DEVELOPMENT OF A RESILIENT WATER-ENERGY-AGRICULTURE STRATEGY PLAN FOR THE CITY OF CAPE TOWN, THROUGH PREDICTIVE SIMULATIONS

Report to the
Water Research Commission

by

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Executive Summary

Rationale

The 'Day Zero' drought in the City of Cape Town was precipitated by 3 consecutive seasons of below average rainfall, and in early 2018 the metropolis was in danger of becoming the first world city to run out of water. The potential disaster was avoided though a combination of controllable and uncontrollable factors: the City implemented interventions and consumers decrease water usage, and in 2018 the rainy season brought sufficient rain to replenish reservoirs. The crisis did, however, highlight the immediate need for longer-term planning to ensure sustainable water supply to the various users within the municipal boundaries of the City, especially in the face of impending climate change that predicts a decrease in average annual rainfall for the Western Cape.

The water supply for Cape Town, is however, a complex system that is intertwined with other resource systems (notably food production and energy supply). Water is supplied through a combination of reservoirs, aquifers and water recycling and there are multiple users: residential, industrial and commercial, and agricultural sectors all compete for the water required to maintain and expand their operations. This leads to a difficult scenario for the City of Cape Town to plan for future water security, especially in the face of an expanding population due to in-country immigration into the Western Cape.

The quantitative tools to enable longer-term planning for a situation such as the one Cape Town faces, are limited and often not appropriate to describe such a highly complex system at the city scale. The water-energy-food (WEF) nexus framing enables a conceptual understanding of interconnected and complex resource systems, yet quantitative descriptions of city scale WEF nexus scenarios, especially forward-looking ones that incorporate potential changes in climate, are not often encountered in academic literature. This project therefore set out to achieve two main goals: to develop a WEF nexus description for the City of Cape Town that enables future planning, and to train researchers that are able to set up and operate the required tools and models, and to make conclusions and recommendations that are implementable for a governing city administrator.

Research gaps

There are various research gaps, both within the wider academic WEF nexus literature, and within the South African context. Overall, WEF nexus case studies are underrepresented within the Global South, and this includes urban WEF nexus work. Developing urban WEF nexus case studies is important for the Global South, as the context of urbanisation, economic and social development status and anticipated climate change impacts are likely very different from the Global North. Building quantitative tools to assess the WEF nexus in Global South case studies will enable evidence-based policy guidance. Additionally, cities in the Global South remain poorly studied, much of which is a result of data scarcity and the difficulties in obtaining the data that are available. Work that identifies data sources, collates data sets and does quantitative modelling for cities in the Global South provides valuable research and insights. In the South African context, WEF nexus studies on an urban scale remain scarce.

The work therefore plays into these research gaps, and makes a useful contribution toward filling them.

Objectives

Overall, this work had two main goals: (i) to develop the models and tools required to describe and examine the urban WEF nexus specifically for the City of Cape Town from the perspective of urban metabolism, to aid medium- to long-term planning of sustainable development, and (ii) to develop human capital around this knowledge area, to enable future development in this particular field. The specific objectives of the project were:

1. To develop a systems-wide understanding of the state of water-energy-food nexus situation (supply and demand, infrastructure, social, institutional and policy context, etc.) of Cape Town, and the dynamics within the WEF nexus of Cape Town from a systems dynamics perspective.
2. To evaluate different modelling frameworks and data requirements to set up a predictive model of the WEF-nexus in Cape Town, and select an appropriate modelling framework.
3. To obtain the required data, develop and implement the systems dynamic models supplemented by stochastic elements within the models, and employ these to identify specific areas in the City of Cape Town's WEF nexus where resilience can be increased. In doing this, the models were anticipated to demonstrate how the evaluation and prioritisation of policy changes and government-sponsored interventions can improve sustainable planning in the WEF-nexus in Cape Town.
4. To build, enhance and support research capacity of various early career researchers (academic staff, a postdoctoral fellow and postgraduate students), and disseminate the results of the work to wider stakeholders, including those that participated during the early phase of the project.

Scope

The project consisted of a 3-year research effort, and entailed completion of a detailed literature review on the urban WEF nexus, followed by selecting a modelling framework, setting up a qualitative (conceptual) model followed by a quantitative (mathematical) model. Data and information were sourced to enable running the mathematical model and results of the model were verified. Throughout the project, various academics participated in the work, either as direct participants or through contributing expertise. Two postgraduate students completed their Masters degrees in January 2024, and one postdoctoral fellow provided dedicated time and support to the project.

Methodology

The initial stage of the project focused on reviewing literature to ascertain the current status of urban WEF nexus work, and reviewing different potential quantitative modelling frameworks. Systems dynamics modelling was eventually settled upon as the most suitable tool to set up a quantitative WEF nexus tool for the City of Cape Town. It is a dynamic tool that can capture significant system complexity, it requires less data than some other methods (which is important in situations where data may not be readily available), and there are well-developed electronic packages that are specifically developed for systems dynamics, thereby decreasing the need for mathematical tool development. Three studies were developed as part of this project, where the complexity of the case studies were systematically increased. Chapter 4 reports mainly on the interdependencies of water and food, Chapter 5 on water-energy dynamics, whereas Chapter 6 describes the entire WEF nexus for the City. Each chapter has its own specific methodology, with only the overall approach to setting up and implementing the quantitative models provided here.

Model set up comprised of developing a problem statement and system boundary, describing the WEF nexus system through a qualitative model, setting up a quantitative model, finding and validating data, populating and running the quantitative model, validating the model, and developing and implementing different scenarios.

Results

The main findings of the work are on the one hand fairly general and to be expected (the water system for the metropole is complex and difficult to describe, more and higher quality data will improve modelling certainty, it is difficult to know exactly what all the impacts of climate change will be on future water availability), and on the other hand quite specific. Particularly useful findings include the fact that the various aquifers are likely to play a very important role in ensuring sustainable water provision in future, but that there is a danger of over-extraction and permanent degradation due to saltwater infiltration. The different water recycling initiatives of the City of Cape Town remain important to ensure diversification of water supply options, and when the different recycling schemes come online, these will ensure additional water supply of 3.5% (Faure New Water Scheme), 8.9% (Zandvliet New Water Scheme) and 8.4% (Cape Flats New Water Scheme) compared to current availability. Considering energy provision, the City of Cape Town's various initiatives to procure electricity from independent producers, coupled with the establishment of a 650 MW solar farm, are important actions to increase energy security, although total energy independence remains unlikely within the modelling timeframe under the assumptions made. Additionally, the impact of small scale electricity production are difficult to estimate and remain an uncertainty within the modelling exercise.

As with all modelling studies, there are certain limitations which need to be acknowledged. In describing a complex system such as the WEF nexus for the City of Cape Town, issues related to general data availability and quality are unavoidable. Added to these are more nuanced aspects such as misalignment in the timeframe for which data are available, and the difficulty and uncertainty in predicting changes in the dynamics of the City of Cape Town within the same timeframe as that over which climate disturbances are expected to become important. Whereas changes and interventions at city level can be viewed as fairly short term (a few years), changes in climate typically occur much slower, i.e. over decades.

Conclusions

The WEF nexus framing was successful to provide a basis for analysing the interconnected nature of the water-, energy- and food systems within the City of Cape Town, and system dynamics modelling was able to quantitatively model the dynamic system. The models were further able to make predictions that incorporate climate impact over the modelling period, and to incorporate other system disturbances.

The results from the work clearly indicate that increased population growth and anticipated climate-related changes in rainfall will put the water resources of the City of Cape Town under pressure in the coming decades. Additional water availability is created through internal recycling of water, and through the utilisation of water from the various aquifers. The utilisation of aquifer water comes at the risk of over-extraction, which could result in seawater infiltration and salinification of the affected aquifers. Frequent monitoring is therefore essential to ensure that this water resource remains viable in future.

The efforts of the City of Cape Town to supplement electricity supply to the metropole will significantly increase energy security, although there remains some uncertainty about the impact of small scale production on energy supply. The procurement of electricity from independent producers and the establishment of a 650 MW solar farm will result in significant increases in energy availability (assuming the national grid remains constrained for a significant period), although total independence from electricity imported from beyond the City's borders remain unlikely.

The food component of the WEF nexus seems particularly challenging to pin down for the City of Cape Town. Although there is a good grasp of agricultural activity within the metropole's boundaries, a very large proportion of food is still imported from beyond the city boundaries, meaning that the impacts on the food sector are mostly not controllable through city-level policies. Local food production is also subject to external market forces, and policy impacts from the City are likely only to have indirect impacts on local food production.

Recommendations

Direct recommendations flow from the project, some of which are likely already being implemented by the City of Cape Town, but for completeness they are included here.

The mitigation and long term intervention activities being implemented and/or planned by the City, like internal water recycle and procurement of electricity from independent power producers, should be supported going forward. These activities make significant contributions to increasing resource availability, and will contribute toward increased sustainability of the

City. These efforts are aligned with other sustainability efforts within cities globally, and should be encouraged. Diversification of the type of interventions pursued, both on demand side management and supply side increase, will ensure a holistic approach.

Aquifers form an important part of future water supply, yet are vulnerable to over-extraction. Frequent monitoring should be performed on these crucial sources of fresh water, as over-extraction can result in seawater infiltration and salinification of the affected aquifer(s). Frequent monitoring is therefore essential to ensure that this water resource remains viable in future.

Increased release of non-sensitive data should be seriously considered. There is significant capability within the South African academic system to process good quality data sets, which could in turn have significant benefits to the originators of such data. The difficulty in finding and validating data prevents more collaboration between academia and local government, and having a central repository where data are synchronised and curated, will be of immense value to facilitate future investigations, to the mutual benefit of academia and local government.

Future research

There are important areas where modelling can be improved, both to expand the models and to increase certainty in model results. Firstly, the models can be supplemented by integrating economic aspects, where the impact of policy changes on some economic indicators at various scales can be evaluated. Economic aspects are likely going to play a large role in future decision-making, and incorporating the capability of current models to make economic indicators part of the outputs will increase the utility of the resulting outputs. Secondly, the increase in population needs to be verified, as much of the models rely on data specified on a per capita basis. Given that 'semigration' is a significant contributor to population increase within the City's boundaries, it is important to take this into account to make accurate predictions of expected population growth. Finally, a particularly important aspect that can be added to the work is uncertainty analysis, and pinpointing the largest contributors to model uncertainty, which in turn will guide where future efforts need to be focused to improve the certainty in model outputs.

The current project mostly viewed system disturbances as single events and modelled the predicted outcomes. Although it is difficult to reliably determine the co-occurrence of multiple system disturbances (e.g. sudden semigration increase coupled to multi-year drought), the system resilience should be evaluated at the hand of such 'perfect storm' scenarios in future. The Day Zero drought was an exceptional occurrence and was only narrowly avoided; setting up some multi-disturbance scenarios could yield results that are helpful to elucidate specific pressure points in the overall system that are particularly vulnerable.

Finally, the work can benefit from adding additional disciplines to the project team in future expansion of the project. The work undertaken was already of a multidisciplinary nature and although the project team made good strides in setting up and validating the systems dynamic models, the expansion of disciplines to include, e.g. economics could add significant additional value.

Innovation

The innovation in this project lies in the WEF nexus models (both the qualitative ones and the quantitative ones) created, implemented and validated throughout the project. Setting up these complex models is a significant challenge and requires perseverance and creativity to achieve. Reaching the point where these models are validated and therefore produce useful results, represents significant innovation, particularly since these models are among the few quantitative models set up within the South African context, particularly within the urban WEF nexus context.

Beneficiaries

The beneficiaries of the work are from among two groups: firstly, academia as a whole, seeing that these models are now fully described and will be available to expand and build on, and secondly, local government who may want to utilise and/or adapt these models to evaluate particular policy proposals.

Acknowledgements

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Project Reference Group

The Reference Group consisted of the following members:

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Chapter 1: Introduction

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The project is set against the background of the narrowly-avoided 'Day Zero' event, when the City of Cape Town (CoCT) would have run out of water in early 2018, following 3 consecutive winters of below average rainfall in 2015, 2016 and 2017. The CoCT eventually did not run out of water, through a combination of metropole-wide implementation of interventions to increase water supply and decrease demand, societal response to achieve the same, and a return to more normal rainfall patterns in the 2018 rainy season. Despite avoiding the immediate threat that 'Day Zero' posed, two long-term issues became apparent: 1) the CoCT's water supply remained vulnerable to unexpected fluctuations in seasonal rainfall, and measures to increase the overall system resilience are required to ensure long-term water security for the growing metropole, and 2) the water system is complex and highly intertwined with particularly the energy and agricultural sectors, which makes the implementation of new measures difficult, while likely also resulting in significant trade-offs.

The tools that enable predictive mathematical modelling of such a complex system have been developed, but it remains a challenge for governing bodies to deploy these tools for a number of reasons. Among these are the specialized skills required to gather and curate the large amounts of data required, to set up and run the complex tools, and then to interpret the communicate the results in a way that enable decision makers to act on them (Egieya et al., 2022). The scant resources available for such specialized activities in local and regional government hampers long term forecasting, leaving it to academic institutions and sometimes to consultancies.

This report is the outcome of a 3-year long exploratory project to select and set up a model able to capture the complexities within the water supply system of the City of Cape Town, and to use it to demonstrate some forecasting results for water availability, given the potential impacts of predicted climate change. The work builds on and complements previous research that has been commissioned through the South African Water Research Commission, and fills a particular gap by addressing quantitative modelling of the urban WEF nexus, specifically for the City of Cape Town. Mabhaudhi et al. (2018) assessed the state of the WEF nexus for South Africa, Senjanje et al. (2023) built a web-based WEF nexus integrative model with GIS capability to act as a WEF nexus analytical tool, which was then applied to develop a case study for Southern Africa (Mabhaudhi et al., 2023), Nhamo et al. (2021) developed a WEF nexus framework for urban settings and Gauteng and highlighted the need for cities to develop adaptation strategies in the face of climate change, and Methner et al. (2021) investigated how the WEF nexus can assist in improving household and local community level livelihoods. In this report, we set out the selection process to identify a suitable modelling methodology, how the methodology was applied and the models developed, and provide the results of these efforts.

1.1 Rationale

The current and future water supply system of the City of Cape Town consists of a number of inputs, including rainfed dams, aquifers, and water recycling facilities (at the time of writing, desalination plants have been decommissioned after the end of the Day Zero drought). There are multiple and sometimes competing demands for this water for agricultural, urban, domestic and industrial purposes. Water supply, however, cannot be isolated from the supply and use of energy and food, and is viewed to be interconnected with these other two resource systems . The water-energy-food (WEF) nexus has been proposed as a framework in which such interconnected systems can be conceptualized and analysed (Hoff, 2011), and it has found widespread use in research literature since its introduction in 2011.

The current and future water supply of Cape Town can be viewed as a finite resource, based on rainfall, groundwater flow, storage capacity, water recycling and reclamation and alternative water supply methods, while serving a growing, multi-user base in the presence of climate change that is predicted to reduce rainfall and by implication, water availability. Fossil-fuel derived energy has climate change consequences, yet energy is also required to ensure water supply for the CoCT. Cape Town therefore needs to develop a resilient, quantitative water plan to guide investments in additional water supply capacity, by ensuring a balanced supply and utilisation of natural resources in the WEF-nexus within this dynamic environment. Planning for sustainable urban development requires a balanced supply and utilisation of natural resources through systematic thinking, to ensure that all of the components of the urban WEF-nexus can function efficiently. Ignoring the dynamic interconnections of WEF-components will have adverse consequences: Food production requires water and energy, water supply and treatment need energy, while energy production also consumes water.

Although there are a number of ongoing initiatives within the City of Cape Town to supplement current water supply systems, these have two shortcomings: (i) they largely focus on the water aspect with some consideration of impact on agriculture, but the impacts on energy supply is not often considered, and (ii) some interventions are ‘stop-gap’ and not long-term sustainable, and have since been discontinued, notably some of the desalination operations commissioned during the Day Zero drought. There is therefore a need for a holistic system description for the City of Cape Town, which explicitly accounts for all 3 resource systems. Furthermore, estimates of future rainfall that account for climate variability are needed to enable planning of future resource requirements. Developing such models and capabilities now and employing them for longer-term planning, will enable building resilience into the City’s supply systems. This is directly aligned with the City’s own strategy of taking into account interactions between various sectors, and building long-term resilience into its operations in line with the CoCT 2019 Resilience Strategy.

Improved management and planning of sustainable urban development can be achieved by using “urban metabolism” as an approach for an integrated and broad nexus system with multiple material and energy flows. Employing systems dynamics modelling, the interdependencies and feedback between the different system components can be elucidated, while stochastic simulation can be employed to quantify the uncertainty in the system in the face of future changes. Efficient planning and implementation around the complexity, dynamics and interconnectedness of a WEF nexus will benefit from a structured systems approach, and can assist decision-making to move Cape Town closer to achieving the Sustainable Development Goals (SDGs) (Mpandeli et al., 2018), by building sustainable cities and communities (SGD11), with zero hunger (SDG2), and to achieve universal access to clean water and sanitation (SDG6), as well as affordable and clean energy (SDG7). This entails sustainable consumption and production (SDG12), and it addresses the climate impacts of these activities (SDG13).

1.2 Aims and Objectives

Overall, this work had two main goals: (i) to develop the models and tools required to describe and examine the urban WEF nexus specifically for the City of Cape Town from the perspective of urban metabolism, to aid medium- to long-term planning of sustainable development, and (ii) to develop human capital around this knowledge area, to enable future development in this particular field. It was envisaged that the modelling would enable measurement of the impacts of policy changes and government-sponsored interventions, and measurement of the resilience of the overall WEF-system in the face of short-, medium- and long-term dynamics.

The objectives of the project were set out to investigate urban system structure, processes and functions that underly the dynamics of the WEF nexus of Cape Town, and to model the nexus to better inform sustainable urban strategy development, policy design and decision-making practices. The specific objectives of the project were:

5. To develop a systems wide understanding of the state of water-energy-food nexus situation (supply and demand, infrastructure, social, institutional and policy context, etc.) of Cape Town, and the dynamics within the WEF nexus of Cape Town from a systems dynamics perspective.
6. To evaluate different modelling frameworks and data requirements to set up a predictive model of the WEF-nexus in Cape Town, and select an appropriate modelling framework.
7. To obtain the required data, develop and implement the systems dynamic models supplemented by stochastic elements within the models, and employ these to identify specific areas in the City of Cape Town's WEF nexus where resilience can be increased. In doing this, the models were anticipated to demonstrate how the evaluation and prioritisation of policy changes and government-sponsored interventions can improve sustainable planning in the WEF-nexus in Cape Town.
8. To build, enhance and support research capacity of various early career researchers (academic staff, a postdoctoral fellow and postgraduate students), and disseminate

the results of the work to wider stakeholders, including those that participated during the early phase of the project.

1.3 Project Scope

The project consisted of a 3 year research effort, and entailed completion of a detailed literature review on the urban WEF nexus, followed by selecting a modelling framework, setting up a qualitative (conceptual) model followed by a quantitative (mathematical) model. Data and information were sourced to enable running the mathematical model and results of the model were verified. Throughout the project, various academics participated in the work, either as direct participants or through contributing expertise. Two postgraduate students completed their Masters degrees in January 2024, and one postdoctoral fellow provided dedicated time and support to the project.

The document that follows is divided into a total of 4 research chapters, each with a different set of authors reflecting the different researchers that contributed to the work. Chapter 2 provides a detailed literature review about the WEF nexus, how the research literature developed in general, after which it focuses on the urban WEF nexus. Chapter 3 provides a brief overview of the methodology employed, whereafter three modelling-oriented chapters follow where the work is built up systematically: Chapter 4 captures the dynamics in the water-food nexus for the City of Cape Town, Chapter 5 investigates the water-energy nexus, whereas Chapter 6 describes the overarching water-energy-food nexus. The modelling efforts included a predictive aspect to forecast the changes in the dynamics within the system, and attempted to set out potential scenarios to model in order to gain insight into potential pressure points within the interconnected systems that may arise. The document is rounded out with a concluding chapter that also makes recommendations for future work.

1.4 References

Egieya, J., Görgens, J.F., Goosen, N.J., 2022. Chapter 2: Some quantitative WEF nexus analysis approaches and their data requirements, in Mabhaudi, T. (Ed.), Water-Energy-Food Nexus Narratives and Resource Securities. eBook ISBN: 9780323918374

Hoff, H. (2011). Understanding the Nexus. Background paper for the Bonn2011 Nexus Conference: Stockholm Environment Institute, November, 1-52

Mabhaudhi, T., Simpson, G., Badenhorst, J., Mohammed, M., Motongera, T., Senzanje, A., Jewitt, G.P.W., 2018. Assessing the State of the Water-Energy-Food (WEF) Nexus in South Africa. Water Research Commission of South Africa, p. 62.

Mabhaudhi, T., Taguta, C., Senzanje, A., 2023. From theory to practice: Developing a cast study and guidelines for water-energy-food (WEF) nexus implementation in Southern Africa. Water Research Commission, p. 235.

Methner, N., Midgley, S.J.E., Price, P., Ningi, T., Nxumalo, N.P., Rebelo, A.J., Stuart-Hill, S.I., Zhou, L., Mjanyelwa, V., Taruvinga, A., 2021. Water Research Commission, p. 323.

Nhamo, L., Mpandeli, S., Hlophe-Ginindza, S., 2021. Urban nexus as a transformative pathway towards a resilient Gauteng City Region. 17.

Senzanje, A., Taguta, C., Kiala, S., Mabhaudhi, T., 2023. Developing a web-based and GIS-enabled WEF nexus integrative model. Water Research Commission of South Africa, p. 113.

Chapter 2: Literature Survey

Authors: Hachaichi, M., Egieya, J., Görgens, J., Goosen, N.

The nexus of water, food, and energy is critical to short, medium, and long-term development. Growing global populations, increased urbanization, changing diets, and economic expansion are all increasing demand for these three resources. Agriculture consumes the majority of the world's freshwater resources, while food production and supply consume more than a quarter of the world's energy. Moreover, due to the inextricable links between WEF, guaranteeing global water and food security, as well as sustainable agriculture and energy production, require a fully integrated approach.

On the other hand, the majority of the world's fast-growing cities are domiciled in middle and low-income nations, where there is a gap in resource utilization assessment which limits their ability to plan and control urban expansion and its effects on water and energy consumption. Consequently, about a seventh of the world's population (dubbed the "bottom billion") has no reliable food supply with limited access to clean water, sanitation, and modern energy sources (Hoff, 2011).

In terms of food, demand is surging with population growth, and there is a global shift from a primarily starch-based diet toward a rising need for more water-intensive meat and dairy foods as incomes rise in many countries. Water is a finite resource that depends on the energy and food sectors. As such, decision-makers are increasingly focusing on water management, supply, and sanitation by identifying synergies to resolve conflicts between the various sectors and decision-makers.

2.1 Definition of the Water-Energy-Food nexus

The Water-Energy-Food nexus (WEF nexus) is a recent concept that has taken root in wider scientific literature since in 2011. The nexus concept acknowledges that the three resource systems are interconnected, and that an integrated management approach is required to sustainably manage these three systems simultaneously (Hoff, 2011). Water, food, and energy are essential resources, and a sufficient supply thereof is required to achieve sustainable development to ensure poverty reduction and societal well-being (FAO, 2014). The WEF nexus optimization directly impacts and bolsters 10 of 17 SDGs (Bieber et al., 2018), and can therefore play a key role toward achieving sustainable development.

Resources availability and consumption vary from region to region as illustrated in Figure 1. The "nexus reasoning" approach seeks to amplify synergies and minimize trade-offs between the three systems to improve the management of natural resources in a cross-sectorial approach (Scott et al., 2016). WEF nexus aims to achieve water, food, and energy security.

Water security is defined by the Millennium Development Goals as "access to safe drinking water and sanitation" which are considered to be a human right. This definition does not account for accessibility and use of water for other human and ecosystem needs; hence, the WEF nexus approach urges incorporating such usages. However, 97% of the water on Earth is salt water, leaving only 3% as freshwater, only 1% of which is readily available for human consumption. For power, irrigation, industrial activities, and daily use, the world's population is becoming increasingly dependent on this valuable resource.

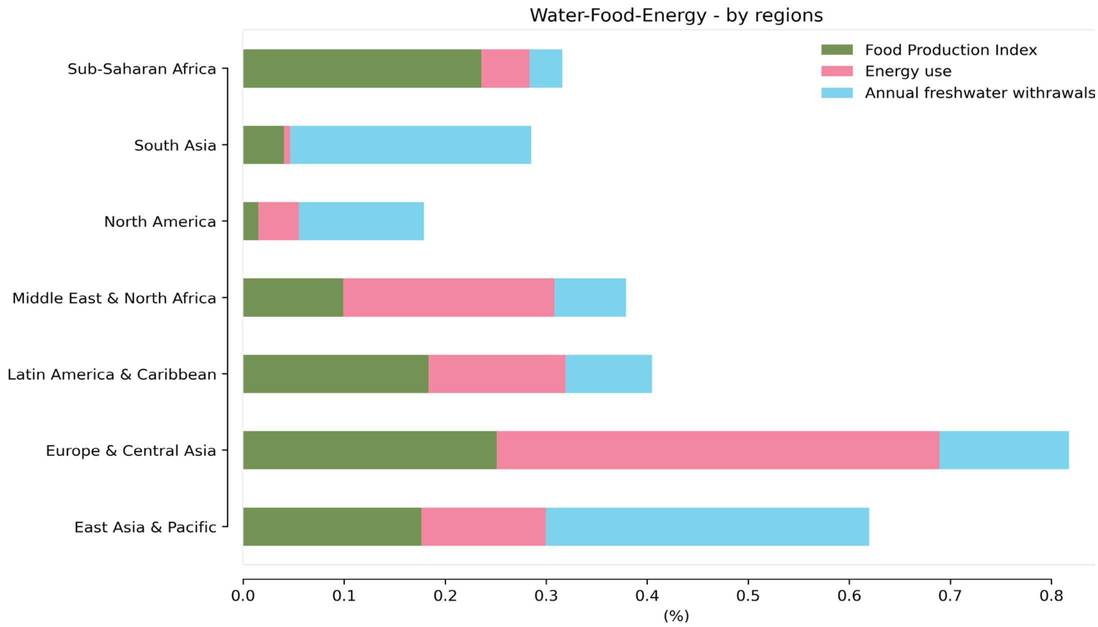

Figure 1 Water-energy-food consumption worldwide (Data source: world Bank).

Food security is defined by the Food and Agriculture Organization of the United Nations (FAO-UN) as "availability and access to sufficient, safe and nutritious food to meet the dietary needs and food preferences for an active and healthy life". Implies that everyone has physical, social, and economic access to enough, safe, and nutritious food that satisfies their food preferences and dietary needs, at all times.

Energy security is defined by the United Nations (UN) as "access to clean, reliable and affordable energy services for cooking and heating, lighting, communications, and productive use", and by the International Energy Agency (IEA) as "uninterrupted physical availability of energy at a price which is affordable, while respecting environmental concerns". The term "energy security" has two connotations whereby the first connotation refers to the diversity of basic energy sources (i.e. energy security improves as diversity rises), while the second connotation implies the reliability of the power system.

2.2 Genesis of the "nexus" thinking approach

The genesis of the WEF nexus can be classified into two categories as displayed in Figure 2. The first category that started in the 1980s followed a two-pronged approach involving only "Food" and "Energy". Alternatively, the second category commenced ten years ago (i.e. 2011) whereby the concept incorporated the "Water" variable. It is interesting to note that in 1983, the first Food-Energy Nexus Program (FEN-P) was initiated by the United Nations University (UNU) to display the mutual-linked issues between energy and food sectors (Sachs and Silk, 1990). One year later, in 1984, Brasilia (Brazil) hosted the first conference on “Food, Energy, and Ecosystems”. Moreover, in 1986, New Delhi (India) hosted the second international symposium on “Food-Energy Nexus and Ecosystems” while in the late 1980s and early 1990s, the term “nexus” was spread and used by the World Bank to connect water, food, and trade (Macalla, 1997). Finally, the “Water-energy-food Nexus” thinking was officially adopted at the Bonn nexus conference in 2011 highlighting a new concept of “green economy”. All these events were accumulated and mutually reinforced to create a holistic framework to necessitate radical socio-ecological change.

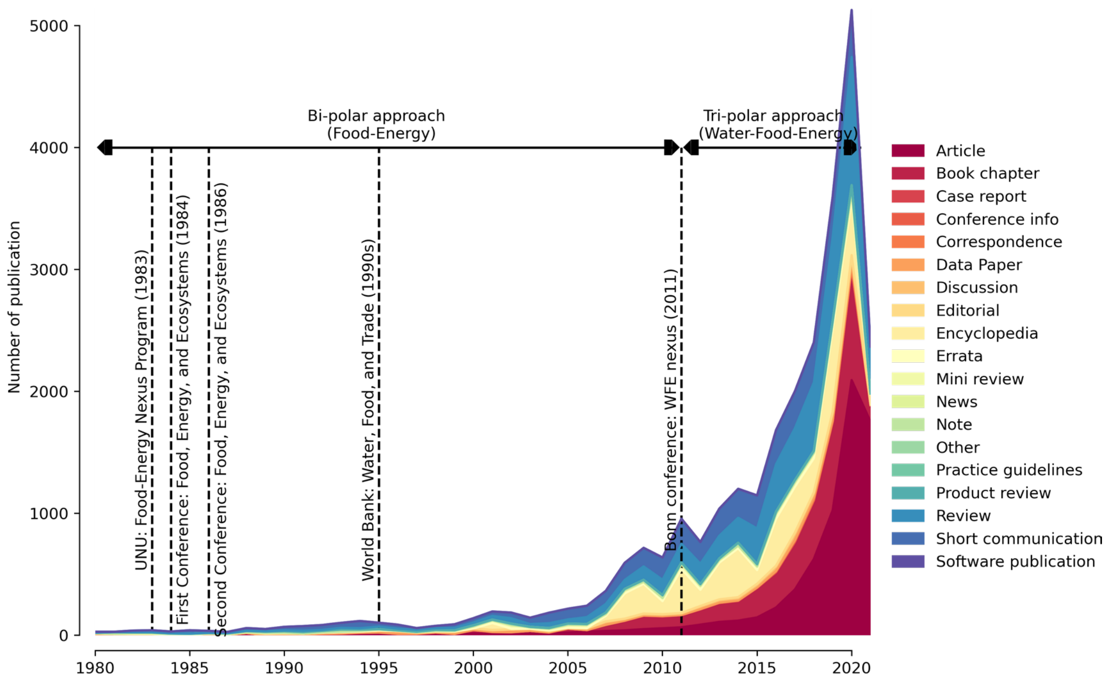

Figure 2 The evolution of publication related to the WEF nexus from 1980 onwards

The WEF nexus approach implies that water, food, and energy security can be achieved simultaneously through the application of integrated management and green-governance across sectors, spaces, and scales favouring ”Green-Economy” which can enable in return more resource efficiency and policy coherence.

Currently, the biosphere is encumbered with four major multi-scalar environmental and socio-economic concerns that must be addressed holistically (McCarl et al., 2017) namely i) climate change augments the frequency of extreme weather events (Konapala et al., 2020) that presents negative impacts on food and water security; ii) population growth associated with an increase in resources consumption (York, 2007); iii) increased affluence pushes consumers to acquire goods and services that have a larger environmental footprint (Wiedmann et al., 2020) which manifest on a planetary scale (Kim and Wolinsky-Nahmias, 2014); iv) Economic growth – the more the industry grows the more it requires raw materials inputs, including energy and water (Kjaer et al., 2019). Therefore, energy, water, and food security should ignore the traditional business as usual approach and incorporate the new concerns and with the global environmental uncertainties.

2.3 General WEF nexus literature

Original research article publications within the WEF nexus research space reveal in the last four years (2016-2020) that there is an annual 5% growth of publications with 2,091 research case studies put forward in just 2020. Alternatively, when review article publications are considered, it shows a modest 2.5% average annual growth within the last four years with about 1,050 comparative case studies review published in 2020. The majority of journals considered in WEF nexus research are sustainability-, environmental-, and management-focused journals Figure 3.

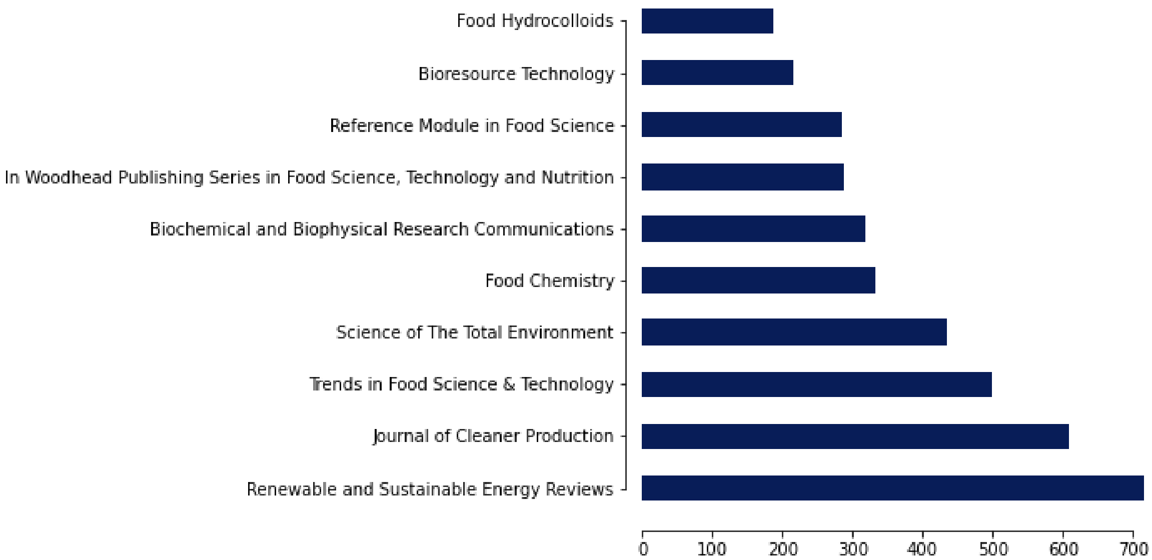

Figure 3 Journals where WEF nexus research is most often published

2.3.1 WEF nexus methods evolution

A critical look at the chronology of methods used over time in the global WEF nexus research space is illustrated in Figure 4, which shows the methods employed since 1992. The top four methods comprise Life cycle analysis (LCA) with 505 case studies, Input-output analysis (IOA) with 474 case studies, Remote sensing with 108 case studies, and Decision Support (DS) with 75 case studies. These methods have been showing increased utilization, and emphasize the measurement of environmental challenges (Hoff, 2011) associated with all life stages of a given resource (water, energy, food) or product (service or commodity) counting in-boundary and out-boundary impacts. The scientific community also recognizes the environmental component constitutes overlapping scales, which gave birth to the concept of transboundary pollution (i.e. pollution of a region in a given country could cause damages to other regions across the world). This pollution is transported via such channels as economic exchanges. This transboundary effect has engendered green models such as the final consumer philosophy or consumption-based account (CBA) (Kitzes, 2013). In the CBA framework, for instance, environmental impacts are allocated to the final consumers in the form of household consumption, gross fixed capital formation, and government consumption (Lenzen et al., 2007). CBA offers a bottom-up approach to safeguard the earth's life-support system as it captures several footprints including biodiversity, water, GHG, and energy (Afionis et al., 2017).

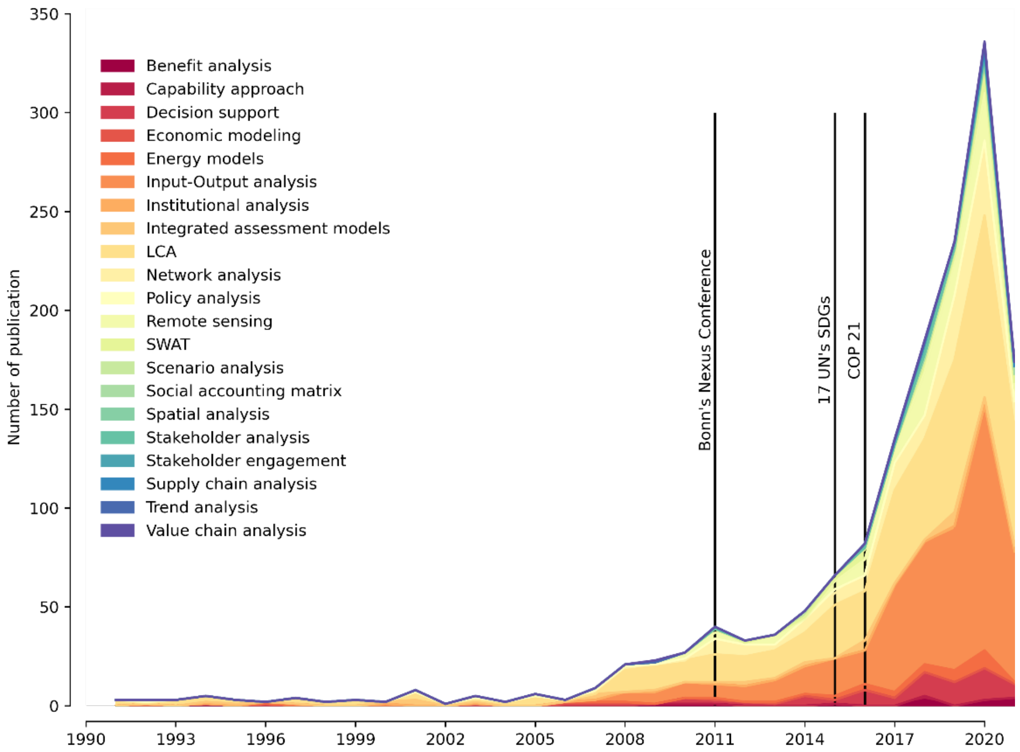

Figure 4 The chronology of the development of WEF nexus methods

Since 2011, WEF nexus approach applications or publications have shown three peaks as displayed in Figure 4. The first occurred as a backdrop of the "The Water-Energy and Food Security Nexus – Solutions for the Green Economy" conference held in Bonn (Germany) in 2011 (Hoff, 2011). Following the Bonn conference, the Sustainable Development Goals (SDGs) revealed the second peak in the WEF nexus approach space. The SDGs have a mission to provide "a blueprint to achieve a better and more sustainable future for people and the world by 2030" (SDGs 2015). After the introduction of the SDGs, the Conference of the Parties (COP 21) was held in Paris (France) in November 2016, which emphasized finding innovative paths to maximize synergies and reduce trade-offs on a city scale as a core element to shrinking urban GHG emissions illuminated the third peak. Therefore, WEF nexus studies are also motivated by global conference trends.

As climate change continues to place severe strain on global societies to be more resilient and sustainable, current WEF nexus studies are including climate sub-system component into their holistic models through the dual-lens of (i) Temperature – climate change is forecasted to increase the earth's surface temperature and therefore many regions will experience extreme weather events with less precipitation and increased surface/groundwater evaporation process, and widespread fires (Bakhshianlamouki et al., 2020) and (ii) GHG emissions – an increase in environmental awareness and the environment as a global space, everyone is urged to preserve. Hence, several models are seeking to shrink carbon emissions in water-related energy studies and vice-versa (Ravar et al., 2020). Since the Water-energy-food Nexus is a new approach for sustainability-directed research (Smajgl, Ward, and Pluschke, 2016) to control water, food, and energy consumption within global societies, a key concern is the growth of the Middle-Class in Africa approaching that of Europe, North America, Latin America, and Asia. In fact, by 2030, there will be almost 5 billion people in this class (Kharas, 2017). Therefore, shifting current lifestyle patterns and shrinking rates of consumption-production is inevitable.

2.3.2 Global contrast: Bias towards the Northern Hemisphere

Analysing WEF nexus-related publications over the last 100 years as illustrated in Figure 5, shows the current dominance of WEF nexus studies in North America (accounting for about 39% of total case studies publication) while Europe follows closely with 24% of total WEF nexus case studies publications to date. The results further confirm the dominance of Northern hemisphere (High-Income countries) regarding WEF nexus research (North America and Europe accounting for about 63% of total WEF nexus case studies publications). The Southern Hemisphere is therefore under-represented in WEF nexus research whereby Africa and South America accounted for just 9% of total case studies publications to date.

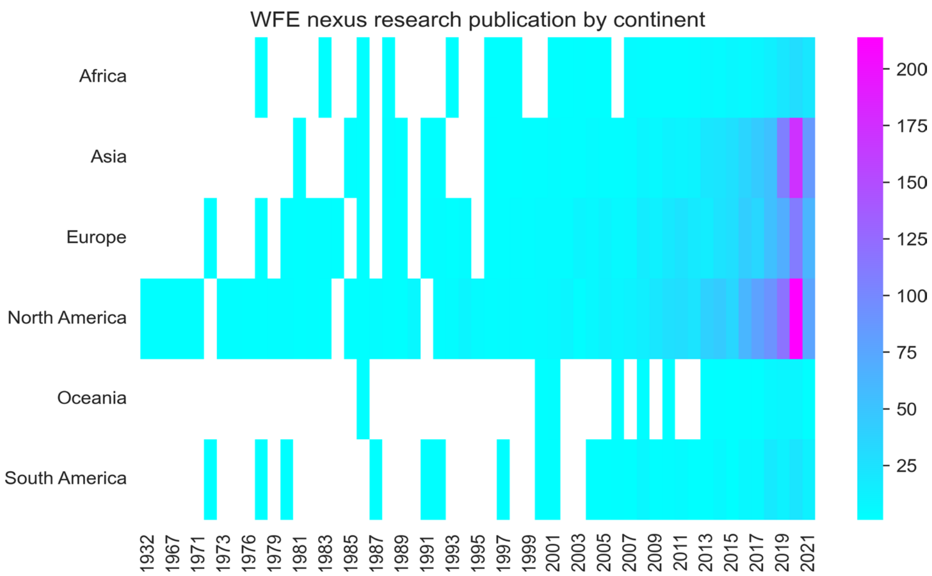

Figure 5 WEF nexus research output by continent

Different regions are facing varied socio-economic development needs which lead to diverse WEF nexus challenges. Thus, each research publication is tailored to the socio-economic and technological advancement of a given region. From preliminary studies, High-Income countries invest more in research to invent new methods or optimize existing ones, while Middle-Income and Low-Income countries focus more on their socioeconomic growth limitations. Hence, with such a situation, Middle and Low-Income countries show unwillingness about joining the climate change mitigation roadmap because it may stifle their socioeconomic growth programs (Network 2010).

Following the trend of demographic growth across the globe, WEF nexus research accounts for global population distribution and should be pivoted towards the Southern Hemisphere to cope with growing population needs Figure 6. For instance, the present global population demographics distribution show that Asia contains about 59.51% of the world's population, followed by Africa with 17.21%, Europe with 9.6%, Latin America and the Caribbean with 8.38%, Northern America with 7.74%, and Oceania with 0.56% (GeoNames, 2021). Hence, by 2030, Africa will be described as the hub of the fastest-growing cities while small Asian cities will host the largest share of the global urban population (Lamb et al., 2019). As such, WEF nexus research in the Southern Hemisphere is underrepresented, presumably due to data unavailability (Musango et al., 2020). Besides the challenge of growing enough food to meet the rising population of Africa and Asia, these regions also face the challenge of coping with their population getting wealthier, and the host cities experiencing increasing infrastructure development and urbanization (Creutzig et al., 2015).

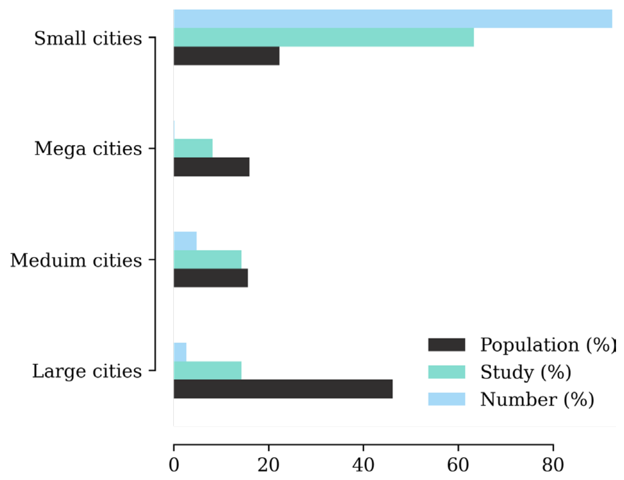

Figure 6 WEF nexus case studies research bias by city size

2.3.3 Modelling the WEF nexus

WEF nexus can be approached from two perspectives. The first perspective occurs through the use of computer-based simulations involving triggering tipping points, whereas the second perspective is a purely analytical approach. Moreover, each perspective has merits and demerits for its use. For instance, a simulation perspective takes a longer time to develop and requires considerable data from different sectors, while the analytical approach requires less data, and it is less complex to carry out. On the other hand, simulation-based studies can capture the dynamics of the WEF nexus, which includes highlighting the role of each system, and how changes in one system affect the other systems, while analytical-based studies can only describe how resources are flowing among sectors.

2.3.3.1 Simulation perspective: White-box approach

Current WEF nexus studies are mostly approached via the simulation-based perspective using different simulation frameworks depending on the study aims and scope. The simulation-based perspective offers the possibility to work on different scales ranging from national to local or even cross-scaling studies. Simulation frameworks used for WEF nexus research are i) System Dynamics Modelling (SDM), ii) Discrete-Event Modelling (DEM), or iii) Agent-Based Modelling (ABM). However, the simulation-based perspective is considered a white-box approach because it aims to examine the internal structures of each system and the role of each processor.

2.3.3.2 Analytical perspective: Black-box approach

Some studies are conducted using the pure analytical perspective such as i) Urban Metabolism (UM), ii) Input-Output Analysis (IOA), or iii) Life Cycle Assessment (LCA). In this approach, there are different software that employs varied methods such as LEAP and WEAP. While the usage of such an approach is easy compared to the simulation perspective, it is unable to capture the dynamic state of the nexus and sectors behaviours. As such, the majority of WEF nexus research uses the simulation-based perspective. However, the analytical-based perspective is considered a black-box approach because it aims to examine the functionality of three systems without peering into their internal structures.

2.3.4 Modelling frameworks for WEF nexus

The water-energy-food nexus aims to understand the water, food, and energy systems by maximizing synergies and minimizing trade-offs. Several modelling frameworks were developed to capture the complexity of the nexus and assist policymakers to design the best actions to regulate these resources. In this section, we provide an analysis of existing modelling frameworks, their evolution, and their future metamorphosis. Our review reveals that the system dynamics modelling (SDM) framework is the mainstream technique used to evaluate cities' WEF nexus. Yet, modelers often aim for simplified models because of (i) the ever-increasing complexity of the nexus, (ii) data availability, and (iii) software's limitations. Agent-Based Modelling (ABM) is showing a promising framework to mitigate the complexity of the nexus and thus shape contextualized policies.

Overall, each framework has its merits, and in terms of the study's goal and desired outcome, the simulation framework chosen may differ (see Table 1). Moreover, we surmise that problem complexity and the model objectives determine the modelling framework used, as against what the modeler is comfortable with. Herein we use the term "modelling" as a proxy for the modelling and simulation-based Data Engineering approach.

Table 1: Summary of the differences between modelling frameworks

	Discrete Event modelling (DEM)	Systems Dynamic Modelling (SDM)	Agent Based Modelling (ABM)
Focus	Queues networks	Flows	Heterogeneous autonomous agents
Time	Discrete	Continuous	Discrete/continuous
Scope	Micro	Macro	Micro/Macro
Nature	Stochastic	Deterministic	Stochastic/deterministic
Adoption	Easy	Easy	Difficult
Development time	Design phase	Conceptual modelling phase	Agents complexity
Variables	Passive	Passive	Active
Life	Expire	Expire	Recyclable
Complexity lens	Events	Stocks	Agents' protocols

2.3.4.1 System Dynamics Modelling (SDM)

Systems Dynamics Modelling was invented in the late 1950s and it involves building causal-loop diagrams (CLD), which aid in visualizing the structure of systems. The CLD is then transformed to a stock-flow diagram (SFD), which helps to quantitatively understand the system's behaviour (Meadows, 2008) and replicate its dynamics. SDM enables the examination of the dynamic behaviour of a given system and its feedback, employing a quantitative lens to produce accurate computer simulations, projections, and perspectives (Qi and Chang, 2011) and trade-off analysis (Sehlke and Jacobson, 2005). The results obtained guide policymakers to discover new leverage points, for maximizing synergies and reducing trade-offs while highlighting the best intervention measures on the system.

System dynamics is utilized to depict how complex systems may develop over time and how their behavioural patterns evolve. System dynamics should not be confused with system theory (Le Moigne, 1994), since system dynamics derives from servomechanisms engineering while system theory is derived from cybernetics (Richardson, 1991). System dynamics applications have three major periods of development. The first period occurred when system dynamics was exclusively reserved to address managerial issues with the publication of "Industrial Dynamics" (Forrester, 1961). The second period corresponds to the expansion of system dynamics application to include the urban environment as a backdrop of the "Urban Dynamics" publication (Forrester, 1970). Moreover, two years later, Meadows and collaborators employed SDM within "The Limits to Growth" report to encapsulate corporate applications (Meadows et al., 1972). Furthermore, the third period of SDM development relates to its application in various sciences including societal, environmental, economics in a nexus approach.

2.3.4.2 Agent-Based Modelling (ABM)

Agent-Based Modelling (ABM) may also be referred to as Individual-Based Modelling (IBM) or Agent-Based Computational Modelling (ABC-M). It is a computer simulation consisting of agents (autonomous, heterogeneous, and dynamic individual entities with a set of rules) (Macal and North, 2005) interacting with one another through communication protocols, and within their recipient environment to study a holistic system. In ABM, the agents and their environment co-evolve. The notion of co-evolving implies that the agents are governed by two characteristics: (i) heterogeneity and adaptability (e.g. behavioural rules) and (ii) stochasticity (e.g. random influences) (Helbing, 2012). ABMs consists of three components: space, time, and agents and ABM applications were triggered as a revolutionary development in social science theory (Bankes, 2002).

Agent-based modelling can be approached through three pathways including (i) General complexity with simple agents: A situation whereby simple homogeneous agents share the same simple agencies that might cause global chaos (cellular automata), (ii) Classical agent-based modelling: Specific complexity with upgraded agents (each entity with its behaviour), and (iii) Artificial Intelligence (AI) through Reinforcement Learning (RL) algorithms: Here, agents can instantly interact with the environment. A major advantage of using ABMs is that they can discover emergent dynamics from examining the behaviour of agents (Bankes, 2002), as "emergence" is a multi-scalar, and multi-resolution concept, and ABMs can depict such complex transformations. ABMs are based on statistical modelling and differential equations which have some limitations such as the imposition of "restrictive" or "unrealistic" assumptions. Linearity, homogeneity, normality, and stationarity are examples of such constraints because ABM simulation does not account for imperfect rationality, the effects of learning and communication, or social structure. Hence, it has not been widely used in public policy recommendations. However, with the spread of computational science, ABMs have been implemented to help and design public policy (Bankes, 2002) especially in designing global climate policy (Robalino and Lempert, 2000). Unlike SDM, ABMs are not a mainstream tool in WEF nexus studies (Mo et al., 2018, Falconer et al., 2020). Current ABMs in WEF nexus research are also oversimplified and do not display the full agents' interactions in a cross-sectorial approach (Magliocca, 2020) as illustrated in Table *1*.

2.3.4.3 Discrete-Event Modelling (DEM)

Discrete-Event Modelling (DEM) or Event-Oriented Modelling (EOM), in contrast to SDM and ABMs, reflect a continuous simulations paradigm. DEM encapsulates entities or agents moving in discrete time, from one area to another based on their attributes (protocol) and available resources (flows), changing the states of the system in the process (Robinson, 2004; Cassandras, 2005). Since there is no change in the system between successive events, the simulation time can leap to the time of the next event occurrence. Therefore, DEM is also referred to as "next-event time progression". DEM developed its taxonomy in the form of event scheduling (ES), activity scanning (AS), and process interaction (PI) ((Miller et al., 2004, Kiviat, 1969). DEMs are ideal for examining the behaviour of complex systems that are composed of a set of connected, stochastically influenced components that change their states in discrete times (Ullrich and Lückerath, 2019). Moreover, the term "Event" in DEM represents an instant in which the state of the system is modified (e.g. can help in triggering tipping points). However, DEM has two types of events: are exogenous and endogenous.

As the modelling process begins by examining the real system a priori, unlike ABMs, DEM entities are parametrized only if they have a strong impact on the system in order to avoid over-complexity. This characteristic makes social scientists choose ABMs over DEM (Ullrich and Lückerath, 2019). Also, entities can be parameterised implicitly or explicitly to mimic the behaviour of the overall system. Ullrich and Lückerath (2019), in their article, emphasized that the modeler must establish in advance, the interactions between specific events and activities based on a simulation's perspective. This involves determining the activities' duration which can be implemented in a deterministic or a stochastic fashion. Besides, DEM can also be understood as a way of sequentially portraying the system's state at each event. DEMs are often coupled with ABMs, resulting in a hybrid modelling framework that mitigates both modelling framework limitations. In essence, DEM provides a platform for displaying a system's state and offers an opportunity to work with stochastic uncertainty (Kuhl et al., 2005). Also, it can be aggregated into distinct categories of schemes based on several intrinsic characteristics, dynamic or static, continuous, or discrete state, time changing or time-invariant, deterministic or stochastic, event-driven, or time-driven, numeric, or analytic (Zeigler and Oren, 1979). Choosing a given modelling architecture is driven by the initial goal of the simulation.

2.3.4.4 System Thinking Modelling (STM)

The System Thinking framework was described in the 1940s, but only gained prominence in the 1990s. System thinking is the theoretical background of the previously discussed simulation frameworks. It involves building casual loop diagrams between system components and their feedbacks (positive or negative) without running any simulation. STM is employed to understand the structure of a given system using graphical language without studying its behaviour and development over time (Le Moigne, 1994; De Rosnay, 2014). A system approach allows one to elaborate a better contextualized strategic vision and sustainable action suited for local concerns (e.g. climate change, WEF nexus). The system thinking approach engendered the "hyper-complex systems (HCS)" employed to approach and mimic natural systems (Bak, 2013; Holland, 2000).

STM has known three key developmental periods. Firstly, between the 1913s and 1920s, A. Bogdanov published three volumes of the "Universal Science of Organization". The second key period occurred in 1949 when Norbert Wiener published the "Cybernetics or Control and Communication in the Animal and the Machine" (Wiener, 1948). The book provided the platform for the emergence of the concept "black box". The third key period was in 1973 when Ludwig Von Bertalanffy published the "General system theory" (Von Bertalanffy, 1973) which considers the components of a given system in a co-evolutionary process. Furthermore, STM has two major periods of utilization. The first period was in the 1950s, borne from structuralism, cybernetics, and information theory which centred on concepts as structure, information, regulation, holism, and organization. The second period occurred in the 1970s and 1980s. Here, two essential key concepts were integrated including communication and self-organization (autonomy). The new architecture of systems opened the door to the notion of open systems and their capacity to self-organize.

Revolutionary modelling frameworks develop from less significant frameworks (Figure 7). The significance of a specific modelling framework is approached by its application and ability to suit the needs of the science that utilizes it, rather than the technical virtuosity of its invention, which varies from field to field (Bankes, 2002), but also on the described phenomena, model objective and desired accuracy. As such, we can conclude that, according to Figure 7, WEF nexus research is focusing on two major modelling frameworks: System Dynamics Modelling (SDM) and Agent-Based Modelling (ABMs). Note that SDM represents the mainstream framework for WEF nexus research worldwide.

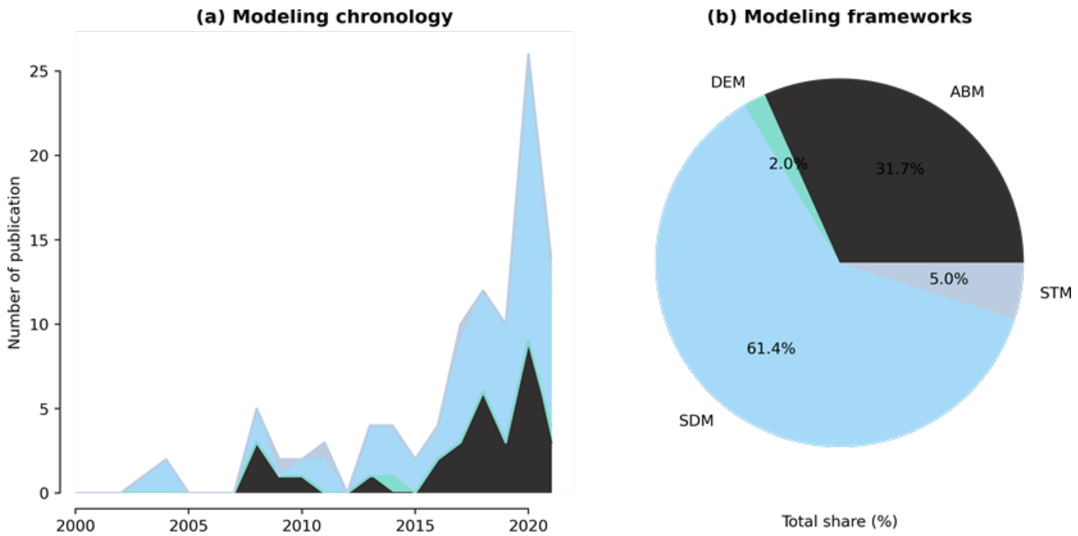

Figure 7 The prevalence of WEF nexus modelling frameworks

As illustrated in Figure 7, SDM is receiving the most attention from researchers for simulating resources production/consumption and urban dynamics (with 62 case studies using SDM compared to 31 case studies using ABM). ABM has some disadvantages when compared to SDM, in the sense that ABM requires a lot of data for model calibration (Gebetsroither-Geringer, 2014) which increases exponentially with the model sophistication and the final model output is obscure, exhaustive, and difficult to communicate (Sustainability for Water, Energy and Food 2021). Additionally, the output of ABM is hard to evaluate while requiring more effort to validate (Werker and Brenner, 2004; Fagan, Reuter, and Langford, 2010).

Unlike SDM and DEM, ABMs require a longer time for model development. Moreover, Forrester (1961) and Forrester, 1968 highlighted that the methodology provided in SDM is very well suited to estimate complex feedbacks of a given system in constant interaction. However, Nikolic et al., 2013, Yang et al., 2018 and Khan et al., 2017 mentioned several limitations using of SDM for modelling spatial heterogeneity which reduces the effectiveness of the integrated resources management approach.

Conversely, SDM is based on intensive data requirements compared to the Long-range Energy Alternatives Planning (LEAP) (SEI, 2021a) and Water Evaluation and Planning (WEAP) (SEI, 2021b). Yet, SDM is more powerful in terms of simulation feedback compared to combined LEAP-WEAP models (Lin et al., 2019). Helbing (2012) stressed that equation-based models (SDM and DEM) are not fully applicable to social sciences, as social behaviours were not created through mathematical equations. She added that ABMs are more suited to socio-economic systems corroborating other studies (Gilbert and Troitzsch, 2005; Epstein and Axtell, 1996; Conte, 2007; Jennings, 2000; Uhrmacher and Weyns, 2009). In addition, according to Helbing, 2012 and Helbing and Balietti, 2010, ABMs are ideal for displaying interdependencies of human activities. Hence, such models are exceptionally suited for systems' sustainability and resilience studies. Consequently, the reason system dynamics may be getting more attention from scholars is its "computational efficiency". For instance, traffic flows cannot be well represented using agents, but instead with system dynamics (Treiber et al., 2000). The utility of ABMs is tilted towards the understanding of the effect at the individual agent level (i.e. integrating human behaviour) on the global level such as social learning, adaptive behaviour, and technology adaptation while SDM is more attuned to understanding the function and behaviour of the whole system.

According to Magliocca (2020), the current implementation of ABMs in the WEF nexus does not incorporate agents' interactions, nor utilize existent behavioural theories for agent decision-making. Models are often designed with data limitations, thereby not being fully comprehensive or sufficiently conclusive. The authors also raise the issue of "...agent representations lacking explicit decision-making processes for social interactions", knowing that social interactions are important for influencing demand/supply chains, consumption/production, and pro-sustainability behaviours (Kaiser, et al., 2020; Pfenninger, Hawkes, and Keirstead, 2014; Koch et al., 2019).

Both SDM and ABM can display the properties of the entire system rather than the properties of the components of the system, which may lead to misunderstanding the final goal, as the behaviour of the holistic system cannot be described solely by the behaviour of its components (because the whole does not equal to the sum of the components) (De Rosnay, 2014).

According to Figure 8, we notice that the most used simulation framework in WEF nexus case studies is system dynamics (9), followed by agent-based modelling (7) highlighting that the SDM is the mainstream modelling framework for cities' WEF nexus, worldwide. On the one hand, Asia (India, Iran, Pakistan, Singapore and Hong Kong), Africa (South Africa), Oceania

(Australia), and South America (Argentina) focus on the medium, large, and megacities using SDM. On the Other hand, Europe (United Kingdom, Italy, and the Netherlands) and North America (United States) focus on small cities using agent-based modelling. SDM is flexible in its application regarding city size, therefore, it is more suitable to use SDM to study the nexus in medium, large, and megacities. Unlike ABM which requires setting, a priori, the communication protocols, and the set of rules for each agent, as such, the WEF nexus using ABM tend to focus on small cities because they have fewer agents, and socio-economic dynamics in small cities are less complex compared to megacities. This leads to fewer communication protocols and sets of rules for agents. We can conclude that with the increase in city spatial boundaries and socio-economic metabolism complexity, modelers tend to prefer the SDM framework over ABM. Moreover, ABMs are currently only applied to small cities because they have lower complexity.

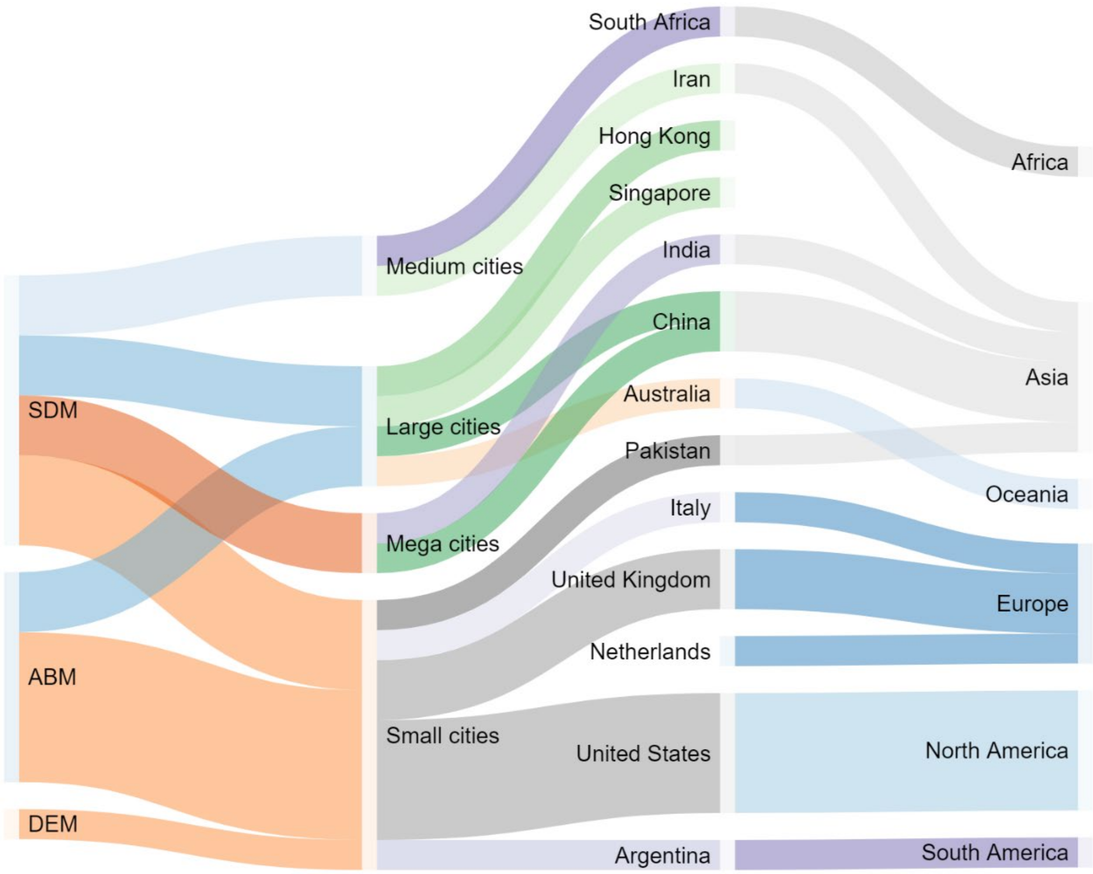

Figure 8 Simulation frameworks distribution by city size and continent

Notice that ABM is an advanced simulation framework compared to SDM and is considered to be the state-of-the-art simulation framework. A critical look at Figure 8 shows that High-Income countries are employing ABM, while low-income and middle-income countries are using system dynamics modelling. This may be explained by the financial capacity for each country, city, or project. In fact, application of ABMs requires a higher engineering skill, computational capacity (cluster computer), and available funds to support a given project.

2.3.5 The Future of WEF nexus modelling frameworks

Water-energy-food system nexus represent overly complex three-dimensional phenomena linking: "time", "space" and "behaviour" (spatio-temporal behavioural pattern formation for a given system). With the increasing complexity of the world, there is a need for new powerful and insightful modelling approaches that work in a holistic fashion. Old modelling approaches can no longer mimic present-day complexity, and several challenges are encountered ranging from design limitations, data availability and quality, and model scalability to incessant software breakdowns (Macal and North, 2005).

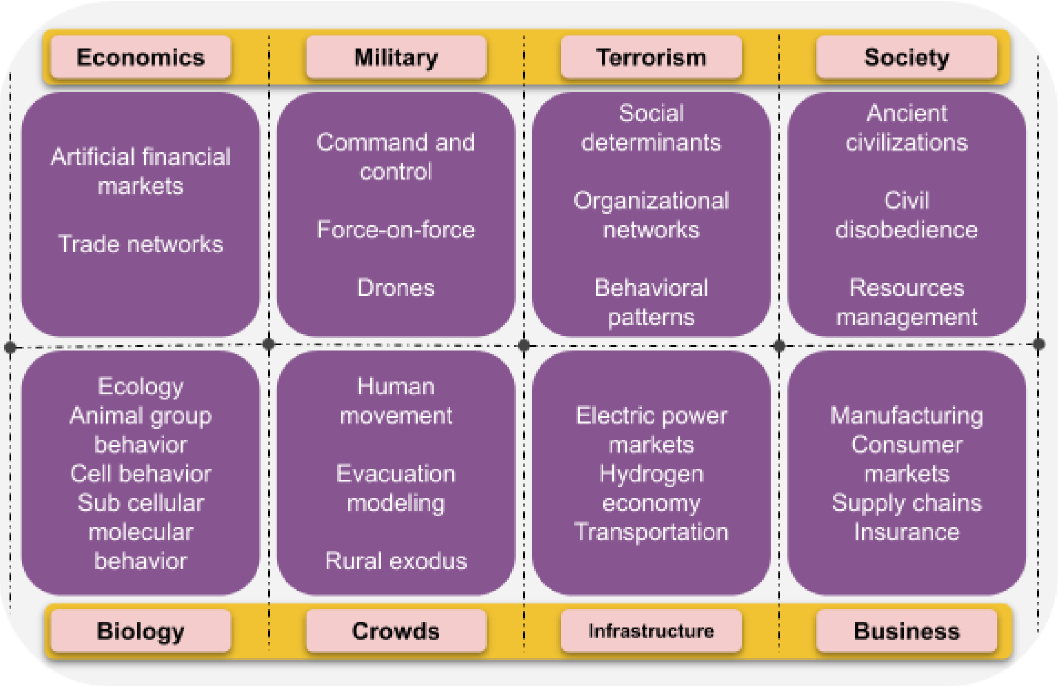

Figure 9 Agent-Based Modelling applications

The future of WEF nexus modelling research will have to encompass two main constraints: (i) Nexus output data representation: the output of any developed model regardless of the sophistication spectrum, and modelling framework should not simply exhibit the output data as the sum of resources' output (water, energy, food) aggregated by sectors (agriculture, industry, domestic, transport), which does not fully fall into a "nexus paradigm"; (ii) Apprehending complexity: future models will have to incorporate a larger set of variables with their evolution, and communication protocols. It is clear that there will be more than one single framework that can address all types of complexity, especially hyper-complex ones, independently of their nature (Helbing, 2012). Current WEF nexus models using system dynamics framework present several limitations, which can in return over-simplify the intricacy. To address such constraints, ABMs have the ability to be the dominant future modelling/simulation frameworks because of their ability to represent all the variables (yet, not aiming for over-complexity), especially with the improvements of computer hardware, and optimization algorithms.

If the inherent complexity and computational requirements of ABMs can be overcome, this framework offers a useful set of features such as flexibility, modularity, expressiveness, and running in a parallelized fashion (Helbing et al., 2010). It can also display the integration between the micro and macro-scale considering: (i) structure: heterogeneity of agents, spatio-temporal variability, and perturbations, and (ii) features: time scheduler, communication protocols, flexible interactions topologies, different structures, and architectures. Facilities that can encapsulate the agent's state, both characteristics can alter the system's behaviour and substantially swop the outcome of the system (Helbing and Balietti, 2010). ABMs can be reinforced with a Complex Adaptive System (CAS) to solve problems with dynamic, interconnected variables comprising multiple objectives and considerable uncertainty (Cheng et al., 2015). Some adaptive behavioural methods, such as genetic algorithms and neural networks can further enhance ABMs, as can the automatic integration of Geographical Information Systems (GIS).

The ABM framework was implemented to simulate the "Beer Game" (originated from system dynamics). The model was able to replicate the SDM's results, and portray the "Bull-Whip" effect (Sterman, 1989). This example demonstrated how ABM can be used to investigate hyper-complex real-systems, particularly those related to WEF nexus. ABMs are currently utilized by most of the science' fields as portrayed in Figure 9, because of their ability to examine a given system in a cross-sectoral and cross-scale approach. For instance, in social sciences, Hebert Simon (1990) developed the "satisficing" notion to describe how people and organizations behave in the real world and whether they are optimized. In economic science, a new discipline known as "Agent-Based Computational Economics (ACE)" has evolved, focusing on the implementation of ABMs in economic systems (Tesfatsion, 2002). Anthropologists are utilizing large-scale ABMs to model the emergence and demise of ancient civilizations such as the case of Mesopotamia (Middle East – current Iraq) (Christiansen and Altaweel, 2004) and Anasazi (in the Southwest United States) (Kohler et al., 2005).

In social science, agents may represent people or a group of individuals, while their interactions/communications portray social relationships (Gilbert and Troitzch, 1999) and their interaction with the host environment (nature) portray social metabolism (Fischer-Kowalski and Weisz, 1999) by which population maintains and thrive. Accordingly, people and their social interactions may be modelled at some reasonable level of abstraction for specific and well-defined aims. In contrast to the more general goals of ABM, current WEF nexus models based on ABMs have a limited scope for representing agent actions (Cheng et al., 2015). Macal and North (2005) raised two important questions: "How much do we know about credibly modelling people's behaviour?" and "How much do we know about modelling human social interaction?". In furtherance, Kuhl et al. (2005) added some relevant social ABM-related questions: "How much information are people able to process in the given amount of time for making a decision? What key factors and indicators do people consider in making their decisions? How do people's past experiences enter their decision-making process? Which strategies do people formulate that are most effective?". It is critical to model the autonomous heterogeneous agents at a fine level to be able to model a fully comprehensive WEF nexus for a given city because the ecological transition is only applicable at the individual level (e.g. empowering societies to rethink their nexus).

Modelling human social behaviour and individual decision-making at the individual scale are fundamental pillars of ABMs; it's not only about building and comprehending "artificial" agents. As a result, it becomes necessary to depict social interaction, collaboration, group behaviour, and the formation of higher-level social structures (Bonabeau, 2002). Specific ABM frameworks provide a significant benefit over traditional modelling frameworks, such as Belief-Desire-Intent (BDI) (Rao and Georgeff, 1991) and Behaviour-Oriented Design (BOD) (Bryson, 2002). Because the whole system behaviour is not equal to the sum of the behaviour of the individual agents, agent simulation can be used to examine how patterns and organizations emerge, as well as how system behaviour emerges that is not observable from individual agent behaviours. Social cognitive science is currently pushing forward ABMs framework by expanding the ideas of cognitive science's notion of agency to social settings (Bandura, 1999). Cognitive scientists are developing agent-based models of emotion, cognition, and social behaviour based on the concept that a person's emotional state affects their conduct as well as their social interactions (Gratch and Marsella, 2001). The goal is to create synthetic agents that can capture the intricate interactions between emotion, cognition, and social behaviour which can in return offer a great modelling approach for WEF nexus.

Despite the current limitations of ABMs, it will be prevalent for studying techno-socio-economic-environmental systems because of their three advantageous features: (i) Modelling not only heterogeneous agents but also participatory agents which can be implemented to mimic and develop new agent-level behaviour; (ii) metropolitan statistical areas (MSA's) new capabilities in harvesting and mining real-time data, known as "nowcasting" or "reality mining" which can reduce measurement time (Magliocca, 2020; Henderson et al., 2012), and implement models simultaneously in parallelized forms: real and simulated. In this context, Helbing (2012) subscribed that researchers should be able to conduct novel interactive socio-economic studies, dubbed "Social Supercomputing". This innovative approach would allow for the cross-collaboration of many types of data (geographic, demographic, and socioeconomic) at various scales and levels of detail; (iii) ABMs are developed as a large-scale model which includes hierarchical modelling and model reuse (Silver et al., 2011) which implies that the model can be recycled or re-appropriated to other problems. In contrast to ABMs, almost all system dynamics models have a short life cycle determined a priori (design, evaluate, implement, perish).

2.4 Urban WEF Nexus literature

2.4.1 Mapping global urban WEF nexus research

Global WEF nexus research tends to focus more on small cities accounting for 86% of studies across all regions (Figure 10). This focus may be as a result of small cities representing 92.4%

of the total number of cities across the globe while medium cities, megacities, large cities each account for 4.79%, 2.63%, and 0.15% respectively. However, the total population in each of these categorized cities portrays a different story. For instance, large cities host 46.1% of the global population, followed closely by small cities with 22.3%, then megacities and medium cities containing 15.9% and 15.7% respectively (also see Figure 6). In this study, the metric employed was able to identify the most intensive WEF nexus research-focused cities (see Figure 11). The results show that for the case studies of large cities, the top three cities are Singapore city (Singapore) with 18 direct WEF nexus research outputs, followed by Washington (USA) with 17 case studies, and Hong Kong (China) with 15 research items. On the other hand, when megacities are considered, the algorithm shows the city of Beijing (China) as the dominant with a total of 31 case studies, closely followed by New York (USA) with 28 research items and Paris (France) with 27 case studies. However, the results negated the notion that WEF research output should increase with population increments. For instance, medium cities (i.e. 0.3-1 million inhabitants) and large cities (1-10 million inhabitants) should have received more research attention, since these cities are growing at an accelerating rate, especially, in Africa, Latin America, and Asia.

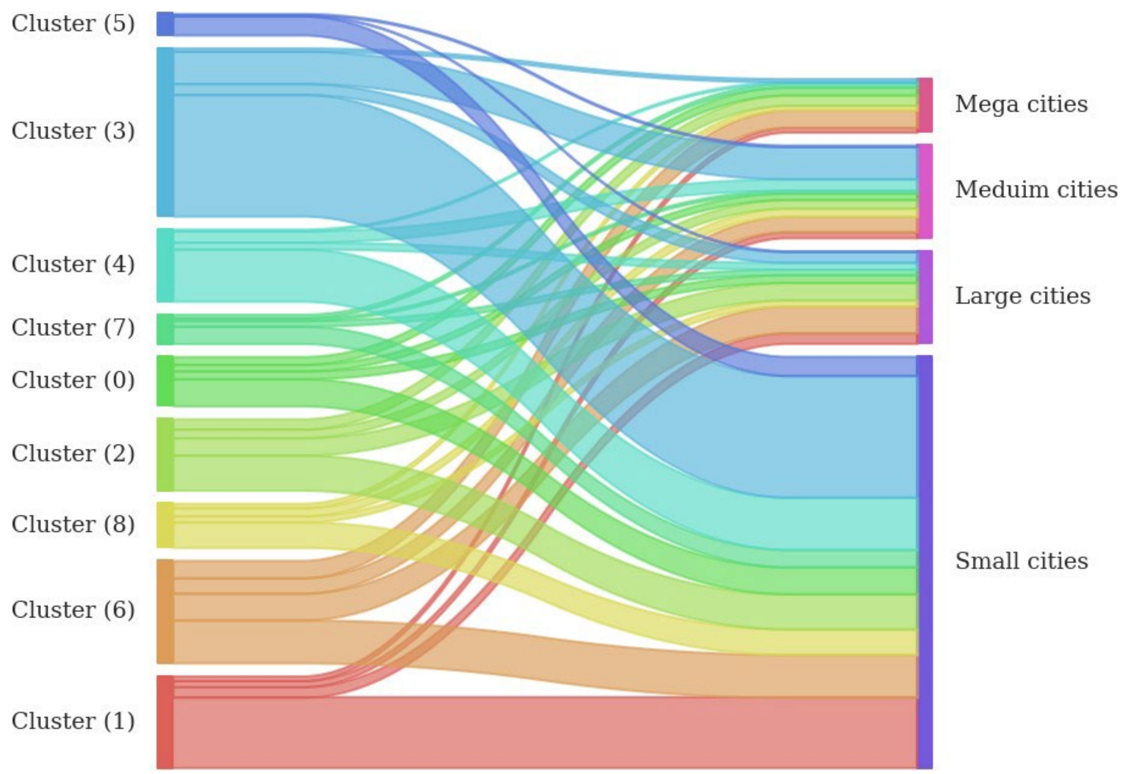

Figure 10 Mapping WEF nexus research according to city size

WEF nexus research as discussed in earlier sections is an umbrella term comprising diverse study domains regarding current global-local concerns (socioeconomic and environmental sustainability), sectors decomposition (transport, waste, household, agriculture), policy and governance level (citizens implication, the role of mayors, environmental taxes), optimization process (energy grid, soil additives, water pipelines) and domains (urbanism, ecological habitat, diverse ecosystems). Scoping and filtering global WEF nexus research by type of cities and geographical location (Figure 11) is relevant to understand the challenges researchers and policymakers face within a given context with determinant parameters, and how the poorest cities with less urban/rural intelligence (managing capacity), following a similar context, may utilize the same policy recommendations of another city (also referred to a generalization, upscaling or blueprinting).

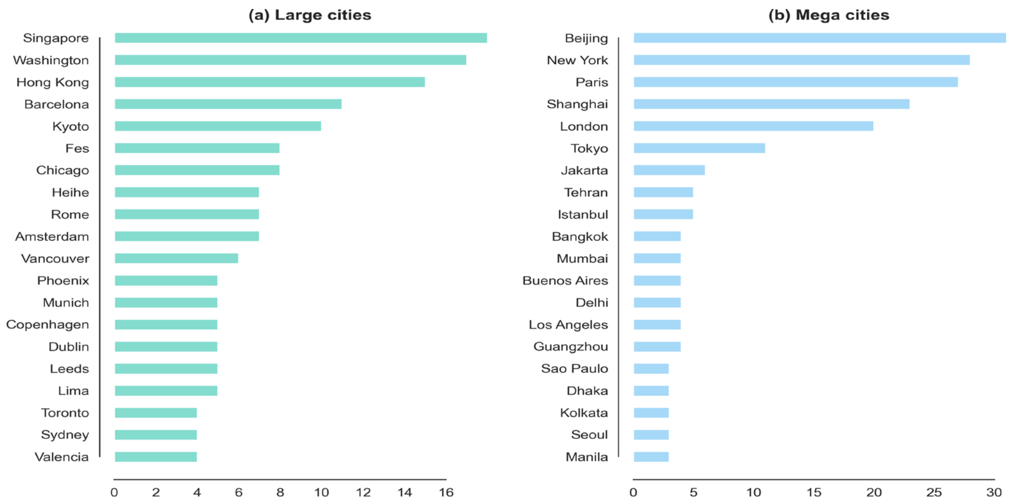

Figure 11 Most prevalent mega- and large cities on which WEF nexus research has been conducted

WEF nexus challenges may be categorized into two branches that are wide-ranging and involve identifying the characteristic context for a region. While wide-ranging challenges imply all cities face the same generic WEF nexus issues such as water scarcity, increased energy consumption, affluence, urban population, and the ongoing trend for infrastructure and urbanization, which places severe strain on the global WEF networks, on the other hand, identifying the challenges regarding the context characteristics, such issues as mirroring climate change issues and local climate mitigation actions are mostly tailored to city typologies, local culture and beliefs, energy/water price, infrastructure development level, environmental education, and awareness. Herein lies a window of opportunity, whereby fully scoping WEF nexus studies and clustering them according to topic contents, type of cities, geographical location, GDP per capita, income/expenditure level could represent a stepping stone towards reproducing a similar policy in a location which has not yet been documented or is underrepresented, including Latin America and Africa.

Figure 12 maps the compiled topic clusters of case studies concerning WEF nexus regarding city sizes. The topic "Water resource management in irrigation Water footprint" (Cluster 3) is the most studied topic globally, with about 750 case studies showing the importance attached to sustainably meeting water demand and supply needs. Moreover, the WEF nexus is a core element in defining current global change, and by far, water ("water efficiency") seems to be the core opportunity to design a holistically integrated efficient system (Hardy et al., 2012), because agriculture requires a huge amount of clean water to produce food. Clean water can be obtained by treating and pumping it using energy, and visa-versa. Water is required to cool energy generators and transfer heat for more energy production. Hence, if we used less quantity of water for agriculture, we reduce the amount of energy used to clean and move it from one place to another. Societies must also recognize and adopt the use of organic wastes to generate energy, which may have a significant impact on the local and global environment, since fossil fuel consumption needs to be decreased to mitigate climate impacts. The second top-most WEF nexus research topic is "Climate change research development Sustainable land-use policies" (Cluster 6) with about 417 case studies. This implies that designing a fully integrated WEF nexus model is geared towards tackling the global challenges of climate change and land-use sustainability patterns.

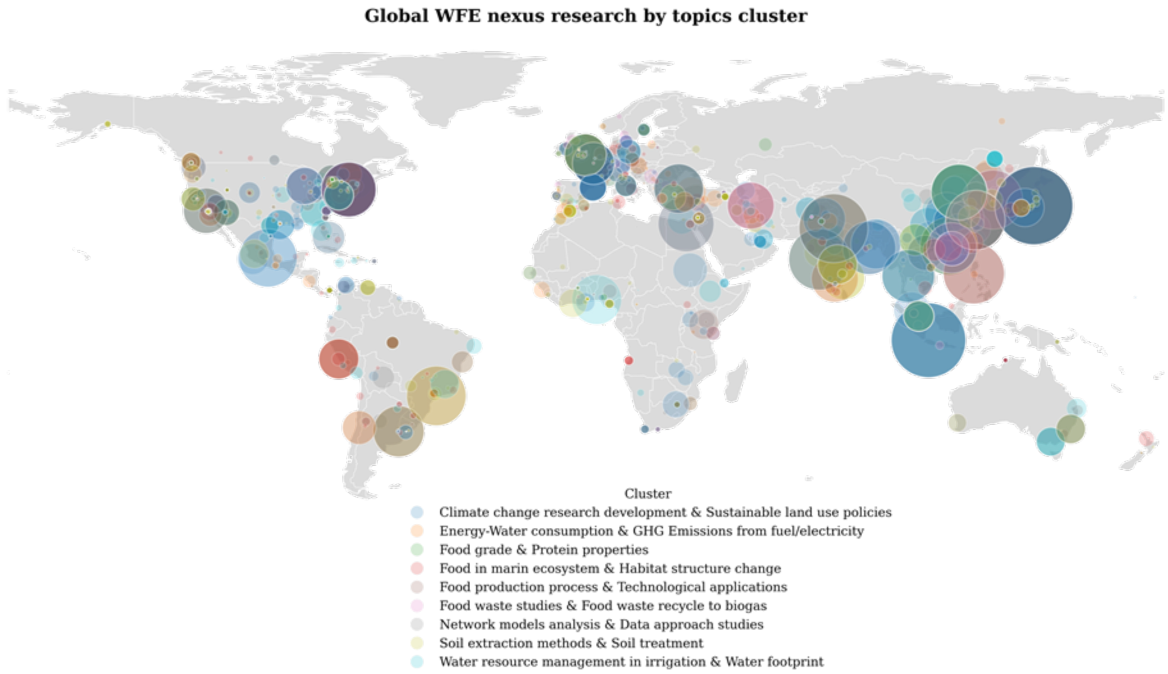

Figure 12 WEF nexus research by city size

The uneven distribution of all topics according to the size of cities further highlights the point that cities, regardless of their size, face similar WEF nexus challenge (food waste, water recycling, the need for biogas production, and water scarcity). However, an in-depth analysis of results do reveal differences: WEF nexus research in small cities is biased to the topic "Cluster 3: Soil extraction methods & Soil treatment" with about 482 case studies, followed by "Cluster 1: Food production process & Technological applications" with an estimated 281 case studies. Large cities tend to shift focus to "Cluster 6: Climate change research development & Sustainable land-use policies" with about 106 case studies followed by "Cluster 2: Water resource management in irrigation & Water footprint" with 69 case studies. On the other hand, medium cities show similar attributes as small cities with a focus on "Cluster 3: Soil extraction methods & Soil treatment" (estimated 128 case studies), closely followed by attention to "Cluster 6: Climate change research development & Sustainable land-use policies" with 45 case studies. In megacities, a similar trend as large cities are portrayed whereby the main emphasis is on Cluster 6 with 69 case studies and "Cluster 2: Water resource management & Water footprint" with 41 case studies. The size of the cities hence affects the WEF nexus research focus which tends to be directed to climate change and sustainability-related studies as the size of city changes.

When the results in Figure 12 are considered on a continent level, WEF nexus research in South America focuses more on topics related to "Cluster 0: Energy-Water consumption & GHG Emissions from fuel/electricity" with 25 case studies. Europe-centric research focuses on "Cluster 6: Climate change research development & Sustainable land-use policies" with 188 case studies. North America concentrates on "Cluster 1: Food production process & Technological applications" with an estimated 258 case studies, while Africa emphasized "Cluster 8: Network models analysis & Data approach studies" with 45 case studies and "Cluster 7: Food waste studies & Food waste recycle to biogas" with 27 case studies. Asia, on the other hand, places more emphasis on "Cluster 1: Food production process & Technological applications" with 198 case studies and "Cluster 6: Climate change research development & Sustainable land-use policies" with 105 case studies. Finally, the Oceania region pivots research towards "Cluster 4: Food in marine ecosystem & Habitat structure change" with 11 case studies and "Cluster 5: Food grade & Protein properties" with 9 case studies.

2.4.2 WEF nexus topics perspectives

The trend of WEF nexus case studies research publication over time according to major complied topics is illustrated in Figure 12. The Figure shows that the most treated topic within the WEF nexus literature space is "Soil extraction methods Soil Treatment" with a total publication, of 750 case studies (accounting for 27% of the total). Furthermore, the second studied topic centres "Climate change research development Sustainable land-use" with 417 case studies (15%), followed by "Food production process Technological applications" with 379 case studies (13.6%). The topic clusters "Food in marine ecosystem Habitat structure change" and Water resource management in irrigation Water footprint" each account for 11.2% of total publications while the remaining clusters "Energy-Water consumption GHG Emissions from fuel/electricity", Network models analysis Data approach studies", "Food waste studies Food waste recycle to biogas" and "Food grade Protein properties" respectively contribute 7.5%, 7%, 4%, and 3.3% to the total WEF related case studies so far.

Figure 13 displays how different research topic clusters developed over time. Three major WEF nexus topic clusters showed sharp increases in output recently: "Cluster 0: Energy-Water consumption & GHG Emissions from fuel/electricity", where publications grew by 9% in 2019, and 24% in 2020. Likewise, "Cluster 7: Food waste studies Food wastes recycle to biogas" publications rose by an average of 18% from 2018 to 2020, and "Cluster 6: Climate change research development & Sustainable land-use" publications increased by 5.9% in 2017, 9.8% in 2018, 10% in 2019, and 19% in 2020. Future WEF nexus research will focus on how to maximize synergies between the water-energy-food system in a cross-sectoral fashion, while integrating climate change and sustainable land-use patterns, and therefore tackling the global challenge of climate change.

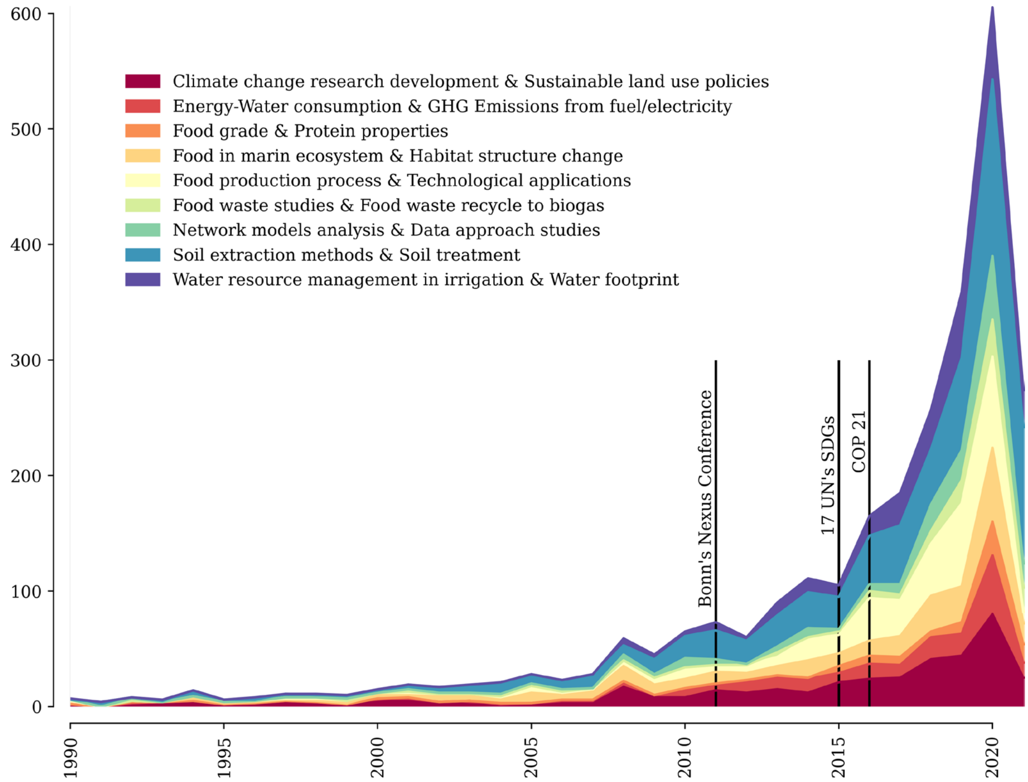

Figure 13 Global WEF nexus research topic content evolution

Current WEF nexus research is currently almost exclusively focused on humankind as a species when evaluating resources availability and demand, with few studies including environmental impacts including land use and climate change (Bakhshianlamouki et al., 2020, Boluwade, 2021). However, evidence shows the approach of the sixth mass extinction of several species on the biosphere, where it is expected that wildlife will decrease by 67% by the end of the decade (Beaufort et al., 2016), and there is no sign that this rate will halt (Barrett et al., 2018), even though this phenomenon can be prevented by conserving and restoring nature (Almond et al., 2020). Therefore, biodiversity must be included as a core element for any WEF nexus model, knowing that biodiversity is a core pillar in the UN 17 SDGs, as captured within goals 14: Life below water and 15: Life on land. Unfortunately, almost all WEF nexus models focus only on human resources' demand and supply and consistently exclude wildlife. This situation may be attributable to the current modelling framework limitations such as data availability, and software barriers.

Exploring Water-energy-food nexus case studies, in a big-data-driven fashion using quantitative analytical tools, can increase our understanding of the challenges/solutions cities are facing across the globe and the contextual nature of WEF nexus governance. Results showed several key points that may help better understand how societies are shaping the global environmental future concerning (i) the studied region, (ii) type of cities, (iii) Income level, and (iv) methods used for case studies, seeking to assess and allocate environmental degradation, through a trans-boundary lens, from producers to final consumers. The results obtained highlight Life Cycle Analysis (LCA) and Extended-Environmental Input-Output Analysis (EE-IOA) as the most relevant methods used to assess water-energy-food nexus operations, worldwide. Yet, we stress that research on cities from low and middle income countries, especially from the Southern Hemisphere, are systemically underrepresented in literature.

2.5 WEF nexus challenges in the City of Cape Town

2.5.1 Presentation of Cape Town's dynamics

Water supply to agriculture, industrial and domestic uses, are all dependent on energy supply, both existing sources of electricity as well as the growing share of renewable electricity. Cape Town, therefore, needs to develop a resilient, quantitative water plan to guide medium to long-term investments in additional water supply capacity, by ensuring a balanced supply and utilisation of natural resources. This project considers interlinks between water supply, energy supply, and agriculture within the WEF-nexus, in this dynamic environment. Planning sustainable urban development requires a balanced supply and utilisation of natural resources through systematic thinking, to ensure that all components of the urban WEF-nexus function effectively. A lack of, or incomplete, understanding of the dynamic interconnectedness of WEF components will have adverse consequences: Food production requires water and energy, water supply and treatment need energy, while energy production also consumes water.

There are ongoing resilience initiatives within the City of Cape Town to forecast future water supply and demand, and to supplement current water supply systems. However these have two key shortcomings: (i) they largely focus on the water supply system with some consideration of the impact on agriculture, but the impacts on energy supply are often not considered, and (ii) some interventions are 'stop-gap' have since been discontinued such as decommissioning of desalination operations after the recent drought. There is therefore a need for a holistic system description for the City of Cape Town, which explicitly accounts for all three WEF-resource systems, with integrated planning for the future. Furthermore, estimates of future rainfall that account for climate variability are needed to enable the planning of future resource requirements. Developing such models and capabilities will enable building resilience into the City's supply systems. This directly impacts the City's strategy of taking into account interactions between various sectors and building long-term resilience into its operations and the need for increased collaboration with external experts.

2.5.1.1 Water

The Day Zero water crisis was a time of acute water scarcity in the Western Cape area, with the City of Cape Town being severely affected. The Cape Town water crisis peaked between mid-2017 and mid-2018 when water levels fluctuated between 15 and 30 percent of total dam capacity. In late 2017, the first discussions of planning for "Day Zero" emerged, a colloquial term for the day when the water level of the major dams that feed the City might fall below 13.5 percent (Cassim, 2018; Poplak, 2018). Level 7 water restrictions would begin on “Day Zero,” when municipal water supplies would be substantially shut off and inhabitants might be forced to queue for their daily allotment of water. If this had happened, Cape Town would have been the first large city in the world to run out of water (Booysen et al., 2019). The water crisis happened at the same time as the Eastern Cape drought, which is still prevalent as of 2021.

In March 2018, the City of Cape Town introduced severe water restrictions to reduce water use. This effort led to a 50% reduction in daily water consumption equivalent to about 500 million litres. The City’s projection for “Day Zero” was postponed due to a change in consumer behaviour and a decrease in water use, and heavy rainfall beginning in June 2018 helped dam levels recover. With dam levels nearing 70%, the city began relaxing water restrictions in September 2018, signalling that the worst of the water crisis was passing (Pitt, 2018). When dam levels hit 95 percent in 2020, it effectively ended the drought and the resulting water deficit.

2.5.1.2 Food

Horticulture – fruit, wine, and vegetables – are the province’s main exports. It also raises cattle, meat, and dairy products, as well as crops such as wheat, barley, and canola. The amount of water available for irrigation varies based on the catchment region. For example, irrigation consumes a third of the water in the Western Cape Water Supply System, which also feeds the city of Cape Town. However, in the Breede-Gouritz catchment region, south of Cape Town, approximately 75% of the water is used for agriculture. Agriculture has a significant role in the province’s socioeconomic structure, and decreasing water availability to agriculture can have severe impacts on rural areas where a large proportion of economic activity is dependent on agricultural production. The competition for water between agriculture and other uses is also prevalent in other parts of South Africa. Overall, the agricultural sector provides 2% to South Africa’s national GDP, with the Western Cape accounting for more than 20% of it.

2.5.1.3 Energy

The City of Cape Town’s State of Energy Report (2015) shows that Cape Town’s energy use is dominated by petrol (31%), electricity (29%), and diesel (22%). The transport sector dominates energy consumption by 64% of total energy, followed by Commercial (13%), Residential (12%), Government (1%), and Agriculture (less than 1%) sectors. Cape Town Energy and Climate Change Strategy assert that the City’s transportation system is becoming increasingly inefficient, with a lack of public transport and a rise of private cars leading to congestion and GHG emissions. Total final energy consumption in Cape Town for 2012 was estimated at 158 685 055 GJ, which translates to global greenhouse emissions of 21 282 238 tCO_2.

In terms of the energy supply and according to Cape Town Energy and Climate Change Strategy, Cape Town's energy supply is significantly dependent on imported petroleum products and coal-fired electricity with a very small contribution of wind energy from Darling Wind and rooftop photovoltaic (PV). Cape Town also mirrors the national energy mix by which Eskom generates 95% of the power, whereby 91% is coal-based and 4% is nuclear. Renewable-energy generation from Private Power Producers accounts for around 5% of capacity, and another 1 512 MW is produced by a commercial operation that was also added to the grid. Considering carbon emissions, the City of Cape Town transport system dominated carbon inventories (33%), followed by the Commercial sector with 26% of the total city's carbon emissions, residential (22%), and Industrial (11%) sectors. Government, Agriculture, and energy losses accounted for 2%, 1%, and 5% of energy respectively.

2.5.2 Local resilience strategies

2.5.2.1 Cape Town Resilience Strategy

The Cape Town Resilience Strategy provides general recommendations on the possible future of the City of Cape Town. While it provides a panoramic view of the status quo profile of the city, it remains ineffective in terms of the usability of such recommendations. The resilience strategy focuses more on qualitative parameters rather than quantitative measurements, and as such the recommendations proposed seem to be fragmented in scales and spheres (sectors, actors, governance) that constrains the contextualised aspect of the strategy (for instance, the initiative of "Be a Buddy"). In saying this, it is acknowledged that the City of Cape Town is one of the leading cities in South Africa and Africa in terms of developing strategies for resilience and sustainability, and their efforts are not portrayed in a negative light; rather, the comments serve to highlight where they can be improved in future.

2.5.2.2 Cape Town Water Resilience Strategy

Cape Town's Water Strategy is built on five pillars. The first is to examine the possible ways forsafe access to water and sanitation. The second is based on how to possibly reduce water waste and promote judicious water use. The third shows how to provide a sufficient and reliable water systemfrom diverse sources. The fourth shows how to share benefits from regional water resources and increase synergies among policy-makers, while the final pillar displays how the city aims to achieve a "water sensitive city" by 2040. The majority of the recommendations suggested within CT's Water Resilience Strategy can be helpful to build diverse scenarios geared towards creating a water-sensitive city.

2.5.2.3 The 100 Resilient Cities: Case of Cape Town

The 100 Resilient Cities project is an international program that has been tested on global cities. It was developed and tested on several developed and developing cities such as Cape Town which represents the first case study to deploy CWRF by the 100RC team. The aim is help shape Cape Town to be a water-sensitive city by 2040. However, one major limitation of the 100RC methodology is that while cities of developed and developing countries do not have the same consumption-production profile, the use of one single approach to examine two types of cities dynamics may be inaccurate and insufficient, as each city faces distinctly local WEF nexus challenges. Therefore, it is recommended to establish a specific methodology for each city to capture the resources flow. Scalable approaches are indeed powerful in comparingcities resources flows among final consumption sectors, but they are limited in studying the local dynamics which diminishes its feasibility in terms of policy recommendations.

2.6 Conclusions

To promote economic growth and satisfy social requirements while decreasing local and global environmental consequences, the City of Cape Town recognizes the need to adopt more sustainable methods for its energy production and usage. Parallel to these mitigation measures, a need has been highlighted to reduce climate change's damaging effects on vulnerable populations and ecosystems.

The current and future water supply system of the City of Cape Town, consisting of dams, aquifers, water recycling facilities, and desalination plants, etc. serves an interconnected system of agricultural, urban, domestic and industrial purposes. Water supply is interconnected with energy supply and agriculture (food production) in the so-called urban water-energy-food (WEF) nexus. Both irrigated and rain-fed agriculture play critical roles in the supply of food and economic development of the Western Cape region, of which a substantial portion shares its water resources with the City of Cape Town. The City of Cape Town is prone to periods of drought, as experienced in 2016-2018 when the city came close to "Day Zero". It would have been the first major city on a global scale to run out of water completely. The current and future water supply of Cape Town may be viewed as a finite resource, based on rainfall, groundwater flow, storage capacity, water recycling, and reclamation and alternative water supply methods while serving a growing, multi-user basis in the presence of climate change that is predicted to reduce water availability. Moreover, the use of fossil-fuel-derived energy brings climate change consequences that will reduce water availability in Cape Town. Water supply to agriculture, industrial and domestic uses, are all to some extent dependent on energy supply, both existing sources of electricity as well as the growing share of renewable electricity.

Cape Town, therefore, needs to develop a resilient, quantitative water plan to guide medium- to long-term investments in additional water supply capacity, by ensuring a balanced supply and utilisation of natural resources. The present project will specifically consider the interlinks between water supply, energy supply, and agriculture within the WEF-nexus, which are not adequately captured in current forecasting models. Planning for sustainable urban development requires a balanced supply and utilisation of natural resources through systematic thinking, to ensure that all of the components of the urban WEF-nexus can function efficiently. Ignoring the dynamic interconnections of WEF components will have adverse consequences: Food production requires water and energy, water supply and treatment need energy, while energy production also consumes water.

2.7 References

Afionis, Stavros et al. (2017). "Consumption-based carbon accounting: does it have a future?" In: Wiley Interdisciplinary Reviews: Climate Change 8.1, e438.

Almond, REA, Monique Grooten, and T Peterson (2020). Living Planet Report 2020-Bending the curve of biodiversity loss. World Wildlife Fund.

Bak, Per (2013). How nature works: the science of self-organized criticality. Springer Science & Business Media.

Bakhshianlamouki, Elham et al. (2020). "A system dynamics model to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia lake Basin, Iran". In: Science of the Total Environment 708, p. 134874.

Bandura, Albert (1999). "Social cognitive theory: An agentic perspective". In: Asian Journal of Social Psychology 2.1, pp. 21-41.

Bankes, Steven C (2002). "Agent-based modelling: A revolution?" In: Proceedings of the National Academy of Sciences 99.suppl 3, pp. 7199-7200.

Barrett, Mike et al. (2018). "Living planet report 2018: Aiming higher".

Beaufort, Imre et al. (2016). "Living Planet Report 2016-Risk and resilience in a new era. Synthesis"

Bieber, Niclas et al. (2018). "Sustainable planning of the energy-water-food nexus using decision making tools". In: Energy Policy 113, pp. 584-607.

Boluwade, Alaba (2021). "Impacts of climatic change and database information design on the water-energy-food nexus in water-scarce regions". In: Water-Energy Nexus 4, pp. 54-68.

Bonabeau, Eric (2002). "Agent-based modelling: Methods and techniques for simulating human systems". In: Proceedings of the national academy of sciences 99.suppl 3, pp. 7280-7287.

Booysen, MJ, Martine Visser, and Ronelle Burger (2019). “Temporal case study of household behavioural response to Cape Town’s “Day Zero” using smart meter data”. In: Water research 149, pp. 414-420.

Bryson, Joanna J (2002). “The behaviour-oriented design of modular agent intelligence”. In: Net. Object Days: International Conference on Object-Oriented and Internet-Based Technologies, Concepts, and Applications for a Networked World. Springer, pp. 61-76.

Cassandras, Christos G (2005). “Discrete-event systems”. In: Handbook of networked and embedded control systems. Springer, pp. 71-89.

Cassim, Zaheer (2018). “Cape Town could be the first major city in the world to run out of water”. In: USA Today 22.

Cheng, Kun et al. (2015). “Regional food security risk assessment under the coordinated development of water resources”. In: Natural Hazards 78.1, pp. 603-619.

Christiansen, John H and Mark Altaweel (2004). “Simulation of natural and social process inter-actions in bronze age Mesopotamian settlement systems”. In: 69th Annual proceedings of the society for American archeology.

Conte, Rosaria (2007). “Review of Generative Social Science: Studies in Agent-Based Computational Modelling (Princeton Studies in Complexity)”.

Creutzig, Felix et al. (2015). “Global typology of urban energy use and potentials for an urbanization mitigation wedge”. In: Proceedings of the national academy of sciences 112.20, pp. 6283-6288.

De Rosnay, Joël (2014). Le macroscope. Vers une vision globale. M´edia Diffusion.

Epstein, Joshua M and Robert Axtell (1996). Growing artificial societies: social science from the bottom up. Brookings Institution Press.

Fagan, JE, MA Reuter, and KJ Langford (2010). “Dynamic performance metrics to assess sustainability and cost effectiveness of integrated urban water systems”. In: Resources, Conservation and Recycling 54.10, pp. 719-736.

Fischer-Kowalski, Marina and Helga Weisz (1999). “Society as hybrid between material and symbolic realms: Toward a theoretical framework of society-nature interaction”. In: Advances in Human Ecology 8, pp. 215-252.

Forrester, Jay W (1968). “Industrial dynamics – after the first decade”. In: Management Science 14.7, pp. 398-415.

Forrester, Jay W (1970). “Urban dynamics”. In: IMR; Industrial Management Review (pre-1986) 11.3, p. 67.

Forrester, JW (1961). “Industrial Dynamics MIT Press Cambridge”. In: MA.[Google Scholar].

Gebetsroither-Geringer, Ernst (2014). “Multimethod modelling and simulation supporting urban planning decisions”. In: Understanding complex urban systems: Multidisciplinary approaches to modelling. Springer, pp. 13-27.

Gilbert, Nigel and Klaus Troitzsch (2005). Simulation for the social scientist. McGraw-Hill Education (UK).

Gratch, Jonathan and Stacy Marsella (2001). “Tears and fears: Modelling emotions and emotional behaviours in synthetic agents”. In: Proceedings of the fifth international conference on Autonomous agents, pp. 278-285.

Grubic, Tonci et al. (2020). “Micro-generation technologies and consumption of resources: A complex systems’ exploration”. In: Journal of Cleaner Production 247, p. 119091.

Hardy, Laurent, Alberto Garrido, and Luis Juana (2012). “Evaluation of Spain’s water-energy nexus”. In: International Journal of Water Resources Development 28.1, pp. 151-170.

Helbing, Dirk (2012). “Agent-based modelling”. In: Social self-organization. Springer, pp. 25-70.

Helbing, Dirk and Stefano Balietti (2010). “Fundamental and real-world challenges in economics” In: Science and culture 76.9-10.

Helbing, Dirk, Attila Szolnoki, et al. (2010). “Evolutionary establishment of moral and double moral standards through spatial interactions”. In: PLoS Computational Biology 6.4, e1000758.

Henderson, J Vernon, Adam Storeygard, and David N Weil (2012). “Measuring economic growth from outer space”. In: American Economic Review 102.2, pp. 994-1028.

Hoff, Holger (2011). Understanding the nexus: Background paper for the Bonn2011 Nexus Conference.

Holland, John H (2000). Emergence: From chaos to order. OUP Oxford.

Jennings, Nicholas R (2000). “On agent-based software engineering”. In: Artificial Intelligence 117.2, pp. 277-296.

Kaiser, Kendra E, Alejandro N Flores, and Vicken Hillis (2020). “Identifying emergent agent types and effective practices for portability, scalability, and intercomparison in water resource agent-based models”. In: Environmental Modelling & Software 127, p. 104671.

Khan, Hassaan Furqan et al. (2017). “A coupled modelling framework for sustainable watershed management in transboundary river basins”. In: Hydrology and Earth System Sciences 21.12, pp. 6275-6288.

Kharas, Homi (2017). “The unprecedented expansion of the global middle class: An update”.

Kim, So Young and Yael Wolinsky-Nahmias (2014). “Cross-national public opinion on climate change: The effects of affluence and vulnerability”. In: Global Environmental Politics 14.1, pp. 79-106.

Kitzes, Justin (2013). “An introduction to environmentally-extended input-output analysis”. In: Resources 2.4, pp. 489-503.

Kiviat, Philip J (1969). Digital computer simulation: Computer programming languages. Tech. rep. Rand Corp Santa Monica CA.

Kjaer, Louise Laumann et al. (2019). “Product/service-systems for a circular economy: The route to decoupling economic growth from resource consumption?” In: Journal of Industrial Ecology 23.1, pp. 22-35.

Koch, Jennifer et al. (2019). “Conceptual modelling for improved understanding of the Rio Grande/Rıo Bravo socio-environmental system”. In: Socio-Environmental Systems Modelling 1, pp. 16127-16127.

Kohler, Timothy A, George J Gumerman, and Robert G Reynolds (2005). “Simulating ancient societies”. In: Scientific American 293.1, pp. 76-84.

Konapala, Goutam et al. (2020). “Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation”. In: Nature Communications 11.1, pp. 1-10.

Lamb, William F et al. (2019). “Learning about urban climate solutions from case studies”. In: Nature Climate Change 9.4, pp. 279-287.

Le Moigne, Jean-Louis (1994). La théorie du systéme général: théorie de la modélisation.

Lenzen, Manfred et al. (2007). “Shared producer and consumer responsibility – Theory and practice”. In: Ecological Economics 61.1, pp. 27-42.

Lin, Jianyi et al. (2019). “Modelling the urban water-energy nexus: a case study of Xiamen, China”. In: Journal of Cleaner Production 215, pp. 680-688.

Macal, Charles M and Michael J North (2005). “Tutorial on agent-based modelling and simulation”. In: Proceedings of the Winter Simulation Conference, 2005. IEEE, 14pp.

Magliocca, Nicholas R (2020). “Agent-Based Modelling for Integrating Human Behaviour into the Food-Energy-Water Nexus”. In: Land 9.12, p. 519.

Meadows, Donella H (2008). Thinking in systems: A primer. Chelsea Green Publishing.

Meadows, Donella H, Jorgen Randers, and Dennis L Meadows (1972). The Limits to Growth (1972). Yale University Press.

Milanovic, Branko (2003). “The two faces of globalization: against globalization as we know it”. In: World development 31.4, pp. 667-683.

Miller, John A et al. (2004). “Investigating ontologies for simulation modelling”. In: 37th Annual Simulation Symposium, 2004. Proceedings. IEEE, pp. 55-63.

Musango, Josephine Kaviti et al. (2020). “Urban metabolism of the informal city: Probing and measuring the ‘unmeasurable’ to monitor Sustainable Development Goal 11 indicators”. In: Ecological Indicators 119, p. 106746.

Network, Global Footprint (2010). “Ecological footprint atlas 2010”. In: Retrieved May 25, p. 2014.

Nikolic, Vladimir V, Slobodan P Simonovic, and Dragan B Milicevic (2013). “Analytical support for integrated water resources management: a new method for addressing spatial and temporal variability”. In: Water Resources Management 27.2, pp. 401-417.

Pachauri, Rajendra K et al. (2014). Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Ipcc.

Pfenninger, Stefan, Adam Hawkes, and James Keirstead (2014). “Energy systems modelling for twenty-first century energy challenges”. In: Renewable and Sustainable Energy Reviews 33, pp. 74-86.

Pitt, Christina (2018). “City of Cape Town relaxes water restrictions, tariffs to Level 5”. In: News24 Accessed 13.

Poplak, Richard (2018). “What’s actually behind Cape Town’s water crisis”. In: The Atlantic 15. Qi, Cheng and Ni-Bin Chang (2011). “System dynamics modelling for municipal water demand estimation in an urban region under uncertain economic impacts”. In: Journal of environmental management 92.6, pp. 1628-1641.

Rao, Anand S and Michael P Georgeff (1991). “Modelling rational agents within a BDI-architecture.” In: KR 91, pp. 473-484.

Ravar, Zeinab et al. (2020). “System dynamics modelling for assessment of water-food-energy resources security and nexus in Gavkhuni basin in Iran”. In: Ecological Indicators 108, p. 105682.

Robalino, David A and Robert J Lempert (2000). “Carrots and sticks for new technology: Abating greenhouse gas emissions in a heterogeneous and uncertain world”. In: Integrated Assessment 1.1, pp. 1-19.

Robinson, Stewart (2004). Simulation: the practice of model development and use. Vol. 50. Wiley Chichester.

Schelling, Thomas C (1978). “Sorting and mixing”. In: Micromotives and macrobehaviour.

Scott, Christopher A, Arica Crootof, and Sarah Kelly-Richards (2016). “The urban water-energy nexus: Building resilience for global change in the “urban century””. In: Environmental resource management and the nexus approach. Springer, pp. 113-140.

Sehlke, Gerald and Jake Jacobson (2005). “System dynamics modelling of transboundary systems: the Bear River basin model”. In: Groundwater 43.5, pp. 722-730.

Silver, Gregory A et al. (2011). “An ontology for discrete-event modelling and simulation”. In: Simulation 87.9, pp. 747-773.

Simon, H.A. (1990). “Bounded rationality”. In: Eatwell J., Milgate M., Newman P. (eds) Utility and Probability. The New Palgrave. Palgrave Macmillan, London.

Smajgl, Alex, John Ward, and Lucie Pluschke (2016). “The water-food-energy Nexus – Realising a new paradigm”. In: Journal of Hydrology 533, pp. 533-540.

Tesfatsion, Leigh (2002). “Agent-based computational economics: Growing economies from the bottom up”. In: Artificial life 8.1, pp. 55-82.

Treiber, Martin, Ansgar Hennecke, and Dirk Helbing (2000). “Congested traffic states in empirical observations and microscopic simulations”. In: Physical review E 62.2, p. 1805.

Tschirley, David et al. (2015). “The rise of a middle class in East and Southern Africa: Implications for food system transformation”. In: Journal of International Development 27.5, pp. 628-646.

Uhrmacher, Adelinde M and Danny Weyns (2009). Multi-Agent systems: Simulation and applications. CRC press.

Ullrich, Oliver and Daniel Lückerath (2019). “An Introduction to Parallel Discrete Event Simulation.” In: Simul. Notes Eur. 29.2, pp. 63-72.

Von Bertalanffy, Ludwig (1973). “The meaning of general system theory”. In: General system theory: Foundations, development, applications, pp. 30-53.

Werker, Claudia and Thomas Brenner (2004). Empirical calibration of simulation models. Tech. rep. Papers on Economics and Evolution.

Wiedmann, Thomas et al. (2020). “Scientists’ warning on affluence”. In: Nature communications 11.1, pp. 1-10.

Wiener, Norbert (1948). Cybernetics or Control and Communication in the Animal and the Machine. MIT press.

Yang, Jie et al. (2018). “Quantifying the Sustainability of Water Availability for the Water-Food-Energy-Ecosystem Nexus in the Niger River Basin”. In: Earth’s future 6.9, pp. 1292-1310.

Zeigler, Bernard P and Tuncer I Oren (1979). “Theory of modelling and simulation”. In: IEEE Transactions on Systems, Man, and Cybernetics 9.1, pp. 69-69.

Chapter 3: General methodology

Author: Goosen, N.

This section aims to provide a broad overview of why system dynamics was chosen as the modelling framework, and the methodology employed in setting up the system dynamics models used to eventually generate the results in Chapters 4-6. Because the three different technical studies each had a different problem statement, each of Chapters 4-6 therefore also has a specific methodology, which can be accessed in the individual chapters. Seeing that each of these chapters investigated essentially the same overall WEF nexus system, many elements will be similar between the models, but the particular focus of each model was different and there are thus important nuances to each model and the way these were set up, that need to be appreciated.

Following the literature review and a brief scoping of the public domain data available for the City of Cape Town, systems dynamics modelling was identified as the preferred modelling methodology. Systems dynamics was the most suitable framework to employ for the purposes of this particular project, seeing that:

- it allows a dynamic description of a WEF nexus, unlike some indicator-based static methods
- it has been proven to be suitable for quantitative WEF nexus research and is a the most often employed framework for quantitative WEF nexus modelling
- it requires less data to calibrate the model compared to agent based modelling, which is a distinct advantage in scenarios where the amount and type of data for the study area might be limited, as was the case in this project
- it is a good framework enabling the understanding of an entire system and its feedback loops and mechanisms
- it is less computationally intensive than particularly agent based modelling
- there are multiple suitable electronic packages available that facilitate setting up, validating and implementing models

Much initial work went into selecting a suitable electronic package to aid in the modelling, and Stella Architect was eventually chosen.

Three individual projects were set out: two to be completed by Masters students, and one as a larger group effort, mainly driven by the postdoctoral researcher on the project. Topic definition was followed by refinement, based on literature, discussions within the wider research group and engagement with other academics.

Once topics were refined, the system dynamics methodology requires setting up a qualitative description of the system, and determining feedback loops and the impact of these feedback loops on system elements. This was done through setting up causal loop diagrams, where critical system elements were identified and direct links between these elements were described. These causal loop diagrams were verified through expert inputs, and formed the basis for setting up the quantitative part of the models. Although the process of setting up the qualitative and then the quantitative models sounds linear, it is not. There was constant interaction between the qualitative and quantitative models, and frequent adjustments to the qualitative models based on realisations from the quantitative ones.

Quantitative modelling comprised of setting up stock and flow diagrams where the relationships between system elements were formalized, followed by the collection, assessment and cleaning of data-sets. The models were then set up to predict specific aspects of the system (e.g. water levels in the storage reservoirs) over the chosen modelling time (20 years). Debugging of models and improvements in models and data sets formed a continuous process, as were incorporation of changes made in the qualitative models. Key results were highlighted and are reported in Chapters 4-6.

Chapter 4: The interdependencies of food and water within the water-energy-food nexus for the City of Cape Town

Authors: Hofmann, V., Egieya, J., Görgens, J., Goosen, N.

Abstract

Climate change increasingly affects the supply of resources such as water and food. From 2015 and 2018, Cape Town endured its most severe drought on record. Yet, resource management often occurs in isolation, which contrasts with the holistic perspective provided by the nexus concept that recognizes the interdependence of resource sectors. This study employs system dynamics modelling, to examine the City of Cape Town's (CoCT) water-food trade-offs and interactions, qualitatively and quantitatively. It assesses various policies aimed at improving system resilience, as proposed by the CoCT and aimed at boosting future water supplies, analysing their efficacy and potential drawbacks. The findings indicate that the CoCT's strategies will effectively secure adequate water for its expanding population. However, a major concern was found to be the proposed intensification of aquifer exploitation. The model predicts that such an approach may potentially lead to over-abstraction of some aquifers, jeopardizing their sustainability.

4.1 Introduction

Climate change, population growth and urbanisation present significant challenges for major cities, exerting pressure on vital resources like water and food. The City of Cape Town (CoCT) faced an acute drought between 2015 and 2018, causing the water levels of the six major dams supplying water to plummet to critically low levels (City of Cape Town, 2019). Traditionally, resource-related issues have been tackled in isolation, without taking into account their interconnectedness. The water-energy-food (WEF) nexus, introduced at the 2011 Bonn conference, advocates a comprehensive and holistic approach to resource management (Hoff, 2011). This nexus facilitates an understanding of these resource systems, and also examines their interdependencies (as illustrated in Figure *14*). For instance, water is essential in the production of food for irrigation and food processing, while food or food waste can be used to synthesize biofuels. Similarly, energy is indispensable for food processing and transportation, for water conveyance or for water treatment and desalination. Additionally, water can be used to generate energy. Holistic strategies applied to the WEF nexus can reveal potential trade-offs and synergies among various strategies. As the 2030 deadline for the United Nation's Sustainable Development Goals (SDG) approaches, the WEF nexus method is increasingly recognized as a crucial instrument for achieving key objectives such as *clean water and sanitation* (SDG 6), *zero hunger* (SDG 2) and *affordable and clean energy* (SDG 7) (Egieya et al., 2024).

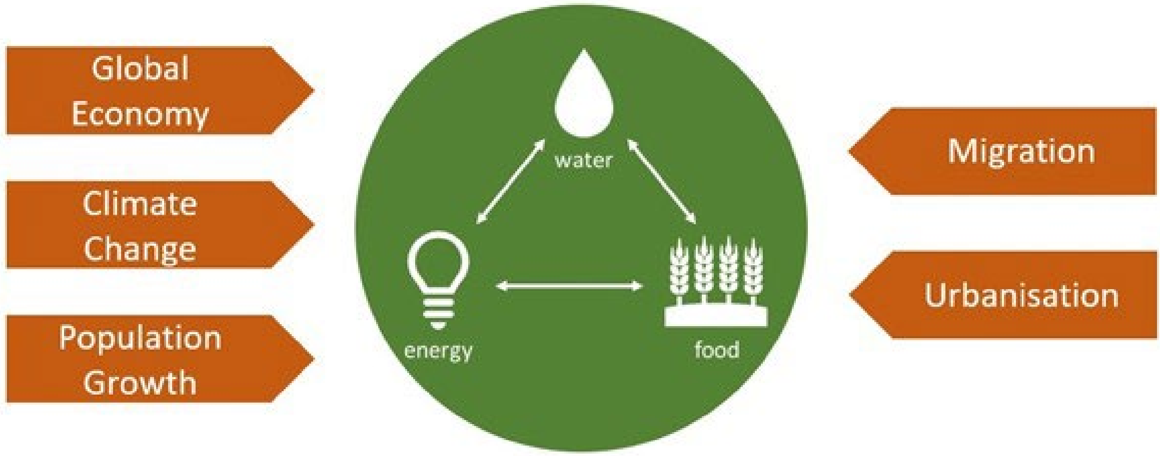

Figure 14 Challenges to the WEF nexus, adapted from (Hoff, 2011)

The nexus approach is versatile, and applicable over a range of scales, from global to household scales. On a global scale, Sušnik (2018) explored WEF nexus resource use and gross domestic product (GDP) correlations. At the national level, van den Heuvel et al., 2020 examined the impacts of policies on WEF resources. Many nexus studies are focused on water and use natural boundaries, such as river basins as their system boundaries, e.g. Siderius et al. (2022) assessed water conservation approaches in the Tanzanian Rufiji basin. Administrative boundaries such as provinces or federal states can also define study areas as evidenced by Wu et al. (2021) who used system dynamics to analyse the WEF nexus within the Canadian Saskatchewan province. Another scope commonly used for nexus studies is the urban level. Through combining a hydrological model with agent-based modelling Ding et al. (2021) investigated the effects of water-related policies on the WEF nexus in Cape Town. Moreover, Egieya et al. (2024) utilized system dynamics to make projections for the availability of WEF resources in Cape Town. On the smallest scale, household resource use is studied within the nexus framework, as seen in Hussien et al. (2017). Criticism of the WEF nexus concept often mentions the lack of real-life results following nexus research (Cairns & Krzywoszynska, 2016),and the lack of a universally agreed upon nexus concept (Sušnik & Staddon, 2021). This flexible definition is, however, as Brouwer et al. (2020) argue an advantage, as the nexus concept can be expanded or narrowed down as needed.

To effectively address the intricacies of the WEF nexus, various tools and methodologies are used. Although numerous existing tools such as CLEWs (climate, land, energy and water systems approach) and MuSIASEM (multi-scale integrated analysis of societal ecosystem metabolism) are available, they often face criticism for their lack of user-friendliness, or for their limited applicability to a narrow range of use cases (Dargin et al., 2019). Tools also need to be chosen based on what is expected from the analysis: some tools are static whereas others are able to model dynamic characteristics within a system, some are qualitative whereas others are quantitative (Egieya et al., 2022). System dynamics provides a versatile approach to modelling the nexus, as it allows for application at any scale and accommodates both qualitative and quantitative modelling of the problem (Ford, 2009). Furthermore, although most nexus studies primarily focus on the integrated Water-Energy-Food (WEF) nexus, specific components of the nexus, such as the water-food, the water-electricity, or the electricity-food nexus (Gozini et al., 2021; Koppelmäki et al., 2022; Strokal et al., 2019) can be studied.

There is limited existing literature on the Cape Town WEF nexus. Ding et al. (2021) tested the effects of three different policies on the nexus where two of the tested policies centre around water tariffs, while the third policy involved supplementary water resources. They conclude that the policy providing additional water supplies showed the most beneficial results, as water tariff increases were likely to negatively impact indigent and lower-income households. The research done by Egieya et al. (2024) utilised system dynamics to predict WEF resource usage within the CoCT over a span of 20 years, providing an overview of the developments in the three sectors. They investigated some predicted impacts of climate change on the system and quantifying how the addition of a water supply stream in the form of water reuse could mitigate these impacts. While there is a large body of research on the WEF nexus, and some research specifically on the WEF nexus for Cape Town, an in-depth study of the interconnections of water and food resources has not been done. The focus is often either exclusively on water or on the water-energy node, whereas the food aspect of WEF nexus research is often poorly described (Endo et al., 2017).

In this work, the interconnections specifically between food and water in the City of Cape Town (CoCT) are explored, and policies planned to be implemented by the CoCT by 2035 are analysed using system dynamics. By examining the water-food node of the system, possible benefits and drawbacks of interventions can be better understood.

4.2 Case study description

As South Africa's second-largest city, Cape Town was home to approximately 4.6 million residents in 2020 (City of Cape Town, 2020). Figure 15 illustrates the location of the city within the Western Cape Province of the country. Characterised by its temperate climate, Cape Town experiences dry summers and wet winters. The city's average annual temperature is 16.7^0C with an average yearly precipitation of 515 mm (Petschelt & Hermann, 2013).

Figure 15 Map of the Western Cape Province (source: Shutterstock/Rainer Lesniewski).

Climate change and an expanding population are exacerbating the scarcity of water resources in Cape Town. The city faces challenges in meeting residents' water needs if winter rainfalls are inadequate. An illustrative example of this issue was the severe drought from 2015 to 2018, the most intense in Cape Town's recorded history (Egieya et al., 2024). During this period, the levels of water in the six major dams which account for 96% of the city's water supply, dropped to below 13.9% (Webster, 2019). This severe situation necessitated the implementation of stringent water conservation measures. Given the strong interdependence of water and food through irrigation and the water required for food production and processing, the drought had profound effects on agriculture and food production in Cape Town and its surrounding regions (Green Cape, 2019). Water scarcity can thus precipitate food scarcity, specifically in areas where agriculture plays an important role in the local economy, e.g. in Cape Town, where agriculture is vital for food production and a significant source of employment with 44 000 residents working in this sector in 2020 (City of Cape Town, 2020). A decline in agricultural productivity inevitably leads to job losses. Moreover, resource shortages in the water and food sector are further compounded by the nationwide electricity shortage in South Africa, which necessitates regularly scheduled power outages called "load-shedding". This energy shortfall hampers the provision of other resources, as electricity is essential for water transportation and food production (Ryan, 2022). These interlinked challenges underscore the need for sustainable policies to ensure the future fulfilment of Cape Town’s resource demands.

4.3 Methodology and data

The WEF nexus is best understood as a systems thinking challenge. This perspective is supported by Schlör et al. (2021), who analysed the nexus employing the system criteria developed by Meadows (2008). Consequently, system dynamics was selected as the most appropriate methodology for describing the Cape Town water-food nexus. For modelling purposes, the chosen software tool is STELLA Architect by isee systems.

4.3.1 Data

The majority of the data employed in the model is open source, primarily sourced from the CoCT’s open data online portal (City of Cape Town, 2023c). Additional data were gathered from government and municipal reports, as well as research papers. In instances where specific data needed for the model were unavailable, assumptions were made using data for the Western Cape Province, or at the national level.

4.3.2 Causal loop diagram

The construction of the causal loop diagram (CLD) was based on extensive research on into the water-food system and its interconnections. Central to the diagram portrayed in Figure *16*, are variables related to the water and food availability of water and food resources. The water availability variable forms reinforcing loops with water resource elements such as dams and aquifers, implying that more water in the reservoirs equates to greater overall water availability. Conversely, water-utilising variables like residential water use or food processing establish balancing loops, meaning that an increase in water use would lead to a decrease in overall water availability The reinforcing loops are labelled with an “R” in Figure *16*, while the balancing loops are denoted with a “B”. The nexus between food and water availability is connected primarily through the water used in food production, processing, and crop irrigation. Food availability is significantly influenced by factors such as the number of households, land use and food imports. Moreover, population growth, climate change and land use changes were identified as external variables exerting a substantial impact on the water-food system.

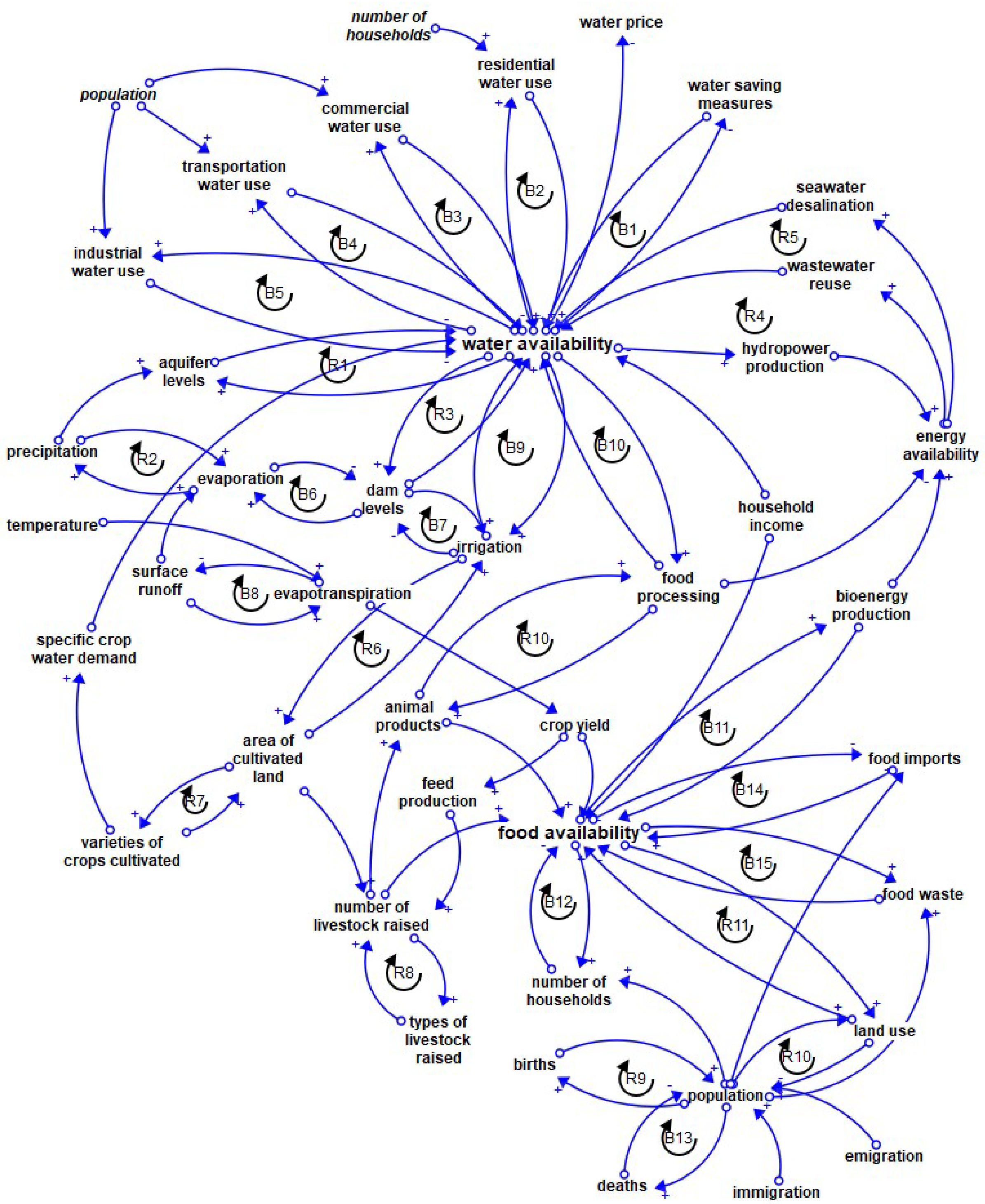

Figure 16 Causal loop diagram of the Cape Town WEF nexus

4.3.3 Policy scenarios

To assess the impact of various policies, three distinct scenarios were formulated: a *base case scenario*, a *business-as-usual scenario (BAU)* and a *water interventions scenario (WI)*. The base case scenario depicts the system's progression over time without incorporating climate change projections serving as reference point for comparing the outcomes of other scenarios. The business-as-usual scenario integrates climate change forecasts, specifically a gradual increase in average temperatures by 1°C to 1.8°C and a reduction in average precipitation by up to 20% until 2060 (Jack et al., 2022). The water interventions scenario encompasses measures planned by the CoCT aimed at augmenting water availability by 2035, to improve the resilience of the system (City of Cape Town, 2023a). As the frequency and severity of droughts are projected to increase in the future, a *drought sub-scenario* was included to simulate the effects of a three-year drought within both the BAU and WI scenarios (Orimoloye et al., 2022). Further details of these scenarios are elaborated in Table 2.

Table 2: List of the scenarios implemented into the stock and flow diagram.

Scenario	**description**
base case	- Simulation of the system based on historical data. - Includes population growth based on projections (City of Cape Town, 2020). - Does not include climate change projections or interventions. - Serves as a basis for comparison with other scenarios.
business-as-usual (BAU)	- Two sub scenarios with different climate change severities: - Increase in average temperatures of 1°C and decrease of precipitation of 5% (best case). - Increase in average temperatures of 1.8°C and decrease of precipitation of 20% (worst case).
water interventions (WI)	- Based on the BAU scenarios. - Include the CoCT's planned water strategy comprising increased aquifer use, dam augmentation, water reuse and seawater desalination.
drought sub-scenario	- Simulation run of BAU and WI scenario with an included 3-year drought scenario. - The drought sub-scenario sets in after 360 months and reduces the average precipitation by 50% for 36 months.

4.3.4 Stock and flow diagram

Building on the insights about qualitative connections within the nexus derived from the CLD, a stock and flow diagram (SFD) was developed. Following the recommendations from isee systems, the Euler integration method was selected for this simulation due to its suitability for models that incorporate IF-THEN-ELSE logic and discrete objects (isee systems, 2023a). Through a series of tests, the optimal timestep for the simulation was established to be 0.25 months, with the total simulation duration of 480 months, or 40 years commencing in January 2023. For clarity, the diagram was segmented into five sectors: water, food, population, land and climate. The interconnections between these sectors are facilitated using "ghosts", which in STELLA (isee systems, 2023b) are shortcuts to other variables within the system.

In Figure 17, we see a diagram showing the allocation of water resources in the system. At the centre of this diagram is the "Available Water" stock, which is the amount of water left after subtracting the water used (demand) from the available water (supply). On the water supply side, most of the water (approximately 96%) comes from the six major dams that serve the city. There are also three groundwater sources (aquifers) used (City of Cape Town, 2023b). The diagram also includes water from seawater desalination and reused water, which are part of the plan to increase the resilience of water supply (WI scenario). On the demand side, the water is used in three main ways: agriculture, urban areas, and non-revenue water (water losses), which is water that is lost and not paid for (McKenzie et al., 2012). The urban water demand is further split into different users. As different crops and livestock have different water requirements, the agricultural water demand outflow is split between the variety of livestock and crops cultivated in the CoCT and its surrounding agricultural areas.

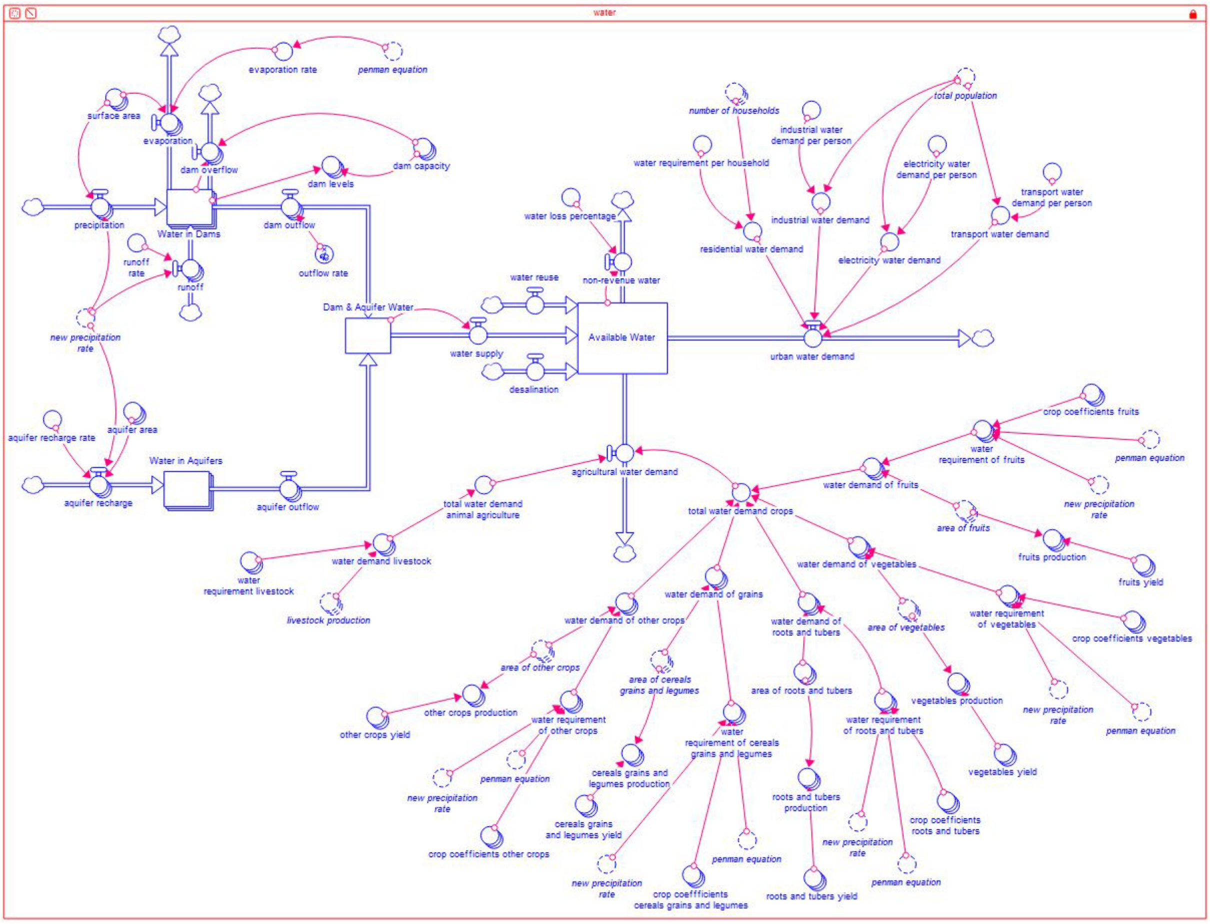

Figure 17 Water sector of the stock and flow diagram.

In Figure 18, the food sector shown in the stock and flow diagram has a similar structure to the water sector. Here, the focus is on “Food Availability”, which is the amount of food available after considering both food supplied, and food demanded.

The supply side consists of two main sources: food that is imported and food that is produced locally. There sources contribute to the overall food supply in the area.

On the demand side, there are three ways food leaves the system: through exports (food sent to other places), food waste (food that is not consumed or used), and food consumption (food eaten by the local population).

The “Food Availability” stock thus shows the balance between the supply and demand for food. It is important to note that this stock includes an array of foods, both staple and non-staple, to reflect the different eating habits of various population groups. The variety indicates a diverse food supply to meet the varied needs and preferences of the population (F. A. Odunitan-Wayas et al., 2020).

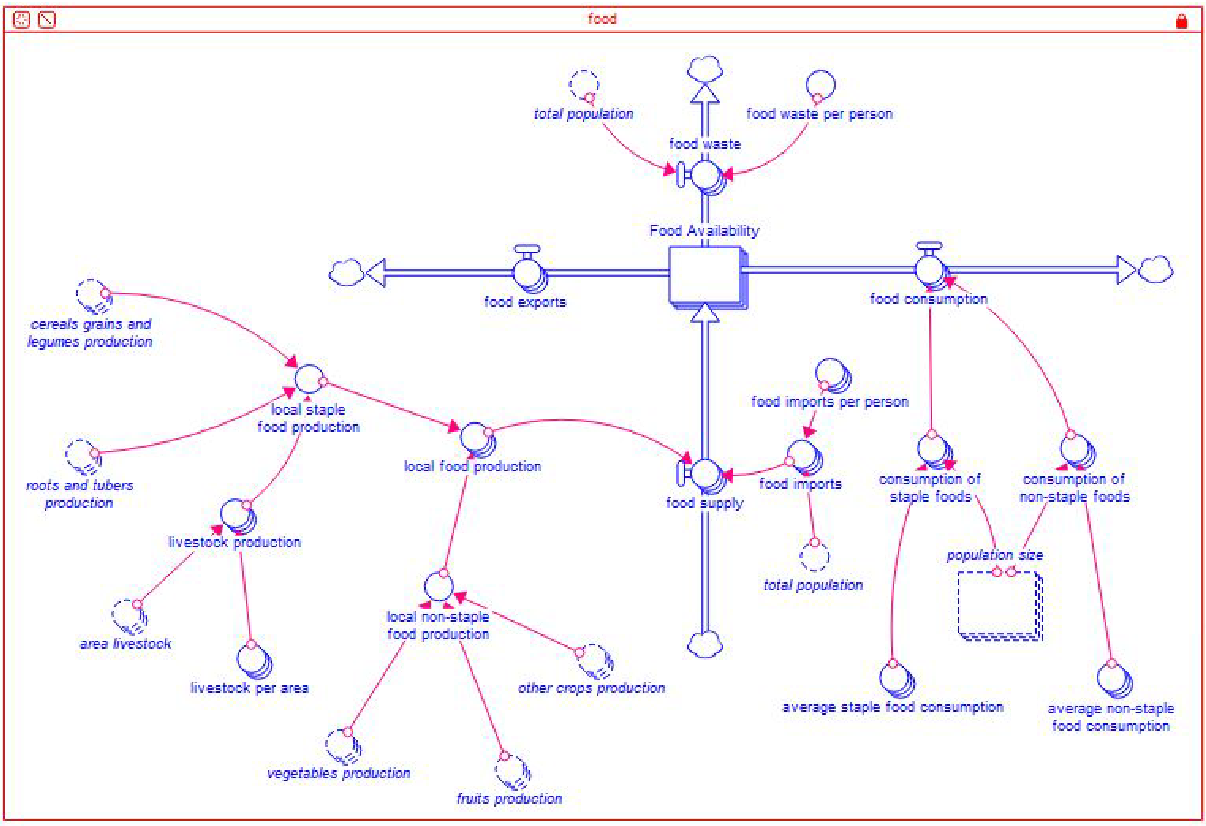

Figure 18 Food sector of the stock and flow diagram.

Since population growth has a strong influence on resource use, it is pertinent to include a population sector, as shown in Figure *19*. This sector is centred around a key element called "Population Size". The "Population Size" stock is like a container that changes based on people coming in and going out. On the one hand, people coming into the population, either by being born (births) or moving in from other places (immigration), are the inflows. On the other hand, people leaving the population, either by passing away (deaths) or moving to other places (emigration), are the outflows.

An important feature of this population model is that the population size is categorized into different Living Standard Measure (LSM) groups. These groups are based on the average incomes and spending habits of different population groups. By dividing the population into these LSM groups, the model can more accurately represent different parts of the population use resources (Ntloedibe et al., 2020). This categorization helps in understanding and planning for varying needs and resource usage patterns of different segments of the society, as highlighted in the study by Odunitan-Wayas et al. (2018).

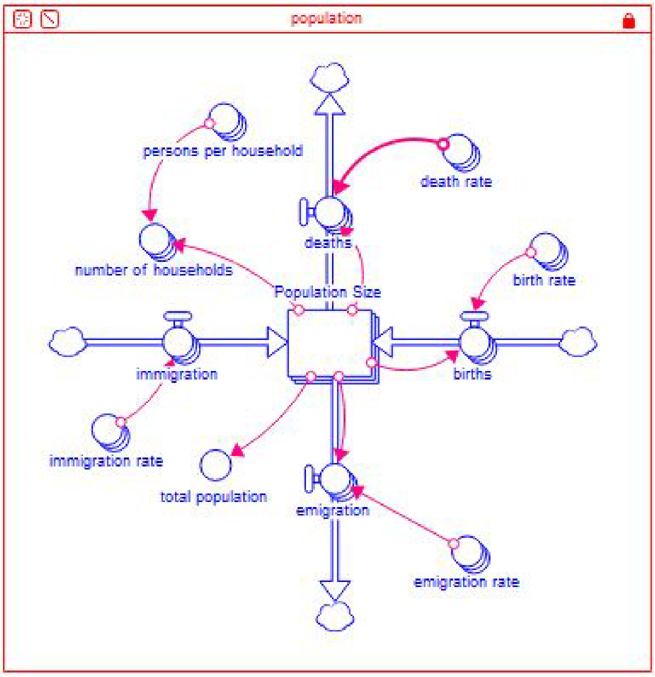

Figure 19 Population sector of the stock and flow diagram.

In Cape Town, the amount of land available for different uses is limited. Because of this, any changes in how land parcels are utilised affect the city's demand for resources (see Figure *20*). For instance, if agricultural land is converted to residential areas, the amount of food that Cape Town can produce will decrease (Le Roux et al., 2016). To manage this situation effectively, the agricultural land is further split into the areas used for specific crops and livestock to track their respective water requirements.

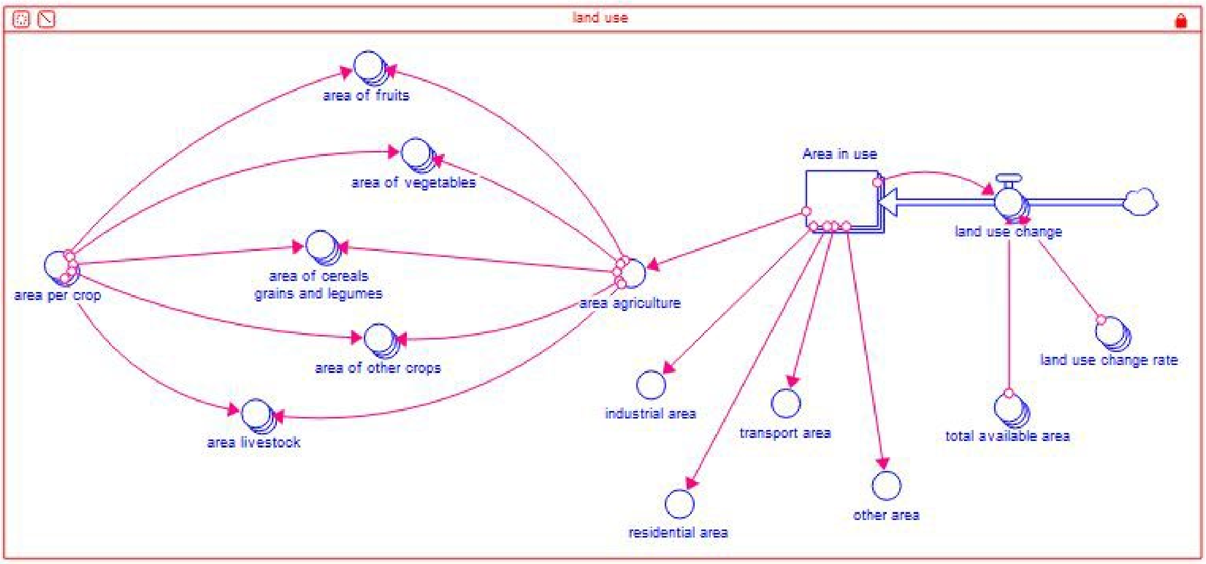

Figure 20 Land use sector of the stock and flow diagram.

To account for the effects of climate change on the system, a climate sector (Figure *21*) was included. This sector is crucial because an increase in average temperatures can significantly affect water resources. Specifically, higher temperatures lead to more evaporation of water from dams and increased evapotranspiration (the combined process of water evaporation and plant transpiration) from crops (Nistor et al., 2017). To accurately estimate the effects of these temperature changes, the Food and Agriculture Organization (FAO) suggests using the Penman-Monteith equation (Allen & Pereira, 2006). This equation is a widely recognized method for calculating evapotranspiration. It considers various factors like temperature, humidity, sunlight, and wind speed to provide a more precise understanding of how much water crops need and how much water is lost from reservoirs due to evaporation. For this study, not all of the aforementioned data was available. For this reason, a simplified version of the Penman equation, developed by Linacre (1977) was employed (Equation (1)). This equation requires fewer climate parameters to estimate potential evapotranspiration.

$$E_0 = \frac{500(T + 0.006h)/(100 - A) + 15(T - T_d)}{(80 - T)} \quad (1)$$

Where E_0 represents the evaporation rate in mm per day, T is the mean temperature in °C, h the elevation in metres. A denotes the latitude in degrees and T_d the mean dew point in °C.

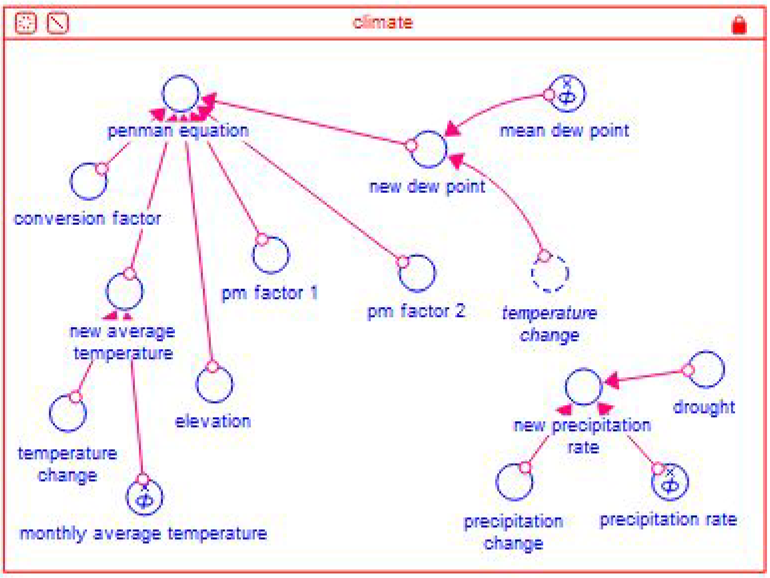

Figure 21 Climate sector of the stock and flow diagram.

4.3.5 Validation and verification

Once the model was completed, it went through various validation and verification methods to ensure accuracy and reliability. This process involved two main types of validation tests: structural and behavioural (Barlas, 1989). The structural validity analysis comprises tests for the model's structure, parameter tests, extreme conditions testing, boundary adequacy, and dimensional consistency (Forrester & Senge, 1979). The model's structure was also validated by presenting it to stakeholders for their input and validation. To establish its behavioural validity, the model was tested on behaviour anomalies and sensitivity (Forrester & Senge, 1979). Any behavioural anomalies that the model showed in the early stages were identified and corrected. For the sensitivity analysis, different parameters, such as population size and dam levels were chosen to assess the model's responsiveness to changes. After successfully completing all these tests, the model was used to generate results based on the scenarios described in Section 2.3. This thorough testing and validation process was crucial in ensuring that the model was both accurate and reliable, providing confidence in its ability to simulate real-world conditions and predict outcomes effectively.

4.4 Results

In the context of this study, a large number of results were created through the combination of different scenarios and sub-scenarios. The following section summarizes a selection of the most significant results gained from the simulation runs. The selected results show the results of population growth and climate change on the Cape Town water-food system. Furthermore, the benefits and trade-offs of the city's planned water interventions are revealed. The results are presented in a comparative manner to showcase the implications of different scenarios and interventions.

4.4.1 Food availability

The base case simulation, which represents a standard set of conditions without any major changes or interventions, reveals a noticeable decrease in the food availability stock – approximately 13% for staple foods and 9% for non-staple foods during the simulation period from January 2023 to December 2060. This decline in food availability is closely linked to the population growth depicted in Figure 22a. Furthermore, Figure *22*b presents a comparative analysis between the outcomes for the Food Availability stock in two different scenarios: the base case and the BAU (worst case) scenario. The comparison shows that there is no significant difference in the results of both scenarios for the Food Availability stock, and that the BAU scenario results show approximately the same percentage in decline in staple and non-staple foods as the base case scenario. This outcome suggests that, under both the base case and the BAU worst-case scenario, the city might experience a similar decline in food availability, irrespective of the specific conditions or interventions of each scenario.

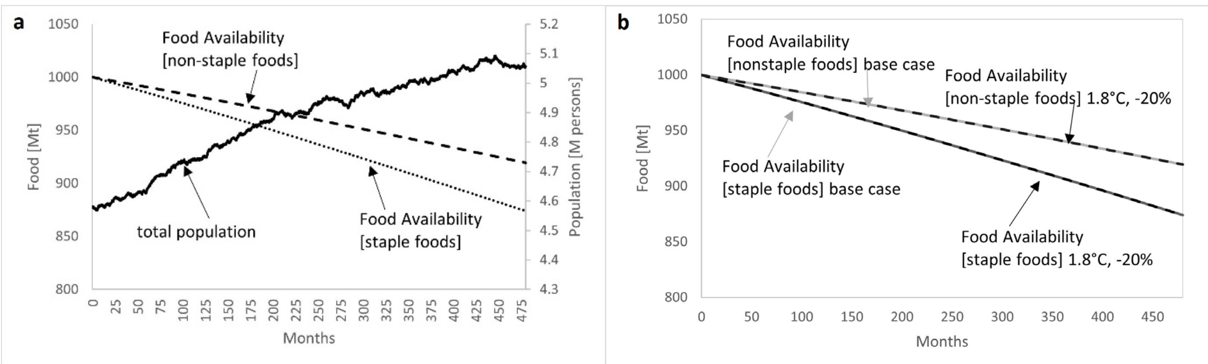

Figure 22 Results for the Food Availability stock in the base case scenario with increasing population (a) and comparison of Food Availability in the base case and BAU scenario (b).

4.4.2 Water availability

Figure 24a offers a comparison of the simulation results for the Available Water stock under three scenarios: the base case, the BAU best case and the BAU worst case scenario. The graph reflects the fluctuations in the water stock levels which are attributed to seasonal variations in precipitation between summer and winter months in Cape Town. The graph in Figure 23a distinctly illustrates that as the severity of climate change increases, the city's water resources start to diminish, particularly noticeable after May 2050 – 330 months into the simulation. Throughout the simulated period, the Available Water stock approaches but does not reach zero under these scenarios, indicating that despite the specific challenges modelled, the city manages to meet its water demands, although water stocks decrease to very low levels. During last decade of the simulation, there is an average of 4 million cubic metres less available water in the system that during the first decade.

However, this situation changes when the drought sub-scenario, as illustrated in Figure 24b, is introduced. Here, after 394 months, the Available Water stock hits zero. This means that under the conditions of this sub-scenario, the city can no longer fulfil its water requirements. The significant drop observed in both graphs after 330 months will be discussed in further detail below, providing insight into the factors contributing to this steep decline in water availability. This analysis is crucial for understanding the impact of climate change and

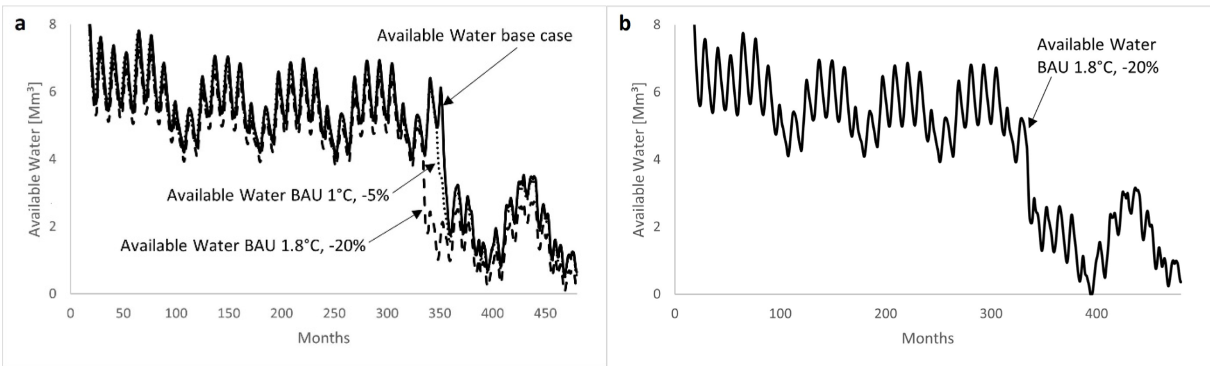

Figure 23 Comparison of the Available Water stock for the base case and BAU scenarios (a) and Available Water for the BAU worst case scenario with inclusion of the drought sub-scenario (b).

drought conditions on the city's water sustainability and for planning effective water management strategies.

In the water interventions (WI) scenario Figure 25a, there is a noticeable improvement in the availability of water compared to the business-as-usual scenario: On average, there are 16 million cubic metres more available in the WI scenario, suggesting that the planned interventions have a positive effect on maintaining water levels. Specifically, Figure 23b displays the results on combining the WI scenario with the drought sub-scenario. During this simulation, a three-year drought period is modelled between the months 360 and 396, when the water stock remains relatively stable and does not exhibit any significant decrease.

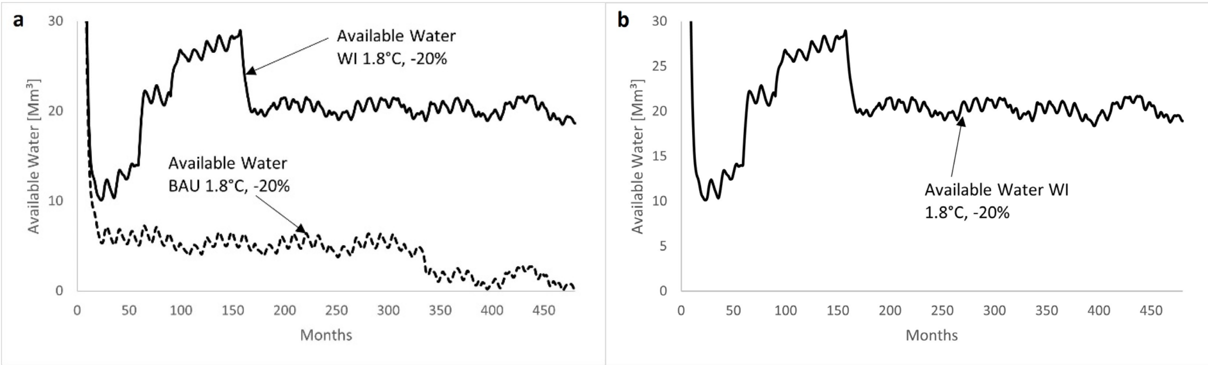

Figure 24 Comparison of the Available Water stock for the BAU and WI worst case scenarios (a) and Available Water for the WI worst case scenario with inclusion of the drought sub-scenario (b).

When considering the aquifer system, the simulation results reveal some important developments. In a, under the base case scenario with the current rate of water extraction, the Cape Flats Aquifer (CFA) is projected to deplete completely after 350 months. In the BAU worst-case scenario, the depletion of the CFA occurs even faster – it runs dry 17 months earlier than in the base case Figure 25. This accelerated depletion highlights the increased strain on the aquifer system in this scenario.

In the WI scenario, the CFA exhausts its resources after 156 months, and there is a significant decline in another major aquifer, the Atlantis-Silverstroom Aquifer. The trend observed in the simulation suggests that under this scenario, this aquifer is also on a path to complete depletion, potentially reaching zero just a few months beyond the end of the simulation period.

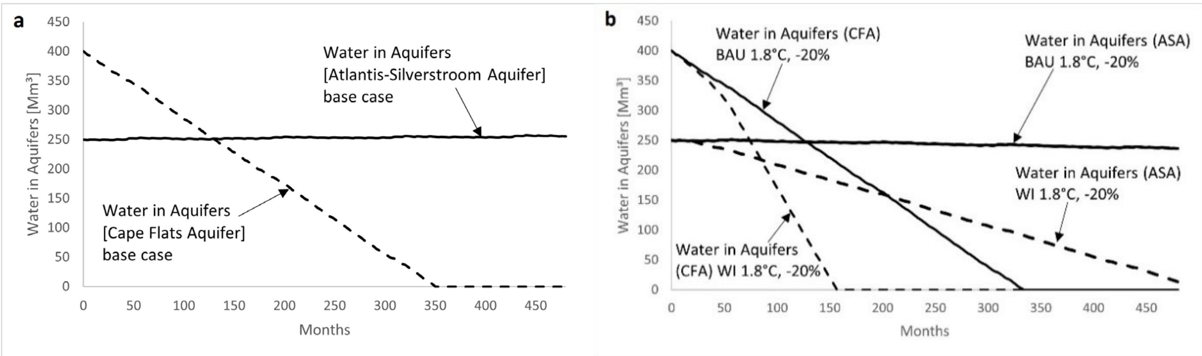

Figure 25 The Water in Aquifers stock for the AS and CF aquifers for the base case scenario (a) and comparison of the Water in Aquifers stock for the BAU and WI worst case scenarios (b).

4.5 Discussion

Regarding food availability, the model implicitly underscores the role of agriculture in the socio-economic fabric of Cape Town, and the consequent importance of policies and strategies related to food security, as they do not only affect the availability of food but also have broader implications for employment and economic stability in the region. The production of food within the city boundaries itself may have only a minor impact on the overall food availability in Cape Town, but agriculture remains a significant sector in terms of employment. Of the approximately 1.6 million residents pursuing formal employment in the city, about 44 000 work in agriculture, and it can be assumed that agriculture also provides a significant amount of informal employment (City of Cape Town, 2020). The Food and Agriculture Organization of the United Nations (FAO) gives a four-part definition of the term "food security": the availability of food, access to food, nutrient utilisation and the continuation of the first three components over time (FAO, 2008). An important component in the accessibility of food is economic status (Battersby et al., 2014). Employment is therefore a vital factor when it comes to food access.

Within the model, the observed decrease of 13% in staple foods and 9% in non-staple foods in the Food Availability stock over time (Figure 22) is primarily due to the assumption that food import rates remain constant. In a real-world scenario it is reasonable to expect that an increase in food demand would lead to higher import rates (Charles & Battersby, 2019). However, import rates will be a function of many variables, including economic and logistic factors which can be difficult to predict (Haysom et al., 2017). In light of a lack of reliable predictions of future changes in food import rates, the model maintains the assumption of constant import rates for simplicity and consistency.

Agriculture in and around the CoCT makes up approximately 30% of the City's water usage (City of Cape Town, 2023a). It is important to balance this demand with the demands of other water consumers in Cape Town, such as industry and residential water demands. Some of the major dams and aquifers, such as Theewaterskloof Dam provide water for both urban and agricultural consumers (City of Cape Town, 2022). There are, however, no clear policies on the prioritisation of water allocation in times of water stress (Matthews, 2021). As urban agriculture plays a major role in in the City's resilience against food insecurity, it is therefore important that sufficient amounts of water are allocated to this sector – even in times of water stress (Charles & Battersby, 2019).

Cape Town's increasing population, as well as the expected increase in mean temperatures due to climate change are going to put the City's water resources under pressure. The trends observed in the results align with findings from the research conducted by Ding et al. (2021) which employed an agent-based modelling approach. This consistency between different modelling methods reinforces the validity of the conclusions drawn. Particularly noteworthy is the BAU drought scenario, which underscores Cape Town's susceptibility to prolonged drought periods. This scenario illustrates the challenges the city could face during multi-year droughts, which are projected to become more frequent and severe (Orimoloye et al., 2022). These findings are significant as they highlight the pressing need for effective water management strategies in Cape Town. The increasing likelihood of extended droughts due to climate change, combined with the pressures of a growing population, presents a substantial challenge to maintaining a sustainable water supply. These factors necessitate proactive planning and the implementation of adaptive measures to mitigate the risks associated with water scarcity and to ensure the long-term resilience of the city's water resources (City of Cape Town, 2022).

With the inclusion of the City's water interventions, the "Available Water" stock stabilises around 20 million cubic metres after approximately 200 months into the simulation. This stability indicates that the strategies, which may include measures like increased water conservation, improved water management practices, or additional water supply sources, are sufficient to sustain the city's water supply even under severe drought conditions. This finding is crucial for water resource planning and management, especially in the context of changing climate patterns and increasing instances of drought due to climate change. It provides valuable insights into the potential effectiveness of proactive water management strategies in ensuring water security.

Despite the apparent success of the water interventions, the modelling results highlight the vulnerability of the aquifer system under management by the CoCT. The noticeable drop in the Available Water stock seen in Figure 23 after 330 months can be understood by examining the aquifer stocks in Figure 25. This decrease specifically aligns with the depletion of the Cape Flats Aquifer around month 350. The fact that the Available Water stock in the WI scenario does not show a significant decrease during the drought sub-scenario suggests that water management strategies planned by the CoCT are effective in sustaining water availability. Figure 25, however, reveals a concerning trend: even under the base case scenario, the simulation results show over-extraction of the aquifer. This issue is exacerbated in BAU scenario due to the impacts of climate change and is most severe in the WI scenario. The increased reliance on groundwater in these interventions strategies leads to heightened exploitation of aquifers (City of Cape Town, 2023a). Over-abstraction of aquifers can lead to several adverse environmental impacts including the lowering of the groundwater table and the intrusion of seawater into freshwater aquifers (Blake et al., 2023). Addressing the over-abstraction of aquifers and sustainable aquifer management is therefore crucial (Mauck & Winter, 2021).

The implementation of the drought sub-scenario into the BAU and WI scenarios emphasize the CoCT's vulnerability to resource scarcity – especially when multiple stressors such as rapid population growth and droughts coincide. Modelling scenarios with simultaneous adverse events like the depletion of an aquifer and a multi-year drought therefore highlights Cape Town's need for resilience-oriented policies to guarantee the continued supply of water and food resources in the future.

4.6 Limitations

Accurate and relevant input data is crucial for the integrity and reliability of a model. For the model discussed here, most of the data utilized is sourced from open access platforms. However, there were instances where some of the collected data did not align other information about the system. In such situations, decisions regarding which data to include were made based on an understanding of historical behaviour of the system. This approach helped in maintaining the consistency and coherence of the model. Moreover, due to the unavailability of certain information about the system in public domains, assumptions were made to fill these gaps. These assumptions were based on the characteristics and behaviours of similar systems, providing a reasonable basis for modelling in the absence of direct data.

One area where data was notably lacking is in the realm of food imports into the city. The scarcity of detailed and specific data in this domain limited the depth and accuracy of the food sector component of the model. More comprehensive and precise data on food imports would enable the model to generate more insightful and meaningful results in this area. Another part of the model that heavily relies on assumptions is the recharge rate of aquifers. Therefore, the results shown should not be treated as accurate future predictions. Nevertheless, these projections show important trends in the use of water resources. As Forrester (1961) points out, the omission of variables critical to the system's behaviour can lead to greater inaccuracies than those that might arise from making educated assumptions to compensate for missing data. He underscores the importance of including all relevant variables in a model, even if it means relying on assumptions or estimations, to accurately capture the system's dynamics. Such an approach is essential for building a robust and predictive model that can be effectively used for planning, analysis, and decision-making.

4.7 Conclusion

The main goals of this research were twofold: firstly, to develop both a qualitative and quantitative system dynamics model focused on the water-food nexus for the City of Cape Town, and secondly to evaluate the effectiveness of various policies proposed by the city in addresses resource shortages and identifying possible trade-offs.

The reliability and accuracy of the model was ensured through the application of various validation and verification techniques, as recommended in the relevant literature. A key finding from the modelling results, which aligns with expectations is the increase in resource demands corresponding with population growth. However, the model also underscores a critical need for sustainable resource management, because of the susceptibility of the city to prolonged droughts in the future.

One significant outcome is that the water interventions planned by the CoCT appear to be effective in ensuring adequate water supply to its residents, as per the model's predictions. Nevertheless, the model reveals certain trade-offs associated with the City's policies. A notable concern is the possible over-abstraction of two major aquifers, which poses a risk to long-term water sustainability. This finding furthermore showcases the importance of highlighting the different nodes of the nexus in more detail, as this trade-off could only be revealed by modelling the individual water resources.

This research, therefore, not only assesses the efficacy of proposed policies but also provides valuable insights into the complexities and challenges of managing the water-food nexus. It emphasizes the importance of considering both immediate and long-term impacts of policy decisions, especially in the context of environmental sustainability and resource conservation.

4.8 References

Allen, R. G., & Pereira, L. S. (2006). Crop Evapotranspiration (guidelines for computing crop water requirements).

Barlas, Y. (1989). Theory and Methodology Multiple tests for validation of system dynamics type of simulation models *. European Journal of Operational Research, 42, 59-87.

Battersby, J., Tawodzera, G., Mclachlan, M., Crush, J., Battersby, J. ;, Haysom, G. ;, Tawodzera, G. ;, Mclachlan, M. ;, & Food, ". (2014). Food System and Food Security Study for the City of Cape Town. https://scholars.wlu.ca/afsunhttps://scholars.wlu.ca/afsun/27

Blake, D., Hartnady, C. J. H., Hay, E. R., McGibbon, D. C., Towers, L. C., Riemann, K., & Hugman, R. T. (2023). Geoethical issues around water security for the City of Cape Town (South Africa) and groundwater resilience in uncertain circumstances: development of the Atlantis, Cape Flats and Table Mountain Group Aquifers. Sustainable Water Resources Management, 9(5), 148. https://doi.org/10.1007/s40899-023-00928-w

Brouwer, F., Anzaldi, G., Laspidou, C., Munaretto, S., Schmidt, G., Strosser, P., Acteon, F.), & Vamvakeridou-Lyroudia, L. (2020). COMMENTARY TO SEI REPORT "WHERE IS THE ADDED VALUE? A REVIEW OF THE WATER-ENERGY-FOOD NEXUS LITERATURE." https://magic-nexus.eu/

Cairns, R., & Krzywoszynska, A. (2016). Anatomy of a buzzword: The emergence of 'the water-energy-food nexus' in UK natural resource debates. Environmental Science & Policy, 64, 164-170. https://doi.org/10.1016/J.ENVSCI.2016.07.007

Charles, A. ;, & Battersby, J. ; ; (2019). CITY OF CAPE TOWN FOOD SYSTEMS SCENARIO ANALYSIS FINAL REPORT. www.arup.com

City of Cape Town. (2019). Cape Town Resilience Strategy.

City of Cape Town. (2020). Socio-Economic Profile 2020.

City of Cape Town. (2022). OUR SHARED WATER FUTURE – Cape Town's Water Strategy.

City of Cape Town. (2023a). Cape Town Water Outlook – March 2023. www.capetown.gov.za/thinkwater.

City of Cape Town. (2023b, September 15). Dam levels. Https://Www.Capetown.Gov.Za/Family%20and%20home/Residential-Utility-Services/Residential-Water-and-Sanitation-Services/This-Weeks-Dam-Levels.

City of Cape Town. (2023c, December 13). Cape Town Open Data Portal. Https://Odp-Cctegis.Opendata.Arcgis.Com/.

Dargin, J., Daher, B., & Mohtar, R. H. (2019). Complexity versus simplicity in water energy food nexus (WEF) assessment tools. Science of the Total Environment, 650, 1566-1575. https://doi.org/10.1016/j.scitotenv.2018.09.080

Ding, K. J., Gilligan, J. M., Yang, Y. C. E., Wolski, P., & Hornberger, G. M. (2021). Assessing food-energy-water resources management strategies at city scale: An agent-based modelling approach for Cape Town, South Africa. Resources, Conservation and Recycling, 170. https://doi.org/10.1016/j.resconrec.2021.105573

Egieya, J. M., Görgens, J., & Goosen, N. (2022). Some quantitative water-energy-food nexus analysis approaches and their data requirements. In Water-Energy-Food Nexus Narratives and Resource Securities (pp. 15-31). Elsevier. https://doi.org/10.1016/B978-0-323-91223-5.00016-2

Egieya, Parker, Hofmann, V. S., Daher, B., Gorgens, J., & Goosen, N. G. (2024). Predictive simulation of the water-energy-food nexus for the City of Cape Town. https://ssrn.com/abstract=4654444

Endo, A., Tsurita, I., Burnett, K., & Orencio, P. M. (2017). A review of the current state of research on the water, energy, and food nexus. Journal of Hydrology: Regional Studies, 11, 20-30. https://doi.org/10.1016/j.ejrh.2015.11.010

FAO. (2008). An Introduction to the Basic Concepts of Food Security. www.foodsec.org

FAO. (2014). The Water-Energy-Food Nexus A new approach in support of food security and sustainable agriculture.

Ford, A. (Frederick A. (2009). Modelling the environment (Second edition.) [Book]. Island Press.

Forrester, J. W. (1961). Industrial Dynamics.

Forrester, J. W., & Senge, P. M. (1979). Tests for building confidence in system dynamics models.

Gozini, H., Zahraie, B., & Ravar, Z. (2021). System Dynamics Modelling of Water-Energy Nexus for Resource-Saving Policy Assessment. International Journal of Environmental Research, 15(2), 349-367. https://doi.org/10.1007/s41742-021-00321-5

Green Cape. (2019). Building economic resilience to water scarcity: Cape Town's response to a severe drought.

Haysom, G., Crush, J., & Caesar, M. (2017). The Urban Food System of Cape Town, South Africa (rep., pp. i-65). In Hungry Cities Partnership. Hungry Cities Report (Issue 3). https://scholars.wlu.ca/hcp

Hoff, H. (2011). Understanding the Nexus. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus.

Hussien, W. A., Memon, F. A., & Savic, D. A. (2017). An integrated model to evaluate water-energy-food nexus at a household scale. Environmental Modelling and Software, 93, 366-380. https://doi.org/10.1016/j.envsoft.2017.03.034

isee systems. (2023a, May 20). STELLA integration methods. Https://Www.Iseesystems.Com/Resources/Help/v3/Default.Htm#08-Reference/05-Computational_Details/Euler's_method.Htm?Highlight=cycle%20time.

isee systems. (2023b, October 2). Ghosts. Https://Www.Iseesystems.Com/Resources/Help/v3/Default.Htm#03-BuildingModels/Creating_variable_aliases.Htm?Highlight=ghost.

Jack, C., van Aardenne, L., Wolski, P., Pinto, I., Quagraine, K., & Kloppers, P. (2022). SmartAgri: Updated Climate Change Trends and Projections for the Western Cape. https://www.greenagri.org.za/assets/documents-/SmartAgri/Briefs-/Smart-Agri-Status-

Koppelmäki, K., Hendriks, M., Helenius, J., Kujala, S., & Schulte, R. P. O. (2022). Food-Energy Integration in Primary Production and Food Processing Results in a More Equal Distribution of Economic Value Across Regional Food Systems: Nordic Case Study from Circular Perspective. Circular Economy and Sustainability. https://doi.org/10.1007/s43615-022-00233-2

Le Roux, A., Mans, G., Cooper, A. K., Tizora, P., & Cooper, A. (2016). Land Use and Land Cover Change in the Western Cape Province: Quantification of Changes & Understanding of Driving Factors. 7th Planning Africa Conference 2016 – Making Sense of the Future: Disruption and Reinvention, 108-125.

Linacre, E. T. (1977). A simple formula for estimating evaporation rates in various climates, using temperature data alone. Agricultural Meteorology, 18, 409-424.

Matthews, S. (2021). Keep on saving – Water demand management in a time of plenty. The Water Wheel, 12-15.

Mauck, B., & Winter, K. (2021). Assessing the potential for managed aquifer recharge (Mar) of the cape flats aquifer. Water SA, 47(4), 505-514. https://doi.org/10.17159/WSA/2021.V47.I4.3801

McKenzie, R. S. (Ronald S., Siqalaba, Z. N., Wegelin, Willem., South Africa. Water Research Commission., & WRP Pty Ltd. (2012). The state of non-revenue water in South Africa (2012). Water Research Commission.

Meadows, D. H. (2008). Thinking in systems : a primer (D. Wright, Ed.) [Book]. Chelsea Green Publishing.

Nistor, M. M., Cheval, S., Gualtieri, A. F., Dumitrescu, A., Boţan, V. E., Berni, A., Hognogi, G., Irimuş, I. A., & Porumb-Ghiurco, C. G. (2017). Crop evapotranspiration assessment under climate change in the Pannonian basin during 1991-2050. Meteorological Applications, 24(1), 84-91. https://doi.org/10.1002/met.1607

Ntloedibe, M., Ngqinani, P., & Geller, L. (2020). Understanding the Living Standards Measure Segmentation in South Africa. https://www.saarf.co.za/lsm/lsms.asp

Odunitan-Wayas, F. A., Okop, K. J., Dover, R. V. H., Alaba, O. A., Micklesfield, L. K., Puoane, T., Levitt, N. S., Battersby, J., Meltzer, S. T., & Lambert, E. V. (2020). Food purchasing behaviour of shoppers from different South African socio-economic communities: results from grocery receipts, intercept surveys and in-supermarkets audits. Public Health Nutrition. https://doi.org/10.1017/S1368980020001275

Odunitan-Wayas, F., Okop, K., Dover, R., Alaba, O., Micklesfield, L., Puoane, T., Uys, M., Tsolekile, L., Levitt, N., Battersby, J., Victor, H., Meltzer, S., & Lambert, E. V. (2018). Food purchasing characteristics and perceptions of neighborhood food environment of South Africans living in low-, middle- and high-socioeconomic neighborhoods. Sustainability (Switzerland), 10(12). https://doi.org/10.3390/su10124801

Orimoloye, I. R., Belle, J. A., Orimoloye, Y. M., Olusola, A. O., & Ololade, O. O. (2022). Drought: A Common Environmental Disaster. In Atmosphere (Vol. 13, Issue 1). MDPI. https://doi.org/10.3390/atmos13010111

Petschelt, L., & Hermann, S. (2013). A Small Scale CLEW Analysis of the Cape Town Region Estimating the Effects of Climate Change on the Water Provision.

Ryan, J. (2022). Load-shedding and water shortages. Farmer's Weekly (21 October), 4-4.

Schlör, H., Märker, C., & Venghaus, S. (2021). Developing a nexus systems thinking test – A qualitative multi- and mixed methods analysis. Renewable and Sustainable Energy Reviews, 138. https://doi.org/10.1016/j.rser.2020.110543

Siderius, C., Biemans, H., Kashaigili, J., & Conway, D. (2022). Water conservation can reduce future water-energy-food-environment trade-offs in a medium-sized African river basin. Agricultural Water Management, 266. https://doi.org/10.1016/j.agwat.2022.107548

Strokal, M., Biemans, H., & van Oel, P. (2019). The challenge to balance water and food objectives for sustainable development. In Current Opinion in Environmental Sustainability (Vol. 40, pp. A1-A4). Elsevier B.V. https://doi.org/10.1016/j.cosust.2019.11.007

Sušnik, J. (2018). Data-driven quantification of the global water-energy-food system. Resources, Conservation and Recycling, 133, 179-190. https://doi.org/10.1016/j.resconrec.2018.02.023

Sušnik, J., & Staddon, C. (2021). Evaluation of Water-Energy-Food (WEF) Nexus Research: Perspectives, Challenges, and Directions for Future Research. Journal of the American Water Resources Association. https://doi.org/10.1111/1752-1688.12977 van den Heuvel, L., Blicharska, M., Masia, S., Sušnik, J., & Teutschbein, C. (2020). Ecosystem services in the Swedish water-energy-food-land-climate nexus: Anthropogenic pressures and physical interactions. Ecosystem Services, 44. https://doi.org/10.1016/j.ecoser.2020.101141

Webster, J. (2019). Cape Town Water Strategy never waste a good crisis.

Wu, L., Elshorbagy, A., Pande, S., & Zhuo, L. (2021). Trade-offs and synergies in the water-energy-food nexus: The case of Saskatchewan, Canada. Resources, Conservation and Recycling, 164. https://doi.org/10.1016/j.resconrec.2020.105192

Chapter 5: Assessing water-energy nexus dynamics for sustainable resource management in Cape Town: A system dynamics approach

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Abstract

This study addresses the critical intersection of energy and water resources within an urban context, which has not been vastly explored in WEF nexus studies. The intricate interplay between these resources, particularly within cities where energy and water consumption are linked, can be explored using a system dynamics approach. Previous studies conducted in Cape Town have examined the energy-water nexus; however, none have used system dynamics to quantify the relationships existing between water and energy. This research fills this gap by developing a system dynamics model that simulates the energy-water relationship for Cape Town's metropolitan area.

The model was rigorously evaluated across various scenarios, each providing distinct approaches to enhance water resource management in Cape Town. The scenarios tested on the water sub-model include measures focused on Water conservation and Water Demand Management (WC&WDM). These measures encompass initiatives such as leak repairs, pressure regulation, and extensive user education on water conservation. Strategies involving the development of groundwater resources for augmentation purposes were analysed to enhance water supply. The potential for wastewater reuse as a sustainable water management solution was assessed, contributing to a more integrated approach. Considerable attention has been given to evaluating the effects of temperature and rainfall changes since they are crucial factors in understanding evolving water dynamics.

The findings highlight increased water and electricity supply as key leverage points that could prevent future shortages while emphasising potential behavioural changes to reduce wasted water to enhance sustainability efforts. By 2035, the model predicted a balance between the supply and demand. Additionally, the model considered energy scenarios involving constructing a 650 MW solar farm and the integration of independent energy producers. These interventions were predicted to significantly increase the energy supply within Cape Town, effectively mitigating the risk of energy shortages. Integrating independent energy producers contributes to a more diversified and resilient energy network while reducing dependency on centralised sources. This approach aligns with global trends towards decentralised and renewable energy systems, reinforcing Cape Town's position as a forward-thinking and sustainable city.

This chapter is based on the Masters thesis work of T. Ndlela

5.1 Introduction

During the 1970s, predictions were made that if several factors such as fast-paced population growth, industrialization and resource depletion persisted without change then Earth's capacity for growth would cease within a century (Meadows et al., 1976, 2005). With resources becoming increasingly scarce, providing crucial goods and services at affordable costs becomes an urgent matter, especially for those encountering surging expenses (Ringler et al., 2013). There is a prediction that the global demand for energy and water will rise by 80% and 55%, respectively, by the year 2050 (Cai et al., 2019). This growing need triggers conflicts among different industries reliant on these resources including residential, industrial, and agricultural sectors that compete over constrained land assets which may lead to unexpected outcomes affecting climate change mitigation measures; environmental sustainability initiatives evidence-based research results indicate there can be negative implications too such as impacts on socio-economic well-being (FAO UN, 2014).

Cape Town faced a severe drought in 2018, considered one of the city's worst ever and causing widespread concern. The water reserves depleted at an alarming rate, forcing authorities to instigate stringent conservation measures. "Day Zero," representing the day when the taps would run dry loomed over residents with anxiety hanging heavily in their minds. However, through the implementation of water-saving methodologies, along with some encouraging climatic changes, Cape Town managed to narrowly avoid a catastrophic event (City of Cape Town, 2018; Ziervogel, 2019)). The drought highlighted the need for sustainable resource management while noting that adequate planning plays an integral role in safeguarding against potential crises.

An integrated approach to managing the water, energy and food resources is essential (Bhatnagar & Guettier, 2011). A holistic approach, known as a nexus study, delves into the intricate web of interactions between two or more elements. The water-energy-food nexus examines how the three resource sectors are connected, dependent on each other, and interrelated. Any changes in one sector impact the others, making it crucial to manage these sectors (Bhatnagar & Guettier, 2011; Daher & Mohtar, 2015; Chen & Chen, 2020). The nexus approach promotes sustainable development by managing resources to reduce environmental degradation, climate change, and resource depletion (Mabhaudhi et al., 2022). By identifying the connections, synergies, trade-offs, and conflicts among the sectors, decision-makers and policymakers gain valuable insights for managing all resource sectors simultaneously, instead of separately (Allouche et al., 2015; Liu et al., 2017). External factors such as population growth, economic factors, climate change, and environmental pressures complicate the relationships between water and energy systems (Mohtar & Daher, 2012).

Including external factors in the nexus approach makes it a comprehensive but complex tool. Addressing the challenges associated with managing the complex relationships among resource sectors using the nexus approach has driven the development and utilisation of various tools to unpack these complexities (Taguta et al., 2022). Given the complexity, feedback loops, nonlinearity, and time-varying nature of the nexus study done for the city of

Cape Town, a suitable tool needs to be selected to simulate complex systems, allowing for the identification of opportunities within a given context and some degree of future control (Sušnik et al., 2012).

A System Dynamics (SD) model is a valuable tool for studying the supply-demand dynamics of the water-energy-food (WEF) nexus system and achieving a dynamic balance between the energy and water sectors (Chen & Chen, 2020). The WEF-SD model simulates WEF nexus system behaviours and facilitates measuring changes in upcoming scenarios. Through conducting scenario tests using this model, we can evaluate and analyse how decisions and policies affect various resource sectors (Bahri, 2020; Bakhshianlamouki et al., 2020). The versatility of SD models, which have been demonstrated in multiple applications, makes them suitable for studying the WEF nexus in Cape Town (Simonovic, 2002; Feng et al., 2016; Hussien et al., 2017). Understanding the dynamic consumption patterns and requirements for water, energy, and food resources, while recognizing the limitations of these resources, is important. Moreover, understanding the potential outcomes of proposed solutions is essential to creating long-term plans and strategies to achieve a resource-resilient city (Sušnik & Staddon, 2021; Mabhaudhi et al., 2022).

5.2 Methods

5.2.1 Conceptual model of the water-energy nexus

The water-energy nexus is a complex system that consists of water, energy, and population. Mathematical equations are used to quantify the relationships between the variables of different subsections of the WEN system, it is difficult to simulate the WEFN system with general mathematical methods. The variables are connected using feedback loops in a system dynamics model (Bahri, 2020) The SD model is used to investigate the relations of the WEN system qualitatively and quantitatively to achieve system simulation and predictions (Bakhshianlamouki et al., 2020). The conceptualization of the WEN can be represented using a causal loop diagram, as shown in Figure 26. The sections highlighted in blue, yellow, purple, and green relate to water, energy, population, and climate subsystems, respectively. Positive correlations among variables in the WEN system are represented by red arrows, while negative correlations are represented by green arrows. The simulation model was developed using Stella Architect software.

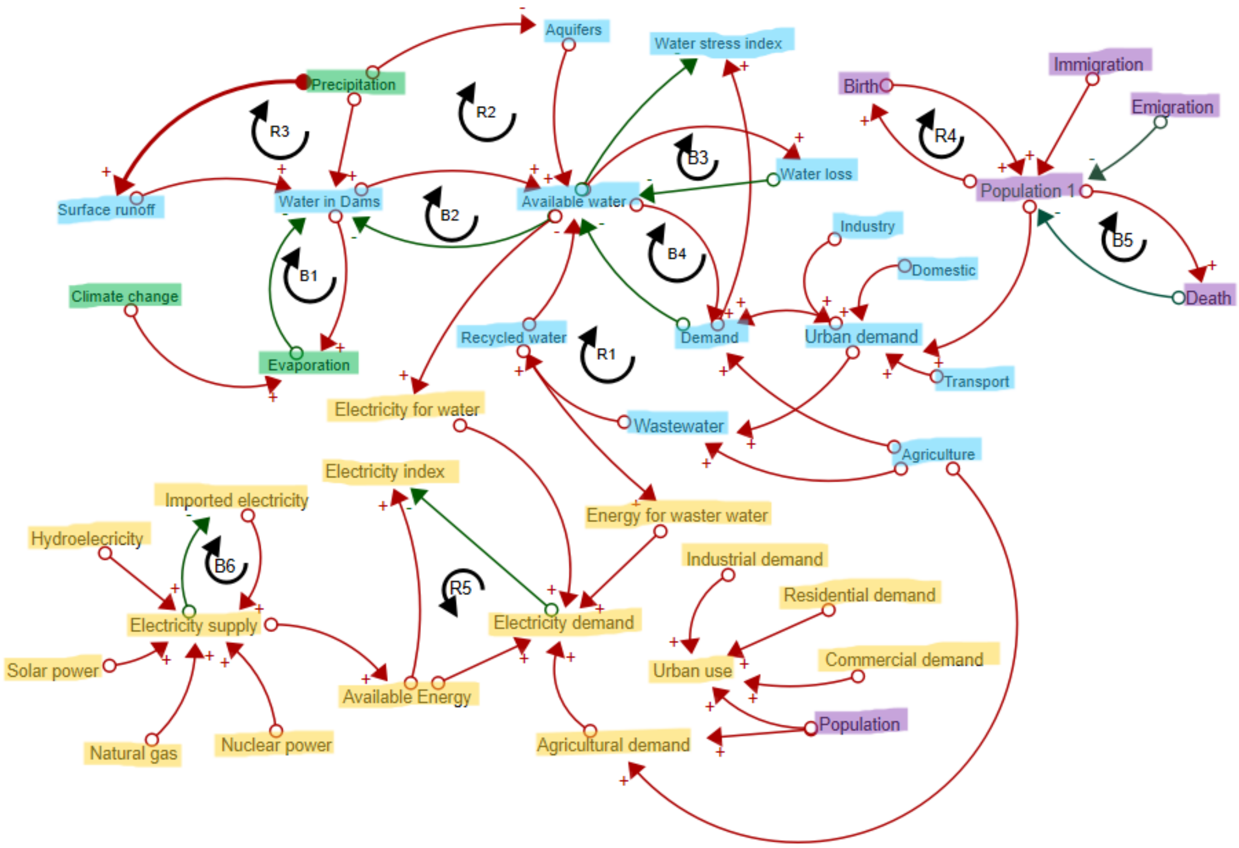

Figure 26 Water-energy nexus causal loop diagram for Cape Town.

5.2.2 WEF nexus model formulation

The water-energy nexus is a complex system comprising multiple variables, and predictions were made by considering the feedback between these variables both within and outside the 32 system. The system dynamics (SD) model, developed by Forrest (Ford, 2009; Sušnik et al., 2012), was employed in this study. The SD model developed consists of stocks (accumulation of material), flows (movement of material in and out of stores), converters (variables), and modules that define subsection boundaries. Connectors link the components, allowing for information transfer and creating feedback loops within the model. To create and execute the model, it was necessary to establish parameters, initial variables, and assumptions. The equations utilised in service activities involve subscripts for consistency; however, each service requires distinct parameters, initial variables, and assumptions, which will be addressed within their respective sub-models.

5.2.2.1 Population sub-model

This sub-model encapsulates the population dynamics of the City of Cape Town (CoCT). Population growth is a crucial factor in driving water demand. This model effectively tackles the complexities of estimating population growth and predicting how it will be distributed between urban and agricultural areas. It considers essential factors influencing population dynamics, such as mortality, birth, and migration rates. The model comprises a single stock denoted as “population” (P) whose changes are determined by births (Bs), deaths (Ds), and net migration (M_{net}). This can be expressed as in Equation 2*:*

$$P(t) = P(t_o) + \int_{t_o}^{t_n} [B_s - D_s + M_{net}]\, dt \qquad (2)$$

5.2.2.2 Water sub-model

This section explores explicitly the sub-models that revolve around water resources in Cape Town comprehensively covering the supply and demand. In this section, the supply side is composed of surface water, groundwater and recycled water, and the demand side is divided into four sectors: agriculture, industry, households, and transport. The water sub-model is related to the energy sub-model through the water used for energy production. The population sub-model is linked to the water sub-model through the demand side of the resource resources.

This water demand (WD) in the model is dependent on four variables, namely domestic (D), transport (T), industry (I), and agriculture (A). This section discusses the dependence of water demand variables on their specific growth factor (population). It provides an elaboration on how stocks and flows govern these demands in the following manner:

$$WD(t) = D(t) + T(t) + I(t) + A(t) \qquad (3)$$

Where,

$$D(t) = D(t_o) + \int_{t_o}^{t_n} D * P\, dt \qquad (4)$$

$$T(t) = T(t_o) + \int_{t_o}^{t_n} T * P\, dt \qquad (5)$$

$$I(t) = I(t_o) + \int_{t_o}^{t_n} I * P\, dt \qquad (6)$$

$$A(t) = A(t_o) + \int_{t_o}^{t_n} A * P\, dt \qquad (7)$$

The surface water and groundwater that contribute to the water available are presented as stocks, with several flows showing the movement of water into and out of these sources. Equation 8 shows how changes in rainfall (R), surface runoff (Sr), evaporation rate (E), and monthly water drawn from the dams (Wo) dynamically impact the stock representing water in dams (W). In Equation 8, the inflow of available water (AW) is determined by the water from the dams(W) and the aquifers (Aq). The outflow from the available water stock consists of unaccounted-for water (UAW), which includes losses due to infiltration, maintenance issues causing leaks, and evaporation and the water fed into the different demand areas (WD).

$$W(t) = W(t_o) + \int_{t_o}^{t_n} [R + Sr - E - Wo]\, dt \qquad (8)$$

$$AW(t) = AW(t_o) + \int_{t_o}^{t_n}[W + Aq + Re - UAW - WD]\, dt \quad (9)$$

Estimating evaporation rates is commonly accomplished using the Penman-Monteith equation (Equation 10). This equation incorporates h elevation in metres (h), mean temperature (T), latitude in degrees (A) and mean dewpoint (T_d) as crucial factors that impact the evaporation rate of water from a specific surface, giving the units in mm/day. The Penman-Monteith equation can still accurately estimate evaporation rates using solely temperature data in its basic form. This makes it an advantageous resource for situations where thorough weather information is not easily obtainable (Linacre, 1977).

$$E_O = \frac{\frac{700T_m}{(100-A)} + 15(T - T_m)}{(80-T)} \quad (10)$$

$$T_m = T + 0.006h \quad (11)$$

Equation 11 yields values that deviate by approximately 0.3 mm day^{-1} for yearly averages, 0.5 mm day^{-1} for monthly averages, and 0.9 mm day^{-1} per week or a difference of about 1.7mm day^{-1} when compared to observed data results. Suppose the precipitation is a minimum of 5 mm per month and $\mathrm{T} - \mathrm{T_d}$ equals or exceeds 4°C. In that case, one can derive monthly mean values for the term ($\mathrm{T} - \mathrm{T_d}$) from an empirical table or by using Equation 12 (Linacre, 1977).

$$(T - T_d) = 0.0023h + 0.37\,T + 0.53\,R + 0.35R_{ann} - 10.9°C \quad (12)$$

5.2.2.3 Energy sub-model

In the energy sub-model, the energy supply consists of imported electricity (E_I), and electricity generated from natural gas (E_{ng}), nuclear power (E_{np}), solar (E_s) and hydro (E_h) while the supply comprises of energy demand for agriculture, industry, commercial and domestic. The energy sub-model is connected to the water sub-model through the energy requirements for water extraction, processing, and distribution. The population sub-model is linked to the energy sub-model through the demand side of the resource.

It is essential to account for the possibility of an increase in solar energy capacity due to advancements in technology with time. An exponential growth equation is used to achieve this. The solar energy (E_s) in the model depends on the initial solar capacity (E_{so}), the growth factor that incorporates the growth rate (k) and time (t) (Schwartz, 2016; Kurinec, 2022).

$$E_s = E_{so} * e^{kt} \quad (13)$$

Imported electricity (E_I) was assumed to be the difference between the energy the city requires and what is supplied from the sources. It is calculated by Equation 14.

$$E_I = E_{required} - (E_s + E_h + E_{np} + E_{ng}) \quad (14)$$

Total Electricity generated (E_T) is the sum of contributions from all energy sources.

$$E_T = E_I + E_s + E_h + E_{np} + E_{ng} \quad (15)$$

The overall electrical power demand (E_D) as shown in Equation 16, represents the combined quantity of energy needed by different categories of consumers. The model encompasses residential (E_R), commercial (E_C),), industrial (E_{Ind}) and agricultural (E_A).

$$E_D = E_A + E_{Ind} + E_R + E_C \quad (16)$$

Were,

$$E_R\ (t) = E_R(t_o) + \int_{t_o}^{t_n} E_R * P\, dt \quad (17)$$

$$E_C\ (t) = E_C(t_o) + \int_{t_o}^{t_n} E_C * P\, dt \quad (18)$$

$$E_{Ind}\ (t) = E_{Ind}(t_o) + \int_{t_o}^{t_n} E_{Ind} * P\, dt \quad (19)$$

$$E_A\ (t) = E_A(t_o) + \int_{t_o}^{t_n} E_A * P\, dt \quad (20)$$

5.2.3 Model validation

To guarantee the accurate reproduction of the system's behaviour, it is imperative to validate the System Dynamics (SD) model before it is implemented. Following the utilization of the SD model for simulation, a set of key variables was chosen for testing. Assessment of the reliability of the SD model was conducted using behaviour structure and model behaviour. The structure was tested using the extreme conditions test. This test examines the believability of rate equations when hypothetical maximum and minimum values of related stock variables are incorporated into the model. Additionally, the model behaviour sensitivity was used to assess the behaviour of the model. This method explores if plausible adjustments to model parameters can lead the model to fail previously passed behaviour tests.

5.2.4 Scenario testing

Once the model had been confirmed and validated, scenario testing was conducted to explore the impacts of different strategies and policies. This involved modifying existing parameter values or introducing the documented plans of the CoCT to observe how the model and the real-world system respond.

5.2.4.1 Changes in climate

Reductions in precipitation will decrease runoff and compromise water quality, causing depletion of available resources. Rising temperatures will increase evaporation rates and worsen drought severity, with projections indicating that an average 3.5% amplification could occur due to a 1.8°C temperature escalation. These changes threaten the economic stability of this region known for diverse agriculture, as limited water sources coupled with elevated evaporation levels present serious challenges.

5.2.4.2 Water scenarios

Table 3 summarises the changes that were made to different variables in the scenario testing exercise. These influenced variables are categorised based on their corresponding interventions and details regarding the magnitude of change and its implementation year provided. It should be noted that certain modifications in the model occur as step functions, whereas others are presumed to transform over designated periods.

Table 3: Summary of Water Scenario Input parameters (Van Weele & Maree, 2018; City of Cape Town, 2022)

Scenario	Variable	2017	2025	2035
WC&WDM	Fraction of water lost from the system (%)	34.3	20	10
	Reduction of domestic water consumption %	5	8	10
Groundwater	Fraction of extracted underground water (%)	40	50	60

Scenario	Variable	2017	2025	2035
Wastewater	Fraction of recycled wastewater and fed back into the system (%)	55	70	85
Climate change	Decrease in Precipitation (%)	10	15	20
	Temperature change (°C)	1	1.5	1.8

5.2.4.3 Energy scenarios

Cape Town is confronted with increasing energy requirements and a pressing need for sustainable power sources. Incorporating independent electricity producers combined with the development of a 650 MW solar farm emerges as the ideal solution for the city of Cape Town (City of Cape Town, 2023). Table 4 summarises the energy scenarios tested on the model.

Table 4: Summary of Energy Scenario Input parameters (City of Cape Town, 2023)

Scenario	**Variable**	**2028**	**2035**
Solar farm	Energy produced (MW)	650	
Integrating independent electricity producers	Fraction of energy from independent energy producers (%)	10	20

5.3 Results and Discussion

5.3.1 Model validation results

5.3.1.1 Extreme condition test

The extreme condition tests that were conducted on the model will be explained here. The test specifically analysed the monthly demand. It was presumed that up until 2025, the monthly demand would remain consistent with business as usual (BAU). After that, it decreased to almost zero in equal intervals between 2025 and 2035, as shown in Figure 27. This decrease adversely impacted domestic and industrial water demands, subsequently influencing overall water requirements leading to a deficit between supply and demand.

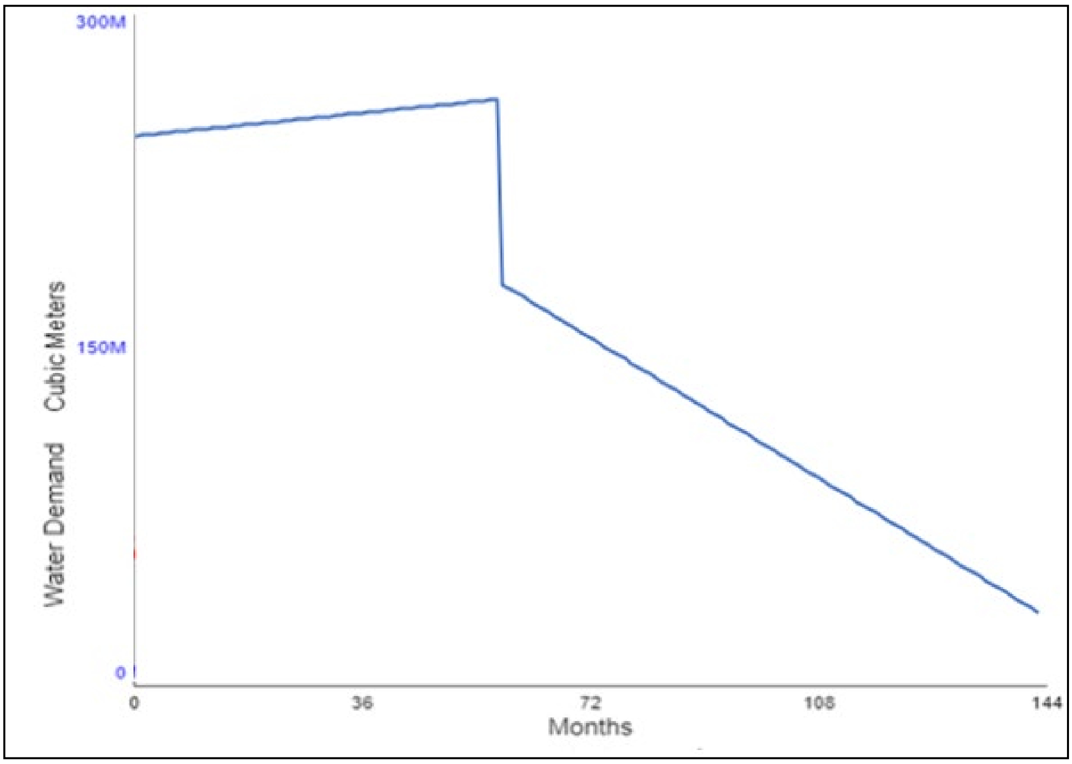

Figure 27 Results for water demand extreme condition test

The difference between the supply and demand is also shown in extreme conditions and compared to the BAU results. In Figure 28, both the BAU scenario and the outcomes obtained from conducting an extreme condition test using the model are shown. An analysis of this figure reveals that when the water supply is increased by 50%, the model responds reasonably by reducing the difference between the water supply and demand. This proves the model's ability to generate credible predictions while accurately accounting for parameter input values.

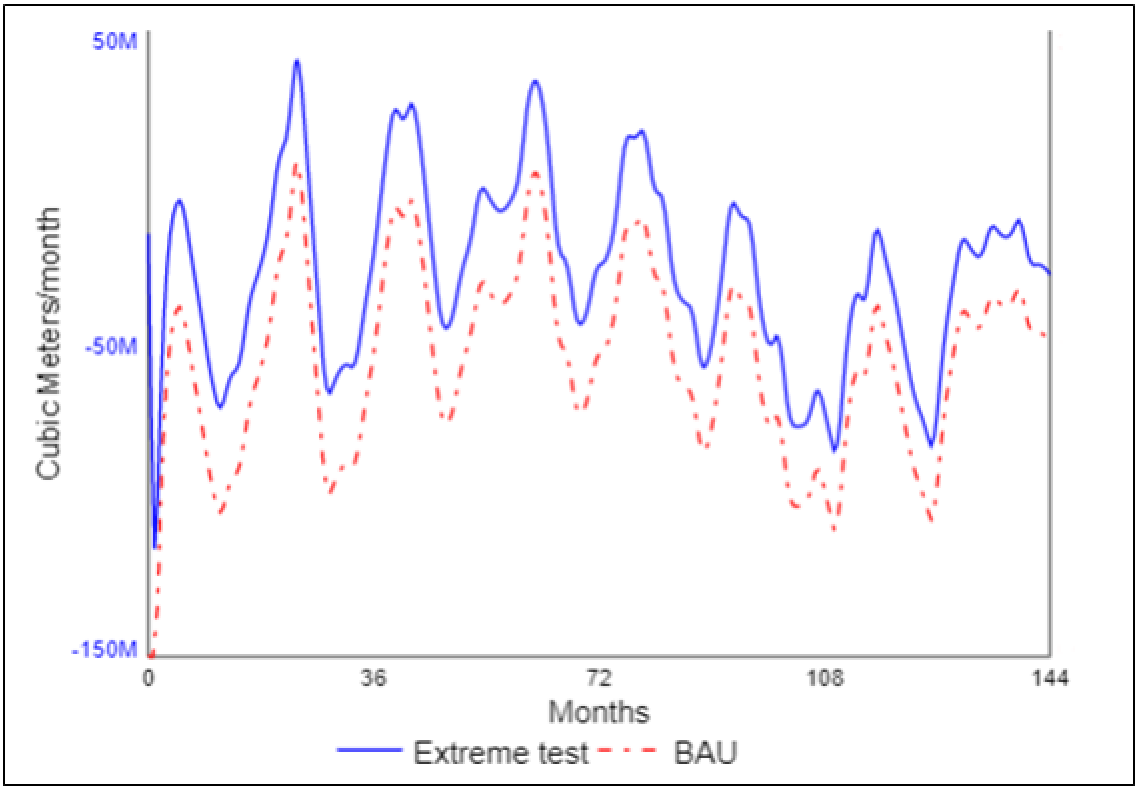

Figure 28 Comparison of extreme conditions test and 'business as usual' (BAU)

5.3.1.2 Behaviour sensitivity test

The graphical behaviour of monitored variable during the sensitivity analysis, facilitated by the "Monte Carlo" tool is responsive to change as shown in Figure 29 Variables influencing the total system demand were particularly sensitive. Precipitation is crucial in regulating the system's water supply, acting as a critical source for dams and groundwater reserves. Montecarlo simulations were done on the water drawn from dams while the results were observed on the available rainfall. The smallest change showed noteworthy results on the overall water available. This shows great sensitivity of the model.

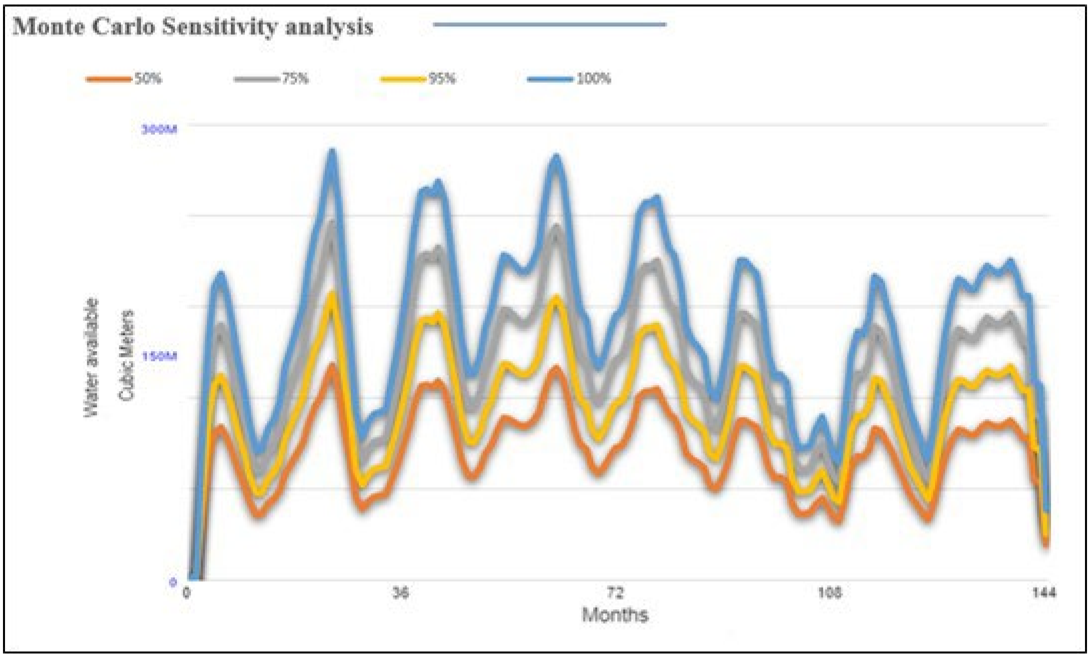

Figure 29 Results of Monte-Carlo sensitivity test

5.3.2 Model results

This section presents the results obtained from the Stella Architect model. The development of the model involved putting a specific dataset, outlined in Appendix A, into various variables before running it to derive outcomes. For example, Figure 30 illustrates how the population sub-model provides an interconnected representation showcasing varying degrees of influence among its variables.

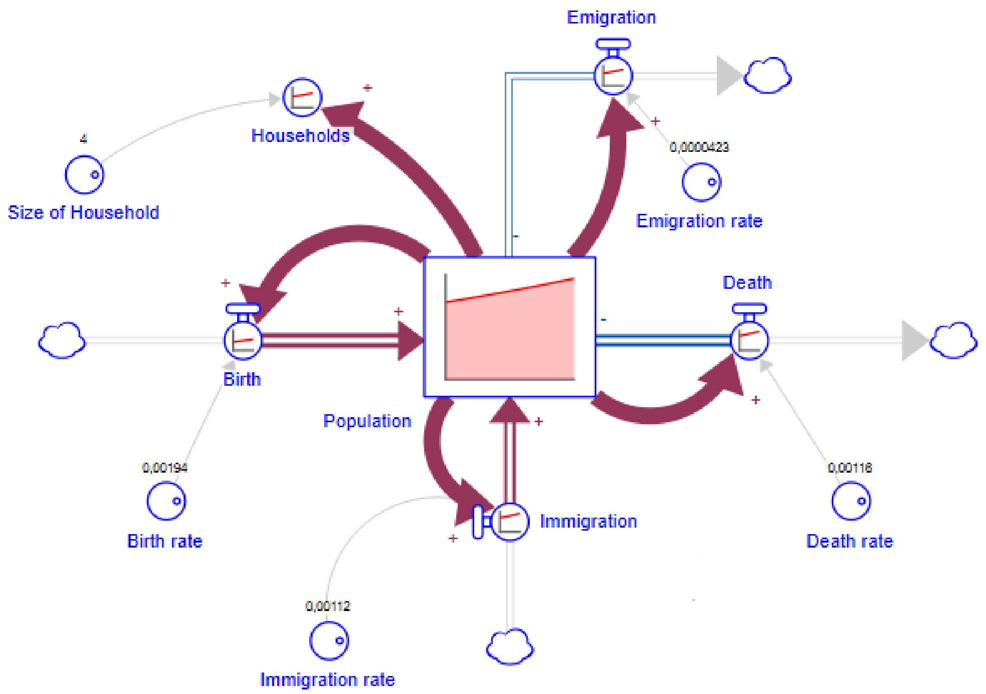

Figure 30 Population Sub model: Visual Representation of Interconnected Relationships and Variable Influences with Varying Degrees of Impact

In Figure 30, the direct impact of the population variable on birth, death, immigration, and emigration variables is shown by thick maroon lines. At the tip of these bold connections, a positive charge is indicated, symbolizing a positive relationship between the population and the other variables. The positive charge shows the direct and proportional relationship where population changes positively impact the values of birth, death, immigration, and emigration. The faint lines that can be seen between households and the size of the household. These connections show a subtle influence in the Population dynamics representing that there is an indirect correlation. They have effects on their respective flows which have a greater effect on the population stock.

5.3.3 Scenario testing results

To ascertain various water strategies, a review of the Cape Town strategy document which highlighted civic efforts aimed at augmenting supply while curtailing demand took place. Similarly, the possible energy solutions were taken from the 2023 Cape Town Energy Solutions Plan along with recommendations provided by the Department of Energy to integrate independent electricity producers into existing grids.

5.3.3.1 Water sub-model scenario test results

Scenario 1: business as usual (BAU)

Figure 31 visually shows how water demand and supply are expected to change over time. The current evidence indicates that water demand will increase from 175 Mm^3 to 200 Mm^3

per month in Cape Town at a rate of 1.47% per year. Balancing the summer and winter trends in water availability, a projected deficit of around 80 million cubic metres per month between water supply and demand is anticipated by 2035 in the City of Cape Town.

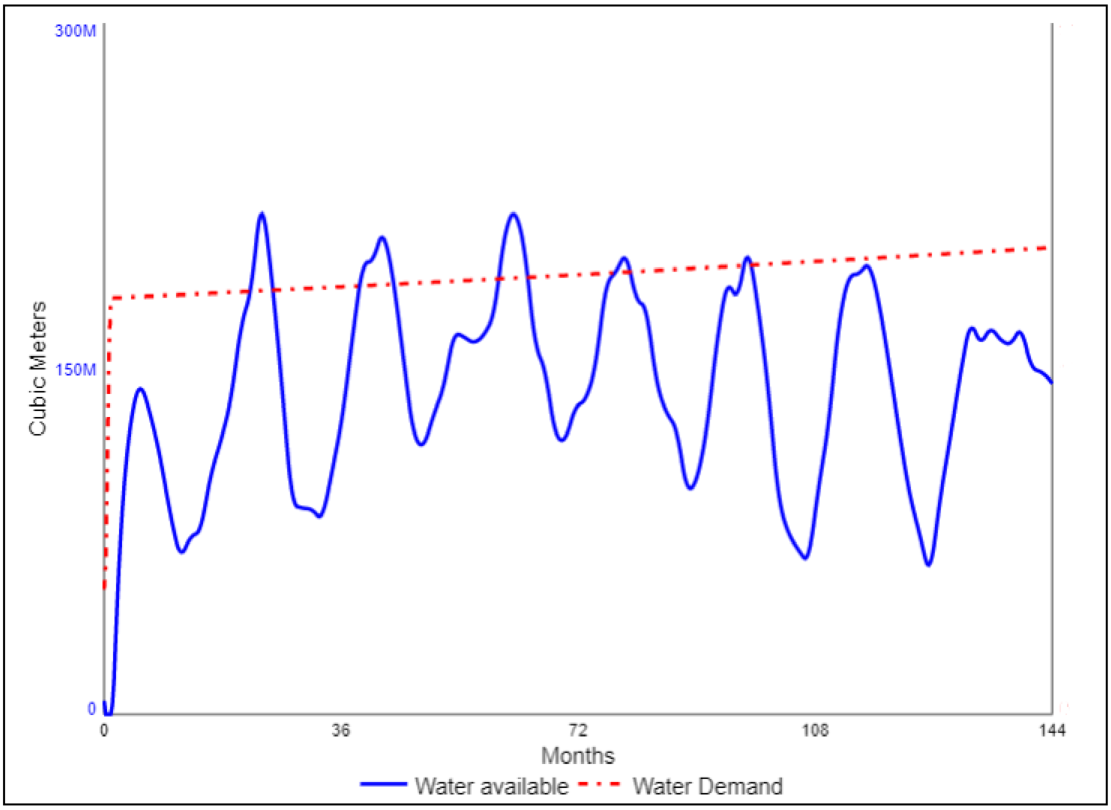

Figure 31 Water Supply and Demand: Results for BAU scenario

Scenario 2: Water conservation and water demand management (WC&WDM)

The water supply demand after implementing WC&WDM is shown in Figure 32. This graph shows an increase in water availability of approximately 23%. This is caused by increasing and reducing the losses from 34.3% to 10% by 2035. Balancing the water supply trend reveals a deficit of approximately 50 Mm^3 per month. This graph demonstrates that WC&WDM successfully increases the water available for Cape Town. However, its effectiveness is not sustainable but coupling with other interventions may result are recommended for sustainable water management.

It was discovered that reducing the domestic water consumption by 10% results in a decrease in water demand of 3.5% by the year 2035 under the WC&WDC scenario when compared with the Business as Usual (BAU) scenario.

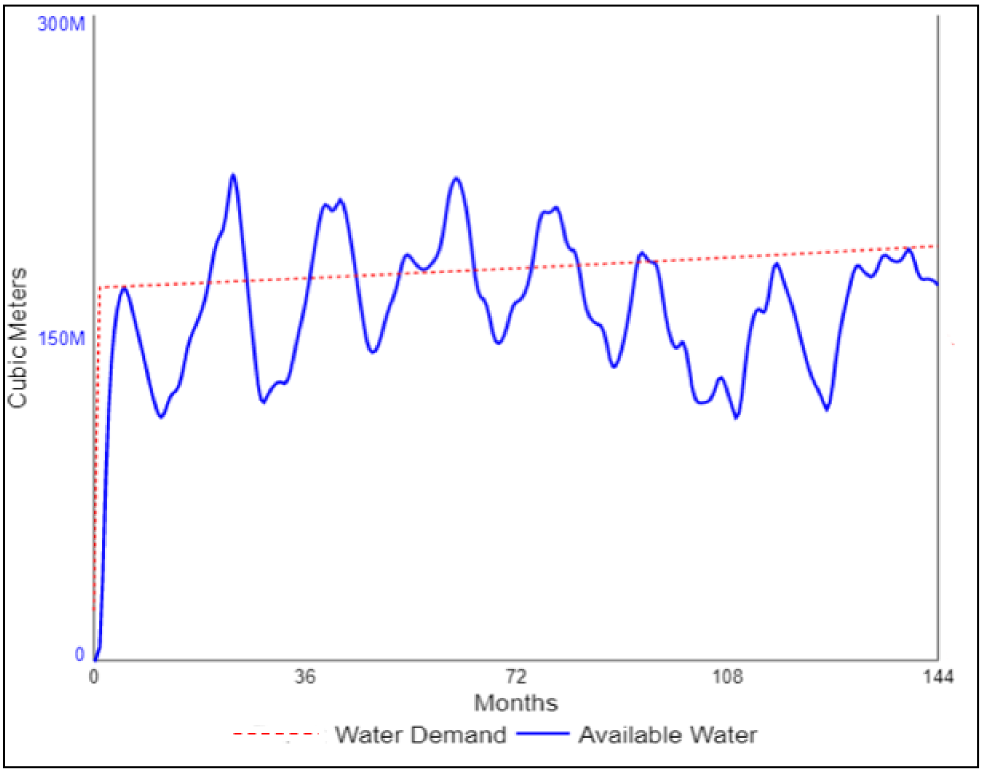

Figure 32 Water Supply and Demand: Results for water conservation and water demand management scenario

Figure 33 shows how the Unaccounted-for Water (UAW) compares with, comparing outcomes derived for both BAU scenarios and those obtained from simulating the WC&WDM scenario about the reduction of leaks and losses across respective treatment and distribution systems. The evidence suggests that thriving water demand reduction-focused approaches result in significant decreases in the UAW volumes compared to standard practices. This comparison offers a viable solution for increasing the water available.

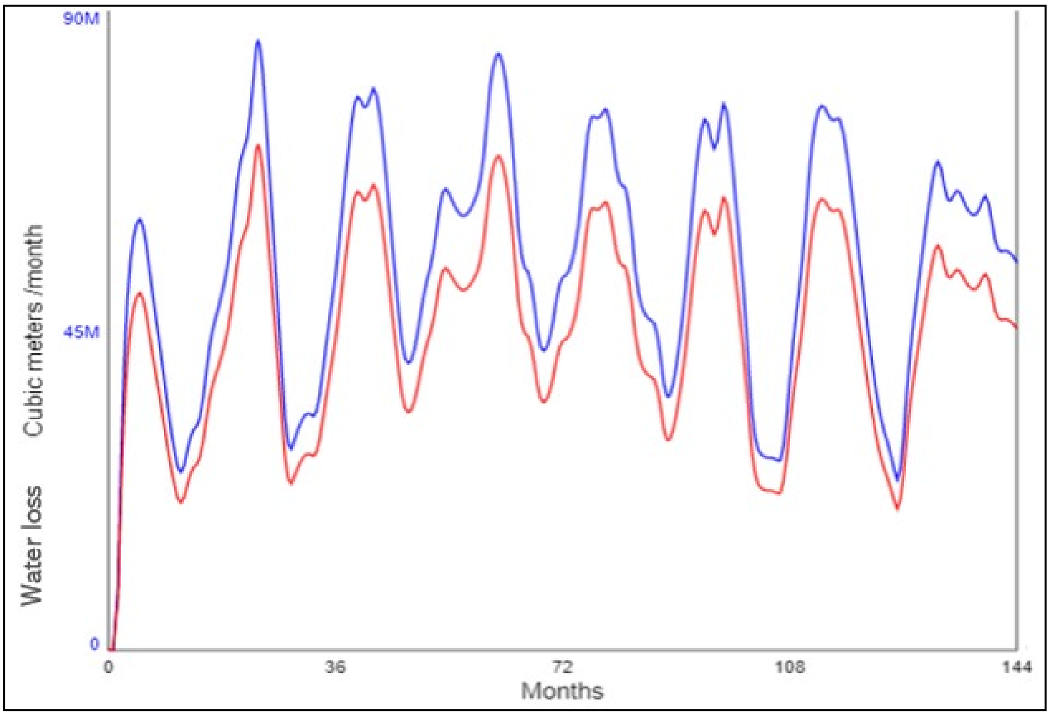

Figure 33 Water Losses: Business as Usual (BAU) versus the WC&WDC scenario

Scenario 3: WC&WDC and groundwater extraction

Figure 34 shows the comparison between water supply and demand when a scenario combining WC&WDC and the 20% increment in groundwater exploration is simulated. The figure shows an increase of 33% in the available water for the city of Cape Town by 2035. The increase of water extracted from the aquifers was simulated and predicted an increase of approximately 10% to the available water. The combination of the two interventions gives a better result. By 2035, the difference between supply and demand is estimated to be zero, indicating that the water demand is close to the available water supply.

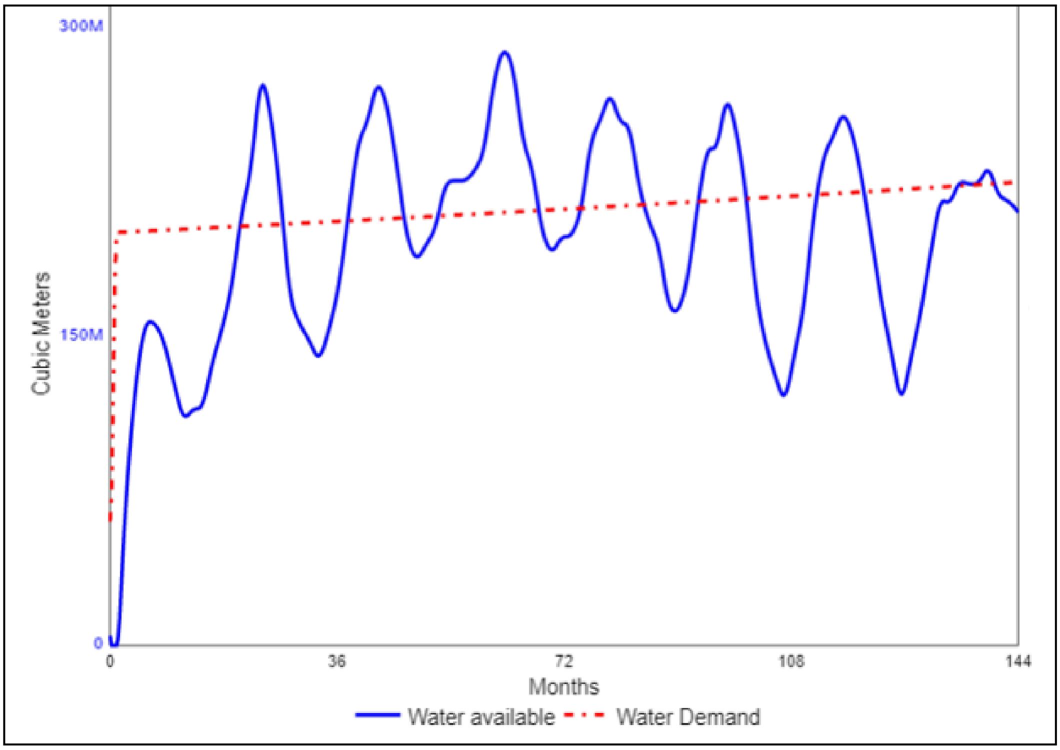

Figure 34 Water Supply and Demand: Results for a combination of water conservation and water demand management and increased groundwater extraction scenario.

Scenario 4: WC &WDC, increased groundwater and wastewater reuse

Figure 35 illustrates the comparison between water supply and demand for a combination of the 3 interventions. In this scenario balancing the water supply trend shows that the water supply will increase by an additional 7% by 2035. with the model predicting a near-perfect balance between water demand and supply by 2035. This gives a 2% surplus of water available for the city of Cape Town. This optimistic projection suggests that implementing an optimised wastewater reuse strategy at an efficiency rate of 85% can adequately fulfil Cape Town's growing need for water.

Assuming the priorities of Scenario 4, which emphasises enhancing wastewater reuse, there is an expected rise in demand for wastewater treatment. The model predicts that by 2035, treatment facilities will be working at maximum capacity and dealing with about 900,000 cubic metres of sewage each month. This significant usage highlights how critical recycling water plays in increasing the city's available water supply.

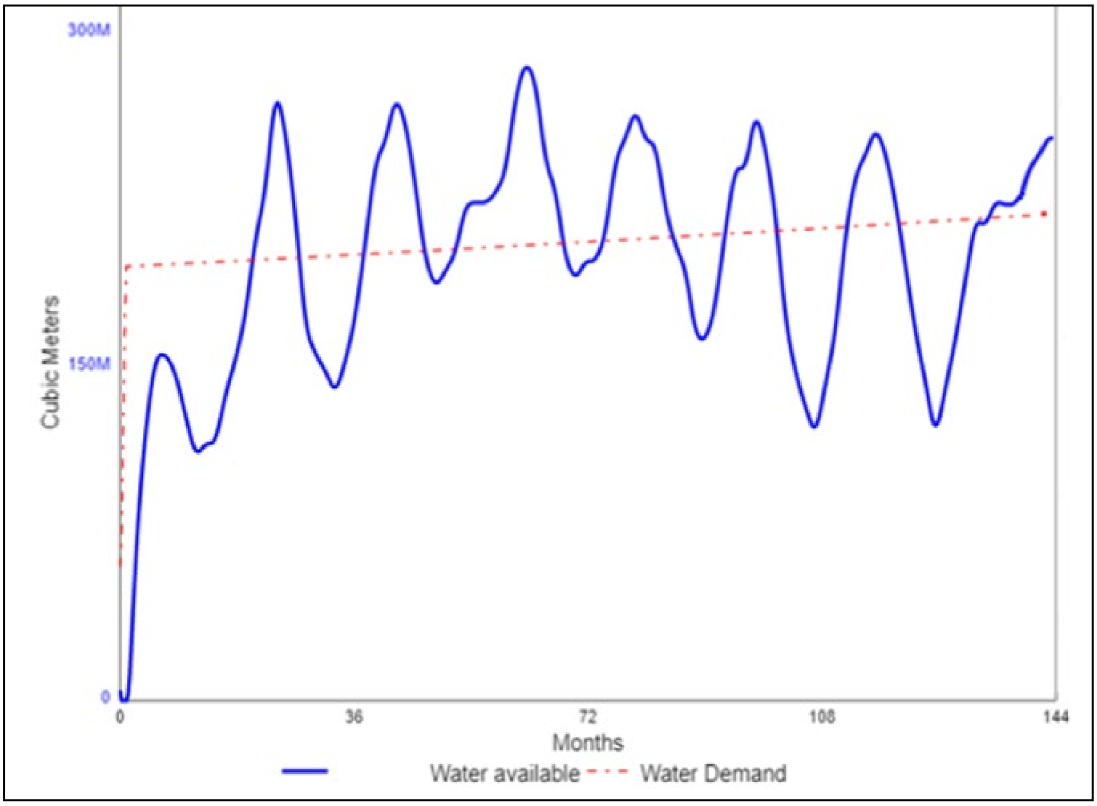

Figure 35 Water Supply and Demand: Results for a combination of WC&WDC, increased groundwater extraction and increased wastewater reuse scenario.

Scenario 5: Climate change scenario

Figure 36 shows the comparison between water supply and demand for the temperature increase and rainfall decrease. This scenario shows a decrease in the water available by approximately 23%. This is because of reduced rainfall which is the main source for dam and aquifer refill. It can also be attributed to the increase in evaporation of water from dams due to an increase in temperature. The model predicts an increase of approximately 30 million cubic metres difference between the water supply and demand by 2035 compared to the BAU scenario. Secondly, under climate change conditions, it is projected that water supply will become more unpredictable, characterised by frequent periods of drought.

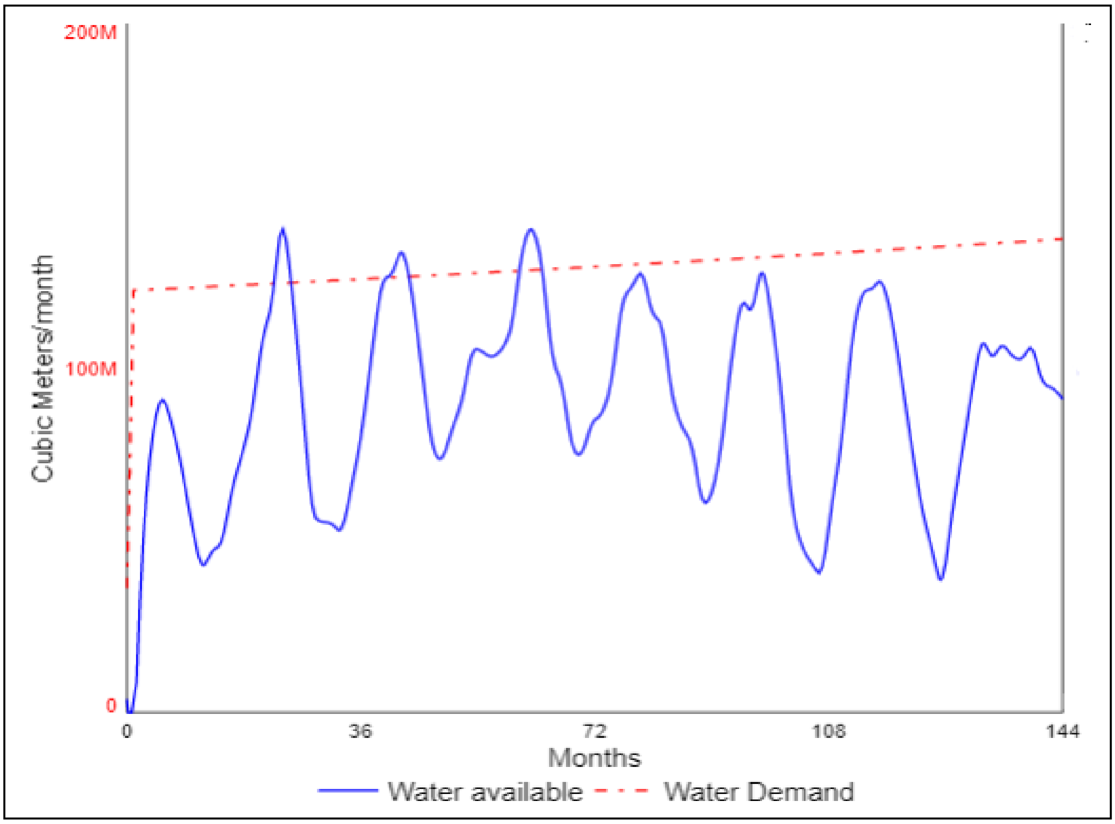

Figure 36 Water Supply and Demand: Results for a combination of temperature increase and rainfall decrease scenarios.

5.3.3.2 Energy model scenario test results

Scenario 1: Business as usual (BAU)

Figure 37 shows that comparison between the energy demand and supply for the city of Cape Town for a business-as-usual scenario. Significant change is noted at the 36-month point. This is due to the historical data fed into the model. This is imitating the 2018 transition which initiated the load shedding. The model shows that domestic demand contributes to the overall demand. In 2017, the residential sector represented 76.1% of total electricity demand from end users. By 2035, the model shows that the proportion rises to approximately 77.9%. The distribution of electricity demand across sectors shows minimal change between 2022 and 2035.

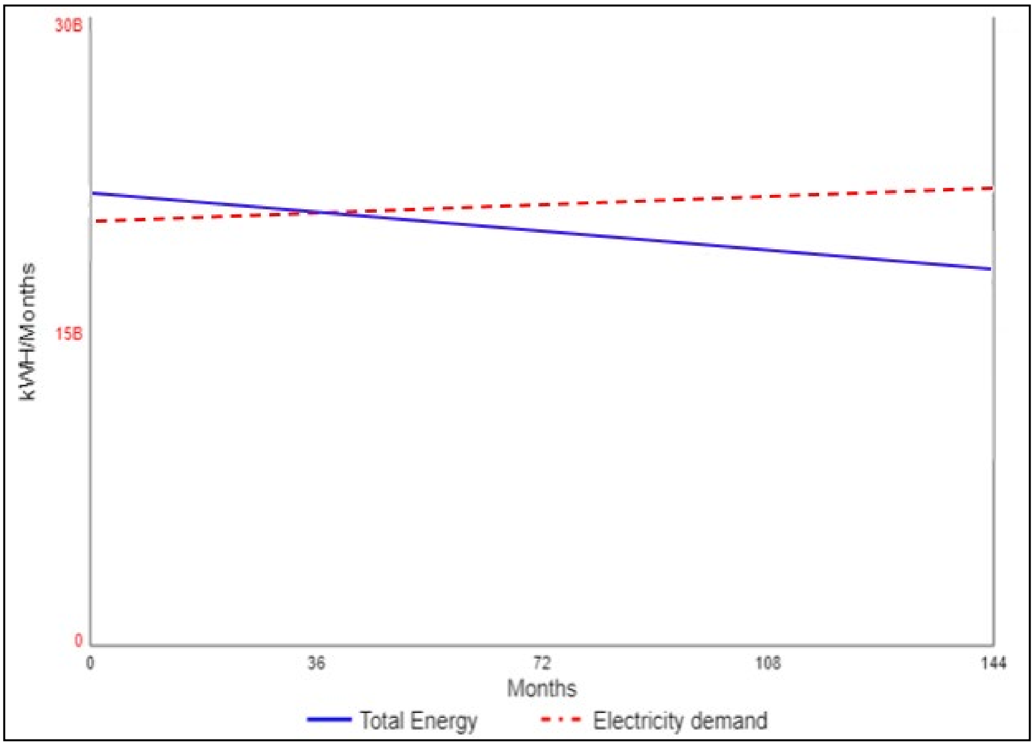

Figure 37 Energy supply and demand: Results for BAU scenario

Scenario 2: Solar farm and integrating independent electricity producers

As shown in Figure 38, the interventions result in a significant increase in power availability. This achievement can be seen through an energy supply graph being greater than the energy demand graph. The total energy supply will increase by 34% in 2035. The implementation of this scenario was assumed to be completed in the next 5 years. The graph shows the gradual increase of electricity supply for 5 years then becoming constant after that up to 2035. The integration of independent electricity producers did not produce a notable change compared to the business-as-usual scenario. Combining the integration of independent producers and the 650 MW solar farm had a substantial difference by 2035, as shown in the graph.

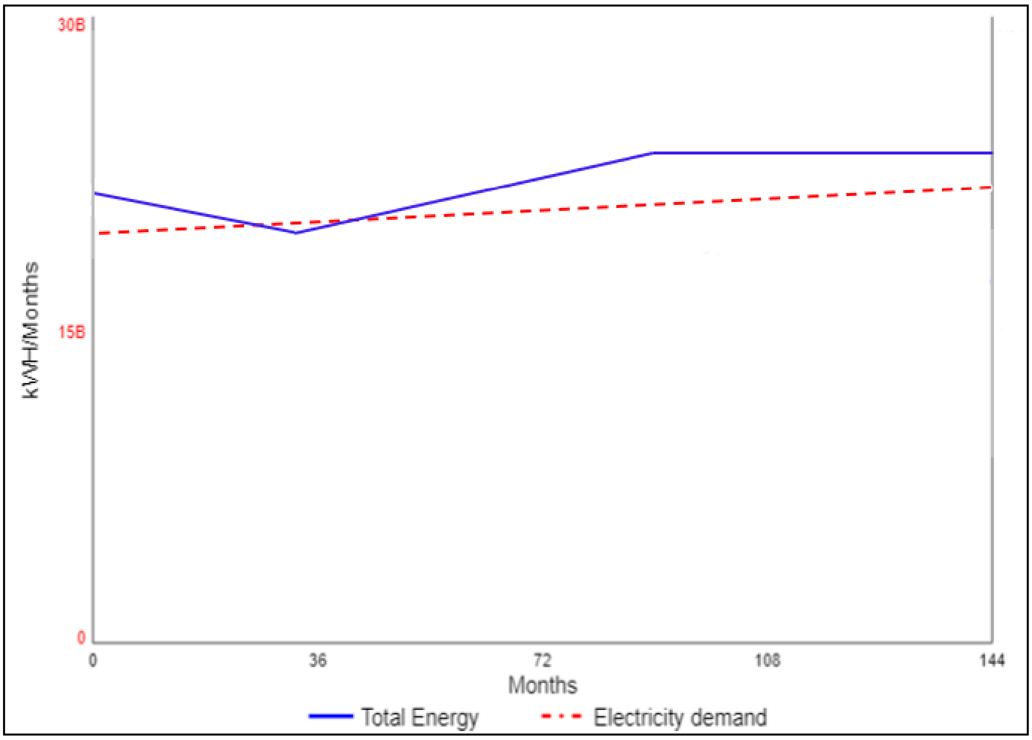

Figure 38 Energy Supply and Demand: Results for a combination of 650 MW solar farm and integrating independent electricity.

5.4 Conclusion

A qualitative model was developed, highlighting the interdependence of population dynamics, water supply, and energy sources and demands. The system dynamics model for the energy-water nexus in Cape Town proved to be a valuable tool, providing insights into the complex resource dynamics within the city limits. Scenario testing using the System Dynamics Model revealed crucial insights into the effects of interventions on the water-energy system in Cape Town.

In scenario testing, the model projected a potential water crisis by 2035, necessitating water-saving interventions. Water conservation and demand management strategies showed effectiveness but were not entirely sustainable. Combining interventions such as groundwater exploration and wastewater reuse proved to be a more robust solution, contributing to informed decision-making for water resource management. In the energy scenario, addressing electricity shortages through a combination of solar farms and independent electricity producers significantly increased the available electricity, mitigating energy challenges in Cape Town.

In conclusion, the study successfully achieved its objectives, contributing valuable insights into the water-energy nexus in Cape Town and providing recommendations for sustainable resource management.

5.5 References

Allouche, J., Middleton, C. & Gyawali, D. 2015. Technical Veil, Hidden Politics: Interrogating the Power Linkages behind the Nexus. *Water Alternatives*. 8(1):610-626. Available: www.water-alternatives.org.

Bahri, M. 2020. Analysis of the Water, Energy, Food and Land Nexus Using the System Archetypes: A Case Study in the Jatiluhur Reservoir, West Java, Indonesia. *Science of the Total Environment*. 716(3):1-15. DOI: 10.1016/j.scitotenv.2020.137025.

Bakhshianlamouki, E., Masia, S., Karimi, P., van der Zaag, P. & Sušnik, J. 2020. A System Dynamics Model to Quantify the Impacts of Restoration Measures on the Water-Energy-Food Nexus in the Urmia Lake Basin, Iran. *Science of the Total Environment*. 708(1):1-17. DOI: 10.1016/j.scitotenv.2019.134874.

Bhatnagar, S. & Guettier, W.P. 2011. *Bonn 2011 Conference: The Water Energy and Food Security Nexus – Solutions for the Green Economy*. Bonn, Germany.

Cai, Y., Cai, J., Xu, L., Tan, Q. & Xu, Q. 2019. Integrated Risk Analysis of Water-Energy Nexus Systems Based on Systems Dynamics, Orthogonal Design and Copula Analysis. *Renewable and Sustainable Energy Reviews*. 99:125-137. DOI: 10.1016/J.RSER.2018.10.001.

Chen, Y. & Chen, W. 2020. Simulation Study on the Different Policies of Jiangsu Province for a Dynamic Balance of Water Resources under the Water-Energy-Food Nexus. *MDPI*. 1(1). DOI: 10.3390/w12061666.

City of Cape Town. 2018. *Mayor Plato announces City's move to Level 3 "recovery" restrictions*. Cape Town. Available: https://www.capetown.gov.za/Mediaandnews/MayorPlatoannouncesCity'smovetoLevel3'recovery%E2%80%99restrictions [2022, October 06].

City of Cape Town. 2022. *City of Cape Town Water Services Development Plan-IDP Water Sector Input Report*. Cape Town.

City of Cape Town. 2023. *Our Shared Energy Future: The 2050 Energy Strategy for the City of Cape Town*. Cape Town.

Daher, B.T. & Mohtar, R.H. 2015. Water-Energy-Food (WEF) Nexus Tool 2.0: Guiding Integrative Resource Planning and Decision-Making. *Water International*. 40(5-6):748-771. DOI: 10.1080/02508060.2015.1074148.

Feng, M., Liu, P., Li, Z., Zhang, J., Liu, D. & Xiong, L. 2016. Modelling the Nexus Across Water Supply, Power Generation and Environment Systems using the System Dynamics Approach: Hehuang Region, China. *Journal of Hydrology*. 543(2):344-359. DOI: 10.1016/J.JHYDROL.2016.10.011.

Food and Agriculture Organization of the United Nations. 2014. *The Water-Energy-Food Nexus: A new approach in support of food security and sustainable agriculture*. Rome.

Ford, A. 2009. *Modelling the Environment: An Introduction to System Dynamics Modelling of Environmental Systems*. 1st ed. vol. 2. Washington, D.C: Island Press.

Hussien, W.A., Memon, F.A. & Savic, D.A. 2017. An Integrated Model to Evaluate Water-Energy-Food Nexus at a Household Scale. *Environmental Modelling & Software*. 93(1):366-380. DOI: 10.1016/J.ENVSOFT.2017.03.034.

Kurinec, S.K. 2022. Silicon Solar Photovoltaics: Slow Ascent to Exponential Growth. 221-243. DOI: 10.1007/978-3-030-91546-9_15.

Linacre, E.T. 1977. *A simple formula for estimating rates in various climates, using temperature data alone*.

Liu, J., Yang, H., Cudennec, C., Gain, A.K., Hoff, H., Lawford, R., Qi, J., de Strasser, L., Yillia, P.T. & Zheng, C. 2017. Challenges in Operationalizing the Water-Energy-Food Nexus. *Hydrological Sciences Journal*. 62(11):1-8. DOI: 10.1080/02626667.2017.1353695.

Mabhaudhi, T., Senzanje, A., Modi, A., Jewitt, G. & Massawe, F. 2022. *Water-Energy-Food Nexus Narratives and Resource Securities: A Global South Perspective*. South Africa: Candice Janco, Elsevier.

Meadows, D.H., Randers, Jørgen., Meadows, D.L. & Meadows, D.H. 2005. *Limits to growth: the 30-year update.* 1st ed. London: Earthscan.

Meadows, D.L., Behrens Iii, W.W., Meadows, D.H., Naill, R.F., Randers, J. & O Zahn, E.K. 1976. *Dynamics of Growth in a Finite World*. vol. 12. Cambridge: MA: Wright-Allen Press.

Mohtar, R.H. & Daher, B. 2012. Water, Energy, and Food: The Ultimate Nexus, in *Encyclopedia of Agricultural, Food, and Biological Engineering*, 2nd ed., Indiana, USA: CRC Press. 1-5. DOI: 10.1081/e-eafe2-120048376.

Ringler, C., Bhaduri, A. & Lawford, R. 2013. The Nexus Across Water, Energy, Land and Food (WELF): Potential for Improved Resource Use efficiency? *Current Opinion in Environmental Sustainability*. 5(6):617-624. DOI: 10.1016/j.cosust.2013.11.002.

Schwartz, E.I. 2016. The hazards of exponential growth for the solar industry – and how innovating stronger business models is key to survival, in *SOLAR 2016 – American Solar Energy Society National Solar Conference 2016 Proceedings*, Lexington, Massachusetts: American Solar Energy Society. 28-32. DOI: 10.18086/solar.2016.01.23.

Simonovic, S.P. 2002. World Water Dynamics: Global Modelling of Water Resources. *Journal of Environmental Management*. 66(3):249-267. DOI: 10.1006/JEMA.2002.0585.

Sušnik, J. & Staddon, C. 2021. Evaluation of Water-Energy-Food (WEF) Nexus Research: Perspectives, Challenges, and Directions for Future Research. *Journal of the American Water Resources Association (JAWRA)*. 58(6):1189-1198. DOI: 10.1111/1752-1688.12977.

Sušnik, J., Vamvakeridou-Lyroudia, L.S., Savić, D.A. & Kapelan, Z. 2012. Integrated System Dynamics Modelling for Water Scarcity Assessment: Case Study of the Kairouan region. *Science of The Total Environment*. 440(1):290-306. DOI: 10.1016/J.SCITOTENV.2012.05.085.

Taguta, C., Senzanje, A., Kiala, Z., Malota, M. & Mabhaudhi, T. 2022. Water-Energy-Food Nexus Tools in Theory and Practice: A Systematic Review. *Frontiers in Water*. 4(1):1-21. DOI: 10.3389/frwa.2022.837316.

Van Weele, G. & Maree, G. 2018. *State of Environmental Outlook Report for the Western Cape Province: Introductory Matter*. Cape Town, South Africa.

Ziervogel, G. 2019. Building Transformative Capacity for Adaptation Planning and Implementation that Works for the Urban Poor: Insights from South Africa. *Ambio*. 48(5):494-506. DOI: 10.1007/S13280-018-1141-9/FIGURES/3.

Chapter 6: Systems dynamics model describing the water-energy-food nexus for the City of Cape Town

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Abstract

Between 2015 and 2018, the City of Cape Town (CoCT) in South Africa faced a critical situation where the municipal water supply was almost completely depleted. This circumstance, commonly referred to as Day Zero, arose from a decline in rainfall, resulting in one of the most severe droughts in history. Simultaneously, rapid population growth and urbanization aggravated the crisis. The CoCT was on the verge of becoming the first city in the past decade to experience a complete cessation of water supply for urban and agricultural purposes. Besides the effects of reduced rainfall and population surge, energy consumption from urbanization and increased food demand directly affected the available water resources. In this study, a system dynamics modelling (SDM) approach was employed to evaluate the interlinkages between water utilization, water production, energy supply and demand, and food production and demand, over 20 years. The model is developed as a stock and flow diagram utilizing Stella Architect, encompassing five interconnected nodes: water, energy, food, land, and population. The findings revealed that by the end of the 20-year modelling period, the volume of water available and stored in all the major dams was approximately 454 million cubic metres, with residential usage accounting for about 85% of urban water usage while agricultural usage was about 30.37% of total water demand. Moreover, the model illustrated the impact of precipitation rate, runoff, and evaporation on other variables such as land-use change and population dynamics. The impact of alternative energy sources integration into the model was also considered especially for the increased uptake of solar energy. It is anticipated that the outcomes of this study will serve as valuable inputs for decision-making processes, not only within the CoCT, aiming to mitigate or prevent the recurrence of Day Zero, but also for other cities facing similar challenges.

This work is based on the work done by Dr. Jafaru Egieya during his involvement in the project, and captured in the article titled "Predictive simulation of the water-energy-food nexus for the City of Cape Town", which is currently under review.

6.1 Introduction

The world population is projected to climb by about 25% in 2050 (9.9 billion), accelerating economic growth, growing prosperity, and climate change are expected to lead to a corresponding 100% surge in demand for energy and an accompanying 50% rise in the demand water, and food (IRENA, 2015). Moreover, present statistics indicate that the agri-food supply chain accounts for about a third of global energy consumption and about 70% of all freshwater use while energy supply contributes approximately 19% of yearly global freshwater withdrawals (UNESCO, 2022). The status quo is unsustainable and there needs to be conscientious efforts put in place to meet the increasing demand for these limited resources without affecting the ability of future generations to meet their demand. However, a possible solution to mitigating this situation is understanding how water, energy, and food use interact in a water-energy-food (WEF) nexus. The WEF nexus first proposed in 2011 at the Bonn conference in Germany is further indicated as a veritable tool or framework to assess the trade-offs and interlinkages of water, energy, and food resources while seeking strategies for sustainable development of their use (Hoff, 2011).

Developing a comprehensive understanding of the Water-Energy-Food (WEF) nexus holds great significance for both short-term and long-term planning purposes. When appropriately applied, a WEF nexus approach can facilitate the implementation of policies and projects within the respective sectors, thereby enhancing overall system efficiency, while minimizing adverse impacts on other sectors. This approach directly contributes to the achievement of the United Nations' Sustainable Development Goals (SDGs). For instance, ensuring water security, food security, and energy security significantly influences the reduction of poverty (SDG 1), eradication of hunger (SDG 2), and provision of clean water and sanitation (SDG 6), which, in turn, supports good health and well-being (SDG 3). To sustainably meet these goals, it becomes imperative to provide affordable and clean energy (SDG 7), which ultimately contributes to addressing climate change (SDG 13). Considering that food resources originate from land (SDG 15) and water bodies (SDG 14), a comprehensive assessment of the WEF nexus guides the development of policy frameworks necessary for the sustainable utilization of available resources. Furthermore, the WEF nexus plays a crucial role in addressing inequalities in resource access and meeting the needs of vulnerable groups, thereby advancing SDG 10. Moreover, it guides sustainable urban planning and infrastructure development, fostering resilient and sustainable cities and communities, in alignment with SDG 11. In-depth knowledge of the WEF nexus also supports SDG 12 by promoting responsible consumption and production practices, ensuring the optimal utilization of limited resources. Additionally, it contributes to SDG 16 by bolstering peace, justice, and strong institutions through the development of robust policies and regulations that foster effective coordination and transparency among stakeholders. SDG 17 emphasizes the importance of collaboration and knowledge sharing, and a profound understanding of the WEF nexus facilitates the creation of integrated solutions for achieving the SDGs. In essence, comprehending the interrelationships among water, energy, and food resources holds implications not only for the present generation but also for future generations. It underscores the imperative of conducting assessments and adopting approaches that promote sustainability and support the attainment of the SDGs.

Nevertheless, since 2011, there are several tools and policy frameworks put forward in reviews on different spatial and temporal levels of abstraction to understand the WEF nexus approach for research and policymaking implementation. For instance, Albrecht et al. (2018) provided a knowledge base of WEF nexus methods conducted on 245 articles published in the year 2016 under four key features of innovation, the influence of context, collaboration, and implementation. They concluded that there needs to be more WEF nexus methodologies directed to policy implementation (Albrecht et al., 2018). In another review, Zhang and colleagues studied 161 WEF-related articles whereby two definitions of WEF nexus are delineated. While some WEF nexus studies defined the nexus as the interlinkages or relations of the nodes (i.e. water, energy, and food), others suggested that the nexus be defined as quantitative assessments of the nexus nodes showing relationships between two nodes (i.e. water and energy), three nodes (i.e. water, energy, and food) and even four nodes (i.e. water, energy, food, and climate). However, they improved on the Albrecht et al., 2018 study by providing conceptual applications of the WEF nexus to address policy issues (Zhang et al., 2018). These two reviews have in the past five years provided a fulcrum for the future direction of WEF studies.

Additionally, considering the reviews of modelling approaches, computational modelling of the WEF nexus is gaining traction due to its advantage of quantifying different WEF nexus scenarios for policy analysis while bolstering sustainable and implementable decision-making steps (Bieber et al., 2018). For instance, Zhang and Vesselinov developed a novel socioeconomic multi-period optimization model to forecast WEF demands based on environmental controls, production costs, and socioeconomic demands (Zhang et al., 2018). Furthermore, in another study, Bieber and colleagues carried out a scenario-based approach to integrate the modelling of urban water (potable and wastewater) and power generation in a metropolitan city in Ghana. They combined Agent-Based Modelling (ABM), a socio-demographic module, and mixed-integer linear programming (MILP) to evaluate the human interactions present in power generation, wastewater treatment, and the opportunity cost for food production forgone in the WEF nexus. They considered different policy directions and concluded that there is a decreasing influence of hydroelectric power generation over the timeframes considered (Bieber et al., 2018). On the other, Purwanto et al. (2021) in a more recent study utilized the systems dynamics modelling (SDM) approach to quantitatively assess the implications of planned policy interventions in a regency of Indonesia. They concluded that there will always be trade-offs in every stage of the policymaking process, but improving synergies and reducing the trade-offs amongst stakeholders and institutions will bolster policymakers' ability to enjoy the positive aspects while minimizing the demerits of policies (Purwanto et al., 2021).

Conversely, a holistic discussion of eight modelling approaches providing guidance on model selection in the WEF nexus was proposed by Zhang et al. (2018). Out of the eight modelling approaches posed, three of them including computational general equilibrium (CGE), ABM, and SDM are related to computational modelling which is the subject of discussion of this study. It is worth noting that while CGE poses an inability to mirror the realities of policy evaluation since it utilizes simplistic economy hypotheses and assumptions, ABM which is a “bottom-up” approach has the disadvantage of requiring large data inputs and computational requirements. Alternatively, SDM, a top-down modelling method overcomes these challenges by using causal feedback loops that assist in identifying sources of bottlenecks and understanding the feedback of such systems as the WEF nexus. Hence, further discussions of this study are based on the SDM modelling approach whereby a conceptual model is developed to evaluate the interaction of the WEF nexus.

Therefore, the objective of this study is to develop a holistic conceptual WEF nexus model called the CoCT-WEF nexus model based on the City of Cape Town, South Africa. The novelty of this study is that the model is built on an SDM modelling approach that assesses the interface of the water node (consisting of crop demand, power plants demand, population demand, and climate change impact), agriculture or food node (energy input in agriculture), and the energy node (energy production and water use for energy production). Another novelty is the integration of the CoCT wastewater reuse scheme which differs from previous studies. Hence, subsequent sections of this study are as follows: Section 2 describes the case study and the problem statement; Section 3, gives a holistic view of the model and its five sub-models that make up the CoCT-WEF nexus model; Section 4, illustrates an application of the model with scenario and sensitivity analysis of key parameters or variables; lastly, Section 5 presents a conclusion and recommendations for future research.

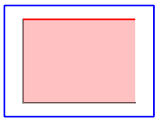
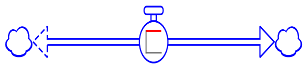
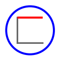
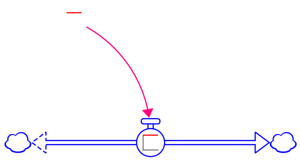
6.2 Methodology

Here, the quantitative SDM framework upon which the CoCT WEF nexus model is built is discussed. This is followed by an analysis of the study area and its problem statement.

6.2.1 Quantitative System Dynamics model (QSDM)

The CoCT WEF nexus model is built following a QSDM approach that makes use of stocks and flow diagrams (SFDs). The model is constructed on the iThink software called Stella Architect (www.iseesystems.com). However, as depicted in Table *5*, SFDs consist of four main elements including stocks, flows, converters, and connectors (Egieya et al., 2023). It is noteworthy that while stocks represent the current state of a system, flows signify the actions that drive changes in that state over time (Ford, 2010). Therefore, stocks accumulate the effects of flows, and they persist in their current position as long as there are no active flows influencing them.

Table 5: Key features of Stock and flow diagrams (Egieya et al., 2023)

S/No.	Item	Representation	Description
1.	Stock		The stock is a quantifiable measure that necessitates continuous tracking over time. It can take concrete forms, such as the number of cars present in a parking lot, or abstract forms, such as the amount of time required to complete a task.
2.	Flow		A flow, whether uniflow (in one direction) or biflow (in two directions), contributes to the increase or decrease of material within a stock. It is akin to the process of material entering or exiting a lake.
3.	Converter		A converter encompasses constants or equations and represents an integral aspect of the system's functioning; however, it does not serve as the stock itself.
4.	Connector		The red arrow that connects the converter to the flow is referred to as the connector. Connectors illustrate the interactions between elements within the System Dynamics Model (SDM). For example, the birth rate and death rate of a specific region or country directly impact the total population. The connector establishes the link between the birth rate, death rate, and the total population.

6.2.2 Study Area

The City of Cape Town (CoCT) as illustrated in Figure 39, is a metropolitan port city located in the Western Cape Province of South Africa. In 2018, the population of the city was about 4,423,921 growing at 1.85% per annum (CoCT, 2021). The GDP of the CoCT was about 22 billion USD in 2017 with three dominant sectors: finance, trade, and manufacturing. In terms of land mass, the CoCT accounts for an approximate area of 2,446 km^2 whereby about 17% of the area is set aside for arable farming purposes of such crops as canola, wheat, and wine grapefruit while another 72% of the CoCT land area is adapted to livestock rearing of cattle, sheep, chickens, and pigs (Western Cape Agriculture profile 2017). In fact, in 2017 the gross revenue from the agriculture sector of the CoCT amounted to about 880 million USD (CoCTa, 2020).

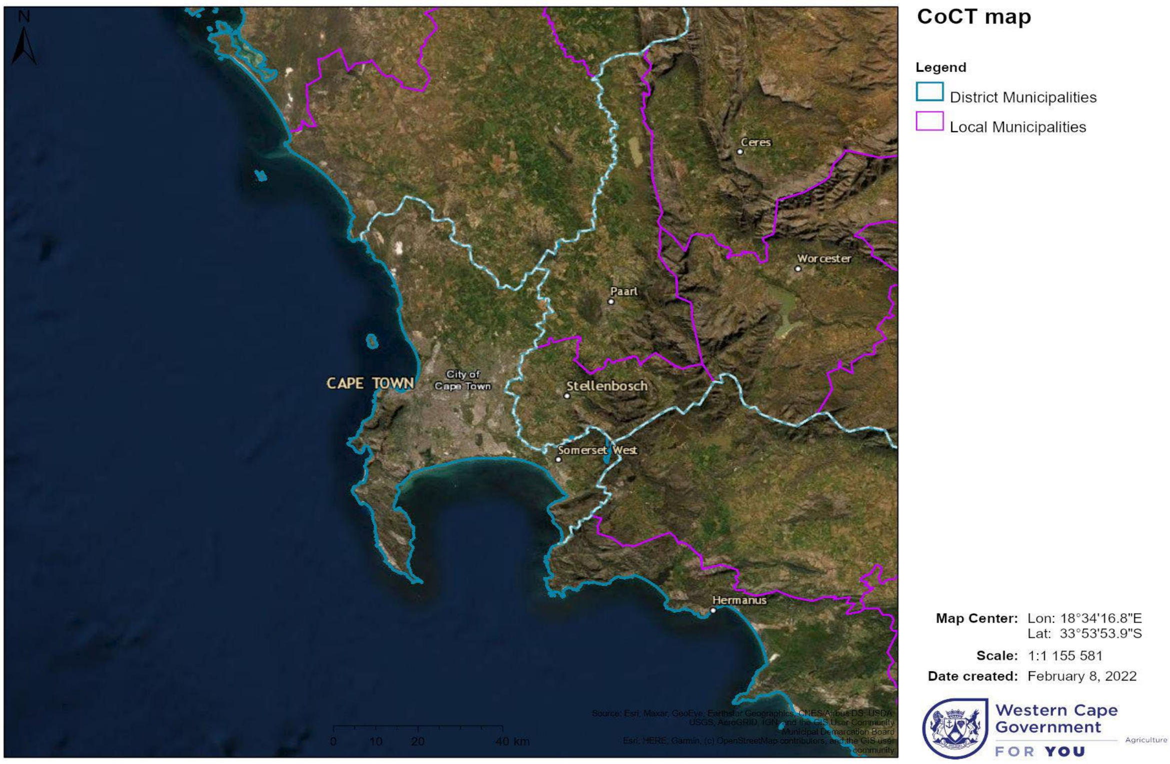


Figure 39 Map of the City of Cape Town

6.2.3 Problem Statement

The CoCT is confronting issues of climate change, to which water is most sensitive and directly impacts agriculture. For instance, between the years 2015 to 2017, the CoCT grappled with a series of consecutive dry winters (limited precipitation) that resulted in the Cape Town “Day Zero” drought in early 2018 (Pascale et al., 2020). The drought caused approximately 400 million USD in economic loss due to lower crop yields and thousands of job cuts (Stanford News, 2020). There are perceptions of an imminent drought again if the business-as-usual activities are not changed. Surface water is the main source of water in the CoCT obtained from 14 dams with 900,000 million litres combined capacity.

Against this backdrop, the current and proposed water supply system of the CoCT, consisting of dams, aquifers, water recycling facilities, and desalination plants, serves an interconnected system for agricultural, urban, domestic, and industrial purposes. Moreover, importantly, the water supply is interconnected with the energy supply and agriculture (food production) in the water-energy-food (WEF) nexus.

Water supply to agriculture, industrial, and domestic uses, are all to an extent dependent on energy supply, both due to existing sources of electricity as well as the growing share of renewable electricity. Cape Town, therefore, needs to develop a resilient, quantitative WEF plan to guide medium- to long-term investments in additional WEF supply capacity to ensure a balanced supply and utilization of natural resources. The presented CoCT-WEF nexus model considers the interaction between water supply, energy supply, and agriculture within the WEF nexus. Planning for sustainable urban development requires a balanced supply and utilization of natural resources through systematic thinking, to ensure that all components of the urban WEF nexus function effectively. A lack of, or incomplete understanding of the dynamic interconnectedness of WEF components will have adverse consequences: Food production requires water and energy, water supply and treatment need energy, while energy production also consumes water.

Although there are "resilience" initiatives within the CoCT to forecast future water supply and demand, and supplement current water supply systems, these have two key shortcomings: (i) they largely focus on the water supply system with limited consideration of the impact on agriculture, while the energy supply impacts are often not considered in forecasting models, and (ii) some interventions are `stop-gap' and not sustainable for the long-term, and have since been discontinued such as the desalination operations commissioned during the recent drought. Hence there is a need for a holistic system description for the CoCT, which explicitly accounts for all three WEF-resource systems, with integrated planning scenarios for the future. Furthermore, estimates of future rainfall relating to climate variability are introduced to enable the planning of future resource requirements. Developing such models and capabilities now will enable building resilience in the City's supply systems. This is directly aligned with the CoCT's own strategy of considering interactions between various sectors and building long-term resilience into its operations, and the need for increased collaboration with external experts (CWRA, 2020). Hence the general model development and data abstraction sources are presented in the next section.

6.2.4 City of Cape system boundary

The CoCT system boundary consists of variables impacting the consumption/use of food, water, and energy. Hence, the scope of this falls within the geography illustrated in Figure 39. It is worth noting that while several studies consider CoCT to be made up of ten sectors including: Agriculture, forestry & fishing (also called Agriculture for simplicity); Mining & quarrying; Manufacturing; Electricity, gas & water; Construction; Finance, insurance, real estate, & business services; Wholesale & retail trade, catering & accommodation; Transport, storage & communication (also called Transport sector); General government; Community, social & personal services (CoCTb, 2020), this study follows the prescription of CoCT (2015) to blend these ten sectors into six sectors involving, residential, industrial, commercial, local government, transport, and agriculture sectors. Therefore, the industrial comprises Mining & quarrying; Manufacturing; Electricity, gas & water sectors; Construction sectors while the commercial sector consists of Finance, insurance, real estate, & business services; Wholesale & retail trade, catering & accommodation sectors. Moreover, the residential sector is linked to the Community, social & personal services sector. Hence, the rest of this study and data are based on the six sectors.

Thus, the following subsections 2.3.1 to 2.3.4 give an overview of CoCT's WEF nexus relating to data from the six sectors.

6.2.4.1 Agriculture

The agricultural sector of the City of Cape Town holds a pivotal role in both the economy and the livelihoods of many within the region. This significance arises from the sector's contribution, which accounts for approximately 10% of South Africa's total export earnings. The primary exports, by value, encompass citrus, wine, table grapes, corn, and wool (Investcapetown, 2023). This sector boasts a remarkable diversity, encapsulating the production of major grains, oilseeds, deciduous and subtropical fruits, sugar, citrus, wine, and a myriad of vegetables. Additionally, a competitive livestock industry flourishes, yielding meat, dairy, eggs, and poultry. A comprehensive overview of agricultural products is detailed in Appendix F, based on the commercial agriculture census of 2017 (StatsSA, 2017).

Employing approximately 18% of the workforce within South Africa's Western Cape province, this sector assumes a paramount role in offering food security and income prospects to numerous vulnerable groups, especially within urban areas. Nonetheless, the sector encounters a slew of challenges, including water scarcity, climate change, land reform, market access, and competition. The drought that gripped the province in 2017-2018 inflicted a severe blow to both crop yields and livestock production.

In response, the City of Cape Town (CoCT) has embraced an urban agricultural policy, strategically aimed at bolstering, and championing urban agriculture as a catalyst for fortifying food security, enhancing economic prospects, and elevating social well-being. This policy entails a comprehensive framework encompassing land use management, strategic partnerships, support programs, and aid for practitioners engaged in urban agriculture (CoCT, 2006).

6.2.4.2 Energy Demand and Supply Data

The CoCT's Energy Report (2015) shows that Cape Town's energy consumption is dominated by petrol (31%), electricity (29%), and diesel (22%). On the other hand, the Cape Town State of Energy and Carbon 2021 Report shows that the transport sector leads the energy consumption by 63% of total energy. The transport sector is followed by Industrial (12.03%), Commercial (10.57%), Residential (9.02%), Agriculture (1.80%), and local government (1.19%) with an accompanying energy loss of 2.14%. The total final energy consumption in Cape Town for 2018 was estimated to be 169,166,045 GJ, which translates to global greenhouse emissions of 19,932,984 tCO_2e per capita.

When electricity generation is considered the CoCT derives about 5% of its electricity from such sources as solar energy (photovoltaics), 2-units nuclear power plants, hydroelectric power plants, and two gas-powered plants. The remaining 95% of the electricity is imported from outside the CoCT, basically from coal power plants. Details of these electricity-generating sources are presented in Appendix C of the supplementary material.

In terms of carbon emissions, the City of Cape Town's transport sector leads the carbon inventories by 33%, followed by the Commercial sector with 26% of the total city's carbon emissions, residential (22%), Industrial (11%), while Government, Agriculture, and electricity loses were accounted 2%, 1%, and 5%, respectively.

6.2.4.3 Water

Water plays a vital role in the WEF nexus, as it is needed both in the production of energy and food. The majority of the CoCT's fresh water comes from surface water whereby over 97% of it is supplied by six dams including Theewaterskloof, Wemmershoek, Steenbras upper, Steenbras lower, Voëlvlei, and Berg River dams. These six dams have a combined full capacity of 898.22 million cubic metres. The remaining 3% of water is provided by smaller dams and aquifers (CoCTa, 2022). On the other hand, it is worth noting that the main consumers of fresh water in Cape Town are agriculture with an annual average of 4.9 million cubic metres and urban water demand with an average yearly consumption of 10.4 million cubic metres of water per year (CSAG, 2022).

Consequently, due to the semi-arid climate and landscape of the CoCT, it experiences primarily dry summers and winters with heavy rainfalls (Jury, 2022). In years with insufficient winter rain, the city is vulnerable to droughts and water shortages as exemplified in the years of 2016 to 2018 as discussed in the problem statement (see Section 2.2.1). Because of climate change, climate models predict not only a rise in average daily temperatures, but also a decrease of up to 20% in precipitation (Jury,2022). This, among other factors, such as rising water demands due to a growing population, puts the city at an even higher risk of droughts.

To counteract this development, the CoCT has put in place several measures to be implemented in stages until 2035. These include the augmentation of aquifers, the addition of surface water supplies, seawater desalination and the reuse of treated wastewater. These measures are estimated to supply an additional 9 million cubic metres of water per month to the city (CoCTa, 2022).

6.2.4.4 Land

The CoCT has a land mass of about 2,445 km^2. The land area is split into different land use categories based on a zoning scheme and spatial development framework. Moreover, according to the CoCT's Open Data Portal (CoCT, 2023), the land use distribution for the year 2023 is as follows: Industrial 6.4% (i.e. 157.9 km^2), Commercial 3.1% (i.e. 76.3 km^2), Residential 23.7% (i.e. 583.4 km^2), Forests 8.5% (i.e. 209.2 km^2), and Agriculture 58.3% (1,434.2 km^2). Also, following the stipulations of the same reference, about 19% (i.e. 414.84 km^2) of agriculture is set aside arable land (i.e. for crop production) while the remaining is grazing land (AgriFarms, 2023). However, the Western Cape province reports that only about 22% (i.e. 91.57 km^2) of the arable land in the CoCT is planted (StatsSA, 2020).

6.3 Model development

There are six steps involved in the process of model development (see Figure 40) as described by Purwanto et al. (2021). These steps are categorized into two segments, namely the qualitative approach and the quantitative approach. The initial three steps (Steps 1 to 3) follow the qualitative approach, while the quantitative approach encompasses Steps 4 to 6 with an interface to Step 3. It should be noted that these steps are iterative rather than linear. A brief explanation of each step is presented below:

Step 1: In this step, the problem is examined and defined. Alongside the "Day Zero" issue discussed in Section 2.2.1, objectives are established, and a comprehensive literature review, formal and informal interviews are conducted.

Step 2: This step involves the implementation of model conceptualization, engaging stakeholders, and consulting experts to define the system and its boundaries.

Step 3: Causal loop diagrams (CLDs) are developed to identify the key loops and variables influencing the CoCT WEF nexus.

Step 4: The development of System Flow Diagrams (SFDs) takes place in this step, along with further engagement with experts and stakeholders for the identification of model elements.

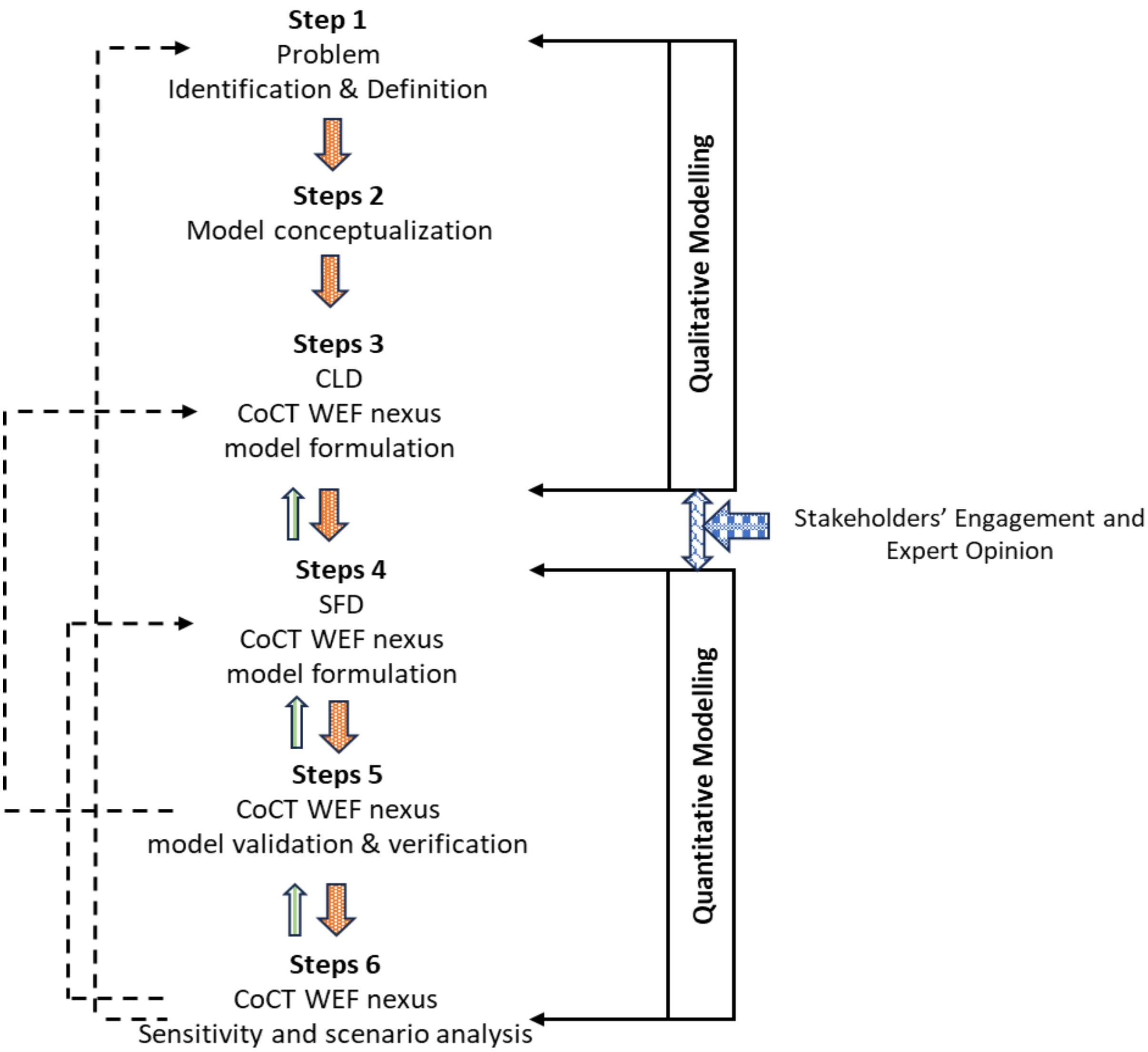


Figure 40 The modelling steps portrayed in an iterative fashion.

Step 5: Validation and verification of results are crucial in any model development process. In this step, three tests are conducted to instil confidence in the model: historical behaviour analysis, face validity assessment, and detailed model checks.

Step 6: Sensitivity and scenario analysis are implemented to gain a better understanding of policies that can enhance system behaviour.

These steps collectively contribute to the comprehensive development of the model and facilitate improved insights into the CoCT WEF nexus.

Consequently, following the steps taken in the model development steps 1 and 2 involved 14 stakeholder engagement and experts from collaborating organizations (Stellenbosch University, University of KwaZulu-Natal, and Rhodes University) in South Africa. These collaborators have on average over 10 years of experience working individually in the energy, water, and agriculture sectors and their interface in the WEF nexus space (Appendix showing qualifications/expertise). Two meetings are carried out to formulate the model system boundary and key variables impacting the WEF nexus of the CoCT. The first meeting was carried out in November 2021 to discuss the system boundaries and variables while the second meeting took place in August 2023 to assess the robustness of the SFD model development. Hence, the results of the engagements and modelling process show the interacting five sectors or nodes (water, energy, food, population, and land) forming the CoCT WEF nexus model. A brief discussion of these sectors is presented in the following subsections.

6.3.1 Water sector

The water sector of the CoCT WEF nexus model (see Figure 41) focuses on integrating the volume capacity of the six dams mentioned in (2.3.3). These dams are condensed into a single stock named “Dam”. This stock represents the sum of the available water in each dam. The Dam-stock is supplied by an inflow runoff, depicted as the flow “dam inflow” and by the precipitation flow, which describes the precipitation falling directly over the dams’ surfaces. The outflows of the “Dam” stock are the flows of “evaporation”, representing the water loss through evaporation from the dams’ surfaces and “other out”, which is the sum of agricultural and urban water demand. The agricultural water demand comprises the water demand for livestock raised in the CoCT and the irrigation water demand for crops grown in the city. The crops are split into the categories “fruits and vegetables” also called non-staple foods and “other crops” also called staple foods, which are the products of the water demand of the respective crops per square kilometres and the size of the area in which these crops are grown. The area of the crops is connected to the land sector, which provides the area of arable land. To calculate the water demand of livestock in the Cape Town area, the populations of the various livestock are multiplied by the water requirements of the livestock. Additionally, a livestock population growth factor is included to represent the changing number of animals over time.

For the urban water demand, the sub-sectors are split into residential, industrial, commercial, transport, and government water demand. Commercial, transport, and government water demands are the respective product of the specific water demands per person in this sector. With the water demand for electricity, consisting of hydropower, solar, and nuclear power, the industrial sector is a product of the sum of the electricity water demand and the water demand for other industrial processes. Lastly, the residential water demand is a product of the population stock and the per capita water consumption in Cape Town. In each of the urban sectors, the number of persons in that sector is connected to the population stock, which makes the urban water demand highly dependent on the size of the population. The total water demand is thus comprised of the sum of agricultural and urban water demand.

The water sector of this model shows the fluctuations of dam levels over time and the in- and outflows that cause them. The outflows are connected to the population-, energy- and land sector through the water demands of the sub-sectors, which illustrates the interconnectedness of the WEF nexus. In addition, most of equations W1 to W22 are the key interactions of the water sector while Appendix D provides other information and inputs to the model.

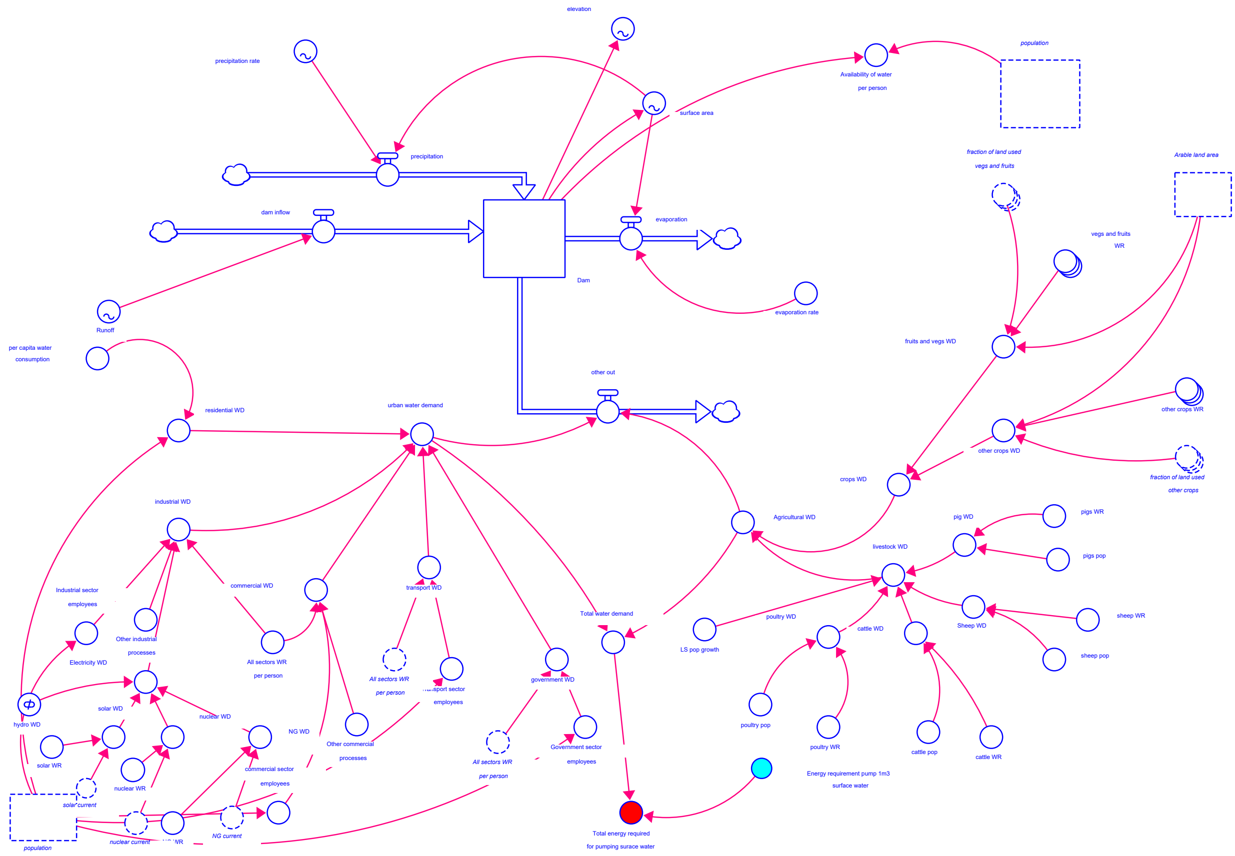
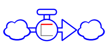
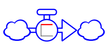
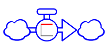
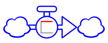
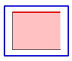


Figure 41 Causal loop diagram of the water sector

Table 6: Model equations for the food production sector

Symbol	Equations	Units	Eq. No.
	Agricultural_WD = crops_WD + livestock_WD	$\frac{m^3}{month}$	W1
	cattle_WD = cattle_pop*cattle_WR	$\frac{m^3}{month}$	W2
	crops_WD = (fruits_and_vegs_WD+other_crops_WD)*100	$\frac{m^3}{month}$	W3
	pig_WD = pigs_WR*pigs_pop	$\frac{m^3}{month}$	W4

Symbol	Equations	Units	Eq. No.
	poultry_WD = poultry_pop*poultry_WR	$\frac{m^3}{month}$	W5
	Sheep_WD = sheep_pop*sheep_WR	$\frac{m^3}{month}$	W6
	livestock_WD = (poultry_WD+cattle_WD+pig_WD+Sheep_WD)*(1+LS_pop_growth)	$\frac{m^3}{month}$	W7
	commercial_WD = (All_sectors_WR_per_person*commercial_sector_employees) + (All_sectors_WR_per_person*commercial_sector_employees*Other_commercial_processe)	$\frac{m^3}{month}$	W8
	Electricity_WD = hydro_WD+solar_WD+nuclear_WD+NG_WD-hydro_WD	$\frac{m^3}{month}$	W9
	residential_WD = (per_capita_water_consumption*population)/	$\frac{m^3}{month}$	W10
	transport_WD = (Transport_sector_employees*All_sectors_WR_per_person)	$\frac{m^3}{month}$	W11
	urban_water_demand = (industrial_WD+commercial_WD+transport_WD+government_WD+residential_WD)	$\frac{m^3}{month}$	W12
	precipitation_rate = RANDOM(0.023, 0.585, 0.07)	$\frac{m}{month}$	W13
	precipitation = surface_area*precipitation_rate	$\frac{m^3}{month}$	W14
	dam_inflow = Runoff	m^3	W15
	other_out = (urban_water_demand+Agricultural_WD)	$\frac{m^3}{month}$	W16
	evaporation_rate = Numerator/(80-Temperature)	$\frac{m}{month}$	W17

Symbol	Equations	Units	Eq. No.
	fruits_and_vegs_WD = Arable_land_area*(fraction_of_land_used_vegs_and_fruits*vegs_and_fruits_WR	$\frac{m^3}{month}$	W18
	industrial_WD = (Other_industrial_processes*Industrial_sector_employees*All_sectors_WR_per_person+((All_sectors_WR_per_person*Industrial_sector_employee+Electricity_WD))	$\frac{m^3}{month}$	W19
	evaporation = surface_area*evaporation_rate	$\frac{m^3}{month}$	W20
	Dam(t) = Dam(t - dt) + (dam_inflow + precipitation - evaporation - other_out) * d	m^3	W21
	nuclear_WD = nuclear_WR*nuclear_current	$\frac{m^3}{month}$	W22

6.3.2 Energy Sector

The energy sector as discussed in subsection 2.3.2 impacts the WEF nexus directly. In this section, Figure 42 illustrates a model of the supply and demand for energy within the CoCT.

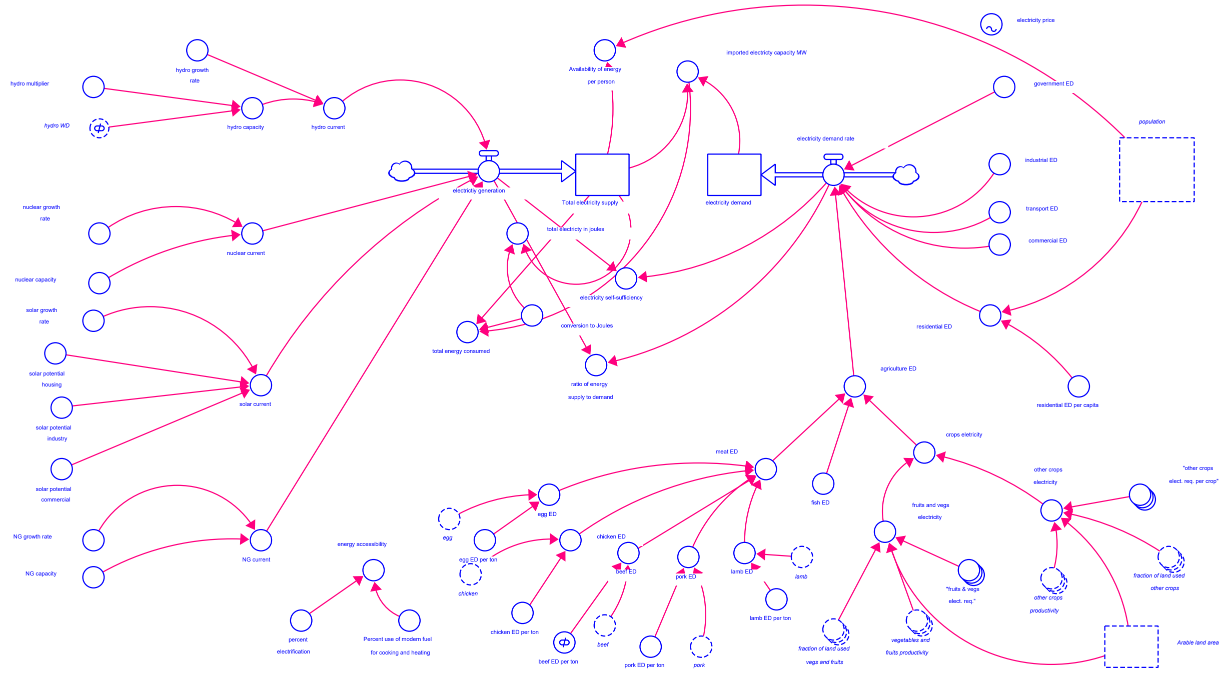
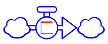
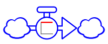
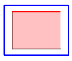
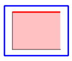


Figure 42 Energy sector supply and demand

The energy sector is split into two sections consisting of the energy supply that accumulates in the "Total electricity supply" stock and the energy demand side that collects in the "electricity demand" stock. The energy supply side for business as usual in the CoCT is dependent on four energy sources that including nuclear power plants (1,860 MW), hydropower plants (181.6 MW), solar energy (300 MW), and gas-fired power plants (1,509 MW) demand side of the energy sector consists of demand from the six economic sectors of the CoCT (i.e. government, industrial, transport, residential, commercial, and agriculture). Moreover, it is worth noting that about 27% of the energy consumed in the CoCT is in the form of electricity and the CoCT is net importer of electricity which is represented by the converter "imported electricity capacity MW".

Hence, the equations E1 to E16 in Table 7 are the main equations impacting the energy sector. The complete documentation of other parameters not shown is given in Appendix C.

Table 7: Main equations for modelling the energy sector

Symbol	Equations	Units	Eq. No.
	hydro_current = hydro_capacity*(1+hydro_growth_rate)	$\frac{MWh}{month}$	E1
	NG_current = NG_growth_rate*(1+NG_capacity)	$\frac{MWh}{month}$	E2
	nuclear_current = nuclear_capacity*(1+ nuclear_growth_rate)	$\frac{MWh}{month}$	E3
	solar_current = IF TIME = 0 THEN 18000 ELSE PREVIOUS (SELF, (solar_potential_housing*Residential_housing_area+solar_potential_industry*Industrial_area+solar_potential_commercial*Commercial_area)*solar_growth_rate)	$\frac{MWh}{month}$	E4
	electrictiy_generation = hydro_current+nuclear_current+solar_current+NG_current	$\frac{MWh}{month}$	E5
	electricity_demand_rate = agriculture_ED+residential_ED+commercial_ED+industrial_ED+government_ED+transport_ED+Total_energy_required_for_pumping_surace_water	$\frac{MWh}{month}$	E6
	Total_electricity_supply(t) = Total_electricity_supply(t - dt) + (electrictiy_generation) * dt	MWh	E7
	electricity_demand(t) = electricity_demand(t - dt) + (electricity_demand_rate) * dt	MWh	E8
	agriculture_ED = meat_ED+fish_ED+crops_eletricity	$\frac{MWh}{month}$	E9
	meat_ED = egg_ED+chicken_ED+beef_ED+pork_ED+lamb_ED	$\frac{MWh}{month}$	E10
	crops_eletricity = fruits_and_vegs_electricity+other_crops_electricity	$\frac{MWh}{month}$	E11
	electricity_self-sufficiency = electrictiy_generation/electricity_demand_rate	-	E12

Symbol	Equations	Units	Eq. No.
	fruits_and_vegs_electricity = (vegetables_and_fruits_productivity*fruits_&_vegs_elect._req. *fraction_of_land_used_vegs_and_fruits) *Arable_land_area	$\frac{MWh}{month}$	E13
	Other_crops_electricity = (other_crops_elect._req._per_crop* other_crops_productivity*fraction_of_land_used_other_crops) *Arable_land_area	$\frac{MWh}{month}$	E14
	Availability_of_energy_per_person = Total_electricity_supply/population	$\frac{MWh}{month}$	E15
	Imported_electricity_capacity_MW = Total_electricity_supply - electricity_demand	$\frac{MWh}{month}$	E16

The variables: fraction of land used for vegs and fruits; vegetables and fruits productivity; fraction of land used for_other_crops; other_crops_productivity; fruits_&_vegs_elec._req and other_crops_elec._req are arrays. These arrays contain information on the different crops, fruits, and vegetables grown in the CoCT.

6.3.3 Food sector

The food sector models the availability of food over the modelling period. It is basically split into two parts that include stocks representing food supply and food demand within the CoCT. The food supply is further split into two for simplicity and contains a stock that measures the quantity of staple foods available and the quantity of non-staple food available (in tons) as illustrated in Figure 43. On the food supply side, a Living Standard Measure (LSM) (Vermeulen et al., 2015) is employed to assess the impact of income on the purchasing power of the inhabitants of the CoCT. In essence, The LSM serves as a pivotal instrument within South Africa, strategically employed to classify both the standard of living and disposable income of individuals. This mechanism adeptly divides the population into ten distinct deciles, each discerned by their relative means. Notably, LSM 1 embodies the decile characterized by the most modest means, while conversely, LSM 10 embodies the decile marked by the most affluent means. This assessment hinges on the ownership of a standardized basket of goods, a composition that evolves over time (Vermeulen et al., 2015). In this study, the LSM decile has been split into three classes. The LSM 1-4 represents the lower class with the lowest purchasing power. LSM 5-8 represent the middle class while LSM 9-10 represent the upper class with the highest purchasing power.

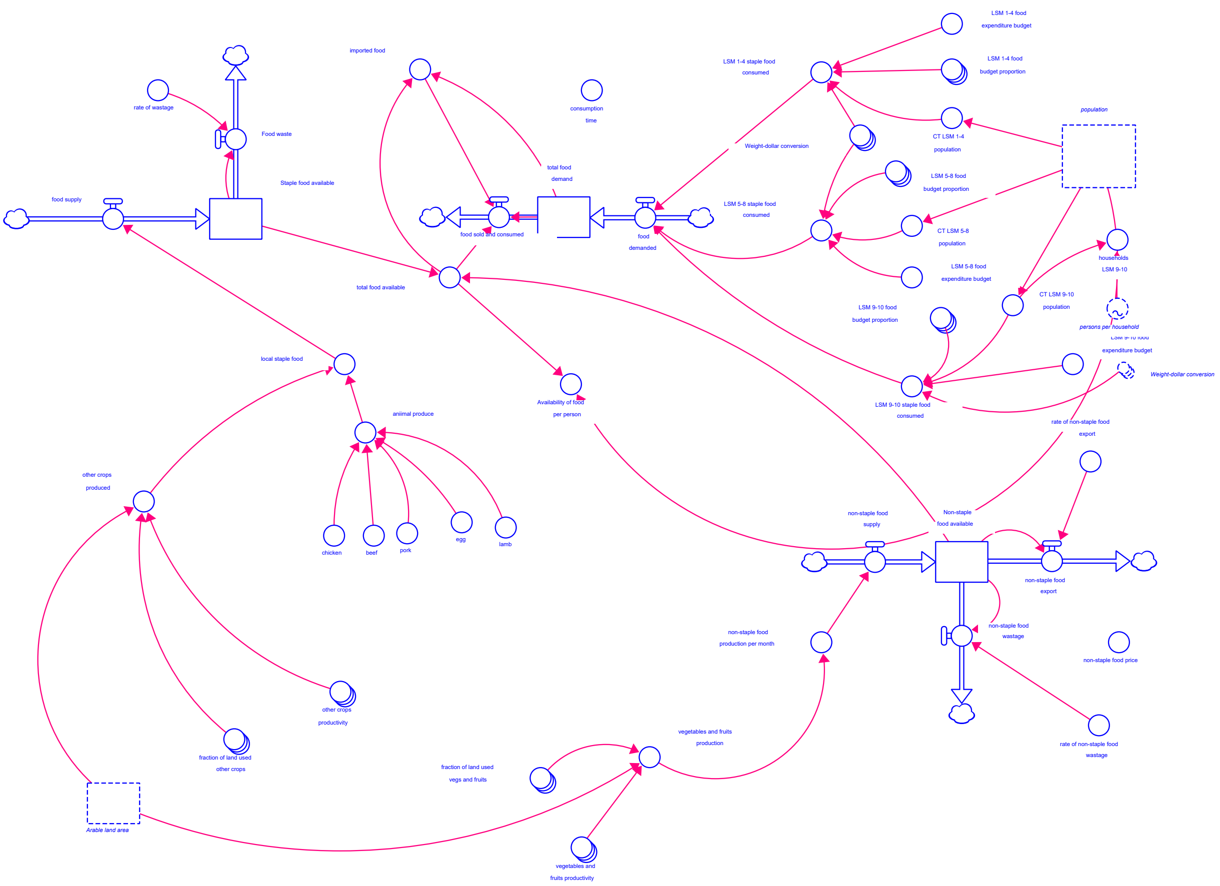
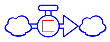
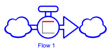
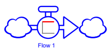
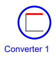
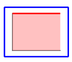
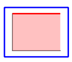
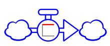
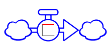
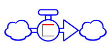
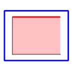


Figure 43 Food sector supply and demand sector

It follows that the CoCT LSM produced for each of the three class categories has budget proportions related to grains, vegetables, eggs, meat, and other products. This information is implemented as LSM staple food consumed and shown together with other important equations for the CoCT WEF nexus model from equations F1 to F17. Other parameters and variables not mentioned here may be found in the general model initial inputs presented in Appendix F.

Table 8: Equations that describe supply and demand for the food sector

Symbol	Equations	Units	Eq. No.
	animal_produce = beef+pork+egg+lamb+chicken	$\frac{ton}{month}$	F1
	CT_LSM_1-4_population = population*0.223	$people$	F2
	CT_LSM_5-8_population = population*0.612	$people$	F3

Symbol	Equations	Units	Eq. No.
	CT_LSM_9-10_population = population*0.165	*people*	F4
	food_demanded = "LSM_1-4_staple_food_consumed"+"LSM_5-8_staple_food_consumed"+"LSM_9-10_staple_food_consumed	$\frac{ton}{month}$	F5
	IF (imported_food/TIME<0) THEN (total_food_available/TIME) ELSE (total_food_demand/TIME)	$\frac{ton}{month}$	F6
	Food_waste = rate_of_wastage*Staple_food_available	$\frac{ton}{month}$	F7
	"households_LSM_9-10" = "CT_LSM_9-10 population" /persons_per_household	*household*	F8
	local_staple_food = aniimal_produce+other_crops_produced	$\frac{ton}{month}$	F9
	total_food_available = Staple_food_available+"Non-staple_food_available"	*ton*	F10
	Staple_food_available(t) = Staple_food_available(t - dt) + (food_supply - Food_waste) * dt	*ton*	F11
	Non-staple_food_available"(t) = Non-staple_food_available"(t - dt) + ("non-staple_food_supply" - "non-staple_food_export" - "non-staple_food_wastage") * dt	*ton*	F12
	"non-staple_food_export" = Non-staple_food_available"*"rate_of_non-staple_food_export"	$\frac{ton}{month}$	F13
	"non-staple_food_wastage" = "Non-staple_food_available"*"rate_of_non-staple_food_wastage"	$\frac{ton}{month}$	F14
	"non-staple_food_supply" = "non-staple_food_production_per_month"	$\frac{ton}{month}$	F15
	total_food_demand(t) = total_food_demand(t - dt) + (food_demanded - food_sold_and_consumed) * dt	*ton*	F16

Symbol	Equations	Units	Eq. No.
	vegetables_and_fruits_production = Arable_land_area*vegetables_and_fruits_productivity*fraction_of_land_used_vegs_and_fruits	$\frac{ton}{month}$	F17

6.3.4 Land sector

As a follow-up of the discussion in section 2.3.4, the land sector is modelled with six sectors (i.e. residential housing area, industrial area, commercial area, CoCT total land mass area, forest area, and arable land area) as portray in Figure 44. The model assumes that due to increase in population growth, there will be increased need for residential housing, industrial, and commercial areas while the arable land and forest areas will decrease. Hence, the following equations are representative of the sector.

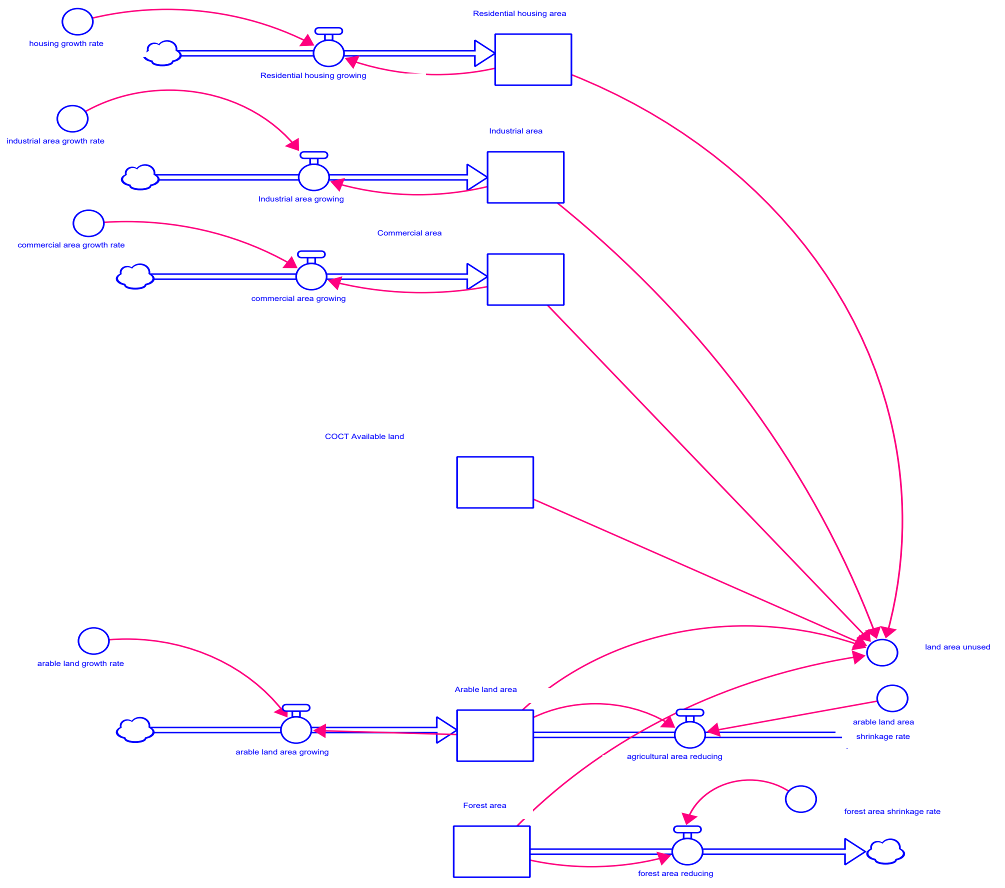
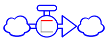
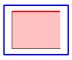
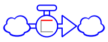
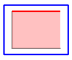
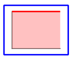
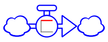
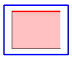
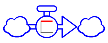
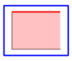
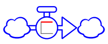
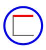
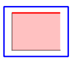
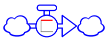


Figure 44 Stock and flow diagram for the land use sector

Table 9: Equations describing the land use sector

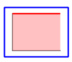
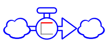
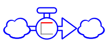
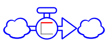
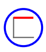
Symbol	Equations	Units	Eq. No.
	agricultural_area_reducing = arable_land_area_shrinkage_rate*Arable_land_area	$\frac{km^2}{month}$	L1
	Arable_land_area(t) = Arable_land_area(t - dt) + (arable_land_area_growing – agricultural_area_reducing) * dt	km^2	L2
	arable_land_area_growing = arable_land_growth_rate*Arable_land_area	$\frac{km^2}{month}$	L3
	COCT_Available_land(t) = COCT_Available_land(t - dt)	km^2	L4
	Commercial_area(t) = Commercial_area(t - dt) + (commercial_area_growing) * dt	km^2	L5
	commercial_area_growing = commercial_area_growth_rate*Commercial_area	$\frac{km^2}{month}$	L6
	Forest_area(t) = Forest_area(t - dt) + (- forest_area_reducing) * dt	km^2	L7
	forest_area_reducing = Forest_area*forest_area_shrinkage_rate	$\frac{km^2}{month}$	L8
	Industrial_area(t) = Industrial_area(t - dt) + (Industrial_area_growing) * dt	km^2	L9
	Industrial_area_growing = industrial_area_growth_rate*Industrial_area	$\frac{km^2}{month}$	L10
	land_area_unused = COCT_Available_land - (Arable_land_area+Industrial_area+Residential_housing_area+Commercial_area+Forest_area)	km^2	L11
	Residential_housing_area(t) = Residential_housing_area(t - dt) + (Residential_housing_growing) * dt	km^2	L12

Symbol	Equations	Units	Eq. No.
	Residential_housing_growing = housing_growth_rate*Residential_housing_area	$\frac{km^2}{month}$	L13

3.1.5 Population sector

The population sector as illustrated in Figure 45 consists of one stock (i.e. “population”) measured in the number of people at a given time with two inflows that include the number of births per month (i.e. “births”) and the number of people immigrating to the CoCT per month (i.e. immigration). The sector also involves two outflows in the form of “deaths” (i.e. the number of deaths per month) and the emigration of people from the CoCT (i.e. “emigration”). The sector further comprises six converters (including birth rate, death rate, immigration rate, emigration rate, households, and the average number of persons per household. The equations relating to these key variables are given in equations P1 to P5. The initial input values for the variables are given in Appendix E and the model input file in Appendix F.

Table 10: Equations describing the population sector

Symbol	Equations	Unit	Eq No.
	population(t) = population (t - dt) + (births + immigration - deaths - emigration) * dt	$people$	P1
	Births = birth_rate*population	$\frac{people}{month}$	P2
	Deaths = population*death_rate	$\frac{people}{month}$	P3
	Immigration = immigration_rate	$\frac{people}{month}$	P4
	households = population/persons_per_household	$households$	P5

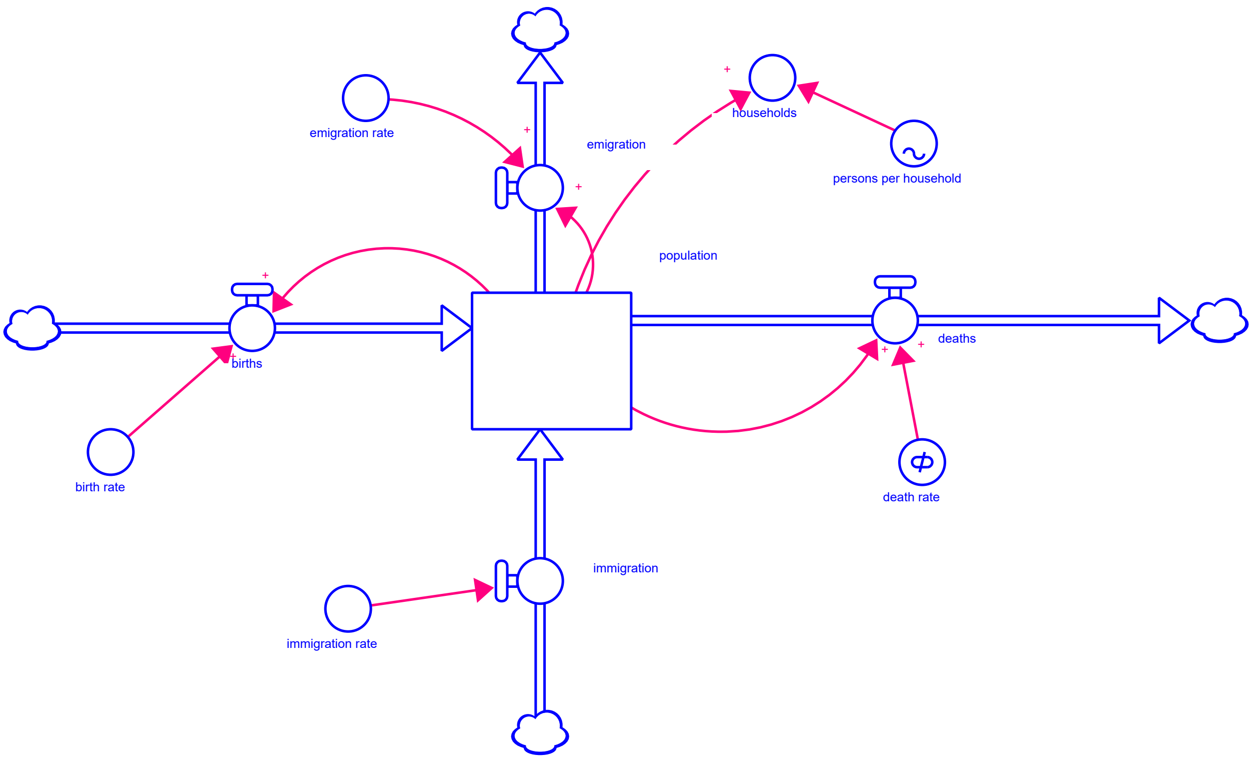


Figure 45 Stock and flow diagram for the population sector

6.4 Results and Discussion

Within the past decade, the CoCT experienced a drought that almost led to the complete drying of the city's main source of water from dams. However, to prevent a reoccurrence of the situation, the CoCT water-energy-food nexus needs to be evaluated and assessed. This section highlights the application of the CoCT WEF nexus model discussed in Section 3 to a business-as-usual scenario and then to two other scenarios of wastewater recycling and the effects of increasing crop production.

The CoCT-WEF nexus model has been formulated using Stella Architect and *iThink* version 3.2.1, employing the stock-and-flow diagram (SFD) approach. It encompasses a network of 209 interconnected variables, 14 distinct stocks, 26 dynamic flows, and 169 converters. Additionally, the model integrates 88 constants, 107 equations, and 6 graphical functions, enabling time-varying adjustments with discrete values allocated for each model time step. The computational process is executed on a personal computer equipped with 8 GB of RAM and an Intel® Core™ i5-4210U processor running at 2.40 GHz. Remarkably, the model resolves within a matter of seconds, effectively showcasing its efficiency and computational feasibility.

6.4.1 Business-As-Usual

This scenario remains consistent with the prevailing energy demand trends of the City of Cape Town (CoCT), as indicated by the State of Energy and Carbon reporting (CoCTa, 2021). The CoCT-WEF nexus model is now implemented over a modelling period of 20 years starting from 2018 based on the approach discussed in Section 3. Also, because of the level of discrimination needed and the time interval of most of the data used, the model has time units in months. Note that all sectors are expected to change according to prevailing inputs.

Consequently, the results show that at the end of the modelling period, the population of Cape Town will grow by about 30% (i.e. around 5,631,400 people) as illustrated in Figure 46. This value validates and agrees with similar values estimated by the United Nations for the CoCT population growth (UN, 2022). On the other hand, the cumulative volume of water in the dam presents a volume of approximately 454 million cubic metres at the end of the modelling period Figure 47. Moreover, the results show that the total water consumed is about 1.57 million cubic metres per month, split between urban water use (i.e. comprising residential, industrial, commercial, government, and transportation sectors) with almost 928,000 cubic metres per month of water consumed and the agriculture sector that consumes about 639,000 cubic metres per month of water. In addition, out of the total urban water consumption, almost 85.8% is due to the residential sector water use which is just over 20% more than the contribution of Calverley and Walther (2016) (i.e. 64.5% of total water use). The reason for the high influence of the residential sector on urban water use may be due to about 30% of the water being diverted to outdoor use for such activities as filling pools, water gardens, and most importantly the impact of tourists.

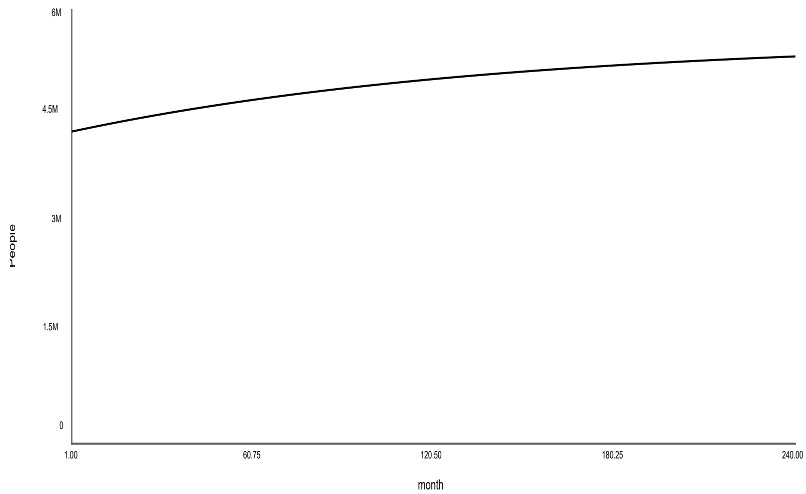


Figure 46 Projected population growth of the CoCT

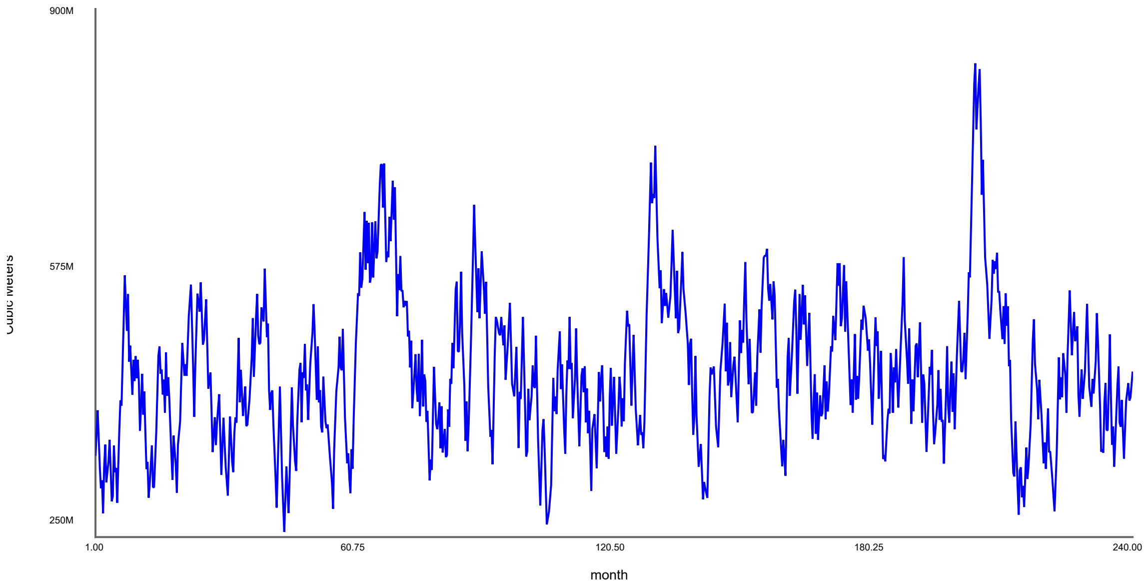


Figure 47 Projected collective water levels in the dam system of CoCT

Alternatively, when the energy sector is considered, it is observed that the total electricity supply accumulates to about 247 million MWh which is about 21.5% less than the electricity demand after 20 years (i.e. the modelling period). The result aligns with the City of Cape Town's plan to improve its energy self-sufficiency whereby considering the base year less than 10% of the electricity consumed within the CoCT is generated within the city. On the other hand, the model results indicate that the city's self-sufficiency will have increased to 91% as a backdrop of the ratio the electricity generation flow to the electricity demand rate flow. A closer look at the electricity demand for the agriculture sector (i.e. 33,800 MWh/month) shows that the demand is split into three subsectors including meat, fish, and crops production with electricity contributions of 38%, 34%, and 28% respectively. The electricity requirement for crops production seems to be the lowest because water can be supplied to crops without electricity during the rainy seasons compared to the water required for meat and fish production.

When the food sector is considered, it is noted that in constraining the arable land available to a maximum of 400 square kilometres just over 10,000 tons per month of non-staple foods should be produced (i.e. fruits and vegetables) as given in Appendix A. These non-staple foods will have a water requirement of approximately 247,000 m^3/month and an energy requirement of 8,260 MWh/month. Conversely, approximately 2,400 tons per month of staple foods (including wheat, barley, oats, canola, dry beans, and grass) will be produced at the end of the modelling period of 20 years. The staple foods' electricity and water demands are respectively 10,600 MWh/month and 494,000 m^3/month.

6.4.2 Water recycling scenario

The scenario analysis illustrates the impact of water reuse and climate change on the water demand. As this study addresses the impact of drought (or climate change) on the CoCT, the municipal authorities of the City have chosen to enhance the treatment of wastewater from both urban and agricultural water consumption. Consequently, a demonstration plant is being developed as an integral part of the Faure New Water Scheme within the CoCT, with the objective of achieving a monthly production of 2.1 million cubic of purified water from wastewater by the year 2024. Similarly, there are plans for additional water reuse schemes in the future, including the Zandvliet New Water Scheme. This scheme aims to produce 3.6 million cubic metres of purified water per month from wastewater by 2026. Moreover, the Cape Flats New Water Scheme, expected to be operational by 2030, seeks to generate 3.3 million cubic metres of purified water monthly from wastewater. These initiatives collectively contribute to the City's overarching objective of diversifying its sources of water supply and bolstering its water resilience by the year 2030.

Hence, Figure 49 illustrates the formulation used to recycle streams into the system and how they affect the volume of water in the dams at the base case scenario. Considering the model, the starting date for each of the water schemes are Faure (72nd month), Zandvliet (108th month), and Cape Flats (156th month) following the base model year of 2017. The equations for the recycle factors and recycle flows are given in Table 11:

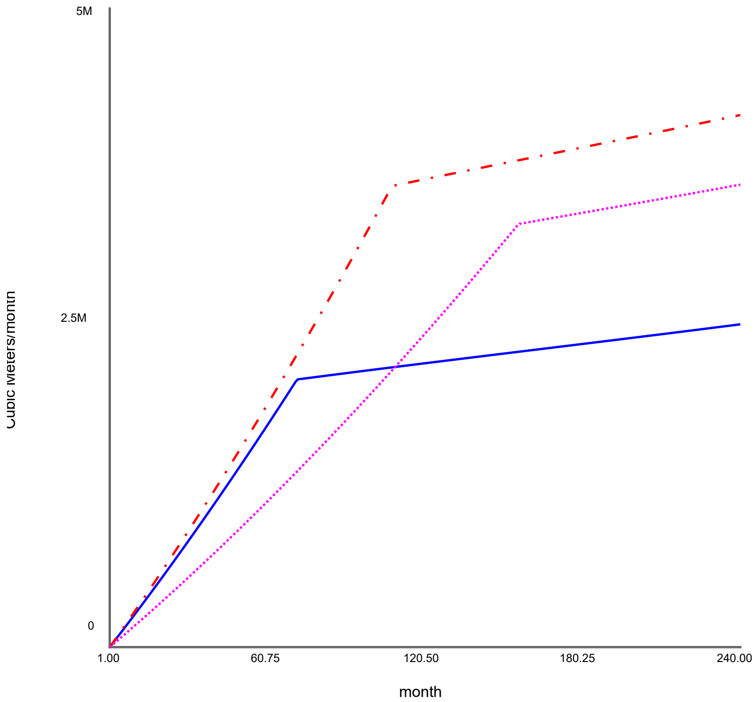
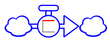
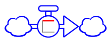
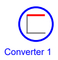
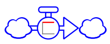


Figure 48 Step implementation of wastewater reuse schemes for Faure, Zandvliet, and Cape Flats New Water Schemes

Table 11: Equations utilized to integrate water recycling rates and recycling factors.

Symbol	Equations	Units	Eq. No.
	Fuare_Water_Scheme_2024 = (Agricultural_WD+urban_water_demand)*recycle_factor_Faure_2024	$\frac{m^3}{month}$	S1
	recycle factor Faure 2024 = RAMP (0.016, 1, 72)	-	S2
	Zandvliet_Water_Scheme_2026= (Agricultural_WD+urban_water_demand)* recycle_factor_Zandvliet_2026	$\frac{m^3}{month}$	S3
	recycle_factor_Zandvliet_2026 = RAMP (1.87, 108)	-	S4
	Cape_Flats_Water_Scheme_2030 = recycle_factor_Cape_Flats_2030*(Agricultural_WD+urban_water_demand)	$\frac{m^3}{month}$	S5
	recycle_factor_Cape_Flats_2030 = RAMP (1.62, 156)	-	S6

The results show that when the Faure New Water Scheme is integrated at the back end of 2024, the volume of water increases by about 3.5% indicating an additional purified volume of 24 million cubic metres at the end of the modelling period. Also, when the Zandvliet New Water scheme is incorporated 2 years after the Faure scheme, the available water increases to approximately 525 million cubic metres, which is an increase of approximately 8.95%. Lastly, with the integration of the Cape Flats New Water Scheme in 2030, the volume of water in the dams rise to nearly 569 million cubic metres representing another increase of approximately 8.4% of additional water.

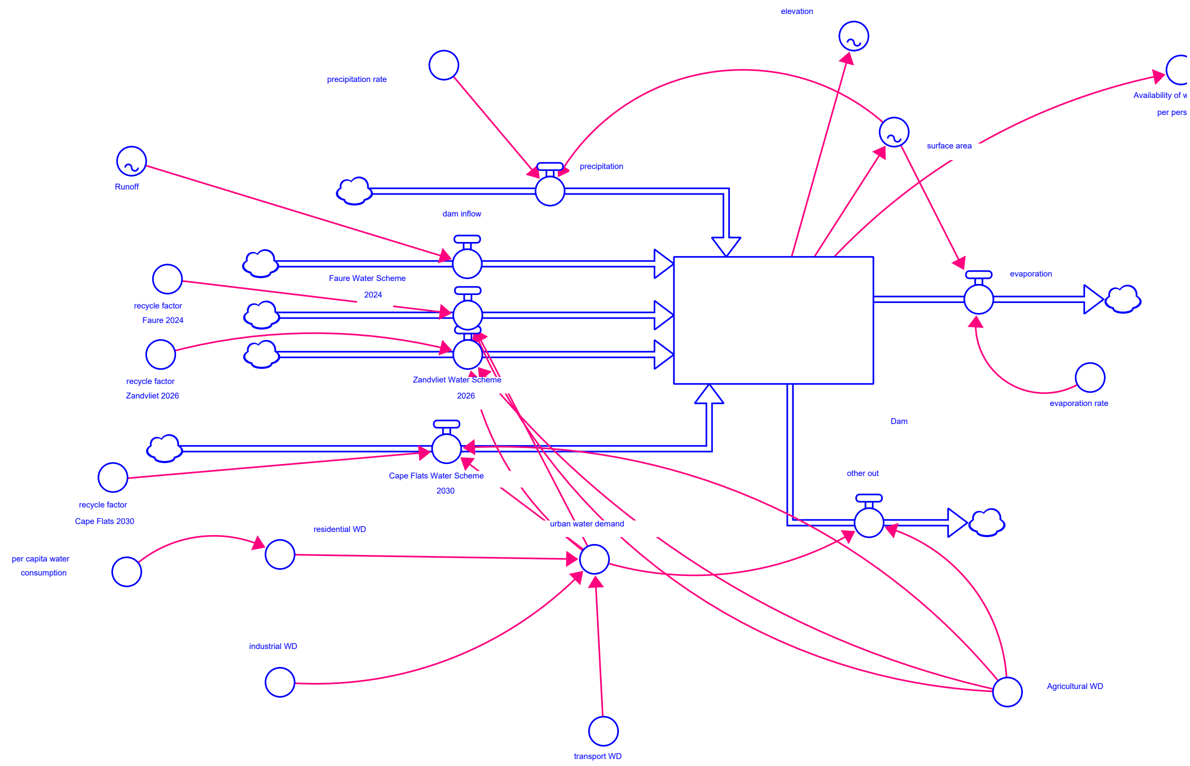


Figure 49 Cross section of the water sector showing recycle streams integration

6.4.3 Climate change

In this study, it is assumed that the evaporation rate (E_o) is affected by temperature change over time in different climates. Hence, the Penman equation for evaporation rate is applied (Linacre, 1977) as illustrated in Equation S7.

$$E_o = \frac{\left(\frac{700T_m}{100 - A} + 15(T - T_d)\right)}{80 - T} \quad \left(\frac{m}{month}\right) \qquad \text{(S7)}$$

Where $T_m = T + 0.006 * elevation$ (measured in metres), T represents the mean temperature, A stands for the latitude (degrees), and T_d denotes the mean dew-point temperature. The values presented in equation W23 typically exhibits variations of approximately 0.0003 metres per day for annual averages, 0.0005 metres per day for monthly averages, 0.0009 metres per day for weekly averages, and 0.0017 metres per day for daily averages. The equation is applicable across a broad range of climates. It is noteworthy, however, that the monthly mean values of the term $T - T_d$ can be obtained either from an empirical table or from an empirical relationship (see Equation S8), provided precipitation is at 0.005 metres per month and the $(T - T_d)$ remains a minimum of 4 ^{0}C:

$$T - T_d = 0.0023 * elevation + 0.37T + 0.53R + 0.35R_{ann} - 10.9 \quad (°C) \qquad \text{(S8)}$$

Where R represents the mean daily temperature range and R_{ann} is the disparity between the mean temperatures of the warmest and coldest months. Consequently, the evaporation rate relies on values of elevation, latitude, as well as daily maximum and minimum temperatures (Linacre, 1977). An illustration of the model application of the Penman equation is presented in Figure 50 with equations S9 to S11 giving the mathematical implementation in Stella. It is worth noting that other parameters are given in the model input section of Appendix F.

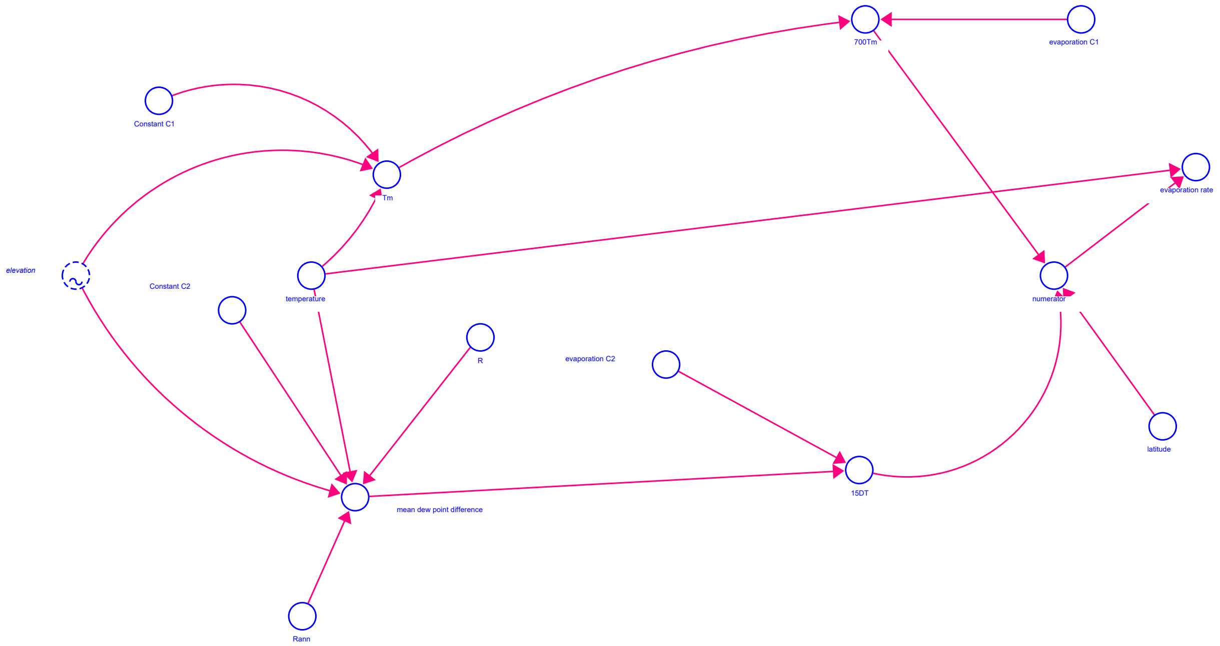


Figure 50 Representation of the Penman Equation to calculate evaporation rate

Table 12: Equations used to integrate the Penman Equation into the model

Symbol	Equations	Units	Eq. No.
Converter 1	mean_dew_point_difference = Constant_C2*elevation + 0.37*Temperature + 0.53*R +0.35*Rann - 10.9	°C	S9
	Numerator = ("700Tm" / (100-latitude)) - "15DT"	$\frac{m}{month * °C}$	S10
	evaporation_rate = Numerator/(80 -Temperature)	$\frac{m}{month}$	S11
Converter 1	Temperature = Random (10, 45, 20)	°C	S12

Predicting the temperature range in Cape Town for the next 20 to 50 years poses a challenge due to its dependency on various factors, including global warming, greenhouse gas emissions, natural variability, and human activities. Nonetheless, utilizing historical data and climate models, it is possible to estimate the temperature range based on potential future scenarios.

To illustrate, as per the Climate & Weather Averages of Cape Town (timeanddate, 2023), the current annual average temperature stands at 17°C, with February being the hottest month at 22°C, and July being the coldest at 13°C. The average annual precipitation is 214 mm, with June being the wettest month at 48 mm and February being the driest at 15 mm. Conversely, the Cape Town, South Africa – Monthly Calendar reveals that historical weather patterns for the past year (2023) exhibited extreme weather events, including heatwaves, droughts, floods, and storms. For instance, in January 2023, Cape Town recorded an unprecedented maximum temperature of 41°C. In March 2023, rainfall reached 113 mm, exceeding the monthly average. Additionally, a severe storm in June 2023 caused widespread damage and power outages (The Weather Network, 2023). Moreover, the Cape Town, Western Cape, South Africa Historical Weather Almanac (World Weather Online, 2023) presents historical weather data spanning from 1980 to 2010, demonstrating Cape Town's relatively stable climate, with minor temperature and precipitation fluctuations over the years. For example, in 1980, the average temperature stood at 17°C, with a total rainfall of 216 mm. In 2010, the average temperature increased to 18°C, with a total rainfall of 212 mm. Lastly, another study indicates that future climate projections for Cape Town anticipate an increased occurrence of intense heatwaves, droughts, floods, and storms over the next 20 to 50 years. The average temperature is expected to rise by 1.5 to 3°C by 2070, leading to more days with temperatures exceeding 30°C and fewer days falling below 10°C. Additionally, the average precipitation is projected to decrease by 10 to 30% by 2070, resulting in greater variability and unpredictability in rainfall patterns. Furthermore, sea levels are forecasted to rise by 0.5 to 1 m by 2100, contributing to increased coastal erosion and flooding (CSAG, 2022).

Consequently, it can be inferred that the temperature range in Cape Town over the next 20 to 50 years will likely fluctuate between 10°C and 45°C, with an average of 20°C. However, this estimation remains approximate, and the outcomes may differ based on our responses to the climate crisis. Therefore, this study models the "Temperature" converter in the climate model within the range of 10°C to 45°C, with an average of 20°C (see equation S12).

Accordingly, the predicted temperature over the next 20 years (i.e. the modelling period) is integrated into the Temperature converter. The results show that at the end of the modelling period, an evaporation rate of 13.3 metres per month is calculated which leads to about 317 million cubic metres of water available.

6.4.4 Sensitivity Analysis of Population

In this section, the effects of a variation in certain critical parameters as population as they affect the base case CoCT WEF nexus system are implemented.

Here the initial population varied from an initial start of 4 million people to 10 million people over the modelling period. Five runs or interactions of the population change are implied as illustrated in Figure 51. The results show that over the modelling period and provided all other variables and parameters remain constant, the population gradually moves to stasis of about 6.2 million people. Alternatively, the impact of the population variation is observed as it affects the availability of water per person (i.e. a ratio of water available in the dam to the population of people present (see Figure 52). The results display values ranging from about 66.2 m^3 per person to 80.6 m^3 per person attesting to the robustness of the model.

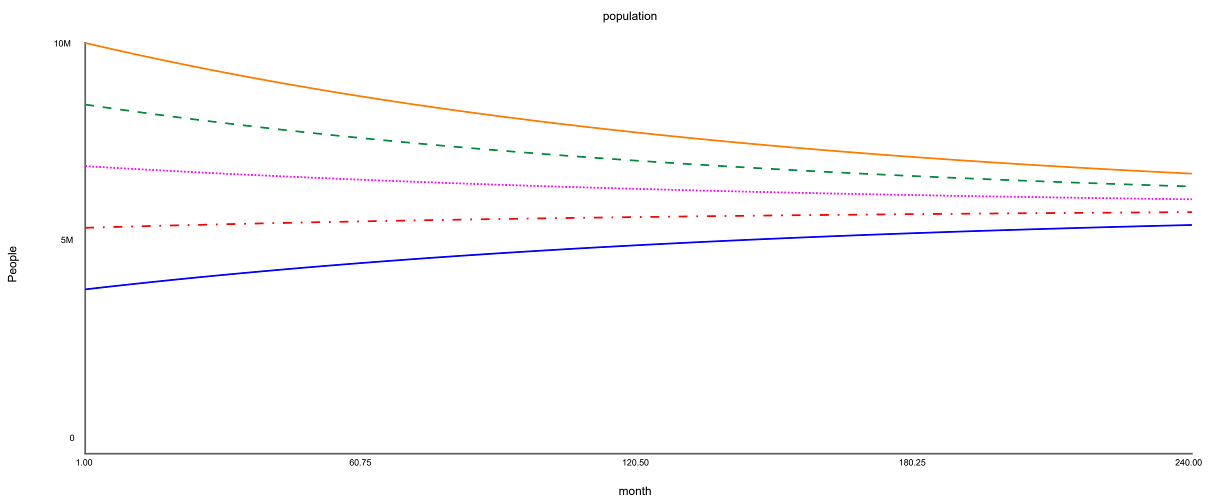


Figure 51 Population variation over the modelling period

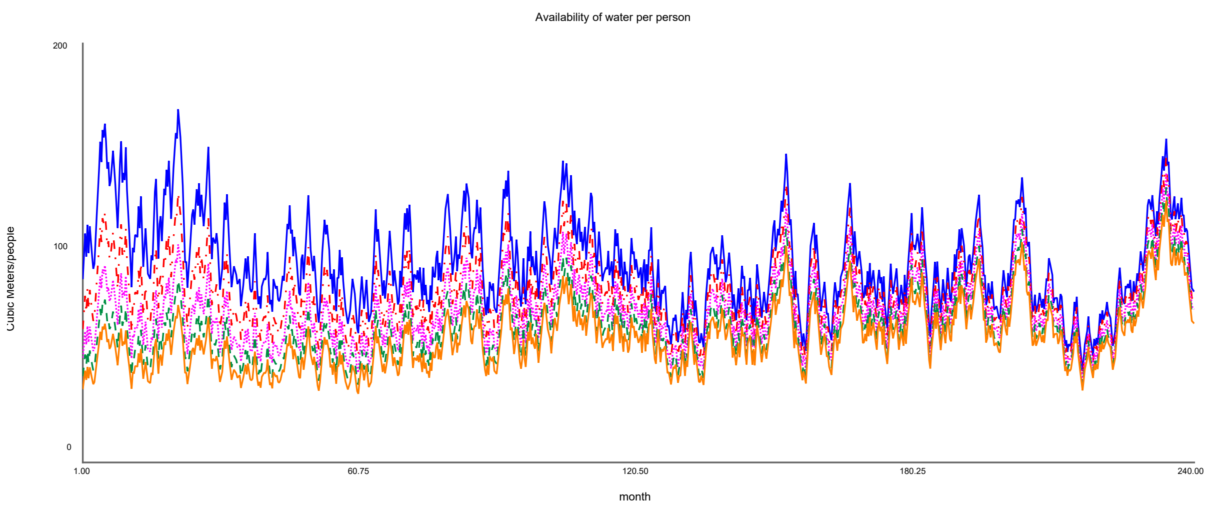


Figure 52 Variation in per capita water availability over the modelling period

6.5. Conclusion

A water-energy-food nexus model has been developed for the City of Cape Town, South Africa, to predict the interplay of these critical resources. This model employs the system dynamics modelling approach within Stella Architect and spans a 20-year timeframe. It encompasses five key sectors: water, energy, food, population, and land-use.

The model's outcomes, based on a base case scenario starting from 2017, indicate that the dams will hold approximately 540 million cubic metres of water. In terms of energy supply, considering four sources—hydroelectric, solar, nuclear, and gas-fired power plants—the model forecasts an accumulation of around 247 million MWh, representing a shortfall of about 21.5% compared to the electricity demand at the end of the modelling period.

Within the food sector, a distinction is made between staple and non-staple foods. The model predicts the production of 10,000 tons of non-staple foods and approximately 2,400 tons per month of staple foods by the end of the modelling period. It's worth noting that staple foods require 10,600 MWh/month and 494,000 m^3/month of electricity and water, respectively, whereas non-staple foods necessitate 8,260 MWh/month and 247,000 m^3/month, indicating lower resource requirements.

Furthermore, the model has been implemented to explore a scenario that integrates three recycling proposals aligned with the City of Cape Town's vision for augmenting water availability. Additionally, it considers the influence of climate change on evaporation rates, drawing from the Penman Equation. A sensitivity analysis on the impact of population changes on water availability has also been incorporated.

However, a notable limitation of this study pertains to the availability and temporal misalignment of certain data aspects within the model. To address this challenge, rigorous verification and validation exercises have been undertaken. Subsequently, future endeavours will encompass an assessment of emission factors and optimization strategies for the various sectors. These efforts aim to enhance the decision-making process in managing the water-energy-food nexus in the City of Cape Town.

6.6 References

AgriFarms, 2023 – The Western Cape. Available at: https://www.agrifarms.co.za/western-cape#:~:text=Available%20Farm%20land%20in%20the,for%20grazing%20and%20mountainous%20areas. Accessed:14/08/2023.

Albrecht, T. R., Crootof, A., & Scott, C. A. (2018). The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. Environmental Research Letters, 13(4). https://doi.org/10.1088/1748-9326/aaa9c6

Bieber, N., Ker, J. H., Wang, X., Triantafyllidis, C., van Dam, K. H., Koppelaar, R. H. E. M., & Shah, N. (2018). Sustainable planning of the energy-water-food nexus using decision making tools. Energy Policy, 113(July 2017), 584-607. https://doi.org/10.1016/j.enpol.2017.11.037

Calverley and Walther, 2022 – Drought, water management, and social equity: Analysing Cape Town, South Africa's water crisis. Frontiers in Water.

CoCT 2023 – City of Cape Town Open Data Portal. Available at: https://odp-cctegis.opendata.arcgis.com/. Accessed: 14/08/2023

CoCT, 2006 – Urban Agricultural Policy for the City of Cape Town

CoCTa, 2020 – Profile and Analysis district development model. City of Cape Town Metropolitan Western Cape Province.

CoCTa, 2021 – Cape Town State of Energy and Carbon 2021. City of Cape Town

CoCTa, 2022 – Water Services Development Plan – IDP Water Sector Input Report

CoCTb, 2020 – Socio-Economic Profile

CSAG, 2022 – Big Six Monitor: Big Six Western Cape Water Supply System. Available at: https://cip.csag.uct.ac.za/monitoring/bigsix.html. Accessed: 28/8/2023

CSAG, 2022 – SmartAgri: Updated Climate Change Trends and Projections for the Western Cape

CWRA. (2020). Water Resilience Profile: Cape Town. https://www.resilienceshift.org/wp-content/uploads/2020/01/Cape_Town_WaterResilienceProfile_FINAL.pdf

Egieya, J. M., Amidu, M. A., & Hachaichi, M. (2023). Small modular reactors: An assessment of workforce requirements and operating costs. Progress in Nuclear Energy, 159(January), 104632. https://doi.org/10.1016/j.pnucene.2023.104632

Endo, A., Yamada, M., Miyashita, Y., Sugimoto, R., Ishii, A., Nishijima, J., Fujii, M., Kato, T., Hamamoto, H., Kimura, M., Kumazawa, T., & Qi, J. (2020). Dynamics of water-energy-food nexus methodology, methods, and tools. Current Opinion in Environmental Science and Health, 13, 46-60. https://doi.org/10.1016/j.coesh.2019.10.004

Ford, A. (1999). Modelling the environment an introduction to system dynamics models of environmental systems. Island Press.

Hoff, H. (2011). Understanding the Nexus. Background paper for the Bonn2011 Nexus Conference: Stockholm Environment Institute, November, 1-52.

Investcapetown, 2023 – Agriculture & Agri-Business in Cape Town. Available at: https://www.investcapetown.com/opportunities/agri-business/. Accessed: 30/08/2023.

IRENA. (2015). Renewable energy in the water, energy and food nexus. International Renewable Energy Agency, January, 1-125.

Isee systems, Stella and ithink version 3.2.1, Retrieved from, https://www.iseesystems.com/resources/help/v1-3/default.htm, 2023. Accessed: 20/06/2023

Jury M.R., 2020 – Climate trends in the Cape Town area, South Africa. *Water SA:* Vol. 46, Pp 438-447

Pascale, S., Kapnick, S. B., Delworth, T. L., & Cooke, W. F. (2020). Increasing risk of another Cape Town "day Zero" drought in the 21st century. Proceedings of the National Academy of Sciences of the United States of America, 117(47), 29495-29503. https://doi.org/10.1073/pnas.2009144117

Purwanto, A., Sušnik, J., Suryadi, F. X., & de Fraiture, C. (2021). Quantitative simulation of the water-energy-food (WEF) security nexus in a local planning context in Indonesia. Sustainable Production and Consumption, 25, 198-216. https://doi.org/10.1016/j.spc.2020.08.009

Stanford News, 2020. In a warming world, Cape Town's 'Day Zero' drought won't be an anomaly. https://news.stanford.edu/2020/11/09/cape-towns-day-zero-drought-sign-things-come/ Accessed 08/02/2022.

Stanford News, 2020. In a warming world, Cape Town's 'Day Zero' drought won't be an anomaly. https://news.stanford.edu/2020/11/09/cape-towns-day-zero-drought-sign-things-come/ Accessed 08/02/2022.

StatsSA, 2020. Census of Commercial Agriculture: Financial and Production Statistics, 2017. Available at: https://www.statssa.gov.za/?page_id=1854&PPN=Report-11-02-01. Accessed: 14/08/2023.

The Weather Network, 2023. Cape Town, South Africa. Available at: https://www.theweathernetwork.com/za/monthly/wes-kaap/cape-town. Accessed: 03/09/2023.

Timeanddate, 2023. Climate and Weather Averages in Cape Town, South Africa. Available at: https://www.timeanddate.com/weather/south-africa/cape-town/climate. Accessed: 03/09/2023.

UN, 2022. World Population Prospects. Available at: https://population.un.org/wpp/. Accessed: 22/08/2022

UNESCO, 2022. Groundwater – Making the invisible visible. The United Nations World Water Report 2022

Vermeulen H., Schonfeldt H.C., and Pretorius B., (2015). A consumer perspective of the South Africa red meat classification system. South African Journal of Animal Science. Vol. 34, pp 339-354

World Weather Online, 2023. Cape Town Historical Weather. Available at: https://www.worldweatheronline.com/cape-town-weather-history/western-cape/za.aspx#google_vignette. Accessed: 03/09/2023

Zhang, C., Chen, X., Li, Y., Ding, W., & Fu, G. (2018). Water-energy-food nexus: Concepts, questions and methodologies. Journal of Cleaner Production, 195, 625-639. https://doi.org/10.1016/j.jclepro.2018.05.194

Zhang, X., & Vesselinov, V. V. (2017). Integrated modelling approach for optimal management of water, energy and food security nexus. Advances in Water Resources, 101, 1-10. https://doi.org/10.1016/j.advwatres.2016.12.017

Chapter 7: Summary

Author: Goosen, N.

7.1 Conclusions

The modelling efforts have largely achieved what it set out to do. From the initial literature survey, system dynamics modelling was identified as the most appropriate approach to employ for setting up quantitative WEF nexus models for the City of Cape Town. The approach incorporates systems thinking and it allows for dynamic simulation of complex systems, which is a requirement for this project. Compared to other suitable methods like agent-based modelling, system dynamics provides an aggregate view (which was appropriate in this project), whereas agent based modelling needs to identify all the actors within a system and model their behaviour and interactions to arrive at a system-wide response. System dynamics can sometimes require less data than agent based modelling, and in the particular case where not all role players in the City of Cape Town's water-energy-food system can be identified (e.g. the large number of privately-owned entities within the City), or their responses predicted, system dynamics was chosen as the appropriate approach.

The WEF nexus framing was successful to provide a basis for analysing the interconnected nature of the water-, energy- and food systems within the City of Cape Town, and system dynamics modelling was able to quantitatively model the dynamic system. The models were further able to make predictions that incorporate climate impact over the modelling period, and to incorporate other system disturbances. The results generated by the various systems dynamics models are an indication that the modelling was robust and produced results that, at first glance, seem realistic. Models were put through structural and behavioural tests to ensure that the models were reliable, and the researchers are confident that after the testing, results are indeed reliable. The models generate results that adhere to 'common sense', without any obvious unexpected results. Of course, using 'common sense' as a measure of whether modelling results are reliable comes with the danger of forcing results to adhere to pre-determined outcomes, but the project team feels that this has been avoided. The systems dynamics models are therefore viewed as robust and reliable, and that the overall methodology was appropriate to achieve the original goals of the project.

The actual results of the modelling were insightful in various sectors. Within the water sector it was clear that the City of Cape Town's efforts to augment current water supply are likely to make significant contributions toward ensuring future water security. However, given the emphasis on aquifer water extraction, there is a risk of over-extraction from some aquifers with subsequent long-term impacts. Aquifer water utilisation therefore requires frequent and rigorous monitoring to negate the risks of long-term negative impacts. The efforts to recycle water within the City's water system are also predicted to lead to increased water availability in the longer term, and these efforts are aligned with the '100 Resilient Cities' initiative that the City forms part of. Despite the ongoing efforts, the work clearly indicate that increased population growth and anticipated climate-related changes in rainfall will put the water resources of the City of Cape Town under pressure in the coming decades.

Within the energy sector, the ongoing efforts of the City of Cape Town to supplement electricity supply to the metropole will significantly increase energy security. The additional electricity supply resulting from a planned 650 MW solar farm, and the procurement of electricity from independent suppliers are likely to significantly increase energy security, although it remains unlikely that the metropole will ever be fully self-sufficient from generation within its own boundaries. There remains a high level of uncertainty about the impact of small scale embedded production on overall energy supply, and efforts should be made to improve data and future estimates of such small scale production, which in turn will improve model certainty.

The food and agricultural sector the WEF nexus seems particularly challenging to describe with high levels of certainty for the City of Cape Town. Although there is a good grasp of agricultural activity within the metropole's boundaries, a very large proportion of food is still imported from beyond the city boundaries, meaning that the impacts on the food sector are mostly not controllable through city-level policies. Local food production is also subject to external market forces, and policy impacts from the City are likely only to have indirect impacts on local food production. Therefore, modelling results within the Schoenfeld agricultural and food sector are less clear. Impacts of policy decisions on this sector are likely going to be indirect through, e.g. decreasing the allocation of water to the agricultural sector and diverting it to other uses, which is likely to play out in an environment of constrained water availability and the need for the City to make decisions based on analysing acceptable trade-offs for different sectors.

Any discussion on modelling of complex systems like the WEF nexus for a metropole will be incomplete without reflecting on the availability and quality of data. In this project, the team relied on data in the public domain, which includes open-source data for the City of Cape Town, and those data available in academic literature. It quickly became apparent that there are data available to set up and run the system dynamics models, but also that there are disparities both within and between datasets. In some instances datasets were incomplete, in others two different sources of the same data yielded very different data, and in other instances data for one resources system (e.g. water) were available for a specific time period, but data for another resource system were not available for the same time period. The result of these data disparities are that a significant proportion of researcher time is devoted to sourcing and validating datasets. After discussions with researchers in similar fields, this seems to be a common drawback of ambitious modelling endeavours. The converse is that if the data challenges can be overcome, the modelling can yield very useful results.

7.2 Recommendations

Some direct recommendations flow from the project. Some of these are likely already being implemented by the City of Cape Town, but for completeness they are included here.

The mitigation and long term intervention activities being implemented and/or planned by the City, like internal water recycle and procurement of electricity from independent power producers, should be supported going forward. These activities make significant contributions to increasing resource availability, and will contribute toward increased sustainability of the City. These efforts are aligned with other sustainability efforts within cities globally, and should be encouraged.

Linking to the interventions being implemented and planned, the City should take care to diversify the type of interventions implemented, as they are already no doubt fully aware. It will take a combination of different approaches, both on decreasing the demand and increasing the supply of water and to a certain extent energy; as mentioned previously, it is difficult for the City to directly increase food availability.

Seeing that the various aquifers form an important part of future water supply, frequent monitoring should be performed on these crucial sources of fresh water. The utilisation of aquifer water comes at the risk of over-extraction, which could result in seawater infiltration and salinification of the affected aquifer(s). Frequent monitoring is therefore essential to ensure that this water resource remains viable in future.

Increased release of non-sensitive data should be seriously considered. There is significant capability within the South African academic system to process good quality data sets, which could in turn have significant benefits to the originators of such data. The difficulty in finding and validating data prevents more collaboration between academia and local government, and having a central repository where data are synchronised and curated, will be of immense value to facilitate future investigations, to the mutual benefit of academia and local government.

7.3 Future Research

There are important recommendations for further work that will build on the current project, and enhance the overall body of WEF nexus research both in South Africa, but also within the global context.

There are important areas where modelling can be improved. Firstly, the models can be supplemented by integrating economic aspects, where the impact of policy changes on some economic indicators at various scales can be evaluated. Initially this project planned on adding economic aspects, but within the scope of the project it was not feasible. Nonetheless, economic aspects are likely going to play a large role in future decision making, and incorporating the capability of current models to make economic indicators part of the outputs will increase the utility of the resulting outputs. Secondly, the increase in population needs to be verified. Much of the models rely on data specified on a per capita basis. Given the phenomenon of 'semigration', where in-country movement of people into the Western Cape is a significant contributor to population increase within the City's boundaries, it is important to make accurate predictions of expected population growth. Finally, a particularly important aspect that can be added to the work is uncertainty analysis, and pinpointing the largest contributors to model uncertainty, which in turn will guide where future efforts need to be focused to improve the certainty in model outputs.

The current project mostly viewed system disturbances as single events and modelled the predicted outcomes. Although it is difficult to reliably determine the co-occurrence of multiple system disturbances (e.g. sudden semigration increase coupled to multi-year drought), the system resilience should be evaluated at the hand of such 'perfect storm' scenarios in future. The Day Zero drought was an exceptional occurrence and was only narrowly avoided; setting up some multi-disturbance scenarios could yield results that are helpful to elucidate specific pressure points in the overall system that are particularly vulnerable.

Finally, the work can benefit from adding additional disciplines to the project team in future expansion of the project. The work undertaken was already of a multidisciplinary nature and although the project team made good strides in setting up and validating the systems dynamic models, the expansion of disciplines to include, e.g. economics could add significant additional value.

Appendix A: Agricultural Sector

Table A1: Available land for agriculture

S/No.	Description	Data (km^2)	Notes
1.	Area of the Western Cape	129,462.00	
2.	Western Cape farmland	115,610.00	
3.	Arable land in Western Cape	21,966.00	
4.	Grazing land	93,644.00	
5.	Area of the CoCT	2,445.00	
6.	CoCT farmlands	2,183.39	Assumed ratio with (2)/(1)
7.	Arable land in CoCT	414.84	Assumed ratio with (3)/(2)
8.	Planted area in CoCT	91.57	
9.	Grazing land	1,768.54	Assumed ratio (4)/(2)

Table A2: Households related to agriculture in the CoCT

S/No.	Description	Data (-)
1.	Households involved in agricultural activities	34,383
2.	Households with cattle	495.00
3.	Households with sheep	347.00
4.	Households with goats	350.00
5.	Households with pigs	307.00
6.	Households with chickens	11,892.00
7.	Households involved in vegetables production	17,136.00
8.	Households involved in the production of other crops	11,245.00

Table A3: Number of livestock in the CoCT

S/No.	Description	Data (herds)
1.	Cattle beef	13,239.33
2.	Cattle dairy	11,393.52
3.	Sheep meat	2,503.15
4.	Sheep wool	8,745.28
5.	Pigs	8,525.36
6.	Chicken broilers	4,259,811.00
7.	Chicken layers	171,200.20

Table A4: Number of farms per source of water used.

S/No.	Description	Data (-)
1.	Dragline, quick-coupling lines	7.
2.	Flood irrigation	4.00
3.	Drip	42.00
4.	Micro-irrigation	15.00
5.	Sprinkler	20.00
6.	Other (headwaters, wetlands)	3.00
7.	Rainwater harvesting	22.00
8.	Treated Wastewater	10.00
9.	Both surface and groundwater	13.00
10.	Groundwater/borehole	30.00
11.	Water boards/schemes	16.00
12.	Dam	32.00
13.	River	11.00
14.	Municipal water supply	7.00
15.	Total irrigation	238.00
16.	Dry land/rain-fed	54.00
17.	Both irrigation and Dry land/Rain-fed	184.00

Table A5: Agricultural crops produced in 2017

S/No.	Description	Produce (t)	Area (ha)	Energy input (MJ/ha)	Water requirements (mm/growing period)	2012 Food consumption per capita (kg.capita/year)	2019 Food consumption per capita (kg.capita/year)
1.	vegetables (beetroot)	3,514.00	97	1,063,200	550 – 750	19.98	24.6
2.	vegetables (butternut)	367.00	16			19.98	24.6
3.	vegetables (cabbages)	2,575.00	103		350 – 500	19.98	24.6
4.	vegetables (carrots)	12501	417			19.98	24.6
5.	vegetables (green beans)	4	1		350 – 500	19.98	24.6
6.	vegetables (onions)	20	0	107,183	350 – 550	8.95	7.9
7.	vegetables (pepper)	10	0		600 – 900	0.03	24.6
8.	vegetables (potatoes)	1654	64	92,290	500 – 700	32.99	29.5
9.	Vegetables (pumpkins excluding melons)	164	8			19.98	24.6
10	vegetables (tomatoes)	901	15		400 – 800	9.5	10.4
11	lemons	2324	54		900 – 1200	0.92	1.2
12	Naartjies	131	3	62,261	900 – 1200	6.04	0.2
13	Oranges	441	156		900 – 1200	6.04	6.9
14	Other soft citrus or easy peelers	817	16		900 – 1200	0.09	5.8
15	Subtropical fruits (berries all kinds) area planted	63	5			3.56	5.8
16	Berries (all kinds) production	30	5			3.56	5.8
17	Apples	8054	744	43,404		1.87	6.80
18	Pears	6711	222			3.56	5.8
19	Peaches	955	37			3.56	5.8
20	Plums	2671	104			3.56	5.8
21	Table grapes	3702	195	45,230	500 – 1200	2.32	1.3
22	Wine grapes	24560	3254	1,063,200	900 – 1200	1.36	1.3
23	Grains/cereals production	13782	7011		450 – 650	0.77	
24	Grains/cereals planted area dry land	13576	6972		450 – 650	0.77	
25	Grains/cereals planted area irrigated	205	39		450 – 650	0.77	
26	Oil seeds production (dry land)	1992	1343			1.17	2.5
27	legumes production (dry land)	64	80	7,982			
28	fodder (total)	633	701				
29	fodder (dry land)	616	650				
30	fodder (irrigation)	17	51				
31	Wheat production	12329	5893	32,493	450 – 650	59	61
32	Wheat production (dry land)	12329	5893	32,493	450 – 650	59	61
33	barley production (total)	567	185	25,656	450 – 650	0	0
34	Barley production (dry land)	567	185	25,656	450 – 650	0	0

S/No.	Description	Produce (t)	Area (ha)	Energy input (MJ/ha)	Water requirements (mm/growing period)	2012 Food consumption per capita (kg.capita/year)	2019 Food consumption per capita (kg.capita/year)
35	Oats production (total)	886	359		450 – 650	0.67	1.1
36	Oats production (dry land)	680	320		450 – 650	0.67	1.1
37	Oats production (irrigation)	205	39		450 – 650	0.67	1.1
38	Canola production (total)	1992	1343	18,558	350 – 1000	1.17	2.5
39	Canola production (dry land)	1992	1343	18,558	350 – 1000	1.17	
40	Dry beans production (total)	64	40	23,667	300 – 500	0.91	2.9
41	Dry beans production (dry land)	64	40	23,667	300 – 500	0.91	2.9
42	Grass production (total)	633	362	32,769			
43	Grass production (dry land)	616	316	32,769			
44	Grass production (irrigation)	16	46				
45	Lucerne/Alfalfa planted irrigated	5	5	81,050	800 – 1600		
46	Cattle beef					15.4	17.58
47	Sheep meat					3.8	3.17
48	Pork					6.8	4.75
49	Chickens broilers					32	37.32
50							

Appendix B: Economics Sector

Table B1: Economic profile of the CoCT

S/No.	Sectors	GDPR (R million value 2018)	Contribution (%)	Sector growth (%)	Employees (persons)	Water use (ML)	Energy use (MJ)	GVA (constant 2016 ZAR)	GVA (constant 2016 ZAR '000)
1.	Agriculture, forestry & fishing	5,846.90	1.38	-3.80	44,216		3,043,589	0.83	3,289,449.14
2.	[a] Mining and quarrying	1,001.80	0.24	-2.70	892		109,958	0.15	594,478.76
3.	[a] Manufacturing	63,284.00	14.95	-0.40	178,510		6,946,048	14.07	55,762,107.78
4.	[a] Electricity, gas & water	12,837.10	3.03	-2.80	6,183		1,408,999	1.44	5,706,996.11
5.	[a] Construction	21,901.90	5.18	-3.60	106,392		2,403,951	3.54	14,029,698.76
6.	[b] Finance, insurance, real estate, and business services	116,076.30	27.43	1.90	351,829		11,010,897	35.88	142,199,319.63
7.	[b] Wholesale & retail trade, catering & accommodation	72,421.70	17.11	-0.20	394,570		6,869,859	16.07	63,688,491.26
8.	Transport, storage & communication	48,207.60	11.39	-0.60	81,694		106,988,775	10.98	43,515,845.31
9.	General government	52,761.60	12.47	1.80	213,821		2,017,361		
10.	[c] Community, social & and personal services	28,870.80	6.82	0.90	244,882		15,253,586	17.04	67,532,787.25
11.	LOSSES						3,622,958		
12.	**TOTAL**	**423,209.70**	**100**	**0.50**	**1,622,989**		**159,676,081.00**	**100**	**396,316,174**

a. Mining and quarrying; Manufacturing; and Construction combine to form the Industrial Sector

b. Finance, insurance, real estate, and business services; Wholesale and retail trade, catering and accommodation combine to form the Commercial Sector

Table B2: Other important economic data

S/No.	Description	Data	Unit
1.	Total people in CoCT	4,423,834.00	people
2.	Growth rate	2.57	%
3.	Total area of CoCT	2,445.00	km^2
4.	Population density	1,809.34	people/km^2
5.	Number of households	1,234,317.00	no unit
6.	GDP at 2005 prices	28,050.00	million USD
7.	Gini coefficient	0.62	
8.	Human development index	0.74	
9.	GDPR per capita	65,302.00	Rand per person

Table B3: Employment

S/No.	Description	Data	Unit
1.	Employed people	1,622,989.00	people
2.	Unemployed	509,114.38	people
3.	Discouraged work seeker	102,117.82	people
4.	Not economically active	1,031,484.89	people
5.	Unemployment rate	23.00	%
6.	Working age	15-64	No unit
7.	Work age population ratio	69.60	%
8.	Available labour resources	3,078,988.46	People

Appendix C: Energy Sector

Table C1: Percentage contribution energy source for cooking, heating, and lighting

S/No.	Energy Source	Cooking	Heating	Lighting
	Electricity	87.6	64.0	94
	Gas	7.5	3.5	0.3
	Paraffin	3.85	14.5	3.8
	Wood	0	1.8	0
	Solar	0.1	0	0.2
	Candles	0	0	1.5
	Animal dung	0	0.1	0
	Other	0.3	0	0
	none	0.65	16.1	0.2

Table C2: Micro-hydroelectricity generation plants owned by the CoCT (2018)

S/No.	Location	Type	Total turbine capacity (kW)	Electricity generated per annum (kWh)
	Wemmershoek water treatment plant	2 x Francis	260	1,138,800
	Blackheath water treatment plant	1 x Turgo	700	3,066,000
	Faure water treatment plant	1 x Turgo	1,475	6,460,500
	Steenbras water treatment plant	2 x Turgo	340	1,489,200
	Total		**2,775**	**12,154,500**

Table C3: Potential locations and size of City-owned solar PV embedded generation development

S/No.	Photovoltaic (PV) site name	PV system size (kW peak)	PV estimated annual generation (kWh)	PV installation type (rooftop or ground-mounted)	PV site type
	Kraaifontein wastewater treatment plant	<1 000	1,755,000	Ground-mounted	Wastewater treatment plant
	Athlone wastewater treatment plant	2,400	1,760,000	Ground-mounted	Wastewater treatment plant
	Bellville wastewater treatment works	2,600	1,755,000	Ground-mounted	Wastewater treatment plant
	Cape Flats wastewater treatment plant	3,400	1,729,000	Ground-mounted	Wastewater treatment plant
	Mitchells Plain wastewater treatment works	1,800	1,751,000	Ground-mounted	Wastewater treatment plant
	Potsdam wastewater treatment plant	2,800	1,793,000	Ground-mounted	Wastewater treatment plant
	Wesfleur wastewater treatment plant	800	1,803,000	Ground-mounted	Wastewater treatment plant
	Ndabeni Electricity depot	750	165,601	Rooftop	Electricity depot/facility
	Athlone power station	50	165,079	Rooftop	Electricity depot/facility
	Atlantis depot	40	168,488	Rooftop	Electricity depot/facility
	Gugulethu Electricity depot	<100	165,215	Rooftop	Electricity depot/facility
	Newlands network centre	100	160,982	Rooftop	Electricity depot/facility
	Wynberg depot	160	160,703	Rooftop	Electricity depot/facility
	Spyker Street depot (Helderberg)	80	161,797	Rooftop	Electricity depot/facility
	Goodwood Transport Management Centre	<1 000	-	Rooftop	Transport Management Centre

Table C4: Electricity generation by City-owned power plants

S/No.	Electricity generated (kWh)	2013	2014	2015	2016	2017	2018	2019
	Athlone	256,780	183,163	646,667	179,407	4,661	158,170	305,148
	Roggebaai	78,950	989,820	586,160	108,960	6,400	157,040	346,720
	Steenbras	122,863,838	141,127,643	112,958,640	50,036,337	22,680,690	69,519,761	80,784,800
	Net energy sent out (kWh)	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
	Athlone	148,190	84,675	551,739	83,054	-83,683	146,774	293,610
	Roggebaai	-25,850	931,590	573,218	92,891	-8,459	153,713	343,515
	Steenbras	-30,222,600	-42,329,115	-27,406,200	5,702,400	703,600	16,067,900	3,408,000

Table C5: Energy sources, contribution, emissions, and growth per annum

S/No.	Energy Sources (2018)	Energy Consumption (GJ)	GJ source contribution (%)	Emissions (tCO_2eq)	CO2 (%)	Growth p.a. (%)
	Electricity	43,438,656.00	27.20	11,527,623.00	57.83	-1.70
	Coal	1,511,117.00	0.95	143,979.00	0.72	-15.30
	Petrol	44,620,887.00	27.94	3,111,816.00	15.61	-1.20
	Diesel	47,195,428.00	29.56	3,517,900.00	17.65	1.90
	Paraffin	1,614,890.00	1.01	116,820.00	0.59	-4.80
	LPG	1,194,491.00	0.75	75,571.00	0.38	-11.20
	NG	0.00	0.00	0.00	0.00	
	Heavy furnace oil	205,370.00	0.13	15,986.00	0.08	-29.20
	Jet fuel	18,796,400.00	11.77	1,352,194.00	6.78	4.50
	Wood	167,610.00	0.10	318.00	0.00	1.20
	Aviation fuel	19,565.00	0.01	1,378.00	0.01	-7.10
	International Marine	911,566.00	0.57	69,398.00	0.35	-21.80
	Losses			1,840,321.00		
	Total	**159,675,981.00**	**100**	**21,773,304**	**100.00**	

Table C6: Energy consumption by sector

z	Energy Sources (2018)	Energy Consumption (GJ)	GJ sector contribution (%)	Emissions (tCO_2eq)	CO2 (%)
	Agriculture, forestry & fishing	3,043,589.00	1.95	263,492	1.21
	[a] Mining & quarrying	109,957.51	0.07	19,890	0.09
	[a] Manufacturing	6,946,047.97	4.45	1,256,475	5.77
	Electricity, gas & water	1,408,999.31	0.90	254,874	1.17
	[a] Construction	2,403,951.21	1.54	434,852	2.00
	[b] Finance, insurance, real estate and business services	11,010,896.66	7.06	3,199,586	14.69
	[b] Wholesale & retail trade, catering & accommodation	6,869,859.34	4.40	1,996,268	9.17
	Transport, storage & communication	106,988,775.00	68.56	8,763,374	40.25
	General government	2,017,361.00	1.29	1,840,323	8.45
	Community, social, and personal services	15,253,586.00	9.77	3,744,170	17.20
	Losses	3,622,958			
	Total	**159,675,981.00**	**100**	**21,773,304**	**100**

Mining and quarrying; Manufacturing; and Construction combine to form the Industrial Sector

Finance, insurance, real estate, and business services; Wholesale and retail trade, catering, and accommodation combine to form the Commercial Sector

Table C7: Electricity consumption by sector

S/No.	Energy Sources (2018)	Energy Consumption (GWh)	GJ sector contribution (%)	Emissions (tCO_2eq)	CO2 (%)
	Agriculture, forestry & fishing	187.72	2.00	217,608.00	1.02
	[a] Mining & quarrying	12.34	0.13	22,878.12	0.11
	[a] Manufacturing	779.78	8.31	1,445,217.76	6.79
	Electricity, gas & water	158.18	1.69	293,161.07	1.38
	[a] Construction	269.87	2.88	500,174.05	2.35
	[b] Finance, insurance, real estate and business services	2,485.34	26.48	3,379,312.53	15.88
	[b] Wholesale & retail trade, catering & accommodation	1,550.64	16.52	2,108,402.47	9.91
	Transport, storage & communication	93.86	1.00	6,974,396.00	32.77
	General government	375.44	4.00	503,635.00	2.37
	Community, social & personal services	3,472.82	37.00	4,752,490.00	22.33
	Electricity Losses			1,084,940.00	5.10
	TOTAL	**9,385.99**	**100.00**	**21,282,215.00**	**100.00**

Appendix D: Water Sector

Table D1: Big six hydrologic model for June 2020 to May 2022 (CSAG, 2022)

S/No.	Months	Urban water use (Million litres per day)	Agricultural water use (Million litres per day)	Rainfall (mm per month)
1.	Jun-20	799	27	150
2.	Jul-20	779	26	123
3.	Aug-20	789	26	136
4.	Sep-20	803	27	69
5.	Oct-20	881	131	44
6.	Nov-20	958	281	79
7.	Dec-20	1048	755	19
8.	Jan-21	1090	978	16
9.	Feb-21	1142	1025	20
10.	Mar-21	1095	847	22
11.	Apr-21	982	467	53
12.	May-21	869	53	109
13.	Jun-21	199	27	150
14.	Jul-21	779	26	123
15.	Aug-21	789	26	136
16.	Sep-21	803	27	69
17.	Oct-21	881	131	44
18.	Nov-21	958	281	79
19.	Dec-21	1048	755	19
20.	Jan-22	1090	978	16
21.	Feb-22	1142	1025	20
22.	Mar-22	1095	847	22
23.	Apr-22	982	467	53
24.	May-22	869	53	109

Table D2: Surface water from dams

S/No.	Dams	Capacity (Million litres)
	Voëlvlei	164,095.00
	Berg River	130,010.00
	Wemmershoek	58,644.00
	Steenbras Upper	31,767.00
	Steenbras Lower	33,517.00

Table D2: Surface water from dams (CoCT 2018)

S/No.	Dams	Capacity (Million litres per day)	Total water produced till 2018 (Million litres)
	Strandfontein	7	880
	Monwabisi	7	550
	V&A Waterfront	2	128

Table D3: Ground water from aquifers (CoCT 2018)

S/No.	Dams	Capacity (Million litres per day)
	Atlantis Aquifer	16
	Cape Flats Aquifer	48
	Atlantis and Silverstroom yield	12

Table D4: Demand and Supply targets

S/No.	Description	Quantity	Unit
	Unconstrained Cape Town target total allocation for 2018	324.00	Mm^3
	Agriculture	144.00	Mm^3
	2019 average restricted allocation (Cape Town)	243.00	Mm^3
	2019 average restricted allocation (Agriculture)	152.00	Mm^3
	2019 average restricted daily demand (Cape Town)	666.00	MLD
	2019 average restricted daily demand (Agriculture)	416.00	MLD
	Average cost including bulk infrastructure and treatment	5.20	R/ '000 L

Table D5: Other details

S/No.	Description	Quantity	Unit
	Precipitation on yearly basis	475	mm/y
	Precipitation per month	39.6	Mm/month
	Source water from regional/local water scheme	97.3	%
	Number of municipal wastewater treatment facilities	1	-

Appendix E: Population Sector

Table E1: Population data

S/No.	Description	Data	Unit
	Population	4,423,834.00	people
	Total area	2,445.00	km^2
	Population density	1,809.34	people/km^2
	Informal settlements area size	195.60	km^2
	Birth rate	19.40	per 1,000 population
	Death rate	11.60	per 1,000 population
	Murder rate (CRIME)	67.00	per 1,000k population
	Life expectancy	67.60	years
	Total population growth rate	1.90	%
	Forecasted growth rate	1.50	%
	Formal population initial	3,445,028.12	people
	Total households in the CoCT	1,234,317.00	households
	Informal initial population	1,133,103.01	people
	Informal households	266,612.47	households
	Informal household size	4.25	people per household
	Formal population initial	3,445,028.12	people
	Formal households	967,704.53	households
	Fraction of water consumed domestically	67.00	%
	Formal domestic water demand	560.00	L/day
	Fraction of water consumed commercially & industry	19.00	%
	Formal household size	3.56	people/household
	Net immigrants to Western Cape (domestic)	292,521.00	population
	Net immigrants to Western Cape (international)	98,317.00	population

Appendix F: Model initial inputs

Variable	Unit	Initial value (2017)	Source/equation
Population Sector			
Population	People	4,8318,000	population (t - dt) + (births + immigration - deaths - emigration) * dt https://www.macrotrends.net/cities/22481/cape-town/population#:~:text=The%20metro%20area%20population%20of,a%202.08%25%20increase%20from%202019.
Birth rate	%/month	0.292	
Births	People	-	Birth rate*population
Death rate	%/month	0.2	
Deaths			population*death rate
Emigration rate	%/month	0.829	Statistics SA 2021 Table 9 on Page 25
Emigration			population*emigration rate
Immigration rate	people/month	39,221	
Immigration			immigration rate.
households	household	-	population/persons per household
Persons per households		3.5	

Appendix G: Capacity Building

The main capacity building activities related to the training and development of two Masters level postgraduate students, Ms Thandekile Ndlela and Ms Viola Hofmann. These capacity building activities were captured in the reports submitted to the WRC. In short, these students underwent extensive training in aspects of planning, performing and reporting sound scientific research, and how to present findings to a wider audience. Both successfully defended their Masters theses, validating the capacity building efforts.

The postdoctoral researcher involved in the project also expanded his skill set and his research management. He was afforded the opportunity to be involved in minor aspects of research management, through contributing to regular reporting on Deliverables, and in co-supervision of the Masters students.

Capacity was also expanded among academics involved in the project. Mr Zwonaka Mapholi is a Junior Lecturer at the Department of Chemical Engineering, and he participated peripherally during the initial stages of the project. Through this participation, he saw how research projects are set up and how collaborative research is performed. He has since been made formal co-supervisor on two other postgraduate students (outside of this project).

Appendix H: Knowledge Dissemination

Publications

The following publications have been produced or are in process:

Egieya, J., Görgens, J.F., Goosen, N.J., 2022. Chapter 2: Some quantitative WEF nexus analysis approaches and their data requirements, in Mabhaudi, T. (Ed.), Water-Energy-Food Nexus Narratives and Resource Securities. eBook ISBN: 9780323918374

Egieya, J.M., Parker, Y., Hofmann, V.S., Daher, B., Görgens, J., Goosen, N.J. Predictive simulation of the water-energy-food nexus for the City of Cape Town, Science of the Total Environment (being revised)

Hofmann, V.S., Egieya, J.M., Parker, Y., Görgens, J., Goosen, N.J., System dynamics modelling to determine the effects of resilience policies on the water-food nexus in the City of Cape Town. Submitted to the journal 'Systems Dynamics Review'

Ndlela, T.J., De Kock, I., Goosen, N.J., Assessing Water-Energy Nexus Dynamics for Sustainable Resource Management in Cape Town: A System Dynamics Approach. Being prepared for submission to the journal 'System Dynamics Review'

Dissemination plan

The various publications form an important part of the dissemination of the work, because it creates visibility in the academic space. The journals that are targeted have been chosen based on the suitability of their scope, plus their academic standing (i.e. their audience, reach and reputation).

Apart from the formal publications, another important dissemination pathway will be a workshop where important role players within the City of Cape Town administration will be invited, along with the important departments within GreenCape, including the Water, Energy and Sustainable Agriculture Desks.

Additionally, should there be suitable forums where the work can be presented (including academic and societal events), these will be done on an ad-hoc basis.

Appendix I: Project outputs

There are 3 types of outputs generated by the project:

1) **Functioning system dynamics models, of which 3 were produced. The first describes the water-food nexus, the second the water-energy nexus and the third the entire water-energy-food nexus for the City of Cape Town.**

2) **Scientific outputs that capture the work done in the project, and comprise of journal papers, a book chapter, and postgraduate theses:**

Egieya, J., Görgens, J.F., Goosen, N.J., 2022. Chapter 2: Some quantitative WEF nexus analysis approaches and their data requirements, in Mabhaudi, T. (Ed.), Water-Energy-Food Nexus Narratives and Resource Securities. eBook ISBN: 9780323918374

Egieya, J.M., Parker, Y., Hofmann, V.S., Daher, B., Görgens, J., Goosen, N.J. Predictive simulation of the water-energy-food nexus for the City of Cape Town, Science of the Total Environment (being revised)

Hofmann, V.S., Egieya, J.M., Parker, Y., Görgens, J., Goosen, N.J., System dynamics modelling to determine the effects of resilience policies on the water-food nexus in the City of Cape Town. Submitted to the journal 'Systems Dynamics Review'

Ndlela, T.J., De Kock, I., Goosen, N.J., Assessing Water-Energy Nexus Dynamics for Sustainable Resource Management in Cape Town: A System Dynamics Approach. Being prepared for submission to the journal 'System Dynamics Review'

Hofmann, V.S., 2024. The interdependencies of food and water within the water-energy-food nexus for the City of Cape Town. Masters thesis, Department of Chemical Engineering, Stellenbosch University.

Ndlela, T.J., 2024. Assessing water-energy nexus dynamics for sustainable resource management in Cape Town: A system dynamics approach. Masters thesis, Department of Chemical Engineering, Stellenbosch University.

3) **Graduated postgraduate students**

Ms Thandekile Ndlela (MEng, Chemical Engineering, 2024)

Ms Viola Hofmann (MEng, Chemical Engineering, 2024)