

How does pedestrian permeability vary in and across cities? A fine-grained assessment for all large cities in Germany

Ariane Droin^{a,c,*}, Michael Wurm^a, Matthias Weigand^a, Carsten Gawlas^b, Manuel Köberl^a, Hannes Taubenböck^{a,c}

^a German Aerospace Center (DLR), German Remote Sensing Data Center (DFD), 82234 Oberpfaffenhofen, Germany

^b University of Heidelberg, Institute of Geography, 69120 Heidelberg, Germany

^c University of Würzburg, Institute of Geography and Geology, Department of Global Urbanization and Remote Sensing, 97074 Würzburg, Germany

ARTICLE INFO

Keywords:

Permeability
Urban morphology
Individual walkable neighbourhood
Navigation
Barriers

ABSTRACT

Pedestrian permeability is a key aspect of the accessibility of urban environments. In particular, high permeability increases the walkability of cities, which is advocated by sustainable urban design practices. Previous research on pedestrian permeability has predominantly focused only on single and very specific, characteristic, and homogenous urban morphologies but investigations at a broader scale have not been conducted up to now. In this paper, we apply the concept of Individual Walkable Neighbourhoods (IWN) to measure local urban pedestrian permeability for all large cities in Germany with more than 100,000 inhabitants. Our results reveal great differences in intra- and inter-urban pedestrian permeability, and based on examples, we explore various factors that influence local permeability, such as topography or structural types. Furthermore, the large-scale analysis is used to identify characteristic patterns of high (e.g., urban centers) or low (e.g., neighbourhoods of single-family detached houses) permeability for German cities.

1. Introduction

Cities, the world's most important habitat for humans, are in a constant state of change. One major pull factor of cities is that they provide proximity and accessibility to everyday services (Kesarovski & Hernández-Palacio, 2023). With the emergence of sustainability-oriented urban planning concepts, walking plays an important role, as it is the most environmentally friendly mode of transport (Pucher, Buehler, Bassett, et al., 2010). In this sense, in research and urban planning, the concept of “walkability” (Frank, Sallis, Saelens, et al., 2010; Lo, 2009) is reinforced and researched thoroughly. “Walkability” is a term that appears in a variety of definitions and methodological implementations (Dovey & Pafka, 2020). In general, it can be summarised as the aspect of how friendly an area, local neighbourhood or town is to walking, while there is general consensus that these are based on (1) density/proximity, (2) mix of land-use and (3) connectivity/access (Dovey & Pafka, 2020; Ellis, Hunter, Tully, et al., 2016; Forsyth & Southworth, 2008; Frank et al., 2010), referred to as the urban DMA by Dovey and Pafka (2020). Further aspects such as aesthetics of the

pedestrian environment, the quality of pedestrian routes, the safety, the maintenance of pedestrian paths, etc. are also important aspects of walkability (Dovey & Pafka, 2020; Ewing & Handy, 2009). Therefore, in relation to the third point, the relevance of pedestrian accessibility has increased significantly (Randall & Baetz, 2001). One important factor of accessibility is the *permeability* of a given neighbourhood, which reflects the ease of movement through the urban fabric (Pafka & Dovey, 2017). For an individual pedestrian, permeability is constrained by limiting factors to personal mobility (e.g., age, physical limitations, endurance) and local obstacles (e.g., fences, stairs, large streets). At the level of a city or neighbourhood, permeability is primarily defined by the street pattern (Ellis et al., 2016; Stangl, 2019) which is a major component of the urban morphology (Conzen, 1960).

When thinking about pedestrian permeability and urban morphology, the subconscious often conjures specific built-up structures and patterns, as physical urban morphologies influence the subjective perception of individuals in the urban space (Wurm, Goebel, Wagner, et al., 2021). Examples of such morphologies are the suburban environments of American cities, which are known to be obstructive to

* Corresponding author at: German Aerospace Center (DLR), German Remote Sensing Data Center (DFD), 82234 Oberpfaffenhofen, Germany.

E-mail addresses: ariane.droin@dlr.de (A. Droin), michael.wurm@dlr.de (M. Wurm), matthias.weigand@dlr.de (M. Weigand), manuel.koerberl@dlr.de (M. Köberl), hannes.taubenboeck@dlr.de (H. Taubenböck).

<https://doi.org/10.1016/j.compenvurbsys.2024.102115>

Received 27 September 2023; Received in revised form 5 April 2024; Accepted 6 April 2024

Available online 17 April 2024

0198-9715/© 2024 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

walking because of their low-density, monofunctional areas of elongated blocks, or the old historic centres of European cities, which are known to be conducive to walking because of their high-density, multifunctional areas with many interconnected streets. More formally, we can therefore associate morphologic characteristics with a certain permeability. Related studies which assessed permeability in relation to urban morphology based their assessments primarily on very distinctive single examples of urban morphologies in different cities around the world (e.g., Pafka & Dovey, 2017; Stangl, 2019). However, cities do not usually consist of only one single, highly distinct morphology, but are built by a composition of a variety of morphologies (Oliveira, 2016; Taubenböck, Debray, Qiu, et al., 2020). Therefore, the scientific body of literature lacks comparative studies using the concept of permeability for large-scale intra- and inter-urban analysis. The analysis of local permeability at a large scale, however, is of high relevance because it would allow for identifying general patterns, morphologies and aspects that influence walkability in various cities and thus allows us to compare cities with each other. Therefore, this study follows the call of Pafka and Dovey (2017) and Majic and Pafka (2019) to assess local permeability at a larger scale and endeavours to calculate the local pedestrian permeability within the residential areas of 78 German cities. With this, new information on the general and spatial distribution of permeability in cities can be accessed.

Several metrics exist to quantify permeability, which are often based on the connectivity of streets. Therefore, these two terms, permeability and connectivity, are often used interchangeably in research. Pafka and Dovey (2017) mention that there are two ways to measure permeability. Either by measuring how the street network enables movement or by measuring how certain features (such as the length of urban blocks) hinder free movement. There is no general consensus on which measures to use to assess permeability based on the street network. The most common measures are intersection density, link-node ratio, (modified) route directness, pedsheds and metric reach (Dunn, Hanson, & Seeger, 2018; Ellis et al., 2016; Stangl, 2019). Ellis et al. (2016) researched which of these measures are best associated with actual levels of physical activity and found that intersection density had the strongest correlation, although it was very weak. Furthermore, (Stangl & Guinn, 2011) show that intersection density does not consider the street layout and is therefore not a good indicator for permeability, as even if intersection density may be high, movement is still significantly impeded. Pafka and Dovey (2017), who measure permeability based on urban blocks, suggest using the area-weighted average perimeter (AwAP). They argue that this measurement considers heterogeneous morphologies as well as large urban blocks that act as barriers to movement. This is a more accurate measure of reality than traditional block-based measures of permeability (e.g., average block area). They have demonstrated that this measure allows for capturing detailed aspects of permeability between different morphologies based on six distinct urban settings. Majic and Pafka (2019) developed a QGIS tool to calculate AwAP using urban block layers and a selected boundary. In comparison, the modified route directness (MRD), as proposed by Stangl (2019), is not based on the calculation of urban blocks but on the network of streets and paths itself. While this method measures the impact of the street layout on permeability, and therefore considers aspects such as major infrastructural barriers, it is not suitable for large-scale applications as it is computationally extremely intensive.

Another common approach is related to the use of so-called *pedsheds* to estimate the pedestrian range of an urban area based on the road network. Pedsheds measure the area accessible within a given time of walking (e.g., 10 min) using the road/footpath network (Schlossberg, 2006). In general, the pedshed area constituted by the street network is mapped by connecting all the outer reachable network points, forming the so-called convex hull (Dovey, Woodcock, Pike, et al., 2015; Dunn et al., 2018; Ellis et al., 2016; Forsyth, Van Riper, Larson, et al., 2012; Pafka & Dovey, 2017; Schlossberg, 2006). However, Pafka and Dovey (2017) argue that pedsheds cannot be used to measure permeability, as

they do not account for the underlying urban morphology, but rather can be used as a measure of catchment. Catchment areas, which are often represented as pedsheds, can be used to assess the (pedestrian) accessibility to different amenities within a given time period (e.g., Kesarovski & Hernández-Palacio, 2023). They differ from permeability in that they do take into account the actual access to specific places, and thus access to daily walking, rather than the spatial extent that can be reached from a given starting point without indicating the necessity of certain routes. Therefore, we propose to use a modified version of pedsheds as introduced by, e.g., Droin, Wurm, and Taubenböck (2023), Forsyth et al. (2012), and Oliver, Schuurman, and Hall (2007). Rather than connecting the outermost points of the network to form a convex hull, as these obliterate areas that are not accessible and do not consider urban morphology, the walkable paths and streets themselves are considered. Hence, areas such as closed inner courtyards, water areas etc. that would be included in pedsheds using the convex hull method are excluded by this approach. This allows us (1) integrate barriers such as motorways, rivers, inner courtyards, etc., (2) consider the underlying urban morphology, and (3) only use paths and areas that are publicly accessible to pedestrians. The latter has been shown to be very influential when calculating pedsheds for pedestrians, for instance in the works of Chin, Van Niel, Giles-Corti, et al. (2008), Dunn et al. (2018), and Ellis et al. (2016). The use of pedestrian network data compared to general road network data resulted in significantly increased connectivity measures highlighting the relevance of their inclusion. Furthermore, the present study adds to the literature on permeability as we do not consider if permeability is high or low for an entire area (e.g. a square), but we take the perspective of the pedestrian from a given starting point and depict their actual possible range of movement within the local neighbourhood.

To summarise, the present study aims to further advance research that has been conducted previously in regard to urban pedestrian permeability in urban areas by (1) calculating it on a large scale and thus enabling inter- and intra-urban analysis, (2) combining it with population data to represent where people live, (3) conducting a descriptive analysis by presenting examples to evaluate the permeability qualitatively and geographically, and (4) describing repeatedly occurring general patterns of pedestrian permeability based on urban morphology and topography. We seek a better understanding of permeability in urban areas, not by showcasing very specific distinctive morphologies, but by assessing it locally and exhaustively, every 25 m within residential areas, for a large number of cities.

2. Data and methodology

The method applied in this research is based on the work of Droin et al. (2023), using the concept of “Individual Walkable Neighbourhoods” (IWN).

2.1. Extracting the pedestrian routing network

In order to compile a pedestrian network for every city, we rely on OpenStreetMap (OSM) data. The extraction of the pedestrian network from OSM (OpenStreetMap Contributors, 2023) is conducted using the Python package *osmnx* (Boeing, 2017). We define the pedestrian network as all network segments that are tagged as accessible by foot and that are not private, using empirically defined tags. This also includes smaller streets which feature walkable sidewalks, and other dedicated foot paths:

```
'["area" != "yes"]["access" != "private"]["highway" ~ "secondary|tertiary|residential|unclassified|living_street|pedestrian|track|footway|bridleway|steps|corridor|path|cycleway|service"]["foot" != "no"]["service" !~ "parking_aisle|emergency_access"]["access" !~ "private|customers"]["sidewalk" !~ "separate"]["cycleway:both" !~ "separate"]["bicycle" !~ "use_sidepath"]["foot" !~ "use_sidepath"]'
```

2.2. Generation of isochronous areas

Within each city that is examined, we set a starting point every 25 m equidistance. All starting points are located only within the residential areas of the central urban morphological zones (UMZ) as defined by the European Environmental Agency (EEA) for the years 2000 and 2006. We used the methodology of the EEA (Simón & Leal, 2011) and the Corine Land Cover Classification (CLC) of 2018 (<https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download>) to calculate updated UMZs for 2018. In order to make the cities as comparable as possible, we use the largest contiguous UMZ within the administrative area of each city, as we believe this best represents the urban core and immediate periphery of each city. Because each UMZ includes areas with different land use (e.g., industrial, residential), we use the data from the European Urban Atlas (UA) (European Commission, 2020) to extract all areas that are predominantly residential within the UMZ (all classes designated as “Urban fabric” except “Isolated structures”). We apply this method for 78 of the 80 largest cities (with more than 100,000 inhabitants) in Germany. Two cities are not included in our dataset: Gütersloh, because there is no UA data available, and the city of Salzgitter, which is divided into many small, scattered urban districts that are not contiguous and therefore not directly comparable to the rest of the dataset.

In a subsequent step, the *osmnx* package is used to extract all segments within the acquired pedestrian networks that can be reached within a given time (isochrone). Routing starts from the closest point on the network to each starting point with an assumed average walking speed of 4.5 km/h (Schimpl, Moore, Lederer, et al., 2011). In terms of accessibility analysis the concept of the x-minute city has been developed (Logan, Hobbs, Conrow, et al., 2022; Moreno, Allam, Chabaud, et al., 2021) and, as work by Kesarovski and Hernández-Palacio (2023), Logan et al. (2022) and Staricco (2022) has shown, the chosen time threshold depends on the size of the city as well as the contextual question and mostly varies between 10 and 20 min. As the present study focuses on the immediate neighbourhood of each individual and takes place in a European setting, where cities are quite dense, 10 min is used as the time threshold.

With the extracted pedestrian network-segments, permeability could normally be calculated using network connectivity measures for every IWN (e.g. network density, intersection density, link-node ratio) (Berghauer Pont & Haupt, 2010; Ellis et al., 2016; Pafka & Dovey, 2017). However, due to inconsistencies, the lack of or wrong attribution, in the OSM pedestrian network we convert the extracted lines to areas using buffers, as proposed in Droin et al. (2023) to enhance comparability between and within the selected cities. For example, on some larger streets, both, the sidewalks and the centreline of the street are extracted. As this is an error that is not evenly distributed in all cities, a buffer of 25 m is created around the pedestrian network-segments, to improve comparability. A feature of OSM streets, that may also be reflected as an error within the pedestrian context, is that for smaller streets (e.g. streets tagged as “residential”), only the centreline of the street is digitised and not the actual sidewalks that exist. To support the choice of the 25 m buffer we conducted a sensitivity analysis by buffering the IWNs with 10 different buffer widths (ranging from 2.5 to 50 m). By comparing the differences in area between the individual IWNs, the absolute normalised difference between them varied only minimally depending on the used buffer size. Hence, the relationship between the IWNs, the ratio, is quite stable regardless of the buffer size applied to the pedestrian network-segments. With this we can conclude, that a comparison between and within cities is feasible.

2.3. Quantifying permeability

We quantify permeability as the ratio of the area of the generated IWN to the area of a circle around the starting point, where the radius is equal to the distance which an individual could cover assuming there are

no barriers (as the crow flies). With a walking distance of 10 min and an average speed of 4.5 km/h this corresponds to a circle with a radius of 750 m (see Fig. 1) and an area of ~177 ha. For the spatial analysis of our results, we used R (version 4.2.2) and the *sf* package (version 1.0–9). For the spatial visualisation of our results, we used QGIS (version 3.22.13).

To estimate the population affected by different levels of permeability, the latest available census data for Germany, dating from 2011 is used (<https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html>). The data is provided by the German Federal Statistical Office (DESTATIS) within a 100 × 100 m grid, following the INSPIRE (Infrastructure for Spatial Information in the European Community) data standard. As the starting points of our IWNs are set every 25 m within the residential areas of the core UMZ of each city, several starting points may exist within one census grid cell. Therefore, for population-related statistics, we calculate the average permeability of all starting points situated within the same census grid cell.

We analyse permeability in three different ways: First, we show the quantitative distribution of permeability measures for each city and combine it with population data to assess where people live. The results of the first analysis can present insightful information about the general distribution of permeability within each city, but it cannot tell *where* in the city the different rates of permeability occur. Therefore, the spatial distribution of permeability for four selected cities is displayed and discussed in a second step. Maps for all the 78 analysed cities can be found in the supplementary material (Fig. S1 - Fig. S78). With this large-scale measurement of permeability, we conduct a descriptive and spatial analysis of several examples of patterns of high and low permeability values that recur in the majority of the cities studied.

To assess the decrease of permeability values from city centres to the periphery we manually digitized all city centres as points and calculated the Euclidean distance from each starting point to the respective city centre point. For every city, we researched its historical development and its morphology, and we compared this information with historical maps and current satellite imagery to identify the centre points (for a similar approach, see Wurm et al. (2021)). For historic towns, the centre is usually represented by a town square with high pedestrian permeability. For towns where there was no clear centre, we researched what people considered to be the respective centre. Using generalized additive models (GAM) we plot the relationship between permeability and the distance to the city centre. Further, to analyse the effect of topography on permeability we use a digital elevation model with a spatial resolution of 25 m provided by the Federal office of Cartography and Geodesy of Germany (BKG, 2016). We derive the slope in degrees (°) and apply a focal mean filter to the slope with a 30 pixels radius (≈750 m). This provides an estimate of the terrain roughness in the neighbourhood for each starting point.

Finally, based on the frequency distribution of all permeability values for Germany within the residential areas, we show which patterns occur how often and where they can be found on the spectrum of permeability.

3. Results

The frequency distribution of the permeability rates weighted by area for the majority of the 78 selected cities roughly follows a normal distribution (see Fig. 2, black lines). The cities of Münster (No.26), Braunschweig (No.35), Chemnitz (No.41), Wolfsburg (No.45), Aachen (No.50), Bremerhaven (No.62), Saarbrücken (No.68), Trier (No.74), and Remscheid (No. 76) are characterized by a left-skewed distribution, indicating that areas with low permeability are more prevalent. The city with the highest median permeability is the city of Ulm (0.45) (No.1), while the city of Siegen (No.78) has the lowest median value (0.27). Although Ulm has the highest median value, the city of Munich (No.3) has the most frequent occurrence of high-permeability values.

When we consider the frequency distribution of the permeability weighted by the affected population (Fig. 2., red lines), on average,

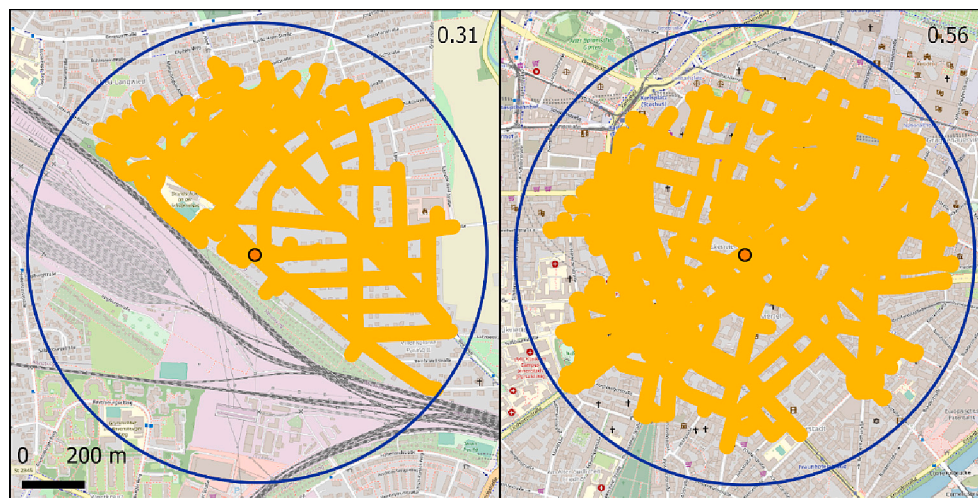


Fig. 1. Two examples of IWNs (orange), the maximum distance as the crow flies (blue, 750 m radius), and the resulting permeability. Orange points represent the starting point. Map data from ©OpenStreetMap. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

higher permeability rates occur more often, skewing the graphs to the right. This indicates that more people tend to live in areas with high permeability. Apart from this shift to the right, for most cities, the distribution appears very consistent between the population-weighted and the area-weighted calculations. Yet, this shift is very pronounced for the cities of Erfurt (No.6), Leipzig (No.13), Kiel (No.21), Jena (No.22), Braunschweig (No.35), Halle (Saale) (No.37), Chemnitz (No.41), Würzburg (No.46), Fürth (No.51), and Potsdam (No.52). In these cities, the number of people living in high-permeability areas is significantly higher than for low-permeability areas.

Fig. 3 shows the decrease of permeability from the urban core towards the periphery. We can see that the majority of the GAMs of all 78 cities (Fig. 3, grey lines) as well as the GAM of all permeability values from all cities (Fig. 3, red line) follows this trend.

To better illustrate the spatial distribution of pedestrian permeability, we have picked four representative examples and displayed them in Fig. 4: the cities of Ulm (highest median value) and Siegen (lowest median value), as well as Berlin and Munich representing two of the largest German cities. The differences between Ulm, where the majority of areas are green (high permeability), and Siegen, with a high proportion of red values (low permeability), is readily visible. The city of Berlin has a high proportion of green values, with yellow and red values increasing towards the edges of the city. The city of Munich appears to consist of predominantly high-permeability areas, with some lower permeability values in the north. All four examples show a clear trend of highly permeable centres surrounded by areas with decreasing permeability in the urban periphery (see also Fig. 3). The strong effect of natural barriers on permeability is particularly visible in Berlin, where residential areas that are close to bodies of water (black areas in the basemap) show very low permeability values.

The high granularity and spatial coverage allows us to examine general patterns of urban morphology and pedestrian permeability at a very local level. Fig. 5 showcases examples of typical areas and urban morphologies that have either high or low permeability. As already apparent in Figs. 3 and 4, urban centres are showing very high permeability values compared to the urban periphery. There is also a clear trend of areas with large housing estates tending to have high levels of pedestrian permeability, whereas areas with single-family homes feature lower levels of permeability. The difference in street patterns, and therefore permeability values, between neighbourhoods featuring large, elongated blocks with private gardens, severing most connections between the streets, and publicly accessible spaces with a variety of small paths between large housing estates, is readily apparent.

Areas with difficultly walkable topographical features, such as hilly terrain, also have a strong negative impact on permeability values. Given a similar building pattern, flat terrain will generally rank higher on permeability than hilly areas. In hilly terrain, streets are often dead ends, and even paths that are physically not far apart from each other are not connected due to the slope. Areas with an average slope of more than 5° have an average permeability of 0.28 and flat terrain has an average permeability of 0.36. The Cohens'D effect size for those two groups is 0.777 which indicates a moderate effect of slope on permeability. Finally, areas traversed by barriers such as railways, highways, or rivers have higher permeability if they are linked by bridges or underground passages. Without such connections, permeability is significantly reduced.

In Fig. 6, the average permeability values of the various patterns identified in Fig. 5 are set in relation to the distribution of permeability of all 78 cities combined. The patterns with low permeability are all located on the left side of the bell curve, with quite similar values. Their position along the frequency density (y-axis) also indicates that those are patterns that are quite common in Germany. The patterns with high permeability are found on the right side of the frequency distribution and are more broadly distributed. Urban centres land on the bottom right side of the curve: they are highly permeable, but scarce.

4. Discussion

The ever-increasing demand for sustainable city designs requires urban planners to minimise car use and promote walkable neighbourhoods (Glazener, Wylie, van Waas, et al., 2022). One key measure in providing access to a large number of variety of places in a short period of time is the permeability of the environment surrounding individuals. In their work, Pafka and Dovey (2017) clearly demonstrated that different urban morphologies feature different rates of permeability. However, as cities are usually made up of a collection of different morphologies which naturally blend into each other, the assessment at city level is challenging without generalizing the local variabilities.

The use of the pedestrian network data presents a number of challenges that need to be considered when interpreting the generated results. Regarding the use of OSM data, we aggregated the network by buffering the pedestrian street segments by 25 m. This was done to reduce impact of inherent artefacts on the results, yet it reduces the differentiation between different street widths and it assumes that people can walk on streets that may have a high traffic load. In addition, pedestrian zones, which are mainly located in the city centres, are stored

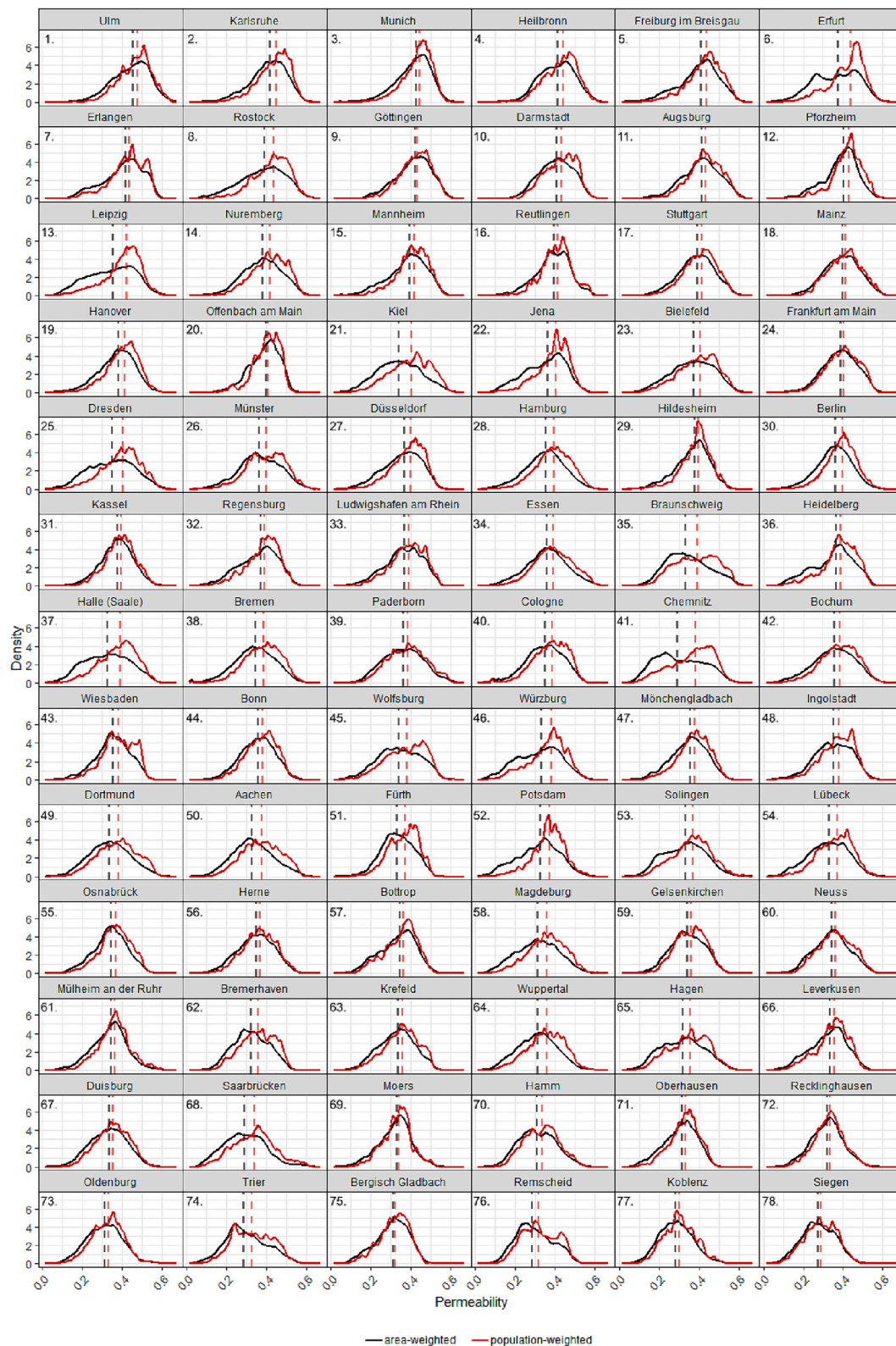


Fig. 2. Frequency distribution of permeability for each city based on density plots. Black lines represent area-weighted frequencies, which show the general distribution of permeability. Red lines represent the population-weighted distribution. Dashed vertical lines represent the median value for each graph. Plots are sorted decreasingly by the area-weighted median. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

as polygons in OSM and only few pedestrian segments are used in these areas, thus these areas may be underestimated. Similarly, in open spaces, such as parks, only the paths in the pedestrian street network are used. However, people can usually move around freely in those places.

Therefore, we likely underestimate the actual local walkable areas of individuals in the innermost urban cores and in green spaces. As this error is consistent across all cities surveyed, however, we are still able to investigate the aspects that hinder free movement at the local scale.

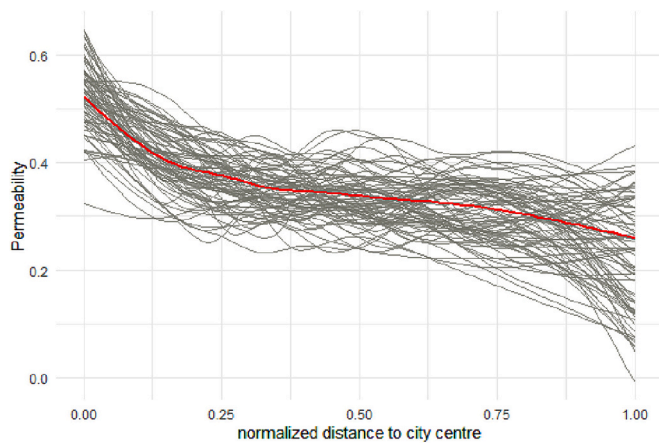


Fig. 3. GAM of decreasing permeability values from the city centre to the periphery. Distance to the city centre is normalized as cities all have different sizes. Red line is the model for all cities together. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Nevertheless, these aspects need to be further investigated and integrated into further works regarding pedestrian permeability.

Even though the data quality and quantity of OSM is quite high in Germany (Zielstra & Zipf, 2010), also for road networks (see Neis, Zielstra, and Zipf (2012)), in regard to specific tags the available data can be rather incomplete (e.g. for sidewalk data roughly ~20% of all sidewalks have been mapped in Heidelberg (Mobasheri, Sun, Loos, et al., 2017)). Therefore, although we have empirically adjusted our network extraction based on our knowledge of a particular city to extract the best possible result, there may be a lot of underestimation of paths that could actually be walked by pedestrians but are not extracted, or overestimation of areas that cannot be walked but are included in the present study. If we were doing shortest path analyses, this would be a serious problem, as the length of the path would be greatly affected if a different route had to be taken. However, as we are working with an area made up of all possible paths that can be taken in a given amount of time, the impact of missing or additional segments is much less. An alternative approach would be to use official pedestrian network datasets. These datasets are rarely available, especially not on such a large scale. By using such datasets our results may vary slightly on the local level, however, the general picture of pedestrian permeability within the cities would probably be very similar. A possible way to analyse the impact of missing or additional street segments on the IWN area is to conduct a sensitivity analysis by randomly adding and/or removing pedestrian paths segments. With this, the impact of errors and incompleteness of OSM data can be quantified.

At the city level, we are able to show that within each city, permeability values of all IWNs follows roughly a normal distribution. The city of Chemnitz (cf. Fig. 2, No.41) has the largest deviation from this general observation, with a high proportion of areas with low permeability. This may be related to its urban structure, which is quite unique: the growth of the city into the urban fringe is based on very narrow and radial settlements (see Supplementary Material Fig. S12). Because these radial settlements are very long and quite numerous, they are responsible for the high number of low-permeability areas. When we add population data to the calculation, however, the picture changes drastically: because the majority of people live in the few areas with high permeability, the average is skewed to the right. This is explained by the fact that these low-permeability radial settlements consist mainly of detached houses with large private gardens. Although they occupy a lot of space, the population density in these areas is low. The much more densely populated city centre typically boasts a higher permeability.

Even though within each city, permeability is roughly normally

distributed, there are significant differences in the distribution across the cities. The difference between the cities with the highest (Ulm) and lowest (Siegen) median value is quite high at 0.18. This means that, on average, 18% less space is locally accessible within 10 min' walk of any given starting point in Siegen than in Ulm. As can be seen in Fig. 4, the city of Siegen is quite dispersed and shows very few high-permeability areas. We argue that two factors are responsible for this: (1) the hilly topography of the city, with mainly industrial zones on the valley floor and residential areas on the hills, and (2) the dominance of detached houses with private gardens throughout the city. The latter is consistent with the findings of Taubenböck, Reiter, Dosch, et al. (2021), who examined the proportion of green spaces within the 80 largest cities in Germany and concluded that Siegen has the highest proportion of green spaces within the city limits. This fact is also reflected in the very similar distribution curves of general permeability and population-weighted permeability, compared to, e.g., Erfurt, Jena, and Potsdam, which feature a comparatively high share of multi-family dwellings and therefore show peaks in the population-weighted distribution that are not seen in the area-weighted distribution curve.

In order to discern the spatial distribution of areas with varying permeability, the results have to be displayed on a map (Dovey, Ristic, & Pafka, 2017; Pafka & Dovey, 2017). For instance, Fig. 3 clearly shows that permeability values decrease with increasing distance from the city centre. It is consistent with our general assumption of urban areas: having a centre with highly interconnected roads and pedestrian paths, and a less densely built periphery with fewer connections, impeding pedestrian movement. This is particularly evident on the very edges of cities. Settlements are often bordered by, e.g., bodies of water, forests, agricultural areas, grassland, railways, highways, or industrial areas, all of which act as barriers to movement. However, it is important to mention that the mere presence of potential barriers does not automatically mean that permeability is lower. If there are links and paths within, above or beneath these areas, like footpaths within a forest, permeability can still be high (e.g., south of Munich, the patch east of the low-permeability area, see Fig. 4). A particularity of our analysis is that while we calculated permeability within the administrative borders, settlements may still extend beyond them (Taubenböck, Weigand, Esch, et al., 2019). To compensate for that, IWNs close to a border still include the pedestrian networks outside of it, meaning that the permeability will still be high in many cases. Examples of this are the south of Ulm or the south-easternmost patch of Munich.

Low permeability values do not only occur at the edge of the city. Barriers such as highways, railways, rivers, etc., also significantly reduce permeability within the city limits if no connections are available. Fig. 5 shows the patterns of urban structural elements with either high or low permeability that were identified by visually examining the permeability values of the 78 cities. The bottom two rows demonstrate how permeability is significantly reduced if connections such as bridges or underground crossings are not provided to overcome such barriers. We have specifically selected areas where there are residential areas on both sides of the barrier to better show the importance of these connections. This is particularly evident in the Cologne and Freiburg examples, as these are densely built-up areas with a relatively well-connected road network. Despite that, the railway in the case of Cologne and the river in the case of Freiburg form a barrier that severely impacts local permeability, as people can only move along the barrier and not across it, reducing their range of movement by at least half. Another striking example is the site in Essen, where permeability is the lowest. In addition to a very sparse street network with many cul-de-sacs, this can be traced back to the twin barriers of a highway and a railway which essentially quarters the area. This confines the inhabitants to very limited zones if they exclusively move on foot.

Permeability is strongly related to a network of dedicated pedestrian paths (Ellis et al., 2016; Stangl, 2019). Steep and hilly terrain hinders the construction of well-connected roads and thus reduces permeability. Fig. 2 also supports this assumption, as for example the cities of Siegen

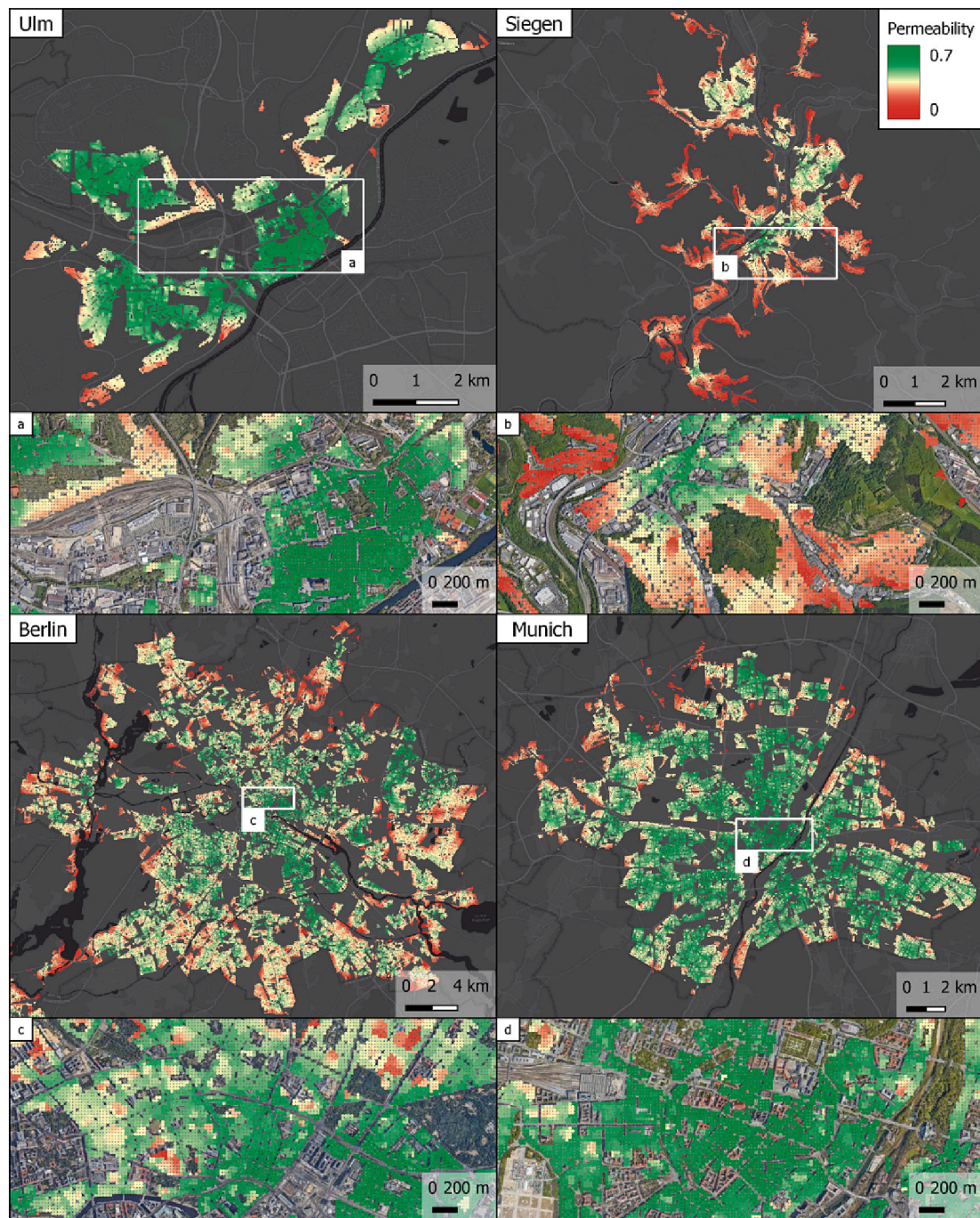


Fig. 4. Spatial representation of permeability for the residential areas of the cities of Ulm (No.1), Siegen (No.78), Berlin (No.30), and Munich (No.3) calculated with starting points every 25 m. High permeability in green and low permeability in red. Basemap: ©2015 Google, ©ESRI. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(No.78), Koblenz (No.77), and Trier (No.74), which all have very low permeability values, are surrounded by, or built on, hilly terrain. By using a DEM we could show that the slope of the terrain has a moderate effect on permeability. It should be noted, that these IWN are not solely influenced by slope but that each IWN is an intermix of different patterns, however, the result is still highly significant.

Large housing estates have a large number of small paths that are all interconnected, and therefore show a high level of walkability (Köberli, Wurm, Droin, et al., 2024). This, in contrast, is not the case for single-family homes. Paths around them are very sparse and often end in cul-de-sacs. Rows of houses tend to form long blocks interspersed with inaccessible private gardens, drastically increasing the distance one has

to cover to get to a connection. These patterns are found in the majority of the 78 cities. However, while they may be quite rare, there are exceptions to this norm: Some areas dominated by single-family homes or hilly terrain have a very high permeability, just as there are large housing estates with low permeability values. Nonetheless, cities are not composed of only single-family homes and large housing estates but are a composition of a variety of urban morphologies built in different historical periods and based on different urban planning principles. As mentioned in the Introduction, related research investigated permeability based on distinctive urban morphologies, however, not on a large scale. A promising alley of research in the future would be to assess permeability on a large scale based on different urban planning concepts

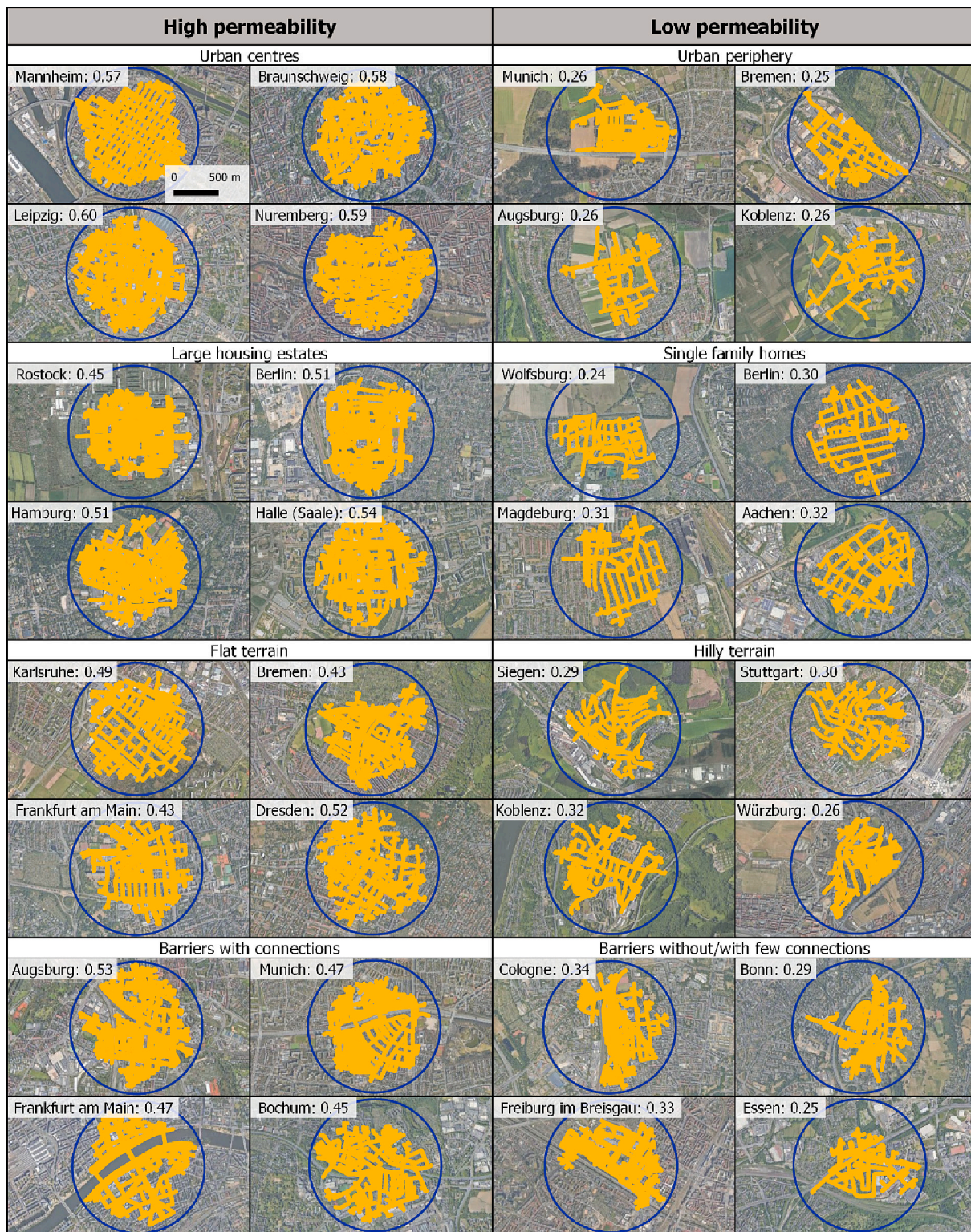


Fig. 5. Examples of IWNs with high or low permeability for different patterns. The permeability value of each IWN is given in the left side corner of each scene. Map data ©2015 Google.

and morphologies on a large scale. Using remote sensing, building types and morphologies, as well as urban structural types can be derived on a large scale (e.g., Heiden, Heldens, Roessner, et al., 2012; Wurm, Schmitt, & Taubenböck, 2016; Wurm, Taubenböck, Roth, et al., 2009). This kind of information can be valuable for future urban planning and design policies to help make cities more sustainable, as levels of walkability can be significantly increased.

We are aware that the proposed measure of permeability may represent very distinctively different morphologies with the same permeability value. However, our goal is not to describe distinct permeability values for every possibly occurring morphology. Rather we aim to demonstrate that permeability can vary greatly within and between cities due to the interplay of several factors, and to add to the existing literature that has so far examined permeability at a more

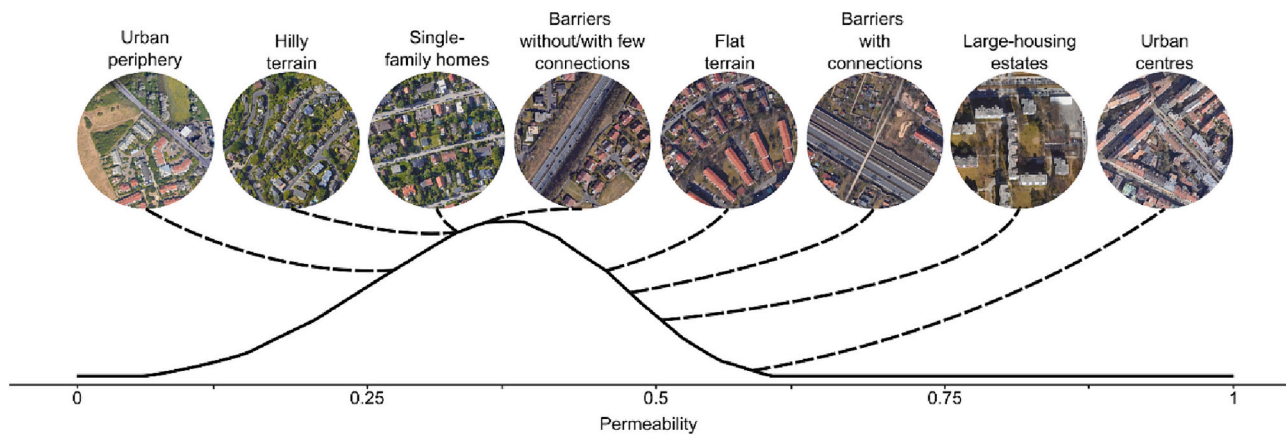


Fig. 6. Frequency distribution of the permeability across all 78 cities. The dashed lines indicate the position of the mean values for the different settlement patterns from Fig. 5, with exemplary images.

theoretical level. By calculating different shape metrics (e.g. the ratio of the IWN to the IWN with filled holes, of the IWN to the convex hull etc.) a differentiation of IWNs with the same permeability value but with different shapes can be conducted. This is an alley of research that needs to be further investigated.

In Fig. 6, the frequency distribution shows that overall, based on the criteria chosen for our calculations, lower-permeability areas are more common within the cities. It is apparent that the patterns with low permeability are positioned near the peak of the normal distribution, meaning that low-permeability patterns occur quite frequently in German cities. This is predominantly caused by the high spatial share of a common urban morphological form in Germany: single-family homes. In contrast, patterns with high permeability values are located on the right side of the frequency distribution. These represent the more permeable areas that coincide with urban centres. We can assume that this is due to the fact that urban centres generally take up less space than sparsely built areas within a city. Even though specific values for specific morphologies are shown in Figs. 5 and 6, it should be noted that no city is defined by any one pattern, but is always a combination of multiple of them. The city of Siegen, for example, is characterized by mainly hilly terrain and the predominance of single-family homes. Even if we stick to those two broad aspects, every single IWN is at least defined by their interplay in this specific location, each being more or less dominant.

With the results of this study, we can now actually locate areas of low permeability and show where action is needed to increase permeability. For example, residential areas that are divided by a barrier (rivers, highways, railways, etc.) and do not have a connection such as a bridge or underground passage can now be targeted. This allows urban planners to locate areas of needs. Future research can simulate the construction of connections and see where they can be best placed to provide the greatest benefit to all residents. For hilly areas, straight pedestrian connections, e.g. stairs, could be constructed to enhance permeability. However, it should be noted that this would not be a solution for physically disabled or elderly people. Thus, when combined with socio-economic data, we can target specific social groups with limited connectivity and use these areas to rethink urban planning principles and identify new ways to improve connectivity. The long-term goal is to plan and create more sustainable cities or local areas. By improving low-connectivity areas through increased connectivity, walking will be encouraged and fewer people will use their cars.

Buehler and Pucher (2023) have shown in their research that walking rates vary considerably not only between countries (e.g. America vs. Germany), but also between cities within the same country and within cities. They found that the modal share of walking decreases significantly from the city centre to the suburbs in both American and European cities. This is consistent with our results, which show that

pedestrian permeability decreases as we move away from the centre (see Fig. 3). We chose a time threshold of 10 min because European cities are quite dense. This could also mean that people could easily walk for more than 10 min. We argue that using larger time thresholds, such as 15 or 20 min, would have smoothed out the differences more, because (1) the further people can walk, the more likely they are to reach different morphological structures, and thus averaging the different permeabilities of these structures, and (2) the impact of barriers is also reduced, as it is more likely that a passage can be reached. In contrast, barriers with no passage reachable in this time span would be more visible as the relative difference would be much greater.

Lastly, we want to highlight that the permeability rates calculated in this study paint an objective, but abstract picture. Even though permeability may be high in an area, this does not mean that the local residents actively walk a lot or utilize all paths equally. Marshall and Garrick (2010) found that certain street patterns were conducive to higher levels of active walking. However, it is not only the street pattern, but also the number of accessible amenities and points of interest that affect actual walking levels. For example, Buehler, Pucher, Gerike, et al. (2017) showed that the level of active walking is highest in city centres and lowest in the suburbs. This is due to mixed land-use, short trip distances because of the proximity to public transport and everyday services, narrower streets, etc. However, as (Koohsari, Badland, Sugiyama, et al., 2015) point out in their study even if the objectively measurable walkable attributes are low, but the area is perceived as highly walkable by the residents they also tend to walk more. Conversely, they also tend to walk less if they perceive the area as not walkable, even if the objective picture describes the area as highly walkable. This highlights the importance of integrating individuals' perceptions and the ability of urban planners to increase levels of walking by making an area perceptually attractive for walking, even if the objective walkability is low. Additionally, if permeability is high but there is nothing worth accessing, walking may not be a viable mode of transport regardless. For this reason, Pafka and Dovey (2017) suggest using permeability in combination with interface catchment to assess the accessible interface. Using the methodology at hand to assess the interface catchment for pedestrians, we suggest refining the generated IWNs by relating them to further attributes such as building facades, architectural specifics, amenities etc., in order to further advance research of pedestrian accessibility.

There are several limitations to this study: First, the use of volunteered geographic information in the form of OSM data introduces inaccuracies in our calculations, as the data may be incomplete or inaccurate (e.g., misattributed or incorrectly mapped). The use of an official dataset would be beneficial for more accurate results. Secondly, our results only paint a picture of objective permeability. We were only

able to study objective permeability based on physical structures. The reduction of permeability due to e.g. subjective (social) barriers was not investigated. We cannot ignore the fact that these aspects may have an even greater influence on the movement of individuals. It would be interesting to investigate the interaction of physical and social barriers in a future study. Finally, even if the computational time is not too high, the physical memory requirement for this amount of IWN is quite high.

5. Conclusion

When aiming for more sustainable cities that enhance the walking experience, permeability is a key component of accessibility (Dovey & Pafka, 2020). We present a framework to explore local urban permeability for 10-min neighbourhoods within urban areas and calculate it at a large scale, i.e., for 78 large cities in Germany. The method presented, using Individual Walkable Neighbourhoods based on the pedestrian network, makes it possible to assess the permeability of an area, adding to existing methods by its computational efficiency, meaning that application at a larger scale for multiple neighbourhoods and cities becomes possible. Furthermore, the method adds to the current state of the art by considering aspects such as barriers (e.g., major roads, railways, highways, and rivers), which have a significant impact on our range of movement, and differentiating between publicly accessible and private pathways. Various typical urban morphologies have distinct effects on permeability, as shown in the works of, e.g., Pafka and Dovey (2017) and Stangl (2019). With the present study, we extend existing knowledge on permeability by analysing local permeability at a large scale. This is achieved by calculating IWNs in a regular 25 m × 25 m grid for the residential areas of the 78 largest cities in Germany, resulting in about 4 million IWNs in total. This allowed us to show that certain urban morphological patterns have a clear influence on the local permeability of an area. Beyond that, we also measure the impact of other local characteristics, such as barriers and the slope of the terrain, on permeability. Barriers such as highways significantly reduce permeability if there are no connections (bridges or underground passages, for instance) between the settlements which they separate. Essentially, residents of these areas are restricted in their range of movement and their ability to access everyday services. When planning a walkable neighbourhood, their mobility must therefore be assessed and considered differently from people within the same morphological pattern, who have the opportunity to approximately double their relative range of movement simply because of the absence of a barrier. Variations in permeability between the cities are generally caused by a different mix of urban morphological patterns, as well as the local topography (e.g., hilly terrain or a large river crossing the city). This quantitative study proves that both factors play a significant role. The interplay of all these local circumstances generates a single specific and quantifiable rate of permeability for each city. By combining this information with the spatial dimension using maps, we can better understand what influences local permeability.

The transparent and straight-forward applicability of the presented methodology makes it possible to further expand our knowledge on the influence of urban morphological patterns and other locally occurring aspects on permeability. For example, by applying such a large-scale analysis to different cities worldwide, in order to better understand the effect of different historical developments and various environmental factors on permeability. We believe that the results of such studies help us understand the perceived differences in urban permeability. In combination with interface catchment (Dovey & Pafka, 2020), this approach can be applied to studies assessing the impact of accessibility on local walkability within cities. The generated data can help urban planners to design cities that meet the new standards of sustainability, and thus improving the quality of life for urban citizens around the globe.

CRediT authorship contribution statement

Ariane Droin: Writing – original draft, Visualization, Software, Resources, Methodology, Formal analysis, Conceptualization. **Michael Wurm:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Conceptualization. **Matthias Weigand:** Writing – review & editing, Software, Methodology, Conceptualization. **Carsten Gawlas:** Writing – review & editing, Software, Methodology, Conceptualization. **Manuel Köberl:** Writing – review & editing, Software, Methodology, Conceptualization. **Hannes Taubenböck:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

None.

Acknowledgements

This work was supported by the European Commission within the HORIZON.2.6 - Food, Bioeconomy Natural Resources, Agriculture and Environment programme [grant number 101083958 - FUTURAL]

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.compenvurbsys.2024.102115>.

References

- Berghauer Pont, M., & Haupt, P. (2010). *Spacematrix - Space, Density and Urban Form*. BKG (Bundesamt für Kartographie und Geodäsie). (2016). Digitales Geländemodell Gitterweite 25 m - DGM 25. Available at: https://sg.geodatenzentrum.de/web_public/gdz/dokumentation/deu/dgm25.pdf.
- Boeing, G. (2017). OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks. *Computers, Environment and Urban Systems*, 65, 126–139.
- Buehler, R., & Pucher, J. (2023). Overview of walking rates, walking safety, and government policies to encourage more and safer walking in Europe and North America. *Sustainability*, 15(7), 7 (Multidisciplinary Digital Publishing Institute: 5719).
- Buehler, R., Pucher, J., Gerike, R., et al. (2017). Reducing car dependence in the heart of Europe: Lessons from Germany, Austria, and Switzerland. *Transport Reviews*, 37(1), 4–28.
- Chin, G. K. W., Van Niel, K. P., Giles-Corti, B., et al. (2008). Accessibility and connectivity in physical activity studies: The impact of missing pedestrian data. *Preventive Medicine*, 46(1), 41–45.
- Conzen, M. R. G. (1960). Alnwick, Northumberland: A study in town-plan analysis. *Transactions and Papers (Institute of British Geographers)*, 27, iii.
- Dovey, K., & Pafka, E. (2020). What is walkability? The urban DMA. *Urban Studies*, 57(1), 93–108.
- Dovey, K., Ristic, M., & Pafka, E. (2017). Mapping as spatial knowledge. In *Mapping Urbanities*. Routledge.
- Dovey, K., Woodcock, I., Pike, L., et al. (2015). Space/time mapping of urban transit: isochrones. *Car-dependency and Mode-choice in Melbourne, 2015*. Epub ahead of print.
- Droin, A., Wurm, M., & Taubenböck, H. (2023). The individual walkable neighborhood - evaluating people-centered spatial units focusing on urban density. *Computers, Environment and Urban Systems*, 99, Article 101893.
- Dunn, A., Hanson, B., & Seeger, C. J. (2018). Evaluating walkability in the age of open data: OpenStreetMap and community-level transportation analysis. *DE: Wichmann Verlag*. <https://doi.org/10.14627/537642013>. Available at. (accessed 9 March 2023).
- Ellis, G., Hunter, R., Tully, M. A., et al. (2016). Connectivity and physical activity: Using footpath networks to measure the walkability of built environments. *Environment and Planning B: Planning and Design*, 43(1), 130–151. SAGE publications Ltd STM.
- European Commission. (2020). *Mapping Guide v6.2 for a European Urban Atlas*. Epub ahead of print 2020.
- Ewing, R., & Handy, S. (2009). Measuring the unmeasurable: Urban Design qualities related to walkability. *Journal of Urban Design*, 14(1), 65–84.
- Forsyth, A., & Southworth, M. *Cities Afoot—Pedestrians, Walkability and Urban Design*. (2008). Available at: <https://www.tandfonline.com/doi/epdf/10.1080/13574800701816896?needAccess=true&role=button>.
- Forsyth, A., Van Riper, D., Larson, N., et al. (2012). Creating a replicable, valid cross-platform buffering technique: The sausage network buffer for measuring food and physical activity built environments. *II(14)*.
- Frank, L. D., Sallis, J. F., Saelens, B. E., et al. (2010). The development of a walkability index: Application to the neighborhood quality of life study. *British Journal of Sports Medicine*, 44(13), 924–933.

- Glazener, A., Wylie, J., van Waas, W., et al. (2022). The impacts of Car-free days and events on the environment and human health. *Current Environmental Health Reports*, 9(2), 165–182.
- Heiden, U., Heldens, W., Roessner, S., et al. (2012). Urban structure type characterization using hyperspectral remote sensing and height information. *Landscape and Urban Planning*, 105(4), 361–375.
- Kesarovski, T., & Hernández-Palacio, F. (2023). Time, the other dimension of urban form: Measuring the relationship between urban density and accessibility to grocery shops in the 10-minute city. *Environment and Planning B: Urban Analytics and City Science*, 50(1), 44–59. SAGE publications Ltd STM.
- Köberl, M., Wurm, M., Droin, A., et al. (2024). *Liveability in large housing estates in Germany – Identifying differences based on a novel concept for a walkable city (under revision)*.
- Koohsari, M. J., Badland, H., Sugiyama, T., et al. (2015). Mismatch between perceived and objectively measured land use mix and street connectivity: Associations with neighborhood walking. *Journal of Urban Health*, 92(2), 242–252.
- Lo, R. H. (2009). Walkability: What is it? *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, 2(2), 145–166.
- Logan, T. M., Hobbs, M. H., Conrow, L. C., et al. (2022). The x-minute city: Measuring the 10, 15, 20-minute city and an evaluation of its use for sustainable urban design. *Cities*, 131, Article 103924.
- Majic, I., & Pafka, E. (2019). AwaP-IC—An open-source GIS tool for measuring walkable access. *Urban Science*, 3(2), 2 (Multidisciplinary Digital Publishing Institute: 48).
- Marshall, W. E., & Garrick, N. W. (2010). Effect of street network design on walking and biking. *Transportation Research Record: Journal of the Transportation Research Board*, 2198(1), 103–115.
- Mobasheri, A., Sun, Y., Loos, L., et al. (2017). Are crowdsourced datasets suitable for specialized routing services? Case study of OpenStreetMap for routing of people with limited mobility. *Sustainability*, 9(6), 6 (Multidisciplinary Digital Publishing Institute: 997).
- Moreno, C., Allam, Z., Chabaud, D., et al. (2021). Introducing the “15-Minute City”: Sustainability, resilience and place identity in future post-pandemic cities. *Smart Cities*, 4(1), 93–111.
- Neis, P., Zielstra, D., & Zipf, A. (2012). The street network evolution of crowdsourced maps: OpenStreetMap in Germany 2007–2011. *Future Internet*, 4(1), 1 (Molecular Diversity Preservation International: 1–21).
- Oliveira, V. (2016). Urban morphology. In *The Urban Book Series*. Cham: Springer International Publishing. Available at: <http://link.springer.com/10.1007/978-3-319-32083-0> (accessed 27 March 2023).
- Oliver, L. N., Schuurman, N., & Hall, A. W. (2007). Comparing circular and network buffers to examine the influence of land use on walking for leisure and errands. *International Journal of Health Geographics*, 6(1), 41.
- OpenStreetMap Contributors. (2023). Open Database License. Available at: https://wiki.openstreetmap.org/wiki/Open_Database_License (accessed 13 April 2023).
- Pafka, E., & Dovey, K. (2017). Permeability and interface catchment: Measuring and mapping walkable access. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, 10(2), 150–162.
- Pucher, J., Buehler, R., Bassett, D. R., et al. (2010). Walking and cycling to health: A comparative analysis of City, state, and international data. *American Journal of Public Health*, 100(10), 1986–1992.
- Randall, T. A., & Baetz, B. W. (2001). Evaluating pedestrian connectivity for suburban sustainability. *Journal of Urban Planning and Development*, 127(1), 1–15. American Society of Civil Engineers.
- Schimpl, M., Moore, C., Lederer, C., et al. (2011). Association between walking speed and age in healthy, free-living individuals using Mobile Accelerometry—A cross-sectional study. *PLoS ONE*, 6(8), e23299. Lucia A (ed.).
- Schlossberg, M. (2006). From TIGER to audit instruments: measuring neighborhood walkability with street data based on geographic information systems. *Transportation Research Record*, 1982(1), 48–56. SAGE Publications Inc.
- Simón, A., & Leal, M. (2011). *Updated UMZs and corresponding methodological documentation*. Epub ahead of print 2011.
- Stangl, P. (2019). Overcoming flaws in permeability measures: Modified route directness. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, 12(1), 1–14.
- Stangl, P., & Guinn, J. M. (2011). Neighborhood design, connectivity assessment and obstruction. *Urban Design International*, 16(4), 285–296.
- Staricco, L. (2022). 15-, 10- or 5-minute city? A focus on accessibility to services in Turin, Italy. *Journal of Urban Mobility*, 2, Article 100030.
- Taubenböck, H., Debray, H., Qiu, C., et al. (2020). Seven city types representing morphologic configurations of cities across the globe. *Cities*, 105, Article 102814.
- Taubenböck, H., Reiter, M., Dosch, F., et al. (2021). Which city is the greenest? A multi-dimensional deconstruction of city rankings. *Computers, Environment and Urban Systems*, 89, Article 101687.
- Taubenböck, H., Weigand, M., Esch, T., et al. (2019). A new ranking of the world's largest cities—Do administrative units obscure morphological realities? *Remote Sensing of Environment*, 232, Article 111353.
- Wurm, M., Goebel, J., Wagner, G. G., et al. (2021). Inferring floor area ratio thresholds for the delineation of city centers based on cognitive perception. *Environment and Planning B: Urban Analytics and City Science*, 48(2), 265–279. SAGE publications Ltd STM.
- Wurm, M., Schmitt, A., & Taubenböck, H. (2016). Building Types' classification using shape-based features and linear discriminant functions. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 9(5), 1901–1912.
- Wurm, M., Taubenböck, H., Roth, A., et al. (2009). Urban structuring using multisensoral remote sensing data: By the example of the German cities Cologne and Dresden. In , 2009. *2009 Joint Urban Remote Sensing Event* (pp. 1–8). Available at: <https://ieeexplore.ieee.org/document/5137555> (accessed 20 December 2023).
- Zielstra, D., & Zipf, A. (2010). *A Comparative Study of Proprietary Geodata and Volunteered Geographic Information for Germany*. Epub ahead of print 1 January 2010.