

Research Paper

Waterfront usage trends across German metropolitan areas: A social-ecological perspective to urban blue-green infrastructure connectivity

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HIGHLIGHTS

- We propose the WDI as a robust and easy method to assess urban waterfront change.
- German urban waterfronts continue changing from natural to human land use.
- Across 91 German cities, 236.5 km of natural waterfront changed (2012–2018).
- Transportation is the most pressing land use along German urban waterfronts.
- Monitoring and planning of urban waterfront development is facilitated by the WDI.

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ABSTRACT

The waterfront connects aquatic and terrestrial habitats, and its landscape quality is an indicator of the status of blue-green infrastructure. Especially in urban areas, the consequences of direct human interventions on the waterfront are evident, yet there is a need for more comprehensive and easy approaches to quantify the dynamics of the waterfront landscapes. Herein, we propose a simple, rapid, and effective method, the “Waterfront Development Index” (WDI), for characterizing the relative waterfront usage in metropolitan areas. Based on the Urban Atlas data provided by the Copernicus program of the European Union for German functional urban areas (FUAs), we validate the WDI by comparing waterfront land use and land cover change at federal state, metropolitan, and urban levels (91 FUAs). Our results show remarkable disparities between waterfront land use along running and standing waters. The urban waterfronts covered a wide range of WDI values, highlighting critical urban freshwater waterfronts being relatively more extensively allocated for human land use. Transportation was identified as the most pressing human land use on the waterfronts, especially along the riverbanks. Between 2012 and 2018, 236.5 km of natural, water, or agricultural waterfront have been altered to urban, industrial, and transportation land use. Even though the national level transformation is relatively low (0.4 %), the change ratios of some FUAs are alarming (~2%). We demonstrate the usefulness and reproducibility of the WDI to monitor and quantify changes in waterfront development over time, posing high relevancy to waterfront landscape conservation, social-ecological systems’ balance, and sustainable urban planning alike.

1. Introduction

The concept of waterfront is broadly relevant to the social-ecological vitality of urban areas, particularly related to urban ecology, social-environmental justice, blue-green infrastructure (BGI), ecosystem services (ES), and nature-based solutions (NBS) to prevailing metropolitan

challenges. Waterfronts serve as critical interfaces between urban water surfaces and green urban areas, playing a vital role in urban metabolism and ecology (Woodland et al., 2022). Moreover, recent waterfront redevelopment projects increasingly integrate the social and environmental justice goals into their visionary proposals (Avni & Fischler, 2020). Waterfront development is particularly relevant to urban BGI, as

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it promotes multifunctional landscapes that can provide NBS to various urban challenges simultaneously, including flood risk mitigation, water quality improvement, biodiversity enhancement, and recreational spaces provision for urban residents (Hamel & Tan, 2022). This translates to urban ES which elucidate the multiple benefits that well-designed waterfronts can provide to cities including supporting services (e.g., habitat for biodiversity), cultural services (e.g., recreation, aesthetic value, social equity), and regulating functions (e.g., climate regulation, flood control, green carbon sink) (Li et al., 2024; Zhao et al., 2024). While the human land uses along the urban waterfront are vital for social cohesion, recreational activities, and human well-being, they may also trigger serious environmental and ecological complications (Wang, Dewanker, & Qi, 2020).

The shorelines along freshwater habitats are critical for sustaining the terrestrial and aquatic ecosystems far beyond their linear spatial extent (Wensink & Tiegs, 2016). They act as fundamental interface elements between seemingly independent ecosystems yet are deeply symbiotic and interconnected via fluxes of resources (Baxter et al., 2005; Polis, Anderson, & Holt, 1997). Human interference on freshwaters and the terrestrial riparian areas significantly affect the interaction between prey and predator species that are naturally found within the water-land gradient (Paetzold et al., 2005; Etherington et al., 2023). The riparian food web is sensitive not only to physical disruptions, but also to intangible anthropogenic disturbances like nighttime lighting and noise pollution along the waterfront (Parkinson, Lawson, & Tiegs, 2020; Shannon et al., 2016). At the same time, extensive human land use on the waterfront is accepted as an initial indicator of severe environmental problems like human-induced eutrophication and water browning (Dodds et al., 2009; de Wit et al., 2016; Häder et al., 2020). The extensive transformation of the waterfront natural land cover through urban land uses, engineered solutions like reservoirs, canals for irrigation, and floodplain diversions elevate the anthropogenic impact on the longitudinal and lateral connectivity of aquatic systems (Pander & Geist, 2010; Pander, Mueller, & Geist, 2015). Thus, in our approach we consider the waterfront line as a vital hinge which facilitates structural and functional connectivity between aquatic and terrestrial habitats (Hysa and Başkaya, 2018).

Considering the social-ecological implications of waterfronts, one would expect that no further transformation of natural and semi-natural habitats to extensive human land use takes place. However, the pressure of human activities (e.g., land reclamation) on the waterfronts is an ongoing persisting process at a global scale (Sengupta et al., 2023), manifested in different forms of urbanization processes like implementation of new transportation infrastructure, building new accommodation facilities, and in some cases even urban sprawl as reported in the case of Athens (Theodora & Spanogianni, 2022). Rentschler et al. (2023) have shown that since 1985, human settlements have rapidly expanded into present-day flood zones at global scale, and particularly in East Asia, where high-risk settlements have expanded 60 % faster than those in flood-safe zones. Sengupta et al. (2023) were able to reveal the extensive scale of coastal land reclamation in 135 large coastal cities around the world, by comparing land use land cover (LULC) data from 2000 to 2020. The human encroachment on urban waterfronts fluctuates LULC dynamics which are also directly correlated with urban ES capacities highly relevant to societal challenges including water quality, nutrient retention, climate regulation, and disaster risk reduction (Yan et al., 2023; Van Looy et al., 2017; Zhou et al., 2022). Thus, assessing and monitoring the waterfront landscape composition facilitates identifying and understanding anthropogenic pressures, especially on the metropolitan freshwater surfaces.

The available literature focuses on the waterfront landscapes either at the site scale (fine scale) or the watershed level (coarser scale). Fine scale studies are vital for providing scientific evidence about the inter-relationship between aquatic ecosystems and the waterfront terrestrial habitats. For instance, Baxter et al. (2005) reviewed how terrestrial invertebrates support aquatic food webs, offering key insights into cross-

ecosystem resource flows. In another study, Bartels et al. (2012) demonstrated that terrestrial insects falling into streams can contribute up to 100 % of the energy and carbon budget of some fish species, highlighting the critical role of cross-ecosystem subsidies among terrestrial and aquatic food webs. In a more recent study, Jermilova et al. (2025), utilized Bayesian Network Relative Risk Models (BN-RRM) to assess how mercury moves from terrestrial sources into aquatic systems, affecting water quality and the lifecycle of certain fish species, revealing the importance of understanding the links between terrestrial and aquatic ecosystems for both aquatic life and human health. The fine scale studies are indispensable for verifying the interdependence of aquatic and terrestrial ecosystems; however, they are context specific and unsuitable for upscaling findings at the landscape level.

On the other hand, coarse scale studies focus either on the water-course morphological dynamics or the landscape transformation within the watershed, with no specific emphasis on the waterfront line as the in-between element. Previous GIS-based remote sensing studies treat the shoreline as a consequence of hydromorphological dynamics of the river channel (Boothroyd et al., 2021). Tomsett and Leyland (2019) provided a comprehensive review of how remote sensing technologies are applied to river corridor studies, and highlighted their utility for various applications, including mapping river morphology, analyzing hydrodynamic processes, assessing habitat diversity, and monitoring changes in land cover. In a recent study, Shravan Kumar et al. (2024) investigate the effect of LULC change on river morphology and riverbanks of Godavari River (India) based on Landsat satellite images (30 m resolution) for a period of 50 years. However, similar studies utilize relatively low spatial resolution and oversimplified thematic (LULC) classification. This type of studies is too coarse to provide insights into whether the waterfronts can sustain habitats and provide ES for approaching a social-ecological balance in urbanized regions.

To our knowledge, no available method analyzed the spatio-temporal land-use dynamics of metropolitan waterfronts at multiple levels (e.g., national, metropolitan, and urban) by highlighting the waterfront line as a fine-scale urban landscape feature and the primary contact element between aquatic and terrestrial ecosystems. Despite the diverse synonyms of waterfront used by previous studies (Durán Vian et al., 2021), we consider the shoreline as a crucial linear element that shapes the interaction between urban water surfaces and waterfront lands. In this perspective, the waterfront can serve two contrasting roles: (i) as connector it can act as a bridge between two ecosystems, facilitating the movement and interaction of species that depend on both environments, and (ii) as barrier it can disrupt the ecological flows between aquatic and terrestrial systems. This dual nature of the waterfront—as both a potential connector and separator—forms the foundation of our conceptual approach, emphasizing the critical role of this transitional linear element in shaping urban ecological dynamics. In this context, we aim to develop a simple but comprehensive method to assess the dynamics of urban waterfront land use (as fine-scale evidence) across large spatial extends (coarse scale) at national, metropolitan, and the urban core levels.

We propose the “Waterfront Development Index” (WDI), as a simple, rapid, and effective method for characterizing the relative waterfront usage in the metropolitan zone. Using the metropolitan areas across Germany as case studies and utilizing the available (open source) LULC datasets, we address the following core questions: (i) What is the current situation in waterfront land use distribution across German functional urban areas? (ii) Are there significant differences between waterfront land use at the metropolitan and urban core scales, and among functional urban areas? (iii) Are the human land use pressures higher along the waterfronts of running or standing waters? (iv) What are the driving factors behind extreme cases of artificial land use along the waterfront? (v) Do the recent river restoration programs have an impact on waterfront landscape dynamics? Based on WDI, our initial hypothesis is that the German metropolitan waterfronts are more urbanized than the rest of the respective metropolitan zone. We also hypothesize that human

land use is significantly more present along the urban than the metropolitan waterfront. We expect that in a period of six years, the waterfront landscapes in German FUA have changed by decreasing the cumulative count and length of the natural & semi-natural waterfronts along freshwater surfaces.

2. Methods and materials

2.1. Conceptual approach and the waterfront development index (WDI)

We propose the WDI as an indicator of the relative development level of the urban waterfronts to the overall development rate within a metropolitan area. In this context, development refers to the human alteration of the natural and semi-natural waterfront based on the presence of a specific human land use (depending on the focus of the study) other than natural and semi-natural land cover. The WDI is based on the conception that inland water surfaces are the central element in a landscape, surrounded by various terrestrial land use types ranging from wildlands to extensive human land uses (Fig. 1a). The connection between aquatic and terrestrial elements, i.e., the waterfront line, is the focus of our approach. Different land uses along the shoreline imply for potentially effective or degraded lateral connectivity between the aquatic and terrestrial habitats (Fig. 1b). Consequently, we assess the LULC dynamics of freshwater waterfronts by splitting the waterfront line and classifying its segments by the corresponding waterfront land use (Fig. 1c).

WDI measures the ratio of waterfront length that is covered by a specific land-use relative to the ratio of the study area that is covered by that same land-use. By specific land-use we refer to categories like urban (WDI_u), industrial (WDI_i), agricultural (WDI_a), transportation (WDI_t), and natural & semi-natural (WDI_n). Arithmetically, the WDI value ranges between 0 (the least developed waterfront) to infinity which indicates the worst scenario where the whole urbanization develops only along the full length of the watercourse within a metropolitan area. WDI of a specific land use is calculated as the ratio of waterfront land use share (length) to the total study area land use share (area) as shown in Equation (1).

$$WDI_x = \frac{\sum_{p=1}^n WL_{px}}{WL_t} \div \frac{\sum_{p=1}^n A_{px}}{A_t} \quad (1)$$

Where WDI_x is the waterfront development index for land use category x , WL_{px} is the length of the waterfront line of patch p covered by land use category x , WL_t is the total waterfront length within the study area, A_{px} is the area of patch p covered by land use category x , and A_t is

the total surface area of the case study.

We developed a series of conceptual diagrams (Fig. 2) that visualize the calculation of WDI_u based on several hypothetical scenarios of urban land use development (grey surfaces) along a waterfront (red line). The scenario with the lowest ecological impact leading to the lowest WDI_u value indicates a metropolitan area with no urban development along water surfaces within it (Fig. 2, scenario ix). WDI_u value increases as the share of urbanized surface area decreases, and the share of urbanized waterfront length remains the same (Fig. 2, scenarios i, ii, and iii) or increases (Fig. 2, scenarios vii, viii, and ix).

As a result, the higher the WDI_u value, the higher the relative development pressure on the freshwater surface (blue line), and the lower the WDI_u value, the less the relative development on the waterfront. Furthermore, equal shares of a specific land use for the waterfront and the study area represent a balanced scenario that consistently delivers a WDI_u value of 1.00. Consequently, the WDI_u indicates the tendency of the urban development towards freshwater surfaces. For example, a city may have been developed by keeping the waterfronts as natural as possible, scoring a WDI_u value below 1.00. On the other hand, there can be cities where intense urban development has consumed most of the waterfront. Thus, the WDI_u index is expected to elevate far above 1.00.

2.2. Urban Atlas data as evidence of waterfront LULC transformation

We rely on the Urban Atlas data (UA) provided by the European Commission via the Copernicus program every six years. The most recent UA data belongs to the reference year 2018. The next updated UA data for the reference year 2024 is expected to be available for use within 2026. UA database delivers reliable LULC information about the functional urban areas (FUA) of a population above 50,000 inhabitants and currently covers more than 750 FUA across Europe. UA data defines a nomenclature of 27 classes (17 urban and 10 rural; see Table 1 and the legend of Fig. 3). UA data have been used as raw material in previous studies focusing on transforming metropolitan landscapes (Hyka et al., 2022; Kukulska-Koziel et al., 2019).

We reclassified the original UA classes into six major categories: urban, transportation, industrial, agricultural, natural & semi-natural, and water (Table 1). This reclassification helps to achieve bolder interpretations of our results about the dominant land use along the waterfront and the respective transformation trend. Detailed information at the UA nomenclature level is available via the appendixes of this article (see Appendix). The UA classes of “pastures” and “green urban, areas” could be reclassified also under agricultural or urban categories, respectively. However, considering the ecological significance and the

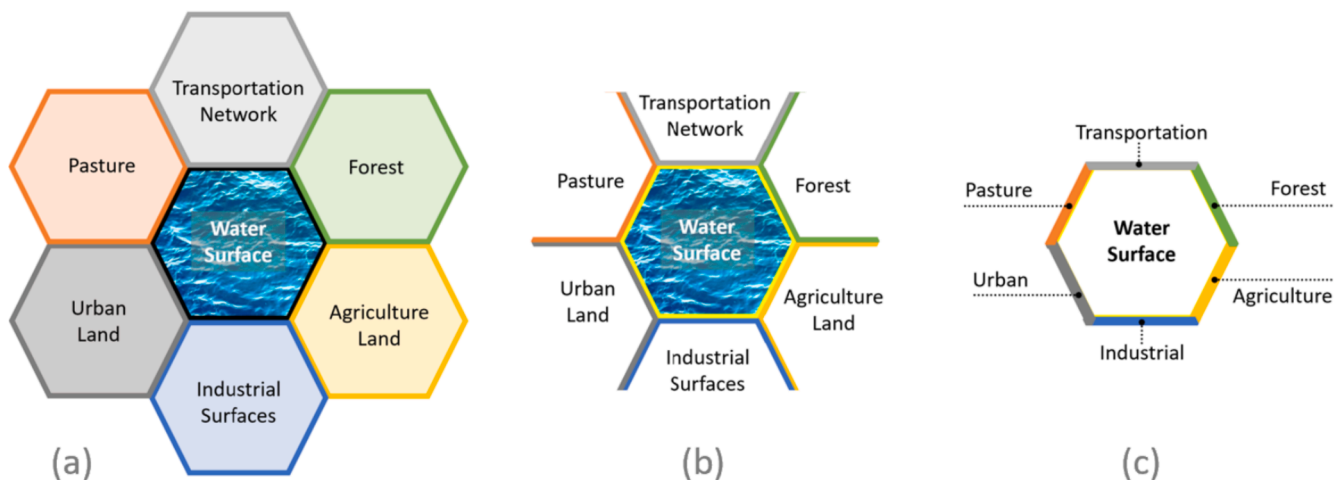


Fig. 1. Conceptual diagram showing (a) a hypothetical landscape mosaic of different land use types surrounding a water surface (lake, river, reservoir, etc.), (b) the bordering condition, and (c) the waterfront line classified by the adjacent land use and land cover type.

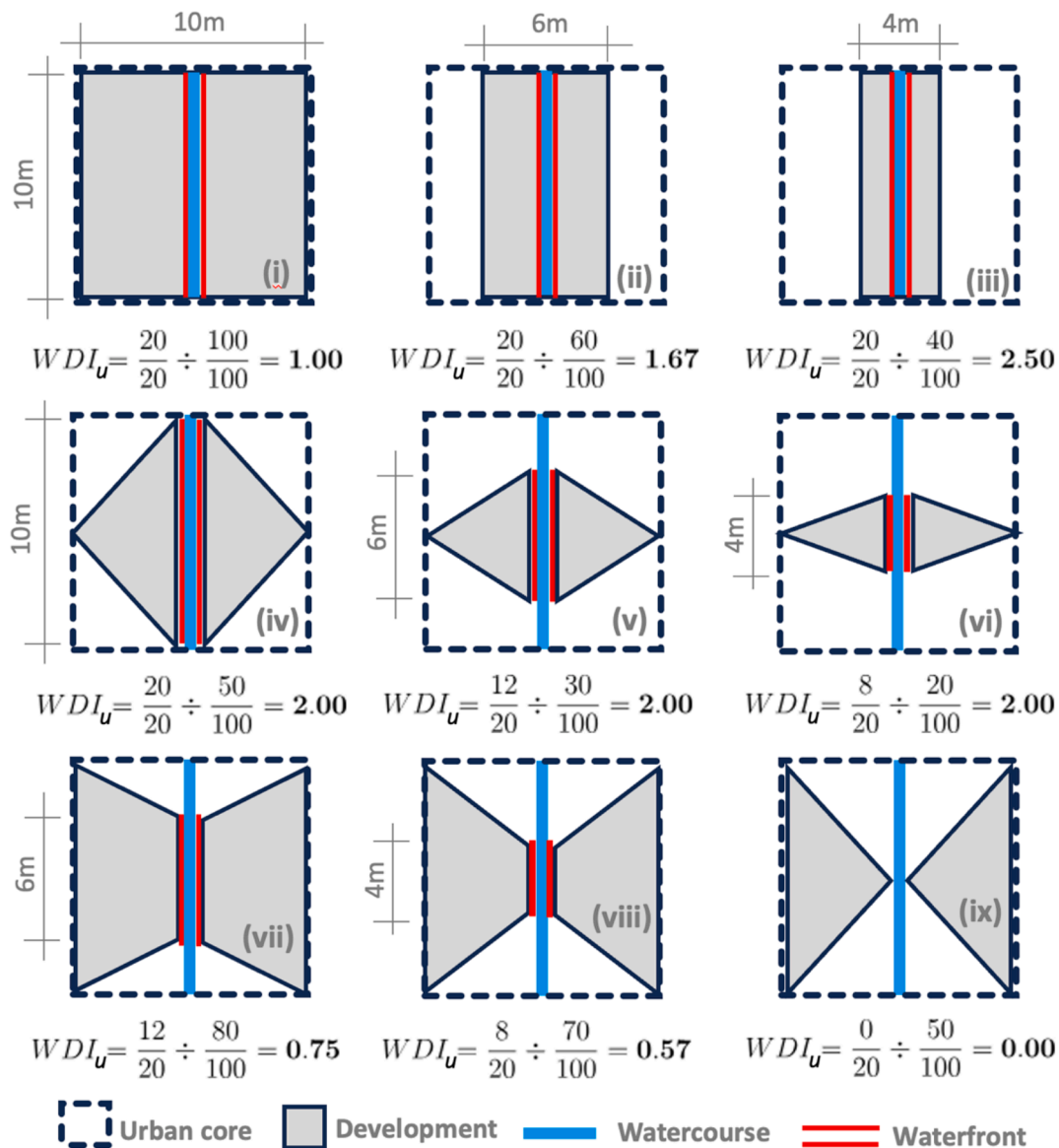


Fig. 2. Conceptual diagrams for WDI_u calculation in various case scenarios of urban development along urban freshwater surfaces ranging from the least developed (scenario ix) and elevated levels of waterfront (scenario iv-vi).

proven habitat potential of both classes in Germany and especially within urban areas (Schwarz et al., 2018; Gilhaus et al., 2017; Hansen et al., 2023), we reclassified them in the natural & semi-natural category. Reclassification procedures in future studies must consider how local circumstances affect each LULC classes ecological significance within the specific study region.

UA data make no difference between standing waters, running waters, and ocean waters. Since we focused on inland freshwaters within Germany, we excluded ocean waters along the North Sea. These were identified using the European coastline derived by the European Environment Agency. Similarly, we differentiated between running waters (rivers, streams, creeks, canals etc.) and standing waters (lakes, reservoirs, ponds etc.) using Germany's national running waters network derived from EU-Hydro River Network Database via Copernicus Geoportal (<https://land.copernicus.eu/en/products/eu-hydro/eu-hydro-river-network-database>). This helped compare between the waterfront usage of both metropolitan freshwater categories (hereafter used as running waters and standing waters).

2.3. Case study dataset

We analyzed the FUAs within 16 German federal states (Fig. 3b) at multiple spatial scales, including the national (Federal States), metropolitan, and urban core levels. Nevertheless, since UA are standardized data which cover the EU and associated countries (more than 750 FUAs), the method is applicable at pan-European scale analysis of metropolitan waterfront usage as far as a robust computing infrastructure is available. UA data provide both metropolitan and urban core boundaries which enable cross-scale comparative analysis, as shown in the example of Munich (see Fig. 3c). In this study, we focus on the intersection line between the water surfaces and the adjacent land use as defined by UA data, as exemplified in the case of the Isar riverfront in Munich (Fig. 3d and 3e).

According to UA data from 2018, there are 91 urban core areas and 96 FUA in Germany. Most of them are in Baden-Württemberg (13), Bayern (14), and Nordrhein-Westfalen (17). The total surface area of metropolitan zones (FUAs) covers nearly 57 % of Germany (357,592 km²), while urban cores cover about 3.9 % of the country area. On the other hand, the population living within FUAs makes up 85 % of

Table 1

Reclassification of Urban Atlas nomenclature to urban, transportation, industrial, agricultural, natural, and water surfaces.

New class	Urban Atlas (UA) Nomenclature	New class	Urban Atlas (UA) Nomenclature
Urban	Continuous urban fabric (>80 %)	Industrial	Industrial, commercial, public, military... Construction sites
	Discontinuous dense urban fabric (U.F.50–80 %)		Mineral extraction and dumpsites
	Discontinuous medium-density U.F. (30–50 %)	Agricultural	Arable land (annual crops)
	Discontinuous low-density U.F. (10–30 %)		Permanent crops (vineyards, fruit trees)
	Discontinuous very low-density U.F. (<10 %)		Complex and mixed cultivation patterns
Transportation	Isolated structures	Natural & Semi-natural	Green urban areas
	Land without current use		Pastures
	Sports and leisure facilities	Water	Forests
	Fast transit roads and associated land		Herbaceous veg. associations (grassland)
	Other roads and associated land		Open spaces with little or no veg. (dunes)
	Railways and associated land		Wetland
	Port areas		Water
	Airports		

the total population of Germany (2018), and about 29 % of them live within urban cores. Another metric we derived from the raw UA data relates to the water surface share (Table 2). It is worth mentioning that the countrywide average of water surface share is higher in urban cores (4.99 %) than in metropolitan regions (3.76 %). The total non-coastal waterfront length within German FUA is 58,667 km, about 18 % of which is within the state of Mecklenburg-Vorpommern. Besides the state-level statistics, we also provide records at the FUA level (see Table A1). According to FUA-level statistics, Berlin has the most extended waterfront at the metropolitan scale (6,275 km) and the largest area of water surfaces at the urban scale (8,433 ha). At the metropolitan level, Neubrandenburg records the largest area of water surfaces (46,540 ha).

3. Results

3.1. Comparison of waterfront land use by freshwater type

Our findings show that the natural & semi-natural land surfaces are more present along the waterfronts of standing waters than the running waters (Fig. 4b and Fig. 4c) across German metropolitan areas. The waterfronts along the running waters are occupied more by human land use for urban development, agriculture, transportation networks, and industry than the waterfronts of the standing waters. The human land use share elevates significantly along waterfronts of the running waters at the urban core level, especially for transportation use (see Fig. 5). Agriculture (arable land) is the second most present human activity on German waterfronts, recording an average share of 9 % for both running waters and standing waters. Our results converge with the processes of watercourse alteration in Germany, which have been extensively modified to serve various purposes, including urban development, agriculture, energy production, water supply, flood control, wastewater

management, transportation, and recreational activities (Petts et al., 1989).

At the national level, 53 % of waterfronts (freshwaters) define the banks of running waters (watercourses), while 47 % outline lakes, reservoirs, or other standing waterbodies. We found that among 2,010,284 LULC patches within German functional urban areas, 78,545 patches (3.9 %) are adjacent to at least one freshwater surface and define the respective waterfront land use. We further analyzed the distribution of waterfront landscapes at the federal state (German Lands) level (see Fig. 4a). Rheinland-Pfalz, Saarland, Hessen, Baden-Württemberg, and Hamburg have the highest percentage of waterfront landscapes along running waters, 76 %, 71 %, 69 %, 68 %, and 68 %, respectively. On the other hand, Mecklenburg-Vorpommern, Sachsen, Schleswig-Holstein, and Brandenburg have the highest share of waterfront landscapes along standing waters, 68 %, 63 %, 64 %, and 61 %, respectively. The sharing of metropolitan waterfront landscapes along the running and standing waters shows different distribution patterns among German federal states.

Most of the metropolitan waterfronts are defined by natural & semi-natural lands across German FUA. However, exceptional cases like the federal states of Berlin, Hamburg, Nordrhein-Westfalen, and Thüringen have a share of natural & semi-natural landscapes along the waterfront of running waters below 46 %, whereas Berlin records as low as 21 %. While most waterfront landscapes along running waters of Berlin and Hamburg are for transportation use, in Thüringen, the running waters' waterfront is mainly occupied by agricultural lands. On the other hand, Mecklenburg-Vorpommern and Schleswig-Holstein record a share of waterfront natural & semi-natural landscapes along running waters above 70 %. The waterfront landscapes of running waters within the state of Berlin have the lowest agricultural use (1 %) and the highest share of industrial (24 %) and urban land use (21 %). The difference between the federal state of Berlin and other German federal states can be attributed to Berlin's extensive metropolitan coverage and high population density (see Table 2 and Fig. 3b). This is expected given Berlin's island-like position within the state of Brandenburg, a region predominantly characterized by natural & semi-natural, and agricultural waterfronts (see Fig. 4).

In most federal states, the share of natural & semi-natural waterfront landscapes is higher along standing waters than along running waters (compare Fig. 4b and 4c). For instance, the share of waterfront natural & semi-natural landscapes of standing waters of Hamburg and Berlin is more than two times higher in comparison to the respective waterfronts along running waters. In the state of Berlin, this difference is compensated by the industrial and transportation land use along running waters, while in Hamburg, the difference is dominated by the transportation percentage being four times higher along running waters than standing waters. On the other hand, while the countrywide shares of waterfront agricultural, industrial, and urban land use are relatively equivalent for both running and standing waters (except for Berlin and Hamburg), the waterfront transportation land use is remarkably higher along the waterfronts of running waters than the standing waters. This difference can be related to the vast usage of riverfronts as port areas in many German FUAs, which is particularly high in port cities like Hamburg. Another reason for this difference may be the local topography, where rivers create natural corridors that are ideal for transportation networks, allowing routes to follow the river over long distances, as seen along the Rhine between Mainz, Koblenz, and Bonn. Bremen is the only state where the metropolitan waterfront transportation land use is slightly higher for the standing waters than the running waters.

Our results at the FUA level reveal that the highest share of agricultural, industrial, natural & semi-natural, transportation, and urban land use along the waterfronts are Weimar (51 % agriculture), Wuppertal (34 % industrial), Fulda (91 % natural & semi-natural), Trier (39 % transportation), and Chemnitz (18 % urban), respectively (see Table A2 and Fig. A1 in the Appendix section). Differences can also be observed between large FUAs. For instance, the natural & semi-natural

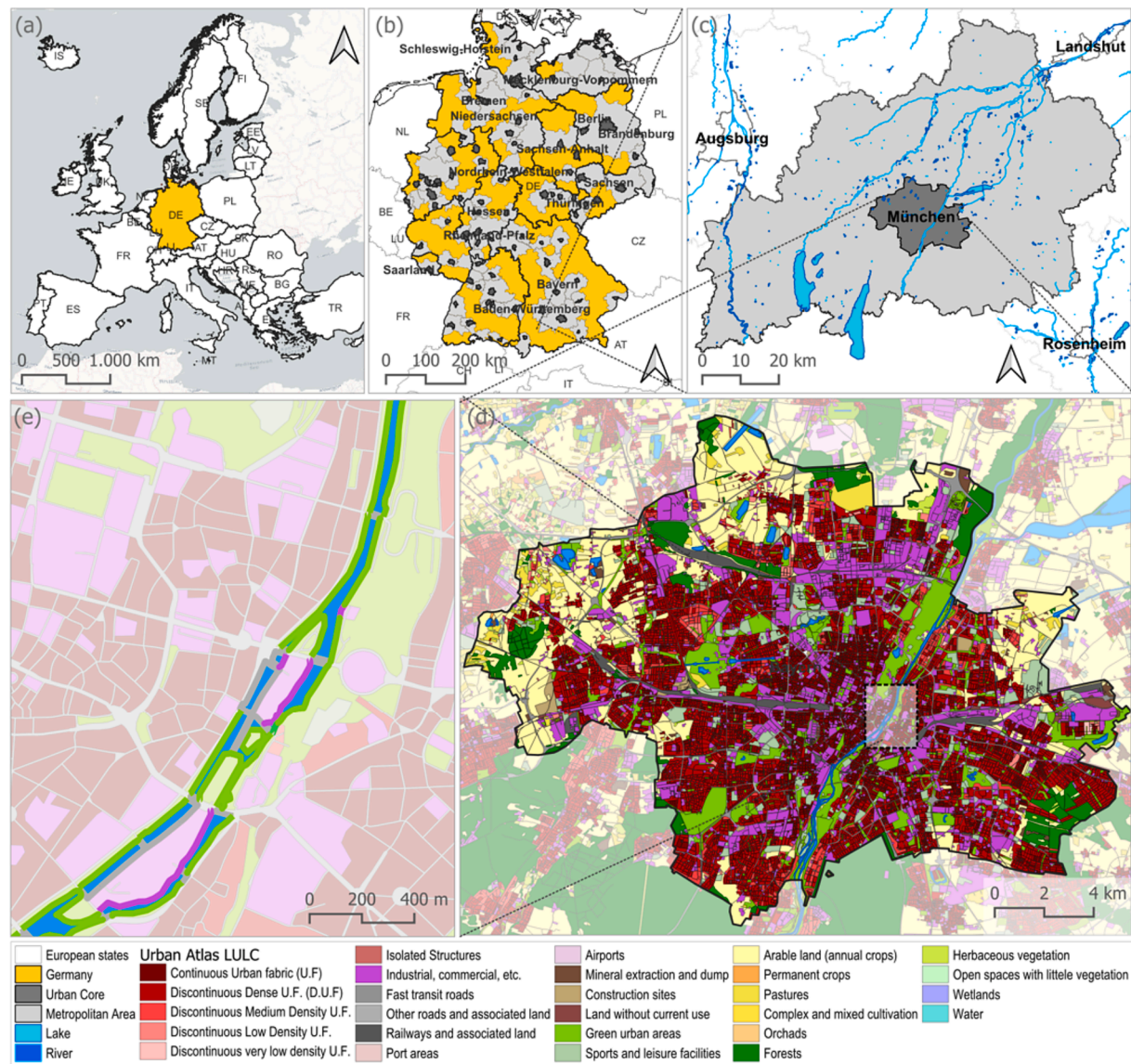


Fig. 3. Study area within (a) the European continent, including (b) all German federal states and the respective functional urban areas; (c) the metropolitan area of Munich and (d) the urban core; and a closer zoom into (e) the Isar River waterfront LULC types based on UA data of 2018.

Table 2
Basic statistics at the state level based on UA raw data of 2018.

German Federal State	Count Urban	Area Urban	Count Metro	Area Metro	Water Urban	Water Metro	Population Urban	Population Metro	Waterfront*
		km ²		km ²	%	%			km
1 Baden-Württemb.	13	1,527	13	18,138	1.55	0.79	2,216,599	7,812,033	4,357
2 Bayern	14	1,398	14	31,673	2.35	1.18	3,237,097	8,492,290	8,758
3 Berlin	1	892	**NA	NA	9.46	NA	3,648,161	5,258,960	6,275
4 Brandenburg	3	542	4	19,701	8.14	7.07	234,094	1,959,262	1,404
5 Bremen	2	403	NA	NA	15.31	NA	703,696	1,583,672	3,555
6 Hamburg	1	739	NA	NA	6.10	NA	1,864,637	3,306,469	2,921
7 Hessen	8	1,057	8	12,065	1.47	0.57	1,689,214	5,043,836	1,839
8 Mecklenburg-Vorp.	5	475	5	21,245	13.35	5.74	488,185	1,444,373	11,651
9 Niedersachsen	8	993	11	26,917	1.95	1.79	1,322,604	5,608,099	5,602
10 Nordrhein-Westfal.	14	2,553	17	24,828	1.81	1.15	4,391,254	19,622,780	5,421
11 Rheinland-Pfalz	4	460	5	8280	3.49	1.60	539,562	3,651,700	1,575
12 Saarland	1	169	1	1538	0.65	0.68	181,517	802,796	430
13 Sachsen	6	1,121	6	14,504	2.76	1.71	1,599,195	3,426,864	4,753
14 Sachsen-Anhalt	3	583	3	5992	3.49	2.16	561,258	1,009,852	1,882
15 Schleswig-Holstein	4	445	5	11,186	7.39	4.27	645,067	4,008,733	3,888
16 Thüringen	4	623	4	5675	0.57	0.50	483,350	1,062,255	805
Grand Total	91	13,979	96	299,802	4.99	3.76	23,805,490	74,093,974	65,116

*waterfront at metropolitan scale (FUA), ** refers to states with administrative boundaries equal to the urban core (UA).

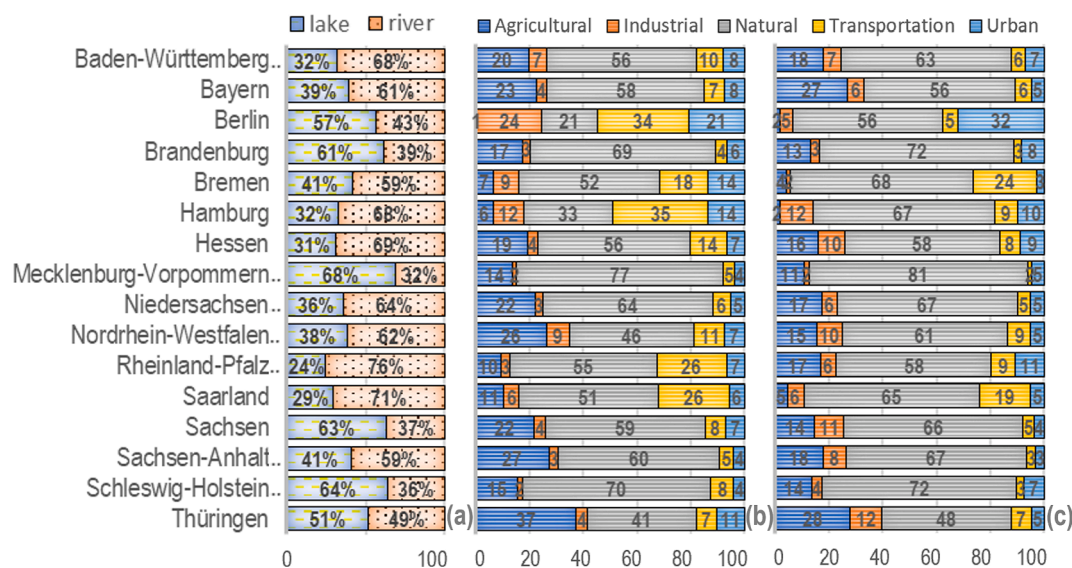


Fig. 4. Distribution of metropolitan waterfront landscapes by (a) freshwater type and land use category for (b) running and (c) standing waters.

land cover share on the waterfront of Berlin (65 %) is higher than in Munich (43 %). However, Munich records lower shares of transportation and urban waterfronts than Berlin (Table A3 and Fig. A1).

3.2. Comparison between metropolitan and urban level results

At the metropolitan level, the waterfront landscapes are dominated by natural & semi-natural surfaces at an average of 62.4 % for the running waters and 65.7 % for the standing waters. Only Berlin and Hessen for standing waters, and Sachsen-Anhalt for running waters have a slightly higher share of waterfront natural & semi-natural landscapes at the urban core compared to the metropolitan level (see Fig. 5) opposing our initial hypothesis. Regarding standing waters, the unexpected result may be attributed to the different uses of lakefronts in urban and metropolitan areas. Within the urban core, lakefronts are often designated for green urban spaces, whereas in the metropolitan region, lakes and reservoirs are predominantly used for mineral extraction or photovoltaic plants (Fig. 8). Similarly, agricultural land use defines a significant portion of the waterfront landscapes, recording an average of 22 % for the running waters and 16.6 % for the standing waters.

On the other hand, the urbanized waterfronts of residential, industrial, commercial, and institutional land use show minor differences between the metropolitan and urban levels. The FUAs within the state of Thüringen (TH) record the highest difference between the industrial land use along the waterfronts of standing waters at metropolitan (27.5 %) and urban core (4.5 %) levels (see Fig. 5). Surprisingly, in many states, the share of urbanized waterfronts is less in the urban core than at the metropolitan level. For example, the urban and industrial land use shares along the waterfronts of standing waters are, respectively, 2.3 % and 1.6 % less within the urban core than at the metropolitan level. This indicates a relatively less residential, commercial, industrial, and institutional land use pressure on the urban waterbodies compared to the metropolitan ones which again contradicts with our initial hypothesis. The reason behind this fact can be related to the integration of green urban areas (see Table A6) along the waterfronts in urban planning and design by municipalities at the respective core urban areas. The waterfronts outside the urban cores are widely used for either industrial purposes or for new touristic developments which sometimes replaces natural waterfronts (Fig. 8h).

Furthermore, the transportation infrastructure occupies the waterfront at an average of 37.1 % for the running waters, and 31.2 % for the standing waters, at the urban level (see Fig. 5, Transportation). In

contrast, at the metropolitan level, the share of waterfront transportation land use declines to an average of 2.7 % along running waters and 1.5 % along standing waters. The urban cores of Saarland (SL) have the highest share of waterfront transportation for both running waters (72 %) and standing waters (79.3 %). This is primarily due to the highway running through the city center along the River Saar, a route shaped by the region's steep topography. On the other hand, the urban cores of Sachsen-Anhalt (ST) record the lowest share of waterfront transportation surfaces for both running waters (13.8 %) and standing waters (13.4 %). It is worth highlighting that the urban core of Berlin has the lowest transportation land use along the waterfronts of standing waters (6.1 %), even though the transportation surfaces outline more than one third of the waterfront along the running waters. This is because urban lakes and ponds are primarily used for recreation within green urban areas, whereas running waters also serve as transportation routes, requiring waterfront spaces for embarkation.

At the FUA level, we found that among 91 cases, the most significant difference between metropolitan and urban waterfronts' share of agricultural use is in Münster (see Table A3). Meanwhile, Heilbronn has an agricultural waterfront that is 10 % more present in the urban core than in the metropolitan zone. On the other hand, Darmstadt records the highest difference between metropolitan and urban waterfronts for industrial use, while Siegen has 19 % more industrialized waterfronts in urban than the metropolitan area. The average natural waterfront share is 20 % higher in metropolitan areas than within urban cores aligning with our initial hypothesis. Yet, FUA cases like Friedrichshafen, Darmstadt, and Münster have a natural waterfront share at least 20 % higher within the urban core than the metropolitan region opposing our hypothesis. On the contrary, the average share of waterfront for transportation use is 29 % higher inside urban cores than at the metropolitan level. Only the FUAs of Mannheim-Ludwigshafen, Friedrichshafen, and Braunschweig-Salzgitter-Wolfsburg record higher shares of waterfront for transportation use at the metropolitan level than the urban core, with a difference of 16 %, 4 %, and 3 % respectively (Table A3).

3.3. Revealing the development level of the German urban waterfronts via the WDI index

Considering the urban core of German FUAs, transportation land use covers a substantially larger share of waterfronts than of the remaining urban area (see Fig. 6d, WDI_{it}). Furthermore, the respective urban waterfronts along running waters are more extensively altered by human land use for agriculture, industry, transportation, and residential

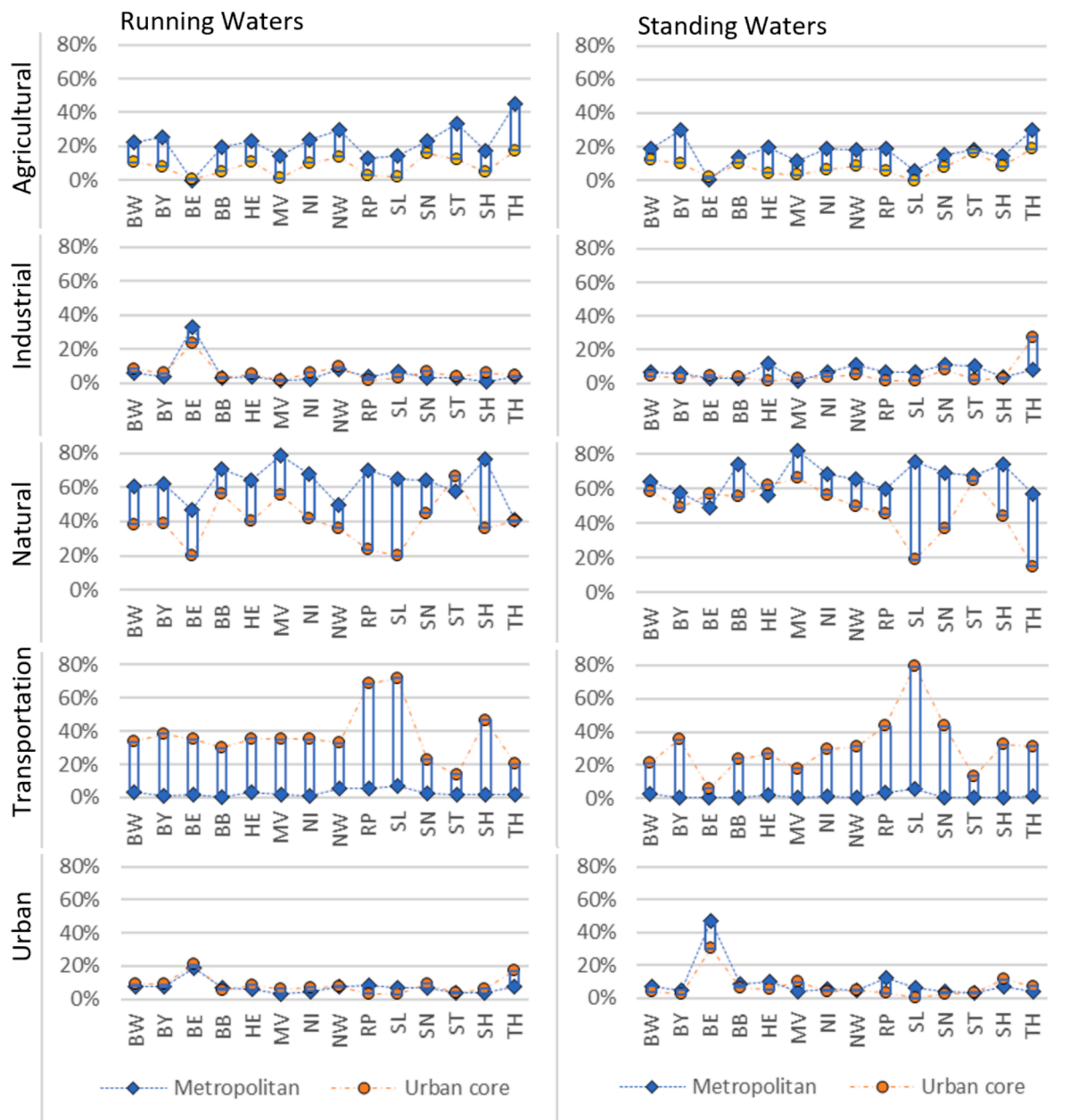


Fig. 5. Distribution of average shares of waterfront landscape type (urban, transportation, natural & semi-natural, industrial, agricultural) by spatial context (metropolitan vs. urban core) at both running (left) and standing (right) waters for FUAs within each German state; Baden-Württemberg (BW), Bayern (BY), Berlin (BE), Brandenburg (BB), Hessen (HE), Mecklenburg-Vorpommern (MV), Niedersachsen (NI), Nordrhein-Westfalen (NW), Rheinland-Pfalz (RP), Saarland (SL), Sachsen (SN), Sachsen-Anhalt (ST), Schleswig-Holstein (SH), Thüringen (TH). Bremen and Hamburg are not included since their federal state boundary coincide with the urban core boundary of UA data and provides no comparative information between urban and metropolitan levels.

purposes (WDIav) than the waterfronts of standing waters (see Fig. 6f). Only the waterfronts of standing waters of Berlin (BE) and Hamburg (HH) remarkably record a WDIav value below the threshold (1.00 as the balanced scenario in Fig. 2), indicating relatively lower artificial surfaces along the waterfronts of standing waters than the rest of their urban core area (Fig. 6f). According to our results (WDIav), waterfronts of standing waters are more artificialized than waterfronts of running waters in Thüringen (TH) and Sachsen (SN) only. At the same time, in most cases, the waterfronts of the standing waters are more often adjacent to natural surfaces compared to the waterfronts along the running waters (WDIn in Fig. 6c).

Almost all waterfronts of the standing waters (except Saarland and Thüringen) have a WDIn value above 1.00 (threshold in dashed red line), indicating relatively more natural & semi-natural surfaces along

standing waters than the respective remaining urban area. However, the case of waterfronts along the running waters is not the same among all federal states (see Fig. 6c). For example, the urban waterfronts along the running waters of Baden-Württemberg (BW), Berlin (BE), and Saarland (SL) record a WDIn value below 1.00 (threshold), indicating less relative greenery along the watercourse than the rest of the urban area. This is in line with the WDIav records, where three states' waterfront human land uses along running waters remarkably exceed the threshold (see Fig. 6f).

Furthermore, there are remarkable disparities regarding the WDI values of human land use categories like agricultural (WDIa), industrial (WDIi), transportation (WDIt), and urban (WDIu). For instance, the urban waterfronts in German federal states are consumed by urban fabric relatively less than the rest of the respective urban areas as WDIu is constantly below the threshold (Fig. 6e), except for the waterfronts

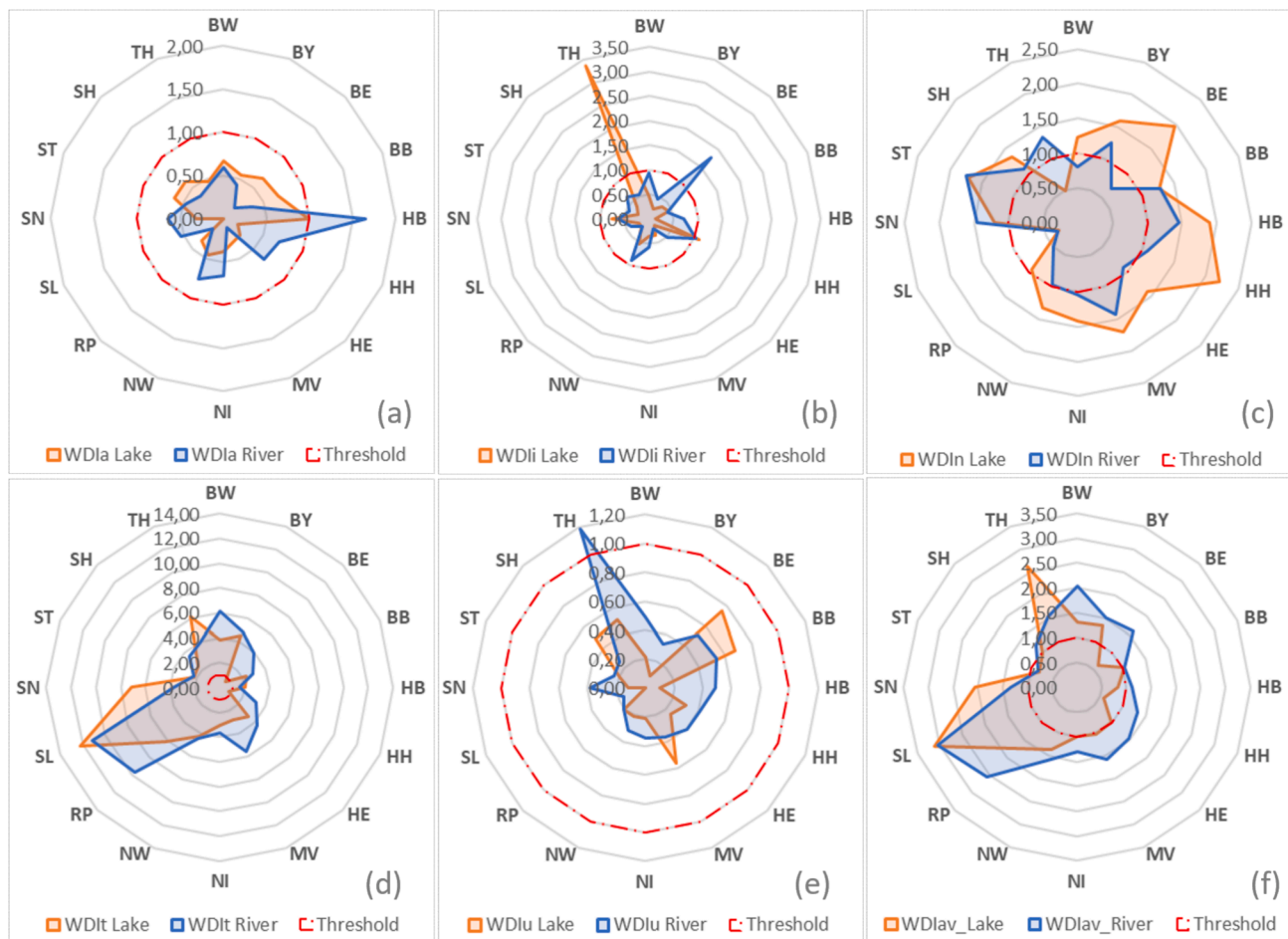


Fig. 6. Radar charts comparing lake and river WDI index values in urban core areas for (a) agricultural, (b) industrial, (c) natural & semi-natural, (d) transportation, (e) urban, and (f) average of human land use. German federal states: Baden-Württemberg (BW), Bayern (BY), Berlin (BE), Brandenburg (BB), Bremen (HB), Hamburg (HH), Hessen (HE), Mecklenburg-Vorpommern (MV), Niedersachsen (NI), Nordrhein-Westfalen (NW), Rheinland-Pfalz (RP), Saarland (SL), Sachsen (SN), Sachsen-Anhalt (ST), Schleswig-Holstein (SH), Thüringen (TH).

along running waters of Thüringen (TH). Similarly, most urban water-fronts are used relatively less for agricultural and industrial purposes than the rest of the urban area (Fig. 6). Only the water-fronts along running waters of Bremen (HB) are consumed relatively more for agricultural purposes than the rest of their urban lands, due to vast suburban areas for orchards, crops, and mixed-cultivation patterns along Weser River. On the other hand, only the water-fronts along running waters of Berlin (BE) and the water-fronts of standing waters of Thüringen (TH) are consumed more intensively for industrial use than the rest of the respective study area (Fig. 6b). Most states have more natural & semi-natural areas at the waterfront than in the rest of the respective urban areas, except the water-fronts of standing waters of Saarland (SL) and Thüringen (TH), and the water-fronts along running waters of Baden-Württemberg (BW), Berlin (BE), Hessen (HE), and Saarland (SL).

However, this is different regarding transportation land use, which is mostly above the threshold, indicating that the waterfront consumed for transportation purposes is relatively higher than the rest of the respective urban area (Fig. 6d) across German FUAs. Yet, there are cases like Berlin (BE) and Hamburg (HH) where the waterfront of standing waters for transportation use is relatively less than their respective urbanized area, which can be attributed to large standing water surfaces like Müggelsee (BE) and Außenalster (HH) lakes for recreational purposes surrounded by green urban areas. The waterfront transportation land use is higher in running waters than in standing waters, except for Saarland (SL), Sachsen (SN), and Thüringen (TH). Berlin (BE), Rheinland-Pfalz (RP), and Sachsen (SN) record the highest relative

transportation use disparity between the water-fronts of running waters (high) and the water-fronts of standing waters (low).

The differences become clearer at FUA level indexing. For example, the relative agricultural use of the water-fronts of running waters is the highest in Siegen (16.15) and lowest in Kaiserslautern, Konstanz, Heidelberg, etc. (0.00). WDli ranges between a value of 4.00 in Siegen again (high relative industrial development along the water-fronts of running waters) and several values of 0 including Aachen, Göttingen, Weimar, etc. (Table A4). The highest relative natural & semi-natural urban water-fronts along running waters (WDIn) are found in Paderborn (3.68), while the least is in Flensburg, Friedrichshafen, and Darmstadt (0.00). The relative transportation development along water-fronts of running waters (WDIt) is the highest in Göttingen (23.56) and Ruhrgebiet (23.09) and the lowest in Paderborn, Remscheid, and Friedrichshafen (0.00). The relative urban fabric development along the water-fronts of running waters (WDlu) is the highest in Bayreuth (1.92) and the lowest in ten urban centers, including Darmstadt, Osnabrück, Neumünster, etc. (0.00). We provide further detailed information about the waterfront LULC distribution according to UA nomenclature for both running waters (Table A6) and standing waters (Table A7).

Low WDlu (urban) and high WDIt (transportation) results can be attributed to the preference of people to construct new roads on the waterfront rather than new buildings, due to elevated construction and maintenance costs of waterfront building structures. At the same time, the low WDla (agriculture) and WDli (industrial) results indicate the allocation of urban water-fronts for urban transportation, recreational, or

residential areas rather than for agriculture and industrial use since the property values of urban waterfront lands are more expensive than the remaining land surfaces. Yet, we revealed outlying cases like Siegen and Wuppertal which record remarkable WDIi (industrial) values of 4.00 and 2.97 and industrial waterfront shares of 26.5 % and 35.5 % respectively (see Table A4 and Table A6). Beyond the general trends, the land use shares at the waterfronts vary strongly across the individual FUAs in Germany (see Table A6 and Table A7), potentially depending on the topography, prevailing industrial profile, and the local natural and cultural heritage of each case.

3.4. Transformation of the German urban waterfronts

Between 2012 and 2018, 846 waterfront landscape patches (totaling 235 km of waterfront line) of natural & semi-natural, agricultural, and water land cover were transformed into waterfront industrial, urban, and transportation land uses across German FUAs (see Fig. 7a). Of these, 80 km consist of natural & semi-natural surfaces (345 patches). At the national level, only 0.4 % of the inland metropolitan waterfront has changed. However, at the FUA level, there are specific cases where the waterfront change ratio approaches 2 %, which can be considered alarming counting the relatively short period of only six years (2012–2018) (Table A5). On the other hand, 89 riverfront patches,

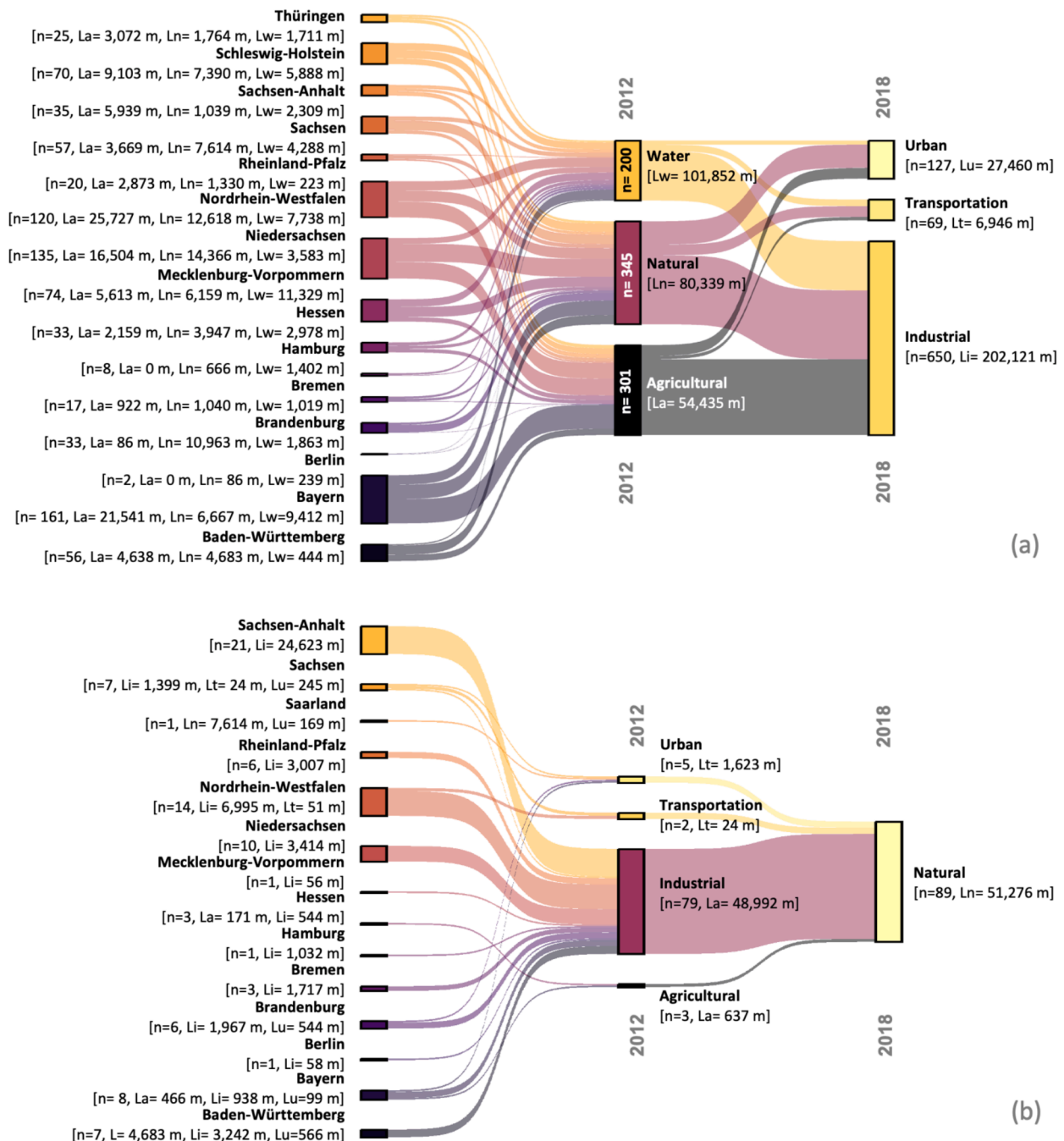


Fig. 7. Sankey charts showing (a) the transformation of water, natural & semi-natural, and agricultural waterfronts (2012) to urban, transportation, and industrial (2018) land use, and (b) the change of riverfront agricultural, urban, transportation, and industrial land use (2012) to natural & semi-natural (2018) land use at the state level. n refers to the number of waterfront patches. La, Ln, Lw, Lu, Lt, and Li refer to the length of agricultural, natural, water, urban, transportation, and industrial waterfront land use, respectively.



Fig. 8. Focal areas representing real cases of waterfront transformation between 2012 and 2018 from different German FUA like (a-c-i) Greifswald, (b) Trier, (d) Cottbus, (e) Rostock, (f) Ruhrgebiet, (g) Munich, (h) Dresden, (j) Lübeck.

spanning a total of 51 km and previously designated for agricultural, industrial, transportation, and urban use, were converted into natural & semi-natural riverfronts. (Fig. 7b). This can be considered a positive result opposing our initial hypothesis, which can be attributed to river restoration projects along rivers like the Emscher in Nordrhein-Westfalen, the Isar River in Bayern, and the Spree Canal in Berlin.

Bayern records the highest number ($n = 161$) of changed waterfront land uses, where the majority of changed land use had been agriculture ($L_a = 22$ km) in 2012, being transformed to industrial waterfronts (2018) (e.g., Fig. 8g). On the other hand, the longest natural & semi-

natural waterfront change has been experienced along the urban waterfronts of Niedersachsen (14.4 km) and Nordrhein-Westfalen (12.6 km). The least waterfront alterations within the same period were found in Berlin ($n = 2$) and Hamburg ($n = 8$). This can be recognized as an ecologically positive result, considering that the waterfronts of both cities are among the highest artificialized waterfronts in Germany (see Fig. 4). It is worth mentioning that during this period, in 17 German FUA, there has been no transformation of waterfront natural & semi-natural, water, and agricultural land cover to urban, transportation, or industrial land use (Table A5).

Overall, the net loss of natural & semi-natural waterfront land use cases exceeded the gain. Notable transformations occurred primarily between industrial and natural land uses, with a predominant shift towards industrial development. Furthermore, a significant proportion of natural & semi-natural land uses were converted into areas designated for transportation infrastructure, especially at the urban level (Fig. A3, Table A9, Table A10). Our results reveal that most newly created industrial waterfronts (2018) are transformed from agricultural and natural areas (Fig. A3). When analyzed by count (each case representing a land use planning decision) the number of 'lost' natural & semi-natural waterfronts is almost twice as high as the 'created' ones. However, when analyzed by length, the created natural & semi-natural waterfronts are about 13 % more than the lost natural ones. This is potentially correlated to the river restoration efforts during the recent decades as extensive river side agricultural lands are restored to natural & semi-natural riparian areas (as exemplified in Fig. A4).

At the site scale, each of the 846 changed waterfronts included in our results represents a real-life case of metropolitan waterfront landscape transformation. We have shortlisted ten examples from different German FUA that represent unique waterfront land use transformation types (Fig. 8). Change from water surfaces (2012) to other land uses (2018) indicates an expansion of land surfaces towards the water. In some cases, it refers to extensions of port areas (Fig. 8e), mineral extraction sites (Fig. 8c and Fig. 8f), or transportation infrastructure (Fig. 8i). Other cases show the clearing of waterfront forested areas and altering them for recreational land use (Fig. 8h) or construction replacing sparsely vegetated wildlands (Fig. 8d). Similarly, waterfront lands previously used for agricultural (Fig. 8g) and pasture purposes (Fig. 8j) have been changed into industrial or commercial land use. Furthermore, there are significant cases of altered waterfronts for photovoltaic power stations (PPS) (Fig. 8a and Fig. 8c).

4. Discussion

The WDI proved to be an effective and reproducible tool for assessing urban waterfront landscape dynamics and urbanization trends at multiple spatial scales, including urban, metropolitan, and national levels. By utilizing fine-scale LULC data with a detailed thematic classification, the WDI can be applied in various urban waterfronts along running and standing waters worldwide, including the coastal areas. Our findings indicate that WDI provides valuable insights into urban waterfront transformations, contributing to broader discussions on the evidence-based sustainable urban planning and urban waterfront management as key aspects of nature conservation and human well-being.

4.1. Waterfront urbanization dynamics and environmental implications

Urbanization is recognized as one of the primary stressors affecting freshwater biodiversity in Germany (Bierschenk et al., 2019; Mueller et al., 2020). Among urban systems, the transportation network contributes significantly to environmental degradation, introducing pollutants such as road salts, dust, and exotic species that impact both aquatic and terrestrial ecosystems (Bernhardt-Römermann et al., 2006; Trombulak & Frissell, 2000). In particular, de-icing salts, widely applied during winter in regions across the USA, Europe, Asia, and Australia, have been found to disrupt freshwater ecosystems by increasing salinity levels beyond the tolerance of sensitive species (Cañedo-Argüelles et al., 2013; Hintz & Relyea, 2019; Li et al., 2014; Shenton et al., 2022). Specifically, road salting in Germany adversely affects endangered species like freshwater mussels (*Anodonta anatina*) (Beggel & Geist, 2015) while also posing public health risks by encouraging salt-tolerant species like mosquitoes and activating heavy metals in drinking water (Schuler & Relyea, 2018a, 2018b). Our findings indicate that

transportation land use has the highest WDI value among German metropolitan waterfronts, emphasizing its pronounced impact on freshwater ecosystems.

Given these consequences, regulatory measures for road salting and transportation practices near water bodies are urgently needed (Schuler et al., 2018). We strongly believe that the regulating measures alone cannot solve this problem in the long run without reconsidering waterfront transportation land uses during urban planning processes. A joint approach integrating thoughtful urban mobility planning and urban waterfront restoration is necessary. This is crucial, especially in urban centers like Koblenz (34 %), Mainz (32 %), or Trier (39 %), where waterfront transportation land use share marks about one-third of the total waterfront line, as we showed in this study. Keeping the waterfronts free of the transportation network is essential not only for environmental and recreational but also for commercial purposes, as the waterfronts with less transportation network have a higher market value, and the willingness of citizens to pay for them is higher (Zhang, Tan, & Tang, 2015).

Our WDI results suggest that port and harbor areas remarkably elevate the rates of German urban waterfronts for transportation use. For instance, the port areas alone consume about 19.9 % of the waterfront along running waters in Hamburg, 16.0 % in Wilhelmshaven, and 11.5 % in Rostock (see Table A6). Apart from delta cities, elevated shares of port areas are present in other inland cities like Passau and Regensburg, being located along the Danube, which have been historically used for goods transportation between the North Sea and Black Sea (Mihic, Golusin, & Mihajlovic, 2011). Port infrastructure has wide-ranging economic, social, and environmental impacts, necessitating their sustainable revitalization (Strain et al., 2019). Since the 1970 s, urban waterfronts, including ports, have undergone major transformations, often resulting in planning conflicts (Avni & Teschner, 2019). Tracking these changes through tools like WDI is essential for evidence-based decision-making during river restoration processes (Geist & Hawkins, 2016).

We have shown also that most recent transformations of natural and semi-natural waterfronts across German metropolitan areas are for industrial purposes (Fig. 7). The elevated share of waterfronts change to industrial land use along standing waters is related to the extensive amount of small pits for mineral extraction purposes as well as other industrial sectors like photovoltaic power stations (PPS) (Fig. 8a, Fig. 8c, and Fig. 8f). Considering the nationwide goal of rapid transition towards renewable energies (solar and wind), the spatial impact of PPS will continue to increase in Germany. In their review on the effects of solar energy development on aquatic ecosystems in the Southwestern United States, Grippo et al. (2015) emphasized that the most effective way to minimize impacts on aquatic habitats is to avoid construction activities near both perennial and intermittent surface waters. Thus, the location of new PPS in relation to water surfaces must be planned wisely to avoid any long-term consequences of PPS on freshwater ecosystems. We argue that the new urban planning decisions, especially regarding industrial areas, must consider the vicinity of freshwater surfaces to minimize their irreversible environmental impact (Auerwald et al., 2019).

4.2. Lateral (transversal) connectivity and the ecological consequences

WDI considers the waterfront as the primary contact interface between water and land. Thus, the artificialization of waterfronts prevents interactions between aquatic and terrestrial ecosystems in the lateral direction. A reduced lateral (transversal) connectivity in lotic and floodplain systems is proven to seriously affect the ecological balances of a healthy habitat along the aquatic and terrestrial gradient (Keruzoré, Willby, & Gilvear, 2013; Pander, Mueller, & Geist, 2018). For example, the widely applied straightening of riverbanks in Germany significantly

impact the lifecycles of certain freshwater fish by altering biological community structures (Mueller, Pander, & Geist, 2011) and fish larval drift patterns (Nagel et al., 2021). The homogenization of riverbanks through straightening/ channelization and levee construction results in decoupling of river systems from their floodplains (Auerswald et al., 2019), and significantly affects the dissolved organic matter that is transported through the channel due to the reduced lateral connectivity with the floodplain (Lynch et al., 2019).

During the last decades, several river restoration projects have taken place in Germany, resulting in improved lateral connectivity and the flourishing of both the terrestrial and aquatic organism groups (Lorenz et al., 2018). Pilotto et al. (2019), after analyzing 43 projects of hydro morphological river restoration applied in Germany, found that the restoration success was positively affected by the lateral connectivity and the re-establishment of dynamic processes of the floodplain. In France, Castella et al. (2015) examined changes in invertebrate benthos following the restoration of lateral connectivity and observed an increase in the density of rheophilic taxa as well as a rise in beta-diversity. The improvements by the ongoing restoration projects align with our results, where 89 patches with a total length of 51 km have been transformed from agricultural, industrial, transportation, or urban land use to natural & semi-natural landscapes (see Table A8, Fig. A3 and Fig. A4). However, our results showed also that the other way around transformation is significantly higher within a relatively short period of six years (see Fig. 7), showing that despite promising restoration initiatives the artificialization processes of urban waterfronts is still an ongoing process across German FUA.

We highlight that the enhanced consumption of the German urban waterfronts by artificial surfaces for human land use may have snowballing effects on other environmental and ecological implications beyond the floodplain scale. At a coarser scale, an interrupted lateral connectivity at the waterfront results in transversally fragmented BGI (Hysa, 2021; Hysa, Lowe, & Geist, 2023) and may cause significant alterations in terrestrial-aquatic ecosystems connectivity, which is critical for supporting the riverine food web (Masese et al., 2022). Furthermore, the lateral connectivity between the river channel and the floodplain affects the ability of some species to complete their lifecycle and is thus essential to sustain (Wohl, Lininger, & Baron, 2017). In a recent study, Stoffers et al. (2022) reviewed 46 river restoration projects along the Rhine floodplain and concluded that freshwater fish biodiversity restoration requires connectivity at multiple spatial scales. This cross-scale interconnected network creates an effective BGI at multiple spatial levels.

In urban scale, BGI can create networks of connected aquatic and terrestrial habitats that spread throughout the landscape, which has an excellent effect on urban biodiversity (Aubrechtová, Bydžovská, & Horák, 2024) and eventually brings several vital benefits related to human well-being. Regulating ES like urban flooding mitigation, air purification, cooling effects against heat waves, and urban biodiversity enhancement are positively affected by BGI that is well-connected beyond the floodplain scale (Kuriqi & Hysa, 2022; Molné et al., 2023; Voskamp & Van de Ven, 2015). Thus, restoring BGI is crucial especially when the ES potential continues to decline across European metropolitan areas (Hysa, Löwe, & Geist, 2024). We advocate that the river restoration agendas in Germany must expand beyond the buffers of the riparian zone and the floodplain, especially within metropolitan areas. The transversal (lateral) connectivity of natural and semi-natural habitats must be secured to the closest freshwater surface, enabling an extensive network of diverse habitats that makes home to a flourishing urban biodiversity, being a non-tangible benefit significantly valued by the citizens (Viti et al., 2023). However, as our results suggest, a significant portion of German metropolitan waterfronts is extensively used

for human activities, thereby acting as a fragmenting agent between the water surface and the natural and semi-natural areas further inland.

4.3. Socio-ecological challenges and policy implications

Urban waterfronts, as unique contact zones between land and water, are areas of social-ecological conflicts, involving issues of ownership, identity, social justice, and environmental concerns (Avni & Teschner, 2019). Historically, these areas were primarily used for transportation and fishing (Martin, 2010). However, with extensive urbanization, waterfronts have become central to civic life, serving recreational, commercial, and tourism functions, and acting as cultural landmarks (Kosok, 2022; Simons, Kinjawadekar, & Kinjawadekar, 2023). As we highlighted in this study, German urban waterfronts exemplify these changes, leading to increased human pressure on freshwater ecosystems, often prioritizing social connectivity over ecological integrity (Kondolf & Pinto, 2017). A holistic, evidence-based waterfront restoration approach is essential to balance these competing interests.

Initiatives for revitalization of waterfronts are described as decision-making actions on the waterfront land or adjacent aquatic habitats that promote human well-being, including social equity, while preserving and enhancing the stock of natural capital, encompassing all types of environmental, ecological, social, and economic aids (Angradi et al., 2019). As climate change intensifies risks such as rising sea levels and increased flooding, urban waterfronts play a crucial role in adaptation strategies (Allen et al., 2019). Restorations serve as buffers against floods and incorporate nature-based solutions (NBS) to mitigate climate impacts. Successful waterfront urban planning can improve water quality, enhance biodiversity, and enhance NBS capacities against prevailing social-ecological challenges of urban areas, although implementing NBS remains challenging (Raška et al., 2022).

Waterfront projects frequently concentrate benefits in affluent areas, which can worsen social and economic inequalities. To mitigate this issue, cities should prioritize equitable access and actively involve impacted communities in the planning and decision-making (Hoover et al., 2021). By adopting a co-production approach to social-ecological systems (Pickett et al., 2022) for urban waterfront revitalization across multiple spatial scales, cities can more effectively address the complex interdependencies that influence urban resilience. Ultimately, thoughtful waterfront development employing co-production methods (Rademacher et al., 2019) safeguards cities against climate risks, fosters social justice, and cultivates vibrant, accessible public spaces for all urban residents. Therefore, urban planning and decision-making processes need to integrate ecological and socio-economic aspects, analogously to floodplain management (Serra-Llobet et al., 2022).

In Europe, significant political support exists to conserve the remaining natural landscapes and restore degraded natural habitats towards the global nature restoration targets. Policies like the Water Framework Directive, Biodiversity Strategy 2030, and the European Nature Restoration Law (NRL), approved on 18 August 2024, demonstrate high-level commitment (Hering et al., 2023). The European NRL is part of the European Union's (EU) broader commitment to address biodiversity loss and combat climate change, contributing to the goals of the European Green Deal (Hermoso et al., 2022). Nevertheless, the European NRL gives freedom and, at the same time, responsibility to each EU member state for developing national implementation plans to ensure target achievement. Thus, Germany is expected to develop strategies and tools to restore urban natural systems. Examples of the political will in support towards revitalization of German federal waterways are reviewed by Steege et al. (2022), exemplifying tangible legislative improvements and respective river restoration programmes and projects starting from 2004. However, more comprehensive and

straightforward tools like WDI must be developed. We advocate that tools and methods such as WDI can be used to monitor urban waterfronts at both national and metropolitan levels over the long term. Additionally, WDI helps identify metropolitan areas with significant waterfront urban development and pinpoint hotspots that require urgent attention.

Our results imply that similar protective regulations and river restoration agendas are the reason behind 17 German FUA with no transformation of natural & semi-natural, water, and agricultural land use to urban, transportation, or industrial use. Additionally, some waterfronts have been successfully renaturalized (see Table A5). For instance, our method is useful to track the effects of these river restoration efforts on waterfront development in Germany as shown in the case of the LIFE + project “My favourite river” Zugwiesen (see Fig. A4). In this study, we were limited to using UA data from 2012 and 2018 due to constraints in data availability. We must recognize the significance of promptly integrating the latest data as it becomes available. Tracking changes in the WDI through upcoming new data is vital for monitoring the success of more recent river restoration initiatives, such as the Integrated EU-LIFE project “Living Lahn” (2015–2025) and the German “Blue Belt,” which commenced operations in 2019 (Steege et al., 2022) and will transform waterfronts from human land use to natural & semi-natural land cover.

The proposed WDI method provides an effective tool for evaluating the enhancement or decline of natural & semi-natural urban waterfronts. Our approach can stimulate future research on the dynamics of waterfront changes in metropolitan areas within Europe and non-European regions, wherever periodic LULC change data are accessible. In Germany, our results suggest that human land use pressure along metropolitan waterfronts is rising in several functional urban areas, including Flensburg, Darmstadt, and the Ruhrgebiet, at concerning rates of approximately 2 % over a relatively brief six-year period. Urban planning efforts in these regions should therefore incorporate offsetting policies that aim to compensate for habitat loss by strategically creating, restoring, or protecting similar habitats in alternative locations to mitigate this issue. We advocate for implementing enforced urban planning policies to curb the expansion of the extensive human land use along the waterfront. This critical step will improve connectivity between blue-green infrastructure in German metropolitan areas, ultimately offering more significant benefits for the urban social-ecological systems and human well-being.

5. Conclusion

This study introduced a simple, rapid, and effective method, the WDI, for analyzing metropolitan waterfronts' land use and land cover dynamics at urban, metropolitan, and national level. We validated WDI in the German functional urban areas (FUA), demonstrating that it is applicable to various available LULC data, regardless of geographical

position of the study area. Our results showed that at the national level, German metropolitan waterfronts are still dominated by natural & semi-natural surfaces, led by the waterfronts of standing waters. However, at the FUA level, we highlighted extreme cases like Mainz and Regensburg, where the natural & semi-natural waterfront share is as low as 8 % and 15 %, respectively. Even though, the national level average of waterfront change ratio (2012–2018) from natural & semi-natural, agricultural and water surfaces to urban, industrial, and transportation land use is low (0.4 %), we could identify outlying FUA cases where this change is alarming at about 2 % (e.g., Flensburg). We also found that a very large share of waterfronts is dedicated to transportation land use in many FUAs, and that this share is higher than the relative area covered by transportation land use within each study area. Our findings have remarkable social-ecological implications with regard to the human well-being and the terrestrial and aquatic ecosystems that tightly depend on the freshwater waterfronts. We advocate for sensitive urban planning and landscape management of the freshwater waterfronts in Germany and beyond, as altering the natural waterfronts will have partly irreversible consequences on the respective ecosystems and degrade their servicing capacities. Integrating such information in ongoing and future restoration projects can provide multiple benefits including human well-being in urban areas and urban biodiversity conservation alike.

CRedit authorship contribution statement

Artan Hysa: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Roland Löwe:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Formal analysis. **Juergen Geist:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Formal analysis.

Declaration of competing interest

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

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Appendix

Table A1

Basic statistics at functional urban level based on UA raw data of 2018, at urban and metropolitan scale.

Federal State	id	FUA	Area Urban [ha]	Area Metro [ha]	Area share %	Pop. Urban	Pop. Metro	Water Urban [ha]	Water Metro [ha]	Waterfront [km]
Baden-Württemberg	1	Freiburg im Bre.	15,431	221,118	7.0	232,816	656,838	117	1,908	488
	2	Friedrichshafen	7,011	66,578	10.5	57,261	207,597	11	354	173
	3	Heidelberg	10,926	116,985	9.3	163,735	708,548	194	1,223	239
	4	Heilbronn	10,053	119,950	8.4	125,884	464,686	168	692	305
	5	Karlsruhe	17,407	125,841	13.8	313,782	754,348	808	2,955	647
	6	Konstanz	5,406	81,776	6.6	79,355	275,404	292	1,085	218
	7	Offenburg	7,786	185,963	4.2	59,636	425,924	110	2,428	682

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Table A1 (continued)

Federal State	id	FUA	Area Urban [ha]	Area Metro [ha]	Area share %	Pop. Urban	Pop. Metro	Water Urban [ha]	Water Metro [ha]	Waterfront [km]
Bayern	8	Pforzheim	9,846	67,162	14.7	125,706	324,314	43	141	109
	9	Reutlingen	8,614	109,228	7.9	115,380	284,792	25	47	22
	10	Stuttgart	20,994	365,422	5.7	637,195	2,779,413	186	1,304	609
	11	Tübingen	10,793	51,963	20.8	90,751	225,934	70	239	108
	12	Ulm	11,939	199,240	6.0	129,918	492,773	222	1,963	615
	13	Villingen-Schw.	16,504	102,595	16.1	85,180	211,462	24	274	142
	14	Aschaffenburg	6,197	147,618	4.2	72,035	373,254	149	1,371	285
	15	Augsburg	14,645	199,776	7.3	296,831	674,731	284	1,350	490
	16	Bamberg	5,495	122,206	4.5	78,279	223,858	116	1,224	352
	17	Bayreuth	6,699	199,884	3.4	74,459	249,996	15	395	201
	18	Ingolstadt	13,354	284,799	4.7	136,907	488,579	495	3,466	921
	19	Kempten (Allg.)	6,320	159,170	4.0	69,137	222,911	92	1,505	432
	20	Landshut	6,614	141,354	4.7	74,198	228,575	140	848	259
	21	München	31,128	549,935	5.7	1,461,627	2,884,482	297	16,333	1,486
	22	Nürnberg	18,409	293,431	6.3	520,767	1,340,152	260	3,864	1,410
	23	Passau	7,027	160,037	4.4	51,538	242,758	484	2,477	488
	24	Regensburg	7,967	253,817	3.1	153,548	464,036	238	3,108	731
	25	Rosenheim	3,642	147,718	2.5	64,136	321,611	71	4,029	771
	26	Schweinfurt	3,545	201,466	1.8	54,436	271,896	128	881	321
	27	Würzburg	8,777	306,067	2.9	129,199	505,451	92	2,297	611
Berlin	28	Berlin	89,185	1,748,435	5.1	3,648,161	5,258,960	8,433	45,279	6,275
Brandenburg	29	Brandenburg(H)	22,936	1,748,435	1.3	72,216	72,216	4,539	4,539	463
Bremen	30	Cottbus	16,514	182,185	9.1	101,797	216,166	174	4,248	865
	31	Frankfurt (Oder)	14,782	1,748,435	0.8	60,081	60,081	529	529	76
	32	Bremen	32,539	589,487	5.5	588,040	1,274,517	3,247	10,872	1,896
Hamburg	33	Bremerhaven	7,719	214,514	3.6	115,656	309,155	1,593	9,212	1,659
	34	Hamburg	73,926	734,458	10.1	1,864,637	3,306,469	4,512	28,707	2,921
Hessen	35	Darmstadt	12,335	78,150	15.8	160,354	454,276	30	328	79
Mecklenburg-Vorpommern	36	Frankfurt am M.	24,831	430,298	5.8	751,949	2,695,696	418	3,580	767
	37	Fulda	10,368	138,210	7.5	72,245	221,571	29	67	62
	38	Gießen	7,280	85,537	8.5	88,748	266,445	67	489	109
	39	Kassel	10,454	139,966	7.5	205,040	437,177	336	688	223
	40	Marburg	12,439	126,207	9.9	76,898	246,639	48	366	208
	41	Wetzlar	7,608	106,516	7.1	53,162	253,653	112	428	226
	42	Wiesbaden	20,381	101,579	20.1	280,818	468,379	719	1,504	165
	43	Greifswald	5,099	350,118	1.5	59,659	222,643	266	17,704	2,559
Niedersachsen	44	Neubrandenb.	8,571	583,902	1.5	64,881	273,092	2,266	46,540	2,970
	45	Rostock	16,908	361,850	4.7	210,202	420,980	589	11,438	1,538
	46	Schwerin	12,993	489,830	2.7	95,773	307,995	3,584	16,674	1,489
	47	Stralsund	3,938	338,768	1.2	57,670	219,663	156	30,929	3,095
	48	Braunschweig-Salz.-Wol.		412,786	NA		996,689		4,007	1,067
	49	Celle	17,640	154,995	11.4	69,978	178,730	188	1,726	518
	50	Göttingen	11,675	238,866	4.9	120,169	387,419	13	808	324
	51	Hannover	20,409	297,358	6.9	539,820	1,310,744	501	7,443	1,024
Nordrhein-Westfalen	52	Hildesheim	9,305	120,748	7.7	102,286	276,972	63	1,019	340
	53	Lüneburg	7,109	132,695	5.4	77,270	183,755	88	2,238	589
	54	Oldenburg	10,367	189,848	5.5	169,060	421,992	342	2,464	580
	55	Osnabrück	12,016	224,156	5.4	167,143	521,841	80	1,817	416
	56	Wilhelmshaven	10,754	74,005	14.5	76,878	174,208	649	3,558	744
	57	Aachen	16,400	70,750	23.2	247,720	554,187	14	575	115
	58	Bielefeld	25,909		NA	332,227	332,227	51	51	17
	59	Bocholt		142,097	NA		370,201		644	245
	60	Bonn	14,186	129,379	11.0	331,107	924,687	674	1,865	366
	61	Düren		93,946	NA		263,273		988	267
	62	Düsseldorf	21,775	184,217	11.8	620,732	1,550,838	1,239	3,252	335
	63	Iserlohn	12,532	106,089	11.8	93,905	415,776	55	753	218
	64	Köln	40,668	162,632	25.0	1,086,152	1,993,197	1,883	3,566	627
	65	Krefeld	13,678	184,217	7.4	227,585	227,587	352	362	68
	66	Mönchengladb.	17,093	184,217	9.3	260,816	260,816	24	24	12
Rheinland-Pfalz	67	Münster	30,352	141,632	21.4	313,621	533,324	686	1,062	350
	68	Paderborn	17,974	124,738	14.4	149,537	305,231	352	927	121
	69	Remscheid	7,406	184,217	4.0	111,106	111,106	72	72	19
	70	Ruhrgebiet		443,909	NA		5,113,576	0	11,259	2,296
	71	Siegen	11,502	177,544	6.5	103,679	406,637	14	318	248
	72	Solingen	8,940	184,217	4.9	161,888	161,888	68	68	44
	73	Wuppertal	16,848	184,217	9.1	351,179	351,179	123	123	73
	74	Kaiserslautern	14,049	135,400	10.4	99,950	275,418	32	269	225
	75	Koblenz	10,602	92,262	11.5	115,327	329,171	530	1,608	215
	76	Mainz	9,766	70,320	13.9	213,388	420,275	577	1,827	215
	77	Mannheim-Ludwigshafen		204,483	NA		1,183,629		3,876	550
	78	Trier	11,612	121,068	9.6	110,897	259,578	328	1,518	370
Saarland	79	Saarbrücken	16,887	153,761	11.0	181,517	802,796	110	1,044	430
Sachsen	80	Chemnitz	22,137	117,094	18.9	245,777	245,777	54	54	45
	81	Dresden	32,800	583,338	5.6	555,716	1,341,896	556	15,331	1,819

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Table A1 (continued)

Federal State	id	FUA	Area Urban [ha]	Area Metro [ha]	Area share %	Pop. Urban	Pop. Metro	Water Urban [ha]	Water Metro [ha]	Waterfront [km]
Sachsen-Anhalt	82	Görlitz	6,748	211,118	3.2	56,354	255,930	705	6,842	999
	83	Leipzig	29,874	397,600	7.5	584,477	1,034,643	826	11,474	1,468
	84	Plauen	10,154	141,233	7.2	65,446	229,381	58	1,054	201
	85	Zwickau	10,383	117,094	8.9	91,425	319,237	81	483	221
	86	Dessau-Roßlau	24,625		NA	81,913	81,913	601	601	134
Schleswig-Holstein	87	Halle a.d. Salle	13,576	157,611	8.6	239,952	425,184	410	4,391	524
	88	Magdeburg	20,058	416,932	4.8	239,393	502,755	1,003	5,160	1,224
	89	Flensburg	4,921	205,331	2.4	89,835	283,843	17	4,103	904
Thüringen	90	Kiel	11,225	353,997	3.2	253,973	645,777	278	20,555	1,905
	91	Lübeck	21,186	162,162	13.1	222,058	414,358	4,885	9,250	1,061
	92	Neumünster	7,143	353,997	2.0	79,201	79,202	261	263	18
	93	Erfurt	27,103	285,671	9.5	213,388	527,675	342	1,683	353
	94	Gera	15,225	99,868	15.2	95,408	194,137	67	919	247
	95	Jena	11,485	93,037	12.3	109,695	194,039	56	267	168
	96	Weimar	8,441	88,879	9.5	64,859	146,404	5	174	37

Table A2

Distribution of main reclassified land use categories within German FUA based on UA raw data of 2018.

	Row Labels	Agricultural	Industrial	Natural	Transport.	Urban
1	Aachen	18,783	7420	58,137	3634	8360
2	Aschaffenburg	10,715	22,259	170,151	12,742	41,049
3	Augsburg	138,964	23,583	275,066	26,407	27,869
4	Bamberg	102,186	22,959	195,393	10,377	23,962
5	Bayreuth	29,606	3,957	143,500	7,282	15,254
6	Berlin	913,068	235,451	3,833,448	313,907	615,144
7	Bielefeld	3,077	470	10,948	1,934	847
8	Bonn	74,752	12,898	221,324	25,330	21,306
9	Brandenburg an der Havel	9,216	13,199	234,528	12,703	43,297
10	Braunschweig-Salzgitter-Wolfs.	161,450	69,616	739,224	37,915	62,653
11	Bremen	375,094	42,849	1,046,414	157,261	67,808
12	Bremerhaven	227,117	26,654	818,689	65,899	53,137
13	Celle	72,515	13,778	384,340	6,147	17,370
14	Chemnitz	3,539	8,254	20,814	5,345	8,584
15	Cottbus	20,303	33,427	489,564	12,933	15,914
16	Darmstadt	29,336	10,490	25,342	6,630	3,532
17	Dessau-Roßlau	6,780	4,981	105,688	2,154	6,847
18	Dresden	245,692	194,503	1,038,347	99,082	53,430
19	Düsseldorf	93,889	37,770	154,116	30,829	13,613
20	Erfurt	144,143	44,323	120,712	26,407	13,529
21	Flensburg	94,601	28,779	316,625	10,605	18,997
22	Frankfurt (Oder)	4,794	530	45,092	1,194	1,985
23	Frankfurt am Main	160,558	53,168	334,012	108,928	59,101
24	Freiburg im Breisgau	68,112	30,737	275,585	24,628	30,718
25	Friedrichshafen	46,979	5,483	76,954	6,471	13,111
26	Fulda	47	721	57,137	810	3,772
27	Gera	31,070	8,308	168,208	18,250	22,045
28	Gießen	10,007	4,554	72,899	4,056	12,219
29	Görlitz	65,357	30,128	637,639	25,352	31,339
30	Göttingen	69,619	9,169	194,754	9,227	15,156
31	Greifswald	84,413	13,744	880,500	29,006	28,844
32	Halle an der Saale	129,090	35,878	297,512	24,200	22,718
33	Hamburg	379,294	163,833	1,459,549	268,322	206,866
34	Hannover	185,085	68,448	573,726	82,241	74,946
35	Heidelberg	17,291	6976	138,131	22,178	24,841
36	Heilbronn	41,528	23,396	198,036	21,365	20,986
37	Hildesheim	128,591	19,927	153,038	18,819	19,149
38	Ingolstadt	398,815	56,923	366,575	49,929	55,819
39	Iserlohn	17,387	23,089	120,901	29,084	7,914
40	Jena	56,419	11,532	29,877	9,456	18,044
41	Kaiserslautern	7,237	7,154	173,853	20,152	18,763
42	Karlsruhe	146,601	27,074	328,499	66,352	30,049
43	Kassel	30,910	3,847	138,874	13,995	15,818
44	Kempten (Allgäu)	7176	18,165	374,297	12,334	20,348
45	Kiel	176,107	39,931	1,016,936	88,124	80,956
46	Koblenz	42,026	9,062	51,894	61,322	17,609

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Table A2 (continued)

	Row Labels	Agricultural	Industrial	Natural	Transport.	Urban
47	Köln	112,506	50,725	340,511	61,115	48,547
48	Konstanz	26,980	7,405	84,550	12,246	22,520
49	Krefeld	7,610	2,801	34,472	11,813	4,825
50	Landshut	68,698	10,007	152,353	11,124	17,926
51	Leipzig	392,180	124,073	717,341	78,511	71,873
52	Lübeck	68,127	13,721	421,171	13,164	45,699
53	Lüneburg	100,183	10,897	377,347	15,403	21,247
54	Magdeburg	266,739	56,043	695,484	53,913	36,965
55	Mainz	19,995	4,738	55,558	43,645	14,497
56	Mannheim-Ludwigshafen	85,210	31,372	237,389	79,731	45,654
57	Marburg	65,423	11,065	115,297	9,079	7,879
58	Mönchengladbach	400	1,007	7,018	1,564	369
59	München	500,681	72,910	634,037	161,734	94,993
60	Münster	168,883	22,349	118,302	24,994	29,997
61	Neubrandenburg	159,716	25,849	2,037,558	36,232	115,306
62	Neumünster	2,198	1,172	9,270	711	1,694
63	Nürnberg	288,670	49,256	870,099	99,389	96,310
64	Offenburg	118,786	26,797	429,212	31,532	23,021
65	Oldenburg (Oldenburg)	76,459	23,019	358,362	61,035	33,503
66	Osnabrück	107,343	27,700	215,952	50,654	17,040
67	Paderborn	39,523	8,665	52,536	8,385	3,917
68	Passau	73,640	17,269	222,589	76,768	21,237
69	Pforzheim	4,178	8,034	78,155	5,164	13,731
70	Plauen	10,389	13,416	133,806	23,267	19,682
71	Regensburg	249,995	30,486	345,411	62,812	42,723
72	Remscheid	175	0	10,994	2,029	56
73	Reutlingen	3,619	1,613	16,897	587	388
74	Rosenheim	12,615	30,630	585,685	28,800	32,463
75	Rostock	244,165	12,769	859,318	22,997	33,557
76	Ruhrgebiet	472,515	222,894	1,082,604	278,144	137,681
77	Saarbrücken	37,020	23,488	232,364	99,146	25,518
78	Schweinfurt	56,501	11,498	228,371	10,433	11,442
79	Schwerin	321,303	46,354	762,949	70,788	74,505
80	Siegen	5,088	18,936	198,634	14,355	13,335
81	Solingen	1,894	1,721	35,612	1,138	3,992
82	Stralsund	57,456	10,622	658,082	14,584	17,765
83	Stuttgart	86,104	94,850	271,067	91,271	71,691
84	Trier	21,278	6,645	148,842	122,150	15,311
85	Tübingen	28,127	10,581	55,006	3,655	12,818
86	Ulm	202,625	24,039	329,166	16,871	34,700
87	Villingen-Schwenningen	42,900	4,235	80,813	5,606	9,280
88	Weimar	18,823	390	12,395	3,033	2,038
89	Wetzlar	10,377	10,554	179,446	12,322	11,844
90	Wiesbaden	7,171	5,669	55,680	33,210	10,037
91	Wilhelmshaven	70,537	19,710	351,861	39,445	31,006
92	Wuppertal	1,621	23,658	24,952	11,347	8,162
93	Würzburg	103,642	42,419	365,906	34,442	49,710
94	Zwickau	21,278	12,105	151,745	9,736	24,041

Table A3

Distribution of main reclassified waterfront land use categories within German FUA.

FUA	Agricultural Urban	Industrial Urban	Natural & semi-natural Urban	Transportation Urban	Urban Urban	Agricultural Metro	Industrial Metro	Natural & semi-natural Metro	Transportation Metro	Urban Metro	Agricultural (Metro-Urban)	Industrial (Metro- Urban)	Natural (Metro- Urban)	Transportation (Metro-Urban)	Urban (Metro- Urban)
Aachen	4	2	38	42	12	20	8	62	0	8	16	6	24	-42	-4
Aschaffenburg	0	9	50	20	20	4	8	68	2	15	4	-1	18	-18	-5
Augsburg	2	4	65	18	8	37	4	52	0	4	35	0	-13	-18	-4
Bamberg	14	7	44	14	19	31	6	57	0	4	17	-1	13	-14	-15
Bayreuth	3	3	42	25	23	16	1	76	0	5	13	-2	34	-25	-18
Berlin	6	9	32	32	19	16	3	70	0	8	10	-6	38	-32	-11
Bielefeld	17	2	63	11	4										
Bonn	4	2	54	30	7	24	3	63	2	5	20	1	9	-28	-2
Brandenburg a.d. H	2	4	74	4	13										
Braunschweig-Salzgitter						15	6	69	3	5					
Bremen	6	4	51	30	6	28	1	66	0	3	22	-3	15	-30	-3
Bremerhaven	8	4	46	35	5	20	1	72	0	4	12	-3	26	-35	-1
Celle	13	3	72	4	5	15	2	79	0	2	2	-1	7	-4	-3
Chemnitz	7	17	44	11	18										
Cottbus	2	9	75	8	3	3	4	88	0	2	1	-5	13	-8	-1
Darmstadt	6	0	51	40	1	45	16	30	2	5	39	16	-21	-38	4
Dessau-Roßlau	5	3	83	1	5										
Dresden	19	3	25	48	3	14	12	67	1	3	-5	9	42	-47	0
Düsseldorf	20	3	49	22	3	33	16	44	0	4	13	13	-5	-22	1
Erfurt	12	22	32	27	5	52	9	35	0	3	40	-13	3	-27	-2
Flensburg	6	0	16	51	25	20	6	69	0	3	14	6	53	-51	-22
Frankfurt (Oder)	8	0	84	2	3										
Frankfurt am Main	8	5	25	52	7	27	8	53	2	8	19	3	28	-50	1
Freiburg im Brei.	6	2	40	35	15	17	7	67	1	5	11	5	27	-34	-10
Friedrichshafen	17	2	80	0	0	31	3	50	4	9	14	1	-30	4	9
Fulda	0	0	91	1	6	0	1	91	0	6	0	1	0	-1	0
Gera	16	4	29	26	23	11	3	76	3	5	-5	-1	47	-23	-18
Gießen	4	6	68	5	15	13	3	71	2	9	9	-3	3	-3	-6
Görlitz	9	3	60	24	1	8	3	82	1	4	-1	0	22	-23	3
Göttingen	3	1	27	65	1	24	3	66	0	5	21	2	39	-65	4
Greifswald	1	3	76	8	10	8	1	85	2	2	7	-2	9	-6	-8
Halle an der Saale	19	3	57	14	5	27	8	58	0	4	8	5	1	-14	-1
Hamburg	5	12	36	33	12	19	4	68	1	6	14	-8	32	-32	-6
Hannover	6	11	37	34	10	22	5	64	0	6	16	-6	27	-34	-4
Heidelberg	0	3	50	38	7	10	3	69	3	13	10	0	19	-35	6
Heilbronn	21	16	19	31	10	11	5	76	0	5	-10	-11	57	-31	-5
Hildesheim	23	3	42	22	8	40	6	45	2	5	17	3	3	-20	-3
Ingolstadt	21	3	44	26	4	47	6	38	0	6	26	3	-6	-26	2
Iserlohn	12	5	34	45	2	7	13	68	5	4	-5	8	34	-40	2
Jena	32	5	26	16	17	50	10	22	3	12	18	5	-4	-13	-5
Kaiserslautern	0	2	58	34	4	3	3	78	6	8	3	1	20	-28	4
Karlsruhe	11	3	50	29	6	32	5	57	0	4	21	2	7	-29	-2
Kassel	3	3	56	23	12	19	1	72	0	6	16	-2	16	-23	-6
Kempten (Allgäu)	1	10	62	22	4	1	3	89	0	4	0	-7	27	-22	0
Kiel	3	3	35	54	2	13	2	76	0	6	10	-1	41	-54	4
Koblenz	3	2	18	67	8	40	6	37	3	11	37	4	19	-64	3
Köln	13	11	43	24	7	20	6	62	2	7	7	-5	19	-22	0
Konstanz	5	8	45	32	7	20	4	57	2	16	15	-4	12	-30	9
Krefeld	12	4	56	19	7										
Landshut	18	2	58	13	8	29	4	58	0	6	11	2	0	-13	-2
Leipzig	12	9	36	31	9	31	8	54	0	4	19	-1	18	-31	-5

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Table A3 (continued)

FUA	Agricultural Urban	Industrial Urban	Natural & semi-natural Urban	Transportation Urban	Urban Urban	Agricultural Metro	Industrial Metro	Natural & semi-natural Metro	Transportation Metro	Urban Metro	Agricultural (Metro-Urban)	Industrial (Metro-Urban)	Natural (Metro-Urban)	Transportation (Metro-Urban)	Urban (Metro-Urban)
Lübeck	10	8	55	9	16	12	0	79	0	6	2	−8	24	−9	−10
Lüneburg	9	9	52	20	7	20	1	74	0	3	11	−8	22	−20	−4
Magdeburg	14	2	57	22	2	26	5	63	0	3	12	3	6	−22	1
Mainz	7	2	11	73	4	18	3	54	10	13	11	1	43	−63	9
Mannheim-Ludw.						17	6	49	16	9	17	6	49	16	9
Marburg	36	3	43	11	4	29	5	60	1	3	−7	2	17	−10	−1
Mönchengladbach	3	9	67	15	3										
München	4	3	25	64	2	39	5	46	0	7	35	2	21	−64	5
Münster	20	8	44	15	11	66	4	23	0	5	46	−4	−21	−15	−6
Neubrandenburg	0	2	68	25	3	7	1	86	0	4	7	−1	18	−25	1
Neumünster	14	7	61	4	11										
Nürnberg	5	4	44	38	7	22	3	64	1	6	17	−1	20	−37	−1
Offenburg	23	4	53	18	1	18	4	70	3	3	−5	0	17	−15	2
Oldenburg (Olde.)	3	3	45	42	4	17	4	71	0	6	14	1	26	−42	2
Osnabrück	5	9	17	65	2	29	6	58	0	4	24	−3	41	−65	2
Paderborn	19	6	52	15	5	46	8	41	1	1	27	2	−11	−14	−4
Passau	0	4	22	67	5	23	4	65	1	4	23	0	43	−66	−1
Pforzheim	0	9	59	10	19	6	5	79	0	7	6	−4	20	−10	−12
Plauen	3	12	47	30	5	5	4	73	5	11	2	−8	26	−25	6
Regensburg	19	4	20	52	4	36	4	51	1	6	17	0	31	−51	2
Remscheid	1	0	82	15	0										
Reutlingen	14	6	74	2	1	26	10	63	0	0	12	4	−11	−2	−1
Rosenheim	1	3	66	25	2	1	4	87	1	5	0	1	21	−24	3
Rostock	4	1	80	10	3	22	1	72	1	2	18	0	−8	−9	−1
Ruhrgebiet	0	0	2	95	0	23	11	53	5	6	23	11	51	−90	6
Saarbrücken	1	3	20	72	2	11	6	68	6	7	10	3	48	−66	5
Schweinfurt	9	8	55	24	2	18	2	74	0	3	9	−6	19	−24	1
Schwerin	3	3	44	37	12	28	3	62	0	4	25	0	18	−37	−8
Siegen	0	24	29	30	14	2	5	85	2	4	2	−19	56	−28	−10
Solingen	4	3	80	2	8										
Stralsund	6	4	46	28	14	7	1	88	0	1	1	−3	42	−28	−13
Stuttgart	0	13	15	65	4	17	15	51	1	13	17	2	36	−64	9
Trier	3	1	25	67	1	11	2	72	4	8	8	1	47	−63	7
Tübingen	27	11	45	6	10	23	7	54	0	13	−4	−4	9	−6	3
Ulm	10	5	61	16	4	36	3	52	0	5	26	−2	−9	−16	1
Villingen-Schwen.	19	5	32	29	13	31	2	59	0	5	12	−3	27	−29	−8
Weimar	41	0	20	38	0	52	1	35	5	6	11	1	15	−33	6
Wetzlar	4	3	68	16	7	4	5	84	1	4	0	2	16	−15	−3
Wiesbaden	6	6	32	45	7	5	1	82	0	10	−1	−5	50	−45	3
Wilhelmshaven	3	4	65	22	4	18	3	70	1	6	15	−1	5	−21	2
Wuppertal	2	33	35	16	11										
Würzburg	9	11	20	50	7	18	6	65	1	8	9	−5	45	−49	1
Zwickau	10	6	71	5	6	9	5	68	4	12	−1	−1	−3	−1	6

Table A4

Urban waterfront development index values for different land use categories for lake and river at FUA level.

FUA	WDIa_Lake	WDIi_Lake	WDIn_Lake	WDIt_Lake	WDIu_Lake	WDIa_River	WDIi_River	WDIn_River	WDIt_River	WDIu_River	WDIav_Lake	WDIav_River
Aachen	0.00	0.36	0.99	6.33	0.71	0.00	0.00	0.46	15.64	0.00	1.85	3.91
Aschaffenburg	0.00	0.00	0.77	0.75	2.70	0.00	0.82	0.91	3.64	0.83	0.86	1.32
Augsburg	0.40	0.09	1.99	2.55	0.03	0.00	0.52	1.68	3.02	0.55	0.77	1.02
Bamberg	0.00	0.00	1.53	5.67	0.00	1.52	0.57	1.03	1.62	0.83	1.42	1.13
Bayreuth	0.15	0.21	1.52	5.20	0.03	0.36	0.58	0.44	4.85	1.92	1.40	1.93
Berlin	2.26	0.29	1.43	1.42	0.59	0.87	1.36	0.52	3.38	0.40	1.14	1.50
Bielefeld	1.30	0.39	1.44	1.33	0.16	0.94	0.00	1.07	3.95	0.60	0.79	1.37
Bonn	0.38	0.52	2.09	0.36	0.00	0.65	0.09	1.13	4.84	0.30	0.32	1.47
Brandenburg a.d Havel	0.21	0.38	1.27	1.20	0.91	0.05	0.90	1.20	1.80	1.01	0.68	0.94
Bremen	1.42	0.07	1.31	2.29	0.10	1.80	0.60	1.31	1.35	0.34	0.97	1.02
Bremerhaven	3.16	0.29	1.46	1.39	0.02	2.34	0.49	0.84	2.88	0.26	1.21	1.49
Celle	0.00	0.00	1.64	1.24	0.25	1.00	0.66	1.10	1.47	0.64	0.37	0.95
Chemnitz	0.28	0.94	2.48	0.00	0.10	0.27	1.93	1.14	2.89	0.85	0.33	1.48
Cottbus	0.08	1.15	0.86	6.10	0.33	0.30	0.17	1.79	0.59	0.22	1.92	0.32
Darmstadt	0.53	0.09	0.97	5.92	0.10	0.00	0.00	0.00	16.37	0.00	1.66	4.09
Dessau-Roßlau	0.52	0.96	1.25	0.88	0.61	0.18	0.52	1.44	0.63	0.44	0.74	0.44
Dresden	0.57	0.20	0.48	8.77	0.13	1.14	0.40	0.77	5.46	0.14	2.42	1.79
Düsseldorf	0.65	0.15	2.40	1.51	0.16	2.02	0.41	1.52	1.58	0.10	0.62	1.03
Erfurt	0.30	3.84	0.77	4.95	0.28	0.15	0.17	3.01	3.22	0.79	2.34	1.08
Flensburg	0.00	0.00	0.29	11.03	0.00	0.70	0.00	0.00	5.33	1.32	2.76	1.84
Frankfurt (Oder)	0.14	0.00	2.25	0.57	0.06	0.34	0.44	1.83	0.77	0.63	0.19	0.55
Frankfurt am Main	0.02	0.13	1.10	4.01	0.21	0.60	0.51	1.03	3.01	0.30	1.09	1.11
Freiburg im Breisgau	0.14	0.19	1.18	2.19	1.16	0.58	0.27	0.53	8.54	0.98	0.92	2.59
Friedrichshafen	0.84	0.23	1.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00
Fulda	0.00	0.00	1.57	0.00	0.00	0.00	0.14	1.42	0.45	0.42	0.00	0.25
Gera	0.55	0.00	0.90	9.08	0.48	0.36	0.99	0.86	5.12	1.90	2.53	2.09
Gießen	0.00	0.11	1.86	0.08	0.17	0.70	0.84	0.79	1.76	1.71	0.09	1.25
Görlitz	0.25	0.49	1.59	8.36	0.02	0.30	0.30	2.51	1.39	0.19	2.28	0.54
Göttingen	0.60	0.51	1.29	3.13	0.36	0.00	0.00	0.22	23.56	0.00	1.15	5.89
Greifswald	0.00	0.00	2.25	0.00	0.02	0.08	0.40	1.63	3.07	0.52	0.01	1.02
Halle an der Saale	0.75	0.14	2.32	2.61	0.06	0.77	0.34	2.38	1.16	0.28	0.89	0.64
Hamburg	0.29	0.92	1.81	1.17	0.28	0.75	0.98	0.99	2.08	0.43	0.66	1.06
Hannover	0.31	0.40	2.15	2.36	0.24	0.73	0.67	1.07	3.78	0.41	0.83	1.40
Heidelberg	0.00	0.00	0.00	20.02	0.00	0.00	0.43	0.95	7.41	0.45	5.00	2.07
Heilbronn	0.00	3.02	0.00	11.12	0.12	0.57	1.46	0.78	5.16	0.65	3.56	1.96
Hildesheim	0.06	1.00	1.78	4.67	0.41	0.88	0.16	1.40	3.04	0.41	1.53	1.12
Ingolstadt	0.64	0.40	2.37	4.28	0.16	0.19	0.21	2.58	7.52	0.31	1.37	2.06
Iserlohn	0.00	0.19	0.39	21.83	0.51	1.07	0.95	0.61	12.78	0.06	5.63	3.72
Jena	1.73	0.25	0.00	5.97	2.64	1.51	0.77	0.65	4.33	0.87	2.65	1.87
Kaiserslautern	0.00	0.69	0.78	7.02	0.88	0.00	0.04	0.88	8.91	0.10	2.15	2.26
Karlsruhe	0.37	0.19	1.66	3.19	0.10	0.69	0.27	1.28	3.21	0.36	0.96	1.13
Kassel	0.00	0.15	2.27	0.28	0.16	1.00	0.41	0.86	5.42	0.50	0.15	1.83
Kempten (Allgäu)	206.91	0.00	0.94	5.99	0.00	0.00	1.27	0.91	4.06	0.31	53.23	1.41
Kiel	0.46	0.20	1.54	4.40	0.11	0.15	0.31	1.01	6.42	0.07	1.29	1.74
Koblenz	0.00	0.00	0.00	12.96	0.00	0.23	0.25	0.38	8.89	0.38	3.24	2.44
Köln	0.55	0.78	2.00	1.32	0.25	1.24	0.65	1.35	1.69	0.35	0.73	0.98
Konstanz	0.71	1.30	0.77	6.52	0.70	0.00	0.00	0.84	14.75	0.00	2.31	3.69
Krefeld	0.35	0.31	1.96	3.07	0.29	1.84	0.54	1.08	2.63	0.19	1.00	1.30
Landshut	0.51	0.05	2.54	0.89	0.05	0.41	0.66	1.23	5.17	0.88	0.37	1.78
Leipzig	0.20	0.94	1.81	5.58	0.09	0.63	0.25	2.21	2.49	0.57	1.70	0.99
Lübeck	0.60	0.63	1.28	0.58	1.08	0.65	1.37	1.32	1.32	0.38	0.72	0.93
Lüneburg	0.90	0.47	1.09	6.36	0.00	0.46	0.89	1.34	3.35	0.41	1.93	1.27
Magdeburg	0.45	0.12	2.89	1.11	0.18	0.41	0.33	2.34	2.76	0.05	0.47	0.89
Mainz	0.35	0.00	1.72	4.37	0.00	0.18	0.32	1.49	4.46	0.19	1.18	1.29
Marburg	3.12	0.00	0.00	5.92	0.00	1.30	0.78	0.82	4.21	0.42	2.26	1.68

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Table A4 (continued)

FUA	WDIa_Lake	WDIi_Lake	WDIn_Lake	WDIt_Lake	WDIu_Lake	WDIa_River	WDIi_River	WDIn_River	WDIt_River	WDIu_River	WDIav_Lake	WDIav_River
Mönchengladbach	0.00	2.03	3.73	0.18	0.00	0.22	0.24	2.73	3.75	0.23	0.55	1.11
München	0.33	0.33	1.33	5.95	0.07	0.25	0.12	1.99	5.54	0.02	1.67	1.48
Münster	0.21	0.15	1.39	9.58	0.19	0.68	1.54	1.27	1.79	0.72	2.53	1.18
Neubrandenburg	0.01	0.18	1.51	5.00	0.19	0.00	0.00	0.62	20.23	0.01	1.35	5.06
Neumünster	1.07	0.43	1.73	0.21	0.65	0.00	0.51	2.51	3.04	0.00	0.59	0.89
Nürnberg	0.00	0.09	1.39	5.03	0.06	0.73	0.34	1.68	2.46	0.32	1.30	0.96
Offenburg	0.34	0.62	1.21	4.39	0.25	1.32	0.52	1.02	2.99	0.03	1.40	1.22
Oldenburg (Oldenburg)	0.28	0.09	1.65	5.02	0.11	1.22	0.37	0.87	8.55	0.13	1.37	2.57
Osnabrück	0.22	1.14	1.29	3.06	0.24	0.32	0.52	0.36	7.25	0.00	1.16	2.02
Paderborn	0.52	0.50	1.98	3.21	0.32	0.00	0.00	3.68	0.00	0.00	1.14	0.00
Passau	0.09	0.30	1.15	5.20	0.00	0.08	0.55	0.31	12.35	0.35	1.40	3.33
Pforzheim	0.00	0.00	0.00	21.48	0.00	0.07	1.23	0.94	2.18	1.07	5.37	1.14
Plauen	0.26	0.32	1.26	4.59	0.28	0.10	2.74	1.02	4.45	0.28	1.36	1.89
Regensburg	0.20	0.05	2.34	6.31	0.00	0.79	0.24	1.14	5.44	0.21	1.64	1.67
Remscheid	0.27	0.00	1.48	3.50	0.02	0.00	0.00	1.83	0.00	0.00	0.95	0.00
Reutlingen	0.73	1.24	1.51	0.80	0.00	0.97	0.49	1.53	0.66	0.14	0.69	0.56
Rosenheim	0.00	0.30	1.46	2.33	0.03	2.05	0.39	0.74	7.65	0.22	0.66	2.58
Rostock	0.95	0.05	1.76	0.04	0.02	0.05	0.20	1.54	1.87	0.23	0.27	0.59
Ruhrgebiet	0.01	0.02	0.00	24.45	0.00	0.02	0.29	0.08	23.09	0.15	6.12	5.89
Saarbrücken	0.00	0.22	0.30	12.19	0.00	0.53	0.38	0.32	11.06	0.16	3.10	3.03
Schweinfurt	0.24	0.15	1.98	3.66	0.26	0.80	0.51	1.81	2.79	0.01	1.08	1.03
Schwerin	0.21	0.31	1.15	4.72	0.77	0.14	0.00	0.25	16.60	0.12	1.50	4.21
Siegen	0.00	1.17	0.33	9.55	0.00	16.15	4.00	0.47	3.58	0.86	2.68	6.15
Solingen	1.45	0.00	1.96	0.00	0.00	0.33	0.45	1.82	0.57	0.31	0.36	0.41
Stralsund	0.66	0.43	1.49	1.93	0.55	0.00	0.03	0.91	6.70	0.38	0.89	1.78
Stuttgart	0.27	0.21	1.48	4.12	0.09	0.04	1.35	0.25	7.76	0.15	1.17	2.33
Trier	0.38	0.05	0.78	9.00	0.03	0.21	0.18	0.41	12.82	0.10	2.36	3.33
Tübingen	2.41	1.67	0.72	2.36	0.00	1.24	2.57	0.69	1.84	1.50	1.61	1.79
Ulm	0.47	0.06	2.05	1.22	0.05	0.30	0.90	1.42	2.82	0.50	0.45	1.13
Villingen-Schwenningen	2.15	0.00	0.62	3.79	0.54	0.55	1.45	0.54	13.26	1.33	1.62	4.15
Weimar	1.28	0.00	0.78	5.58	0.00	0.53	0.00	0.63	14.10	0.00	1.71	3.66
Wetzlar	0.13	0.00	1.36	1.38	0.19	1.16	0.67	0.93	3.87	0.55	0.43	1.56
Wiesbaden	1.02	0.57	1.02	1.83	0.87	0.11	0.45	0.78	9.26	0.06	1.07	2.47
Wilhelmshaven	0.47	0.48	1.24	3.50	0.32	0.68	0.21	1.10	5.78	0.23	1.19	1.72
Wuppertal	0.57	2.47	1.24	0.89	0.22	0.13	2.97	0.73	2.70	0.45	1.04	1.56
Würzburg	0.00	0.00	0.00	15.30	0.00	0.44	1.02	0.74	7.01	0.32	3.82	2.20
Zwickau	0.16	0.19	2.25	1.34	0.55	0.56	0.28	2.25	0.84	0.24	0.56	0.48

Table A5

Urban waterfront change between 2012 and 2018 at FUA level.

no	FUA	Waterfront, 2012	Changed Waterfront	Ratio
1	Flensburg	578,735	10,821	1.86
2	Darmstadt	79,158	1,194	1.5
3	Ruhrgebiet	2,296,065	33,756	1.47
4	Erfurt	353,938	4,798	1.35
5	Osnabrück	416,644	5,025	1.2
6	Weimar	37,172	412	1.1
7	Heidelberg	239,209	2,410	1
8	Bayreuth	201,416	1,834	0.91
9	Bamberg	352,025	3,159	0.89
10	München	1,486,687	12,206	0.82
11	Frankfurt am Main	767,429	6,207	0.8
12	Cottbus	865,238	6,795	0.78
13	Koblenz	215,277	1,655	0.76
14	Münster	350,309	2,557	0.73
15	Würzburg	611,656	4,381	0.71
16	Braunschweig-Salzgitter-Wolfsburg	1,067,405	7,223	0.67
17	Ingolstadt	921,651	5,820	0.63
18	Jena	168,962	1,064	0.63
19	Bocholt	245,043	1,529	0.62
20	Oldenburg (Oldenburg)	580,280	3,607	0.62
21	Düsseldorf	335,481	1,987	0.59
22	Lübeck	356,605	2,105	0.59
23	Hildesheim	340,089	1,957	0.57
24	Wilhelmshaven	464,076	2,579	0.55
25	Schwerin	1,489,616	8,124	0.54
26	Magdeburg	1,224,022	6,478	0.52
27	Bonn	366,197	1,903	0.51
28	Halle an der Saale	524,796	2,692	0.51
29	Hannover	1,024,223	5,084	0.49
30	Leipzig	1,468,707	6,570	0.44
31	Reutlingen	22,302	98	0.44
32	Augsburg	490,595	2,049	0.41
33	Hamburg	2,503,021	10,348	0.41
34	Rostock	1,246,237	5,059	0.4
35	Köln	627,362	2,478	0.39
36	Karlsruhe	647,205	2,485	0.38
37	Villingen-Schwenningen	142,417	544	0.38
38	Kaiserslautern	225,560	851	0.37
39	Bremerhaven	1,342,619	5,063	0.37
40	Dresden	1,819,103	6,655	0.36
41	Ulm	615,698	2,239	0.36
42	Stralsund	711,234	2,547	0.35
43	Celle	518,195	1,651	0.31
44	Gießen	109,989	331	0.3
45	Regensburg	731,471	2,128	0.29
46	Greifswald	1,202,153	3,421	0.28
47	Tübingen	108,671	309	0.28
48	Düren	267,437	747	0.27
49	Siegen	248,636	687	0.27
50	Rosenheim	771,367	2,032	0.26
51	Mannheim-Ludwigshafen	550,736	1,382	0.25
52	Marburg	208,312	504	0.24
53	Paderborn	121,553	288	0.23
54	Kiel	1,505,797	3,552	0.23
55	Stuttgart	609,453	1,363	0.22

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Table A5 (continued)

no	FUA	Waterfront, 2012	Changed Waterfront	Ratio
56	Görlitz	999,578	2,045	0.2
57	Heilbronn	305,247	624	0.2
58	Passau	488,525	975	0.19
59	Friedrichshafen	173,695	310	0.17
60	Neubrandenburg	2,970,565	3,948	0.13
61	Bremen	1,879,828	2,432	0.12
62	Aachen	115,760	142	0.12
63	Freiburg im Breisgau	488,742	576	0.11
64	Offenburg	682,987	802	0.11
65	Gera	247,953	272	0.1
66	Zwickau	221,603	242	0.1
67	Berlin	6,275,531	6,395	0.1
68	Nürnberg	1,410,801	1,431	0.1
69	Pforzheim	109,591	108	0.09
70	Kempten (Allgäu)	432,396	399	0.09
71	Dessau-Roßlau	134,828	117	0.08
72	Lüneburg	589,475	435	0.07
73	Landshut	259,486	150	0.05
74	Mainz	215,294	116	0.05
75	Trier	370,871	116	0.03
76	Schweinfurt	321,955	98	0.03
77	Plauen	201,740	58	0.02
78	Brandenburg an der Havel	463,904	46	0.01
79	Wuppertal	73,662	3	0
80	Aschaffenburg	285,844	0	0
81	Bielefeld	17,323	0	0
82	Chemnitz	45,986	0	0
83	Frankfurt (Oder)	76,070	0	0
84	Fulda	62,200	0	0
85	Göttingen	324,901	0	0
86	Iserlohn	218,951	0	0
87	Kassel	223,202	0	0
88	Konstanz	218,423	0	0
89	Krefeld	68,466	0	0
90	Mönchengladbach	12,189	0	0
91	Neumünster	18,003	0	0
92	Remscheid	19,352	0	0
93	Saarbrücken	430,388	0	0
94	Solingen	44,429	0	0
95	Wetzlar	226,569	0	0
96	Wiesbaden	165,501	0	0
	Average			0.36

Table A6

Land use share (UA data 2018) along the urban riverfronts at German FUA level.

Row Labels	Airports	Arable land (annual crops)	Construction sites	Continuous urban fabric (S.L. : > 80%)	Discontinuous dense urban fabric (S.L. : 50% - 80%)	Discontinuous low density urban fabric (S.L. : 10% - 30%)	Discontinuous medium density urban fabric (S.L. : 30% - 50%)	Discontinuous very low density urban fabric (S.L. : < 10%)	Fast transit roads and associated land	Forests	Green urban areas	Herbaceous vegetation associations (natural grassland, moors...)	Industrial, commercial, public, military and private units	Isolated structures	Land without current use	Mineral extraction and dump sites	Open spaces with little or no vegetation (beaches, dunes, bare rocks, glaciers)	Other roads and associated land	Pastures	Permanent crops (vineyards, fruit trees, olive groves)	Port areas	Railways and associated land	Sports and leisure facilities	Grand Total
Aachen	0	0	0	0	0	0	0	0	0	23,4	0	0	0	0	0	0	0	76,6	0	0	0	0	0	100
Aschaffenburg	0	0	1,4	0	0	0	0	0,6	0	34,1	8,8	0	8,4	0,2	6,8	0	0	8,8	8,8	0	3,6	10,1	8,1	100
Augsburg	0	0	0	1	0,9	0,3	0,4	0	0,2	32,6	28	0,5	6,9	0	0,2	0	0	15,1	0,9	0	0	3,8	9,2	100
Bamberg	0	16,9	0	1,7	7,2	1,7	1,9	1,2	0	8	26	0	8,4	0	0	0	0	7,9	8,6	0	0	2,5	7,9	100
Bayreuth	0	5,5	0	1,3	4,9	1,2	0,3	0	0,3	4,6	1,1	0	5,8	0	13,1	0	0	22	14,5	0	0	0,9	24,7	100
Berlin	0	3,1	0,1	1,1	4,1	0,4	2,7	0	1,6	5,1	7,7	0,6	16,9	0,1	0,6	0	0	43,2	3,3	0	2,1	1,1	6,1	100
Bielefeld	0	14,4	0	0	14,9	0	0	0	9,2	25,4	12,8	0	0	0	0	0	0	13,3	10	0	0	0	0	100
Bonn	0	4,9	0	2,7	3,4	0,3	1,1	0	3,1	14,8	18,7	0	1,1	0,6	0	0	0	31,4	14,4	0	2,3	0	1,3	100
Brandenburg (Havel)	0	0,7	0,3	0,5	0,4	1,1	2,6	0,1	0,1	37,2	4	4,4	7	0,2	1,7	0	0	2	29	0	0	2,5	6,2	100
Bremen	0	8,3	0	0,5	2,9	0	0,8	0	0,2	1,9	6,9	0	7,6	0,1	0,1	0,1	0,4	12,4	45,5	0	7,5	0,4	4,2	100
Bremerhaven	0	7,9	0	0	0,6	0	0	0	0,1	3,7	1,9	0	5,2	0,1	4,6	0	0,3	39,7	31,8	0	2,4	0,2	1,7	100
Celle	0	19,8	0	0	3,1	0	1,1	0	0	17,7	3,5	0,1	5,5	0,1	2,4	0	0	4,5	41	0	0	0,1	1,1	100
Chemnitz	0	7,4	0	2,1	9,8	0,2	0,9	0	0,1	4,3	21,1	0	20,1	0	2,4	0	0	10,6	11,6	0	0	3,6	6	100
Cottbus	0	2,6	0	0,1	0,6	0	0,2	0,9	0,1	28,2	3,8	3,4	3,3	0	0,2	0,6	0	2,3	52,1	0	0	0,1	1,4	100
Darmstadt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	100
Dessau-Roßlau	0	3,9	0	0	0,1	0,5	0,3	0,8	0,1	44,7	0,9	0	2,5	0,3	0	0	2,6	1	39,2	0	0	0,5	2,6	100
Dresden	0	23	0	1,5	0,8	0	0,2	0	0,2	1,1	7,1	0	4	0,1	0,3	0	0	36,5	20,8	0,1	2	1,8	0,6	100
Düsseldorf	0	31,9	0	0,1	2	0	0	0	2,2	6,3	22,2	0	5,5	0	0	0	0	13	12,8	0	1,7	1,2	1,1	100
Erfurt	0	7,7	0	1	2,8	0,3	1,7	0	0,1	4,9	48	0	1,6	0	0	0	0	18,1	8,3	0	0	1,2	4,3	100

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Table A6 (continued)

Flensburg	0	6,7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44,2	0	0	0	0	49	100
Frankfurt (Oder)	0	13,5	0	5,7	0,5	0	0	0	0,6	21,7	15,5	7,8	1,7	0	0	0,5	0	0,6	29,6	0	0	1,3	0,8	100
Frankfurt am Main	0	10,6	0	1,1	1,4	0	0,3	0	1	7,1	13	1,2	6,3	0	0	0	0	38,2	4,6	0	2,4	6,8	5,9	100
Freiburg (Breisgau)	0	8,3	0	0	3,8	0	0	0	0,1	4,4	8,7	0	2,2	0	0	0	0	44,2	17,2	0	0	0,2	10,8	100
Fulda	0	0	0	0,4	1,7	0	1,5	1,5	0	3,4	11,1	0	0,9	0,4	0	0	0	1,7	76,3	0	0	0,1	1,1	100
Gera	0	15,2	0	0	8,5	0,8	4	0,2	0,3	3,4	7,1	0	5,5	0,9	0	0	0	5,3	17,3	0	0	17	14,7	100
Gießen	0	8,4	0	0	0	1,8	1,4	12,5	0,6	10	9	0	11,5	0	0	0	0	10	21,4	0	0	0	13,5	100
Görlitz	0	10,5	0	0	1,1	1	0	0,7	0,1	5,6	0	0	2,9	0	0	0	0,9	6	70,1	0	0	0,2	1	100
Göttingen	0	0	0	0	0	0	0	0	0	11,4	0	0	0	0	0	0	0	88,6	0	0	0	0	0	100
Greifswald	0	1,6	0	0	2,2	2,3	0,1	0	0	3,9	4,2	0	4	1,1	3,1	0	2,4	10,1	61,6	0	0	0,5	3	100
Halle an der Saale	0	19,9	0	0,5	3,3	0,6	1	0	0	20,9	19,3	1,6	4,7	0	0	0	0	6	16,8	0	0,7	2,1	2,5	100
Hamburg	0,8	6,6	0,9	4,2	3	0	0,1	0	0,3	5,1	8	0	8,8	0,1	0,4	0	0	15,7	19	1,1	19,9	1,2	4,8	100
Hannover	0	8,2	0	2	4,5	0	0,6	0	0	6,2	15,5	0	12,6	0	2	0,2	0	36	7,1	0	0	0,6	4,5	100
Heidelberg	0	0	0	0	0,8	0,9	0,5	0	0,6	11,9	9,6	0	3,8	0,2	0,4	0	0	36,5	30,3	0	0	0	4,5	100
Heilbronn	0	22,7	0,3	0,4	1,2	0	0,6	0	0,5	2,9	3,4	0	15,9	0	3	0	0	18	12,4	0,8	7,8	3,4	6,6	100
Hildesheim	0	30,9	0	0,2	1,6	0,7	0	0	0	7,3	11,9	0	1,5	0	0,4	0	0	13,5	21,6	0	0	5	5,3	100
Ingolstadt	0	8,5	0	0	0	0,2	0,1	0	0,3	38,8	6,8	0	2,3	0	0	0	0	34,5	1,4	0	0	0,7	6,3	100
Iserlohn	0	15,3	0	0	0	0	0	0	0	22,2	0	0	6,9	0	0	0	0	37,1	15,2	0	0	2,4	0,9	100
Jena	0	31,5	0	0	0	2,3	0	0	0,2	0,3	25,1	0	6,9	0	0	0	0	13,4	7,7	0	0	1,6	11	100
Kaiserslautern	0	0	0	0	0	0	0	1,2	0	20,5	3,3	0	0,4	0	0	0	0	36,1	38,3	0	0	0,3	0	100
Karlsruhe	0	13,5	0	0,5	2,9	0,2	0,9	0	0,6	31,6	12,7	1	3,1	0,3	0,6	0,2	0	17,9	0,1	0	9,4	1,5	3,1	100
Kassel	0	6,4	0	1,3	2,8	3,4	0,5	0,9	1,1	4,7	12,7	0	5,4	2,7	0	0	0	35,5	16,7	0	0	0,4	5,3	100
Kempten (Allgäu)	0	0	0	0	1,4	1,4	1,9	0	0	29,1	4,6	0	12,7	0	0,1	0	0	20,3	27,8	0	0	0,2	0,6	100
Kiel	0	1,9	0	0,3	0,7	0	0,9	0	0	8,9	5,7	0,2	4,3	0,1	0	0	0	59,1	14,7	0	2,7	0,2	0,3	100
Koblenz	0	3,3	0	1,3	4,1	0	0	0	1,1	2,3	13,5	0	3	0	0	0	0	58,3	2,8	0	1,9	7,3	1,2	100
Köln	0	20,4	0	1,7	7,2	0	0,1	0	1,7	11,7	14,5	0	8,5	0,2	0	0	0	14,9	10,8	0	5,5	1,9	1,1	100
Konstanz	0	0	0	0	0	0	0	0	0	16,1	0	0	0	0	0	0	0	54,3	29,6	0	0	0	0	100
Krefeld	0	35,9	0	0	0	0,5	4	0	0	23,4	3,1	0	7	0	1,3	0	0	14,6	5,3	0	0	4,9	0	100
Landshut	0	15,4	0	3,4	3,2	0	7,5	0	0	19,4	12,4	0	4,4	0	0	0	0	24,7	4,8	0	0	0,5	4,3	100
Leipzig	0	19,2	0	1,5	3	1,1	2,5	0,1	0,1	13	22,6	0	3,5	0,1	0,1	0,3	0	19	6,3	0	0	0,2	7,6	100
Lübeck	0	11,3	0	0	1,9	0,1	0,8	0	0,3	5,2	6,1	0	11	0,1	0,4	0	0	5,6	45,5	0	5,3	1,3	5,1	100
Lüneburg	0	9,3	1,9	2,1	1,5	2,5	1,5	0,2	0,2	34,4	3,2	0,5	9	0	0	0	0	13,1	15,5	0	0	3,6	1,3	100
Magdeburg	0	14	0	0	0,8	0	0	0	0,5	9,1	12,6	0	3,6	0	0	0	0	15,1	34	0	9,2	0,9	0,3	100

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Table A6 (continued)

Mainz	0	7,4	0	0	0	0	0	0	1,6	8,1	5	0	3,8	0,4	0	0	0	52,9	0,3	0	9,6	7,4	3,6	100
Marburg	0	34,8	0	0,1	0,8	0,4	0,8	0,4	2,1	10,3	8,3	0	4	0	0	0	0	9,4	26,6	0	0	0,1	1,8	100
Mönchengladbach	0	7,1	0	0	0	0	0	0	5,5	35,7	8,1	0	2,4	1	0	0	0	21,3	13,2	0	0	0,1	5,5	100
München	0	3,8	0	0	0	0	0,9	0	0	0	32,9	0	1,9	0	0	0	0	60,2	0	0	0	0,1	0,2	100
Münster	0	24,3	0,7	0,1	0,7	1,9	2,6	4	0,3	24	1,9	0,4	10,6	0,8	0,1	0	0	5,4	17,1	0	0	1,9	3,1	100
Neubrandenburg	0	0	0	0	0	0	0	0	0	4,1	0	0	0	0	0	0	0	42,8	27,1	0	0	25,7	0,3	100
Neumünster	0	0	0	0	0	0	0	0	0	50,7	6,1	18,3	8	0	0	0	0	17	0	0	0	0	0	100
Nürnberg	0	9,3	0	1,3	3,6	0,1	1,4	0,2	0,4	15	9,4	0	5,8	0	1,3	0	0	27,4	22,2	0	0,4	0,3	1,7	100
Offenburg	0	28,4	0	0	0	0	0	0	0,2	0	1,1	0	4,4	0	0	0	0	15,5	49,7	0	0	0,1	0,5	100
Oldenburg	0	5,5	0	0	0,4	1	0,6	1,1	0,4	4,6	4,1	0	4,6	0,1	0,6	0	0	49,8	24,9	0	0	1,1	1,3	100
Osnabrück	0	6,1	0	0	0	0,1	0	0	0,1	7,2	0	0	8,1	0	0	0	0	69	4,4	0	0	5,1	0	100
Paderborn	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	100
Passau	0	0,7	0	0,2	1,1	1,5	1,9	1,3	0,6	9	2,5	0	4,3	0,4	0	0	0	61,4	6,5	0	4,2	4,4	0	100
Pforzheim	0	0,3	0	2,6	6	1,1	3,3	1,3	0	33,5	19,5	0	9,2	0,2	0	0	0	10	7,5	0	0	0,1	5,2	100
Plauen	0	2,2	0	0	1	1,3	0,9	0,2	0	15,5	2,7	0	16,1	0,8	0	1,4	0	17,5	27,9	0	0	11,3	1,1	100
Regensburg	0	22,6	0	0,9	0,8	0	0,4	0	1	3,8	8,5	0	4,6	0,1	0,7	0,3	0	45,6	5,2	0	2,7	0,3	2,4	100
Remscheid	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	100
Reutlingen	0	16	0,7	0	0	0	2	0	0	20,8	0	0	3,7	0	0	0	0	2,8	53	0	0	0	0,9	100
Rosenheim	0	4,6	0	0	2,6	0	0,4	0,6	0	23,9	16,4	0	4,7	0	0,8	0	0	43,2	1,8	0	0	0,2	0,8	100
Rostock	0	0,6	0	0,5	1,7	0	0	0	0	7,6	0	4,8	1,7	0	0	0	55,9	4,8	7,8	0	11,5	0,5	2,6	100
Ruhrgebiet	0	0,9	0	0	0	0,1	0	0	0	0,3	0	0	1,4	0	0	0	0	93,7	3,5	0	0	0	0,2	100
Saarbrücken	0	1,8	0	0	0	0	0	0	8,8	3,9	13,4	2,3	3,3	0	0,1	0	0	62	0,1	0	0	1,3	2,9	100
Schweinfurt	0	13,8	0	0	0	0	0	0,2	0,5	3,8	2,3	0	11,1	0	0	0	0	18,6	48,6	0	0	1,2	0	100
Schwerin	0	2,4	0	0	0	0	0	0	0	2,6	0	0	0	0	0	0	0	83,9	8,8	0	0	0	2,3	100
Siegen	0	0,7	0	2,6	3,5	0	4,2	0,7	6,7	16,4	1,9	0	26,5	0	3,6	0	0	18	13,9	0	0	1,3	0	100
Solingen	0	3,3	0	0	0,8	3,2	2,2	1,2	0	72,9	0	6	4,3	0,9	0	0	0	2,7	0,9	0	0	0,1	1,5	100
Stralsund	0	0	0	0	7,3	0	0,5	0	0	1,6	11,3	2,6	0,5	0	0	0	0	55,7	17,2	0	0	0	3,3	100
Stuttgart	0	0,2	0	0,5	0	0	0,1	0	0	2,4	5,6	1,3	15,6	0	0	0	0	69,2	0,1	0,2	0	0,6	4,1	100
Trier	0	2,8	0	0	0,7	0	0,5	0	0,8	7,5	6	3,2	1,5	0	0,2	0	0	67,8	6,7	0	0,8	1,3	0,3	100
Tübingen	0	19,2	0	0	2,1	4,3	5,1	1,8	0	9,3	13,7	0	12,7	0	0	0,7	0	5,1	21,6	0	0	0,4	4	100
Ulm	0	8,6	0	0,2	1,5	0	0,8	0	0,6	33,3	7	0	9,9	0,3	0,1	0	0	16	12,4	0	0	4,3	5	100
Villingen-Schwenn.	0	12	0	5	8	0	0	0	0	0	14,9	0	7,2	0	0	0	0	34,9	18	0	0	0	0	100
Weimar	0	21,8	0	0	0	0	0	0	0	13,2	0	0	0	0	0	0	0	58,6	6,4	0	0	0	0	100
Wetzlar	0	5,8	0	1	1,7	0	0,1	1,4	2,5	1,9	12,4	0	5,4	0,5	0,7	0	0	15	47,3	0	0	0,7	3,6	100
Wiesbaden	0	2,9	0	0,9	0	0	0	0	0,3	14,5	12,7	2,1	4,2	0	0	0	0	60,9	0,3	0	0	0,7	0,4	100
Wilhelmshaven	0	3,8	0	0,9	0,9	0,3	0,5	0,2	0	2,1	5	0,4	3,5	0,2	0,1	0	0	15,4	49	0	16	0,1	1,4	100
Wuppertal	0	1,1	0	4,9	3,1	1,4	2,1	0	1,1	27,9	0,6	0	35,5	0	0,2	0	0	17,7	2,4	0	0	0,4	1,7	100
Würzburg	0	10,9	0	1,6	0,6	0,3	0	0	0,6	5,6	16,8	0	11,4	0	3,1	0,9	0	36,6	0,5	0	4,7	3,9	2,4	100
Zwickau	0	12,8	0	0	0,5	2,5	1,2	0,8	0,2	2,3	37,8	0	2,2	0	0	1,7	0	3,6	32,8	0	0	0,4	1,3	100
Grand Total	0	9	0,1	0,9	2	0,4	0,9	0,3	0,6	11,7	9,5	0,6	7,1	0,1	0,6	0,1	0,7	29,1	17,9	0,1	3,3	1,6	0	100

Table A7

Land use share (UA data 2018) along the urban lakefronts at German FUA level.

Row Labels	Arable land (annual crops)	Construction sites	Continuous urban fabric (S.L. : > 80%)	Discontinuous dense urban fabric (S.L. : 50% - 80%)	Discontinuous low density urban fabric (S.L. : 10% - 30%)	Discontinuous medium density urban fabric (S.L. : 30% - 50%)	Discontinuous very low density urban fabric (S.L. : < 10%)	Fast transit roads and associated land	Forests	Green urban areas	Herbaceous vegetation associations (natural grassland, moors,...)	Industrial, commercial, public, military and private units	Isolated structures	Land without current use	Mineral extraction and dump sites	Open spaces with little or no vegetation (beaches, dunes, bare rocks, glaciers)	Other roads and associated land	Pastures	Permanent crops (vineyards, fruit trees, olive groves)	Port areas	Railways and associated land	Sports and leisure facilities	Grand Total
Aachen	0	0	0	4,4	7,1	2	0	0	33	13,4	0	3,4	0	0	0	0	31	4,2	0	0	0	1,5	100
Aschaffenburg	0	0	0	0	0	0	0	0	12,5	31,2	0	0	0	0	0	0	4,6	0	0	0	0	51,6	100
Augsburg	8,5	0	0,4	0,3	0	0	0	0	61,4	10,9	0	1,1	0	0	0,1	0	16,2	1,2	0	0	0	0	100
Bamberg	0	0	0	0	0	0	0	0	63,5	0	0	0	0	0	0	0	36,5	0	0	0	0	0	100
Bayreuth	2,3	0	0	0	0	0	0,7	0	3,1	7,3	0	2,1	0	0	0	0	24,4	59,8	0	0	0,4	0	100
Berlin	8,1	0	0,6	2,2	3,7	7,5	0,1	0,1	30,3	12,2	1,3	3,6	0,1	0,2	0	0	19,6	2,1	0	0,4	0,1	7,8	100
Bielefeld	20,1	0	0	1,2	0	1,9	0	0	11,5	41,8	0	3,4	0	0	0	0	7,6	11,7	0	0	0	0,8	100
Bonn	2,9	0	0	0	0	0	0	0	5,3	42,1	0	0	0	0	6	0	2,7	40,9	0	0	0	0	100
Brandenburg	3	0	0	0,5	1,9	1,4	1,1	0	42,7	0,4	9	3,1	0,4	1,3	0	0	1,7	27,2	0	0	1,3	4,9	100
Bremen	6,6	0	0,1	0,8	0	0	0	0	4,4	14,4	0	0,9	0	0,5	0	0	24,7	36,3	0	9,7	0,4	1,2	100
Bremerhaven	10,6	1,6	0	0	0	0	0	0	3	7,2	5,1	0,1	0	0,6	1,2	0	15,4	50,1	0	4,6	0,3	0	100
Celle	0	0	0	0	0,2	0	0,4	0	87,4	0	2,5	0	0	0	0	0	3,9	3,1	0	0	0	2,4	100
Chemnitz	7,7	0	0	0	1,2	0	0,6	0	26,2	48,4	0	9,8	0	0	0	0	0	5,3	0	0	0	0,8	100
Cottbus	0,7	0	0	0	0	0,3	0	0	12,5	2,4	4,3	0	0	0	25,9	0,7	26,2	22,2	0	0	0	4,9	100
Darmstadt	6,9	0	0	0	0	0	0	0	35,9	15,7	0	0,8	0	0	0	0	36,2	2,9	0	0	0	1,5	100
Dessau-Roßlau	11,3	0	0	0	0	0,8	1,8	0	42,1	0	0	0,7	0,5	0	4	0	2,2	33,3	0	0	0	3,4	100
Dresden	11,1	0	0	1,7	0	0	0	0,5	6,6	5,7	0	1,5	0,2	0	0,6	0	62,9	5,7	0,4	0	1,7	1,3	100
Düsseldorf	10,2	0	0,1	2,2	0	0	0	0	42,7	13,7	0	2	0	0,4	0	0	17,2	8,8	0	0	0	2,7	100
Erfurt	15,6	0	0	0,2	0	0,4	0	1,1	0	2,2	1,4	1,3	0,1	0	34	0	28,9	12	0	0	0	2,9	100
Flensburg	0	0	0	0	0	0	0	8,2	4,8	0	0	0	0	0	0	0	83,4	3,6	0	0	0	0	100

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Table A7 (continued)

Frankfurt (Oder)	5,7	0	0	0,3	0	0	0	0	56,7	3,3	3,2	0	0	0	0	7,8	1,9	20,7	0	0	0	0,3	100
Frankfurt am Main	0,3	0	0	0	0	0	0	0	21,2	6,6	0	0	0	0	1,5	0	64,5	0	0	0	0	5,9	100
Freiburg-Breisgau	2	0	0	0	0	0	0	0	43,7	22,8	0	0	0	0	1,6	0	11,4	1,1	0	0	0	17,4	100
Fulda	19,6	0	0	0	0	0	0	0	65,3	0	0	2,6	0	0	0	0	12,5	0	0	0	0	0	100
Gera	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	100
Gießen	23,6	0	0	0	0	0	0	0	6,4	1,7	0	0	0	0	0	0	34,3	21	0	0	5,7	7,3	100
Görlitz	0	0	0	0	0	0,2	0	0	14,2	18,9	0	1,5	0	0	0	0	0,5	62,2	0	0	0	2,7	100
Göttingen	8,7	0	0	0	0	0	0,4	0	14,2	0	0	1,7	0	0	3	2	37,6	32,4	0	0	0	0	100
Greifswald	12,6	0	5,7	0	0	0	0	0	0	65,7	0	0	0	0	4,2	0	11,8	0	0	0	0	0	100
Halle an der Saale	0	0	0	0	0	0,6	0	0	1,5	13,8	0	0	0	0	0	0	84,1	0	0	0	0	0	100
Hamburg	19,5	0	0,8	0,2	0	0	0	0	27,2	3,6	15,3	0,6	0,1	0	1,3	0	18,8	11,2	0	0	0,9	0,6	100
Hannover	2,7	0	1,5	2,6	0,1	0,3	0	0,3	8,7	29,5	0	6,5	0	0,1	2,5	0,2	18,7	20,3	0,2	2	0,1	3,6	100
Heidelberg	3,5	0	0	0,1	0	0	0	0	8,1	43,9	0	2,8	0,1	0	4,9	0,3	22,9	5,7	0	0	0	7,7	100
Heilbronn	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	100
Hildesheim	0	0	0	0	0	0	0	0	0	0	0	33,5	0	0	0	0	0	0	0	31,7	32,6	2,2	100
Ingolstadt	2	0	0	0	0	3,2	0	0	18,4	13,2	0	9,6	0	0	0	0	28,4	20,1	0	0	0	5,1	100
Iserlohn	28,8	0	0	0	0,3	0,1	0	0	38,1	0,9	0,4	3,2	0	0,3	1,2	0	18,3	3,8	0	0	2	2,6	100
Jena	0	0	0	0	0	0	0	5,6	12,8	0	8	1,4	0	0	0	0	61,9	3	0	0	0	7,3	100
Kaiserslautern	36,2	0	0	0	0	0	0	0	0	0	0	2,3	0	0	0	0	21	0	0	0	0	40,5	100
Karlsruhe	0	0	0	0	0	0	1,2	0	47,8	2,5	0	6,3	2,1	0	0	0	19,6	4,2	0	0	9	7,4	100
Kassel	7,3	0	0	0,3	0	0,7	0	0	52,8	5,1	0,9	1,6	0	0	0,7	0	29,2	0	0	0	0	1,3	100
Kempten (Allgäu)	0	0	0	0	0	0	0	0	3,6	86,9	0	2	0	0	0	0	1,9	0	0	0	0	5,5	100
Kiel	5,9	0	0	0	0	0	0	0	27,9	0	0	0	0	0	0	0	30,3	35,9	0	0	0	0	100
Koblenz	5,8	0	0	1,2	1,3	0	0	0	27,8	7,5	0	2,7	0	0	0	0	42,5	10	0	0	0	1,2	100
Köln	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	100
Konstanz	9,1	0	0	0	0	0	0	3,3	9,1	38,6	4,3	1,2	0	2,4	9,1	0,5	13	2	0	0	2,5	4,8	100
Krefeld	9,8	0	1,6	0	0,6	1,2	2,2	0	16,9	5,2	0	10	0	0	0	0	24	20,1	0	0	0	8,6	100
Landshut	6,7	0	0	0,2	2,5	0	2,2	0	24	19,1	0	2	0,8	1	2	0	4,9	14,6	0	4,2	13,6	2,3	100
Leipzig	19,4	0	0	0	0	0	0	0	71,3	0	0	0,3	1	0	0	0	4,4	3,7	0	0	0	0	100
Lübeck	6,1	0	0	0	0,2	0,2	0	0	3,5	12,5	4,4	2,6	0,1	0	11,3	0,7	43,1	13,2	0	0	0	2	100
Lüneburg	10,4	0	2,7	3,3	3,5	8,3	0	0	32,8	7,5	0	3,4	0,2	0	1,6	0	5,3	14,8	0	0	0,2	5,9	100
Magdeburg	18,4	0	0	0	0	0	0	0	23,6	12,4	0	5,8	0	0	0	0	27,1	7,5	0	0	5,2	0	100
Mainz	15,5	0	0	0,1	0	0,1	0	0	10	7,2	1,3	0,8	0	0	0,4	0	10,3	50,3	0	0	0	3,9	100
Marburg	11,6	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	9,3	1,4	3	60,7	0	0	100

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Table A7 (continued)

Mönchengladbach	83,7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16,3	0	0	0	0	0	100
München	0	0	0	0	0	0	0	0	57,7	17	0	20,6	0	0	0	0	1,3	3,4	0	0	0	0	100
Münster	5,1	0	0	0,1	0	0	0	0,3	0	21,8	0	1,3	0,1	0	3,8	0	64,5	0,2	0	0	0	2,8	100
Neubrandenburg	7,5	0	0	0,5	0	0,1	0	0	22,8	11,6	0	1,1	0,6	0	0	0	40,4	13,1	0	0	0	2,3	100
Neumünster	0,1	0	0	0	1	0,2	0,6	0	35,3	2,6	0	0,6	0,1	0	2,1	0	16,9	38,2	0	0	0	2,1	100
Nürnberg	21,7	0	0	0	0,6	0,5	6,8	0	35,3	0	0	6,8	0	0	0	0	1,2	16,4	0	0	0	10,7	100
Offenburg	0	0	0	0,3	0	0	0	0	9,2	28,1	0	1,6	0	0	0	0	47,1	1,1	0	9,4	1,6	1,4	100
Oldenburg	7,3	0	0	0	0	0	0	0	12,5	10,5	0,6	1,7	0	0	3,5	0	23,3	37	0	0	0	3,6	100
Osnabrück	1,2	0	0	1,1	0	2,5	0	0	18,4	20,6	0	1,1	0	0	0	0	30,1	24,4	0	0	0	0,5	100
Paderborn	4,2	0	0	2,2	0	0	0	0	17,7	16,8	0	17,7	0	0	0	0	31,3	6,6	0	0	0	3,5	100
Passau	19,4	0	0	0	1,2	0	0,9	0	16,6	1,9	30,4	2	1	0	4,9	0	14	5,1	0	0	0,1	2,6	100
Pforzheim	0,9	0	0	0	0	0	0	0	67,1	0	0	2,3	0	0	0	0	29,7	0	0	0	0	0	100
Plauen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	100
Regensburg	6	0	0	0	0	0	5,3	0	0,7	0	2,2	2,1	0	0	0	0	29,7	54,1	0	0	0	0	100
Remscheid	5,8	0	0	0	0	0	0	0	13,6	22,2	0	1	0	0	0	0	57,5	0	0	0	0	0	100
Reutlingen	1,5	0	0	0	0,5	0	0	0,9	75,6	3,8	0	0	0	0	0	0	16,3	1,4	0	0	0	0	100
Rosenheim	12,2	0	0	0	0	0	0	0	27,4	0	0	0	0	0	11,3	0	3,4	45,7	0	0	0	0	100
Rostock	0	0	0	0	0	0	0	0	75,2	5,1	0,6	3,6	0,1	0	0	0	13,2	1,6	0	0	0	0,5	100
Ruhrgebiet	11,4	0	0	0	0	0	0	0	24,1	2,1	3,5	0,4	0	0	0	4,3	0	53,4	0	0	0,4	0,4	100
Saarbrücken	0,6	0	0	0	0	0	0	0	0,2	0	0	0,1	0	0	0	0	99,2	0	0	0	0	0	100
Schweinfurt	0	0	0	0	0	0	0	0	15,7	2,7	0,2	0	0	0	1,9	0	79,5	0	0	0	0	0	100
Schwerin	4,1	0	0	0	0	0	0	2,5	10,6	0	0	1,3	0	0,2	2	0	24,1	49,2	0	0	0	6	100
Siegen	3,4	0	1,8	3	0,1	0,5	0	0	34,4	8,9	1,8	3,9	0,2	0,1	0	0,4	23,6	8,2	0	0,2	0	9,4	100
Solingen	0	0	0	0	0	0	0	0	16,8	0	0	7,8	0	0	0	0	69,3	6,1	0	0	0	0	100
Stralsund	14,2	0	0	0	0	0	0	0	85,8	0	0	0	0	0	0	0	0	0	0	0	0	0	100
Stuttgart	8,5	0	0,8	5,1	0	6,9	0	0,8	10,2	21	0	6	1	0	0	0	11,6	22,3	0	0	3,6	2,1	100
Trier	2,8	0	0	0,4	0	0	0	0	35,1	19,1	0	2,4	0	0	0	0	37,1	0,5	0	0	0	2,6	100
Tübingen	4,6	0	0	0	0	0	0	0	15,9	3,2	14,1	0,4	0	0	0	0	49,6	11,3	0,5	0	0	0,4	100
Ulm	37,3	0	0	0	0	0	0	0	12,5	0	0	7,6	0	0	1,2	0	7	34,5	0	0	0	0	100
Villingen-Schwen.	13,4	0	0	0	0	0	0	1	22,9	3,1	0	0,6	0	0	0	0	8,1	50,1	0	0	0	0,8	100
Weimar	46,8	0	0	0	0	0	0	0	20,6	0	10,3	0	0	0	0	0	10	7	0	0	0	5,2	100
Wetzlar	52,8	0	0	0	0	0	0	0	4,6	0	0	0	0	0	0	0	23,2	19,5	0	0	0	0	100
Wiesbaden	0,6	0	0	0	0	0	0	0	18,2	0,6	0	0	0	0	0	0	6,5	70,9	0	0	0	3,1	100
Wilhelmshaven	25,8	0	0	0	0	0	0	0	0	4,1	0	5,4	0	0	0	0	0	34,4	0	12,3	0	18	100
Wuppertal	2,7	0	0	0,1	0	0	0,3	0	12,6	0	26,7	7,6	1,1	0	0,4	0	12,6	24,3	0	6,5	0	5	100
Würzburg	4,9	0	0	2,5	0	3,9	0	0	52,9	0	0	17	0	0	12,5	0	6,4	0	0	0	0	0	100
Zwickau	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	100
AVERAGE	9,09	0,01	0,17	0,4	0,28	0,48	0,27	0,27	23,1	11,2	1,66	2,88	0,1	0,07	1,76	0,18	26	15,89	0,04	1,55	0,89	3,48	100

Table A8

Transformation of riverfront agricultural, urban, transportation, and industrial land use (2012) to natural & semi-natural (2018) land use at FUA level, by total waterfront length and count.

FUA	State	Length [m]	Count	FUA	State	Length [m]	Count
Augsburg	BY	157	1	Landshut	BY	308	1
Bamberg	BY	265	1	Leipzig	SN	542	2
Berlin	BE/BB	2,013	5	Lüneburg	NI	304	1
Bonn	NW	86	1	Magdeburg	ST	8,142	11
Brandenburg (Hav)	BB	555	2	Mannheim (Lud)	HE	1,807	4
Bremerhaven	HB/NI	2,435	4	München	BY	508	2
Celle	NI	48	2	Münster	NW	272	2
Chemnitz	SN	244	1	Nürnberg	BY	98	1
Dresden	SN	452	3	Offenburg	BW	1,125	2
Frankfurt a. Main	HE	170	1	Oldenburg	NI	381	2
Görlitz	SN	428	1	Osnabrück	NI	787	1
Greifswald	MV	56	1	Regensburg	BY	88	1
Halle a. d. Saale	ST	16,480	10	Ruhrgebiet	NW	6,449	9
Hamburg	HH	1,032	1	Saarbrücken	SL	169	1
Hannover	NI	558	2	Stuttgart	BW	1,829	3
Heilbronn	BW	566	1	Trier	RP	1,025	2
Karlsruhe	BW	287	1	Ulm	BY	75	1
Koblenz	RP	523	1	Wetzlar	HE	193	1
Köln	NW	186	2	Wilhelmshaven	NI	614	1
				Grand Total		51,276	89

Table A9

Changed (2012–2018) waterfront patches according to their initial (2012) land use classes by count (C) and length (L) for year 2012.

	Agricultural		Industrial		Natural		Transp.		Urban		Total	
	C	L	C	L	C	L	C	L	C	L	C	L
Federal State												
Baden-Württem.	22	5,068	26	8,150	31	4,683	1	189	13	2,496	93	20,586
Bayern	83	22,007	34	6,988	48	6,668	1	16	9	2,020	175	37,699
Berlin			5	876	1	86			4	468	10	1,430
Brandenburg	1	86	16	3,116	25	10,963			6	1,229	48	15,394
Bremen	2	922	5	2,048	8	1,040			1	192	16	4,203
Hamburg			5	1,200	2	667			7	1,808	14	3,675
Hessen	13	2,330	13	4,639	10	3,948					36	10,917
Mecklenburg-V.	15	5,613	13	7,045	34	6,160			3	774	65	19,592
Niedersachsen	59	17,156	53	21,787	60	14,367	1	912	7	966	180	55,188
Nordrhein-West.	53	25,727	46	18,531	36	12,619	4	297	10	3,183	149	60,356
Rheinland-Pfalz	5	2,874	15	6,420	13	1,331			1	349	34	10,973
Saarland			3	454					1	169	4	623
Sachsen	11	3,669	24	7,592	32	7,614	2	24	7	2,190	76	21,089
Sachsen-Anhalt	16	6,235	44	35,491	9	1,040			1	206	70	42,971
Schleswig-Holst.	19	9,104	15	4,481	28	7,390			2	390	64	21,365
Thüringen	11	3,073	7	1,552	8	1,764			1	194	27	6,582
Grand Total	310	103,865	324	130,368	345	80,339	9	1,437	73	16,634	1,061	332,645

Table A10

Changed (2012–2018) waterfront patches according to their changed (2018) land use classes by count (C) and length (L) for year 2018.

	Agricultural		Industrial		Natural		Transp.		Urban		Total	
	C	L	C	L	C	L	C	L	C	L	C	L
Federal State												
Baden-Württem.	2	251	55	8,933	17	6,960	4	256	15	4,186	93	20,586
Bayern	7	1,267	106	26,334	16	4,036	14	691	32	5,372	175	37,699
Berlin			4	552	1	58	3	11	2	810	10	1,430
Brandenburg	2	122	24	11,298	7	2,917	8	391	7	667	48	15,394
Bremen			3	99	3	1,717	5	213	5	2,174	16	4,203
Hamburg			7	2,465	1	1,032	5	18	1	159	14	3,675
Hessen	2	211	16	5,296	6	2,271	2	165	10	2,974	36	10,917
Mecklenburg-V.			23	7,493	2	801	5	4,718	35	6,580	65	19,592
Niedersachsen	3	272	101	29,607	31	13,868	11	1,863	34	9,578	180	55,188
Nordrhein-West.	4	1,590	87	39,574	34	15,443	13	2,212	11	1,539	149	60,356
Rheinland-Pfalz	1	297	11	2,239	12	5,313	1	349	9	2,775	34	10,973
Saarland					2	518			2	105	4	623
Sachsen	1	357	33	8,888	13	3,268	6	427	23	8,149	76	21,089

(continued on next page)

Table A10 (continued)

	Agricultural		Industrial		Natural		Transp.		Urban		Total	
Sachsen-Anhalt	5	4,669	17	6,090	33	28,093	10	3,510	5	610	70	42,971
Schleswig-Holst.			45	16,497	13	4,335	1	5	5	528	64	21,365
Thüringen	1	493	13	3,939	1	225	5	19	7	1,906	27	6,582
Grand Total	28	9,528	545	169,302	192	90,856	93	14,848	203	48,111	1,061	332,645

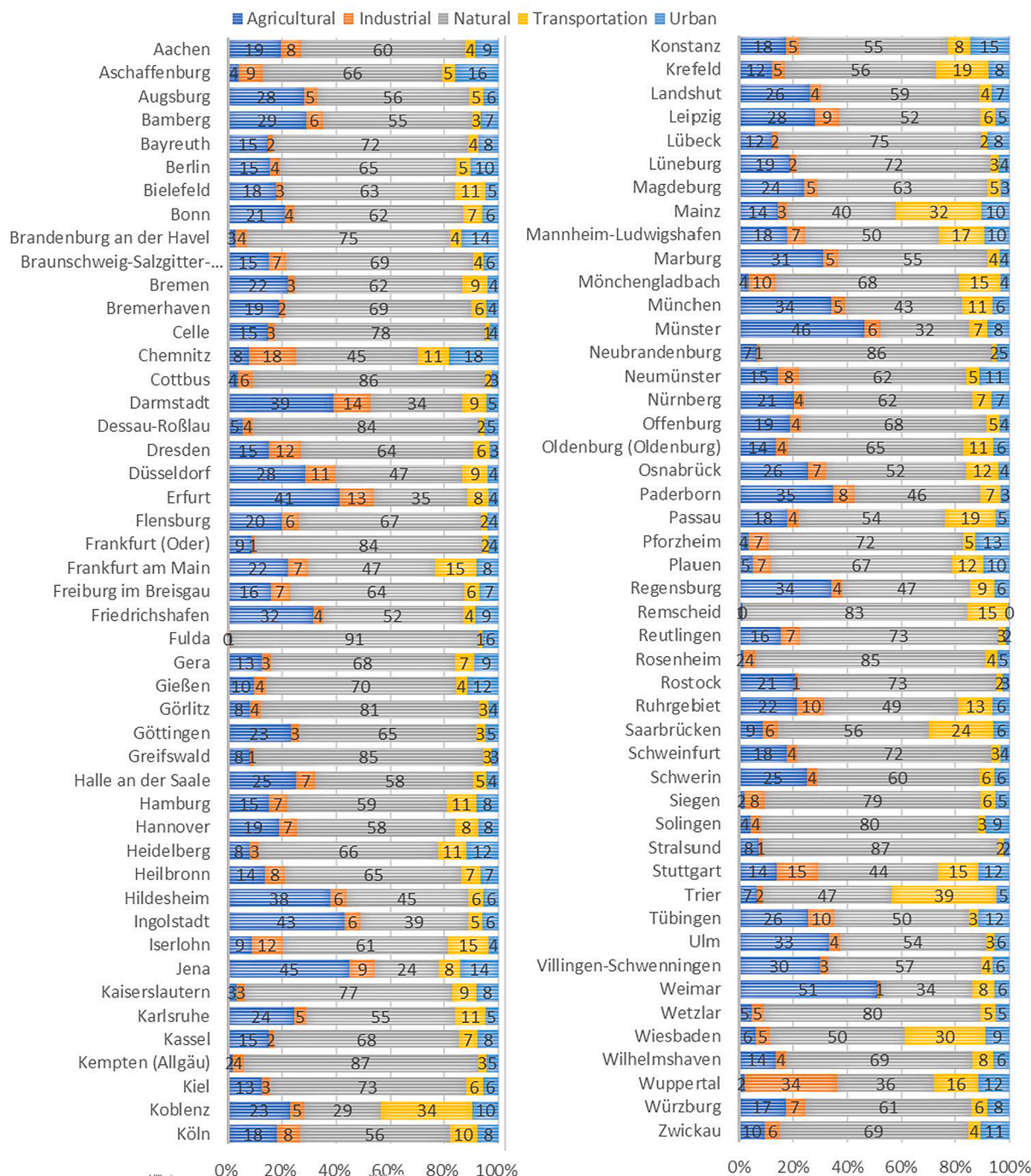


Fig. A1. Distribution of main reclassified land use categories within German FUA based on UA raw data of 2018.

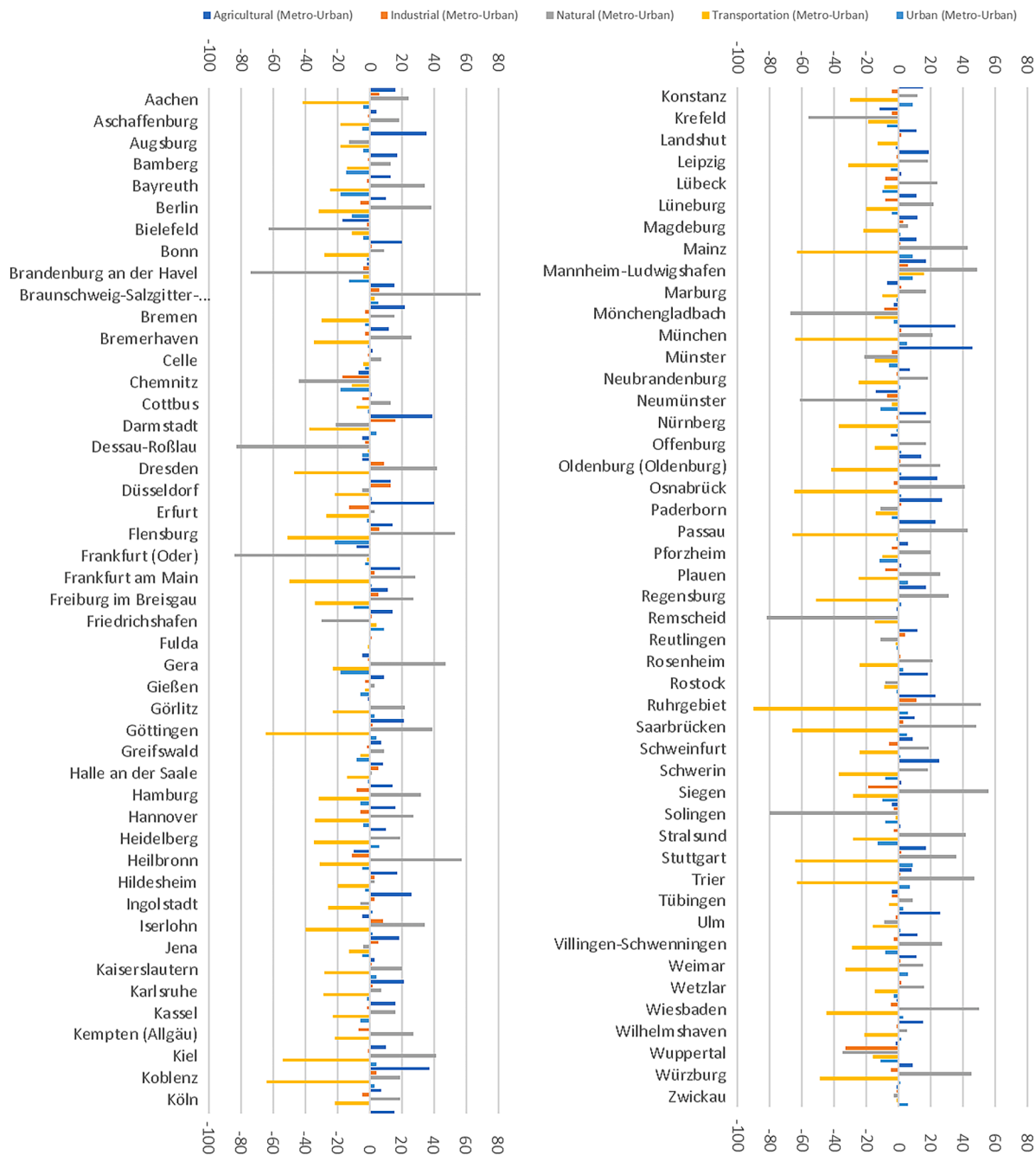


Fig. A2. Differences of waterfront land use category share between metropolitan and urban scale at FUA level.

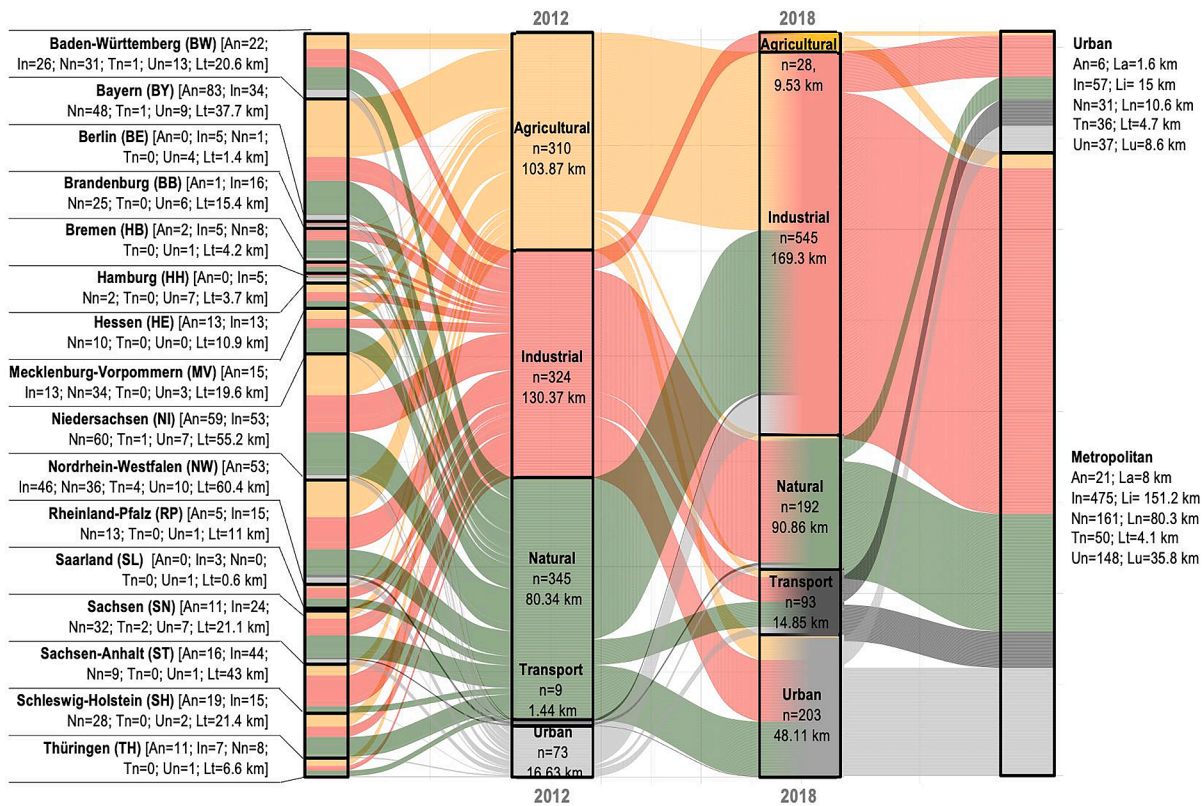


Fig. A3. Sankey chart showing the transformation of waterfront land uses of 2012 to new land uses in 2018, at the Federal state level. n refers to the number of waterfront patches. An, In, Nn, Tn, and Un refer to the count of agricultural, industrial, natural & semi-natural, transportation, and urban waterfront land use, respectively.

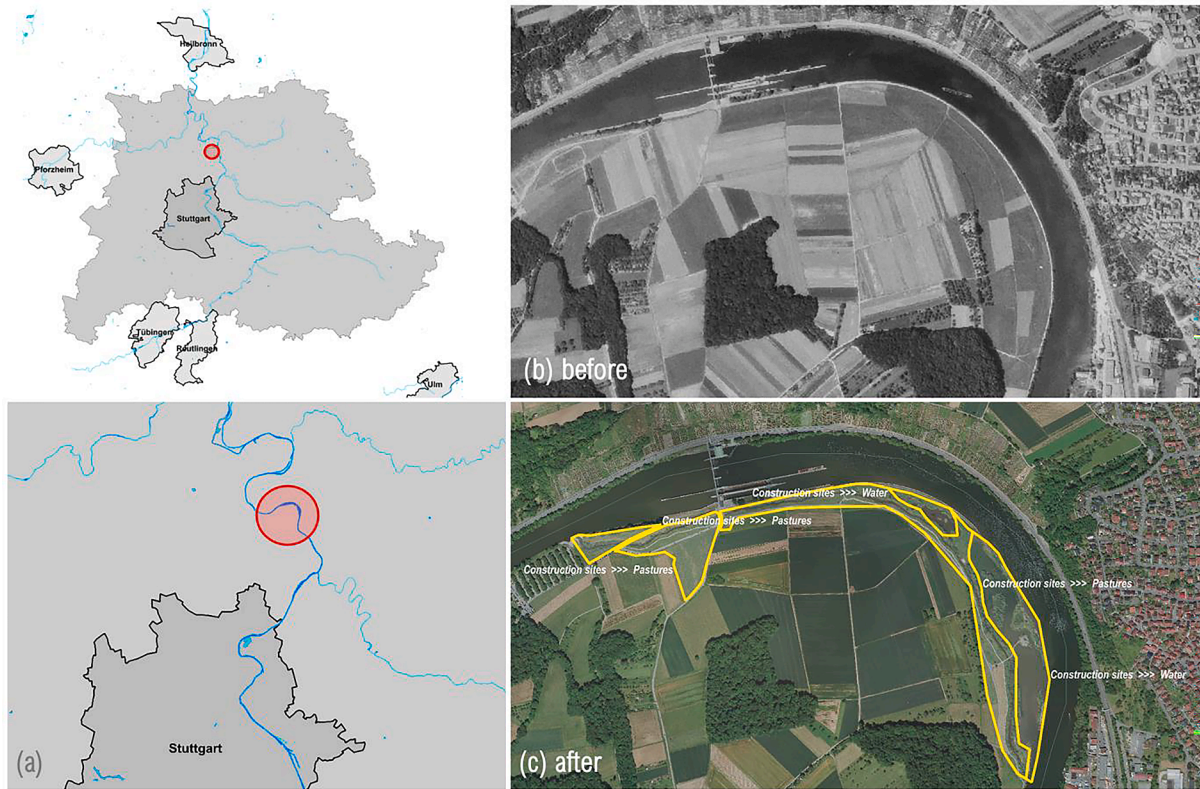


Fig. A4. LULC change along Nectar River following the LIFE + project “My favourite river” in Zugwiesen (a) (as reported by Steege et al., 2022). Before and after historical orthophoto images (b and c) are derived from the geoportal of Baden-Wurttemberg Federal State ().

Data availability

The raw data used in this study are available from Copernicus, Land Monitoring Service by European Union via the following link, <https://land.copernicus.eu/en/products/urban-atlas>. The coastline of Europe is derived from (<https://www.eea.europa.eu/data-and-maps/data/eea-coastline-for-analysis-1/gis-data/europe-coastline-shapefile>), and the running waters network was derived from <https://land.copernicus.eu/en/products/eu-hydro/eu-hydro-river-network-database>. The datasets generated and analyzed during the current study are archived in the Zenodo public repository and are available via the following DOI: <https://doi.org/10.5281/zenodo.14177606>.

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