Imperial College London

Department of Design Engineering

An Urban Morpohological Analysis of Geospatial Water Scarcity in South Africa

Masters Project, Gateway 1 Submission

Conall Templeman

Supervisor: Freddie Page

A report submitted in partial fulfillment of the requirements of
Imperial College London for the degree of
Design Engineering, Master of Engineering

December 12, 2024

Chapter 1

Introduction

Sub Saharan Africa is projected to account for over 50% of the global population growth by 2050 (9), driving urbanisation and increasing demand for critical infrastructure (transport, communications, water etc.) (13). An estimation of around 1.5 billion people will live in these African cities by the same year (5), accelerating urban sprawl, particularly in the fringe settlements around the city's centre, and exacerbating inequalities. Through the lens of water scarcity, we can already see nearly 63% of urban areas in Sub Saharan Africa lack access to basic water and sanitation (5). The African continent needs to invest at least an additional US$30bn per year towards water security and sustainable sanitation (2)

In South Africa, rainfall is particularly low (less than 50% of the global average at a value of 497mm/year (3)), being rated the 38th driest country in the world, and climate change is only set to worsen the potential impacts (15), with a projected gap in demand of around 3.8 billion $m^3/year$. Water is a heavily unevenly distributed resource meaning that millions of South Africans already drink water that was captured in reservoirs in excess of 400km away (3): 19% of the rural population lacks access to sanitised water, 26% of schools and 42% of clinics. Whilst in South Africa the rate of urbanisation is currently decreasing (10), the rate of population increase insists the need for greater urban development going forward. The socioeconomic and political residues of apartheid still have deep roots in the urban system of the country which is resulting in a more and more fragmented urban landscape and a growing gap between rural and urban areas, leading to massive migration pressures (noa).

Following the recent 'Day 0' crisis in Cape Town, it is clear that addressing the issues of water insecurity here are crucial. Urban planners and water infrastructure managers operate in 'silos', not considering the potential impact of multi-city/local settlement cooperation. If we are to see city expansion from somewhere like Cape Town, even catering for the informal settlers may see downstream advantages, alongside the obvious benefits of bolstering water security.

This study aims to investigate how city expansion in Cape Town until this point has worsened water scarcity, and how it might continue to worsen in the future without proper intervention. The complex morphology will provide valuable insights into the underlying growth mechanisms behind city expansion that the project aims to apply in other urban contexts. Urban morphogenesis is a term used to describe the emergence of form and function in a strongly coupled manner, producing an emergent urban landscape or varying classifications of environmental archetypes. The outcome of the project will be in the form of a prescriptive model, assessing the impact of determined policy changes or urban planning guidance against no alternative actions, and a broad assessment of the state of South African water scarcity in both the best and worse case scenarios.

Chapter 2

Methodology

2.1 Existing Research

There are multiple accepted approaches to modelling urban morphology,the leading approaches being: machine learning (ML), agent based modelling (ABM), Clue-S model and cellular automata (CA) (14) (7) (13) (4) (6) (17) (8) (11) (16). In a similar paper looking at South African city growth (13), Manghara, Gidey and Manjoo employ an ML model (Support Vector Machine) for land classification, taking Geographic Information Systems (GIS) data from optical and infrared satellite imaging. They then employ a Markov-informed Cellular Automata (CA) for mapping the growth mechanisms behind Mbombela City in South Africa. Their findings demonstrated a number of valuable findings on the morphology of the city, showing a dominance of vegetative and natural spaces over urban built-environments. They observed a clear decline in the availability of water as a function of the number of 'blue spaces' areas using GIS, and explain the finding in terms of population growth.

The key differences between the aims of this study and the paper mentioned above include: building a direct relationship between water scarcity and different morphological regions, rather than commenting on the general availability of water sources; mapping susceptibility to water scarcity, with a focus on highlighting the impacts of urban sprawl versus densification; targeting a larger, more complex city, such as Cape Town, and integrating a greater range of built environment classes; prescribing interventions and developing a framework for further studies.

Concerning the selection of the most appropriate model, this project looks at also leveraging a Markov-informed CA model given its ability to reflect complex behaviours through simplistic governing rules for a high resolution geospatial data. Given the the Global Human Settlements database already divides regions by grids, this lends itself to the implementation of a Moore neighbourhood.

Features	CA	ABM	Clue-S Model	ML
Computational Speed	5	3	5	4
Short Term Accuracy	4	4	3	4
Long Term Accuracy	3	3	2	4
Flexibility	4	5	3	4
Interpretability	5	5	5	1
Reproducibility	3	2	5	5
Scalability	5	3	2	5
Summary	29	25	23	27

Table 2.1: Evaluation of Suitable Morphological Programming Approaches (/5)

*Flexibility is a measure of how well the system is able to account for seemingly random changes

*Scalability is a measure of whether the models can capture complexity easily for smaller and larger settlements

2.2 Project Direction

As mentioned previously, the Global Human Settlement Database will be used to extract morphological data for Cape Town, with 6 classifications of urban environment and 10 classifications for settlements at a resolution up to $100m^2$ in grid sizing. The file will be interpreted and processed using a combination of ArcGIS and python, as the workflow is well established. Water scarcity and population values by municipality can be taken from the South African Department for Water and Sanitation and superimposed, distributing values expectedly based on morphology within each region. The water scarcity data in particular offers information on the backlog of water demand and how many households sit below or at the Reconstruction and Development Programme (RDP) guidelines.

Using this data, a multi-variate descriptive analysis will be conducted to assess the strength of the relationships between morphology, water scarcity and population (see (12)). A cellular automata model will then be trained on data of the morphology to govern the underlying rules for the transformation matrix. The different ways to include the performance of this model include incorporating: functions of distance to the nearest city epicentre, slope, access to major transport networks etc.; Markov chains to understand the states each cell has previously been in; a Lattice-Boltzmann model to understand how the system performs as a whole; asynchronous feedback to account for the knock on effects of migration or water scarcity; boundary conditions, and fuzzy rules to account for uncertainties in cell states. Each of these adaptations will come at a computational expense, and so there is scope for a linear optimisation algorithm in making an appropriate selection, considering the projected additional accuracy/impact.

With a robust cellular automata mode, a predicted series of models can be run to determine probabilistic forecasts or outcomes to demonstrate how water scarcity is likely to change corresponding with the morphological breakdown of the regions. The outcomes should highlight those regions most at risk, and so the models can then be rerun with policy guidelines implemented as the functions for the cellular automata models to show the potential impact. A yearly budget can be considered for targeted intervention measures.

Similar papers (16) have explored the potential drawbacks of optimising for any one of the United Nations Sustainability Development Goals (SDG). An extension of the research may take the form of modelling how water scarcity and wage equality and related: an early hypothesis for the project is that we will see a significant degree of densification in the city centre, and continued urban sprawl on the outskirts; poorer people would be pushed to the outskirts, and it's these people that may be most susceptible to water insecurity. Here, there is a possibility to integrate 'isobenefit urbanism' (8) into the design, taking these various conflicting SDGs as input driving forces.

Another potential segue includes the integration of an agent based modelling force for demonstrating the interactive forces between neighbouring cities. If our cellular automata model is not over-fit on the training data, the aim is to apply the same model on other cities and test for accuracy. With a generic model for the growth trends, the study could investigate the magnitude or attractive and repulsive forces between 'agents' on a simplified national scale.

References

[noa] Urbanization in South Africa: Building inclusive & sustainable cities.

[2] (2023). How improving institutions can help solve South Africa's water crisis.

[3] (2024). Water Crisis In South Africa.

[4] Batty, M. (2005). Agents, Cells, and Cities: New Representational Models for Simulating Multiscale Urban Dynamics. *Environment and Planning A*, 37:1373–1394.

[5] Berg, R. v. d., Otto, B., and Fikresilassie, A. (2021). As Cities Grow Across Africa, They Must Plan for Water Security.

[6] D'Acci, L. (2019). A new type of cities for liveable futures. Isobenefit Urbanism morphogenesis. *Journal of Environmental Management*, 246:128–140.

[7] Deep, S. and Saklani, A. (2014). Urban sprawl modeling using cellular automata. *The Egyptian Journal of Remote Sensing and Space Science*, 17(2):179–187.

[8] D'Acci, L. S. and Voto, M. (2023). Morphogenesis of Isobenefit urbanism: Isobenefit-cities simulator. *SoftwareX*, 23:101408.

[9] Forget, Y., Shimoni, M., Gilbert, M., and Linard, C. (2021). Mapping 20 Years of Urban Expansion in 45 Urban Areas of Sub-Saharan Africa. *Remote Sensing*, 13(3):525. Number: 3 Publisher: Multidisciplinary Digital Publishing Institute.

[10] Gambe, T. R., Turok, I., and Visagie, J. (2023). The trajectories of urbanisation in Southern Africa: A comparative analysis. *Habitat International*, 132:102747.

[11] Glen, C. M., Kemp, M. L., and Voit, E. O. (2019). Agent-based modeling of morphogenetic systems: Advantages and challenges. *PLoS Computational Biology*, 15(3):e1006577.

[12] Li, X., Gong, P., Yu, L., and Hu, T. (2017). A segment derived patch-based logistic cellular automata for urban growth modeling with heuristic rules. *Computers, Environment and Urban Systems*, 65:140–149.

[13] Mhangara, P., Gidey, E., and Manjoo, R. (2024). Analysis of urban sprawl dynamics using machine learning, CA-Markov chain, and the Shannon entropy model: a case study in Mbombela City, South Africa. *Environmental Systems Research*, 13(1):17.

[14] Mozaffaree Pour, N. and Oja, T. (2021). Urban Expansion Simulated by Integrated Cellular Automata and Agent-Based Models; An Example of Tallinn, Estonia. *Urban Science*, 5(4):85. Number: 4 Publisher: Multidisciplinary Digital Publishing Institute.

[15] Prins, F. X., Etale, A., Ablo, A. D., and Thatcher, A. (2023). Water scarcity and alternative water sources in South Africa: can information provision shift perceptions? *Urban Water Journal*, 20(10):1438–1449. Publisher: IAHR Website _eprint: https://doi.org/10.1080/1573062X.2022.2026984.

[16] Raimbault, J. and Pumain, D. (2022). Trade-offs between sustainable development goals in systems of cities. *Journal of Urban Management*, 11(2):237–245.

[17] Stanilov, K. (2010). Bridging the gap between urban morphology and urban modelling K. Stanilov. *Urban Morphology*, 14(2):123–124. Number: 2.