtual-water trade reveals how far the geography of water use can diverge from that of consumption. A local ecological condition is thereby recast as a global political-economic relation.

Such pairings of maps constitute one of the atlas's most original cartographic devices. Their meaning often lies less in either map taken separately than in the friction between the two. The juxtaposition of *Freedom Rating* and *Prison Population* maps, for example, poses a provocative question about what 'freedom' means in a society where deprivation of liberty is exceptionally widespread, without claiming a straightforward causal relationship between the two indicators. Paired maps can thus range from explanatory comparison to deliberate association, often leading towards a new question rather than supplying a ready-made answer.

The *Middlebury Atlas of Globalization* is most convincing when maps become analytical instruments in their own right. By bringing disparate processes into visual relation, its strongest spreads expose intersections that conventional thematic maps might leave unnoticed. However, the concluding *Global Regions* chapter occupies a different position in the book's architecture. Its brief introduction begins from the proposition that 'each of the regions has unique features' (p. 116). The result feels closer to a conventional reference-atlas coda than to a continuation of *Powerscapes*, *Ideascapes* and *Bodyscapes*. Regional cartography necessarily distinguishes territories, assigns names and reduces continent-scale complexity to manageable categories. Yet this different genre does not suspend the atlas's own principles concerning naming, classification and cartographic choice.

Ethnic maps make this tension between the unavoidable generalisation of regional cartography and the atlas's own critical attention to naming and classification apparent. The classificatory difficulty is especially acute because ethnicity rarely corresponds neatly to homogeneous, clearly bounded territories. Identities may overlap, group names may be self-designations or exonyms, and neither language, self-identification, historical presence nor present-day population offers an automatically privileged criterion. Consistent selection criteria and careful terminology are therefore essential. The map *Global Regions: Asia – Ethnic Groups* offers a revealing example of what happens when such consistency breaks down. An especially striking case concerns the north-eastern Himalayan area of India, much of which forms the state of Arunachal Pradesh and is claimed by China. Across much of this area, the map assigns the ethnonym 'Loba' to its inhabitants. The problem goes beyond that of a conventional exonym rejected by the people concerned. The region's highly diverse populations – including Adi, Nyishi, Galo, Apatani and numerous other groups – are not collectively constituted as 'Loba' either through their own forms of identification or within India's official ethnic classification. The label has no corresponding social or administrative referent in the region that would justify using it as a collective ethnonym. Its relevant institutional use derives instead from the Tibetan term *Lhoba*/*Luoba* as incorporated into Chinese state ethnic classification.

Ordinary cartographic generalisation does not adequately describe what happens here: an external category is projected onto markedly different populations without an evident basis in the social reality being mapped. The inconsistency is compounded by the fact that the territorial representation follows the Indian status of the area rather than China's territorial claim, while the ethnic terminology nevertheless adopts a category institutionalised

by the Chinese state. The atlas gives no indication of the source or classificatory reasoning behind this choice. A more defensible cartographic solution need not have required greater complexity: identifying major locally recognised populations such as the Nyishi and Adi would already have conveyed more meaningful information within comparable spatial constraints. The use of 'Loba' is difficult to reconcile with the authors' assurance that 'the maps in our text have been carefully reviewed, cross-checked with other maps, and are contextualized in scientific scholarship' (p. 11). The pattern continues elsewhere on the Asian map. The designation 'Limbu' in central Bhutan raises a comparable question, as does the selective prominence given to Newar and Lepcha in Nepal while several larger populations remain unnamed. What becomes uncertain is the principle by which groups were selected and classified, rather than merely the degree of simplification involved. These are not isolated cases, but further instances of a broader inconsistency in the way the Asian map combines and prioritises ethnic categories.

The map *Global Regions: South America – Ethnic Groups* presents a related, though somewhat different, version of this classificatory problem. It identifies the Mapuche population of southern Chile and Argentina as 'Araucanians'. Araucanian is a historical Spanish exonym, whereas Mapuche is both the established contemporary self-designation and the name used in official classifications in Chile and Argentina. More generally, the South American map mixes different levels of classification: ethnonyms, linguistic labels and language-family categories appear within the same visual system despite referring to fundamentally different kinds of entities. This inconsistency is not confined to South America or Asia. Across the regional ethnic maps, categories of different analytical status are repeatedly made cartographically equivalent. The North American map of ethnic groups, for example, places Indigenous ethnonyms alongside linguistic, racial and immigrant-population categories, while its counterpart for Australia and Oceania similarly incorporates migrant populations into an ethnic classificatory scheme.

The continental comparison of ethnic maps reveals a deeper asymmetry. North America is represented as a contemporary social space shaped by migration, mixture and historical change, even though dated terms such as 'Eskimos' and 'Nootka' remain problematic. Europe is more static: by explicitly excluding foreigners, refugees and labour migrants, the map produces a museum-like ethnonational landscape in which contemporary mobility largely disappears. Africa, in turn, is assigned a distinct social temporality. It appears principally as a dense ethnolinguistic mosaic of localised groups, while urbanisation, migration, mixed identities and contemporary social transformation disappear from view.

The resulting ethnographic present makes Africa seem almost outside historical time.

Inherited terminology sharpens this problem. The legend's category 'Pygmies (without own languages)' groups heterogeneous Central African populations under an externally constructed collective label historically associated above all with bodily stature. The parenthetical qualification is equally problematic: it suggests a lack of linguistic identity, although communities such as the Aka and Baka speak distinct, identifiable languages. On a contemporary ethnic map, this combination of inherited nomenclature and reductive linguistic classification is difficult to defend. The contradiction is heightened by the introduction to the *Global Regions* chapter itself, which explicitly reflects on the enduring legacy of colonialism in ethnic classification.

Another weakness of *Global Regions* is the absence of the short explanatory texts that work so well in the thematic chapters. Even brief notes on temporal frames, selection criteria, classification systems and sources would make the logic behind these maps more transparent.

A related imbalance appears in the *Global History* chapter. Its *longue-durée* perspective is in itself a major virtue: globalisation does not begin with the economic integration of recent decades but is situated within much longer histories of contact and exchange. The authors are also explicitly alert to the perspectival nature of historical representation, observing that 'the victors write the history' (p. 33). The *Ancient Links* maps open the narrative beyond Europe and acknowledge multiple centres of early connection. Once the sequence moves into the medieval and early modern periods, however, the cartographic story becomes overwhelmingly organised through European expansion, colonisation and, subsequently, the Atlantic world. The accompanying prose acknowledges non-European networks, including long-distance trade across the Indian Ocean and connections linking Africa through trans-Saharan and Red Sea routes. Yet they are not granted comparable independent cartographic presence. The imbalance lies in the difference between being mentioned and being allowed to organise the cartographic narrative. European actors increasingly become the agents through which large parts of the world enter the visual history of globalisation, while extensive commercial and migratory worlds beyond Europe and the transatlantic sphere remain far less visible as autonomous geographies of connection. This tension is especially revealing because the chapter begins by foregrounding the perspectival character of historical narratives.

Taken together, the regional maps' uneven distribution of contemporaneity and the unequal distribution of historical agency in *Global History* eventually lead back to the Washington-centred map

discussed in *The World from Washington, D.C.*, now in a less flattering sense. In its original context, this map deliberately exposes the fact that cartography always has a centre. Yet some of the regional maps appear to reproduce this problem through an implicit US-centred epistemic gaze. Thus, the atlas distributes contemporaneity unevenly. More than geometrical centring is at stake here: the visibility of social complexity and historical agency itself becomes centre-dependent. This is a revealing internal tension in a volume that elsewhere does so much to unsettle the apparent naturalness of cartographic centring and classification.

These shortcomings, concentrated primarily in *Global Regions* and, to a lesser extent, in *Global History*, do not substantially alter the very favourable overall assessment of the volume. The *Middlebury Atlas of Globalization* is an ambitious, original and intellectually engaging undertaking whose thematic core displays considerable cartographic imagination. It refuses to reduce globalisation to economics or geopolitics, bringing political, cultural, social and environmental processes into the same visual and interpretive field. This makes the atlas especially valuable in teaching. Here a map need not function as a finished answer or authoritative visual evidence but can become the starting point for inquiry. What can two juxtaposed maps reveal that neither could show independently? Which categories do readers accept as natural simply because an atlas has placed them on a map? The book's strongest pages therefore teach not only global studies but critical map literacy. Even the volume's occasional weaknesses become conspicuous partly because of its own strengths. The atlas gives readers the critical cartographic tools to question its less successful maps. No map offers a genuinely neutral vantage point; every map simultaneously reveals and orders a world. The largely excellent maps of the *Middlebury Atlas of Globalization* teach us to move the centre; its weaker ones remind us how difficult it is to leave the centre behind.

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McAllister, K.E., Yoshizmizu, A. and Ahadi, D. (eds.): *Migration and the Politics of Methodology. Doing fieldwork, decentring power, and foregrounding migrants' perspectives*. London, Routledge, 2025. 289 p.

In their book *Migration and the Politics of Methodology. Doing fieldwork, decentring power, and foregrounding migrants' perspectives*, the three editors, Kirsten Emiko McAllister, Ayaka Yoshizmizu, and Daniel Ahadi give a unique review of migration studies for those outside the field. The volume draws on micro-level perspectives as core qualitative methods to explore how migrants negotiate the process of resettlement experiences and reconstruct their identity in societies that are often marked by exclusionary and hostile attitudes toward newcomers.

McAllister and her colleagues edited a fresh compilation of studies that provides seminal critical analysis of the methodological and ethical challenges in migration research. The book explores the central question of whether traditional research methods often reproduce the power hierarchies that position migrants as vulnerable or passive subjects of observation. Through the eleven chapters the book reconfigures fieldwork as an active space of political and ethical engagement that prioritises migrant subjectivities and dismantles academic power asymmetries.

The book showcases experimental methodologies designed to break through the limitations of

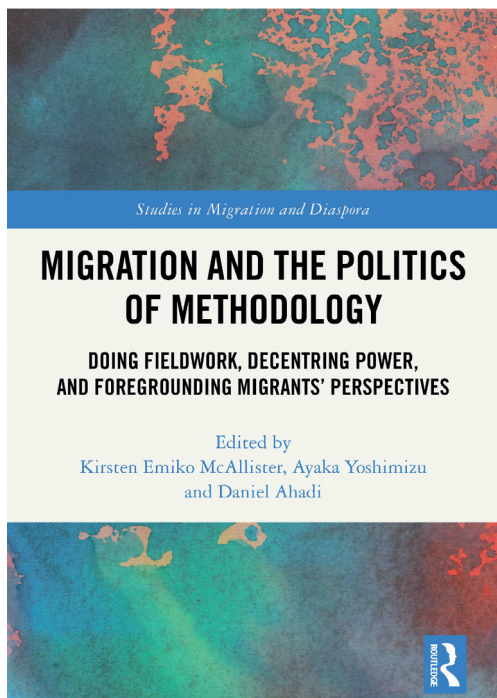
traditional qualitative interviews. When asked to recount their experiences, through digital storytelling, migrants emphasise absolute trauma or flawless economic productivity. Contributors also use auto-ethnography blurring the line between researcher and interviewee.

The diversity of fieldworks also adds new layers to the analysis. Canadian, Scottish, Japanese, Ecuadorian and Uruguayan cases are presented through various community- and/or place-based research approaches, focusing on the feeling of exclusion or the (re-)created and (re-)interpreted space of the home. The book uniquely demonstrates how emerging trends in migration studies are shifting the focus away from traditional research topics – such as the role of nation-states, multilateral organizations, international students, labour force needs, citizenship, training programmes – towards the conditions of migrants' lives, lack of rights, exploitation, racialization and efforts to create liveable conditions and mobilise for rights.

It is important to consider the disciplinary context of this work. This volume is largely shaped by the scholarly perspectives of contributors working within the fields of Communication, Media and Cultural Studies. The diversity of the collaborators guarantees the above mentioned new methodological approaches.

The edited book is divided into three thematic parts concerning various methodological aspects of doing fieldwork about, with, or as migrants. The first section (*Part Section I*) examines community-based research projects grounded in feminist ethnography and intercultural engagement, illustrating the unequal power structures that influence the lives and experiences of underprivileged rural migrant workers (*Chapter 1: Decentring Media and Recentring People*, by Siyuan Yin), discrimination, prejudices and obstacles to integration into the host society (*Chapter 2: Building Solidarity between Im/migrants and the Local Population*, by Jorge Frozzini), expressions of uncertainty, memories of loss and displacement, and new beginning in an unfamiliar place (*Chapter 3: The Tayybeh Turn*, by Adel Iskandar), and further exploring alternative expressions of well-being (*Chapter 4: Embodying Affective Fieldwork with Internal Migrant Women in Ecuador*, by Belen Febres-Cordero).

The second section (*Part Section II*) is concerned with the complex power dynamics of research where contributors examine how they struggle with the operation of power in their research. Widely shared ethical principles of Migration Studies are concerned in this volume, such as the respect of autonomy of participants, the anonymity, the responsibility to



avoid harm or the importance of benefits and burdens of research. This section presents contributions made in the field of forced migration (*Chapter 5: Responsible to Whom?*, by Erin Goheen GLANVILLE), rail-hailing services (*Chapter 6: Criminalizing “Chinese” Ethnic Ride-Hailing*, by Yijia ZHANG), and asylum seekers and community-based art projects (*Chapter 7: Researching Asylum Seekers and Community-Based Art as an “Ethnographic Outsider”*, by Kirsten Emiko McALLISTER).

In the third section (*Part Section III*), spatial dynamics are discussed via the role of fieldwork, power and embodiment, prompting us to rethink how we negotiate and understand transnational and national spaces. Contributors of this section fulfil a dual role: as migrants, the active acknowledgement of the researchers’ lived experiences in the migration process is the key element of this section. Whether conducting research in a country where they live as immigrant researchers, or in a diasporic community in which they share the same ancestry, or returning to their ancestral homeland as a first-generation or second-generation diasporic researcher (*Chapter 8: Walking in the South*, by Marcos MOLDES, and *Chapter 9: Re-Imagining Migration and Communication Studies through Fieldwork in Transnational Yokohama*, by Ayaka YOSHIMIZU) the researcher’s own experience – of being an outsider or an immigrant, and of being regarded as “other” in terms of race, language, and epistemology – significantly shapes how they approach migration research.

MOLDES, M. presents the embodied experience as a second-generation returnee (in Uruguay) exploring the complexity of belonging and non-belonging in his ancestral homeland (in *Chapter 8*). Through the embodied practice of walking, the author illustrates how emotions such as shame and a sense of non-belonging become inscribed in space, shaping the ways places are experienced and stigmatised. Such ethnographic place-making processes can be understood as destabilizing practices that unsettle established forms of connection, attachment, and belonging.

As a first-generation immigrant, YOSHIMIZU, A. re-imagines Yokohama as a diasporic city (in *Chapter 9*). Immigrants’ knowledge of and engagement with the host city challenge the dominant conceptualization of transnational migrants as foreigners, outsiders, or temporary residents, instead revealing their integral role in the city’s diasporic place-making. Her research vividly illustrates the reflexive nature of ethnographic research, showing that the research process not only generates knowledge about the field but also reshapes the researcher’s own perceptions. Consequently, she interprets the city in which the fieldwork was conducted in new and different ways.

MARQUES, Â.C.S. and HERNÁNDEZ, E.B.R. examine how Cuban migrants created transnational bonds

with their homeland through digital and place-based practices and transformed their identities in Canada (*Chapter 10: Not Just Immigrants*, by Ângela Cristina Salgueiro MARQUES and Elisa Beatriz Ramírez HERNÁNDEZ). Michel FOUCAULT’s notion of heterotopia provides a framework for understanding how Cuban migrants transformed their lives and how they assimilated to the various cultures of their host city. The concept of heterotopia enables us to reflect on the reality of social space created by migrants through their conceptions of the places they create, places that offer them refuge whilst simultaneously reshaping their relationships within both the host society and their society of origin. This study presents how a graffiti or a tattoo can be regarded as the centre or heart of a migrant community or tell a story to create a narrative on one’s migration history and identity.

Finally, AHADI, D. examines how racialised migrants are excluded from a space constructed for white settlers in Canada (*Chapter 11: Unpacking “Go back to Where You Came from...”*, by Daniel AHADI). The study foregrounds the existence of hegemonic whiteness, as a dominant culture, which exclude, segregate and discriminate those labelled as “Others” resulting imbalanced power.

The book *Migration and the Politics of Methodology* was also published in line with #Communication-SoWhite movement which brought to the forefront the institutional and ideological biases that arise when critical analysis stops at issues of class and gender, and devalues the views of researchers who are subject to racial discrimination and indigenous researchers when determining the field’s research priorities.

Throughout the volume, contributors show that critical and reflexive forms of fieldwork challenge state- and institution-centred agendas by placing migrants at the heart of social justice projects, thus underscoring that fieldwork constitutes not only a method of inquiry but also a transformative political and ethical practice.

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GUIDELINES FOR AUTHORS

Hungarian Geographical Bulletin (formerly Földrajzi Értesítő) is a double-blind peer-reviewed English-language quarterly journal publishing open access **original scientific works** in the field of physical and human geography, methodology and analyses in geography, GIS, environmental assessment, regional studies, geographical research in Hungary and Central Europe. In the regular and special issues also discussion papers, chronicles and book reviews can be published.

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Books:

PYE, K. 1987. *Aeolian Dust and Dust Deposits*. London, Academic Press.

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