How can nuisance flooding affect Copenhagen residents' Quality of Life?

Arthur Vandervoort*[1], Miguel Costa[1], Martin Drews[1], Francisco C. Pereira[1], and Karyn Morrissey[2]

[1]Department of Technology, Management and Economics, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark.
[2]J.E. Cairnes School of Business & Economics, University of Galway, Galway, Ireland.

Short summary

Cities are more at risk of experiencing flooding as climate change worsens, disrupting transport infrastructure and the social and economic networks that depend on it. Though flood impacts are typically studied by focusing on extreme events, '*nuisance flooding*' — high-frequency, low-impact flood events that cumulatively disrupt the functioning of everyday activities — remains underexplored. We study how nuisance flooding affects everyday accessibility by defining a quality of life (QOL) index based on the accessibility of services and amenities, identifying flood-related changes in QOL, and mapping distributional effects of impacts. Focusing on Copenhagen (Denmark) and rainfall scenarios that cause nuisance flooding, our results suggest nuisance flooding 1) meaningfully lowers QOL, 2) lowers active mode-based QOL more, and 3) affects QOL the most in wealthier neighbourhoods. Our findings suggest nuisance flooding can pose a challenge to policymakers, and that the impacts of nuisance flooding on active transportation modes merit further attention.
Keywords: accessibility, nuisance flooding, quality of life, Copenhagen (Denmark)

1 Introduction

For cities like Copenhagen, the frequency and severity of severe rainfall episodes is likely to increase due to climate change (Olesen et al., 2014). Pluvial flooding can have a wide range of impacts on cities, disrupting social and economic networks and impacting individuals' health and wellbeing (Pregnolato et al., 2016; Zhong et al., 2018). Within flooding scenarios, researchers have drawn attention to the emerging risk of '*nuisance flooding*': low-impact, high-frequency events that don't cause severe property damage or pose a threat to human health, but can nonetheless disrupt everyday activities (Moftakhari et al., 2018). While individual nuisance flood events may not be a reason for concern, the cumulative impacts of nuisance floods over time can nonetheless incur serious costs by way of disrupted activities and lower quality of life.

Though QOL in cities is a complex phenomenon that spans across subjective and objective dimensions (Stimson et al., 2024), it has been closely linked with an individual's ability to access urban infrastructure (Nuvolati, 2009). Because of this, accessibility is increasingly understood to be a crucial focus of transportation policy and research (Vecchio & Martens, 2021). Studying QOL from the perspective of accessibility therefore complements how nuisance floods are thought to negatively impact individuals: by impeding their ability to engage in everyday activities (Moftakhari et al., 2018).

However, studies that focus on the accessibility of everyday urban services and amenities typically don't incorporate disruptions by environmental stressors like flooding (Dobrowolska & Kopczewska, 2024; Nicoletti et al., 2023). Research focusing on accessibility under flood conditions, meanwhile, focuses on extreme events (Li et al., 2018) or critical infrastructure (Yin et al., 2021). To our knowledge, there is no research studying the impact of nuisance-level flooding on everyday accessibility and quality of life across amenity categories.

With this in mind, in this study we investigate how nuisance flooding affects accessibility-based quality of life for Copenhagen residents and how those impacts are distributed over the population.

2 Methodology

Figure 1 outlines our workflow: we take flood maps, compute accessibility from locations to amenities, estimate a QOL score, and analyse population-level distributional effects.

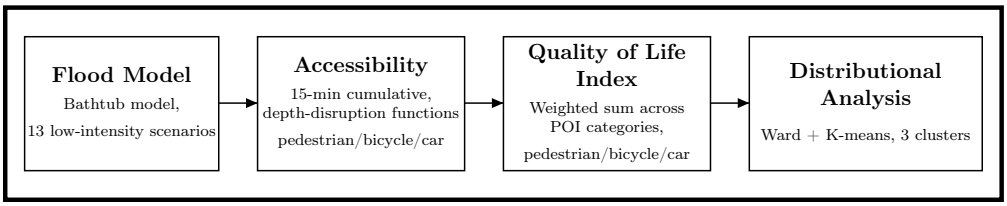


Figure 1: Framework for estimating overall and distributional QOL impacts of nuisance flooding.

Flooding

We estimate flood depth across the municipalities of Frederiksberg and Copenhagen using *SCALGO Live* (SCALGO, 2023): a stationary event-based flood model that estimates water depths for an area based on an elevation map. As depressions saturate, surplus water runs off into other areas, simulating how flood water is distributed across a landscape. Our flood simulations are based on 13 low-intensity rainfall scenarios ranging between 4 mm/day and 52 mm/day rainfall intensities. These range from little rainfall to the lower end of extreme typically considered in flooding research (Yin et al., 2021).

Accessibility

We estimate accessibility (and how floods impact it) by computing the travel times between locations and amenities, applying depth-disruption functions to model flood impacts, and applying accessibility cutoff points.

We start by subdividing the municipalities of Copenhagen and Frederiksberg into grid cells (or hexes) using `h3` (Uber Technologies, Inc., 2026). Amenities' locations were retrieved from OpenStreetMap (OSM, https://www.openstreetmap.org/) using `osmnx` (Boeing, 2024). We estimate accessibility for three transport modes (pedestrian, bicycle, car) by computing travel times between the cells' centroids and points of interest (POI). Amenities are accessible if they are reachable within 15 minutes for each transport mode.

POI categories correspond with amenity categories surveyed in EC/DG REGIO (2023). These categories are `public transport, health, sports, cultural, green spaces, public spaces` and `education`.

As water inundates a road segment, travel times across that segment increase until it becomes untraversable. To model this dynamic, we use depth-disruption functions that map water heights to mode-specific travel speeds. As water depth increases, travel speeds decrease until a certain water height is reached, at which point travelling on that road or path becomes unfeasible. For pedestrians, an edge is considered cut off at a water depth of 900mm (Dias et al., 2021). For cars, this threshold is set at 300mm Pregnolato et al. (2017). To our knowledge, there is no established depth-disruption function for cycling. Because of this, we estimate a depth-disruption function by combining the pedestrian and car functions, setting the threshold at 200mm.

Quality of Life

We estimate QOL by adapting an index previously proposed by Dobrowolska & Kopczewska (2024). We define a per-capita, neighbour-adjusted accessibility score S_{ipm} for hex i, transport mode m, and POI category p as

$$S_{ipm} = \frac{A_{ipm} + 0.5 \sum_{j \in \mathrm{Nb}_i} A_{jpm}}{\mathrm{Pop}_i} \tag{1}$$

where A_{ipm} is the number of POIs of type p reachable from hex i by mode m, Nb_i is the set of hexes adjacent to i, and Pop_i is the residential population of hex i. Residential population is estimated using a spatial interpolation of the *Danish Neighbourhood Atlas* (DNA), OSM building footprints, and land-use data (Lange et al., 2023), with non-residential areas and buildings being excluded. The discounted neighbour term smooths accessibility over neighbouring hexes. A city-wide reference level Q_{pm} is defined as the 75th percentile of S_{ipm} across all hexes under a no-flood baseline,

$$Q_{pm} = \mathrm{quantile}_{0.75}\left(\{S_{ipm}\}_i\right) \tag{2}$$

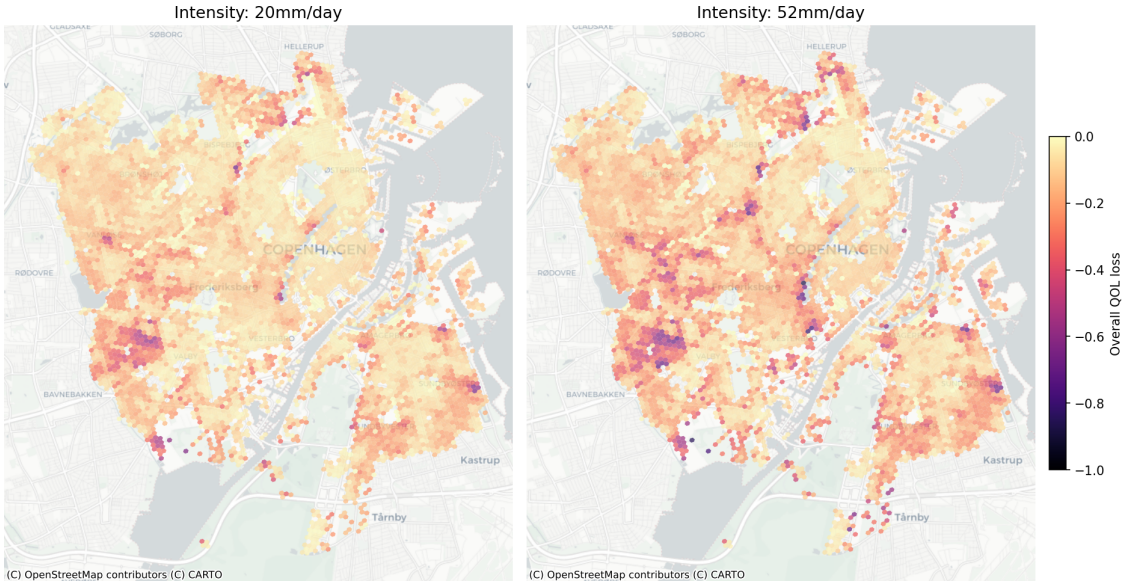


Figure 2: QOL loss per hex in a 20mm/day and 52mm/day rainfall scenario. QOL reported in this plot is average of pedestrian, bicycle, and car QOL.

representing a threshold of adequate provision for POI type p under mode m. The QOL score for hex i under mode m is then

$$\text{QoL}_{im} = \sum_{p \in P} W_p \min\left(1, \frac{S_{ipm}}{Q_{pm}}\right) \tag{3}$$

where W_p is the weight assigned to POI category p. Scores exceeding the 75th percentile of S_{ipm} are capped at 1 using the $\min(1, \cdot)$ operator to counteract the effects of high-accessibility outliers. This results in a metric that ranges from 0 (no POIs of any category accessible) to 1 (per-capita number of accessible POIs is greater than or equal to the no-flood 75th percentile for all POI categories).
W_p is determined by performing Shapley-based decompositions of a regression model predicting life satisfaction for EU residents using satisfaction with the seven amenity categories (Itez, 2024; Castelli et al., 2023).

Distributional Effects

Finally, we identify how flood-related changes in QOL are distributed across different socio-demographic groups by linking our hex-grid QOL data with population data from the *Danish Neighbourhood Atlas* (Lange et al., 2023). In the DNA, the municipalities of Copenhagen and Frederiksberg are subdivided into 924 neighbourhoods based on OSM features, municipality boundaries, and data from the Danish national register. We use a combination of hierarchical (Ward) and K-means clustering to cluster Copenhagen and Frederiksberg's neighbourhoods together into representative groups, using the `scikit-learn` library (Pedregosa et al., 2011). Clustering is based on a set of 21 socio-demographic and economic indicators, using cross-sectional data from 2020.

3 Results and discussion

Results

Figure 2 showcases the spatial distribution of QOL loss for two rainfall intensity scenarios: 20 and 52 mm/day, averaged over all transport modes, respectively. Comparatively benign rainfall scenarios (20 mm/day) produce localised disruptions that temporarily limit individuals' quality of life. This scenario corresponds to a 21.1 % decrease in QOL, corresponding to 287 total POIs not being accessible compared to a no-flood baseline of 1613. In the 52 mm scenario, this loss increases to 28.2 % lower QOL, a QOL loss roughly equivalent to 423 POIs (across all categories) no longer being accessible.

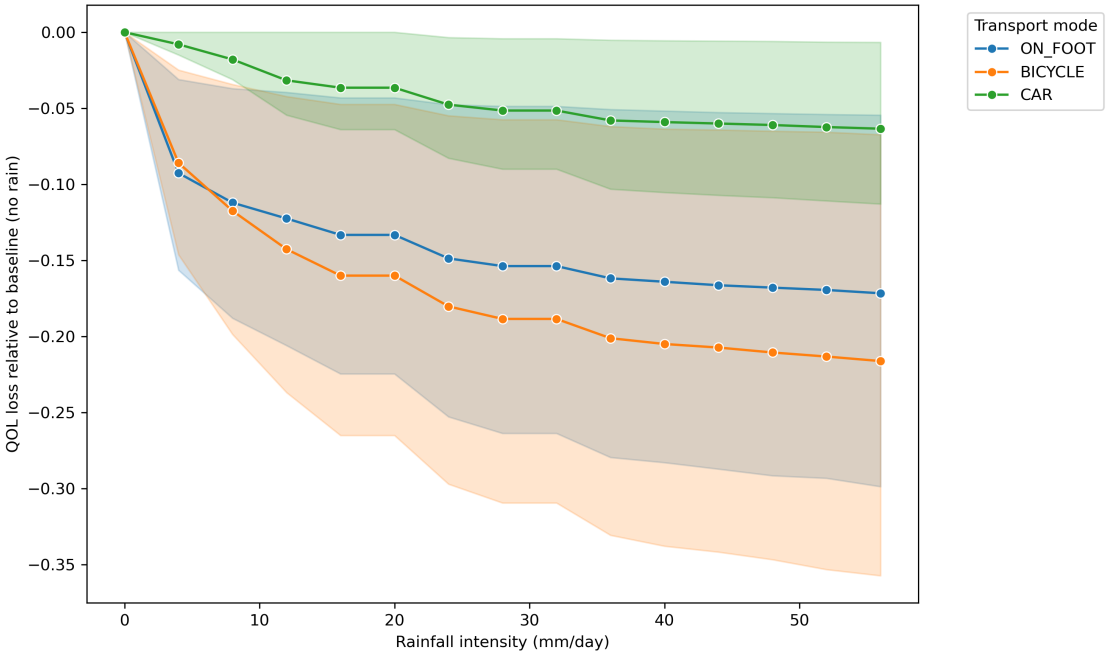


Figure 3: Mean (and 68th percentile shaded) QOL loss per mode over rainfall intensities.

Disaggregating QOL loss by transport modes highlights that QOL loss is highly dependent on transport mode. Based on Figure 3, we note a clear distinction exists between car-based QOL and QOL based on pedestrian and bicycle accessibility. Furthermore, cyclist and pedestrian-based QOL also feature a larger range of outcomes across the city. Taken together, these results suggests that both pedestrian and cyclist QOL are more sensitive to flooding compared to car-based QOL. Figure 4 outlines the results from our clustering analysis, which yielded three distinct and meaningful clusters to group Copenhagen's neighbourhoods into:

- `Young and Mobile`: city areas that have slightly lower disposable income, younger, more childless households, more densely populated and with high residential mobility.
- `Deprived and Settled`: areas that have the lowest disposable income and employment metrics, higher crime rates, less educational attainment, older residents, more single households, and slightly lower residential mobility.
- `Affluent and Established`: areas that are wealthier, have higher educational attainment, older residents, few single households, less densely populated, and the lowest residential mobility.

Figure 5 showcases the impacts of flooding on QOL disaggregated by cluster group and transport mode. For both active modes, **`'Affluent and Established'`** neighbourhoods are worst affected in terms of QOL loss, while **`'Young and Mobile'`** neighbourhoods were least affected. This gap is most pronounced for bicycle-based QOL, where in a 52 mm/day scenario QOL dropped by 25 % compared to baseline for the **`'Affluent and Established'`** neighbourhoods, corresponding to an accessibility loss of 68 POIs down from a baseline of 146.

Discussion

Our results show that the impact of nuisance flooding on QOL presents a policy challenge that could be distinct from the economic and extreme event-based impacts currently considered in Copenhagen's climate adaptation plans (Københavns Kommune, 2012). This is underscored by the fact that relatively common rainfall intensities like 20 and 52 mm/day are still capable of causing significant disruption to QOL. We also find that active (and in particular cycling) modes are linked with more QOL loss, and that the 'Affluent and established' neighbourhoods experience the worst QOL loss out of the three clusters.
Promoting cycling-based mobility is not only culturally important for a city like Copenhagen, but it also represents an important part of city authorities' efforts to mitigate fossil fuel emissions (and dependency), as well as improving public health and air quality (Gössling, 2013). Since cycling

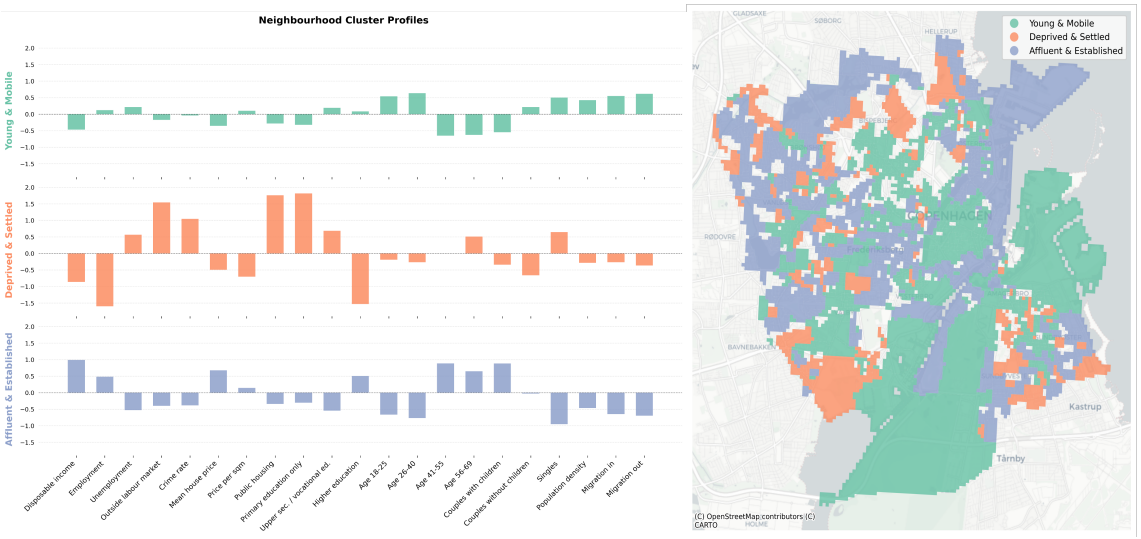


Figure 4: Demographic and spatial differences between clusters. *Left*: Neighbourhood cluster profiles. Standard deviations from overall mean are shown. *Right*: Spatial distribution of clusters.

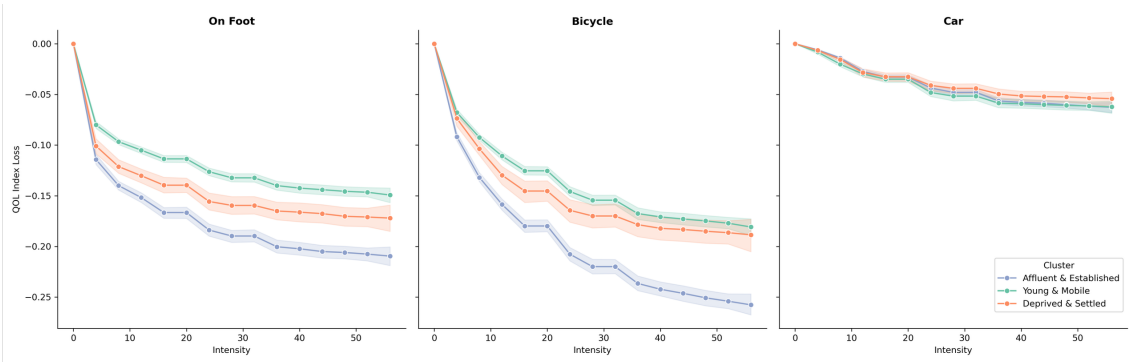


Figure 5: Mean QOL loss per cluster. Shaded areas are 95% CI.

mobility is therefore an important part of the city's future, the fact that the utility or feasibility of cycling is potentially negatively affected by the growing threat of nuisance flooding is significant. While studies focusing on the impact of nuisance flooding on transportation tend to focus on car-based mobility exclusively (Fant et al., 2021), our results suggest that the impact of nuisance flooding on active modes merits attention for cities like Copenhagen.
Finally, the wealthiest neighbourhoods of the city experience the worst QOL loss. The most likely explanation for this is largely geographical; wealthy areas like Frederiksberg are particularly prone to flooding. This has not escaped the attention of Danish researchers who suggest rethinking flood vulnerability in highly resourced contexts like Frederiksberg (Nielsen et al., 2023).
The findings from this study are limited by three main drawbacks: 1) the flood model, which does not take into account ground infiltration, drainage, or sewer drainage networks; 2) the accessibility model, which does not include congestion effects (which might bias car-based accessibility estimates); 3) the normative assumptions underpinning the QOL model, which do not speak to the ability of various neighbourhoods to cope with losses in accessibility.

4 Conclusions

To conclude, the findings from this study underscore the importance of considering flood impacts at the nuisance level. Our estimates suggest that flood events well below the return periods typically considered can nonetheless have a significant overall impact on quality of life and accessibility. Impacts are most pronounced for active modes, highlighting a potential threat specific to cycling-focused cities like Copenhagen. Finally, distributional analysis results prompt questions regarding which areas municipal authorities ought to prioritise in adaptation policies. Future work could focus on increasing the fidelity of the flood and accessibility models or further explore the justice and equity dimensions of nuisance flooding.

Acknowledgements

This work was supported by Villum Fonden grant VIL57387 and Novo Nordisk Foundation grant NNF23OC0085356.

References

Boeing, G. (2024). Modeling and Analyzing Urban Networks and Amenities with OSMnx.

Castelli, C., d'Hombres, B., Dominicis, L. d., Dijkstra, L., Montalto, V., & Pontarollo, N. (2023, October). What makes cities happy? Factors contributing to life satisfaction in European cities. *European Urban and Regional Studies*, *30*(4), 319–342. Retrieved 2025-05-06, from `https://doi.org/10.1177/09697764231155335` doi: 10.1177/09697764231155335

Dias, C., Rahman, N. A., & Zaiter, A. (2021, May). Evacuation under flooded conditions: Experimental investigation of the influence of water depth on walking behaviors. *International Journal of Disaster Risk Reduction*, *58*, 102192. doi: 10.1016/j.ijdrr.2021.102192

Dobrowolska, E., & Kopczewska, K. (2024, April). Mapping urban well-being with Quality Of Life Index (QOLI) at the fine-scale of grid data. *Scientific Reports*, *14*(1), 9680. Retrieved 2024-05-13, from `https://www.nature.com/articles/s41598-024-60241-0` doi: 10.1038/s41598-024-60241-0

EC/DG REGIO. (2023). *Quality of Life in European cities survey.* Retrieved from `https://ec.europa.eu/regional_policy/information-sources/maps/quality-of-life_en`

Fant, C., Jacobs, J. M., Chinowsky, P., Sweet, W., Weiss, N., Sias, J. E., ... Neumann, J. E. (2021, December). Mere Nuisance or Growing Threat? The Physical and Economic Impact of High Tide Flooding on US Road Networks. *Journal of Infrastructure Systems*, *27*(4), 04021044. doi: 10.1061/(ASCE)IS.1943-555X.0000652

Gössling, S. (2013, December). Urban transport transitions: Copenhagen, City of Cyclists. *Journal of Transport Geography*, *33*, 196–206. doi: 10.1016/j.jtrangeo.2013.10.013

Itez, C. (2024). *Shapley-decomposition: Decomposition using shapley values.*

Københavns Kommune. (2012, October). *The City of Copenhagen Cloudburst Management Plan 2012* (Tech. Rep.). Københavns Kommune.

Lange, E. S., Lindberg, M. R., & Thestrup, S. M. (2023). *The Danish Neighborhood Atlas — Detailed insights into over 13,000 Danish Neighborhoods.*

Li, M., Kwan, M.-P., Yin, J., Yu, D., & Wang, J. (2018, November). The potential effect of a 100-year pluvial flood event on metro accessibility and ridership: A case study of central Shanghai, China. *Applied Geography*, *100*, 21–29. doi: 10.1016/j.apgeog.2018.09.001

Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., Allaire, M., & Matthew, R. A. (2018, July). What Is Nuisance Flooding? Defining and Monitoring an Emerging Challenge. *Water Resources Research*, *54*(7), 4218–4227. Retrieved 2024-05-13, from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018WR022828 doi: 10.1029/2018WR022828

Nicoletti, L., Sirenko, M., & Verma, T. (2023, March). Disadvantaged communities have lower access to urban infrastructure. *Environment and Planning B: Urban Analytics and City Science*, *50*(3), 831–849. Retrieved 2025-12-03, from https://journals.sagepub.com/doi/10.1177/23998083221131044 doi: 10.1177/23998083221131044

Nielsen, A. B., Bonati, S., & Andersen, N. B. (2023, September). Discover the dynamics: An intersectional analysis of overt and hidden vulnerabilities to flood risk in urban Denmark. *Landscape and Urban Planning*, *237*, 104799. doi: 10.1016/j.landurbplan.2023.104799

Nuvolati, G. (2009). Quality of Life in Cities: A Question of Mobility and Accessibility. In V. Møller & D. Huschka (Eds.), *Quality of Life and the Millennium Challenge: Advances in Quality-of-Life Studies, Theory and Research* (pp. 177–191). Dordrecht: Springer Netherlands. Retrieved 2026-01-13, from https://doi.org/10.1007/978-1-4020-8569-7_12 doi: 10.1007/978-1-4020-8569-7_12

Olesen, M., Madsen, {. S., Ludwigsen, {. A., Boberg, F., Christensen, T., Cappelen, J., ... Christensen, {. H. (2014). *Fremtidige klimaforandringer i danmark*. DMI.

Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., ... Duchesnay, E. (2011). Scikit-learn: Machine learning in Python. *Journal of Machine Learning Research*, *12*, 2825–2830.

Pregnolato, M., Ford, A., & Dawson, R. (2016). Disruption and adaptation of urban transport networks from flooding. *E3S Web of Conferences*, *7*, 07006. Retrieved 2024-05-17, from http://www.e3s-conferences.org/10.1051/e3sconf/20160707006 doi: 10.1051/e3sconf/20160707006

Pregnolato, M., Ford, A., Wilkinson, S. M., & Dawson, R. J. (2017, August). The impact of flooding on road transport: A depth-disruption function. *Transportation Research Part D: Transport and Environment*, *55*, 67–81. doi: 10.1016/j.trd.2017.06.020

SCALGO. (2023). *The Rainfall-Runoff Model in the Flood Map in SCALGO Live Denmark* (Tech. Rep.).

Stimson, R. J., Marans, R. W., & Webster, N. J. (2024, March). Complexity and diversity of quality of life-related research. In R. W. Marans, R. J. Stimson, & N. J. Webster (Eds.), *Handbook of Quality of Life Research* (pp. 2–12). Edward Elgar Publishing. Retrieved 2025-05-13, from https://www.elgaronline.com/view/book/9781789908794/book-part-9781789908794-7.xml doi: 10.4337/9781789908794.00007

Uber Technologies, Inc. (2026, April). *H3: Hexagonal hierarchical geospatial indexing system.* https://github.com/uber/h3. (Accessed: 2026-04-10)

Vecchio, G., & Martens, K. (2021, November). Accessibility and the Capabilities Approach: A review of the literature and proposal for conceptual advancements. *Transport Reviews*, *41*(6), 833–854. doi: 10.1080/01441647.2021.1931551

Yin, J., Yu, D., & Liao, B. (2021, October). A city-scale assessment of emergency response accessibility to vulnerable populations and facilities under normal and pluvial flood conditions for Shanghai, China. *Environment and Planning B: Urban Analytics and City Science*, *48*(8), 2239–2253. Retrieved 2026-01-06, from https://doi.org/10.1177/2399808320971304 doi: 10.1177/2399808320971304

Zhong, S., Yang, L., Toloo, S., Wang, Z., Tong, S., Sun, X., ... Huang, C. (2018, June). The long-term physical and psychological health impacts of flooding: A systematic mapping. *Science of The Total Environment*, *626*, 165–194. Retrieved 2024-03-21, from https://linkinghub.elsevier.com/retrieve/pii/S0048969718300494 doi: 10.1016/j.scitotenv.2018.01.041