

The Industrial Transformation of the Viennese Danube in the 19th Century. A Socio-Metabolic Approach to an Urban Riverscape

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Title

The Industrial Transformation of the Viennese Danube in the 19th Century. A Socio-Metabolic Approach to an Urban Riverscape

Abstract The transition from agrarian to industrial metabolism in the 19th century reshaped Vienna's colonisation of its Danube floodplain. This article investigates the socio-metabolic implications of the 1870-1875 industrial regulation of the Danube, which converted the dynamic, meandering river system into a stable, single-channel waterway. Utilising GIS (Geographic Information System) reconstructions of historical cadastral data from the district of Leopoldstadt, the study compares the landscape of the 1820s, governed by its agrarian metabolism, with the evolving industrial landscape of 1893. The research tests two central hypotheses. First, that industrial regulation increased the degree of landscape colonisation by incorporating previous 'hybrid' areas, such as gravel banks; and second, that this stabilisation enabled the rapid, extensive urban colonisation of the former floodplain. The findings highlight that industrial regulation profoundly altered colonisation practices in the floodplain, enabling urbanisation to grow fourfold. The regulation also enabled a more profound colonisation of 'hybrid' areas by reducing them in extent. Furthermore, understanding societal interventions into natural systems within the context of a socio-metabolic interaction system allows us to make a direct connection between the material and energy flows of societies and their corresponding landscapes.

Keywords Vienna · Danube · Urban Metabolism · Land Use Change · Industrialisation · River Regulation

Introduction

Between 1870 and 1875, a major river engineering project regulated the dynamic, meandering Viennese Danube, transforming it into a single, stable riverbed. This profound alteration of the river's ecological and hydrological characteristics was achieved using coal-powered excavators that had previously been field-tested during the construction of the Suez Canal (Békési, 2016). In the context of 19th-century urbanisation, the regulation was not an isolated event for Vienna, as coal-based industrialisation began to affect the city in different ways. The uncoordinated interaction among urban sectors – transport and construction, as well as industrial production – led to a new type of industrial city- and landscape that did not remain at the margins but eventually affected every aspect of society. The underlying trend behind the

new landscape, a shift in the energy and material flow regime of societies in relation to their natural environment, has been conceptualised within a general framework of social or urban metabolism (Fischer-Kowalski, 1998; Fischer-Kowalski & Hüttler, 1998; González De Molina & Toledo, 2014). To understand the engineering project on the Viennese Danube and its subsequent repercussions for Vienna's metabolism and landscape transformation, we adapted Sieferle's (1997) socio-metabolic interaction system for the case study.

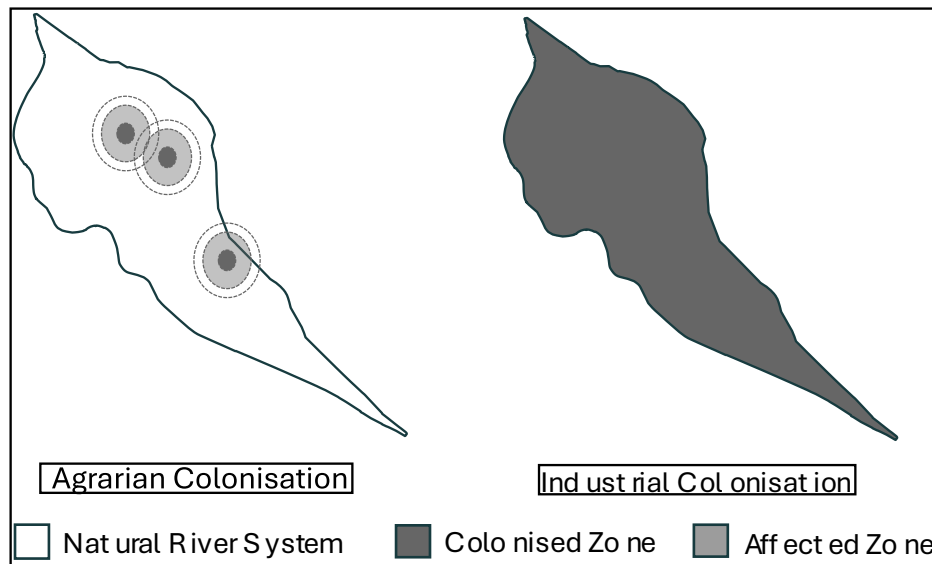


Fig. 1 Socio-metabolic interaction system, adapted from Sieferle (2011). Left side shows agrarian colonisation, with its zones of artefacts as its center. From there effects on the surrounding natural riverscape emanate, which can overlap. The industrial regulation has removed the natural riverscape, transforming the whole study area in a colonised zone.

Fig. 1 schematises the differences in colonisation¹ between agrarian and industrial metabolism. Within the agrarian metabolism, Vienna interacted with and physically altered the natural riverine system of the floodplain through processes of colonisation by performing work, either directly through its population or indirectly through animals and machinery. Colonisation of the natural river system remained incomplete, but it enabled the utilisation of agricultural and horticultural plots, as well as the construction of infrastructure and artefacts such as buildings, bridges, and river-regulation structures. Colonisation is no self-sufficient endeavour and requires ongoing maintenance through work. Beyond zones of actively maintained artefacts, colonisation on the highly dynamic floodplain had unintended consequences in adjacent zones. A spatially discrete regulation of the river altered its hydrology and sedimentation patterns not only at that point but also potentially upstream and downstream, thereby affecting the river's morphological dynamics. If observed, unintended effects of the regulation could be resolved, thereby completing the interaction between the societal and natural systems and, in the process, possibly creating new unintended effects. The boundary

¹ In social metabolism, colonisation describes the controlled intervention of societies into natural systems with the aim of gaining societal functions, such as the cultivation of plants for consumption. For a conceptual introduction, consult Fischer-Kowalski & Erb (2016). For a historical application, Schmid (2022).

between the affected and unaffected natural riverscape is conceptually difficult to assess, as the point at which hydromorphological alteration occurs in river regulation is gradual.

In the Viennese floodplain, the industrial regulation from 1870 to 1875 – aptly named the ‘Great Regulation’ – created an industrial riverscape. The industrial regulation colonised every corner of the Viennese Danube, suspending the river system's natural dynamics along an entire stretch. Within the industrially colonised riverscape, artefacts could safely be integrated into the city’s industrialising metabolism. In the following decades, amid industrial advance, the limitations and flaws of the first industrial regulation became more evident, eventually resulting in another regulation of the Danube.

The Viennese floodplain and its first industrial colonisation have attracted considerable interest from various perspectives, beginning with the regulation itself (Békési, 2016; Hauer & Hohensinner, 2023). A substantial body of studies has focused on long-term developments in the floodplain, including land-use changes (Haidvogel et al., 2013), the dynamics of river morphology (Hohensinner et al., 2013), the impact of regulations on urbanisation (Hauer, 2016), and flood-protection measures throughout history (Hohensinner & Schmid, 2016). This interest in the Vienna waterfront culminated in the publication of a book aptly titled ‘Wasser Stadt Wien’ (Water City Vienna) (Zentrum für Umweltgeschichte, 2019).

Historical urban metabolism studies that focus on the interaction between the city and a waterbody, such as rivers, primarily examine input-output relationships during the industrial transformation. For Vienna and the Danube, scholars have emphasised the river's role as a supply and sewage infrastructure (Gingrich et al., 2012; Gierlinger et al., 2013). Outside Vienna, Watson et al. (2024) applied the same framework to Lake Ontario as a resource hinterland for Toronto, and Barles (2007) applied it to Paris and the Seine's disposal capacities; Olson (2007), meanwhile, explores how hydrological differences – such as Montreal's quick-draining St. Lawrence River and Baltimore's more maritime tidal zone – affect sewage treatment approaches in two North American cities. Häfner's (2026) historical study of Moscow and the Moscow River emphasises natural disasters but lacks a socio-metabolic framework. Meanwhile, Niza et al. (2016) have highlighted historical urban land use that is not explicitly linked to water bodies, while Resch and Lestel (2025) have studied a historical floodplain area without a socio-metabolic framework.

The objective of this article is to identify key differences in landscape characteristics between agrarian and industrial urban riverscapes, thereby contributing to the existing body of research on the Viennese floodplain and its regulation, as well as to a landscape-based approach in urban metabolism studies. The agrarian landscape in social and urban metabolism is

associated with stability. Due to energy constraints, local materials must be used and handled in particular ways when colonising landscapes, giving them a unique appearance and distinct style. Due to enhanced transport capabilities enabled by the mechanical energy potential of fossil fuels, the industrial landscape shifts away from dependence on local and regional materials toward reliance on nationally or internationally sourced materials. This shift is accompanied by an acceleration of societal trends that no longer follow local traditions or existing architectural styles, but instead follow the state of the art, what is modern, in relatively short time intervals (Sieferle, 2003). Floodplains subvert those expectations, as agrarian societies could not fully colonise them, thereby allowing the river to maintain its hydromorphological dynamics. Only within industrial parameters was it possible to stabilise the Danube and then extend the established pattern of industrialisation already present elsewhere in the city to the industrialised riverscape. The analysis will progress in three steps: first, the source material and methodology will be presented. Next, the relationship between Vienna and the Danube floodplain within the agrarian and later industrial urban metabolism will be analysed separately, drawing on the source material. Finally, the 1820s agrarian and 1893 industrialised floodplain will be compared directly.

These sections are guided by two main hypotheses. First, the 1870-1875 industrial regulation was intended to clearly separate terrestrial from aquatic areas, thereby creating a uniform riverbed corridor exclusively for steamship use, with increased water depth to accommodate steamships' increasing draught, while the remaining area was devoted solely to the city and its needs. An important indicator of this colonisation of the landscape is the industrial metabolism's ability to remove landscape features that could not be clearly reduced to aquatic or terrestrial land use following the 1870-1875 industrial regulation. The industrialised riverscape, therefore, contained fewer 'hybrid' landscape elements than the preceding agrarian one. For the anabranching river, prior to the 1870s, gravel banks were part of the riverscape, a necessity of its dynamic hydromorphological processes, but a nuisance to many societal interventions.

The second hypothesis concerns urbanisation in the former floodplain after the 1870-1875 industrial regulation. By restricting seasonal flooding to a designated inundation area on the left riverbank across the downtown core, urban colonisation of newly created terrestrial areas progressed unhindered. The source material also identifies spatio-temporal patterns of landscape shifts beyond urbanisation, providing insights into changes in colonisation within the floodplain.

Sources and Methods

The primary sources for reconstructing the Viennese floodplain landscape are cadastral surveys. For the period after the Great Regulation, a 1893 cadastral plan of Vienna is used (Cadastralplan, 1893). For practical reasons, the area under investigation was limited to the political entity of the second Viennese district, Leopoldstadt, where most of the Viennese floodplain was situated. The historic district of Leopoldstadt included today's 20th district, Brigittenau, which was separated in 1900, and parts of the left bank across the regulated main arm, which were later incorporated into the 21st and 22nd districts. To aid orientation, Fig. 2 shows the location of Vienna within Austria and of the historic Leopoldstadt within current-day Vienna. Finally, the Leopoldstadt figure on the left highlights places mentioned in the manuscript.

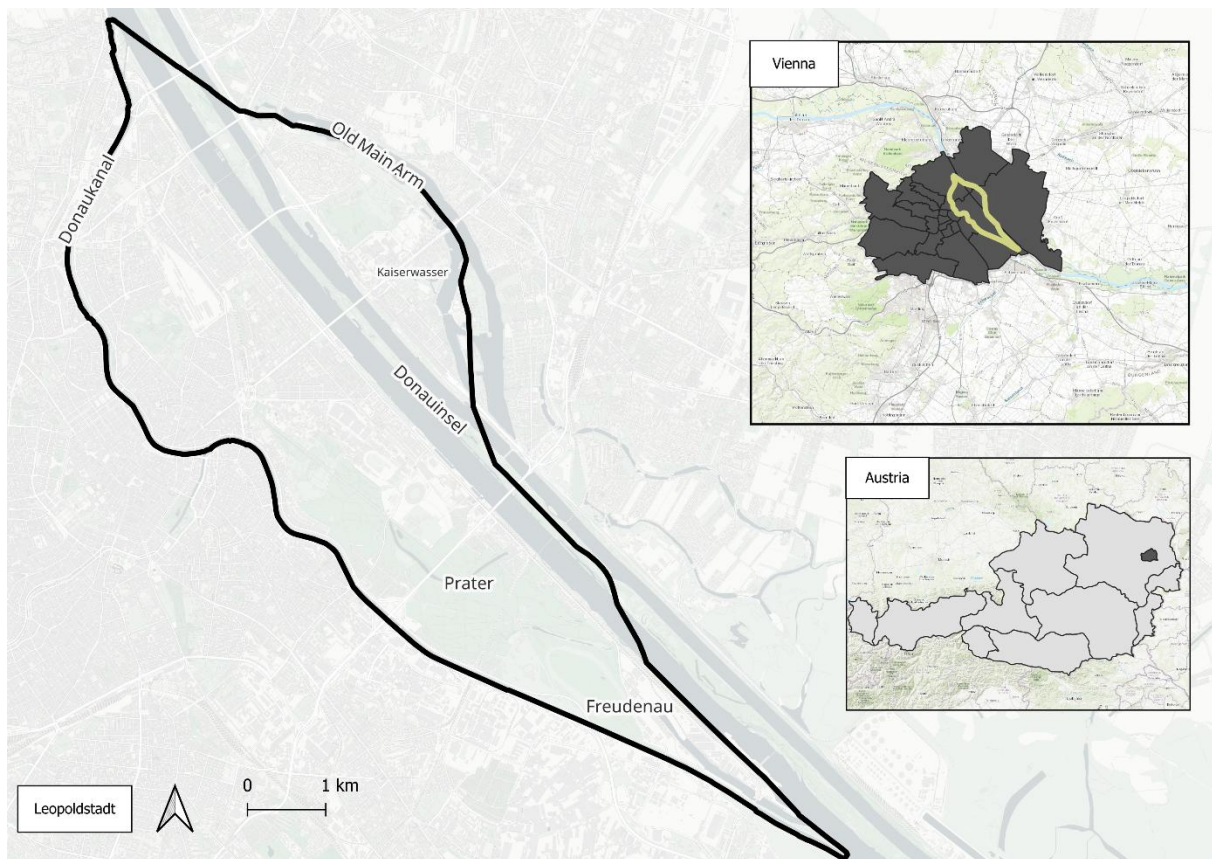


Fig. 2 Leopoldstadt within its 1893 borders. Highlighted are places of interest that appear in the manuscript. Data for Vienna from *Bezirksgrenzen Wien (2025)*, for Austria from *Natural Earth*. The base layer for the main view is *CartoDB Positron [no labels] base layer* (© CartoDB, CC BY 3.0), while the overviews use *ESRI World Topographic Map* (© ESRI).

The cadastral plan was georeferenced in QGIS, and a vector layer of parcels under cultivation was created by combining it with data from the 1892-1894 parcel list of Vienna (WStLA, 1893-1894). The parcel list was updated through 1894 in some areas, but not all, making the assessment of the parcels somewhat arbitrary. Overall, 10 sheets had to be georeferenced to map all parcels in the historical Leopoldstadt district. These cadastral sheets

did not meet satellite-like accuracy standards, requiring adjustments to parcels along sheet borders.

The reference state before the industrial regulation of 1870 to 1875 is based on the Franciscan Cadastre, which captures the landscape of the 1820s (WStLA, 1817-1824 and 1822) – the cadastre was introduced in the Habsburg monarchy in the late 18th century to establish a new standard for taxation, with the Franciscan version being its second iteration during the rule of emperor Franz I. of Austria (Scharr, 2017). The city of Vienna provides an open-source vector layer of the Franciscan Cadastre that required only minor modification (Franzische Kataster Wien, 2025). Leopoldstadt and Jägerzeile, as they were called at the time of the Franciscan Cadastre, encompassed a smaller area than their later editions, extending as far into the river as in 1893, but including only a small part of the Prater (Fig. 2). To make comparison in both points in time easy, we expanded the area of investigation in the 1820s cadastre to the spatial borders of Leopoldstadt in 1893, spanning around 31 km².

The cadastral plans primarily served the purpose of a consistent standardised taxation method. This means the cadastral list primarily contains phenomenological assessments of parcels rather than their actual use (e.g., a forest could be utilised quite differently for silviculture or recreational purposes).

Between the Franciscan Cadastre and the 1892-1894 cadastral parcel list of Vienna, the surveyed categories were simplified, so the databases for both spatial reconstructions had to be made congruent, mostly by reducing the number of categories for Fig. 3. The categories vegetable garden, orchard, park, and ornamental gardens had been summarised into a single category, gardens, by 1893, thereby losing valuable information about whether the parcels contributed to subsistence or recreation. To answer research question one, we created a new category of hybrid parcels from the Franciscan Cadastre, encompassing gravel banks and swamps that constituted mostly silted-up, disconnected Danube side arms, and ditches near meadows, which were of limited use to agrarian Vienna due to its limited capacity for colonisation. A land-use GIS reconstruction of a dynamic floodplain is hampered by year-round fluctuations in the water table. This is something we cannot incorporate into our analysis, but it should nonetheless be acknowledged. Meadows were subdivided into three categories: those frequently inundated with uneven terrain close to the river. Those used only for hay production and those that contained fruit trees. The broadest category amalgamation from the Franciscan Cadastre involved urban parcels, including river regulation structures, paths and streets, including bridge piers anchored in the river, as well as wooden and stone buildings.

For the 1893 cadastral plan (Fig. 5), the adjustments did not need to be as extensive. Here, the difficulty in categorisation lay in the data provided in the parcel list and their correspondence with the cadastral plan. While the cadastral plan remained unchanged, the parcel list was continuously updated. This issue became especially apparent when forests and meadows were swallowed up by urbanisation between 1893 and 1894. In some cases, parcel categories were simply crossed out with no alternative specified, suggesting that urban construction on these parcels was either planned for the near future or the area had already been cleared. If construction was already underway, it was specifically noted. As this vector layer was the original starting point for the GIS reconstruction, to save time in building it, only polygons deemed non-urban were drawn, totalling roughly 2800 parcels. The remaining areas were filled in as a single urban polygon. The urban category is thus an amalgamation of agrarian transport infrastructure (paths, streets, and bridge piers), buildings (and building sites), and train infrastructure. That the landscape was in flux is also evident in newly added forest and pasture parcels in the 1892-1894 parcel list that lacked data related to soil quality, which was normally included for every ‘harvestable’ category, such as fields, forests, gardens, meadows, and pastures. Those forest and pasture parcels were integrated into their respective umbrella categories. Beyond these observations, the only meaningful deviation from the cadastral list is the hybrid category we created. This category includes the remaining, but hydrologically disconnected, former side arms of the Danube that were deemed unusable (“unproduktiv”) for the time being by the cadastral surveyors. They are similar to the swamps in the Franciscan Cadastre, which were included in the 1820s hybrid category.

Fewer categories appear in the cadastral list of 1892-1894 than in the cadastral appraisal 70 years earlier. This is a stark reminder that the cadastres are historical documents that must be understood in their historical context; what was considered relevant for taxation in the 1820s was no longer necessarily relevant in 1893.

The Riverine Landscape in the Agrarian Energy Regime

In the 1820s, Vienna still relied primarily on biomass for energy, while coal use remained marginal (Gierlinger et al., 2016). Its population of ca. 270,000 had already outgrown the surrounding area's resource capacity by 1822 (Magistrat der Stadt Wien, 1912, p. 44), necessitating an extensive agricultural and forestry hinterland (Krausmann, 2013). This hinterland was effectively extended by incorporating the Danube into its transportation infrastructure (Gingrich et al., 2012). Nonetheless, urbanisation into the floodplain progressed slowly. Colonisation of terrestrial areas remained largely confined to agricultural and forestry

production and to hunting for the nobility. The river served as a shipping route and a power source for ship mills when it was free of ice (Spitzbart-Glasl, 2016). In winter, ice could be harvested for food preservation (Winiwarter et al., 2013). Over the centuries, Vienna thus maintained an agrarian landscape within the river's highly dynamic natural environment.

The line between what would still count as a natural, unaffected landscape and what was affected, directly or indirectly, by colonisation is heavily blurred. Urban artefacts remained largely compartmentalised because energy and material densities were insufficient to permanently stabilise the waterfront, necessitating frequent reconstruction (Hohensinner et al., 2013). By 1821, the floodplain area of the second district of Leopoldstadt contained 654 buildings and housed a population of just over 24,000, averaging out at 37 persons per housing unit (Weschel, 1824, p. 541).

At the same time, the cadastral land appraisal found that roughly 45 per cent of the district was unusable (“unbenutzbare Gründe”) but did not clarify in detail what that term meant. Nonetheless, its narrative is telling, offering a contemporary commentary on the assessment of the floodplain (NÖLA, 1821-1835). Especially aggravating to societal control were the floodings and ice jams, which not only threatened buildings and infrastructure such as regulation works and bridges across the Danube, but also human life on the floodplain (e.g., Haidvogel et al., 2013), and drove major morphological changes there (Hohensinner et al., 2013). This also challenged the juridical understanding of landownership, as some floodplain islands expanded while others shrank, and entirely new islands emerged from the river, prompting societal actors to scramble for ownership of these new tracts of land (Sonnlechner et al., 2013).² Furthermore, due to a mix of geological and river morphological characteristics, the Danube shifted away from Vienna, thereby threatening the city's direct access to its shipping network. To prevent this, the sidearm of the river closest to the city was stabilised and regulated, over centuries, to create the Donaukanal from the Vienna Danube arm (‘Wiener Arm’) (Fig. 2; Hohensinner & Hauer, 2019b).

In the agrarian urban riverscape of the 1820s, forests dominated the landscape, covering 34% of the area (Fig. 3). This underscores the importance of wood reserves near urban areas and highlights the city's inability and unwillingness to colonise the river floodplain more extensively. The appraisal reports lament that the lower-quality forest parcels resulted from the nobility's hunting rights, which led to increased deer browsing, rather than from poor soil conditions, as was the case with meadows. Part of the decline in the quality of forest parcels

² Per WStLA [1817-1824](#), the largest landowners at the time were the ‘Bürgerspital’ of Vienna, the municipality of Leopoldstadt, the emperor, Franz I., and the monastery Klosterneuburg

was due to livestock grazing, for which the owners were compensated financially (NÖLA, 1821-1835). Both examples illustrate the multiple pressures the alluvial forest faced within Vienna's agrarian metabolism. 27% of the district was used as meadows, highlighting the importance of hay production near the city. By 1830, mobility within the city hinged on the draft capacity of 5,000 horses, a figure that continued to rise well into the 20th century (Gierlinger, 2015).

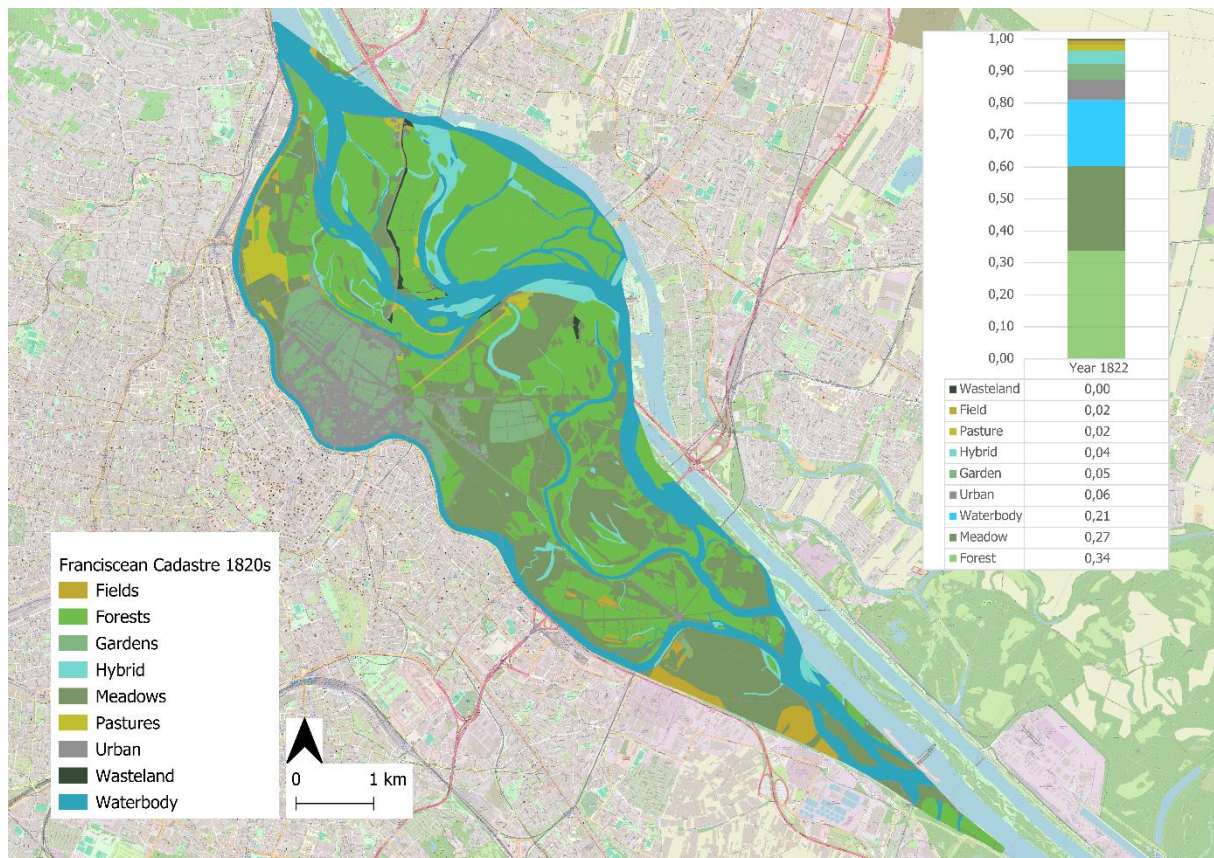


Fig. 3 The map overlays the Franciscan Cadastre (1820s) onto an OpenStreetMap Standard base layer (© OpenStreetMap contributors). The stacked bar chart and the table illustrate the relative share of each category. Data from Franziszeischer Kataster Wien, 2025.

As with the forests, meadows should not be treated as a monolith in terms of what grew there and how they were used. While frequently inundated meadows were generally mown only once a year, those in drier areas could be harvested twice (NÖLA, 1821-1835). The meandering Danube covered 21% of the floodplain and, together with meadows and forests, formed the most significant categories, accounting for over 80% of the agrarian landscape of Leopoldstadt. The river also contributed to Vienna's urban metabolism by supplying the city with fish (Wrška, 2011; Haidvogel, 2019). All remaining categories accounted for only about 20% of the total floodplain landscape. Here, urban artefacts remained the largest group, at around 6%. The houses in Leopoldstadt were built closest to the historic nucleus of Vienna, on the right bank of the Donaukanal (Haidvogel et al., 2013). Beyond the residential areas, parks such as the Augarten were established in or near them to serve both private and public recreational needs. Some paths

led deeper into the Prater and towards the nobility's hunting grounds. A marked urban feature remained the street crossing north (in Fig. 3, it can best be identified by the wasteland area next to it, creating a black line). This was the only way to fully cross the Danube in Vienna at the time, and it required crossing four separate wooden bridges, all of which were vulnerable to flooding and ice jams. The river regulation measures accounted for only a small fraction of the urban artefacts, yet they nonetheless gave the Donaukanal its distinct form and fixed riverbed. Gardens at 5% remained largely within the residential area, with only the ornamental gardens located farther from the houses.

The 4% of hybrid areas were mainly located in the district's less-colonised northern half, near its main arm (Fig. 2), between two of the floodplain islands. Pastures and fields each accounted for only 2% of the total area. Pastures were concentrated north of the residential area, while the fields lay relatively disconnected at the southern end of the district. Wasteland features prominently along the road out of Vienna heading north, but accounted for well below 1% of the total area.

Colonisation of the floodplain remained spatially fragmentary. Extensive agricultural practices remained the dominant form of colonisation within the floodplain, while more intensive land use, in the form of field cultivation and the construction of urban artefacts, remained limited. River regulation was confined to a spatially minor sidearm of the riverine landscape, while the river itself served as a restraining and guiding force in city development. Interaction between Vienna and its natural floodplain remained highly dynamic.

The Riverine Landscape of the Industrial Transformation

Industrialisation in the Viennese floodplain began well before its industrial regulation in 1870. While the Franciscan Cadastre recorded the extent of colonisation capacities within a riverscape by an agrarian energy regime, by 1838, Vienna's metabolism was beginning to hinge structurally on the availability of coal, with the construction of its first railway line to the coal deposits of Moravia (Österreichische Bundesbahnen, 1937, p. 11). Eight years earlier, regular steamship service on the Danube had already been introduced (Dosch, 2009, p. 10). Both modes of transportation placed new demands on the surrounding landscape. Steamships were developing a greater draft than their non-motorised counterparts, while railroads needed stable bridges to cross the dynamic floodplain. The demands of fossil-fueled transportation also informed the planning of the industrial regulation in the early 1870s. By the 1860s, the state of the Danube was deemed untenable (“unhaltbar”) by the commission tasked with determining whether, and to what extent, regulation should be imposed, and a “rational” and “radical”

organised Danube was now, in their words, more feasible. The commission's assessment of regulation was not only focused on addressing immediate needs in flood protection, river navigation, and railway infrastructure, but also on providing spatial flexibility for future infrastructure. In particular, the railway required vast tracts of land for its operations, while both modes of transport required additional space for freight warehousing (Anonymous, 1868, pp. 14 and 65). Coal use in Vienna remained marginal in the 1820s, but by 1870 it had surpassed biomass energy (Gierlinger et al., 2013).

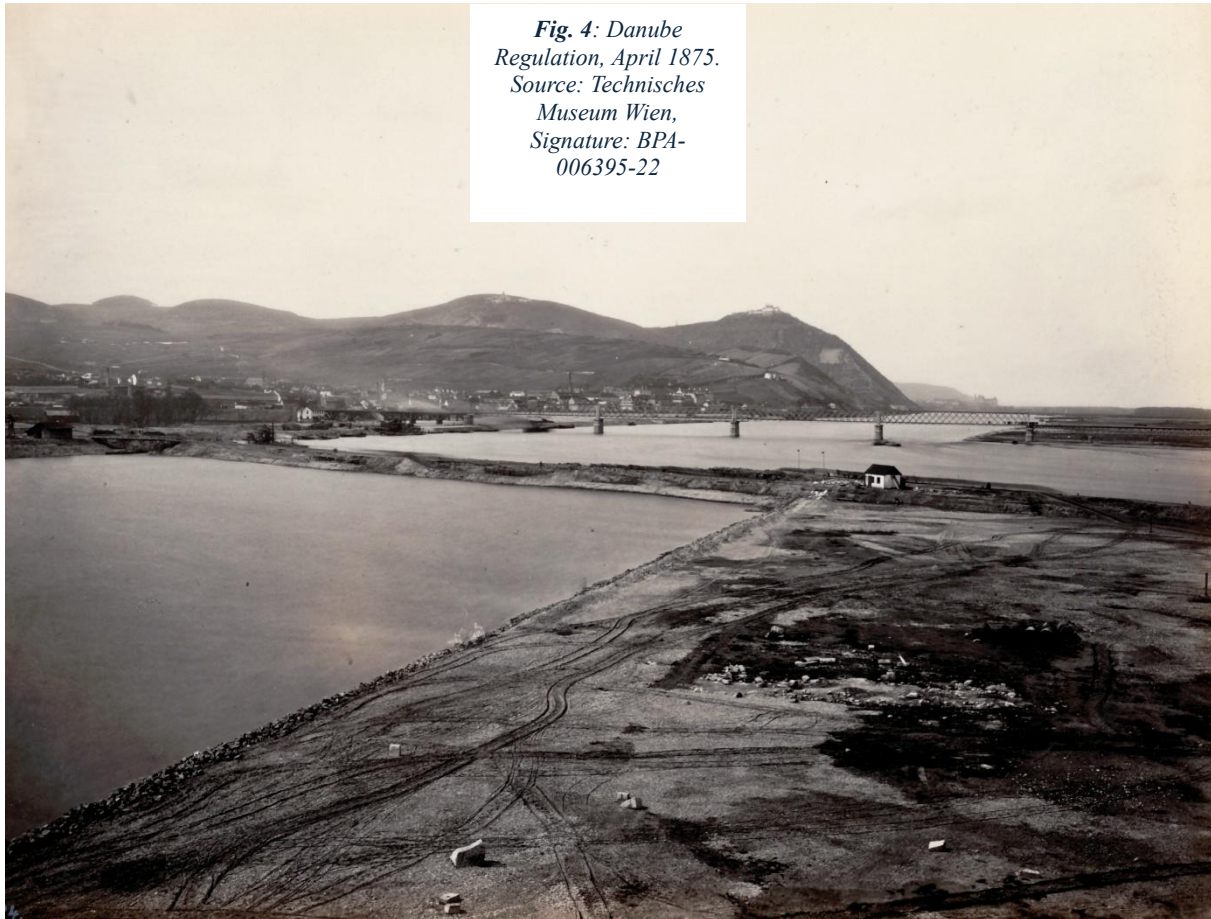


Fig. 4: *Danube Regulation, April 1875.*
Source: *Technisches Museum Wien,*
Signature: *BPA-006395-22*

The regulation was a spectacle, showing the tremendous new scale at which steam engines could alter a landscape, once dominated by floodplain forests, gravel banks and meandering river arms (Fig. 4). Previous regulatory efforts focused on maintaining a sidearm, the Donaukanal, connected to Vienna. However, with the Great Regulation, the Danube's floodplain features were removed, eliminating the river's hydromorphological dynamics and future concerns about the river shifting further away from the city (Hohensinner, 2019). Overall, the regulation was supposed to make the riverscape better suited to the city's industrialising social metabolism. The new riverbed had to accommodate the increasing size of steamships, as the Donaukanal, the artefact of the agrarian energy regime, was too shallow for their draught. The new fixed riverbed enabled the construction of bridges with a reduced risk of damage from flooding and ice jams (Haidvogel et al., 2013; Hohensinner et al., 2013). This was particularly

beneficial for trans-Danubian rail transport to North Moravia and Silesia and to their coal deposits. Simultaneously, the regulation provided land for the necessary freight stations and opened a new area to urbanisation. To protect it from flooding, this newly created area was raised using material excavated from the floodplain by coal-powered steam excavators. Flooding was to be confined to the newly created left riverbank and its 475-metre-wide inundation area, which flooded on average once a year, thereby protecting the city on the right bank (Michlmayr, 2005). On the right bank of the river, a new city skyline was planned to emerge ('Donaustadt'), but these plans proved overly optimistic, at least in the short term (Hauer & Hohensinner, 2023).

The agrarian urban riverscape of Vienna did not gradually recede during the city's industrial transition. Instead, it was abruptly transformed in the absence of alternatives for managing floodplain dynamics. Whereas the agrarian landscape of Vienna had to be planted and maintained within the natural riverscape, well adapted to the permanent threat of the natural system, the industrial energy regime disregarded all natural floodplain dynamics and created an industrial riverscape that remained largely under societal control. With the regulation completed in 1875, Vienna's growth spurred subsequent colonisation and the development of the industrial riverscape. In 1869, the year before the regulation, the district of Leopoldstadt had already reached a population of 84,477 (an increase of around 250% since 1822). In 1880, five years after the regulation was completed, the number stood at 118,577, and by 1890, it was 158,374. The number of constructed buildings had climbed from 654 to 2,574 (Magistrat der Stadt Wien, 1912, p. 45). This development also coincided with a substantial increase in the number of people per housing unit, from around 37 to 62, likely linked to more floors and less available living space per person.

In 1893, forests covered 23% of the landscape in Leopoldstadt (Fig. 5), including parcels either within the zone regulated between 1870 and 1875 or already in heavily urbanised areas. In both instances, the 1893 parcel list provided quantitative information on parcel quality, but no extensive qualitative discussion of the soils. A forest on the right bank of the channelised Danube is highly unlikely to have survived the regulation, as Fig. 4 indicates. Many of those parcels remained in the possession of the Danube regulation fund, suggesting problems selling them, while a young forest had emerged there.

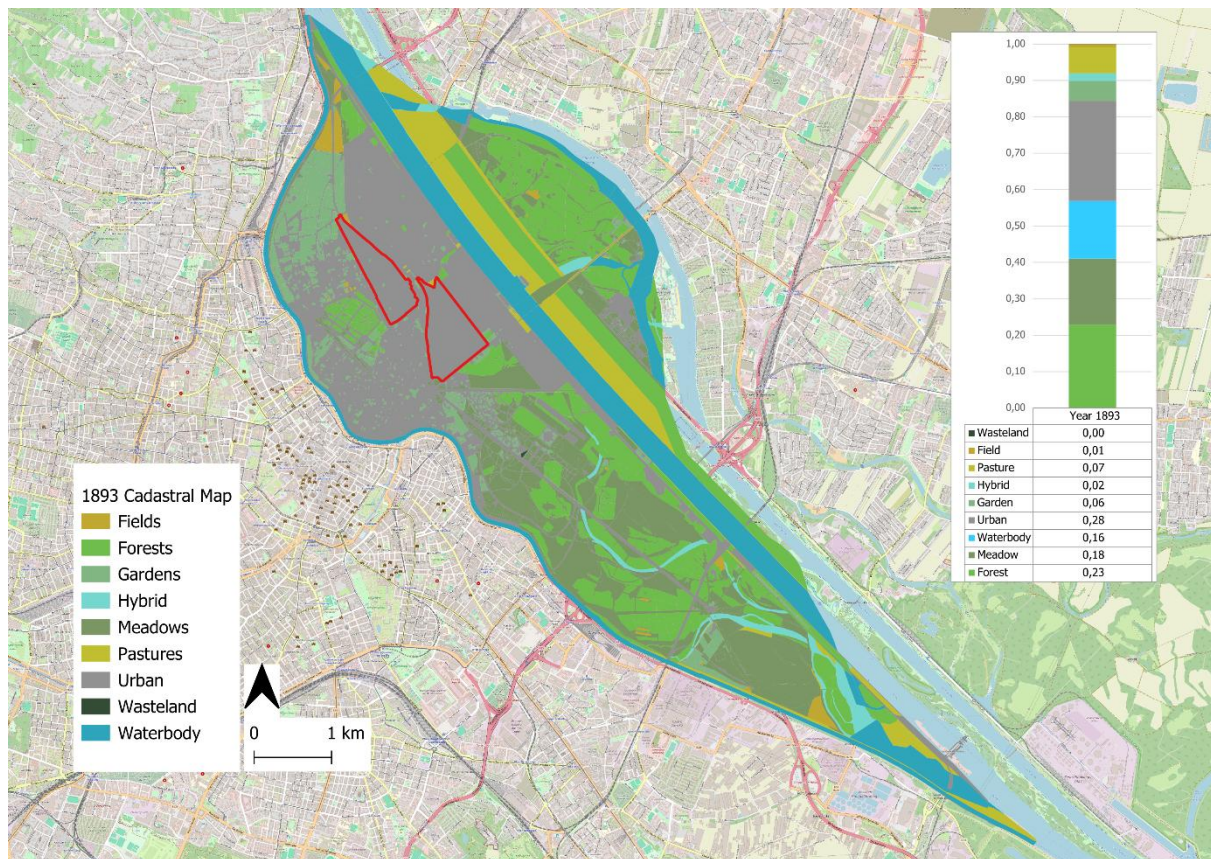


Fig. 5 Vector layer based on the 1893 Cadastral map, overlaid on an OpenStreetMap Standard base layer (© OpenStreetMap contributors). The red outlines indicate the two railheads. The stacked bar chart and the table illustrate the relative share of each category.

Meadows stood at 18%. Those that could be harvested only once a year had disappeared with the floodplain, while new meadows on the left riverbank had come into use by 1893. A new recreational use for meadows was introduced with the construction of two horse-racing tracks in the Prater (Reeger, 2005). Accounting for 16% of the area, the Danube has become restricted to the new main channel, the Donaukanal, which had existed before, and the former main arm to the northeast, now hydrologically disconnected from the main channel, though still connected to its groundwater. During the 1890s, the area in the Freudenuau (Fig. 2) was still being worked on (Schmid, 2013). The urban area now constituted 28% of the district. The residential area expanded from its nucleus and spread onto the left riverbank, where there had previously been no urban features except for the one road crossing the river. Industrial ventures now operated in the district, most prominently the terminal stations for two railroads (red framed areas in Fig. 5). Large areas were also required for a gas plant, a warehouse, the 1873 World Fair building, a river transport discharge area, and a river navigation control building. Gardens stood at 6% and, as in the 1820s, remained close to the residential area. Most prominently, a large garden area had appeared north of the residential area. Hybrid areas accounted for 2%, while pastures accounted for 7%. Most of the pasture was on the newly created strip of land that served as an inundation area on the river's left bank. It faced hurdles

similar to those of the floodplain meadows of the non-channelised Danube, as it was flooded, on average, once a year, temporarily reducing the capacity for livestock grazing. It is also important to note that the area was one of the largest recreational sites, serving as a precursor to the Donauisland.³ The remaining 1% of fields at the district's margins, and the still well below 1% of wasteland, round out Leopoldstadt in 1893.

The industrial riverscape had undergone two transformative processes of colonisation. The industrial regulation had suspended natural floodplain dynamics in the Viennese Danube basin. With the riverbed stabilised, disconnected sidearms remained for scenic purposes within the Prater or where regulation was still incomplete, as in Freudenu. In this already colonised riverscape, Vienna was able to implement artefacts without fear of disruption from the river system. Urban colonisation proceeded extensively, leading to the recreational use of additional land in the Prater and the inundation area. With the industrial regulation completed and the industrial metabolism taking hold in Vienna, natural floodplain dynamics were discontinued. The river still regularly threatened to reintroduce natural river dynamics. In 1876, the dam protecting the left bank partially collapsed under the pressure of an ice jam, necessitating its restoration (Hohensinner & Hauer, 2019a). Interaction between city and natural floodplain ceased while Vienna was eager to maintain control over the industrial landscape.

The spatially restricted industrial regulation of the Danube in Vienna was a precursor to developments yet to come in the 20th century (Schmid et al., 2023), when industrial colonisation not only remained fragmentary but became the dominant form of colonisation, forming a total landscape (Sieferle, 2003) that provoked societal backlash against industrial ‘progress’ (Schmid & Veichtlbauer, 2006). To name but one example, the Danube was severely colonised by the construction of hydropower dams in the 20th century, which reduced sedimentation and hampered fish migration.

³ By 1972, the 1870–1875 regulation was deemed outdated in its capacity to protect the city from floods. For that reason, the Danube was regulated once more, with the river divided into two arms by the ‘Donauinsel’. This regulation was even more elaborate than its predecessor and took 16 years to complete, finishing in 1988 (Nußbaumer & Krippner, 2026).

Comparative Analysis

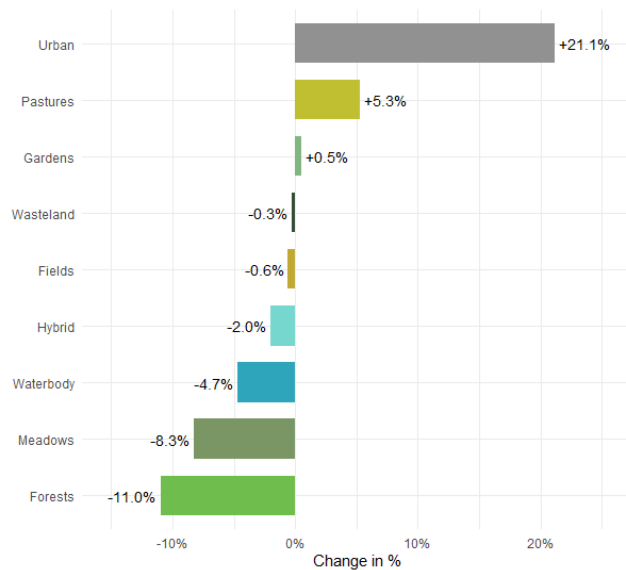


Fig. 6 Total change in landscape categories between the two reconstructions

industrial regulation significantly reduced the share of hybrid landscape elements from 4% to 2% of the total area, thereby increasing the area available for colonisation. Meanwhile, the trend in urbanisation is clear. Urban areas expanded, while forests, meadows, waterbodies, and hybrid areas experienced substantial loss. The only exception was pastures, which can be explained by the multiple-use character of the newly created inundation area for flood protection and pasturing (as well as a recreational area in summer).

The spatial pattern of urbanisation is illustrated in Fig. 7. The left figure shows the extent of the urban artefacts in the agrarian floodplain and the developed urban area by 1893. Urbanisation had expanded from its core near the Donaukanal towards the regulated main arm, including the railhead stations and, near the new Danube arm, the Donaustadt at or near the waterfront. A new dense urban area emerged in trans-Danubia, spearheading residential development on the opposite bank. A grid of newly created paths spanned the entire district, while the new ‘Donauuferbahn’ (Danube bank railway line) was part of a transport network that ran along the Danube through almost the whole district. Development south of the residential area advanced with the construction of the World Fair site in the Prater. The urban area of the Franciscan Cadastre accounted for only 18.6% of the total urban area by 1893, ranking below forests (29.9%) and meadows (19.1%). Previous Danube arms represented 15.2%, and Gardens, which had been located on the outskirts of the residential area in the 1820s, were largely absorbed, accounting for 9.4% of the urban area in 1893.

It is clear from the separate GIS reconstructions that the agrarian and industrial riverscapes differed markedly. While the direct effect of industrial regulation cannot be measured exactly, the reconstructions show the general impact of colonisation capacities across the two energy regimes. Fig. 6 summarises the differences between the landscapes. The findings support the hypothesis that

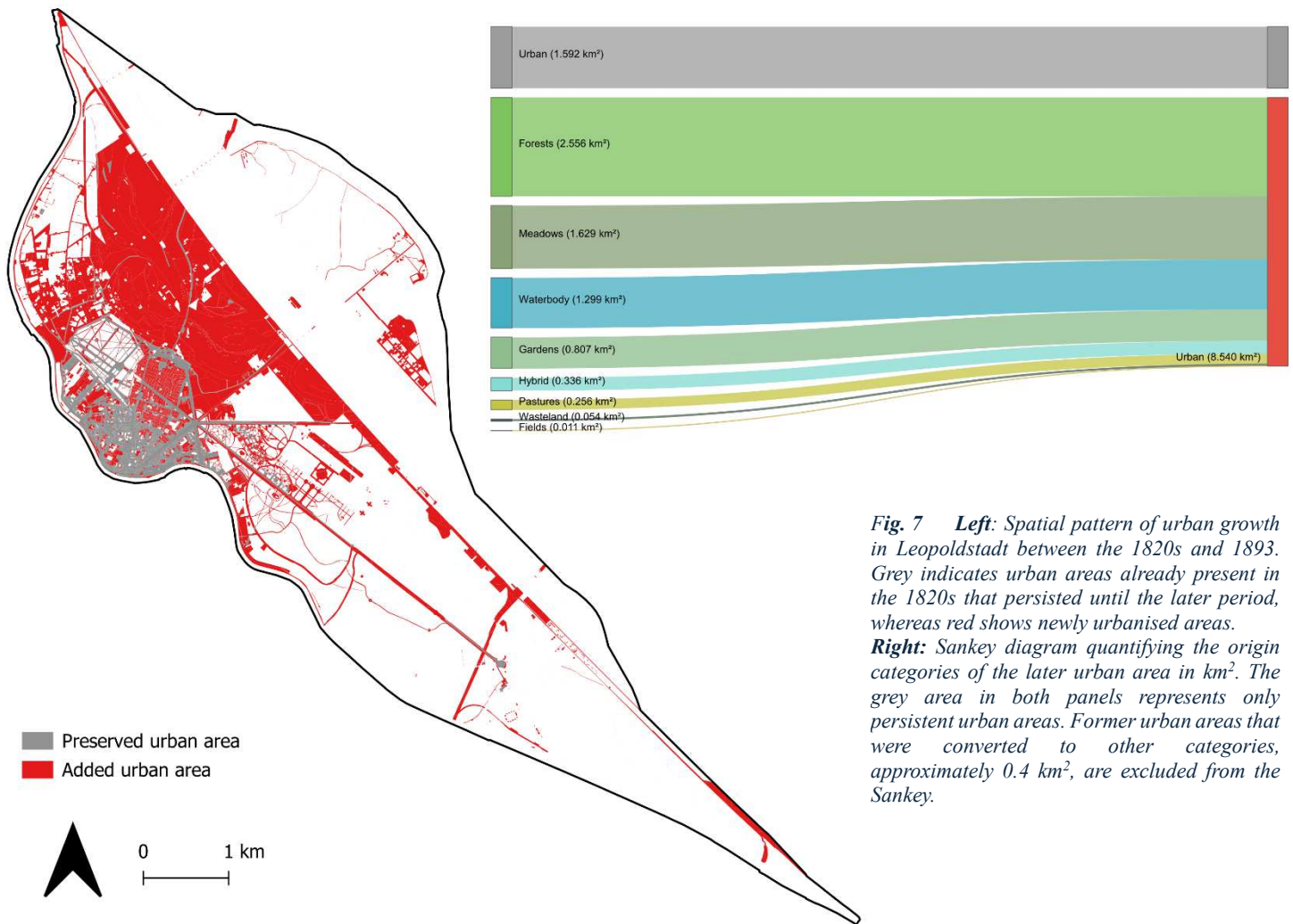


Fig. 7 *Left: Spatial pattern of urban growth in Leopoldstadt between the 1820s and 1893. Grey indicates urban areas already present in the 1820s that persisted until the later period, whereas red shows newly urbanised areas. Right: Sankey diagram quantifying the origin categories of the later urban area in km². The grey area in both panels represents only persistent urban areas. Former urban areas that were converted to other categories, approximately 0.4 km², are excluded from the Sankey.*

The Sankey diagram on the right side of Fig. 7 visualises those shifts to urbanisation, both in proportional terms and in square kilometres. The district of Leopoldstadt had a total area of just under 31 km². In the 1820s, just over one-third of the area, around 10.5 km², was considered forested, of which a little over 2.5 km² had been converted into urban areas by the 1890s. Meadows and urban areas each accounted for around 1.6 km² of the new urban area in Leopoldstadt, while meadows spanned just over 8.2 km² in the reference state. Of the just over 2 km², only about 1.6 km² remained urban. This indicates that nearly 20% or roughly 0.4 km² of the urban area in the 1820s was no longer urban by 1893. A significant factor contributing to this change is the inaccuracy of the historical material or the manufactured vector layers, which we could not quantify directly. Beyond this, myriad agrarian colonisation land uses had disappeared since the 1820s, partly due to the industrial regulation. With the residential expansion, new gardens were cultivated, partly on the sites of former buildings; conversely, roughly 0.8 km² more garden parcels were urbanised. In front of the Augarten, ornamental meadows were introduced, and with changes to paths within the Prater, new meadows appeared where urban areas had previously been. Additionally, urban elements disappeared from the

regulated riverside. The sole street crossing the river to its left bank vanished, along with the buildings along it. Within the former floodplain, regulatory artefacts were disposed of, and the ship mills, which were included in the cadastre, had vanished (Spitzbart-Glasl, 2016). The Danube was the last major source of new urban land, namely the sidearm of Kaiserwasser (Fig. 2), which was removed as part of the industrial regulation. Hybrid areas and pastures still accounted for more than 0.5 km², while wastelands and fields contributed little to new urban land. By 1893, urban colonisation had reached 8.5 km² in the district, just under 28% of the

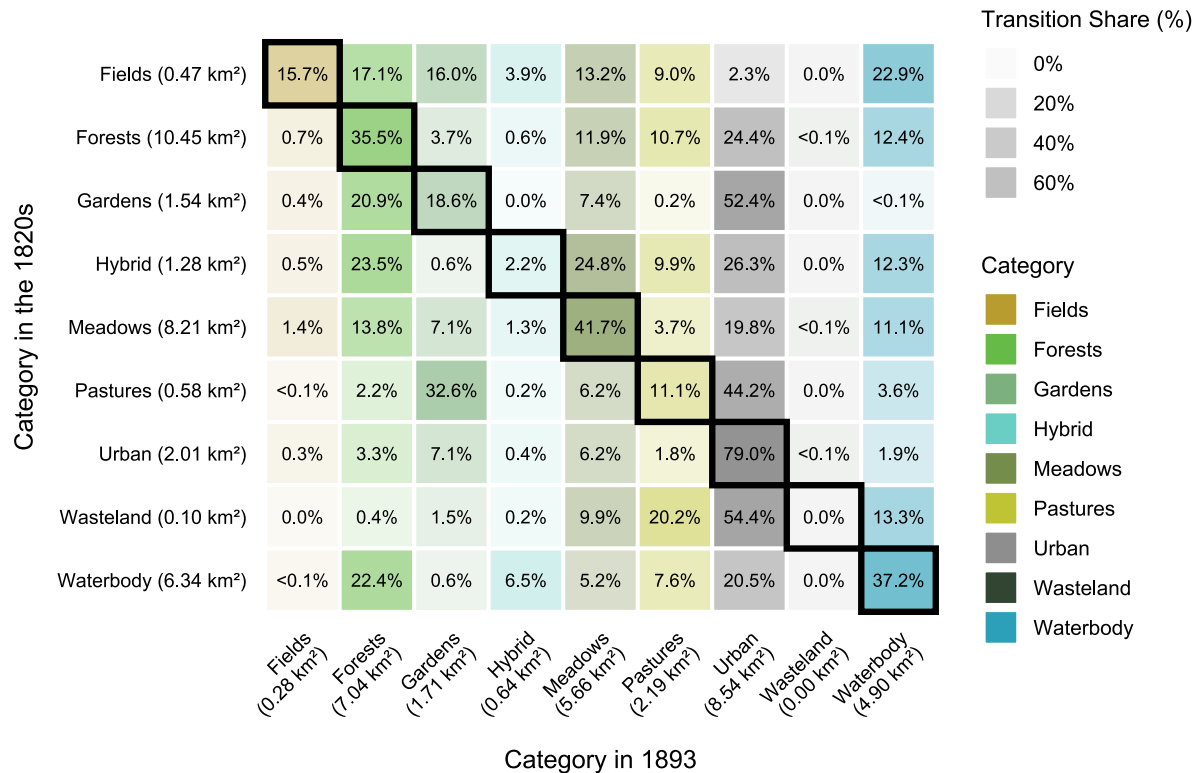


Fig. 8 Rows represent categories derived from the Franciscan Cadastre, while columns represent categories in the 1893 reference state. The matrix is read from row to column: for each category in the 1820s, the values across the row indicate the percentage assigned to each category in 1893. Cell values show row-normalised transition shares, indicating the percentage of each source category that was assigned to each target category. Accordingly, each row sums to 100% and represents the complete area of the respective source category in the 1820s. In contrast, columns are not normalised; their totals deviate from 100%, indicating the relative expansion or contraction of each category by 1893.

total area.

Fig. 8 illustrates all spatio-temporal patterns in land use within Leopoldstadt between the 1820s and 1893 to help identify further changes in colonisation. Apart from the urban area, every category shifted markedly. Only forests, meadows, and the Danube retained their spatial dimensions to some extent, whereas the hybrid areas and wastelands shifted almost completely. The matrix is too expansive to highlight every development in detail, so only rough descriptions will be presented. Fields in the district were halved between the 1820s and 1893, from 0.47 km² to 0.28 km². This area had been repurposed as forests (17.1%), gardens (16%), meadows

(13.2%), and pastures (9%), while 15.7% remained as fields. The largest change of fields to waterbody, 22.9%, was associated with a regulatory shift along the Donaukanal riverbed⁴, while some of the other changes can be explained by the removal of agricultural activity within the Prater.

While the proportion of forests remained relatively stable, the changes in colonisation in this row refer to the much larger area of 10.45 km² (forests accounted for 7.04 km² by 1893). Roughly 23.1%, the combined shift of 10.7% Pastures and 12.4% Waterbody, can directly be traced back to the 1870-1875 industrial regulation, accounting for 2.5km². 11.9% of the forested area in the 1820s had been converted to meadows by 1893, with the largest concentration in the Prater area. Following the industrial regulation, meadows were also introduced into areas formerly covered by floodplain forests.

The gardens' total area increased from 1.54 km² to 1.71 km². Almost 21% had shifted to forests, in part due to methodological changes, as the ornamental garden category had been removed from the cadastral survey by 1893 and was replaced by forests and, to a lesser degree, by meadows. The hybrid areas could be reduced from 1.27 to 0.64 km² by removing gravel banks on the left riverbank, which were subsequently converted to forests (23.5%), meadows (24.8%), pastures (9.9%), or integrated into the Danube itself (12.3%).

Meadows underwent an overall decrease from 8.21 km² to 5.66 km². While the forests ceded 1.25 km² to meadows, meadows, mostly within the Prater, also saw a shift to forest of 1.13 km², representing 13.8% of the 1820s meadows. Similar to the forests, a significant amount of 11.1% was ceded to the regulated river. With the expansion of urban areas into former gardens, extensive new garden plots were created on former pastureland in the northern area near the Donaukanal (32.6%). Overall, pasture area increased from 0.58 to 2.19 km². The strong shift from wasteland to pastures (20.2%) can be explained by the introduction of the inundation area. 22.4% of the Danube, which, following the 1870-1875 industrial regulation, was reduced from 6.34 to 4.90 km², was converted to forests. This encompassed mostly remote areas where no other immediate use for the city was deemed appropriate.

The matrix identifies shifts in colonisation beyond urbanisation, such as changes directly linked to the industrial regulation of the Danube. It also highlights the shifts in colonisation across the remaining categories, but cannot locate changes in time before or after the 1870-1875 industrial regulation.

⁴ This had already happened in the 1830s. Hohensinner & Hauer (2019a) also illustrate the unintended effects of this colonisation measure on the hydrology.

Discussion and Conclusion

The study aimed, on the one hand, to contribute to research on the Viennese Danube by using hitherto unused cadastral material. On the other hand, it sought to contribute to the socio-metabolic framework by explicitly linking energy and material flows to shifts in the colonisation capacities of landscapes across different energy regimes, in this case, the dynamics of a floodplain. This framing was connected to two research questions, first, surrounding the reduction in hybrid areas following the 1870-1875 industrial regulation. Analysis has shown that this was indeed achieved, creating additional areas for the city's colonisation. Additionally, the Danube could be reduced in overall spatial extent, creating even more space for colonisation. The second hypothesis could also be substantiated, as with the river confined to its bed and the inundation area buffering high-precipitation events, the city expanded further into the regulated floodplain, reaching, by 1893, more than four times the size that its agrarian energy regime's colonisation capabilities had allowed. Yet, urbanisation in the colonised floodplain was still ramping up. A fact, the source material also hints at. Urbanisation was also enabled by the creation of a designated inundation area that protected the city against floods while providing pasture and recreational space. Further analysis of the spatio-temporal patterns indicated a high land-use turnover rate in non-urban areas. In part, this was driven by urbanisation, as gardens gave way to residential areas, and new garden plots emerged on former pastures at another site close to the residential area. In other cases, such causality cannot be determined with certainty, as in the removal of fields in favour of meadows and forests in the Prater.

The study has shown that colonisation of a highly dynamic natural system, such as the Viennese floodplain, changed dramatically in the 19th century, with the systematic use of fossil fuels. The artefacts powered by those energy resources, the excavators, enabled a new configuration of the riverscape. In this configuration, the river appears only in a peripheral relation to the city while simultaneously fulfilling its previous function as a provision infrastructure for steamships more effectively than before. This stabilisation of the riverscape enabled the rapid change and accumulation of artefacts that characterise industrial landscapes, while our study also showed that the industrially regulated landscape still contained non-urban elements with a high rate of colonisation turnover. In the case of Vienna, the regulation and its consequences for urban development reverberate to the present day, shifting interest in this early industrial colonisation measure well beyond the historical scope.

With regard to the socio-metabolic interaction system (Fig. 1), industrial regulation and colonisation are interesting in two ways. First, the line between the unaffected natural system and the zone directly affected by industrial regulation became harder to grasp than with its agrarian predecessor. The industrial regulation altered the flow velocity in this section, thereby affecting sedimentation and erosion, while the ensuing lower water level altered the plant community in the surrounding area (Schratt-Ehrendorfer, 2011). Second, even such a major colonisation effort as the industrial regulation had a relatively short lifespan of 100 years before societal actors once again industrially colonised the Viennese Danube, showing that even within industrial metabolism, different modes of colonisation were viable.

Data Availability The vector file will be made available at Zenodo upon acceptance

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