GIS-BASED TIME MODEL. GOTHENBURG, 1960 TO PRESENT

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INTRODUCTION
1.1 Modeling the changes of the built environment over time

Major steps have in recent decades been taken when it comes to understanding how cities work. Essential is the change from understanding cities as locations to understanding them as flows (Batty 2013)[1]. In principle this means that we need to understand locations (or places) as defined by flows (or different forms of traffic), rather than locations only served by flows. This implies that we need to understand the built form and spatial structure of cities as a system, that by shaping flows creates a series of places with very specific relations to all other places in the city, which also give them very specific performative potentials. It also implies the rather fascinating notion that what happens in one place is dependent on its relation to all other places (Hillier 1996)[2]. Hence, to understand the individual place, we need a model of the city as a whole.

Extensive research in this direction has taken place in recent years, that has also spilled over to urban design practice, not least in Sweden, where the idea that to understand the part you need to understand the whole is starting to be established. With the GIS-based time model for Gothenburg that we present here, we address the next challenge. Place is not only something defined by its spatial relation to all other places in its system, but also by its history, or its evolution over time. Since the built

1. Batty, M. (2013), The New Science of Cities, Cambridge: MIT Press.
2. Hillier, B., (1996), Space Is the Machine. Cambridge: University of Cambridge Press

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form of the city changes over time, often by cities growing but at times also by cities shrinking, the spatial relation between places changes over time. If cities tend to grow, and most often by extending their periphery, it means that most places get a more central location over time. If this is a general tendency, it does not mean that all places increase their centrality to equal degree. Depending on the structure of the individual city's spatial form, different places become more centrally located to different degrees as well as their relative distance to other places changes to different degrees. The even more fascinating notion then becomes apparent; places move over time! To capture, study and understand this, we need a time model.

There are several reasons for such a time model. There are many academic reasons, related to the fact that to understand individual places we need to get a grasp of how they have evolved over time and how their relative location has changed, giving

Figure 1. Aerial photo of 1960 overlaid with the street network of 2015 in Eklanda. (source for aerial photo: Lantmäteriet)

rise to its particular history of uses and alterations in their local built form. But it is also necessary, if we are to study and understand dynamic processes such as economic clustering or gentrification, which need to be followed and studied over time. However, a time model can be of equal importance for practice, where it can help us understand the history of places one intends to intervene in, as to not destroy important qualities, but to make informed alterations. Also, if we fully grasp the fact that places move over time, not in geographic location but relatively to other places in the city, it actually changes how we look at urban design at quite a fundamental level. As urban designers, we do not operate in an absolute space where new additions are firmly settled for the future, but rather intervene in an ongoing process, where our additions may change their relation to the rest of the city over time, something we need to consider and make part of our practice.

The GIS-based time model was created following the principles of the model of spatial form of the city, as developed by the Spatial Morphology Group (SMoG) at Chalmers University of Technology, within the three-year research project 'International Spatial Morphology Lab (SMoL)'. The SMoG model introduced a comparative way of modeling urban form across cities and was originally produced for three Swedish cities (Stockholm, Gothenburg and Eskilstuna) and two European (Amsterdam, London)[3]. The model includes the three central elements in urban

3For related literature see,

Berghauser Pont, M., Stavroulaki, G., Bobkova, E., Gil, J., Marcus, L., Olsson, J., Sun, K., Serra, M., Hausleitner, B., Dhanani, A., Legeby, A. (2019). The spatial distribution and frequency of street, plot and building types across five European cities, Environment and Planning B: Urban analytics and city science, Vol. 46(7) 1226–1242

Berghauser Pont, M., Stavroulaki, G., Marcus, L. (2019). Development of urban types based on network centrality, built density and their impact on pedestrian movement, Environment and Planning B: Urban analytics and city science, Vol. 46(8) 1549–1564

Berghauser Pont, M., G. Stavroulaki, J. Gil, L. Marcus, M. Serra, B. Hausleitner (2017). Quantitative Comparison of Cities: Distribution of Street and Building Types based on density and centrality measures, 11th Space Syntax Symposium (SSS11), July 2017, Lisbon.

Berghauser Pont, M., G. Stavroulaki, K. Sun, E. Abshirini, J. Olsson, L. Marcus (2017). Quantitative comparison of the distribution of densities in three Swedish cities, ISUF 2017 XXIV international conference, Valencia.

Marcus, L., Berghauser Pont, M., Stavroulaki, G., Bobkova, E., (2017) Location-based density and differentiation adding attraction variables to space syntax, In: Proceedings of 24th ISUF, City and Territory in the Glo balization Age, Editorial Universitat Politècnica de València. DOI: 10.4995/ISUF2017.2017.5706

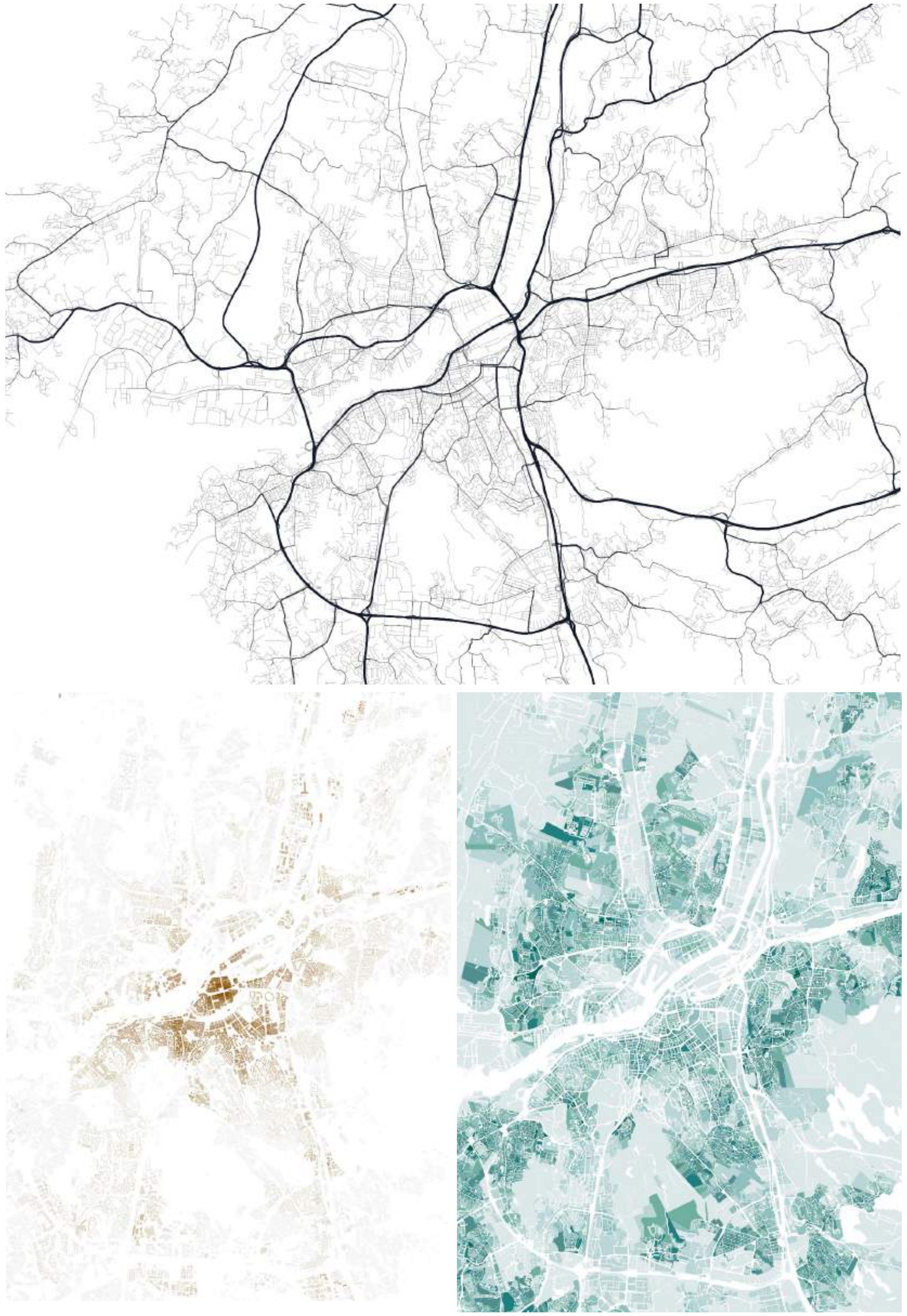


Figure 2. The three layers of spatial form in Gothenburg. Street network: top, buildings: bottom left and plots: bottom right in their current situation (source: Research project 'International Spatial Morphology Lab', Spatial Morphology Group, Chalmers University of Technology).

morphology, streets, buildings and plots, which are understood as the three central variables of spatial form: distance, density and differentiation (Fig 2).

Distance, is here the most essential variable, being the very definition of space to begin with, since if there is no distance there is no space. However, in these models, distance is not isometric, meaning equal in all direction, but rather heavily restricted and directed for human use, by what we generally call the street system. It is this street system which structures human movement and distributes centrality over the city, but also creates the odd fact that places 'move' over time; it puts each and every place in a unique relation to all other places in the city, so that when these relations change, the individual place too shifts, changes and moves. Second, each place may be built according to different building patterns, where built density is decisive in accommodating the amount of people and things in different places. Third, there is the plot system, that on a fundamental level differentiates between ownership, which is, in turn, decisive in differentiating between people and things in the city.

In the GIS-based time model of Gothenburg, these three fundamental elements - street network, buildings and plots - are mapped over time. With that, how the respective spatial variables - distance, density and differentiation - change over time and how they change the functional potential of each and every place in the city can also be mapped, analyzed and studied over time.

The time frame chosen for the presented model is from 1960 to 2015. This, on one hand, brings us back to the time before the major traffic changes of the 1960s and the Million Homes Program between 1965-1974, which dramatically changed the shape and structure of the city, but it also includes the years of slow development that came after that, taking us up to the great changes taking place today. Naturally, it would in the future be most interesting to extend the time frame of the model at least to 1940, to fully include the dramatic changes taking place in Gothenburg since WWII. It would also be interesting to further extend the model to the turn of the 20th century or even beyond that. Since the city becomes rapidly smaller when we move back in time and since there is rather sufficient historical mapping for Gothenburg, it could be possible to extend the model even back to the city's origin in 1621.

In the following sections, the model will be presented in three steps. First, the different layers that constitute the model will be described and explained in detail. Second, a pilot analysis of the model will be presented, focusing on street centrality and built density. Third, a few examples demonstrating how the model can be used in practice and also possible extensions will be described.

1.2 GIS-based time model of Gothenburg. 1960 to 2015

The GIS-based time model consists of:

- 12 GIS-layers of the street network, from 1960 to 2015, in 5-year intervals
- 12 GIS-layers of the buildings from 1960 to 2015, in 5-year intervals
- 12 GIS- layers of the plots from1960 to 2015, in 5-year intervals

The time model was created following the principles of the model of spatial form of the city, as developed by the Spatial Morphology Group (SMoG) at Chalmers University of Technology, within the three-year research project 'International Spatial Morphology Lab (SMoL)'.

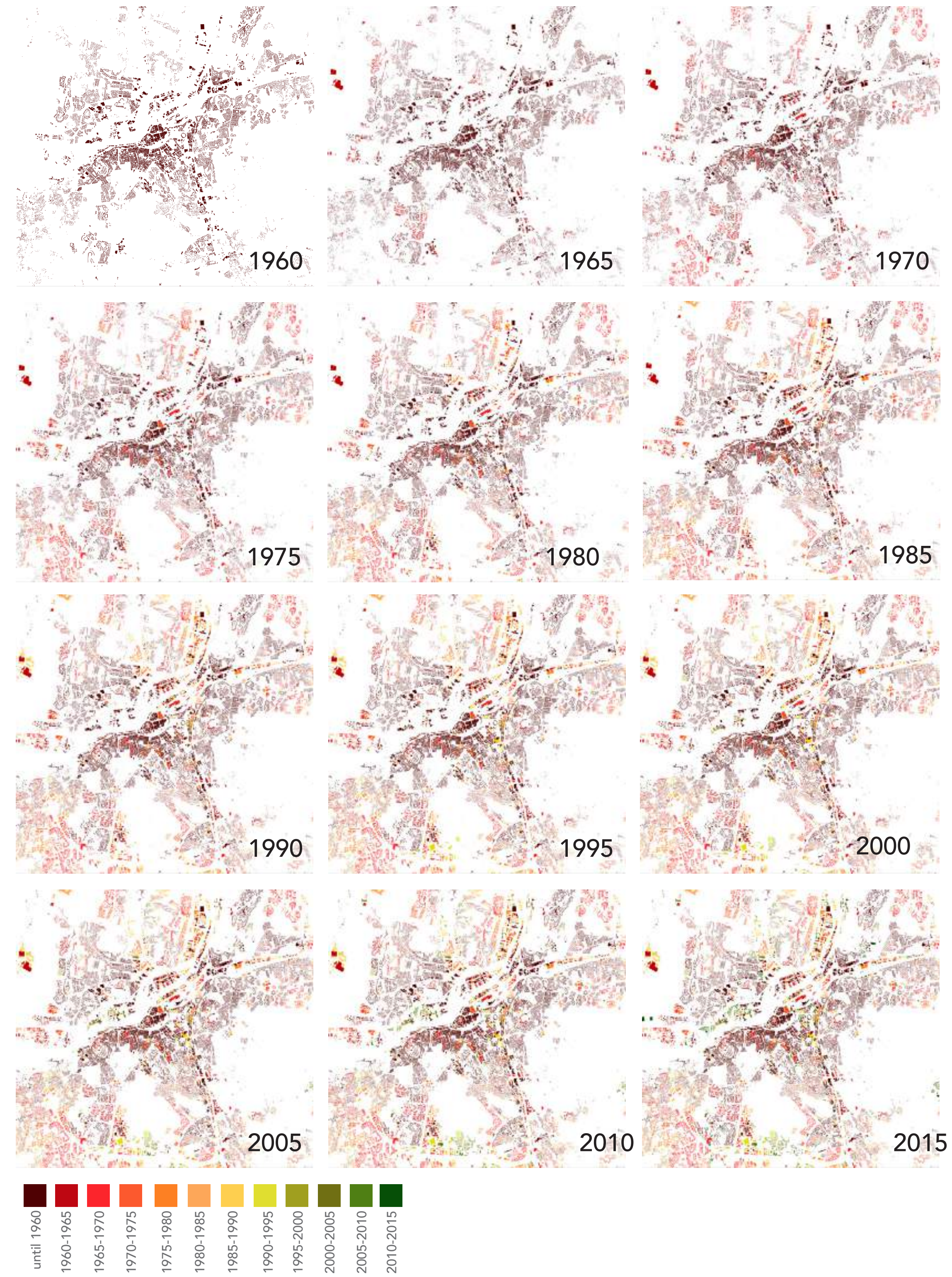


Figure 3. GIS-layers of buildings for every time-frame, colored by their year of construction

The street network layers concern the motorized street network and are complemented with the locations of non-level intersections (e.g. bridges, tunnels, flyovers, overpasses, underpasses); necessary point layers for an accurate network analysis. The building layers also include data on building heights, floors, footprints and GFA (Gross Floor Area). Lastly, the plot layers include the plots that were built upon and developed in each time-frame and not the remaining agricultural or natural land, as the aim is to document the process of urban development. The GIS-layers were produced using a combination of different digital databases (sources: Spatial Morpholohy Group, Lantmäteriet, Trafikverket, Boverket), analogue reference images, such as digitalized tourist maps and aerial photos (sources: SBK, Lantmäteriet), literature and other sources. The production of the model, including the procedures, sources and software used is documented in detail in Appendix 1.

In the final GIS-based Time model, for every time-frame, the combination of the three fundamental components of spatial form, that is streets, plots and buildings, provides a consistent description of the built environment at that particular time. The evolution of three components can be studied individually, where one could for example analyze the changing patterns of street centrality over time by focusing on the street network; or, the densification processes by focusing on the buildings; or, the expansion of the city by way of occupying more buildable land, by focusing on plots. The combined snapshots of street centrality, density and land division can provide insightful observations about the spatial form of the city at each time-frame; for example, the patterns of spatial segregation, the distribution of urban density or the patterns of sprawl. The observation of how the interrelated layers of spatial form together evolved and transformed through time can provide a more complete image of the patterns of urban growth in the city.

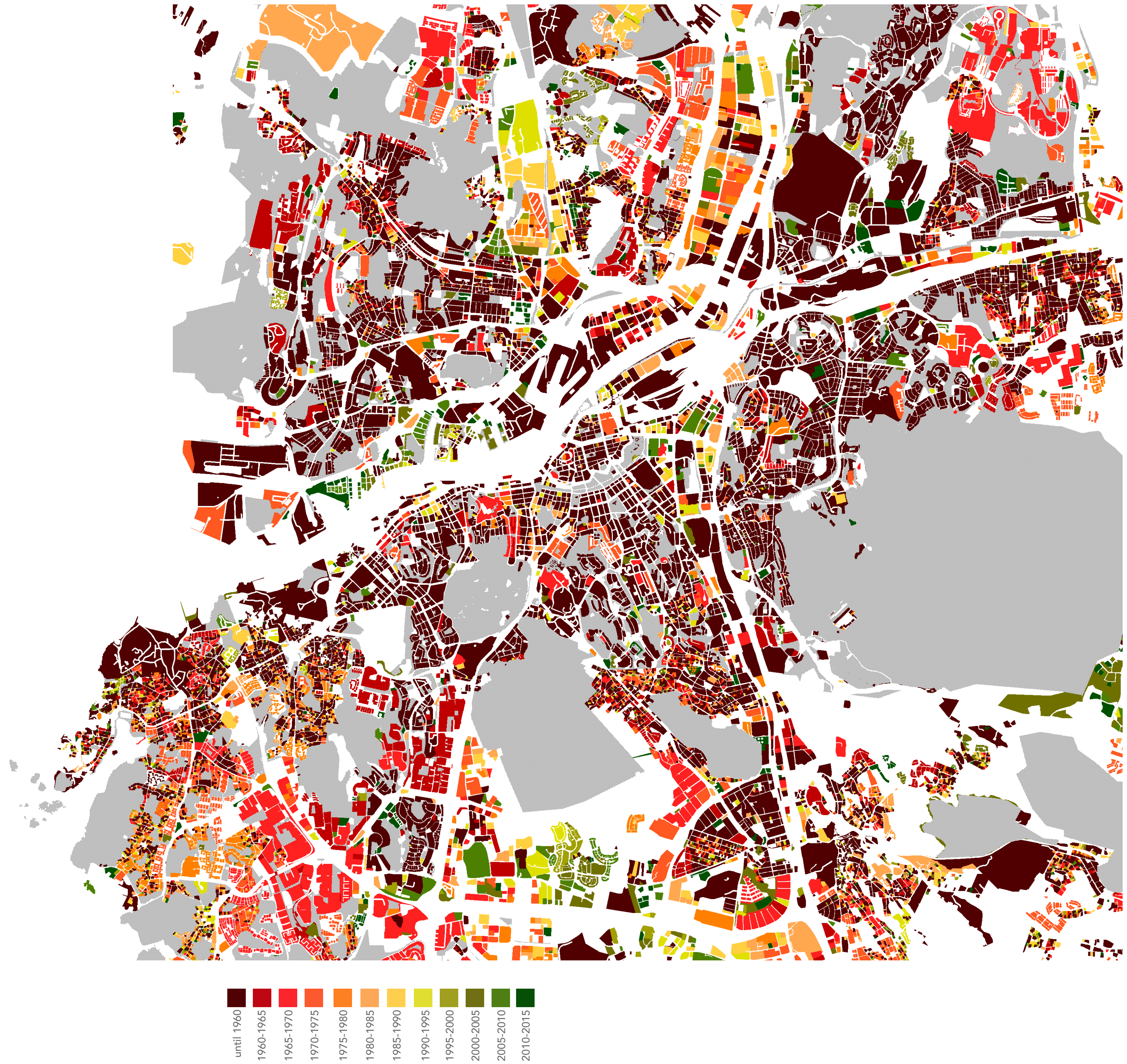


Figure 4. GIS-layer of built-up plots in the 2015 time-frame. The plots are colored by the construction of the older building they contain.

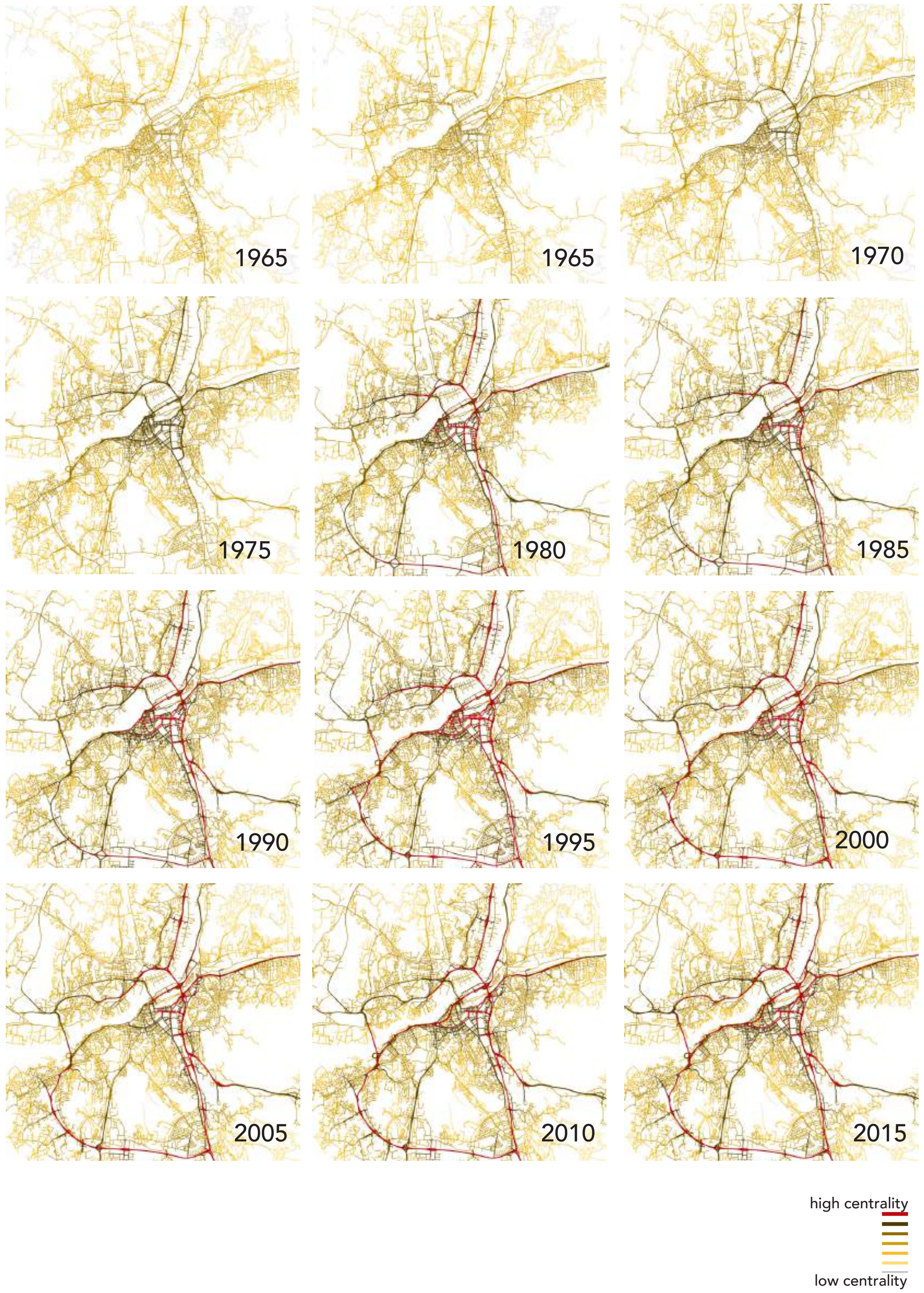


Figure 5. GIS-layers of the street network for every time-frame, colored by their global centrality (see section 3 and Atlas: Appendix 2, for the centrality analysis)

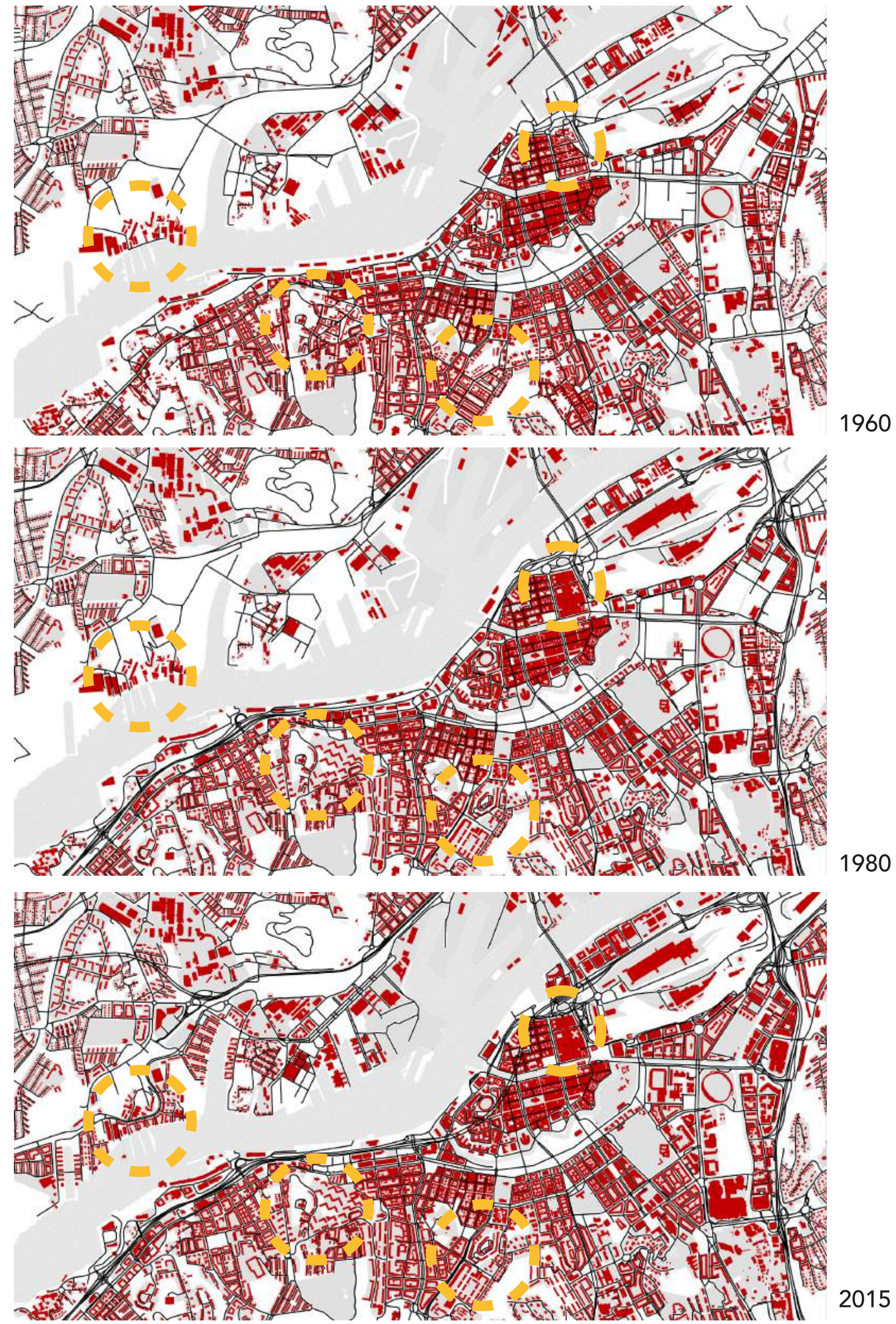


Figure 6. Combined GIS-layers of streets, buildings and plots for 1960, 1980 and 2015. The orange circles show examples of redevelopments in Eriksberg, Stigberget, Annedal and Nordstan (from left to right)

Figures 3, 4 and 5 show separate visualizations of the three layers in each time frame and Figure 6 shows examples of their combination.

The resolution and detailing of the GIS-layers is one that can allow both large scale visualization and analysis that can highlight the global structures of the city, but also detailed inspection and local scale analysis that focus on the micro-structure of the neighborhood, the street and the block. Figure 5, for example, shows in detail the redevelopment of the existing areas in Eriksberg, Stigberget, Annedal and Nordstan with the replacement of older buildings.

With this model each urban location is placed in space and in time, in other words, within its spatial and historical context. In the same way, each development project or added piece of infrastructure is also put in context, not only as for its relations to the existing spatial context, but also in relation to an overall process of urban development which has its own patterns and time cycles. One can study what each top-down development and new infrastructure came to add to the city at a certain point in time. A case in point is the addition of the highways which changed the older street hierarchies and rearranged existing traffic flows, but also attracted further densification along their length and supported further expansion of the urbanized area (Fig 7, 8). Last but not least, one can see the constant and decisive impact of the limitations posed by topography (hills, natural reserves, water) in the way the city grew (Fig 8).

Even without any analysis, the calculation of the street length, the number of buildings, the GFA, and the plot area for every time frame can provide first informative results. In Figure 9, the graphs show longitudinal changes in two ways; first, the change in the total numbers and, second, the change in the amount of new

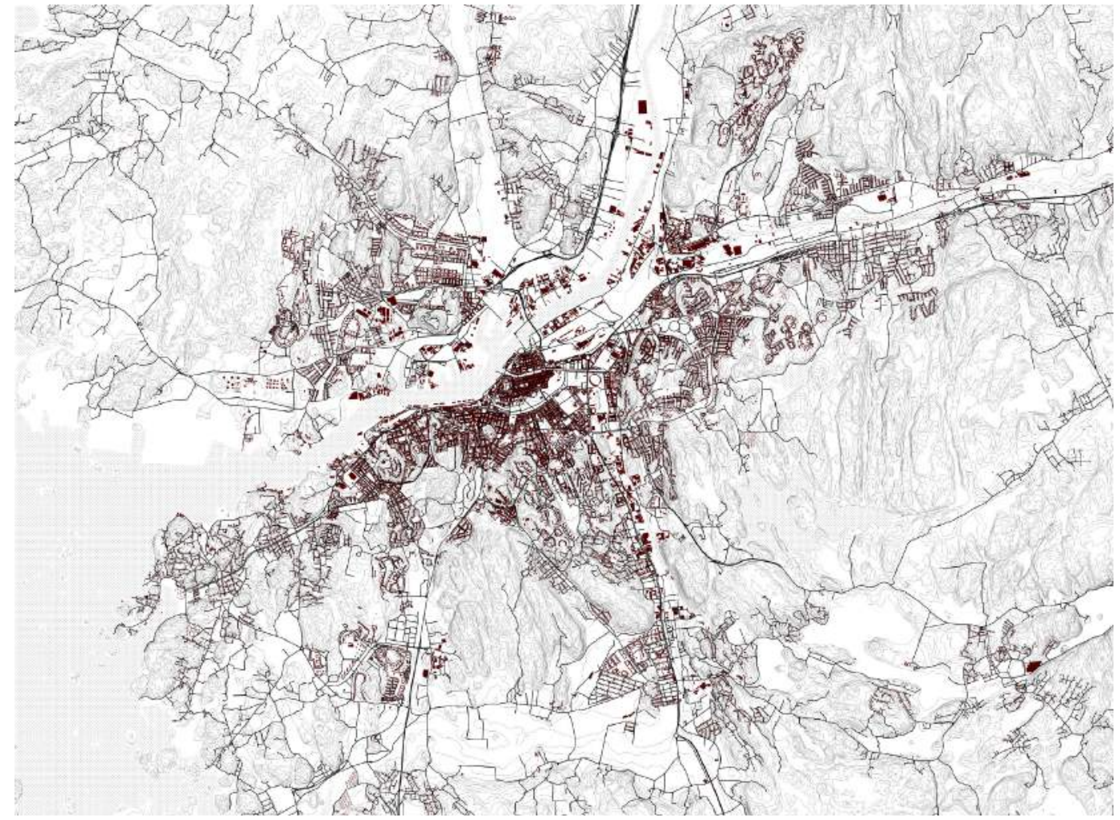


Figure 7. Buildings and streets in 1960 overlaid with topography, natural areas and water of 2015

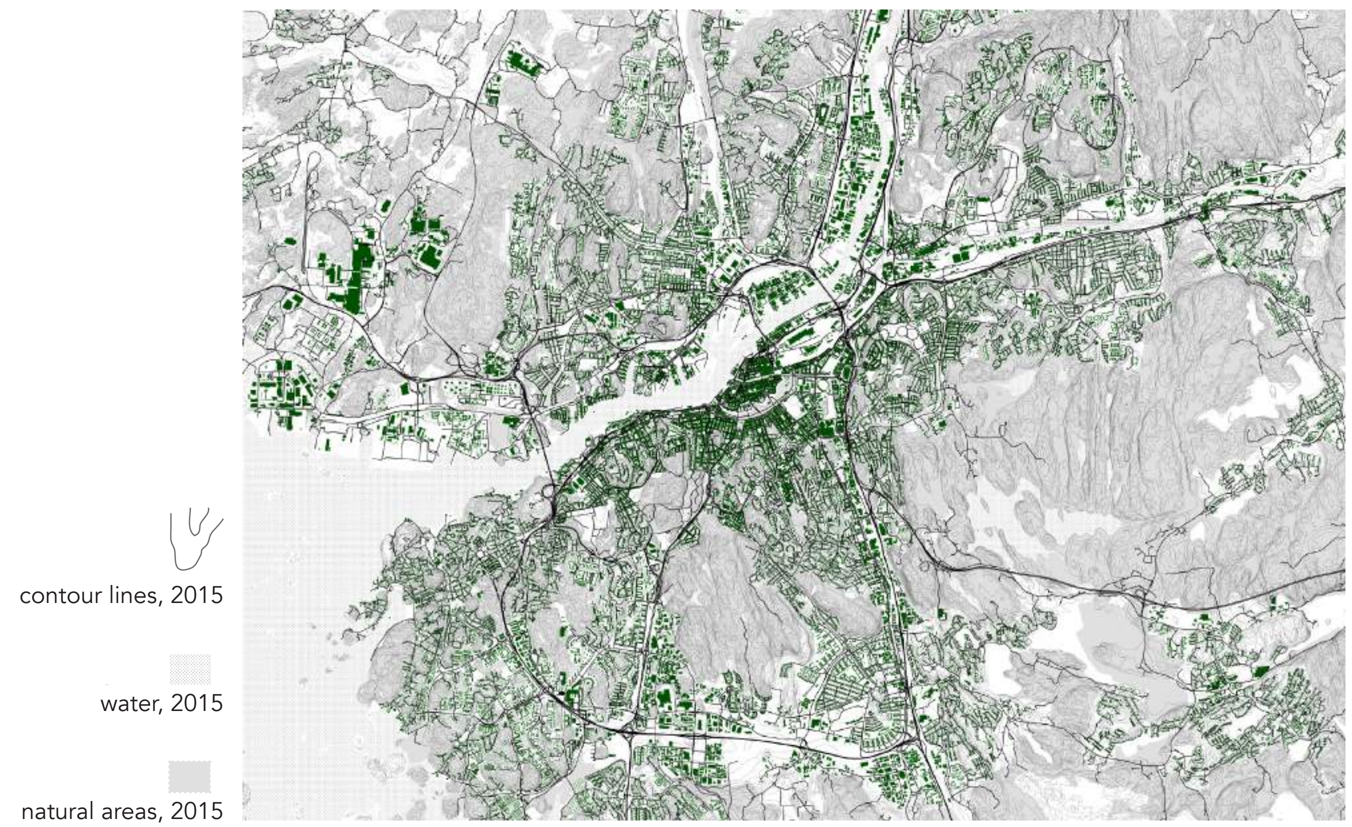


Figure 8. Buildings ans streets in 2015 overlaid with topography, natural areas and water

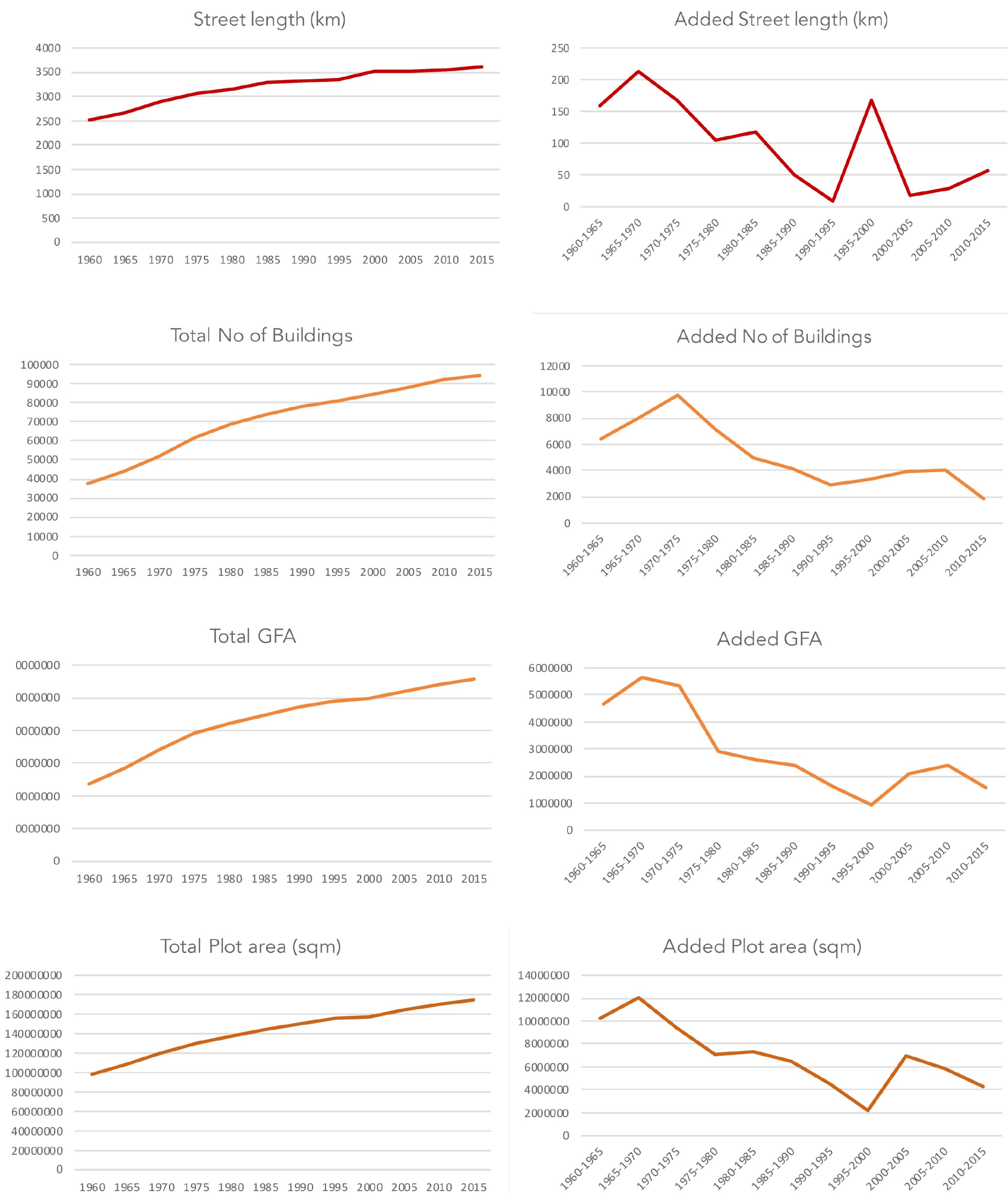


Figure 9. Left column: Total amounts per time-frame, Right column: Added amount between time-frames

additions. When looking at the total numbers, there is a constant addition of new street length (i.e. new roads) new buildings and new plots (i.e. more plots are built upon). However, when looking at the changes in the added amounts we see clear fluctuations, some of which reflect either national political incentives or economic events.

For example, the significant urban developments taking place during the Million program in1965-1974 are documented in all graphs. The curves recording the added amounts of streets, buildings and plots reach their peak during that period. For the buildings in particular, the highest point is reached in the second period, 1970-1975, while for the streets and plots it is reached in the first period, 1965-1970. Looking at the maps one can see that in the Million program neighborhoods, often the infrastructure (i.e. the land and the street network) was set in the first period, while buildings were continuously added also throughout the second.

After 1975 there is a gradual drop in all graphs that reaches the lowest point in the time-frame of 1990-1995, which should reflect the severe economic crisis of that period, ending in 1993. For the street network and the plots only, there is a slight peak before that period, during 1980-1985, which is related to new large-scale infrastructure (i.e. added peripheral highways).

After 1995 and until 2000, there is a significant rise in the new developments, although they don't reach the 1965-1975 levels. The rise is especially clear in the street graph. The time-frame 2000-2005 shows another steep decline, but only in the street network development. This slackening could be perhaps related to the drop in the economic growth of Sweden during the period 2001-2003.

1.3 Pilot analysis of the model. Network centrality and built density over time

As a pilot analysis, network centrality (i.e. angular betweenness centrality and angular closeness centrality) and density analysis were conducted for the 12 time-frames. Space Syntax methodology and its latest development in network analysis was followed[4]. Angular centrality measures calculate the distance between two contiguous street segments by way of measuring their angular deviation. In extension, the shortest path between two distant segments is the path with the least angular turns in total. Angular betweenness centrality of a street segment is the number of shortest paths between all other segments in the network that pass through it. A street segment with high betweenness is one that falls most frequently on such shortest paths, as for example are the bridges, which control all movement between the city center and Hisingen. On the other end, the dead-end streets have zero betweenness centrality since no path passes through them. On a global scale the measure highlights the "through" movement structure in the city.

Angular closeness centrality calculates how 'far', in terms of its total angular distance, is every street segment from all other segments in the network. A segment with high closeness centrality is one that is largely connected to other streets and is highly accessible in few angular turns, as for example the clusters of the well-connected streets in the city center. On the other end, a segment with low closeness centrality has only a few connections to other streets, it is deep in the structure and requires a lot of turns to reach it, making it less accessible and segregated. Such examples are the clusters of the inner meandering streets of the modernistic estates. In a global scale, the measure distinguishes between the integrated and segregated areas in the city. Both measures have been shown to correlate to traffic and pedestrian flows, where high centrality in the motorised network is related to high vehicular traffic whereas high centrality in the non-motorised network is related to high pedestrian flows[5]. They also correlate to the concentration other activities and attractions, such as the development of local markets[6].

Accessible GFA (Gross Floor Area) in 500m was measured as an indicator of built density. By calculating how much GFA in total is reached from any street segment in 500m walking distance in all directions, the measure shows the density of the area surrounding each street segment. In that sense, it brings forth the perceived built density as is experienced by walking the streets [7].

All measures were calculated for the global scale (i.e. the whole network) using PST software[8] .

4 Following:
Hillier, B. and Iida, S. (2005), "Network effects and psychological effects: A theory of urban movement". In: van Nes, A. (ed.), Proceedings of the 5th International Symposium on Space Syntax, Delft: University of Technology Vol.1, p.553-564.
Hillier, B., Yang, T., Turner, A. (2012). "Normalising least angle choice in Depthmap and how it opens new perspectives on the global and local analysis of city space", In: Journal of Space Syntax, vol.3, pp155-193.

5 See for example:
Serra, M., Hillier, B., (2018). "Angular and Metric Distance in Road Network Analysis: A nationwide correlation study". Computers Environment and Urban Systems. 10.1016/j.compenvurbsys.2018.11.003.
Stavroulaki G., Bolin D., Berghauser Pont, M., Marcus L., Hakansson, E., (2019), "Statistical modelling and analysis of big data on pedestrian movement", In: Proceedings of the 12th Space Syntax symposium, 79.1-79-24
Hillier, B. and Iida, S. (2005), "Network effects and psychological effects: A theory of urban movement". In: van Nes, A. (ed.), Proceedings of the 5th International Symposium on Space Syntax, Delft: University of Technology Vol.1, p.553-564.

6 See for example:
Marcus, L., Berghauser Pont, M., Stavroulaki, G., Bobkova, E., (2017) Location-based density and differentiation-adding attraction variables to space syntax, In: Proceedings of 24th ISUF, City and Territory in the Globalization Age, Editorial Universitat Politècnica de València. DOI: 10.4995/ISUF2017.2017.5706
7 For more on the concept of Accessible density, see:
Berghauser Pont, M., and Marcus, L., 2014 "Innovations in measuring density. From area and location density to accessible and perceived density", Nordic Journal of Architectural Research.

8 PST is an open QGIS plugin for performing spatial analyses, developed by Chalmers University of Technology, KTH School of Architecture and SpacescapeAB. It combines the space syntax description of the urban environment with conventional descriptions of attraction into the combined accessibility analysis tool

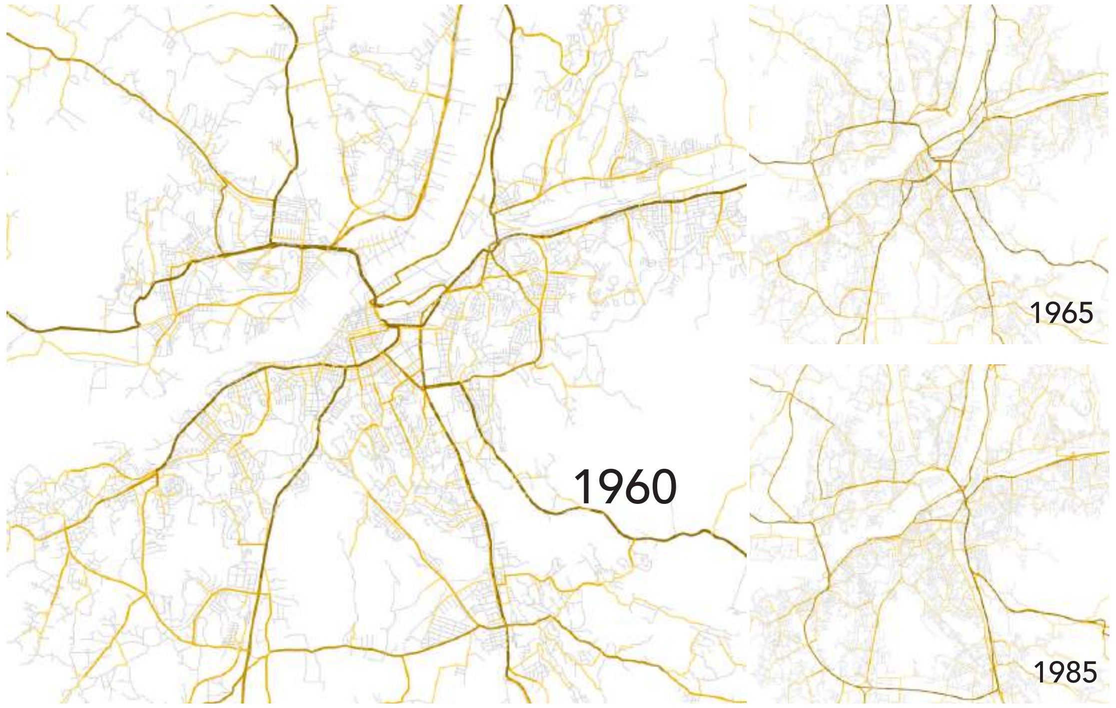


Figure 10. Angular betweenness centrality for every time-frame (continues to next page)

Betweenness centrality shows the global network structure of each time-frame (Fig10). Following the typical visualizations of Betweenness centrality, the most central streets in each time-frame are classified by way of percentages (e.g. 2% most central: heavy brown, the 75% less central streets: light gray). Hence, what is compared is not the absolute centrality values, but the relative street hierarchies in each time-frame.

The results show a clear shift with the addition of the big infrastructure (i.e. peripheral highways, bridges, tunnels). In 1960 the high betweenness paths formed radials spreading out from the historical center to the periphery in all directions. This radial structure was gradually replaced by a ring-road structure, eccentric in relation to the historical city. The peripheral highways, complemented by the added bridges and tunnels, gained the highest betweenness centrality and gradually reorganized the traffic flows, rerouting the global 'through' traffic outside of the inner-city.

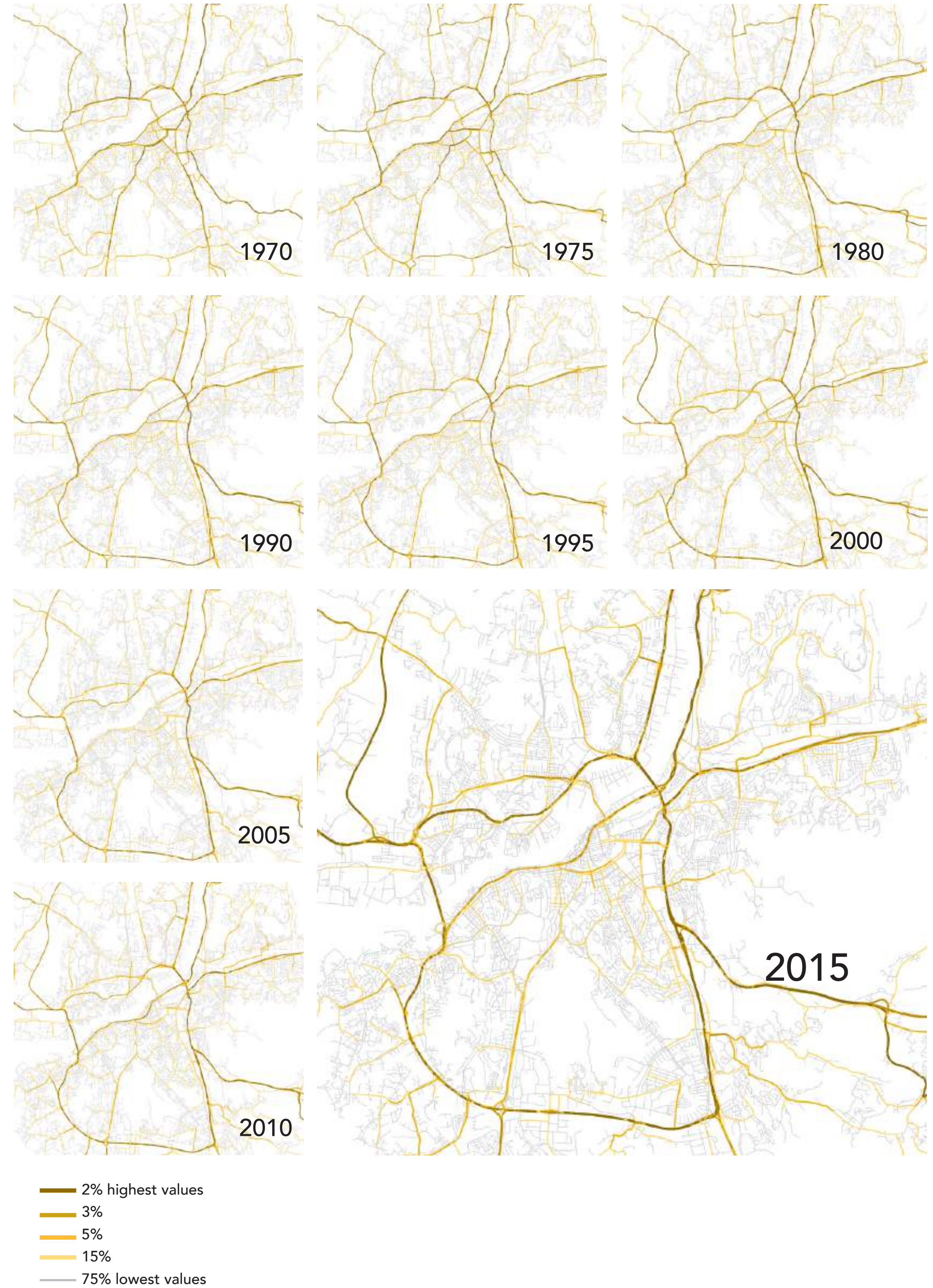


Figure 11. Angular closeness centrality visualized by absolute values for every time-frame (continues to next page). Black circle: Guldheden

The Closeness centrality results can be visualized in two ways both of which are very informative. Since it is a normalized measure, the absolute values of each time-frame can be accurately compared. Figure 11 highlights the overall added centrality in the network from 1960 to 2015. Here, it is again clear that the large scale road infrastructure reorganized existing street hierarchies. With the gradual addition of the peripheral highways complemented by bridges and tunnels, the formed ring structure became a coherent whole and gained the highest centrality in the global scale.

What is also a recurrent observation is the impact of the topography; the hills and the large natural areas close to the heart of the city, by definition did not allow the network to fully connect and expand in a more concentric pattern from center to periphery. Hence, the centrality of the historical city might have increased over time, but it has not largely expanded. In relation, the older neighborhoods in the hills of the inner city, such as Guldheden (black circle in Fig.10), have not gained much centrality through the years, and still form urban 'islands' protected from 'to' and 'through'

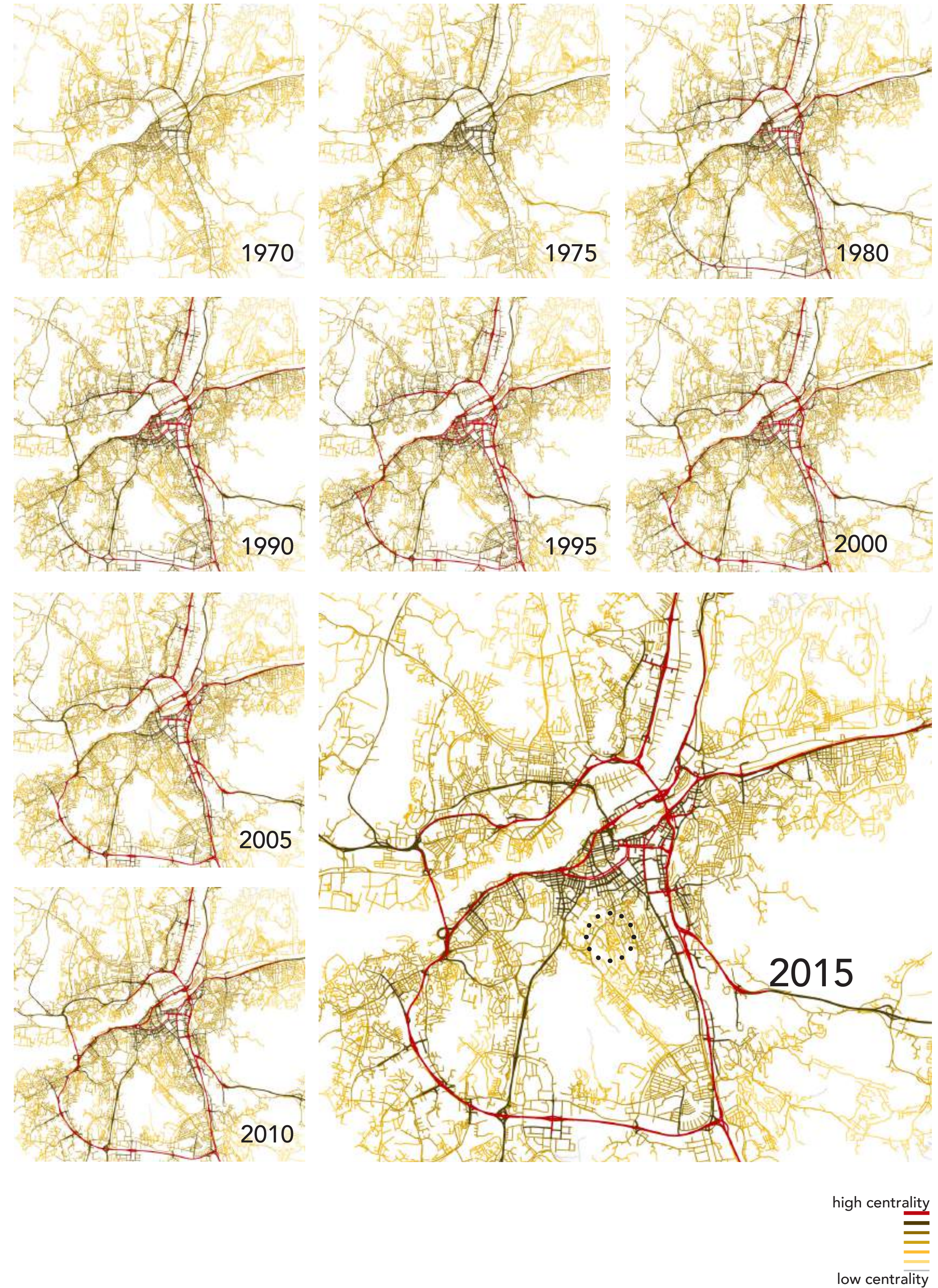


Figure 12. Angular closeness centrality visualized by percentages . Top:1960, Bottom:2015

movement. This is also related to their curvilinear and tree-like street structure that is partly due to the sloping terrain and partly to the respective planning ideology and specific design intention.

The second way of looking at the Closeness centrality results is by visualizing them using relative ranges, as was done for Betweenness centrality. Figure 12 shows the Closeness centrality values of 1960 and 2015 visualized by percentages, where the 6% highest values in each network is red, the 8% lowest values is light gray, and so on. This is informative as it not only visualizes the changing of hierarchies in the network, but also the changes in the relative centrality of each location, neighborhood or area, within these hierarchies. In other words it unveils the relativeness of each urban location, which although is geographically fixed through time, its place in the structure changes. For example, Figure 12 unveils the importance of the historic center as the main centrality core in 1960. One main connection branched through Södra Vägen and Mölndalsvägen towards Mölndal and another towards Hjalmar Brantingsgatan towards Kvillebäcken. The latter was the only connection to Hisingen and created a centrality spine on the other side of the river. As already described in the betweenness analysis results, and is confirmed here, the main structure changed from 1980 on, with the gradual addition of the new large-scale road infrastructure, and with it, the role of the historical center changed as well. The closeness centrality results show that in 1960 the whole center partook in the centrality core. The analysis of the 2015 situation shows that the center is relatively less central than it was in total. However, at the same time, it has become more hierarchised, where the peripheral Nya Allen/Parkgatan and Norra Allegatan have gained extremely high centrality, since they are more directly connected to the highest centrality highways. The new formed street hierarchies in the center are further related to the exclusion of vehicular traffic from specific streets.

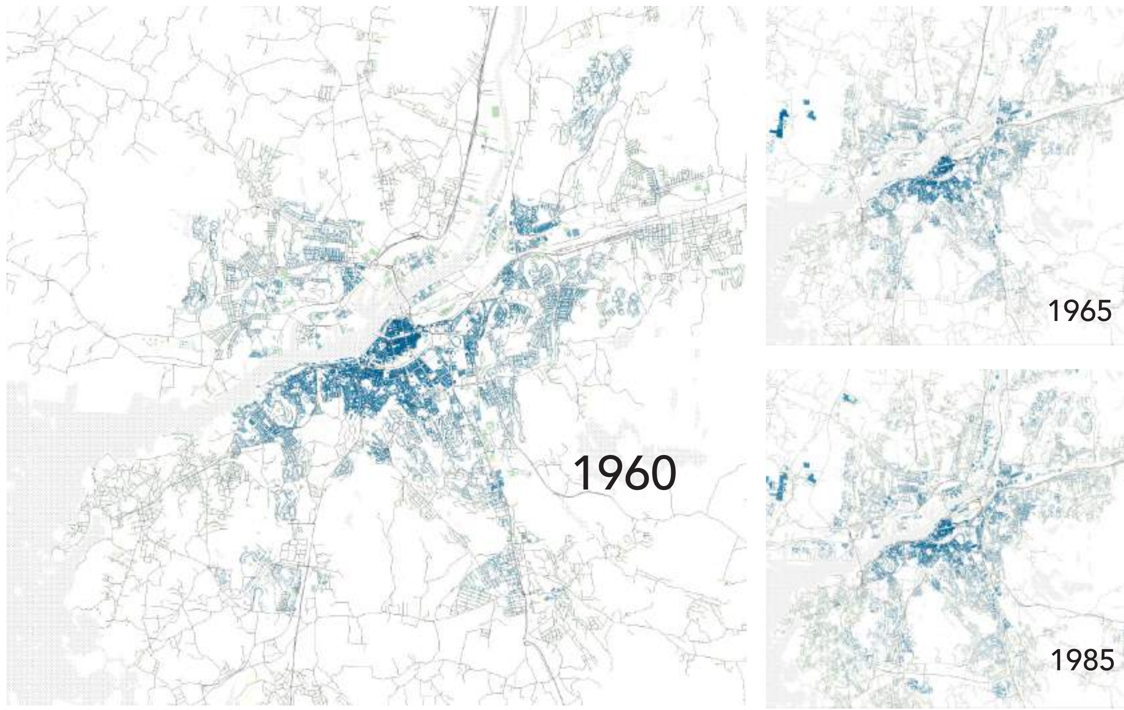
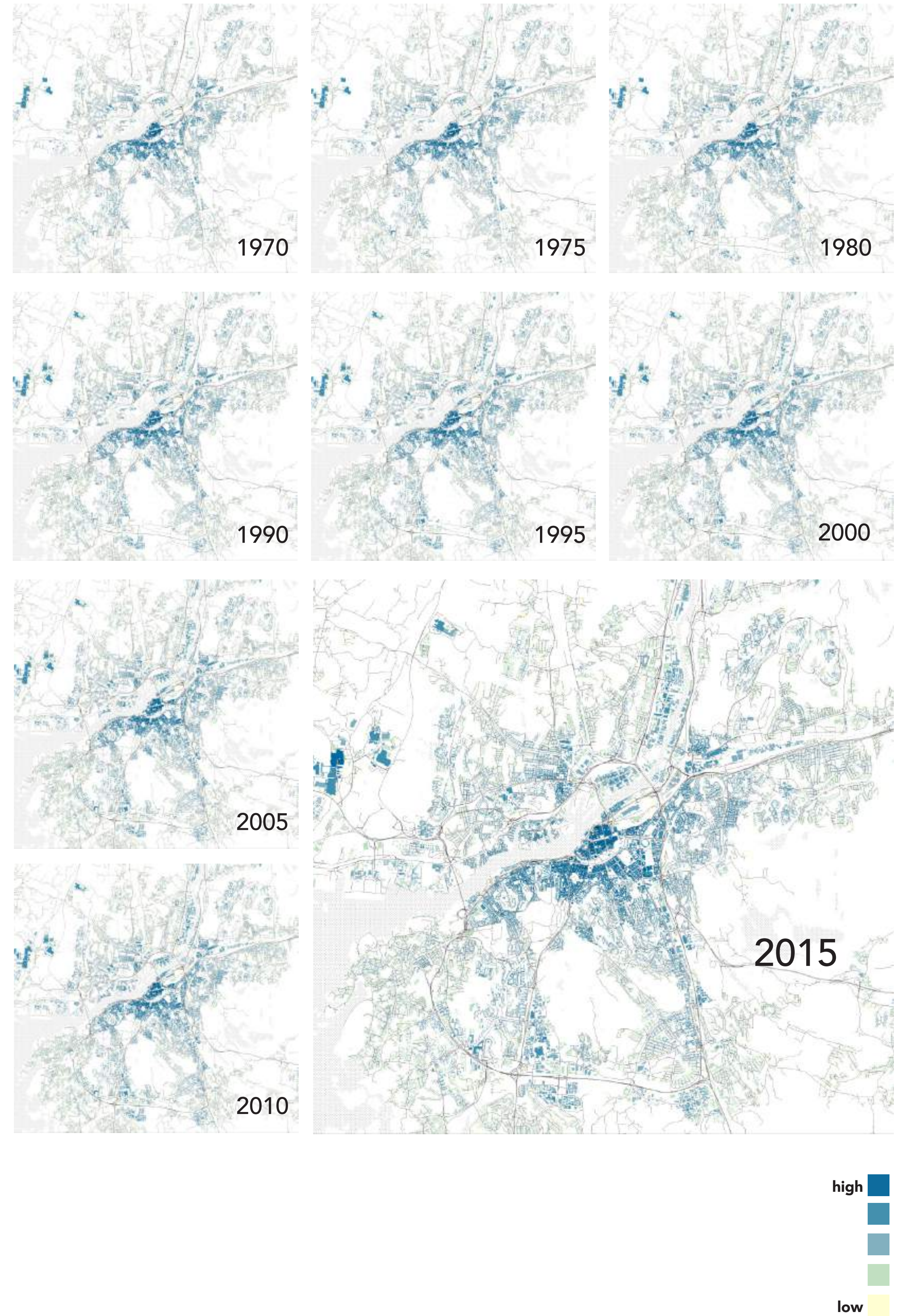


Figure 13. Built density as in Accessible GFA in 500m walking distance, visualized by absolute values for every time-frame (continues to next page).

The densification processes as mapped in Figure 13, also reveal interesting patterns and significant changes in the relative location of certain areas. To start with, the impact of large-scale infrastructure and topography is confirmed; the former by gradually driving densification along the ring-road and towards the outskirts of the city, and the latter by limiting the densification potentials within the inner city. The large-scale top-down development of the suburbs during the Million program is also documented. However, the density analysis also shows how the relative locations of the Million program suburbs, of the large-scale road infrastructure and of nature have themselves changed through the years. In relation to the growing infrastructure, some Million program neighborhoods have become more globally connected to the rest of the city and have gained in global centrality, as for example Högsbo, Frölunda and Biskopsgården (Fig 14). In today's context, their relatively low density in relation to their increased centrality on the global scale have made such suburbs eligible candidates for further densification. Others, such as Bergsjön, have remained segregated in the global scale to this day.



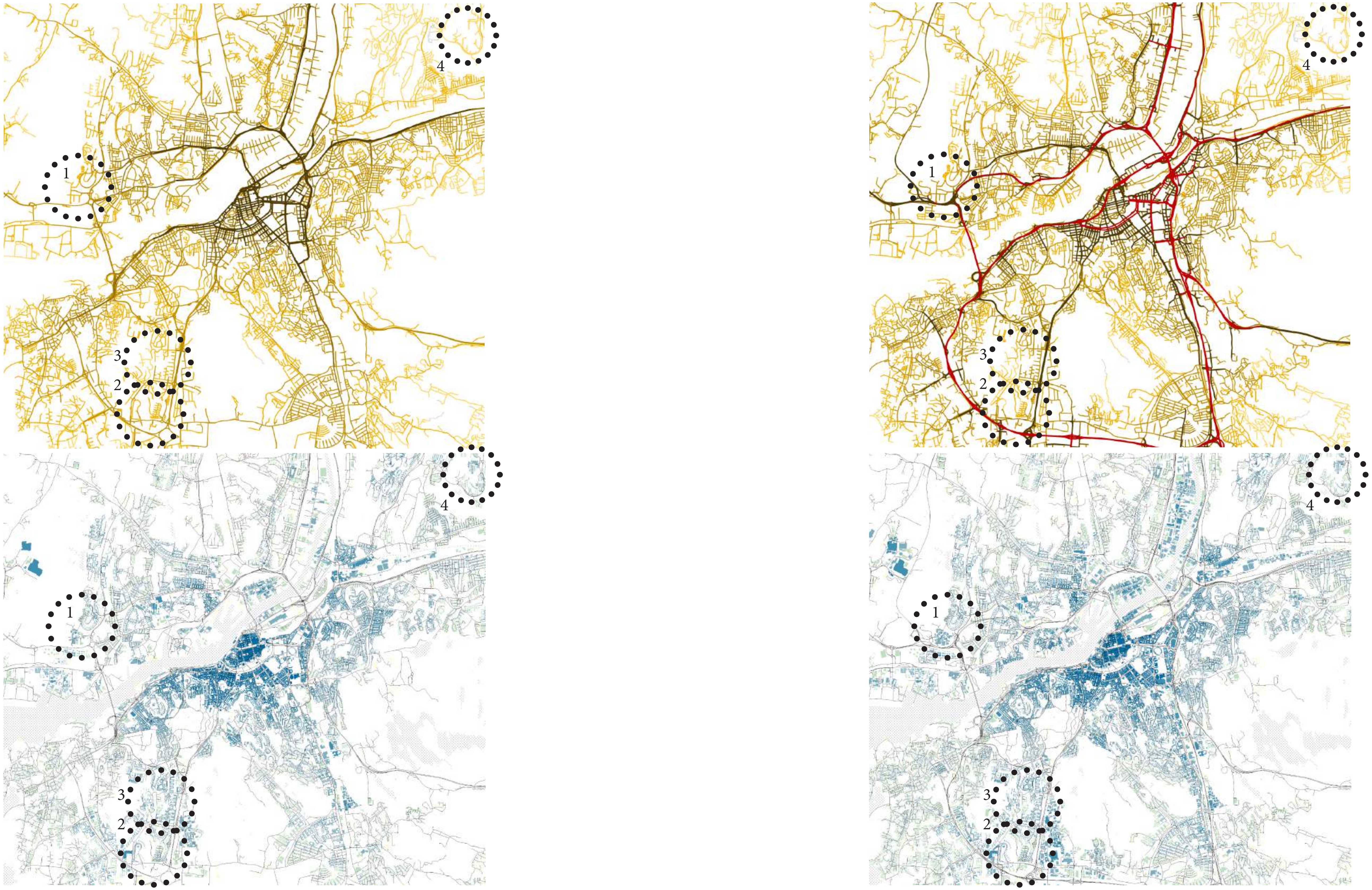


Figure 14. Left column: 1975, right column: 2015. Top: Closeness centrality, bottom: Built density .
In circles: 1: Biskopsgården, 2: Frölunda, 3: Högsbo, 4:Bergsjön (continues to next page)

The highways, as they drove urban growth with densification and sprawl for the last decades, have now become part of the expanded urbanized area and can no longer be considered as being in the urban periphery (Fig15). Cases in point are Söderleden and Västerleden in Västra Frölunda. Similarly, as the new bridges and tunnels crossing the river gradually changed the relation of Hisingen to the rest of Gothenburg, making it more central, the whole Norra Älvstraden area and Backaplan attracted densification. Within the new context Lundbyleden motorway has shifted from being at the lower limit of the urbanized parts of Hisingen to the very center. The changing relative location of the large-scale road infrastructure creates tensions and conflicts with the ongoing densification processes. It poses new challenges to

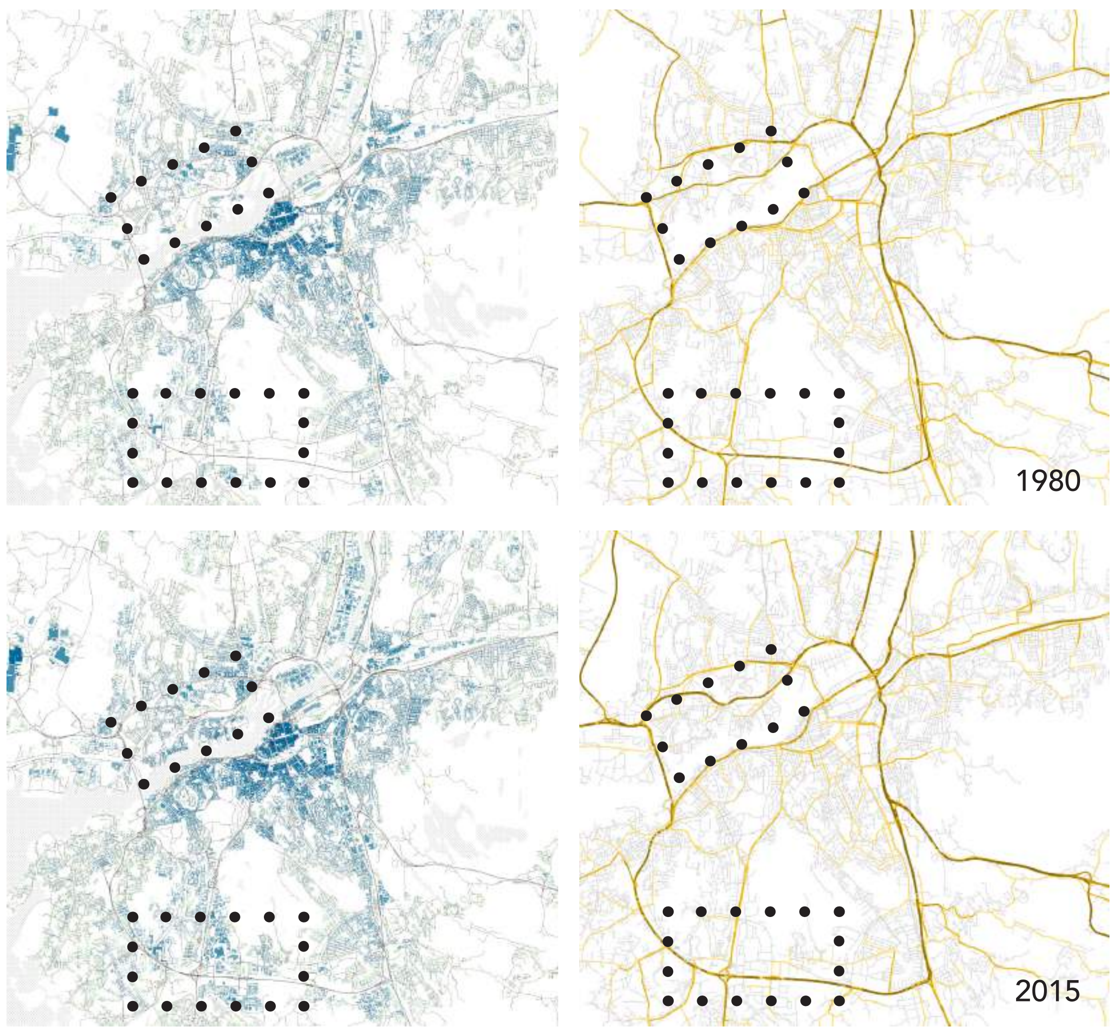


Figure 15. Left column: Built density, right column: betweenness centrality. Top: 1980, bottom:2015. In dots: up, Lundbyleden in Norra Älvstraden, bottom: Söderleden and Västerleden in Västra Frölunda.

the current and future development of the city, as it often creates significant spatial barriers which disrupt the street network connectivity and in extension hinder the integration of the new densified areas to the rest of the city.

The role of nature has itself been transformed within the changing context. Where in the past the large natural areas placed the outer limits to densification, they gradually became encircled by it (Fig 16). New neighborhoods have been developed to the immediate vicinity of the large natural reserves, such as Högsbo, Västra Frölunda and Eklanda around Änggårdsbergen, or Lindholmen and Backaplan around Keillers park. In the new context, these large natural areas acquire a new potential role,

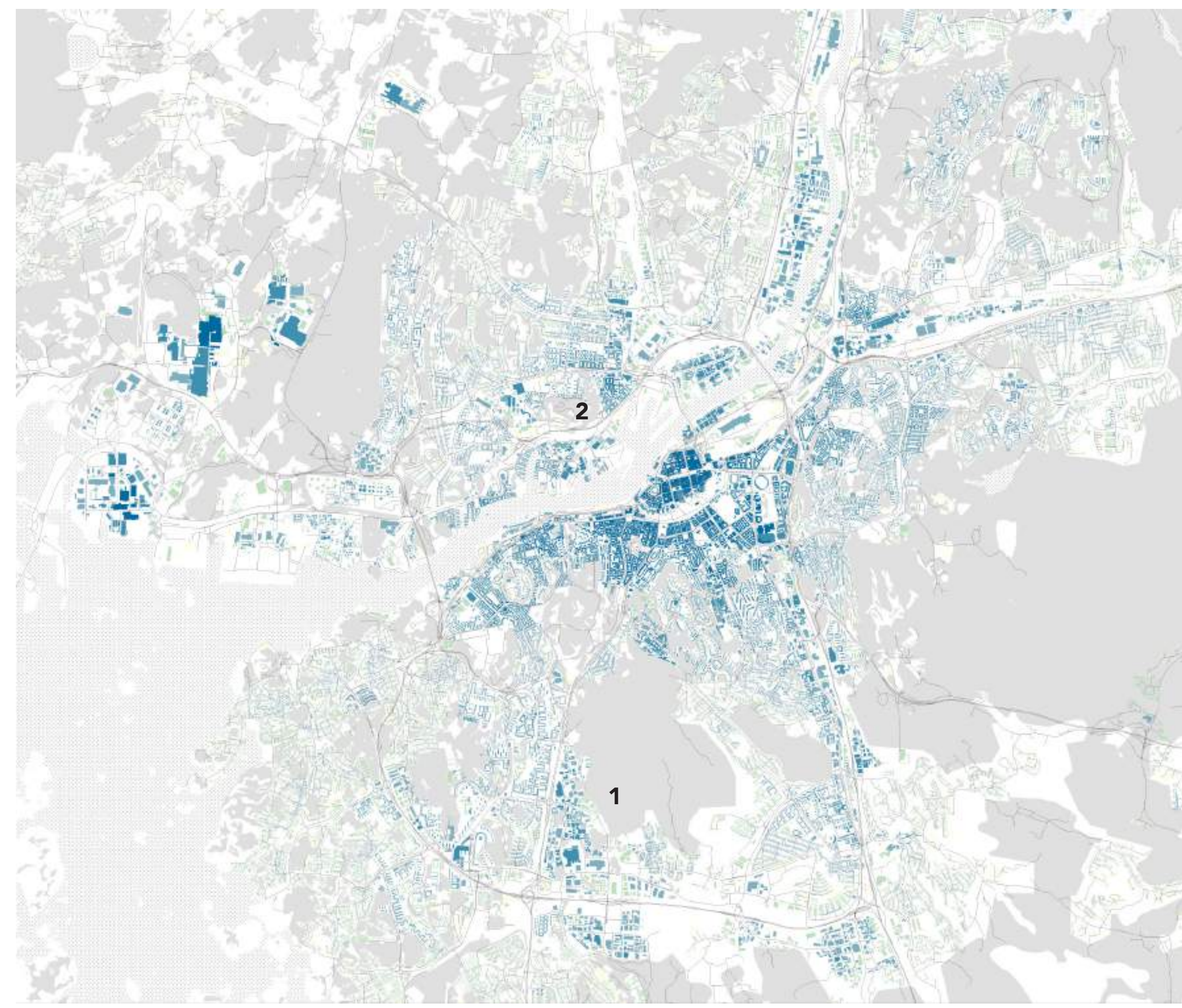


Figure 16. Built density in relation to natural areas in 2015. 1: Änggårdsbergen, 2: Keillers park

as more integral parts of the everyday life of the surrounding areas and can also contribute to fulfilling the increased need for accessibility to nature that comes with the continuous densifications.

The full network centrality and density analysis can be found in Appendix 1: Atlas.

The pilot analysis of the model aimed to demonstrate one of its many possible applications and uses. It neither intended to provide a full report on the changes of spatial form through the years, nor to comprehensively account for the complex reasons behind it, related to economy, historical trends, political incentives, planning ideologies, societal demands etc, many of which go beyond the municipal or regional context to the national and even international. The next section will provide more examples of possible applications of the model, as well as potential extensions and next steps.

1.4 Possible applications of the model and next steps

The GIS-time model aims at being a useful operational tool to be used in analysis and design, both in research and practice, and not merely a visualization tool, although it can in fact produce very informative images. There are numerous possible applications of the tool as well as potential extensions.

An important application of the model would be to relate it to the distribution of the urban development plans in Gothenburg over time. Such a connection would show how the distribution of development plans (detailed plans) changes over time, where and when the investments are placed, but also how they collectively relate to the visions and directives expressed in the respective comprehensive plans at a given time. Such an account would inform the new incentives and the prioritizing of

future development plans, by putting the often-disconnected individual plans in their context in relation to both space and time. The plans can be assessed better when they are seen in their whole urban context, but also as parts of larger patterns of the urban development processes that transcend them.

Another step into the future would be to connect the GIS-time model to the interactive platforms of Digital twin cities, one of which will be developed for Gothenburg in the coming 5 years at Chalmers University of Technology. Such Digital twins already exist for other cities worldwide (e.g. Singapore, London). Although the core idea is to create a real-time virtual mirror of the city as is now, in order to forecast changes in the real city by modeling them in the virtual city, a series of similar mirrors could be added for the different historical phases of the city, which could inform the forecasts with longitudinal data. This could add a unique feature in Gothenburg's Digital twin.

The GIS-based model of Gothenburg can be seen as a pilot for the development of similar ones in other Swedish cities following the same principles. This would allow for cross-city comparisons highlighting on the one hand similar patterns of urban development and growth on national scale, that are the results of for example historic events, economic fluctuations (e.g. economic crisis of 1990-1993) or national political incentives (e.g. the Million housing program), and on the other hand the unique traits in each city, that are the results of the individual topography, municipal and regional political incentives, local economic resources and social dynamics or the local historical patterns of urban evolution.

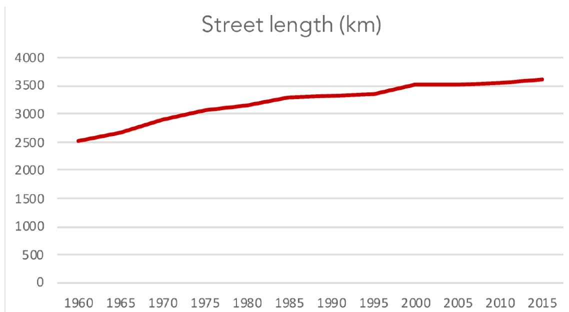
Besides the extension of the time-model to include more cities there are several additions that can enrich the model itself. One such extension would be to add more

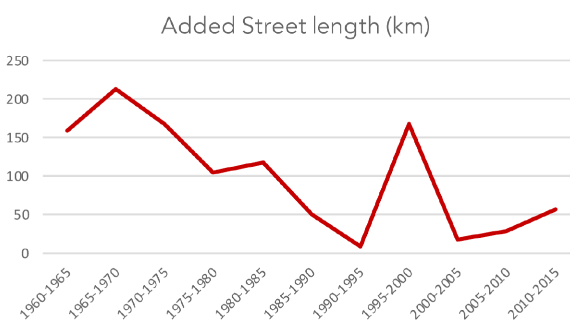
time-frames to the model to go back in time even further, to include the WWII or even reach the turn of the 20th century.
Another important contribution would be the relation of the historical transformations of the spatial form of the city to changes of socioeconomic value, for example changes in the patterns of residential population. To that end, the model can include longitudinal data on the distribution and density of residential population. Such geodata exist (source SCB), although in their present form go back as far as 1982. However, one might still identify informative relations, as for example between the changing housing distribution, the patterns of sprawl and inner-city migration to the overall urban growth and densification patterns and the extension of the network infrastructure.

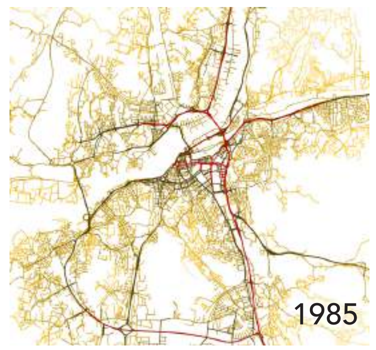
Other longitudinal data that could be added to extend the usefulness of the model are land and building uses, that could provide information on the general land use changes, especially the repeatedly discussed effect of densification on reduced access to green spaces, but also the development of local centers and local markets, the changes in the accessibility to public services, education, health, urban green spaces, public places, as well as to working places. Although, today such longitudinal data might exist on aggregate numbers and perhaps separate districts, there is no systematic mapping of how the accessibility to pubic services has improved in different locations in the city, and how this is related to the changing demands due to the continuous urban development, or to the changing potentials due to the improvements in the street network, new road infrastructure and public transport. The extended GIS-based time model would allow for such relations and bring a more dynamic and holistic, rather than static understanding of complex urban phenomena and processes, such as spatial inequalities, socio-spatial segregation and gentrification. Such processes are by definition dynamic and thus, need to be studied in relation to the ever-changing urban form.

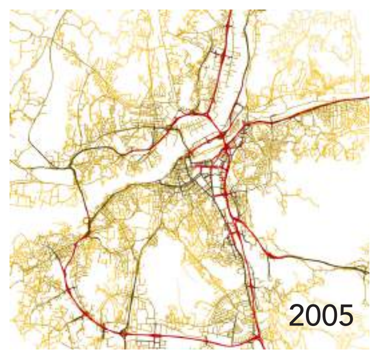
GIS-BASED TIME MODEL OF GOTHENBURG

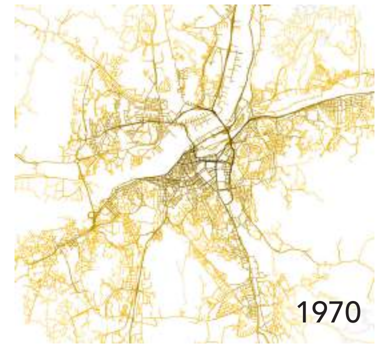
APPENDIX 1. ATLAS

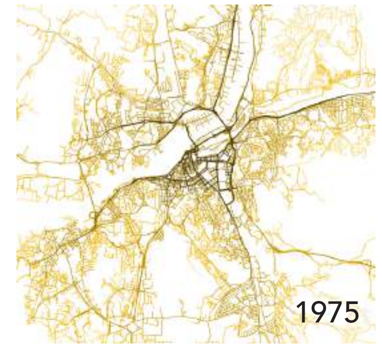


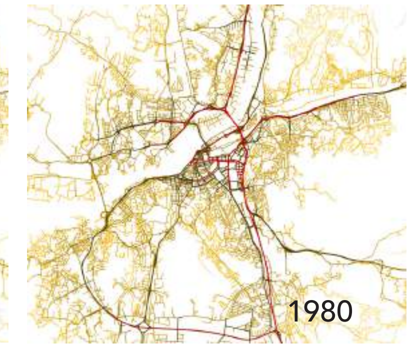


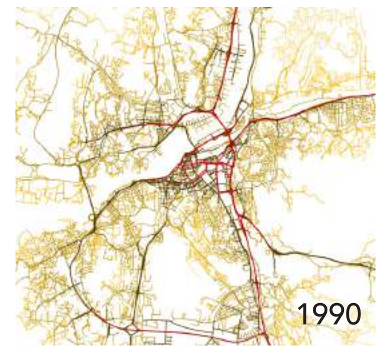


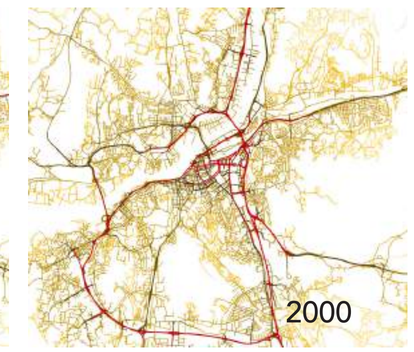


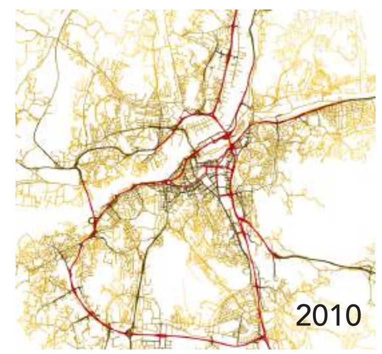


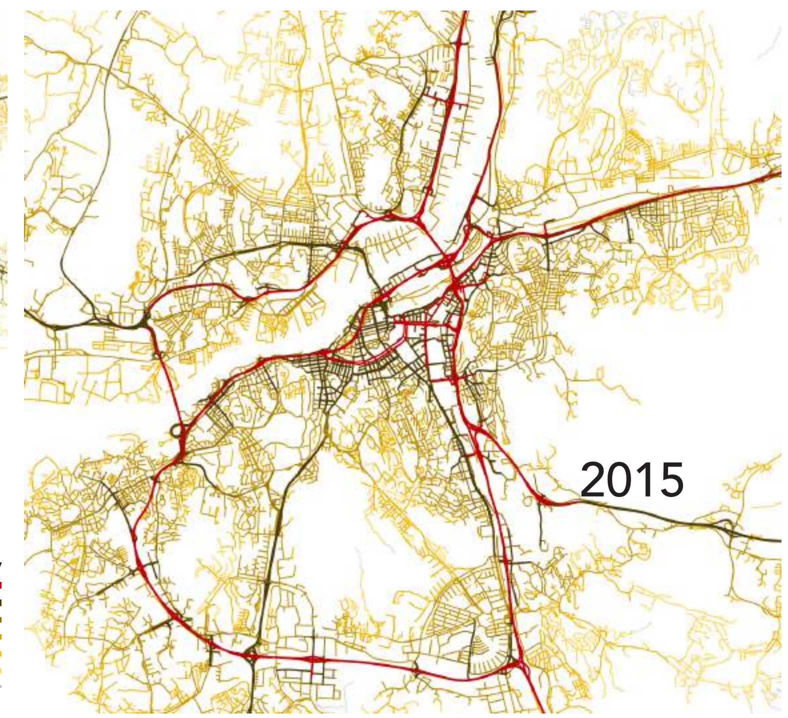






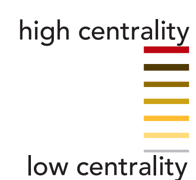






01.Street network

Angular Closeness centrality, global scale (n)

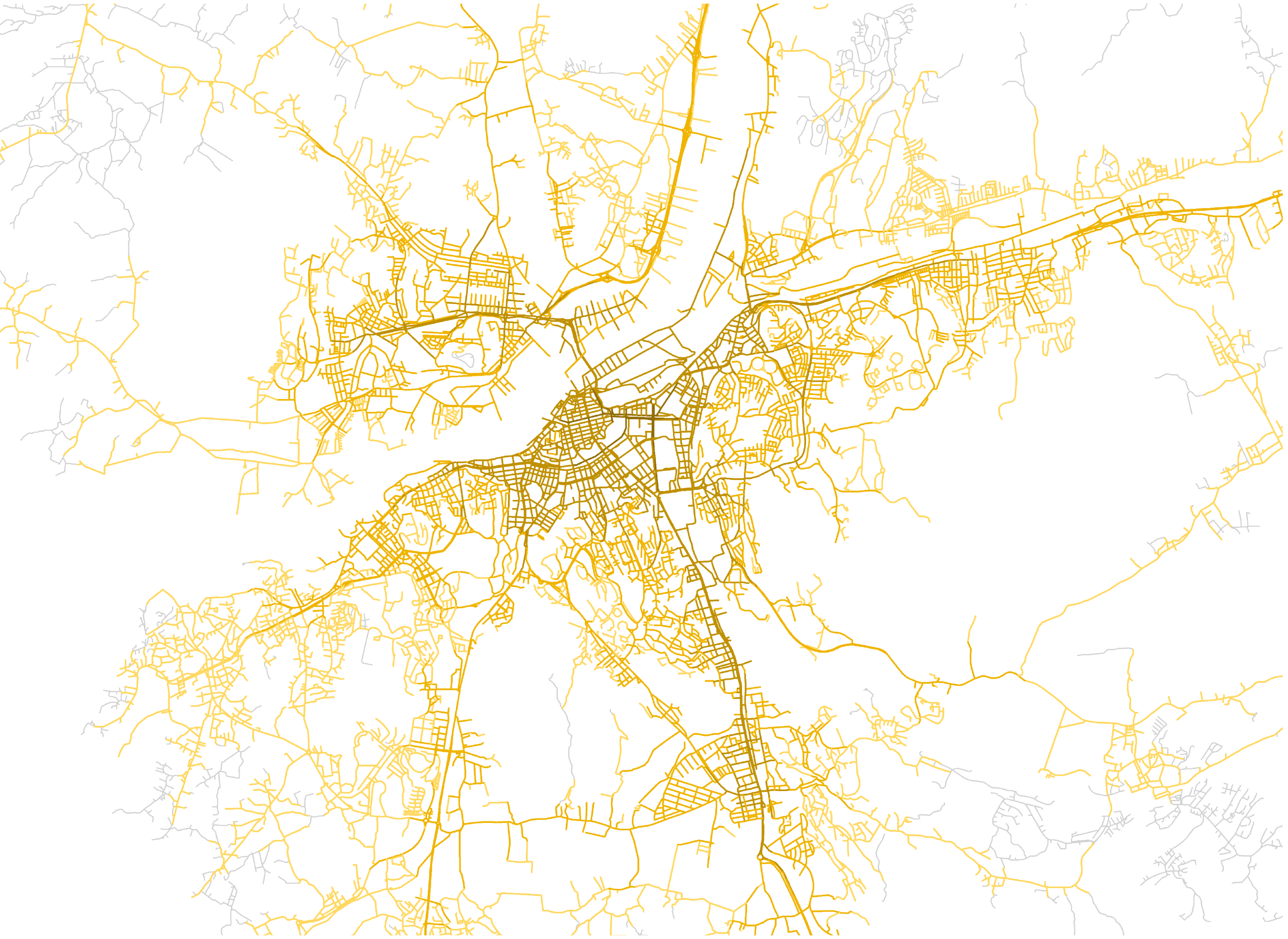


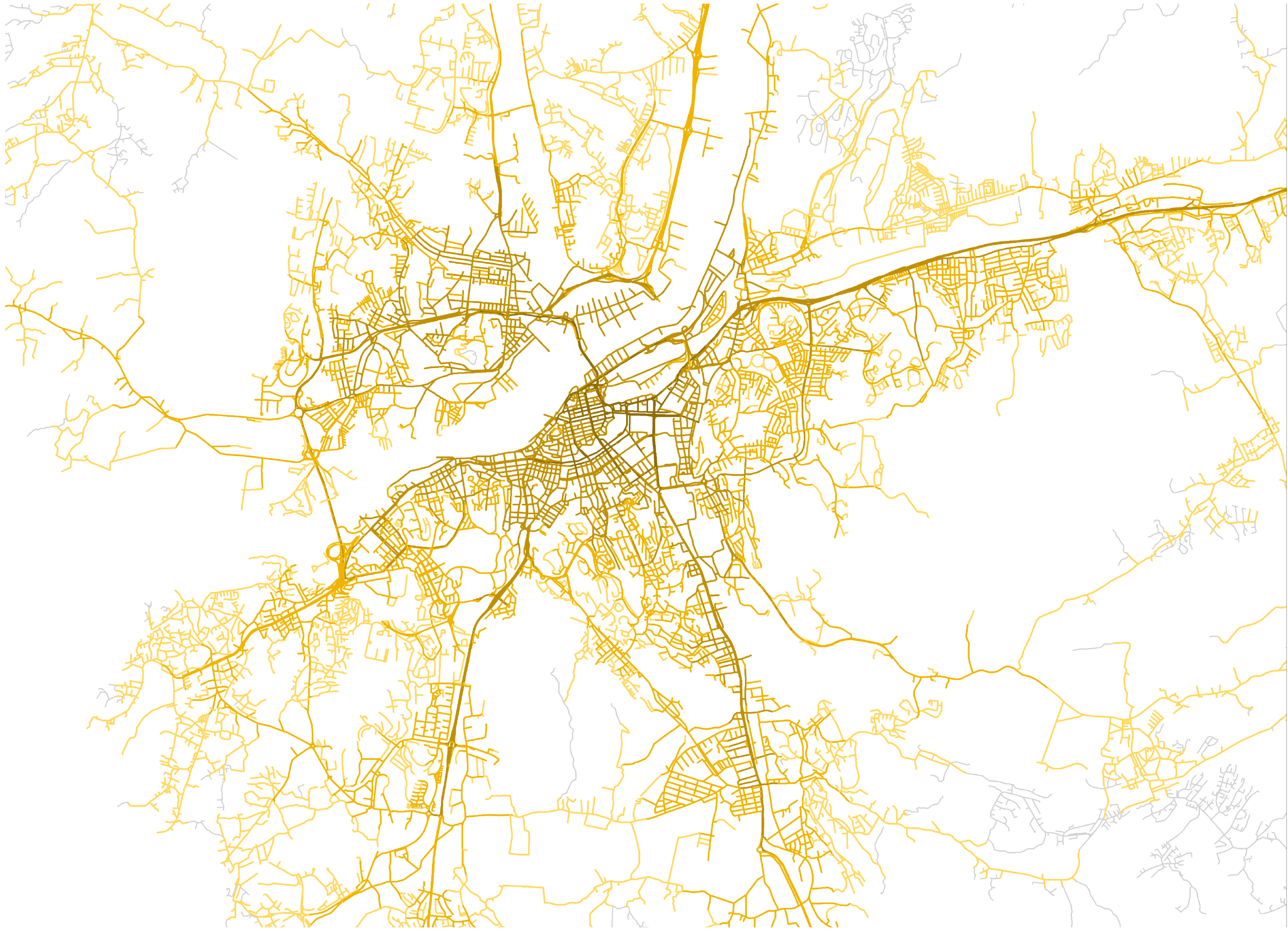
GIS-based time model. Gothenburg, 1960 to present

1960

1965

Angular Closeness centrality, global scale (n)





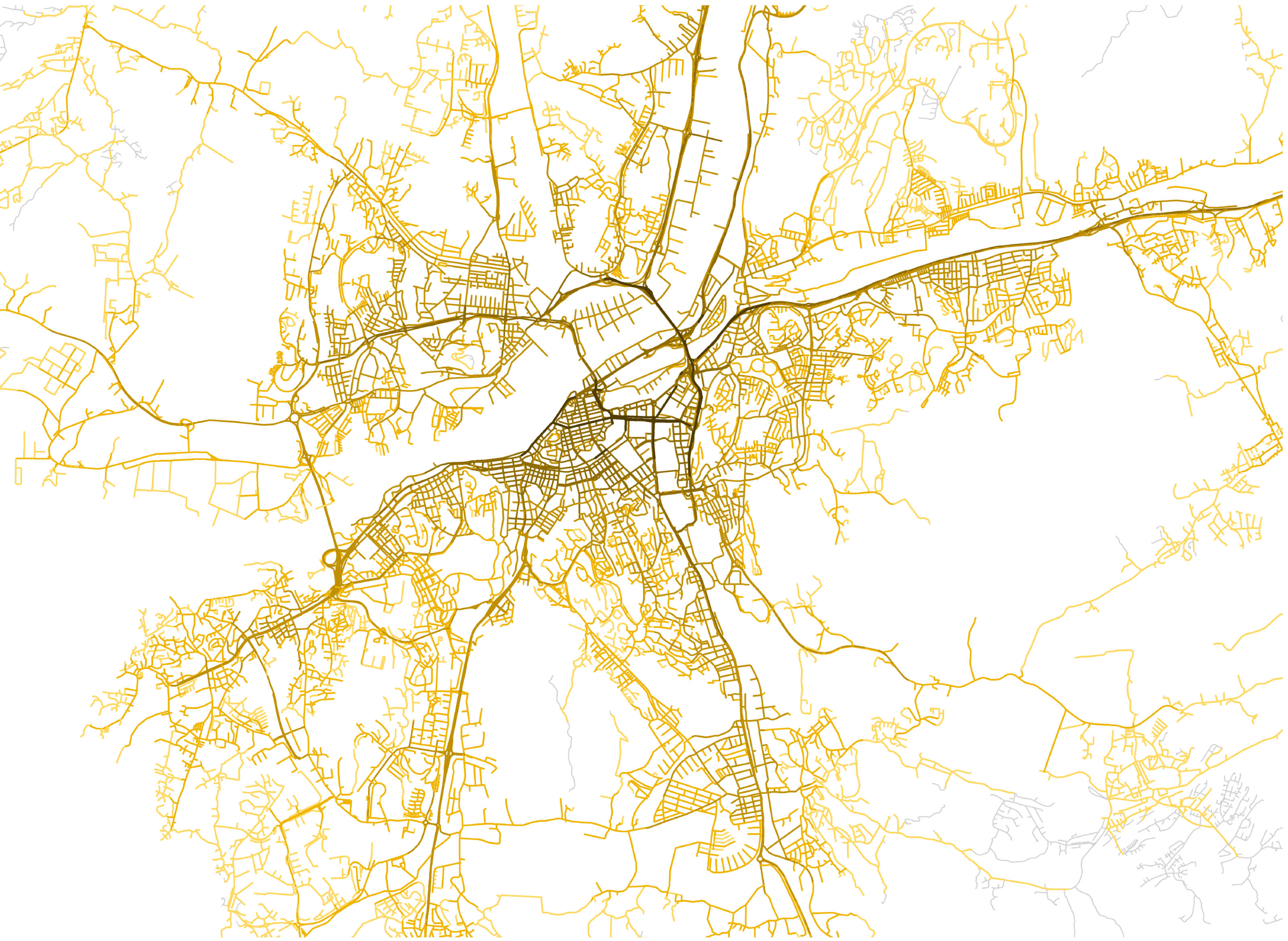
0 2km

high centrality

low centrality

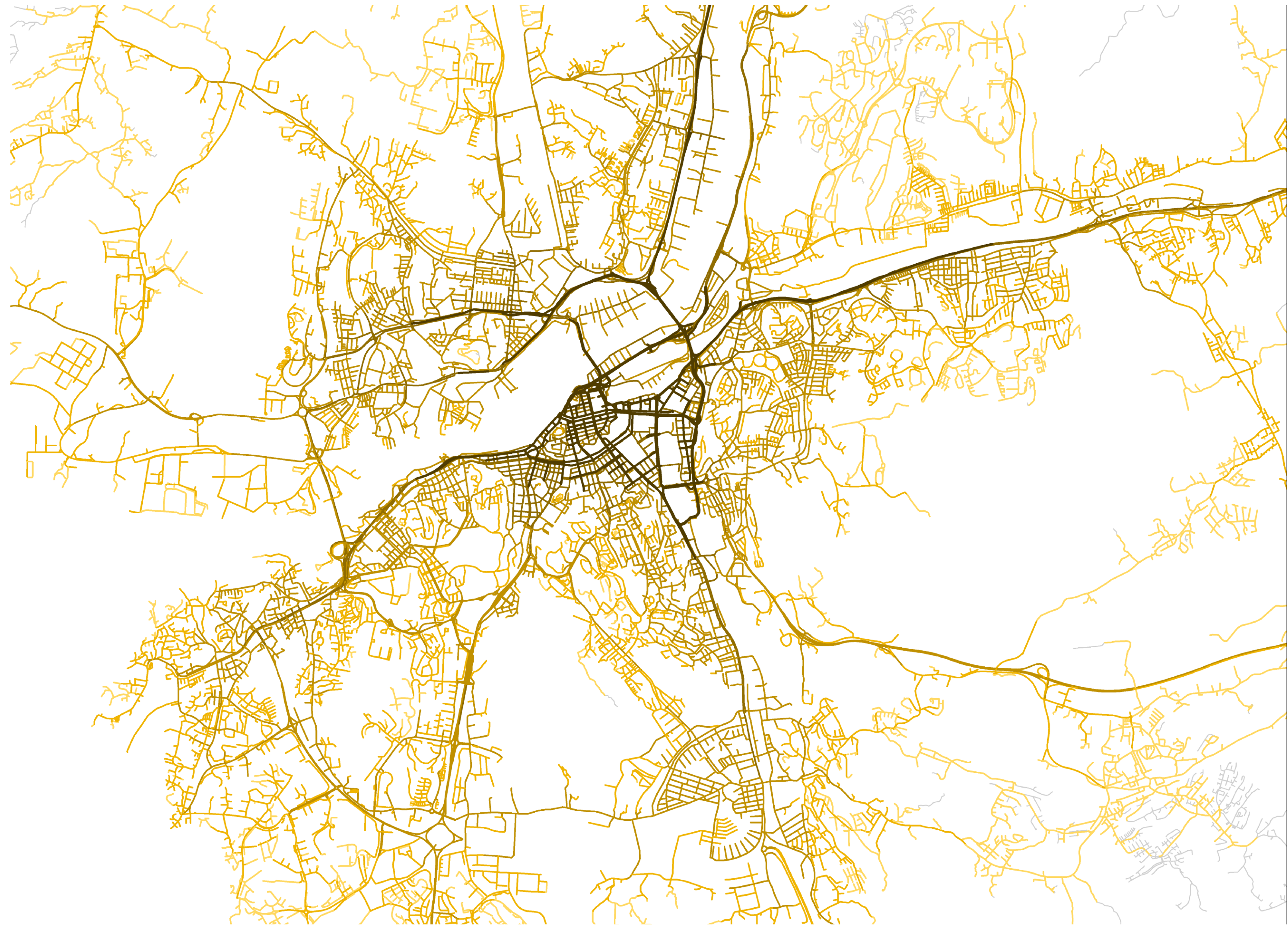
Angular Closeness centrality, global scale (n)

1970



0 2km

1975

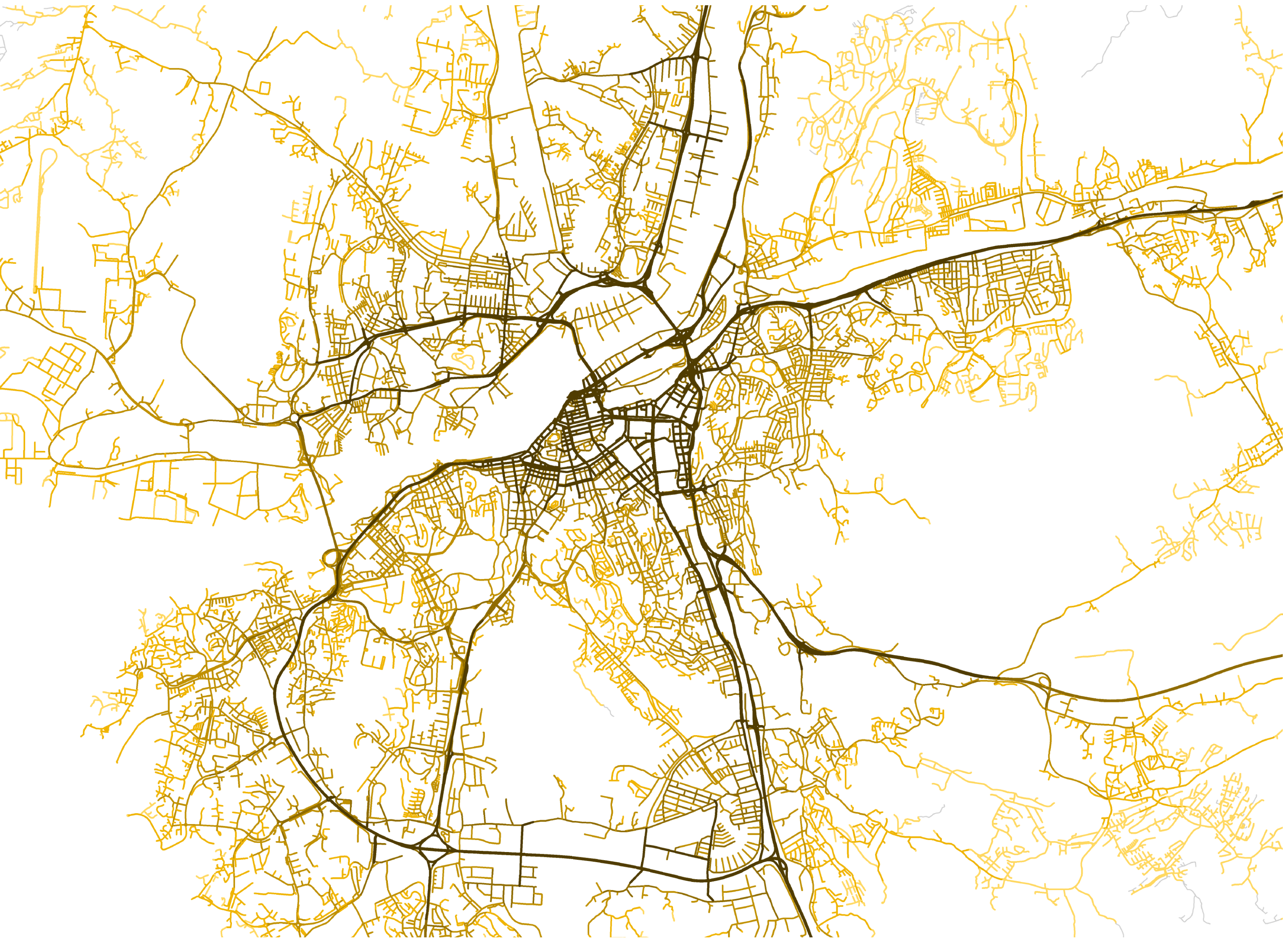


high centrality

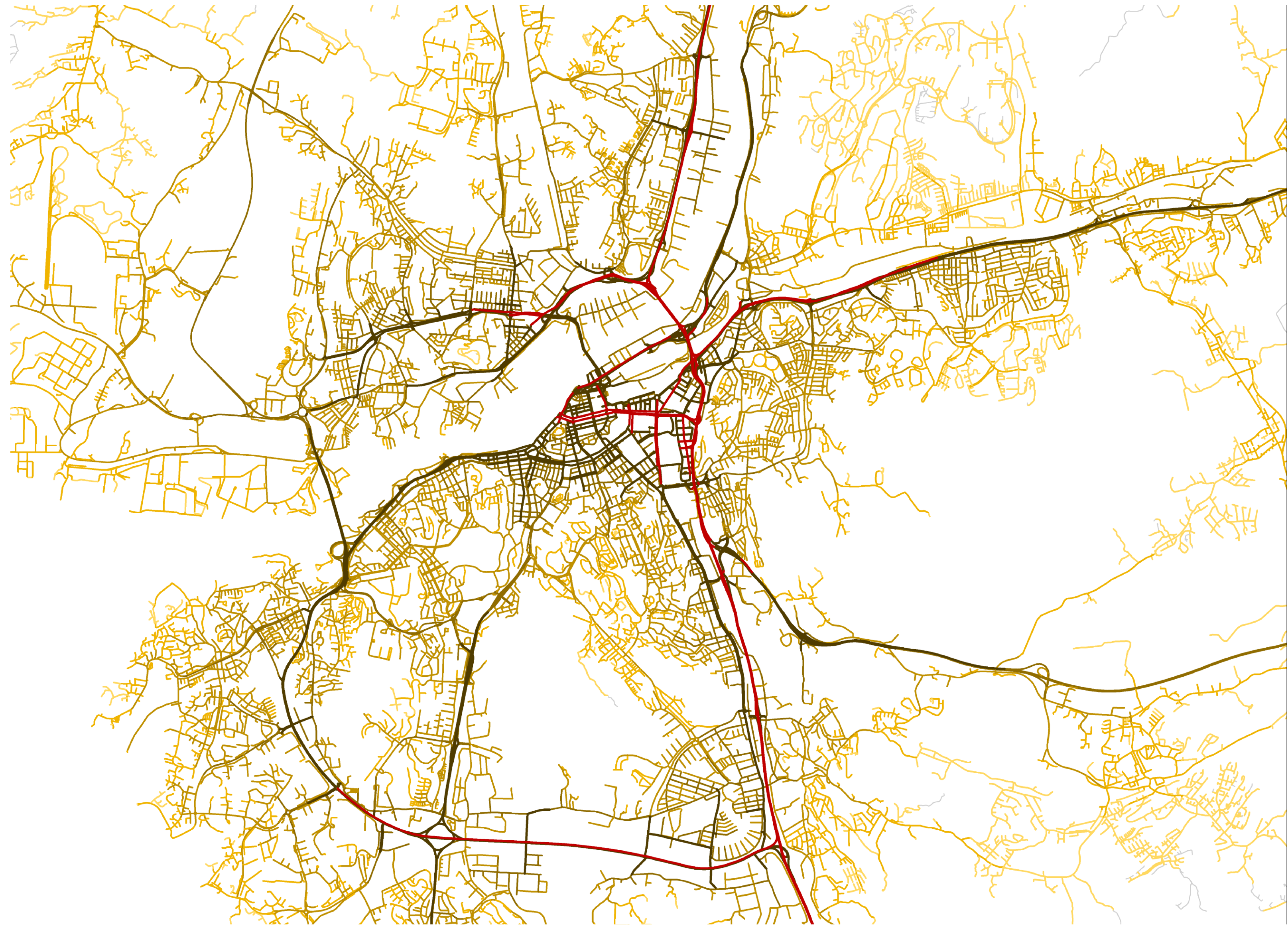
low centrality

Angular Closeness centrality, global scale (n)

1980



1985



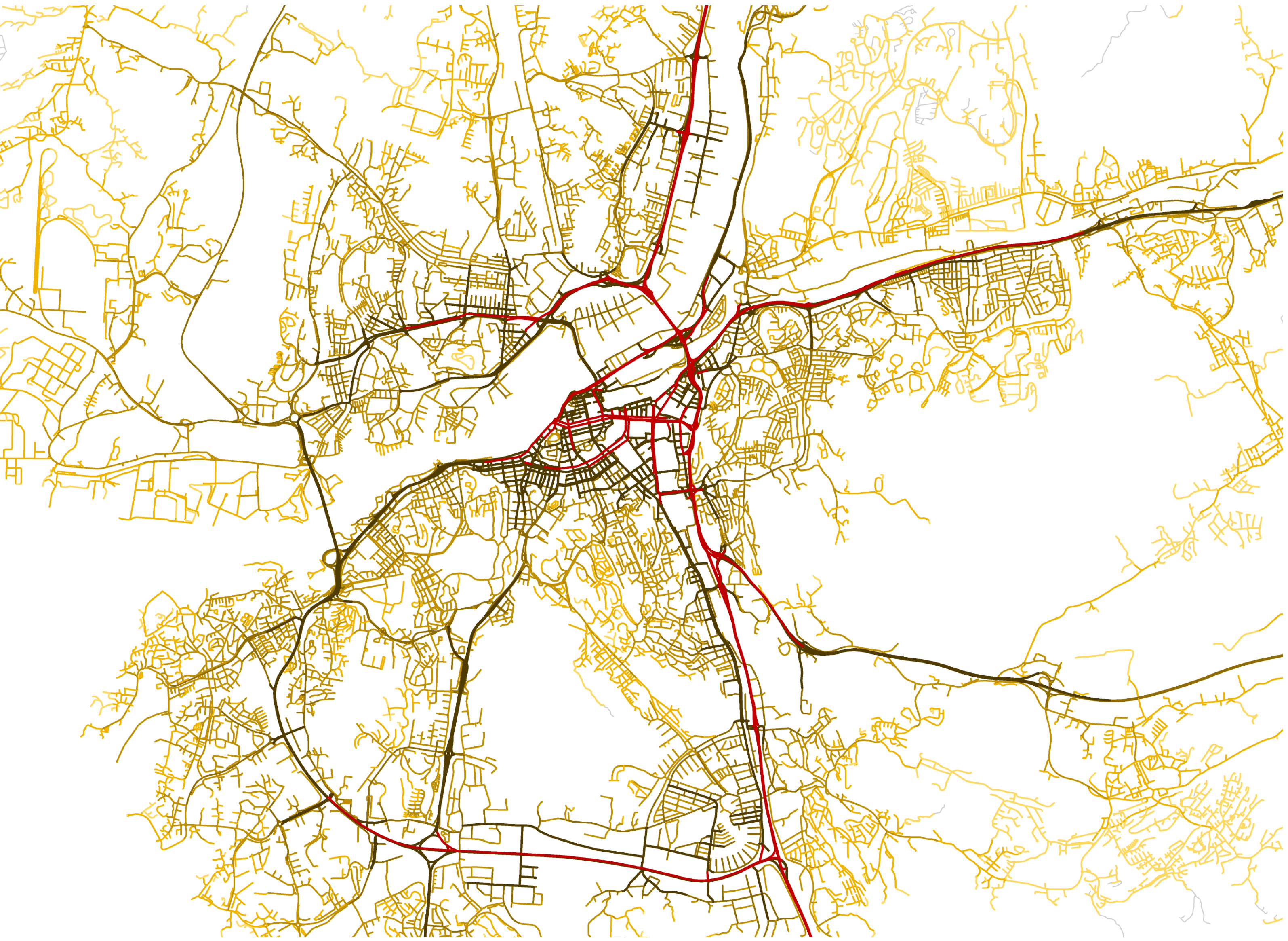
0 2km

high centrality

low centrality

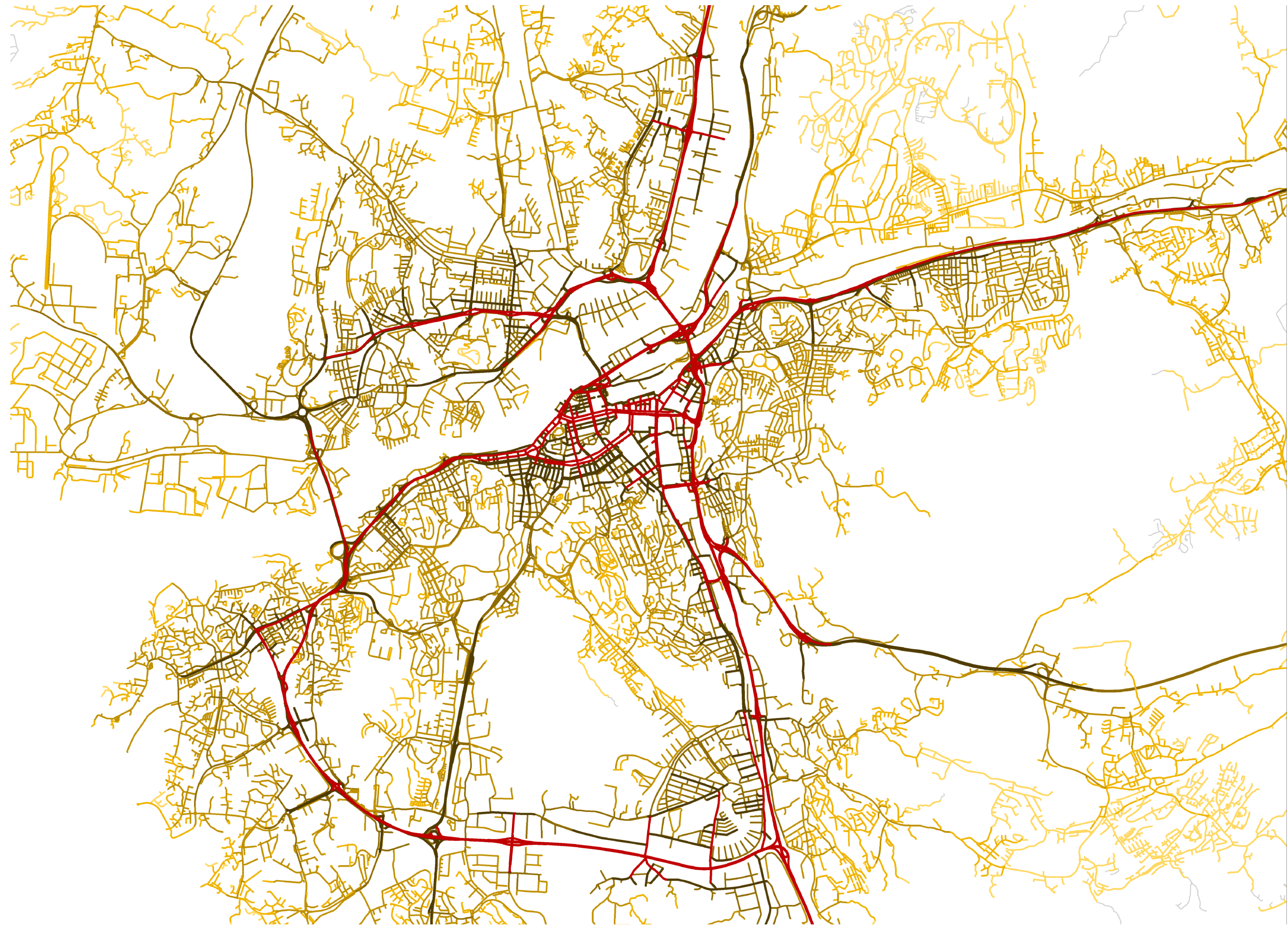
Angular Closeness centrality, global scale (n)

1990



0 2km

1995

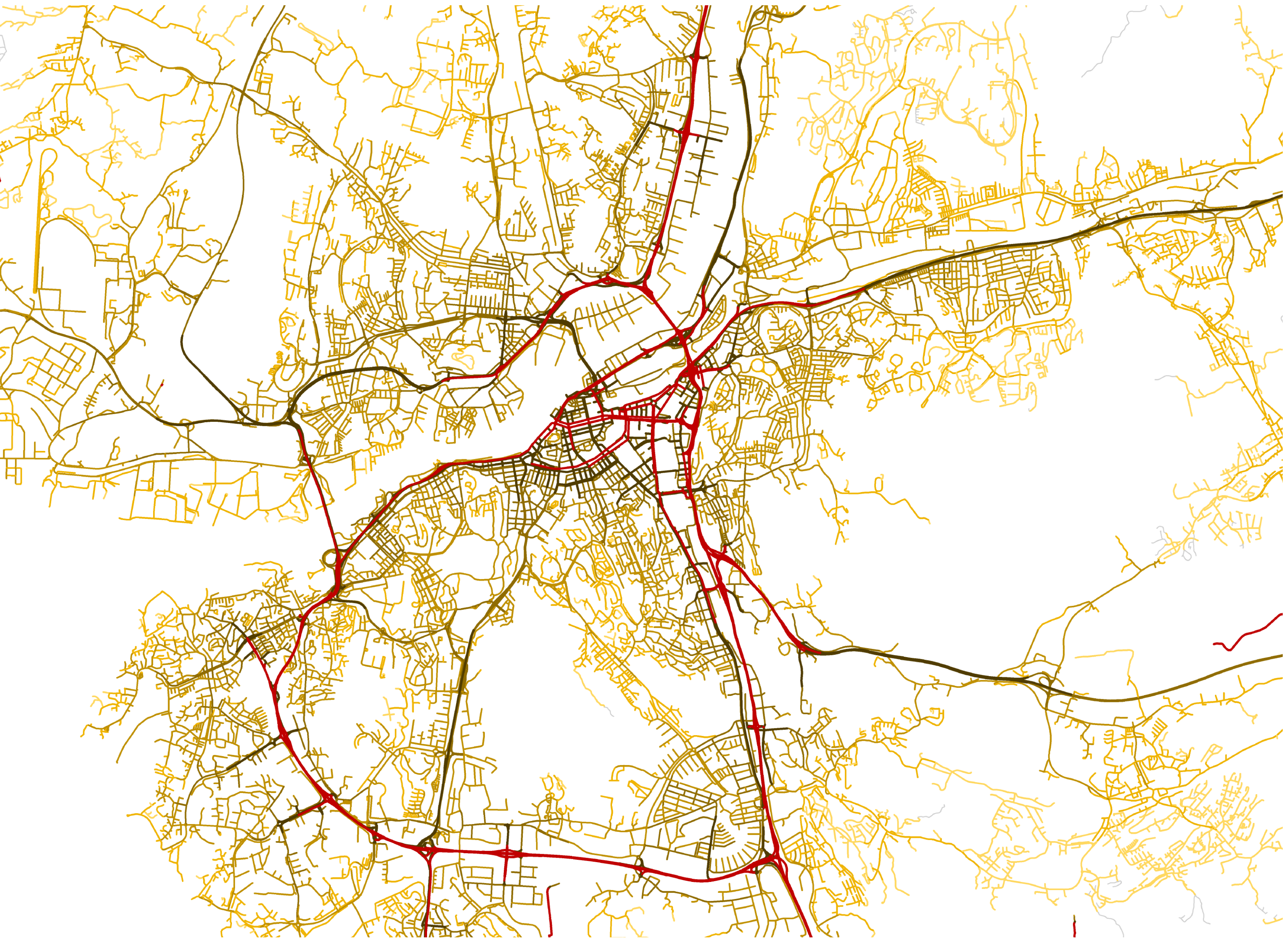


high centrality

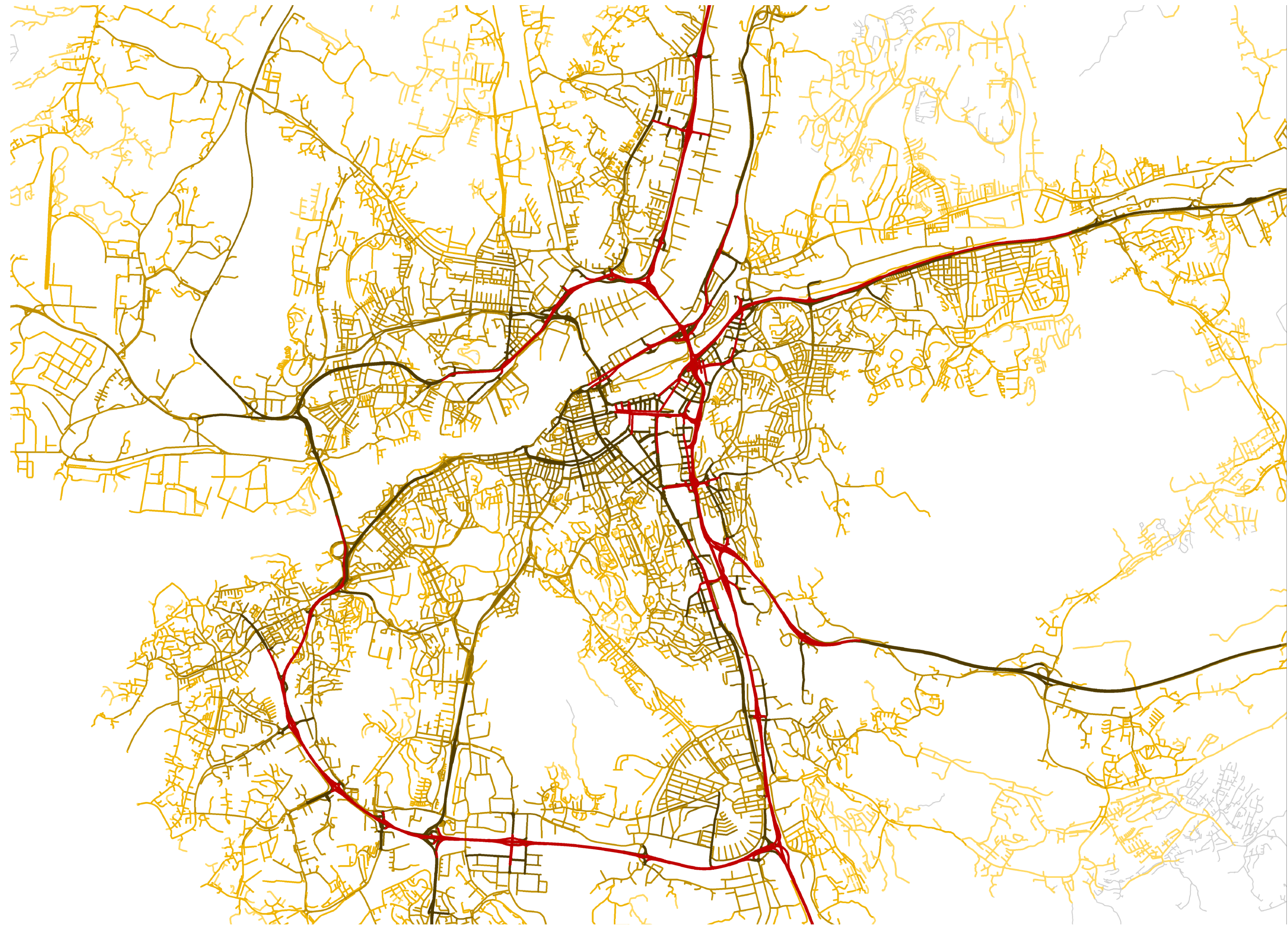
low centrality

Angular Closeness centrality, global scale (n)

2000



2005



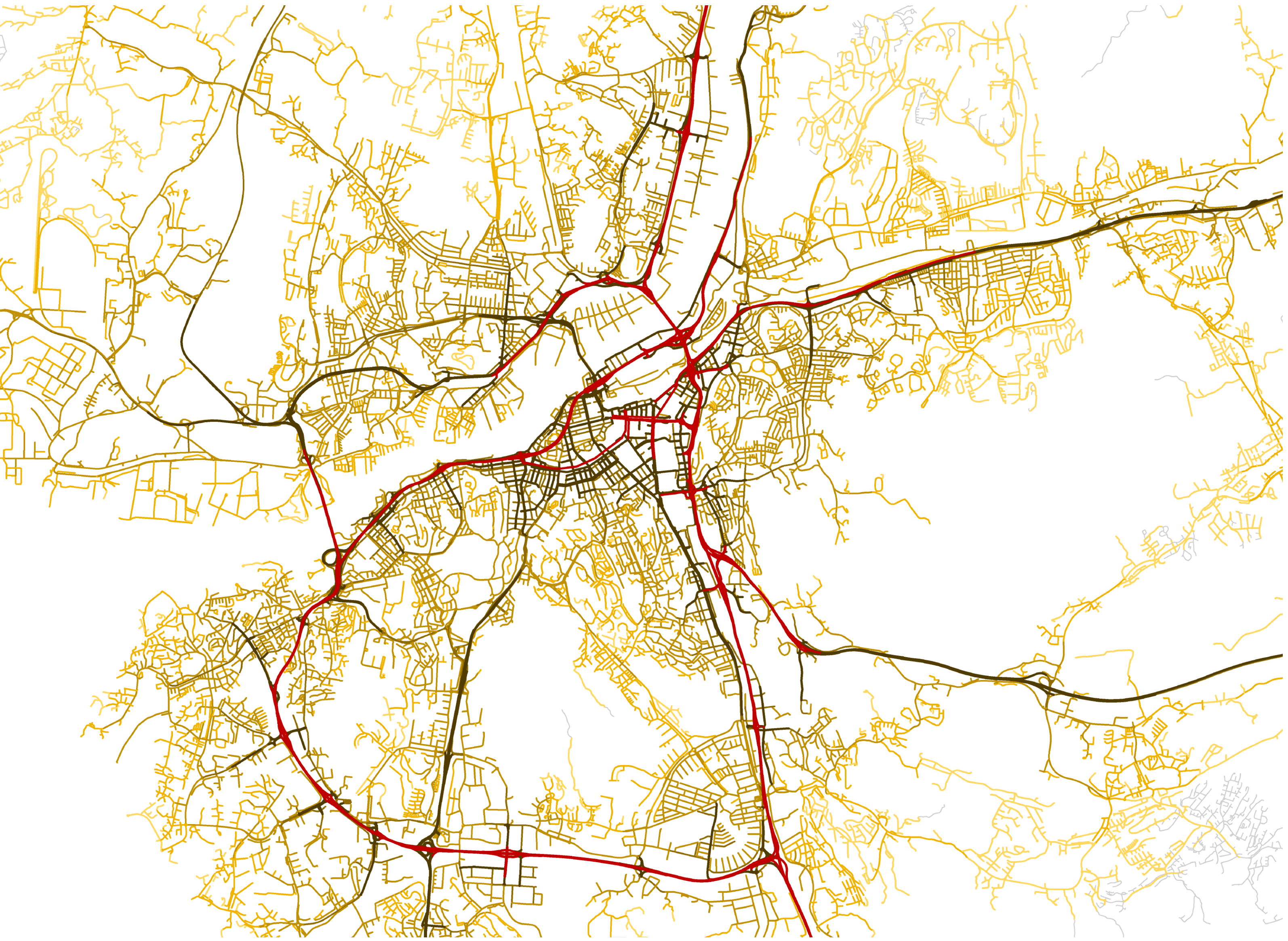
0 2km

high centrality

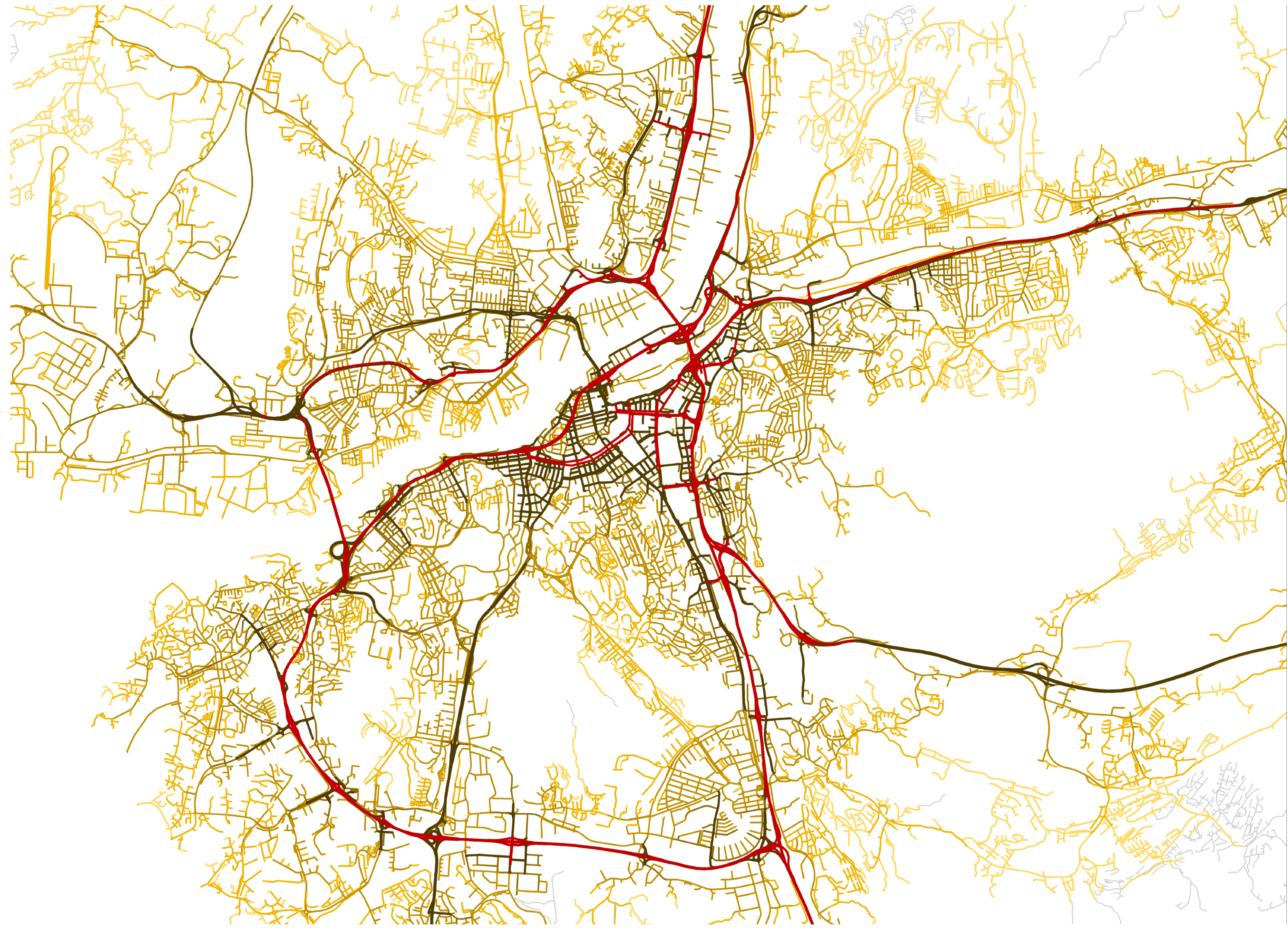
low centrality

Angular Closeness centrality, global scale (n)

2010



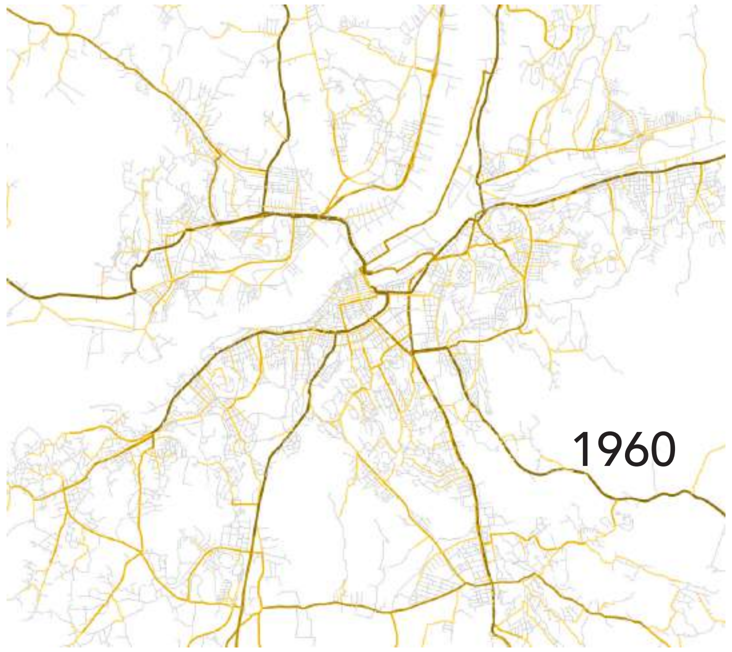
2015

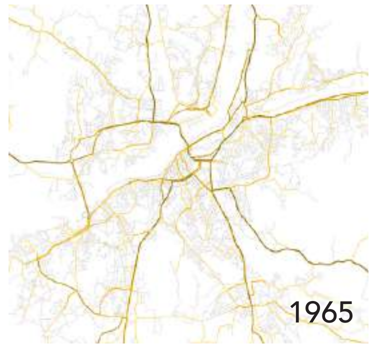


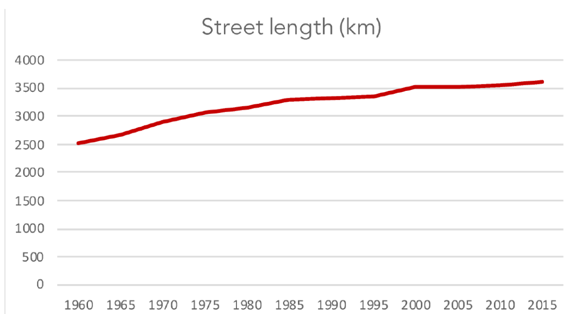
high centrality

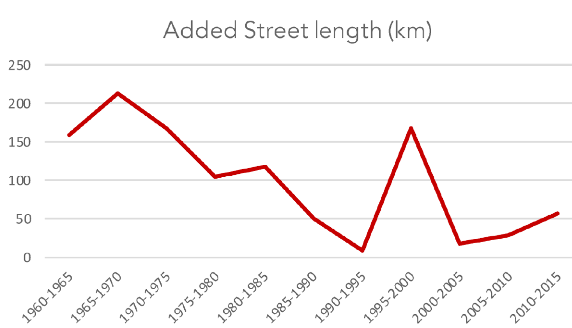
low centrality

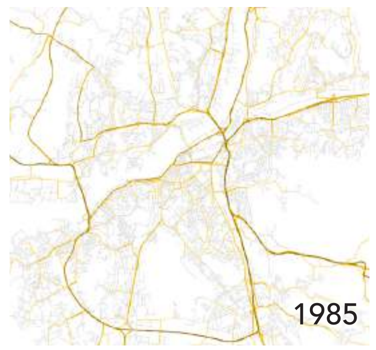
0 2km

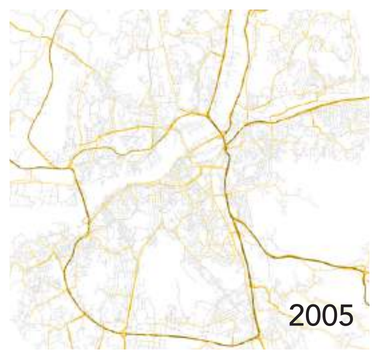


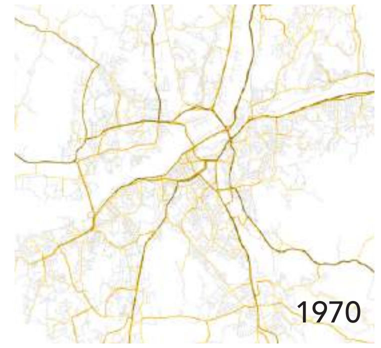


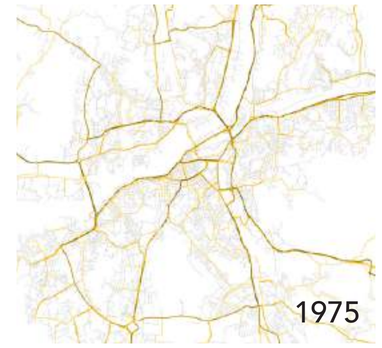


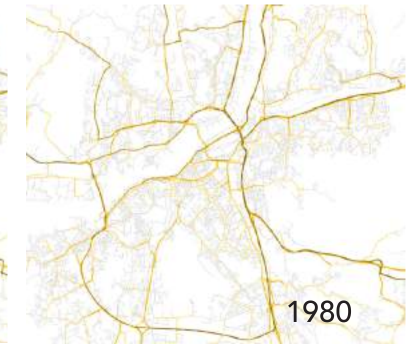


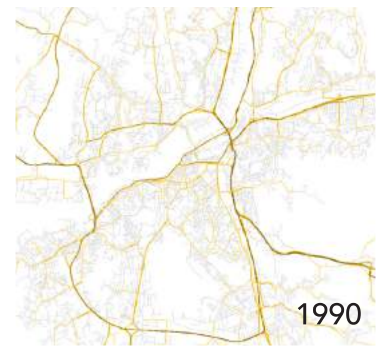


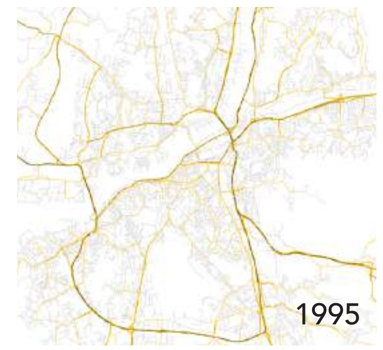


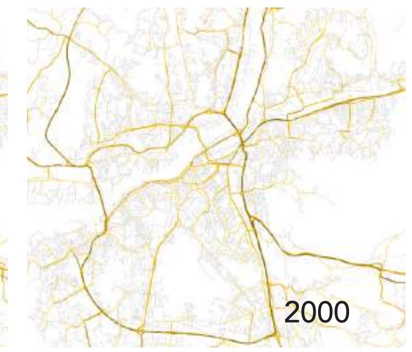


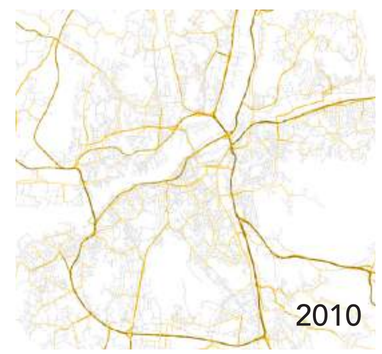


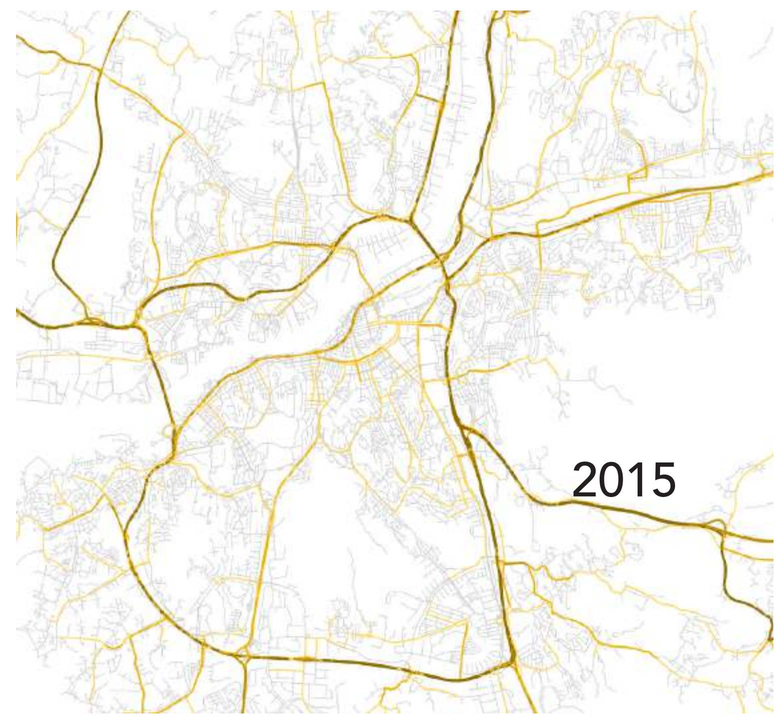










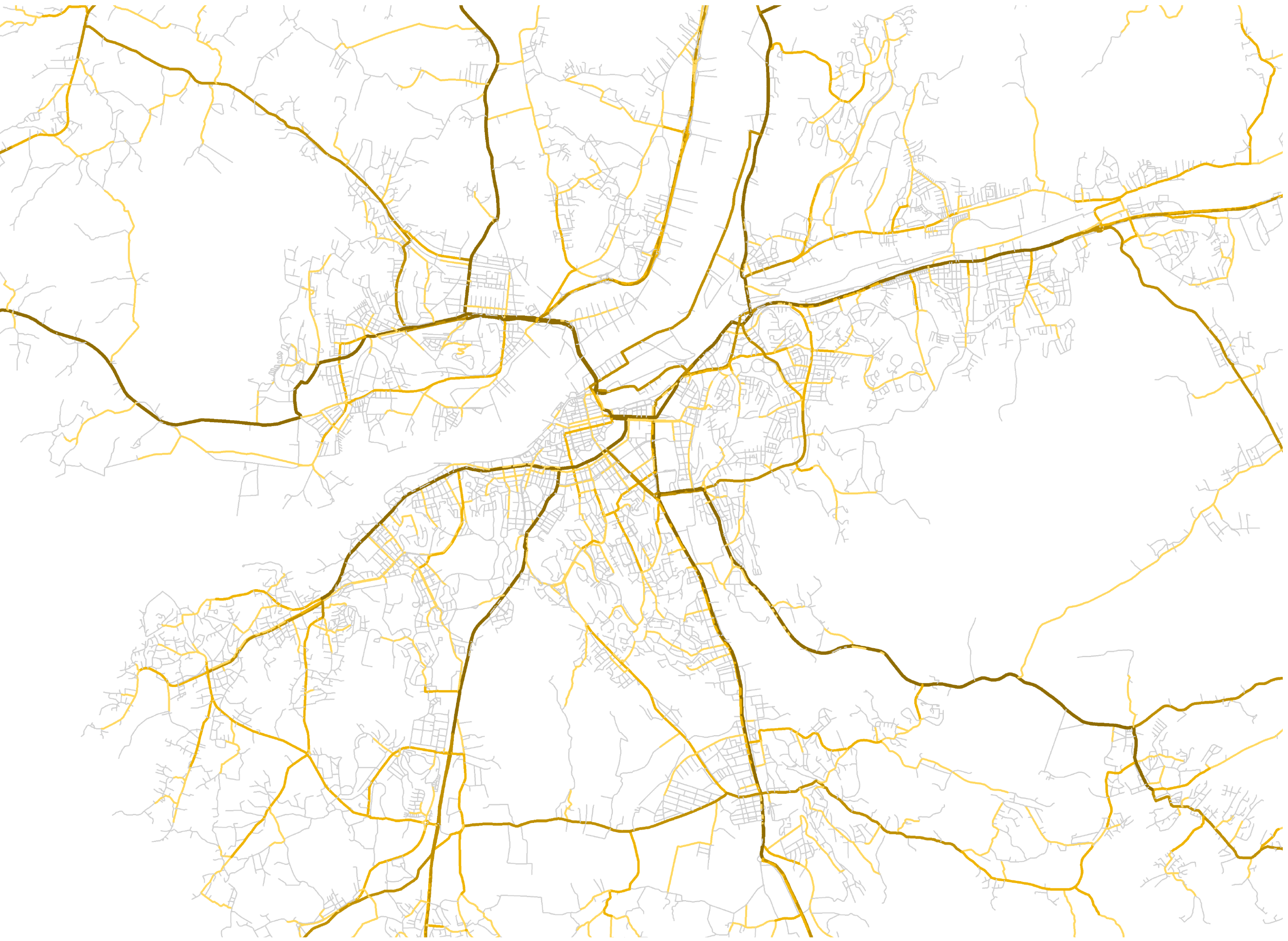


2% highest values
3%
5%
15%
75% lowest values

01.Street network

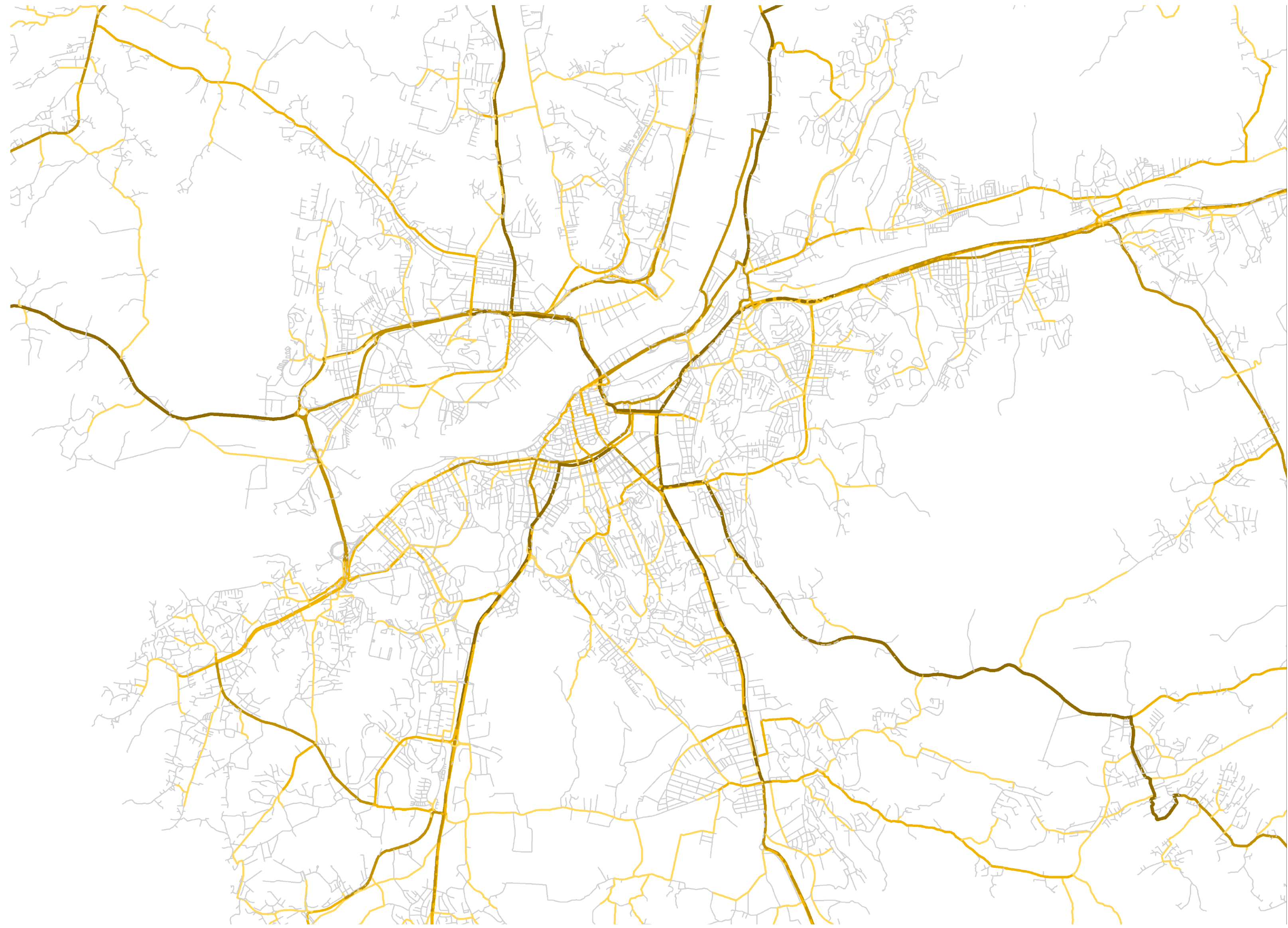
Angular Betweenness centrality, global scale (n)

1960



1965

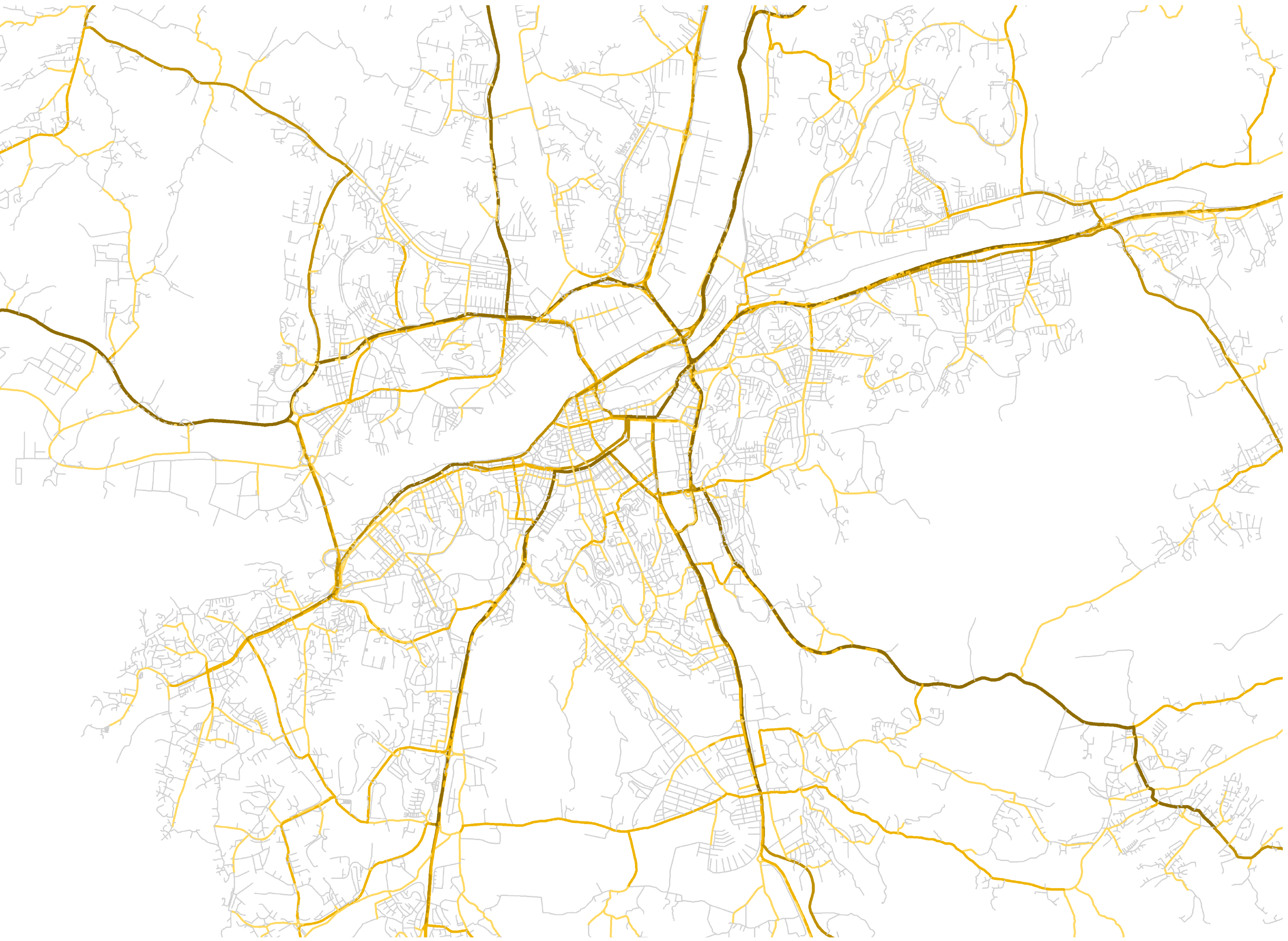
Angular Betweenness centrality, global scale (n)



0 2km

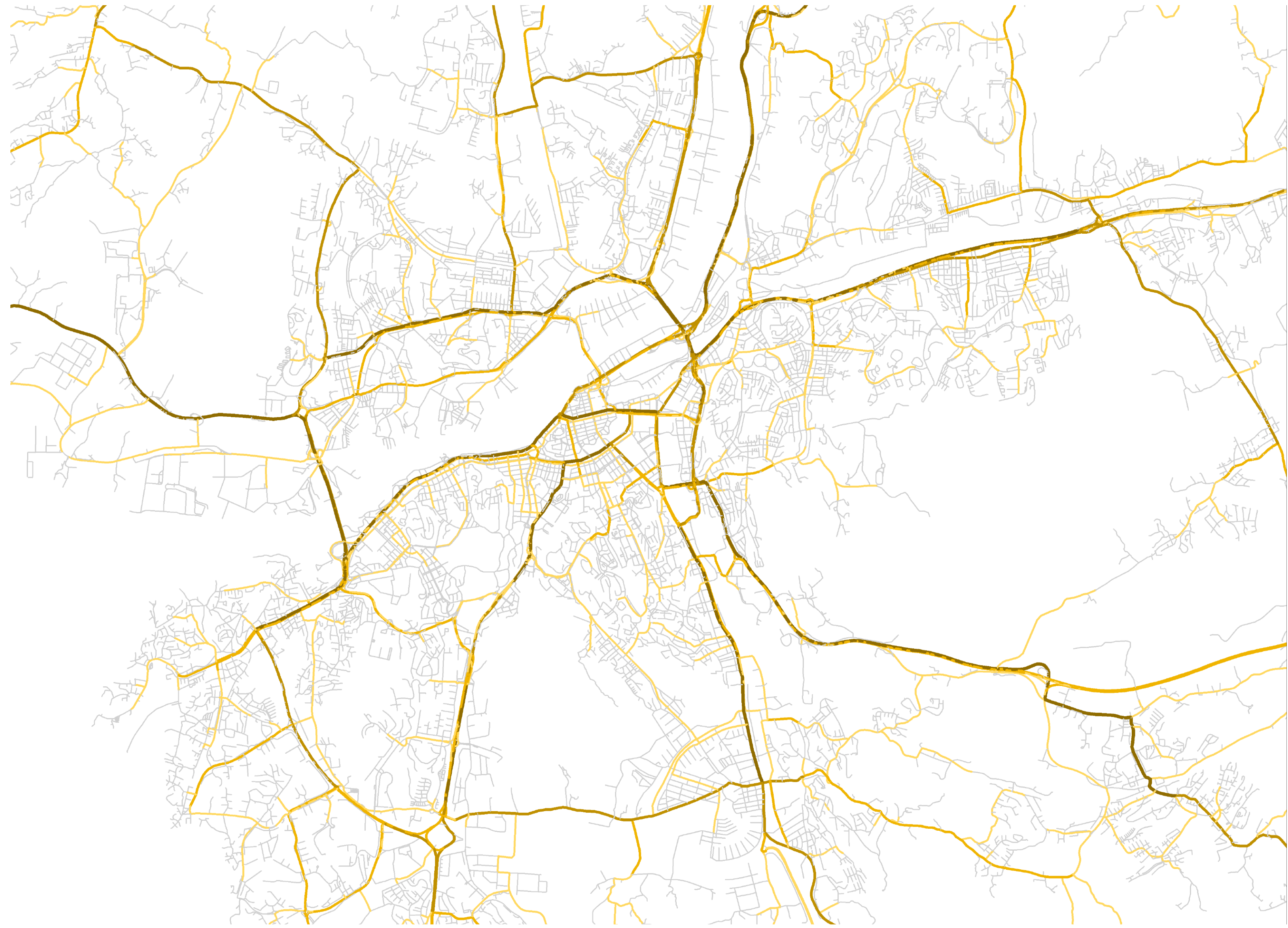
- 2% highest values
- 3%
- 5%
- 15%
- 75% lowest values

1970



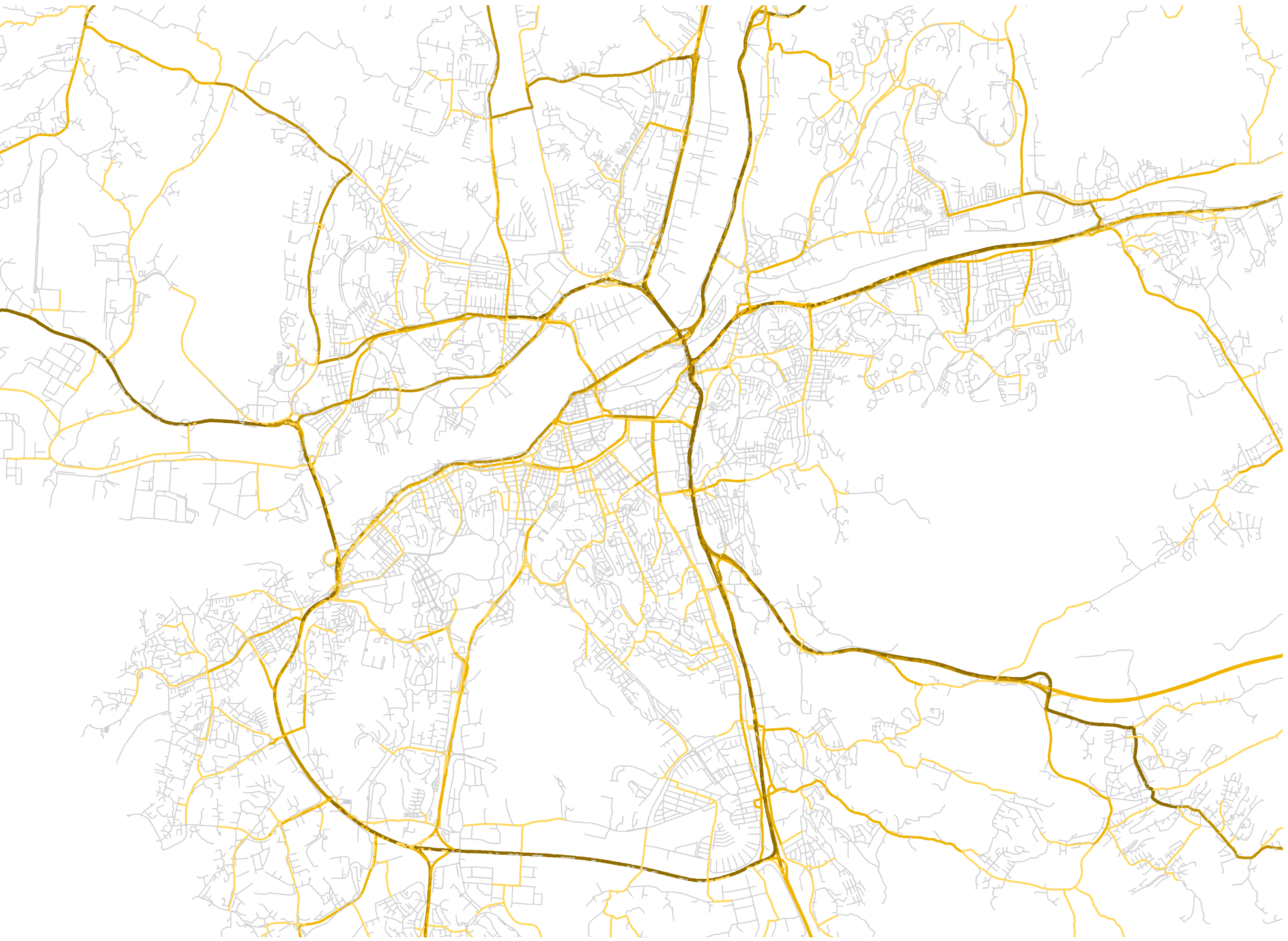
1975

Angular Betweenness centrality, global scale (n)



- 2% highest values
- 3%
- 5%
- 15%
- 75% lowest values

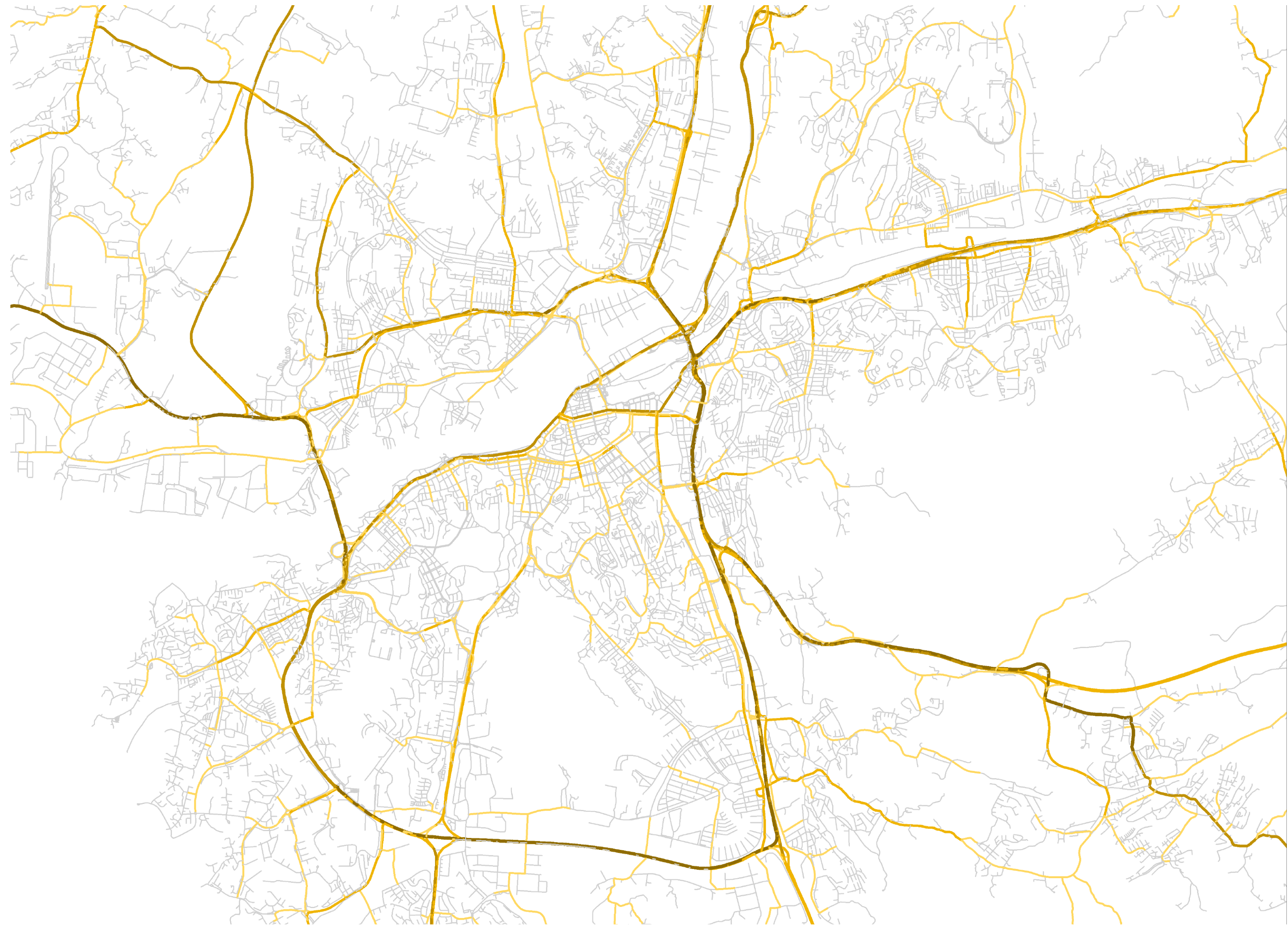
1980



0 2km

1985

Angular Betweenness centrality, global scale (n)



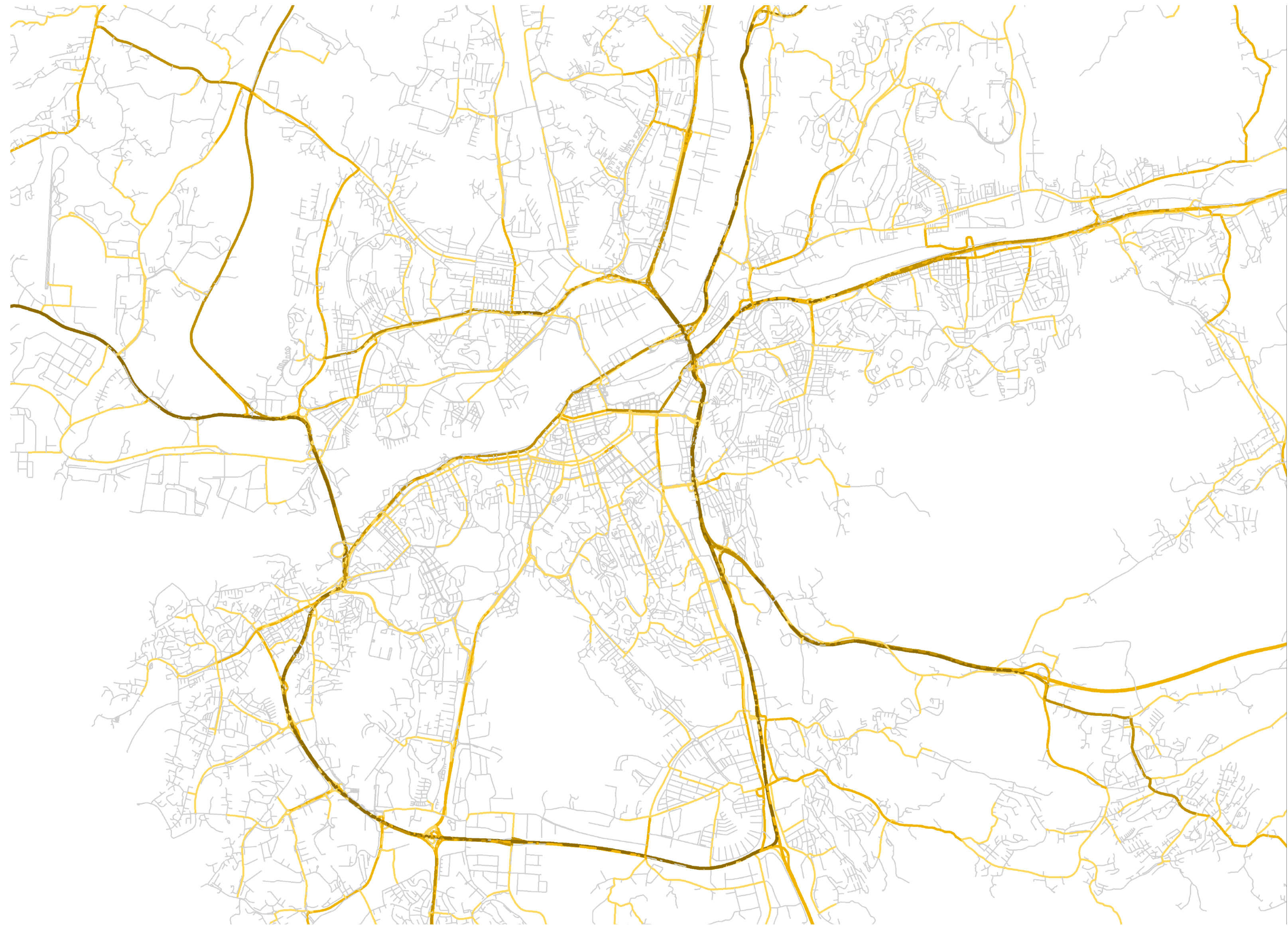
2% highest values
3%
5%
15%
75% lowest values

Angular Betweenness centrality, global scale (n)

1990

0 2km

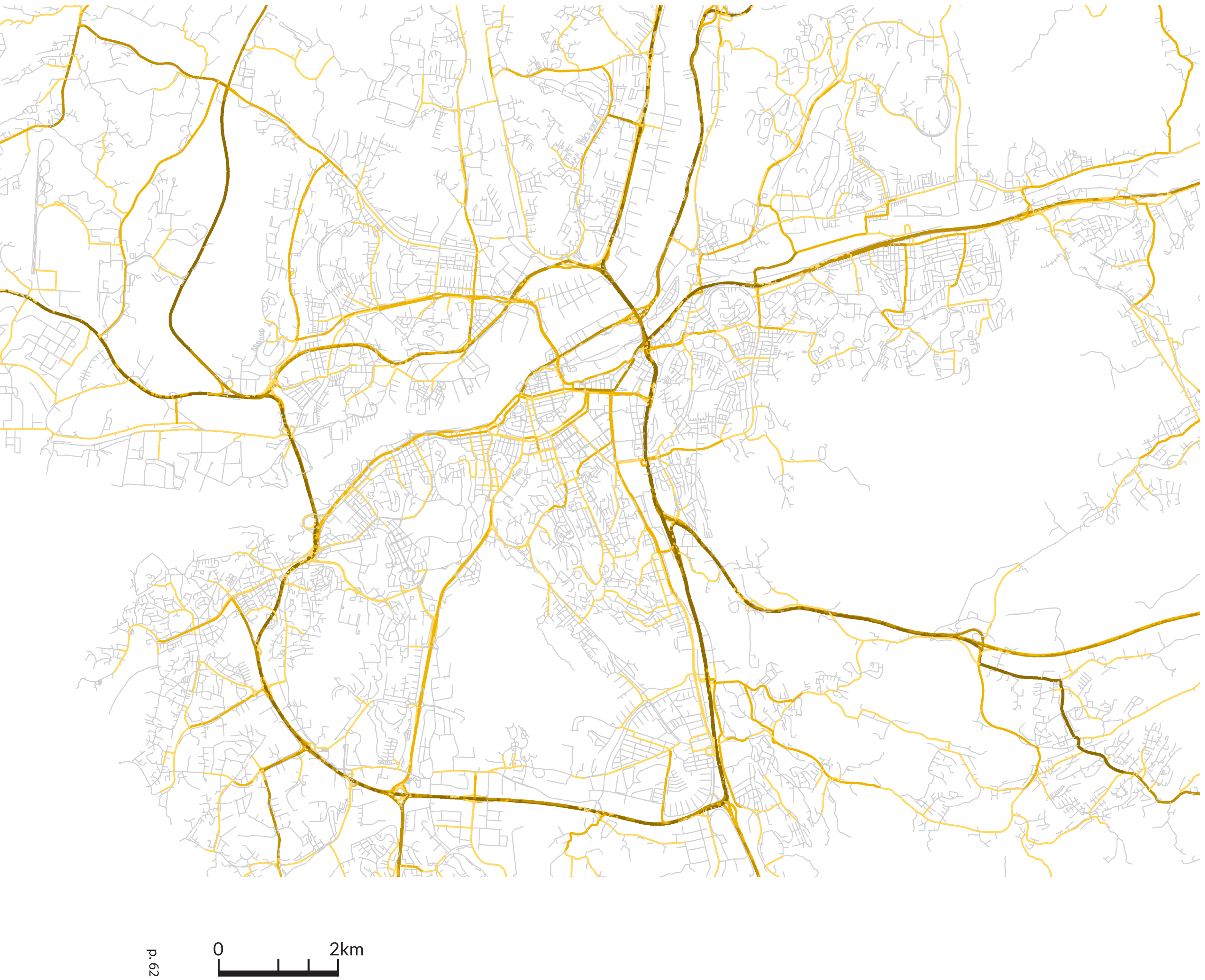
1995



- 2% highest values
- 3%
- 5%
- 15%
- 75% lowest values

Angular Betweenness centrality, global scale (n)

2000



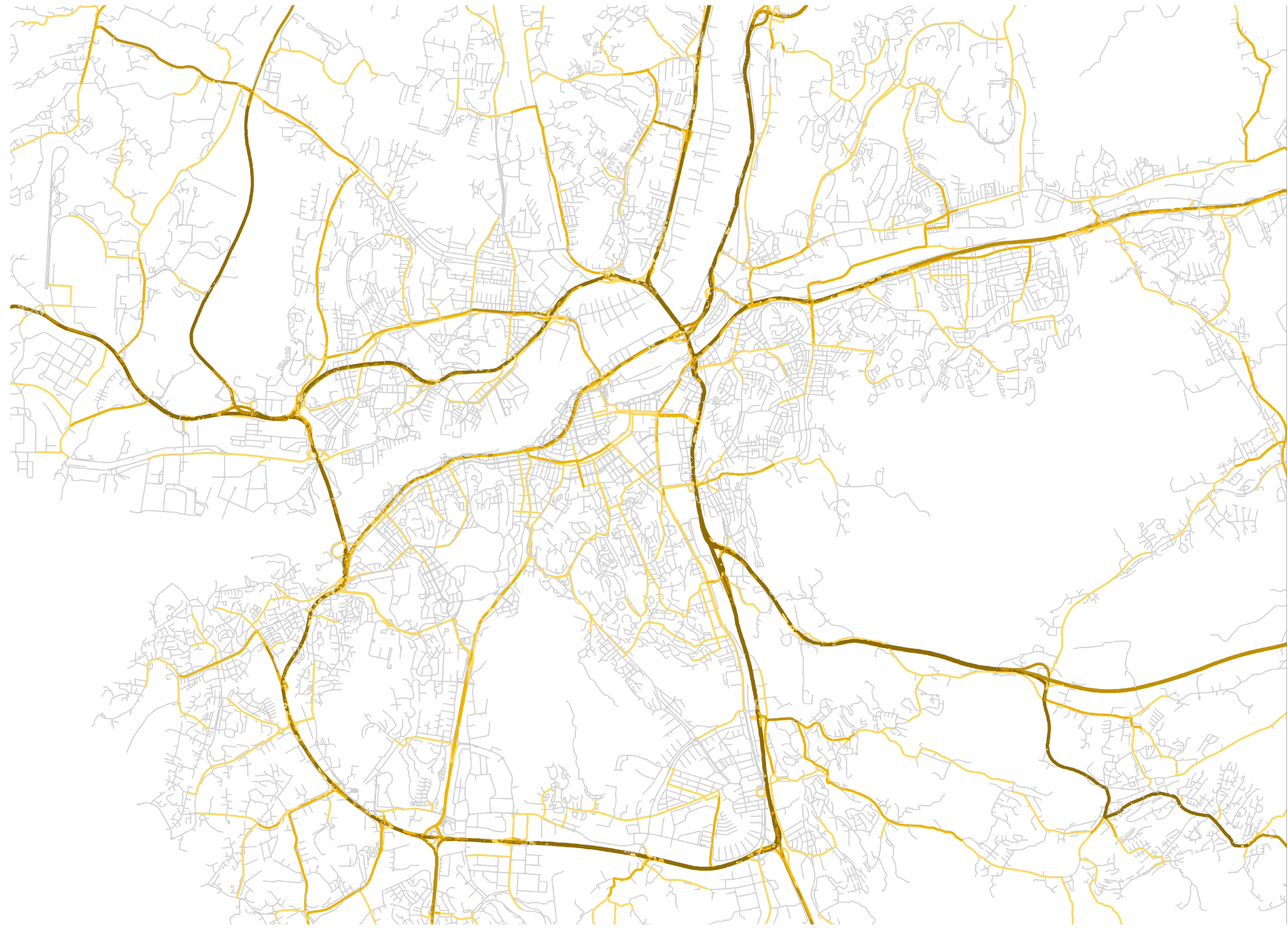
2005

- 2% highest values
- 3%
- 5%
- 15%
- 75% lowest values

2010

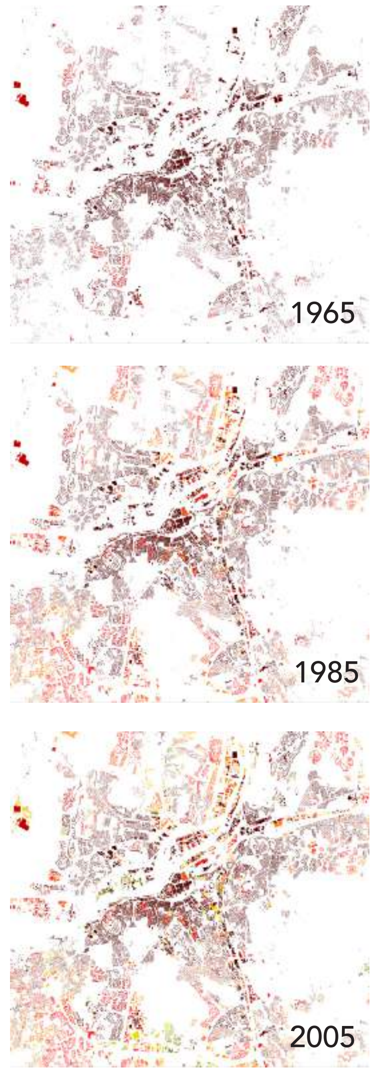
2015

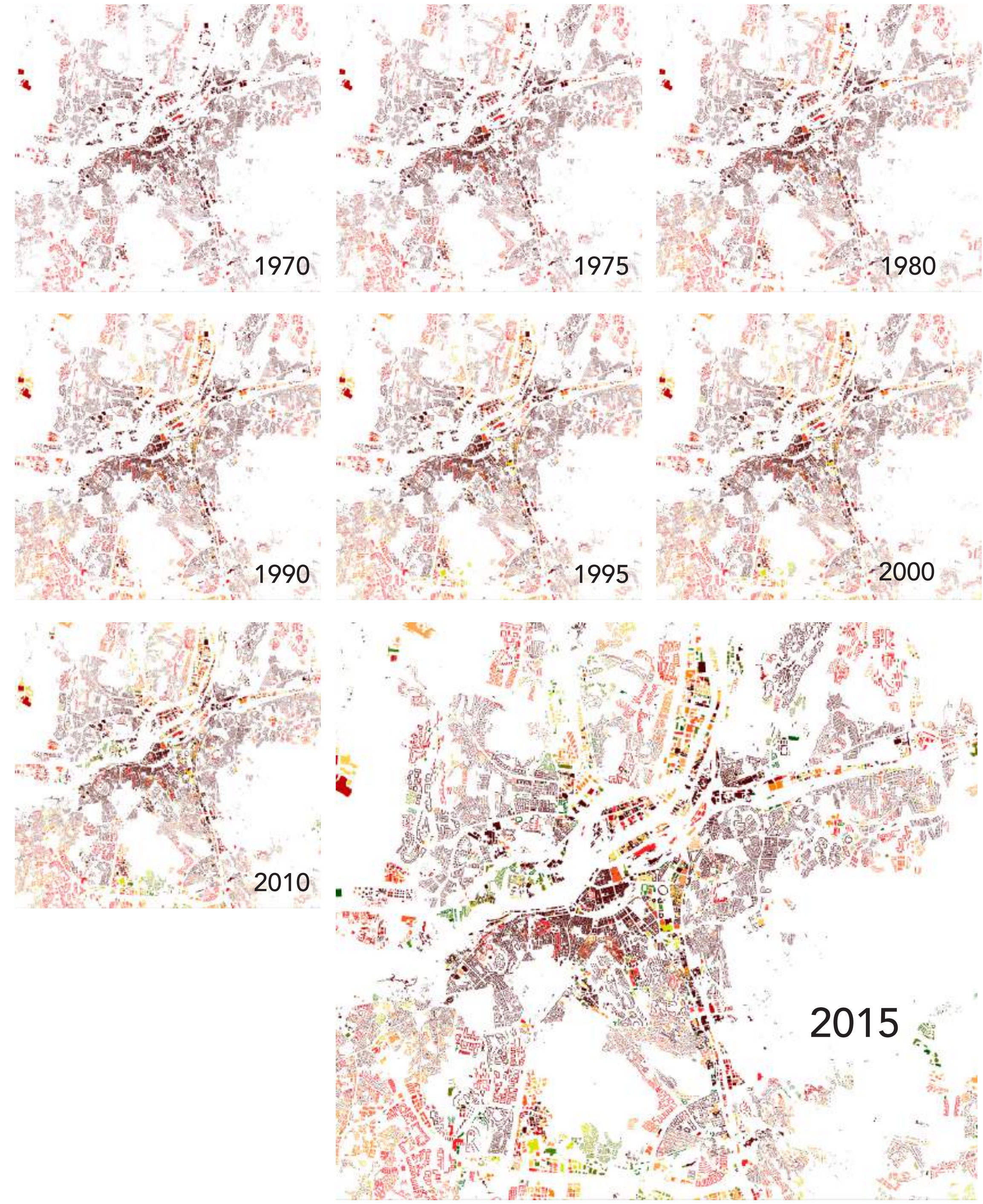
Angular Betweenness centrality, global scale (n)

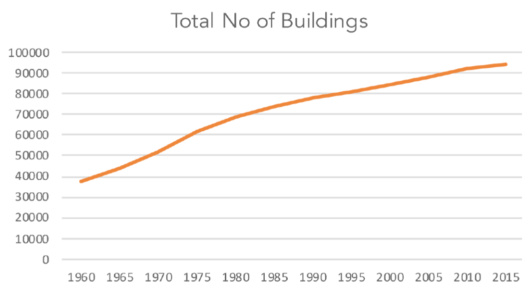


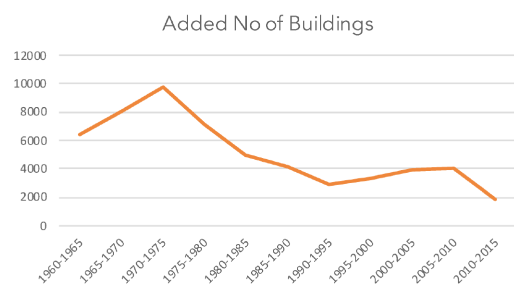
0 2km

2% highest values
3%
5%
15%
75% lowest values



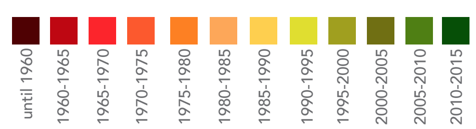




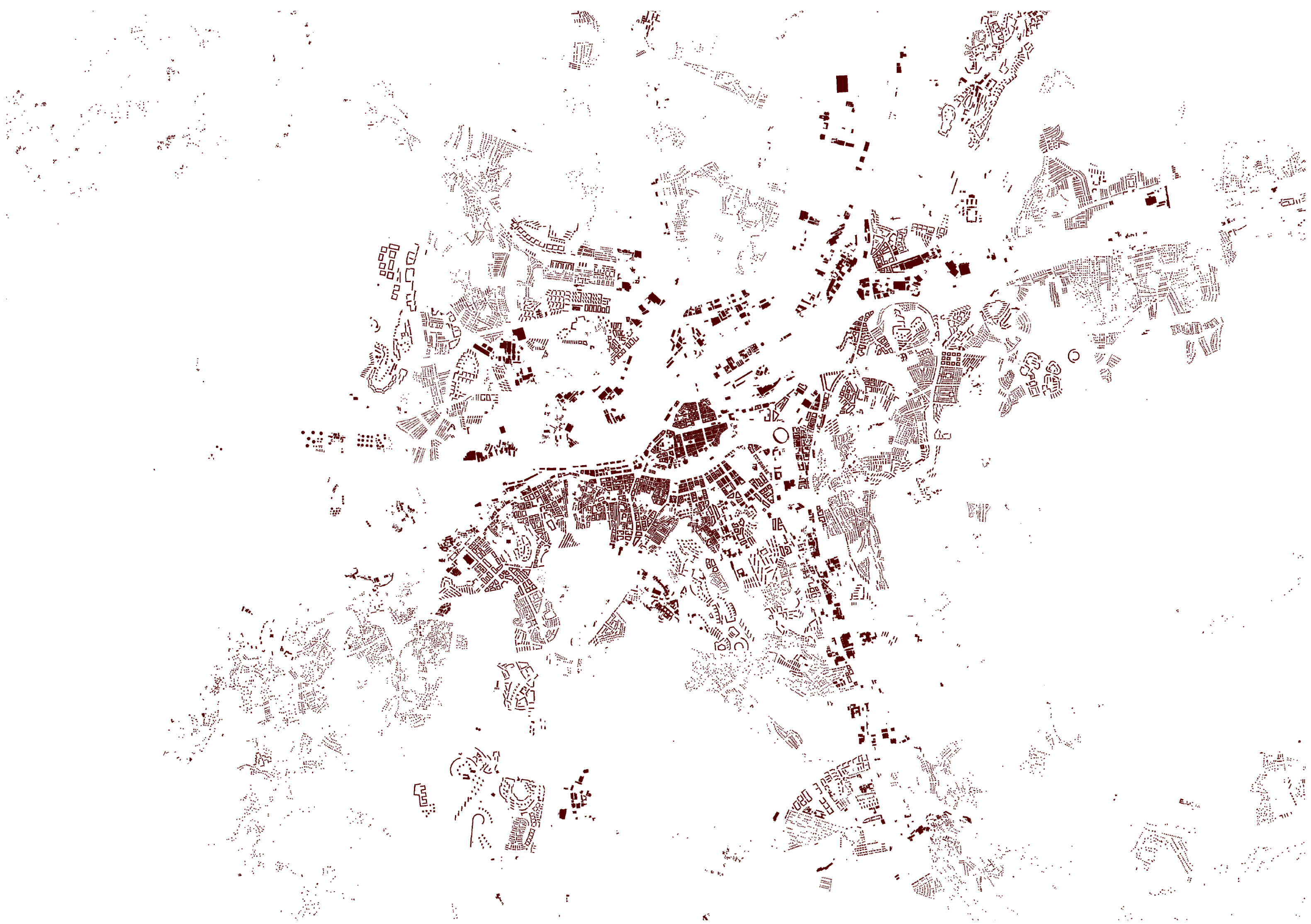


02.Buildings

a. Year of construction



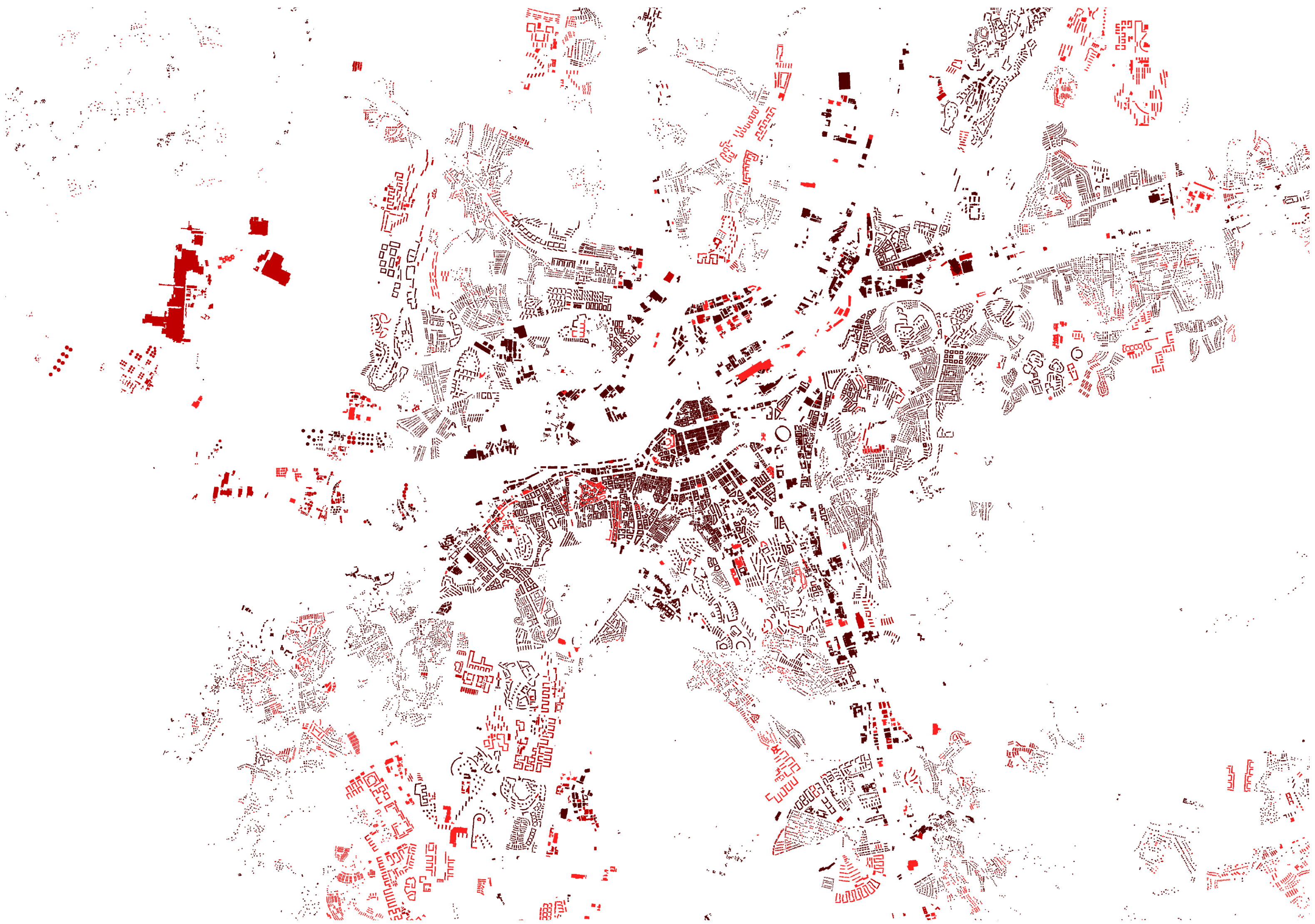
1960



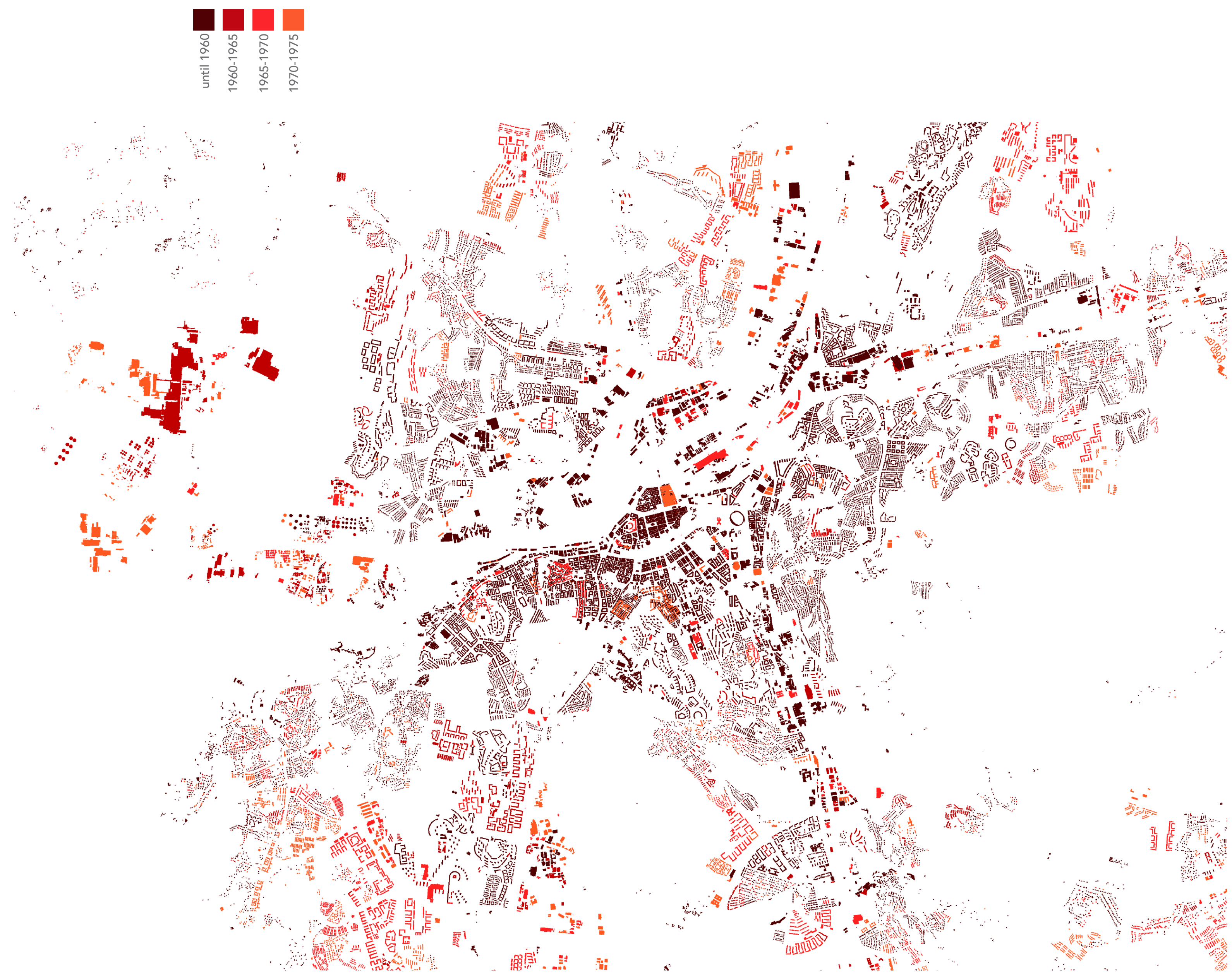
1965

0 2km

1970

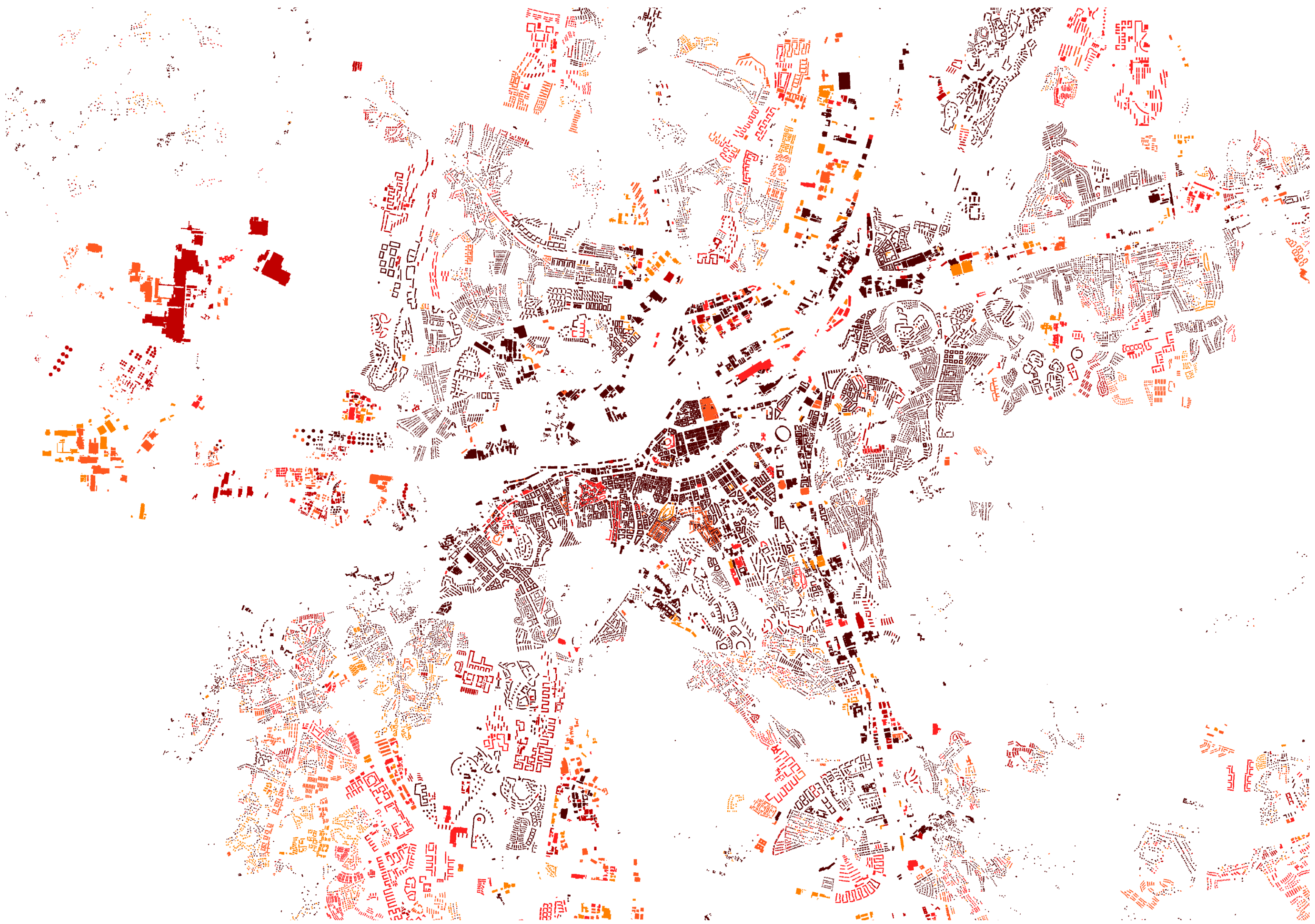


1975

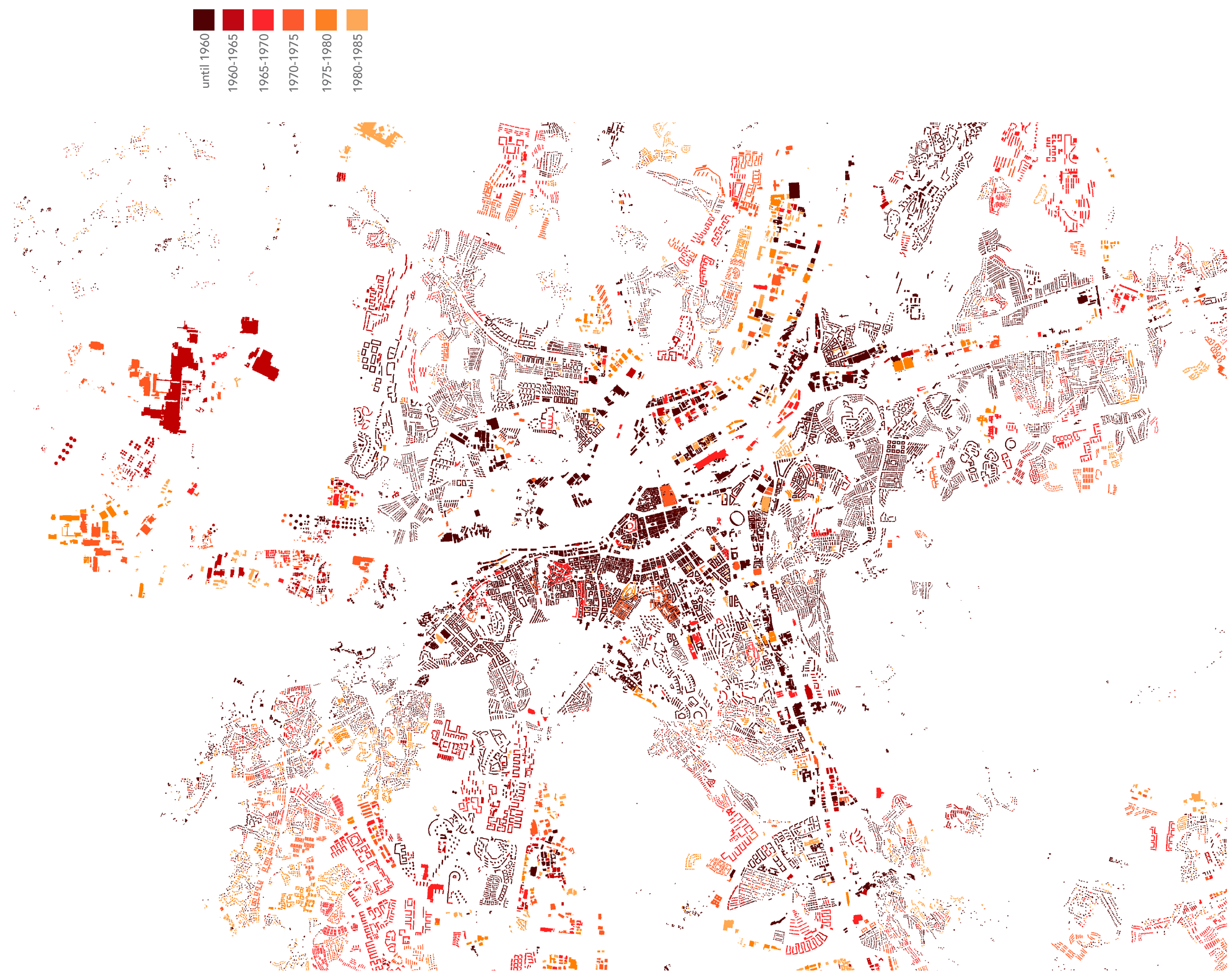


0 2km

1980

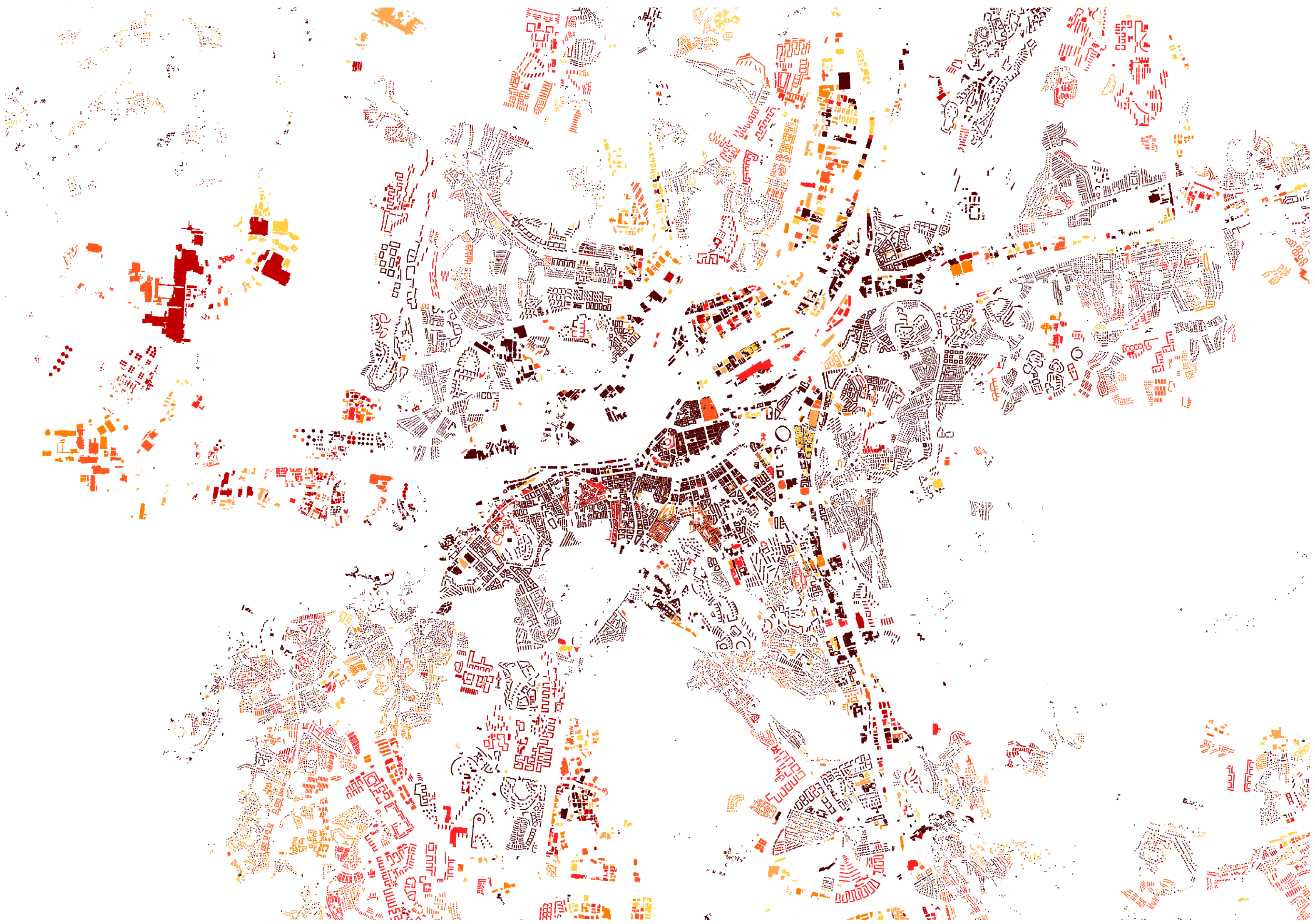


1985

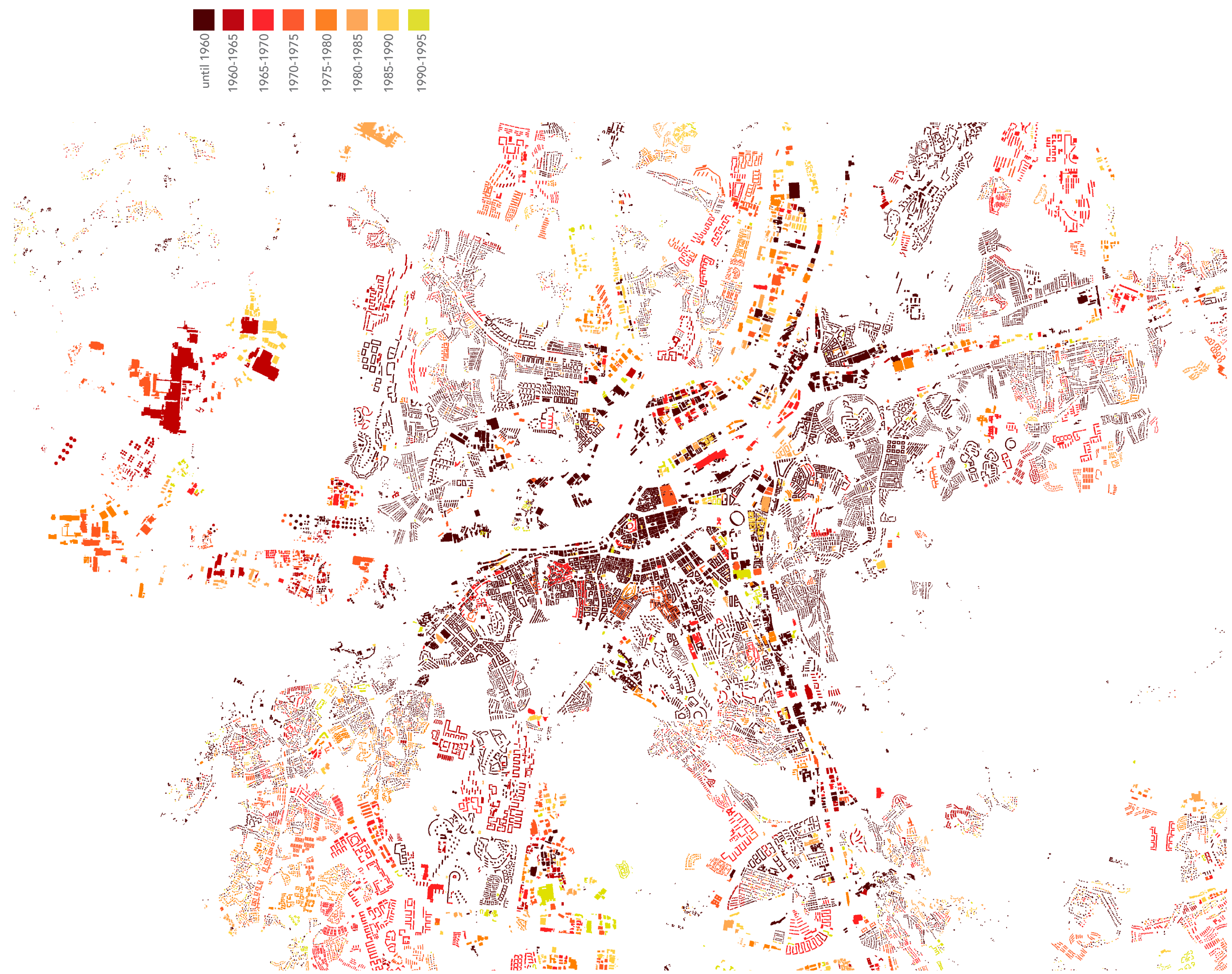


0 2km

1990



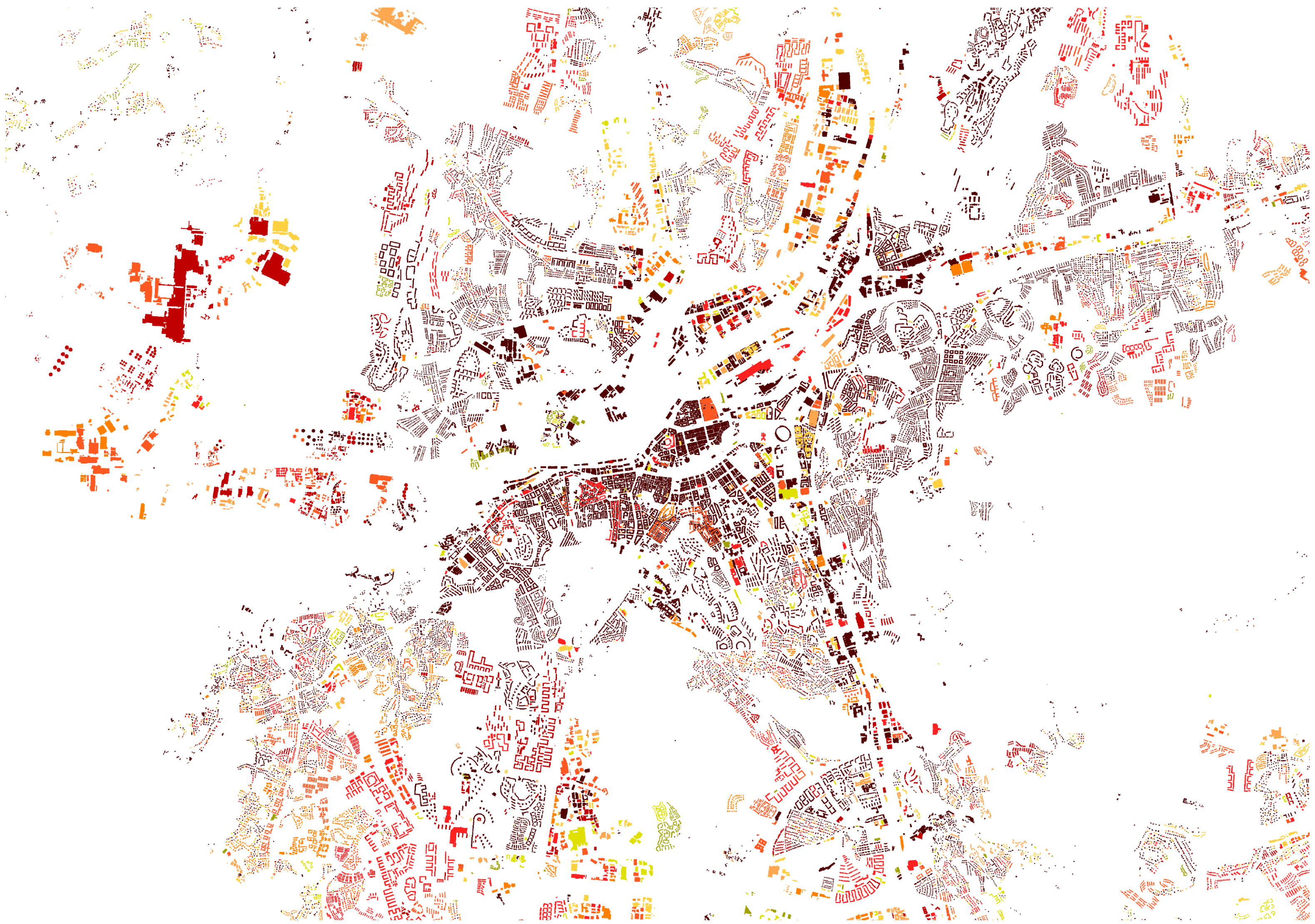
1995


until 1960
1960-1965
1965-1970
1970-1975
1975-1980
1980-1985
1985-1990
1990-1995

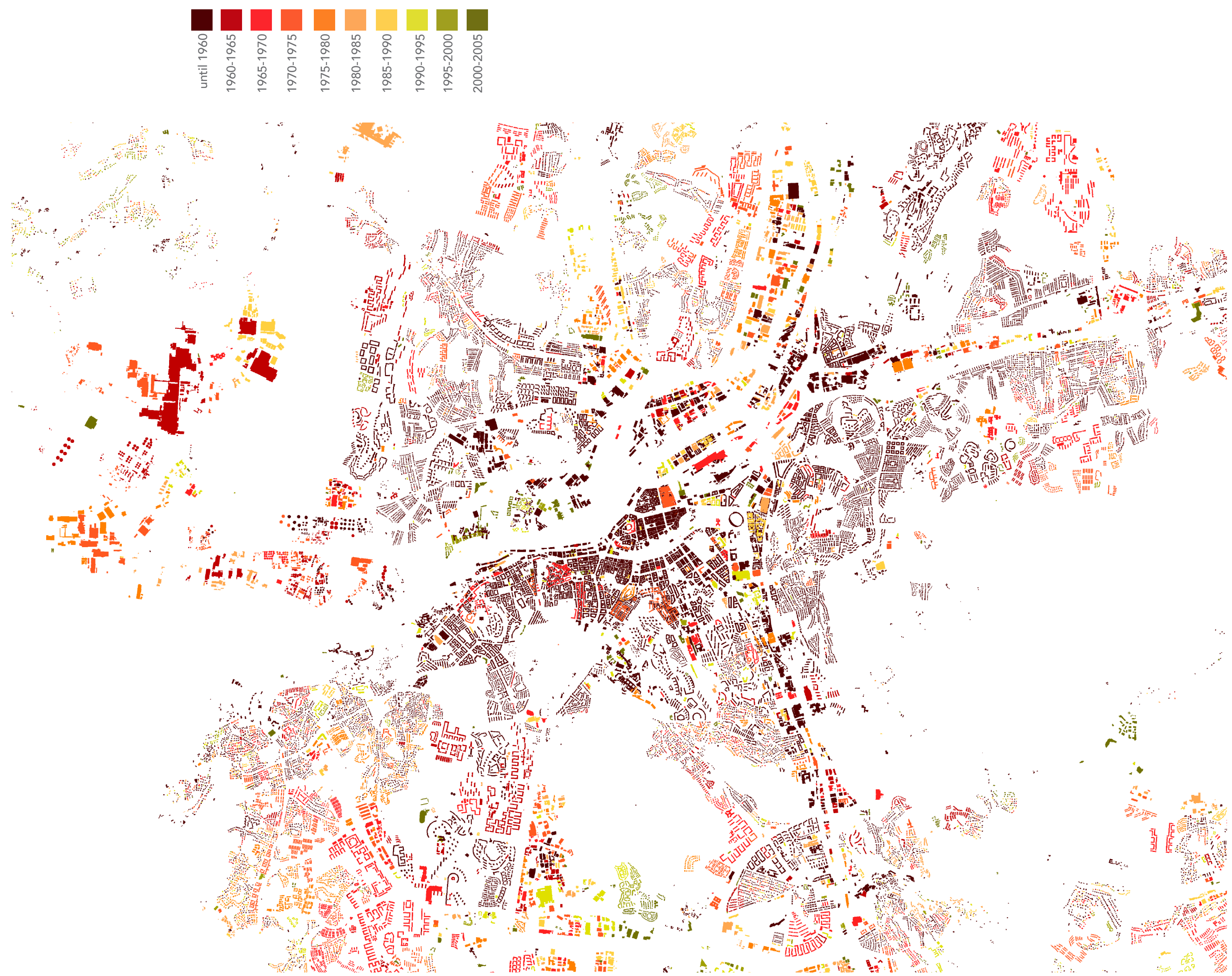

0
2km

GIS-based time model. Gothenburg, 1960 to present

2000

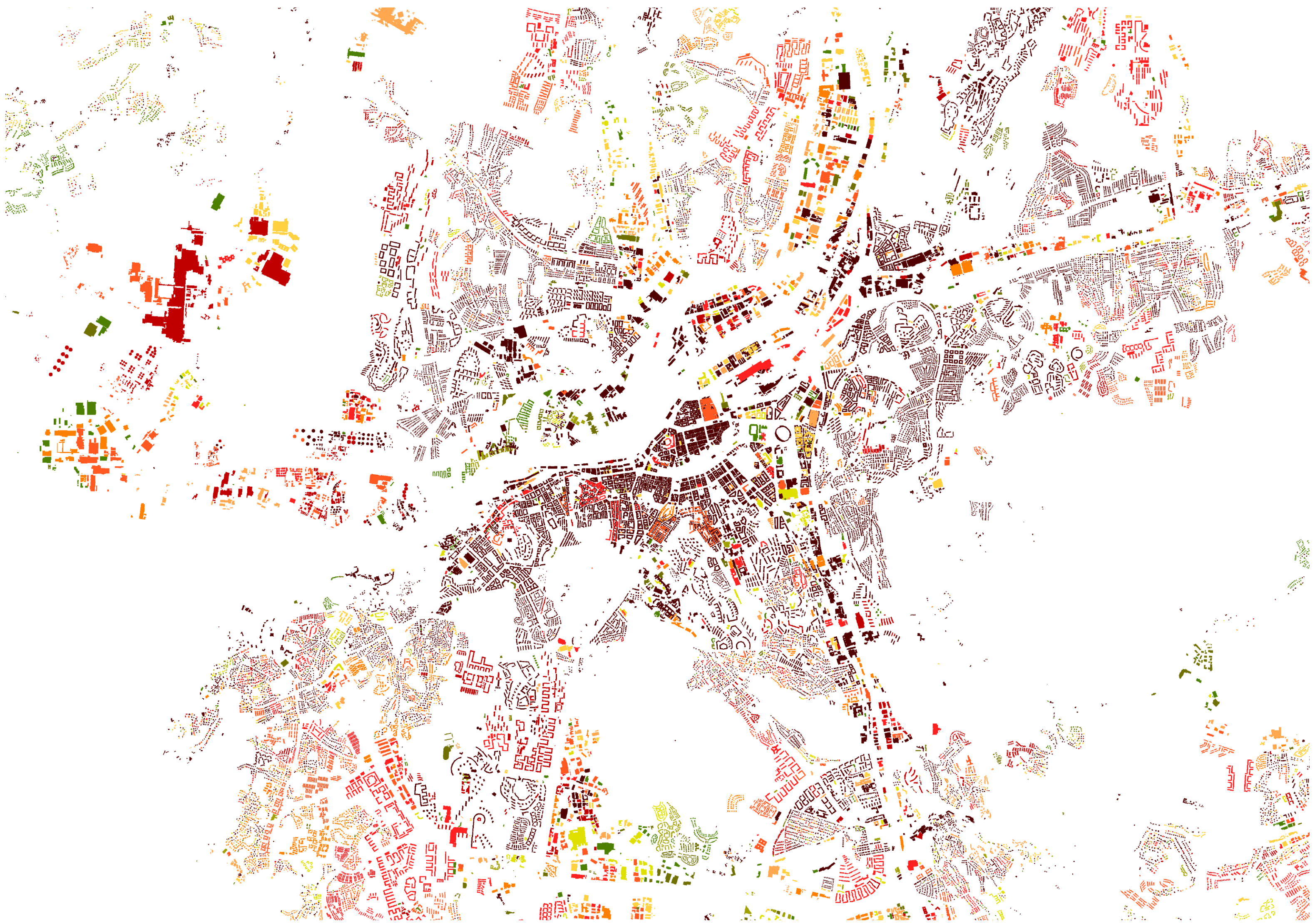


2005

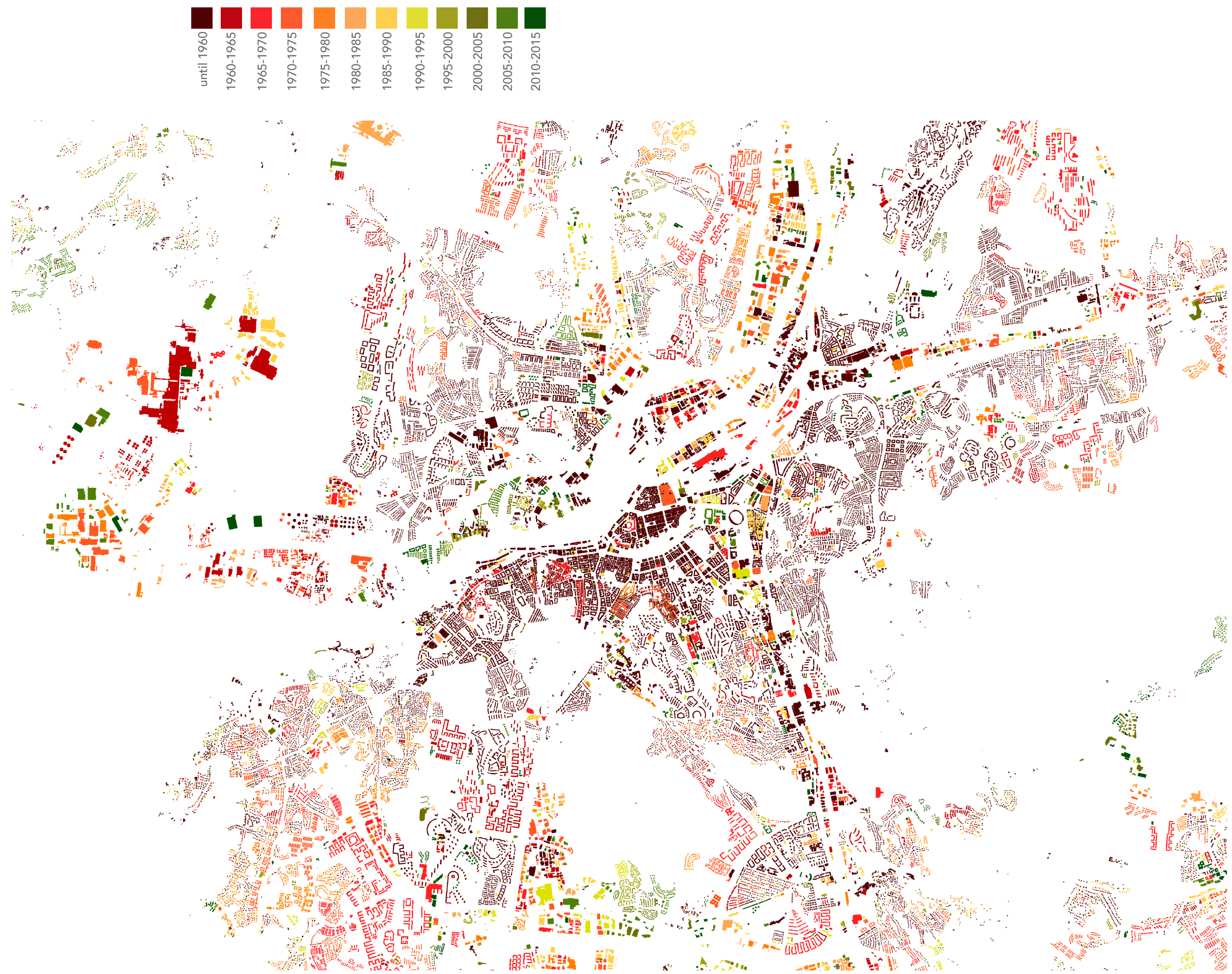


0 2km

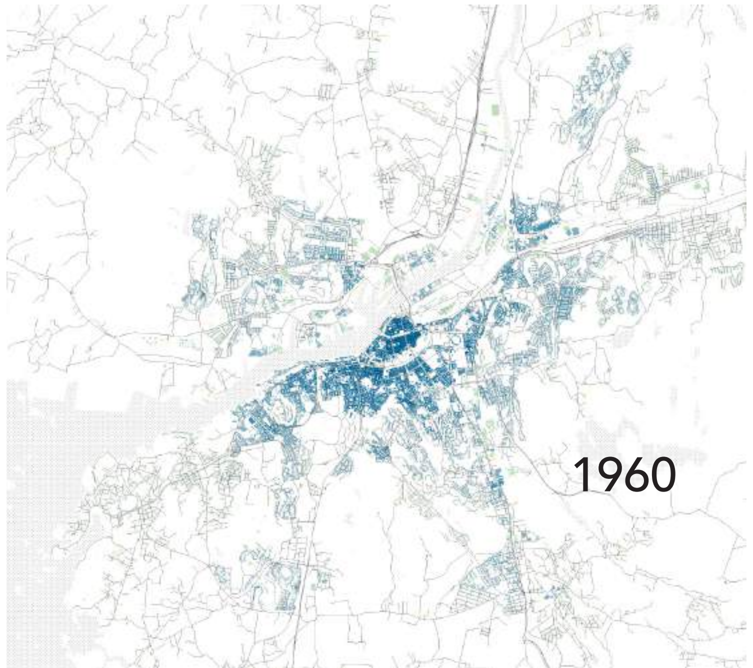
2010

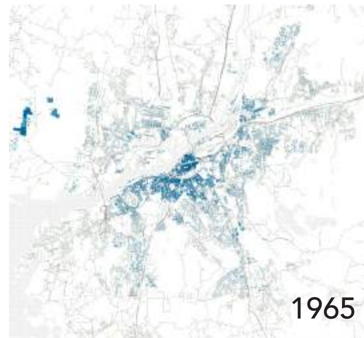


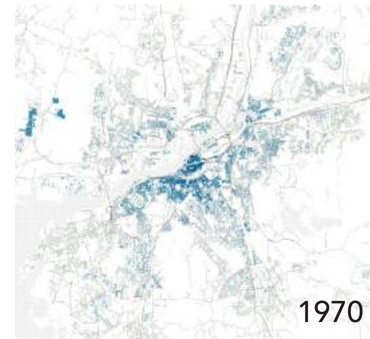
2015

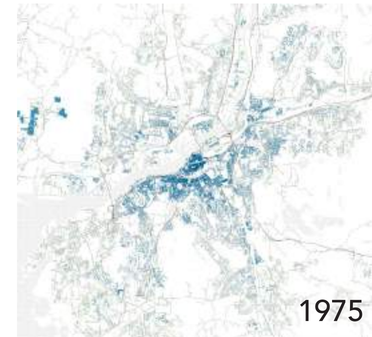

until 1960
1960-1965
1965-1970
1970-1975
1975-1980
1980-1985
1985-1990
1990-1995
1995-2000
2000-2005
2005-2010
2010-2015

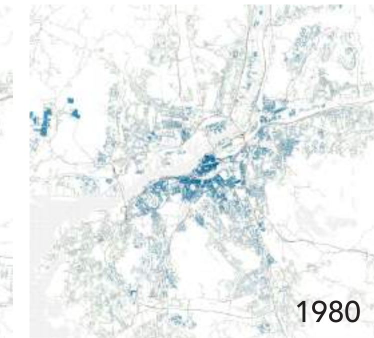

0
2km

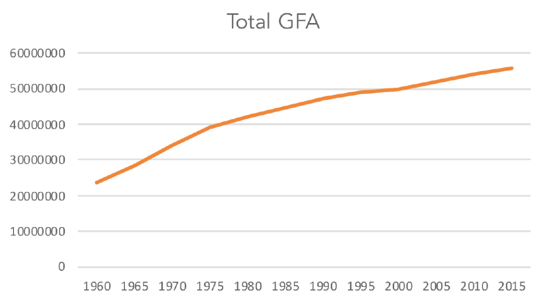


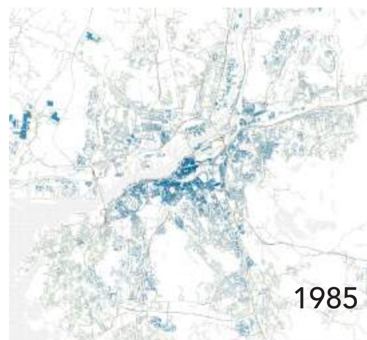


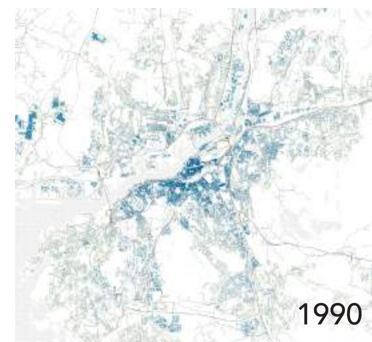


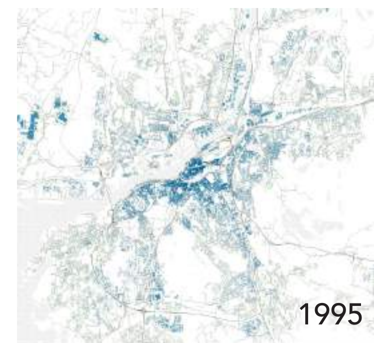


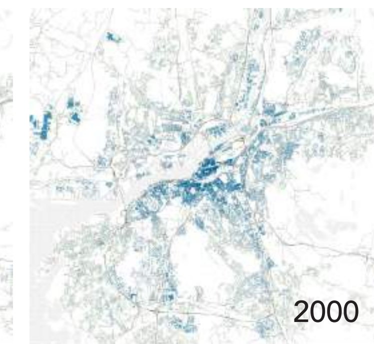


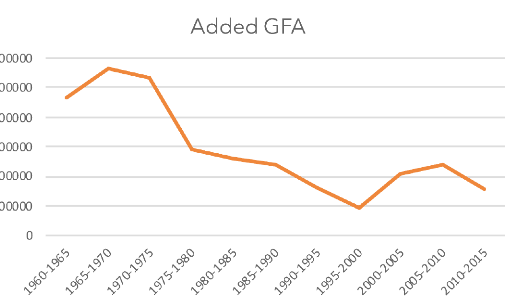


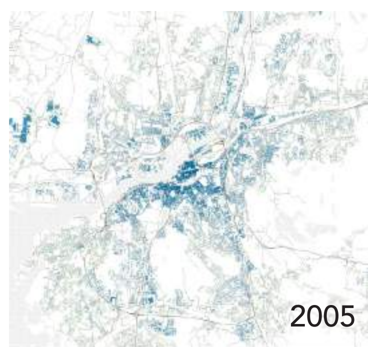


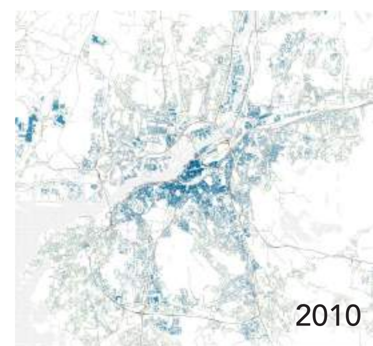


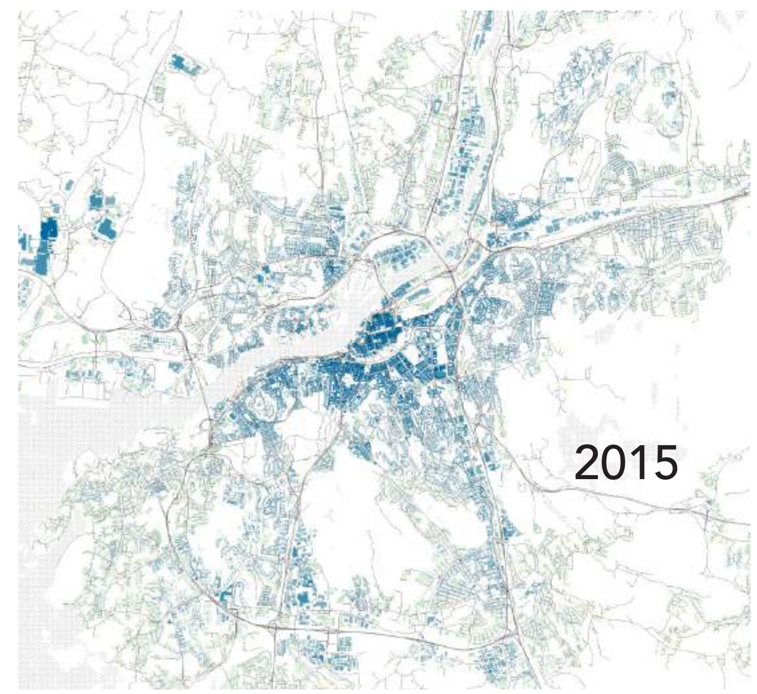










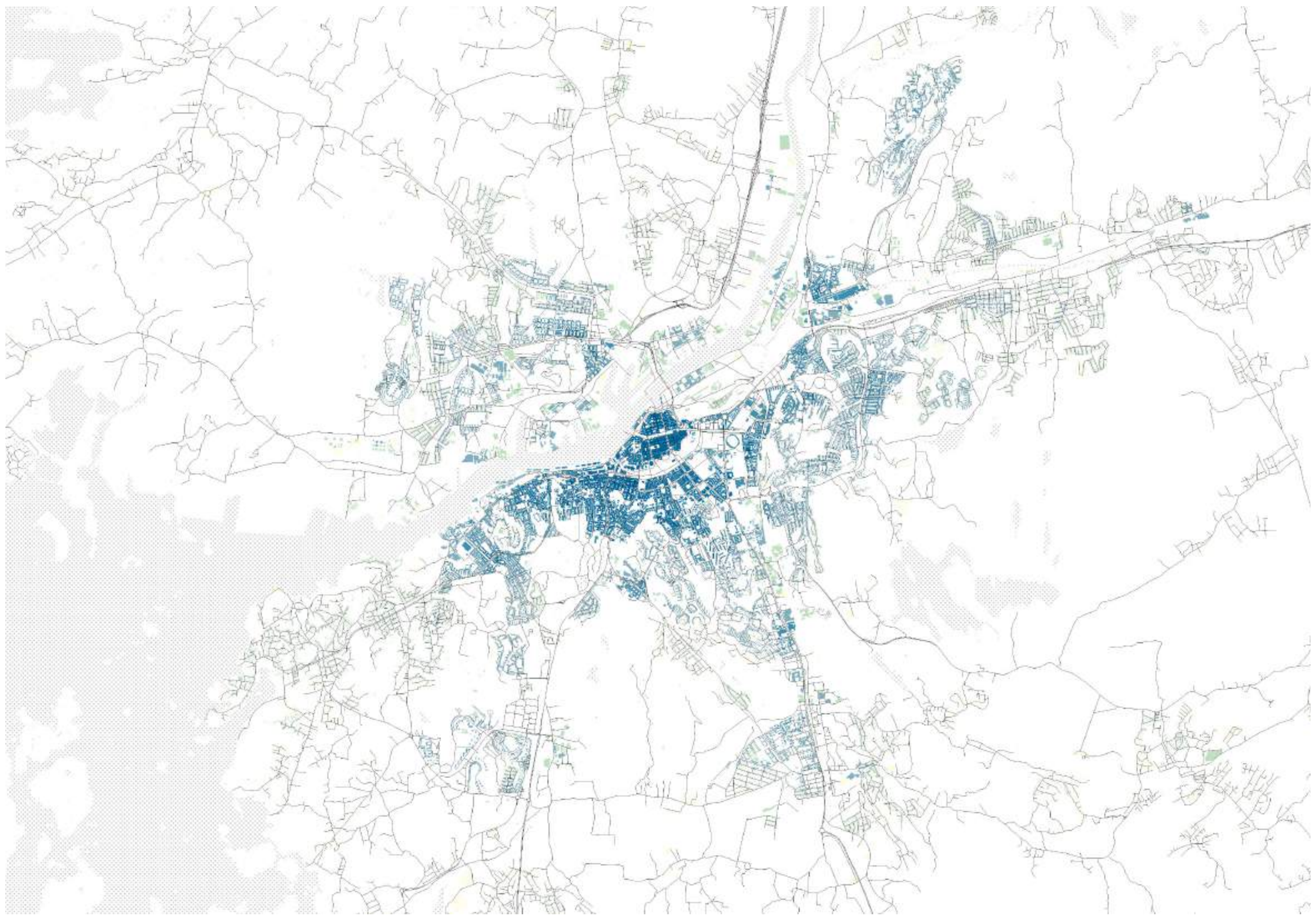


02. Buildings
b. Accessible GFA in 500m walking distance

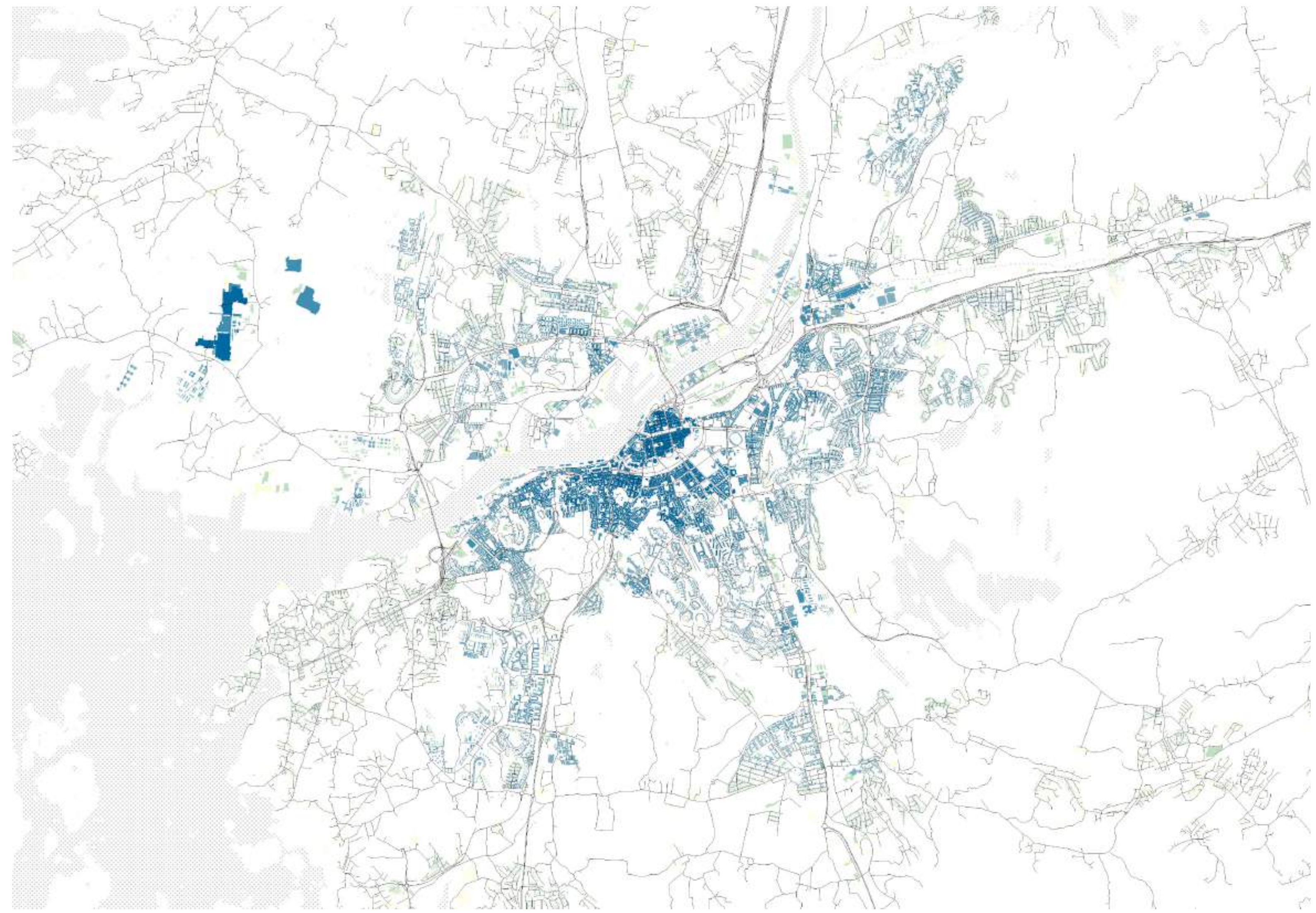
227000 to 750000m³
98000 to 227000m³
44000 to 98000m³
12000 to 44000m³
0 to 12000m³

Accessible Gross Floor Area in 500m walking distance

1960



1965



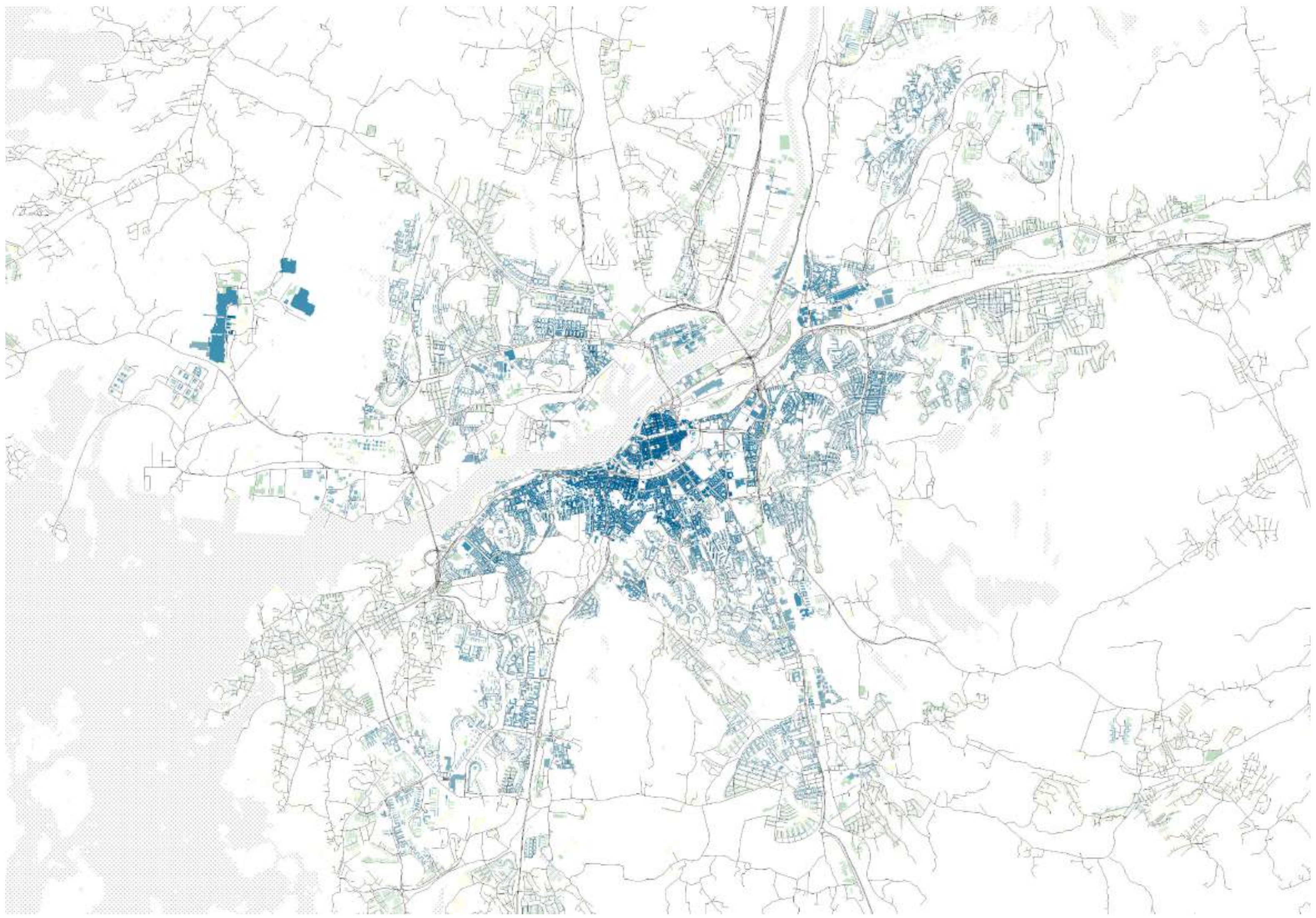
0 2km

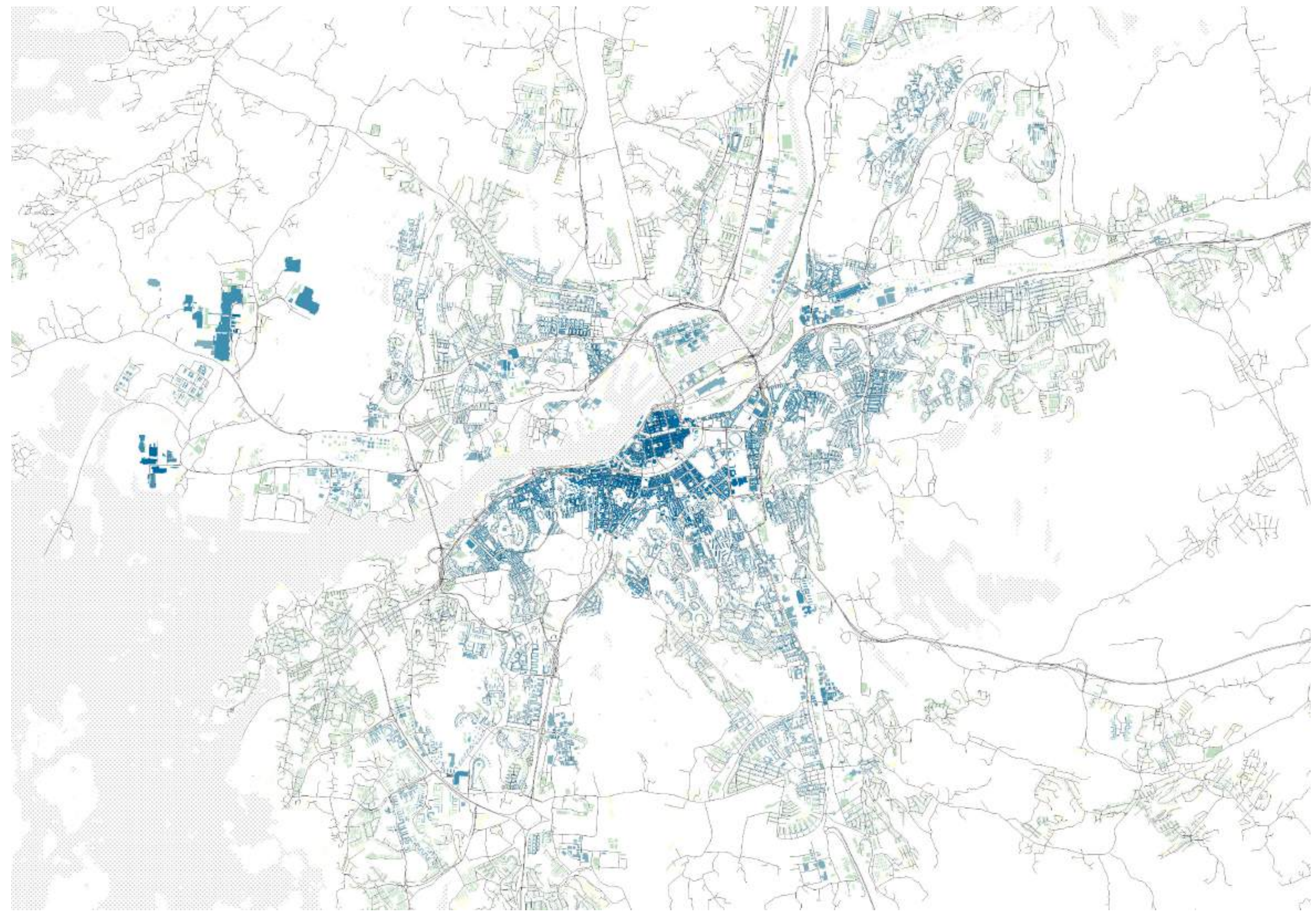
227000 to 750000m³
98000 to 227000m³
44000 to 98000m³
12000 to 44000m³
0 to 12000m³

1970

1975

Accessible Gross Floor Area in 500m walking distance



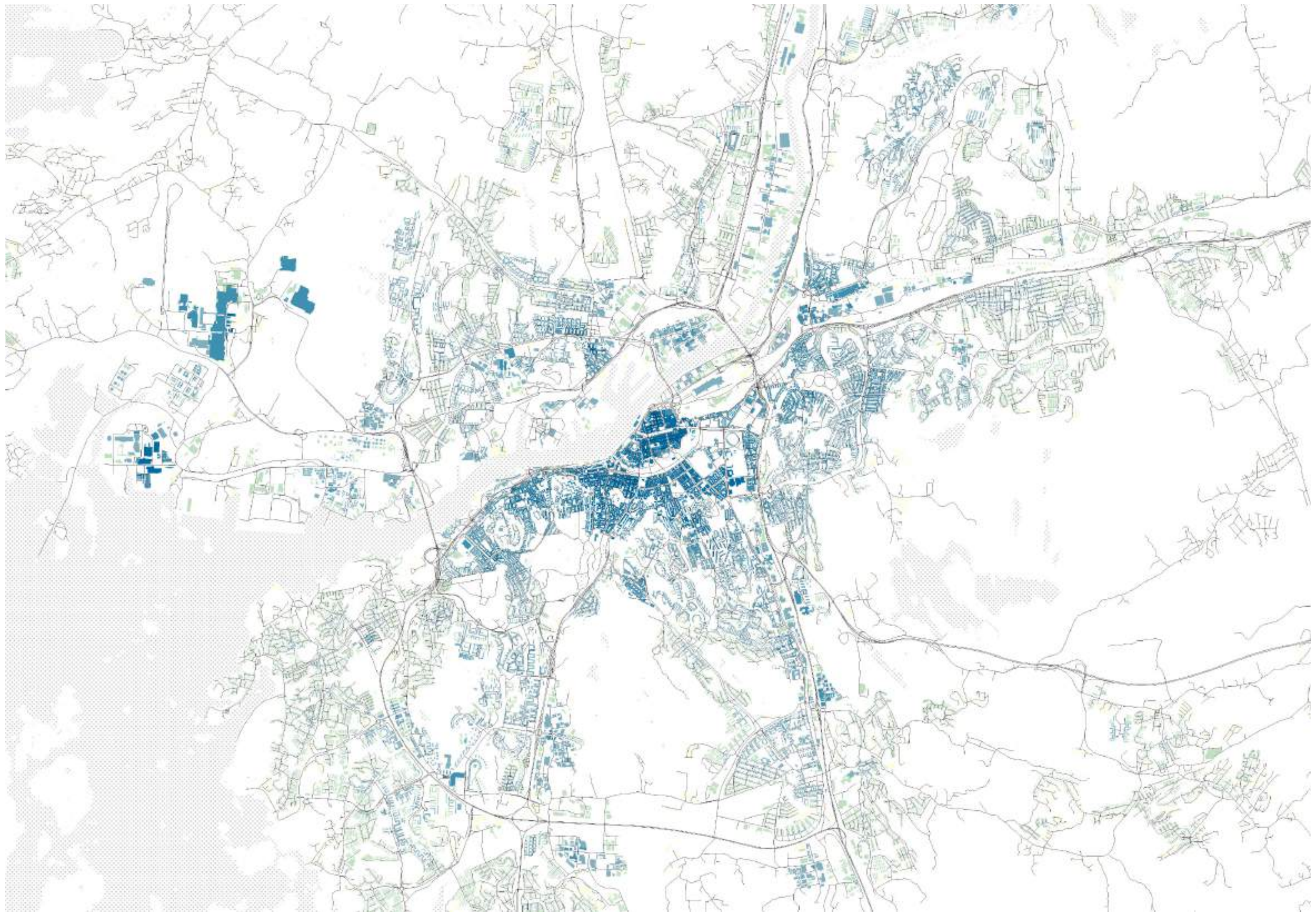


227000 to 750000m^3
98000 to 227000m^3
44000 to 98000m^3
12000 to 44000m^3
0 to 12000m^3

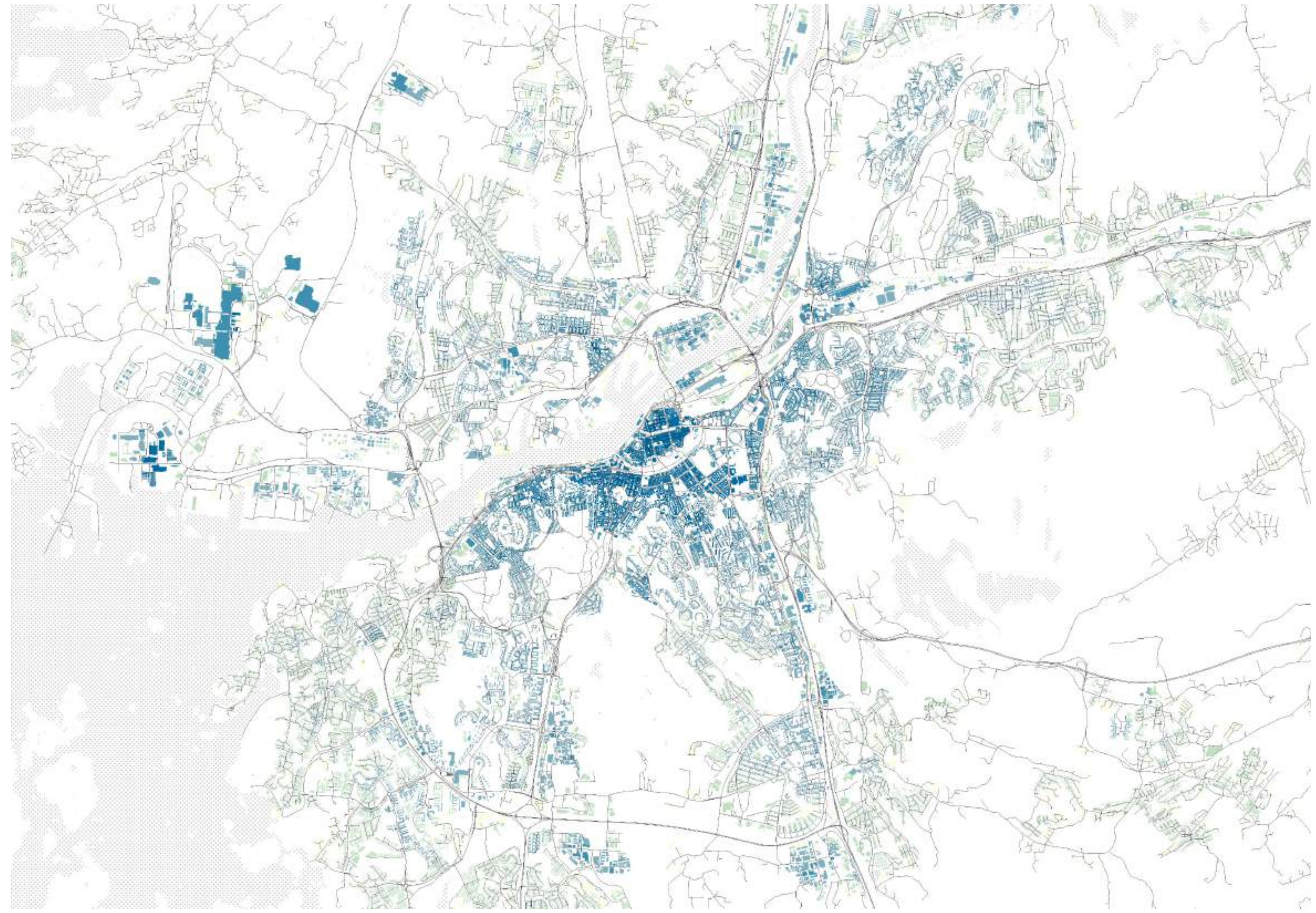
0 2km

Accessible Gross Floor Area in 500m walking distance

1980



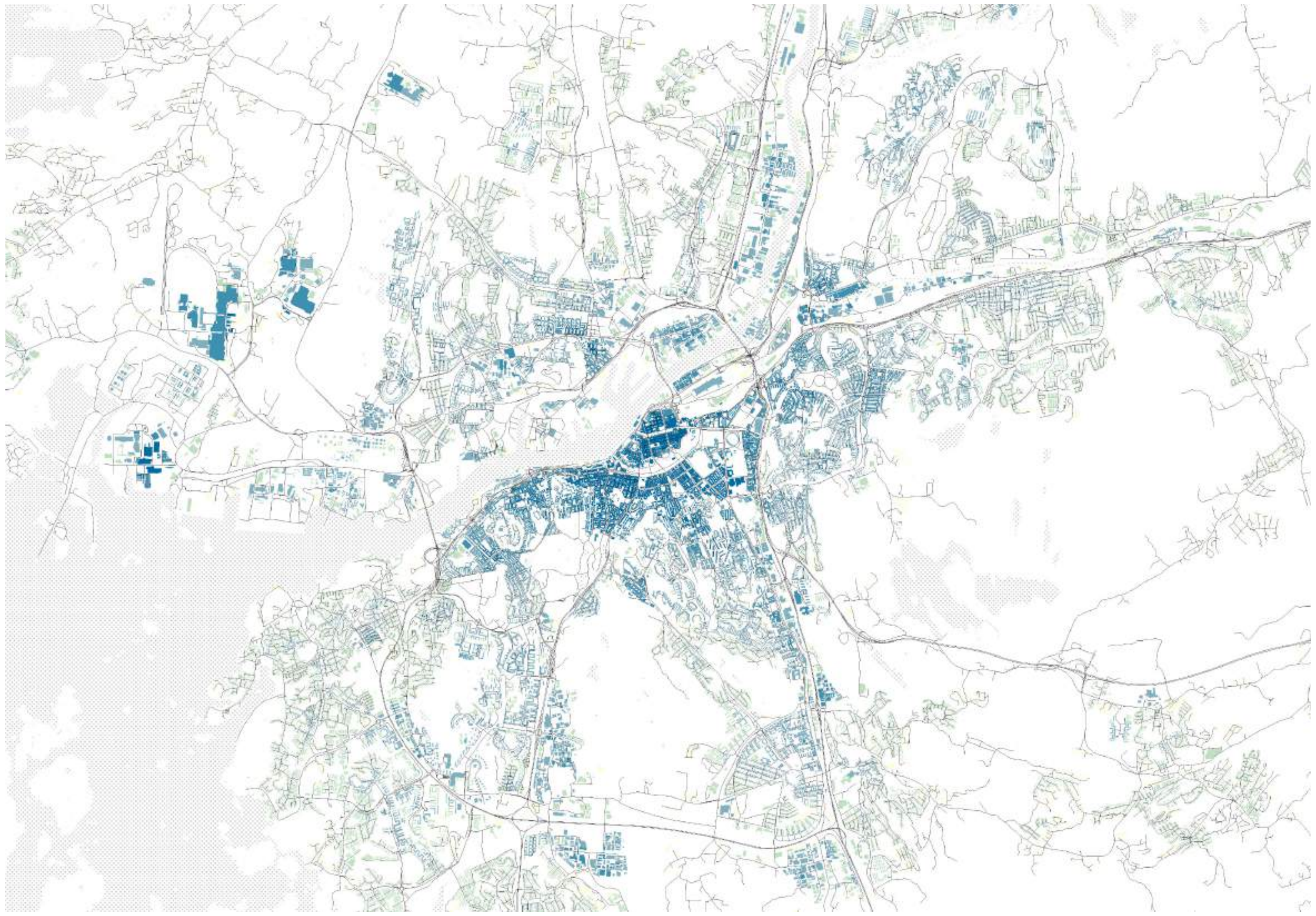
1985



227000 to 750000m³
98000 to 227000m³
44000 to 98000m³
12000 to 44000m³
0 to 12000m³

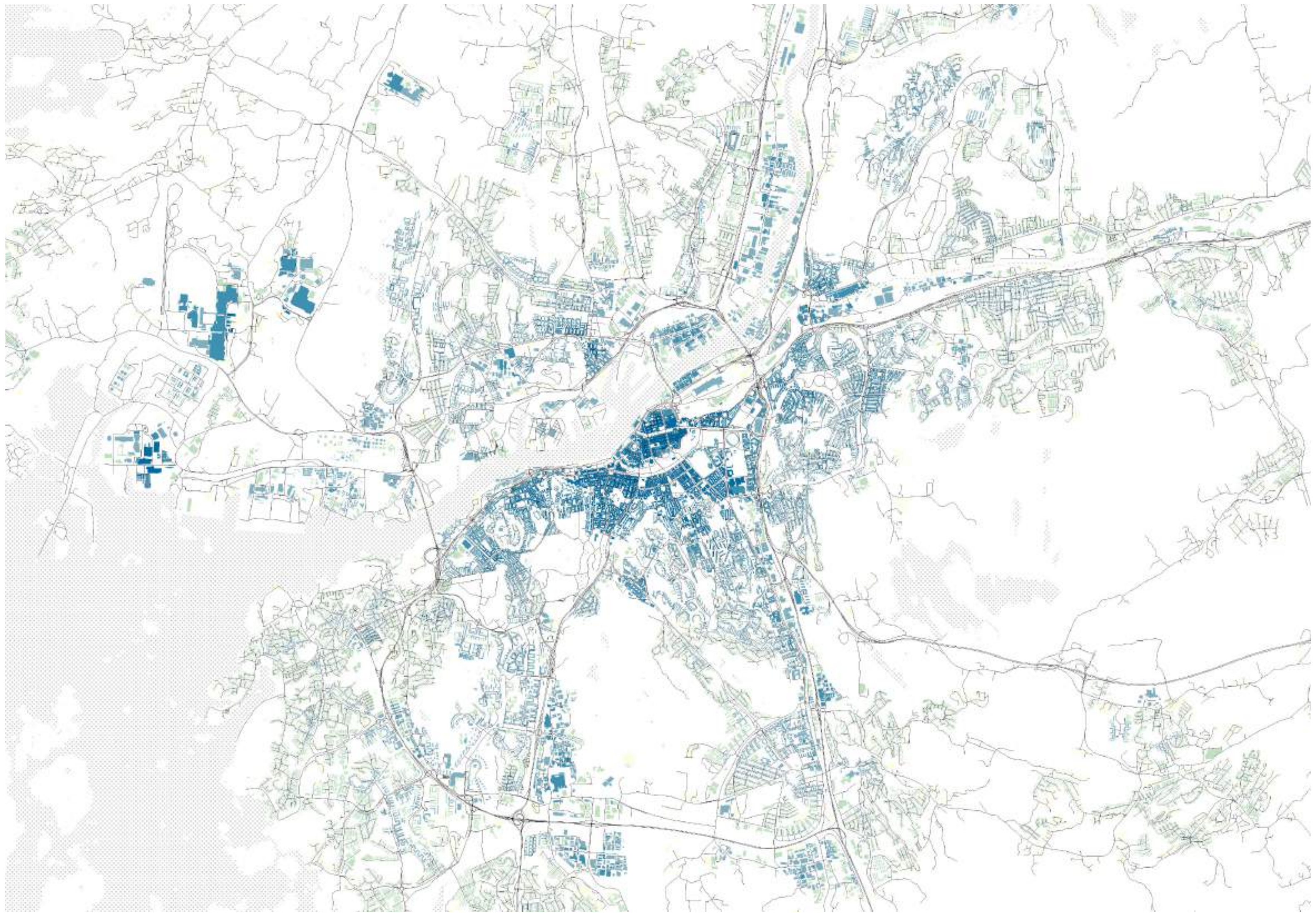
0 2km

1990



1995

Accessible Gross Floor Area in 500m walking distance

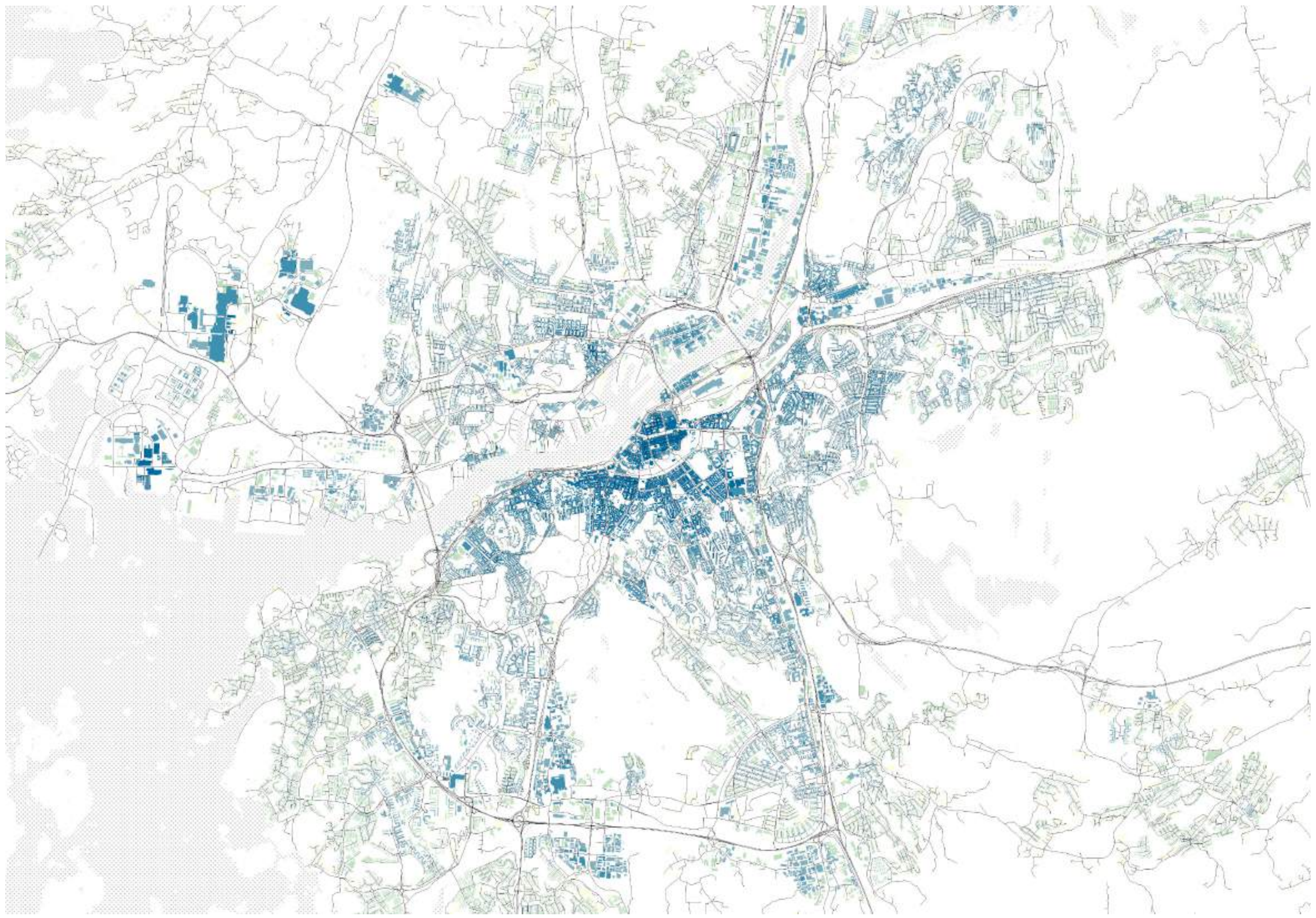


227000 to 750000m³
98000 to 227000m³
44000 to 98000m³
12000 to 44000m³
0 to 12000m³

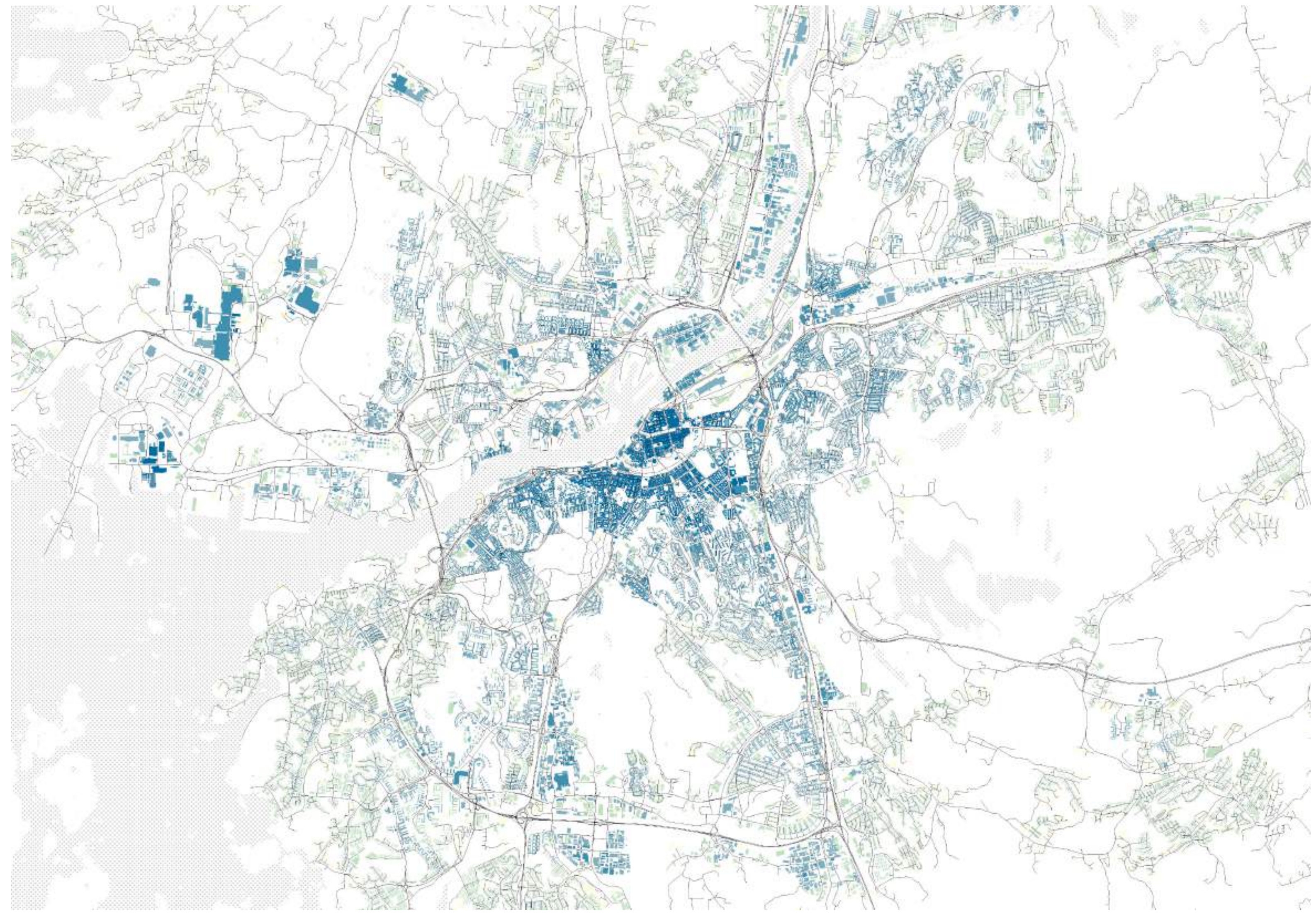
0 2km

Accessible Gross Floor Area in 500m walking distance

2000



2005

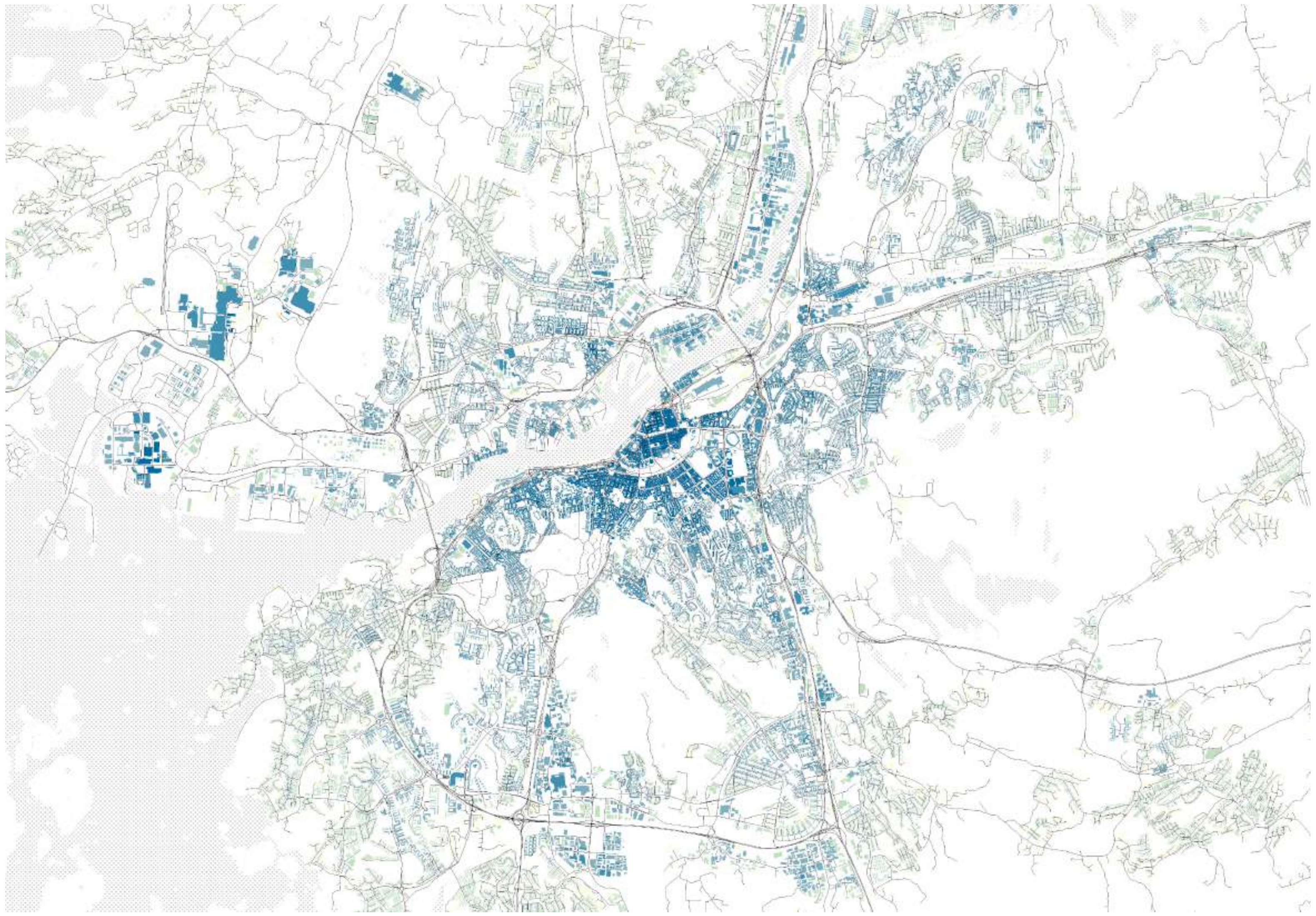


227000 to 750000m³
98000 to 227000m³
44000 to 98000m³
12000 to 44000m³
0 to 12000m³

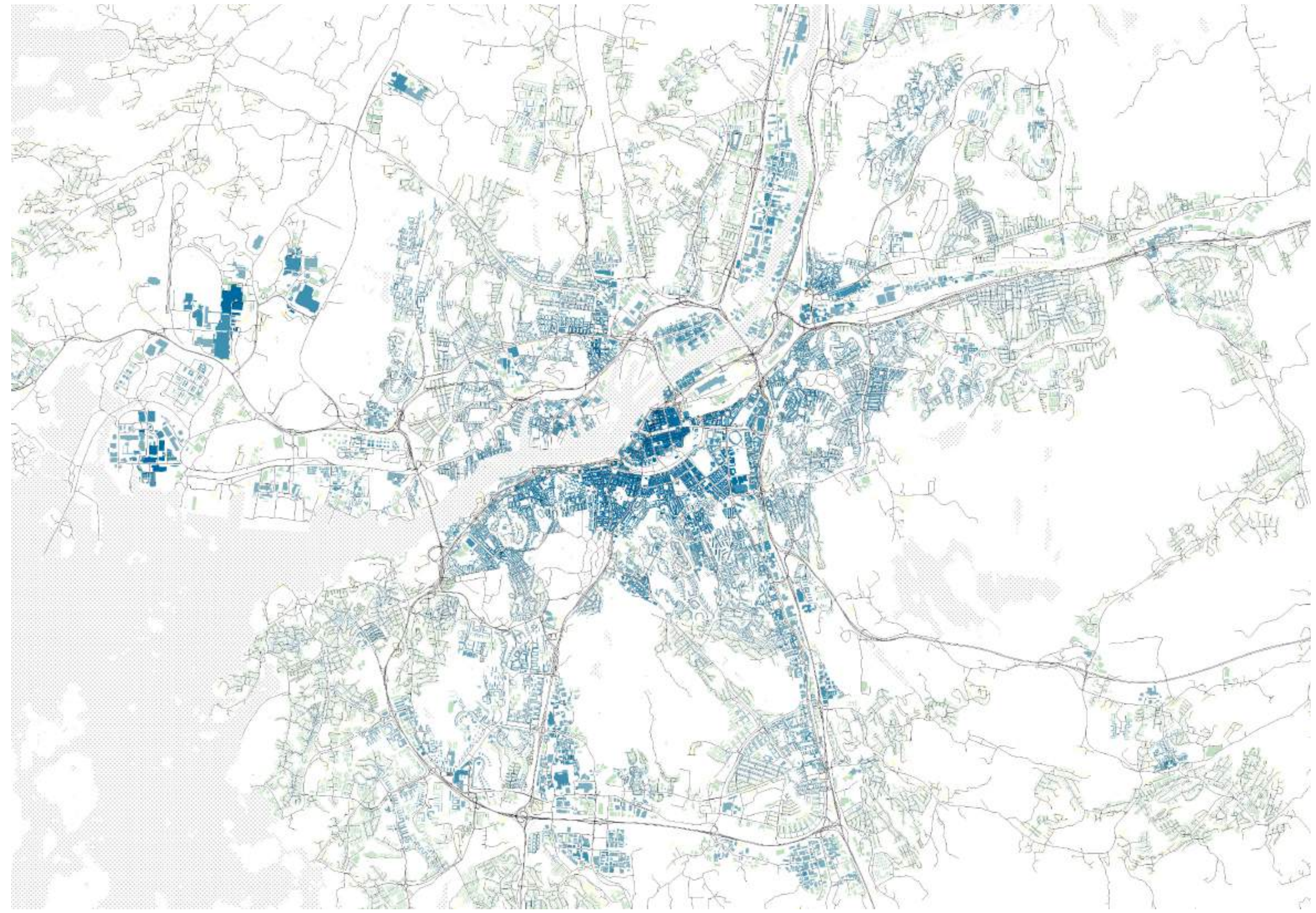
0 2km

Accessible Gross Floor Area in 500m walking distance

2010



2015

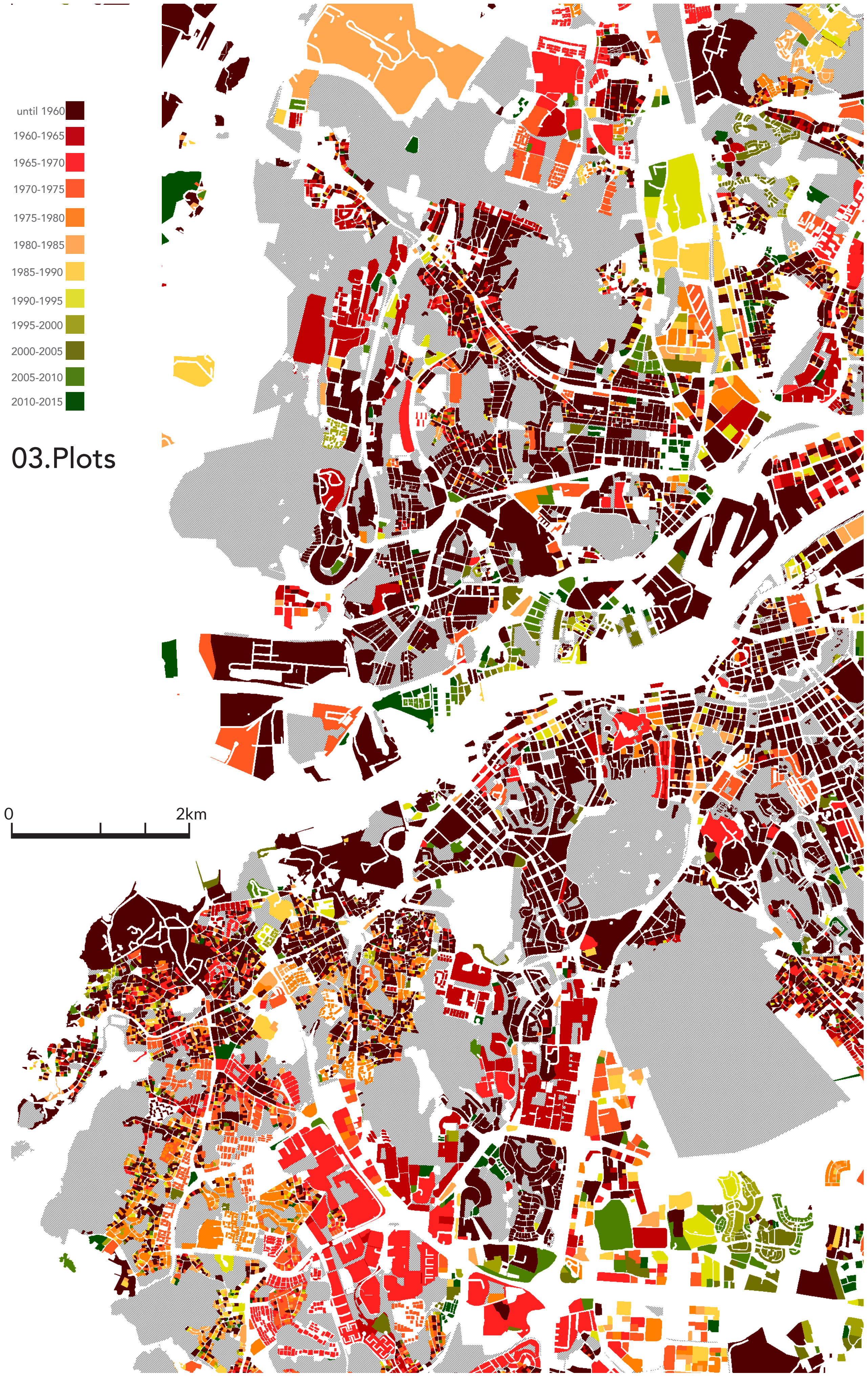


0 2km

227000 to 750000m³
98000 to 227000m³
44000 to 98000m³
12000 to 44000m³
0 to 12000m³

GIS-based time model. Gothenburg, 1960 to present

03.Plots



GIS-BASED TIME MODEL OF GOTHENBURG

APPENDIX 2.
METHODOLOGY AND TECHNICAL DOCUMENTATION

The GIS-based time model of Gothenburg consists of:

- 12 GIS-layers of the street network, from 1960 to 2015, in 5-year intervals
- 12 GIS-layers of the buildings from 1960 to 2015, in 5-year intervals
- 12 GIS- layers of the plots from1960 to 2015, in 5-year intervals

The coordinate system used is SWEREF 99TM, EPSG:3006.

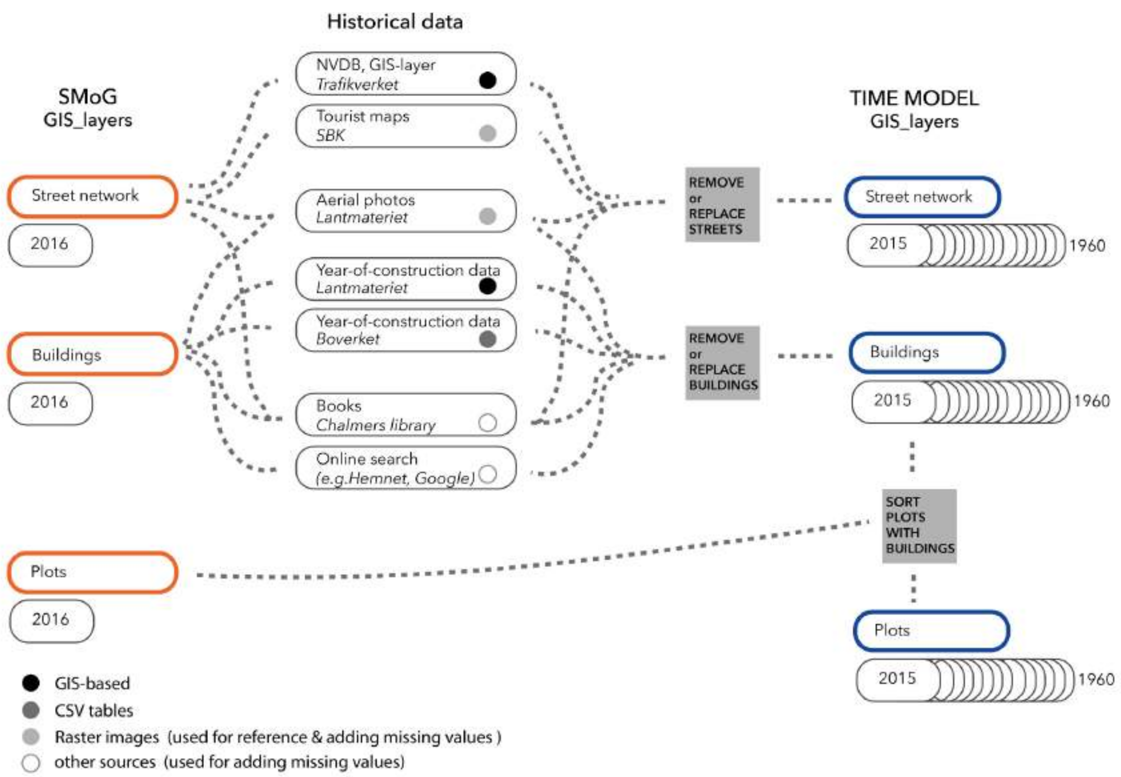


Figure 1. Overall workflow for the production of the GIS-time model of Gothenburg

A. Street network layers

a. Geometric features: Lines

b. Sources:

GIS-layers: Motorised network GIS-layer of 2016 (Spatial Morphology Group)

NVDB, 2016 (Trafikverket)

Analogue images: Tourist maps,1970-2005, 5-year intervals (SBK)

Aerial photos,1960&2001, 2005, 2009 (Lantmäteriet)

Literature references:

GAKO, 1971, *Göteborg bygger*, Göteborgs allmännyttiga och kooperativa bostadsföretag, Göteborg: GAKO

GAKO, 1966, *Göteborg bygger,* Göteborgs allmännyttiga och kooperativa bostadsföretag, Göteborg: GAKO

GAKO, 1960, *Göteborg bygger,* Göteborgs allmännyttiga och kooperativa bostadsföretag, Göteborg: GAKO

Moberg C., Schånberg, 1968, *Vägen till Göteborg*, Göteborg: Göteborgs gatunämnd

Hanson E., 2003, *Göteborg att bygga staden*, Göteborg: Göteborgs stadsbyggnadskontor, ISBN: 9189088115

Andersson, B., Jacobson, H., Jonsson, E., Heijl, M., Josefsson, T., 1977, *Göteborgs utbyggnad : några bidrag till Göteborgsstadsbyggnadshistoria,* Göteborg : Chalmers tekniska högskola, ISBN: 99-0460320-0

c. Method

The 2016 Motorised network provided by the Spatial Morphology Group was used as the starting point. The method followed in order to produce the network of the older timeframes was to go backwards and remove or replace streets that were not present in the immediate previous timeframe. So, to arrive to the network of 2010, streets

were removed or replaced from the network of 2015; to arrive to the network of 2005, streets were removed or replaced from the network of 2005 and so on.

Because of insufficient official data on the road year of construction, four steps were used in order to identify the streets to remove or replace in each timeframe.

1. The NVDB dataset Trafik was used to extract the year of construction, available only for a limited number of roads, mainly of the highways. The attribute used was Byggår.
2. For the inner-city part, visual inspection and tracing was used in GIS (i.e. ArcGIS) by overlapping the GIS layers with the digitalised historic tourist maps (SBK). Although the tourist maps provided great detail, they did not cover the whole urbanised area of Gothenburg and our study area.
3. For the outer-city part, visual inspection and tracing was used in GIS (i.e. ArcGIS) by overlapping the GIS layers with the georeferenced aerial photos (Lantmäteriet).
4. Cross-reference with historical photos in literature

Each network layer is complemented with a GIS-layer of 'Unlink' points, which are the locations of non-level intersections (e.g. bridges, tunnels, flyovers, overpasses, underpasses). These are point layers that were produced following the same method described above. The 'Unlink' point layer is necessary for the accurate network analysis.

B. Building layers

a. Geometric features: Polygons

b. Sources:

GIS-layers: Building layer 2016 (Spatial Morphology Group)

Building layer 2016 (Lantmäteriet)

Datasets: 5597859875 (Boverket)

Analogue images: Aerial photos,1960, 2001, 2005, 2009 (Lantmäteriet)

Literature references:

Caldenby C., Bjur G. L., Ohlsson, S., 2006, *Guide till Göteborgs arkitektur*, Stockholm: Arkitektur Förlag AB, Göteborgs stadsbyggnadskontor, Formas, ISBN: 9186050672

GAKO, 1971, *Göteborg bygger*, Göteborgs allmännyttiga och kooperativa bostadsföretag, Göteborg: GAKO

GAKO, 1966, *Göteborg bygger,* Göteborgs allmännyttiga och kooperativa bostadsföretag, Göteborg: GAKO

GAKO, 1960, *Göteborg bygger,* Göteborgs allmännyttiga och kooperativa bostadsföretag, Göteborg: GAKO

Frendberg, T., 1968, *Vi bygger i Göteborg: en berättelse om Göteborgs stads bostadsaktiebolag*, Göteborg: Göteborgs stads bostads AB

Hanson E., 2003, *Göteborg att bygga staden*, Göteborg: Göteborgs stadsbyggnadskontor, ISBN: 9189088115

Andersson, B., Jacobson, H., Jonsson, E., Heijl, M., Josefsson, T., 1977, *Göteborgs utbyggnad: några bidrag till Göteborgsstadsbyggnadshistoria,* Göteborg : Chalmers tekniska högskola, ISBN: 99-0460320-0

c. Method

The overall method was the same as for the Network layers. The 2016 Building layer provided by the Spatial Morphology Group was used as the starting point. The method followed in order to produce the network of the older timeframes was to go backwards and remove or replace building polygons that were not present in the immediate previous timeframe.

The Lantmäteriet dataset 'Belägenhetsadress, Byggnad och Samfällighetsregister', included an attribute with the buildings' year of construction (attribute Nybyggår). Although it covered the vast majority of buildings, it was still incomplete, with a lot of missing values. To complete the dataset and produce the historic building layers the steps followed were:

1. Cross-reference with the Boverket dataset (STD, Energideklaration, 2018)
2. Visual inspection and tracing in GIS (i.e. Mapinfo) by overlapping the GIS layers with the georeferenced aerial photos (Lantmäteriet), starting from the aerial photo of 1960.
3. Cross reference with historic aerial photos from Google maps Pro, from 2001 to 2018.
4. Literature sources were used especially for the suburbs of the Million Program (Miljonprogrammet) from 1965 to 1974.
5. In some cases, building year information was found in online sales ads for individual dwellings (e.g. Hemnet). Other online sources included cultural heritage documentation from the municipality, annual reports from companies or municipalities and private sources such as blogs about history.

After the aforementioned steps, the resulted dataset still included missing values.

From those, all polygons with area less that 40sqm were removed, as they were mostly complementary one-storey buildings (e.g. garages, small warehouses). The remaining polygons with missing values were either public buildings or industrial buildings, two categories that are not well-documented in the official available data sources. For the industrial buildings that clearly belonged to an industrial complex (e.g. Torslanda 5849) the assigned year of construction for the missing value was that of the complex. The final dataset still includes some missing values mainly of public buildings.

The final building layer includes attributes of GFA, Footprint, Height and No of floors for each building polygon. This information was extracted from the Building layer 2016 (Spatial Morphology Group). For the old buildings that were replaced, the respective values were estimated from their immediate surroundings, and were cross-referenced with sources (i.e. historic aerial photos, books, on-line search).

C. Plot layers

a. Geometric features: Polygons

b. Sources: GIS-layer: Plot layer 2016 (Spatial Morphology Group)

c. Method

The plot layers were produced using the respective building and network layers of each timeframe. The 2016 Plot layer provided by the Spatial Morphology Group was used as the starting point. Using GIS (i.e. ArchGIS) only the plots that included buildings were kept in each timeframe, using the already made historic building layers. To be noted is that the Plot layer documents the plots that were built upon and developed and not the remaining agricultural or natural land. It documents the process of urban development and the gradual addition of agricultural land to the urbanised build up areas.

GIS-based time model. Gothenburg, 1960 to present