Governing Groundwater in City Regions:

Water Metabolism and Actor Networks in the Cases of Cape Town and Nelson Mandela Bay

Report to the
Water Research Commission

by

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Executive Summary

Patterns of growing urban water demand and increasing drought risk intersect in a context of infrastructure deficits, construction delays and insufficient maintenance in many of South Africa's metropolitan municipalities. Groundwater is being turned to in times of crisis as a quick solution to supplement supplies and make up surface water deficits, both by public water service providers and private water users, including domestic, commercial and industrial users. Exploiting groundwater during crises, as an urgent and reactive measure, gives rise to poorly coordinated regulation of increasing users and usage, and fragmented management of aquifers. This undermines the sustainability with which groundwater resources are used and managed, putting both aquifers and those reliant on groundwater at risk of over-depletion and pollution. Designing interventions and innovations that ensure sustainable management of these resources requires systems-thinking, where the city is understood as a system of interdependent actors and flows of water.

This study focused on the metropolitan municipalities of Cape Town and Nelson Mandela Bay (NMB) as 'learning laboratories' to co-produce a more comprehensive understanding of each urban water system. The focus was on how groundwater links with other urban water flows, what actors influence these water flows, and how things may change under various climate change and land use scenarios. The work is framed within the idea and the policy goal of cities transitioning to become water sensitive cities characterised by adaptive, multi-functional infrastructure providing access to diverse water sources, urban design that reinforces water sensitive behaviours, and equitable communities that are resilient to climate change.

An urban water metabolism (UWM) analysis was conducted to build the picture of how groundwater fits into the urban water cycle by quantifying the hydrological and anthropogenic components and conducting an integrated mass balance. The impact of various scenarios of climate change and land use on the water mass balance for each city were explored and discussed at length during the Learning Labs. For NMB, the water mix as of 2022, before any major new drought-response interventions have come online, is compared against the planned future water mix and a hypothetical water mix according to the principles of a water sensitive city. For Cape Town, the scenarios focussed on: (1) only climatic changes, with rainfall reducing by 10% and evapotranspiration increasing by 10%; (2) land cover changes, assessing an extreme of all cultivated land being transformed to residential; (3) an extreme scenario which combines climatic changes (-10% for MAP, +10% for EVT) with all cultivated and residential areas become impervious hard urban spaces; and (4) a slightly less extreme scenario of reduced MAP (-10%), increased EVT (+10%), and land-use change reflecting the drive for residential densification with all existing residential areas becoming hard urban spaces, and all cultivated land becoming residential. The scenarios are broad and crude because the emphasis was not on accuracy but on exploring with Learning Lab participants the heuristic value of the framework for bringing stakeholders with diverse perspectives on and knowledge of the urban water system onto the same page to think about the potential impacts of climate and land-use change on water flows through the city.

The governance analysis comprised individual interviews, reviewing relevant documents, and several participatory exercises conducted during Learning Lab workshops. The analysis highlighted that many state and non-state actors have a stake in shaping the trajectory of groundwater quantities and qualities in cities, as regulators, service providers, water users, knowledge providers, investors in infrastructure, and emergency responders. Currently, neither DWS nor the CCT and NMBM municipal governments have the necessary capacity nor the cooperative governance mechanisms in place to implement what is laid out in the National Groundwater Strategy (DWS, 2016), the Urban

Groundwater Development and Management framework and tactical plan (Seyler et al., 2019), or the municipal water by-laws in either of these two cities. Traditional forms of governing by command and control are proving ineffective in sustainably utilising and protecting groundwater resources in densely populated and growing metropolitan municipalities. Therefore, more consultative and cooperative forms of governance are required that build a culture of care and shared responsibility. New partnerships, trust building and bridging organisations are needed to create the enabling conditions for data sharing and more collaborative forms of decision making. Experiences from Cape Town's aquifer monitoring committees offer a promise of lessons in how to structure and convene urban groundwater user associations to facilitate localised data sharing and self-regulation of usage under dynamic and changing conditions. Intermediary and networking organisations such as the Western Cape Economic Development Partnership, Green Cape and the NMB Business Chamber, need to be encouraged and supported to interface on groundwater issues and act as brokers between government entities, businesses and residents.

The multi-stakeholder Learning Labs created an engaging space to build a shared understanding of how possible urban and climate changes could play out from a holistic water perspective, and which actors have influence over various ways of enhancing the hydrological performance of the cities, notably through enhancing stormwater infiltration and increasing the reuse of treated wastewater for non-potable uses and managed aquifer recharge. We argue that planning for resilience against drought should not be limited to water supply alone. Groundwater and aquifers have a critical role to play in cities providing much needed evaporative free storage and supporting the health of green spaces for urban cooling and recreational spaces for improved liveability and well-being.

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List of acronyms

ASR	Aquifer Storage and Recovery
AWSS	Algoa Water Supply System
CFA	Cape Flats Aquifer
CRA	Coega Ridge Aquifers
CSAG	Climate Systems Analysis Group
DWAF	Department of Water Affairs
DWS	Department of Water and Sanitation
ESA	East Southern Africa
ET	Evapotranspiration
EWR	Ecological Water Requirements
GDP	Gross Domestic Product
GW	Groundwater
IDZ	Industrial Development Zone
IPCC	Intergovernmental Panel for Climate Change
IUWM	Integrated Urban Water Management
MAP	Mean Annual Precipitation
MAR	Managed Aquifer Recharge
MLD	Million Litres per Day
NMB	Nelson Mandela Bay
NMBM	Nelson Mandela Bay Metropolitan
NMU	Nelson Mandela University
NRW	Non-revenue water
SA	Swartkops Aquifer
SANBI	South African National Biodiversity Institute
TMG	Table Mountain Group Aquifer
UAB	Uitenhage Artesian Basin
UWM	Urban Water Metabolism
UWMF	Urban Water Metabolism Framework
VIP	Ventilation Improved Pit toilets
WARMS	Water use Authorization and Registration Management System
WC	Western Cape
WCWSS	Western Cape Water Supply System
WSA	West Southern Africa
WWTW	Wastewater Treatment Works

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1. Introduction

Growing urban settlements in South Africa – growing in terms of numbers of residents, amount and diversity of economic activities, spatial extent, and density – face growing water demands. Where urban settlements experience drought conditions, especially multiple consecutive years of below average rainfall, they face particularly severe water provision short falls. This has recently been experienced in various parts of the Eastern and Western Cape, notably including Nelson Mandela Bay and Cape Town (Seyler et al., 2019). Patterns of growing urban water demand and potentially increasing drought risk intersect in a context of infrastructure deficits, construction delays and insufficient maintenance in many of South Africa's metropolitan municipalities. Groundwater is often turned to in times of crisis as a quick solution to supplement supplies and make up surface water deficits, both by public water service providers and private water users. This is increasingly happening across South Africa, although it is a global phenomenon, leading to rising competition over usage rights between agricultural, industrial and urban users (Foster and Garduño, 2013; Foster, 2020).

Turning to groundwater during crises, as a reactive measure, gives rise to poorly coordinated regulation of increasing users and usage, and fragmented management of the resource as a whole. This fragmentation undermines the sustainability with which groundwater resources are used and managed, putting both aquifers and those reliant on using groundwater at risk of over-depletion and pollution, compromising the quantity and quality of groundwater available (Howard, 2015). Because groundwater is a distributed resource, widespread mechanisms, capacities and incentives are needed to adequately monitor, report and regulate groundwater usage and levels (Luker and Harris, 2019). However, in South Africa, the governance of groundwater remains weak with insufficient monitoring, reporting and enforcement of regulations (Pietersen et al., 2011; Adams et al., 2015; Seyler et al., 2019).

The study of groundwater governance arrangements in growing urban contexts is essential to understand which actors are currently involved in using and managing groundwater and how these relate with the resource and each other (Howard, 2015; Seward and Xu, 2019). An understanding of the current governance network is needed as a basis for designing interventions and innovations to strengthen the arrangements in ways that enable more sustainable management of aquifers and groundwater resources, especially as they become more heavily exploited and relied upon to buffer drought conditions.

The project entitled 'Governing groundwater flows for growing cities facing drought risks' (GoFlow), funded by the Water Research Commission, was designed to strengthen the collaborative capacity to adaptively manage groundwater flows in and around growing urban areas under changing climate conditions. It did so with a focus on the Cape Town and Nelson Mandela Bay city regions as 'learning laboratories' for developing knowledge on urban water metabolism, groundwater governance networks and decision-making that could be applied in other urban contexts. The three objectives of the project were to:

1. Conduct urban water metabolism analysis for two selected city regions by quantifying all anthropogenic (bulk supply, consumption, 'waste' water) and hydrological (precipitation, evapotranspiration, runoff, recharge) components of the urban water cycle and highlight knowledge/data gaps.

2. Using the urban water metabolism analysis, explore changes under a range of likely hydrological shifts (long-term trends) and land cover scenarios (with focus on imperviousness) for 2040-2060.
3. Analyse current institutional arrangements for groundwater governance in the two city regional cases and facilitate multi-stakeholder Learning Lab engagements around the applicability of the urban water metabolism analysis and scenarios to improve a shared understanding of groundwater as part of the larger urban water cycle and strengthen capacity for participation in decision making.

This report, the final deliverable of the GoFlow project, presents a consolidated set of findings from the application of the urban water metabolism (UWM) and nodal governance frameworks in Cape Town and Nelson Mandela Bay, deployed through a stakeholder engagement and learning process. It discusses the extent to which the use of these analytical frameworks in participatory ways shows promise for strengthening adaptive groundwater management in the face of climate and urban change.

The report is structured as follows. Chapter 2 lays out the conceptual underpinnings and framing of the work, in terms of drought risk, urban adaptation, urban water metabolism, and groundwater governance, focussing on social network theory. The following chapter (3) introduces the context of the two South African cities that are cases studied in this research. Chapter 4 focuses on patterns of drought risk facing the two cities. Chapter 5 lays out the methodology for analysing a city's water metabolism, groundwater governance nodes and actor networks, involving participatory exercises in a series of Learning Labs. Chapters 6 and 7 present the findings on urban water metabolism and urban groundwater governance respectively, before chapter 8 then discusses these findings in relation to the use of these analyses and associated scenarios in improving a shared understanding of groundwater as part of the larger urban water cycle and strengthening participation in adaptively managing drought risks. Particular focus is placed on the use and usability of drought risk information and water metabolism information in city-scale and sub-city scale decision-making. Finally, chapter 9 ends the report with a set of conclusions from this study, including recommendations for future research.

This work builds on and relates in important ways to other WRC-commissioned work. Most notable is the recent work undertaken by Kotzé et al. (2019) and Seyler et al. (2019). Kotzé et al. (2019) put together a training manual to be used as a resource by municipal officials and decision-makers in South Africa's cities and towns to increase their knowledge and skills for sustainably using and protecting groundwater resources. Seyler et al. (2019) laid out the status quo of urban groundwater development and management in South Africa, looked at international best practices for urban groundwater management, and suggested a tactical plan to address the gaps between the South African status quo and best practice. The earlier work by Pietersen, Beekman and Holland (2011) laid out the South African Groundwater Governance context, into which the focus on urban contexts fits, and Riemann et al. (2011) suggested a pragmatic framework and proposed set of responsibilities for managing aquifer protection and aquifer utilisation at the local level. The distinction between governance and management is an important one, which will be addressed in the following chapter. The comprehensive study of strategic water source areas across South Africa, Lesotho, and Swaziland, by Le Maitre et al. (2018) clearly identified the lack of effective urban groundwater management as a risk, both with respect to pollution and contamination of aquifers and the potential for unsustainable over-abstraction. Also of relevance is the work of Tanner and Hughes

(2015) exploring the utility of the Pitman model in capturing the interactions between surface water and groundwater at the catchment scale in South Africa as a basis for managing uncertainty in making water management decisions. The more that these strands of work can be brought into conversation and tested operationally the better.

2. Conceptual framing

2.1. Drought risk & urban adaptation

South Africa is a water-scarce country, already severely constrained by low rainfall in most parts of the country. While rural and agricultural water security has been the focus of much research (Bahta, Jordaan and Muyambo, 2016; Meza et al., 2021), and many disaster risk reduction programmes that aim to alleviate drought risk and vulnerability, it is only recently that attention is turning to cities. South Africa has followed the global trend in increasing urbanisation: already more than 63% of the population are living in urban areas with an expected increase to 80% by 2050 (Carden, Ellis and Armitage, 2016). Water security in South Africa is severely challenged by the compounding impacts of population increases, rapid urbanisation, increasing frequency and severity of drought (Richard et al., 2001), decreasing quality of available water and often inadequate management of water resources (Carden, Ellis and Armitage, 2016). This research stems from the risks that drought poses to growing South African cities, however we consider all risks to water security as interdependent and important when looking at governing groundwater as an adaptation measure to a changing climate.

Drought risk takes shape very differently for each city in South Africa owing to its own unique climatic and rainfall regime, as well as the physical and topographic setting of the region, as discussed further in chapter 4. Overlaying the physical components that drive and exacerbate the impacts of drought are the socio-economic and policy landscapes that make risk, response and capacity to adapt to increasing drought contextually very specific. Understanding the true impact of drought on cities requires a focus on interactions between different actors and entities that make up the city as an urban system. It requires being able to see cities in the context of their relations to water sources, to how water moves through the city, to water-reliant ecosystems and uses and to how the socio-economic and policy landscapes shape such interaction currently and in future climatic and socio-economic scenarios.

There is increasing recognition globally and in South Africa of the need to evolve beyond traditional urban water management systems that focus solely on water supply, treatment and discharge of wastewater effluent, drainage and flood control services. Conventional water management approaches are fast becoming ill-equipped to meet the diverse and complex needs of cities in a context of rapid urban growth combined with the impacts of climate change (Wong, Rogers and Brown, 2020). There are now many examples of cities across the globe embracing a more systems-thinking approach to urban water management practices. While various novel water management frameworks and concepts exist, such as *Integrated Urban Water Management* (IUWM) (Werbeloff and Brown, 2011), *Sponge Cities* (Yin etr al., 2021), *Water Wise City* (Koop and van Leeuwen, 2015), *Water Sensitive Cities* (Wong and Brown, 2009; Wong, Rogers and Brown, 2020) and *Water Sensitive Urban Design* (Wong, 2006), all are grounded in a systems thinking approach and aim to integrate liveability, sustainability and climate resilience into water management objectives to varying degrees. Brown et al. (2009) present a framework that characterises cities along the transition towards the aspiration of a sustainable city (see figure 1). The framework describes the several transition states of urban water management, from the most basic of service delivery: the water supply city on the far left of figure 1, to the aspirational future state of a water sensitive city on the far right. Such an envisioned state represents the culmination of water supply, sanitation, flood protection and environmental protection servicing strategies that ensure long term sustainability, liveability, resilience and prosperity (Ferguson, Frantzeskaki and Brown, 2013; Wong, Rogers and Brown, 2020).

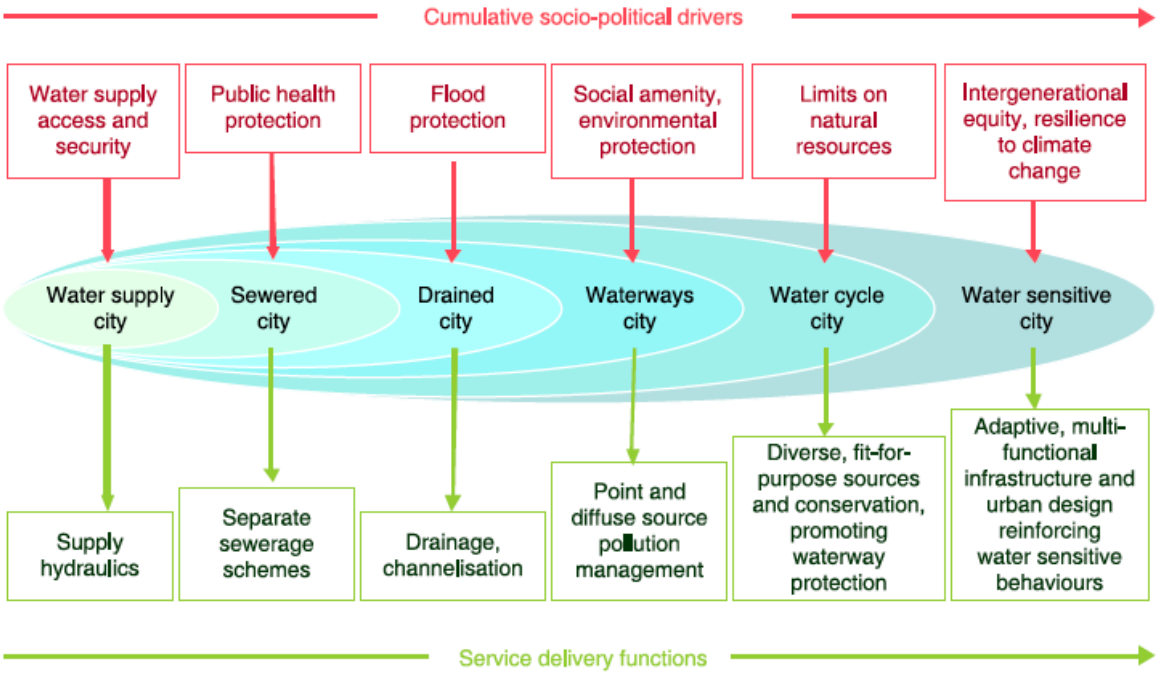

Figure 1. Urban water management transitions framework taken from (Brown, Keath, and Wong, 2009) presenting a typology of different states that cities transition through when pursuing change towards more sustainable futures.

To operationalise the transition to a water sensitive city, three guiding water sensitive cities principles of practice were identified by Wong and Brown (2009), encompassing 3 key pillars: 1) cities as supply catchments within which there is access to diverse water sources, including both centralised and decentralised sources; 2) cities providing ecosystem services through urban landscapes made up of built infrastructures that actively support and supplement ecological infrastructures; and 3) cities comprising water sensitive communities within which socio-political capital accrues from engaging in water sensitive behaviours. Applying such principles requires solutions that are wholly context specific, taking into account geomorphology, hydrology, local operating environments, governance structures and institutional conditions, all of which will influence local water management strategies.

At its core, a water sensitive city approaches urban water management as a holistic system and aims to ensure that basic human needs are met, while protecting and enhancing receiving waterways and aquifers, reducing flood risk and creating beautiful green and blue urban spaces for healthy and happy communities. Globally, examples of water sensitive initiatives can be found in Australia, where cities are caught between drought and seasonal flooding (Wong and Brown, 2009; Dolman etr al., 2014); Singapore who recycle and treat effluent for drinking water (Wong and Brown, 2009; Irvine et al., 2014) and in the Netherlands, where cities are making 'room for the river' (Warner and Van Buuren, 2011). While some cities have achieved elements of the transitions involved in changing from a water supply city to a water cycle city or even a water sensitive city (as depicted in figure 1), comprehensive service delivery functions remain challenged in many cities in the global South. For example, Bangalore in India faces acute water shortages and insecurity in terms of imbalance between water supply and demand, with many poorer residents having no formal access to treated water supply nor adequate sanitation (Raj, 2013; Paul et al., 2018). The challenges and constraints

on improving the supply system include low cost-recovery due to rising unaccounted for and non-revenue water, as well as large water losses (Raj, 2013). However, these socio-economic challenges are severely compounded and magnified by the frequency of drought in the region (Lokesh and Poddar, no date; Reddy, Bhakar and Purohit, no date). Cities in the global South face very real challenges in making the transitions towards a water sensitive city as they are often stuck in crisis response mode, where funding and effort are locked into averting or recovering from disasters and persistent water crises, rather than being used in proactive, future-oriented strategic urban planning.

Urban water insecurity can be considered the culmination of external factors, such as growing urban populations, competition for other uses such as agriculture or erratic supply due to climate change impacts, and internal factors such as reliance on single water sources, linear flows of water, or a failure to use all available sources of water within the city itself (Renouf, Kenway and Serrao-Neumann, 2015). Essentially cities, considered as urban systems, are most often highly resource inefficient and are thus more vulnerable to external stresses and pressures. Despite historical experience of drought, the responses of many municipalities are reactionary, where drought is dealt with as an emergency, rather than in strategic planning processes (Pietersen, 2021). Groundwater is turned to in times of drought or crisis, with boreholes being drilled often in an uncoordinated quick-fix solution to supplement surface water for both public utilities and private water users, leading to rising competition between agricultural and urban users (Foster, 2020). Turning to groundwater during times of crisis as a reactive measure leads to poorly coordinated regulation and fragmented management of the resource as a whole. Groundwater is also often only considered as a water supply option, and rarely viewed through the lens of its contribution to whole-of-system sustainability and resilience, for example feeding streams, wetlands and aquatic ecosystems. Planning for adequate groundwater management in drought mitigation plans also encompasses accounting for storage of water in wetter years, or re-internalising excess wastewater (i.e. managed aquifer recharge or aquifer storage and recovery), ecosystem restoration and improved liveability as a result thereof. La Vigna (2022), by reviewing the relationships between cities and underlying groundwater in 73 cities globally, identifies the 'resilience dividend' of investing in sustainable and adaptive urban groundwater management practices. This includes increased permeability of urban surfaces contributing to more recharge, less run-off and thereby reduced flooding, and increased water for irrigating urban green spaces reducing urban heat stress and associated health impacts. La Vigna (2022, p.1676) concludes that groundwater "should be considered by city planners as one crucial aspect in every resilience assessment and strategy".

2.2. Urban water metabolism

Urban metabolism is a conceptual model for quantifying and analysing flows of resources (materials, energy, water, greenhouse gases, nutrients, etc.) into, within and out of cities (Wolman, 1965; Newman, 1999) with an inferred intent of achieving high resource efficiencies as observed in natural systems. Urban water metabolism has become an increasingly recognised concept and tool in exploring the (in)efficiencies in the urban system as a whole, integrating both the conventional approaches of mass balances for water supply, discharge and drainage, with the hydrological flows of water within the urban system. It is essentially a mass balance of all water that comprises the urban system, accounting for the total water cycle, where both the hydrological (precipitation, runoff, recharge, evaporation) and anthropogenic (water supply, consumption, wastewater effluent, etc.) components are included.

Several urban water metabolism evaluations (UWMEs) have been carried out and reported Within the academic literature. UWMEs have been adopted to quantify all flows of water through a defined

urban area to evaluate the performance of city water management, through the use of performance indicators (Kenway, Gregory and McMahon, 2011), in relation to becoming a water sensitive city. Performance indicators such as supply centralisation, centralised replaceability and total water use replaceability of wastewater, rainwater and stormwater (see table 1) are helpful in understanding whether certain interventions are helping a city move closer towards their water management objectives, or not. They can highlight whether alternative sources of water (such as stormwater and wastewater) are under-utilised as supply options for the city, either as potable or non-potable sources (Kenway, Gregory and McMahon, 2011); assess the impact of urbanisation on hydrological flows (Haase, no date) and to assess the impact of various options of management interventions on the performance of the water metabolism at both local (Farooqui, Renouf and Kenway, 2016) and city-regional scales (Renouf et al., 2018). In terms of urban water metabolism, the use of indicators is still in its infancy, but the work that has been done so far (for the most part in the Australian context) has shown that large flows of water pass through the cities and that utilisation efficiency (e.g. water turnover rates) could be improved substantially and is nowhere close to the resources efficiency of natural systems (Kenway et al., 2022).

Table 1. Performance indicators as derived by Renouf et al. (2017) and Paul et al. (2018).

Indicator (Renouf et al., 2017)	Method	Formula	Unit
Population density	Population/area	Pop/A	capita/km^2
Intensity of water use	Total water use/area	(C+D)/A	ML/d/km^2
Water Efficiency	Centralised supply/population	Cext/Pop	L/d/capita
Supply Internalisation		(Cint+D)/(Cint+Cext+D)	%
Hydrological Performance		(iRoff/oRoff)	ratio
		(iRec/oRec)	
Indicator (Paul, 2018)	Method	Formula	Unit
Wastewater potential for Water supply			
Centralised supply replaceability (%)	Wastewater flow/centralised water supplied	W/C*100	%
Total use replaceability (%)	Wastewater flow/total water use	W/(C + Dg)*100	%
Stormwater Potential for Water Supply			
Centralised supply replaceability (%)	Stormwater flow/centralised water supplied	Rs/C*100	%
Total use replaceability (%)	Stormwater flow/total water supplied	Rs/(C + Dg)	%
Wastewater and Stormwater Combined			
Potential of total water use replaceability (%)	(Wastewater + stormwater)/total water use	(W + Rs)/(C + Dg)*100	%
Loss recovery for Water Supply			
Water loss recovery potential of total water use replaceability	Water loss/total water use	Cufw/(C + Dg)*100	%

2.3. Urban groundwater governance

It is important to recognize from the outset that groundwater governance is a subset of water governance. Water systems comprise the stocks and flows of water from clouds and rainfall, through surface runoff and stream flows to infiltration, discharge and evapotranspiration from plants. Water governance spans the actors, rules and processes shaping decisions and actions on water supplies, storage, reticulation, infrastructure, demand management, access to water services, payments, financing, technologies, river management, flood protection, water quality monitoring and regulation, etc. Or as Enqvist and Ziervogel (2019:2) put it, water governance is "the set of political, social, economic, and administrative systems that formally and informally control decision-making around water resources development and management". Groundwater governance focuses on those aspects pertaining to aquifers and the water drawn from and recharged into aquifers.

Groundwater governance refers to the *processes* of exercising political, economic and administrative authority to shape the decisions taken to allocate, utilise and protect groundwater resources (Foster and Garduño, 2013). Groundwater governance arrangements comprise the institutions, processes and mechanisms through which public and private actors articulate their interests, mediate their differences, and fulfil their legal rights and obligations. A governance analysis includes consideration of the *capacity* to effectively implement and evaluate governance provisions articulated in laws, policies and other collective rules and agreements (Seward and Xu, 2019). Groundwater management, by contrast, is more narrowly defined as actions to *implement* the decisions on how to allocate, utilise and protect groundwater resources.

During stakeholder deliberations undertaken during the project, workshop participants identified groundwater-related decisions and actions to encompass:

- Preparing, reviewing and issuing (ground)water use licences;
- Registering boreholes and wellpoints;
- Installing, operating and maintaining infrastructure to abstract groundwater;
- Using or consuming groundwater;
- Land uses or activities (such as landfills, industrial waste disposal sites, septic tanks, petrol storage, excessive use of nitrogenous pesticides and fertilisers, leaking sewer lines, graveyards, fly ash from coal-fired power plants, over abstraction along the coast leading to saltwater intrusion, etc.) that pollute or contaminate groundwater;
- Taking measurement to monitor groundwater levels and quality;
- Researching groundwater systems;
- Assessing impact of activities on groundwater volumes and flows and on groundwater-dependent ecosystems;
- Communicating groundwater-related information;
- Advocating for groundwater issues to be addressed;
- Enforcing licences and by-laws;
- Rehabilitating and conserving recharge zones;
- Installing, operating and maintaining infrastructure to artificially recharge aquifers;
- Financing the above activities.

The relational dynamics between different actors, particularly the interaction of state and non-state actors, are an important feature of collaborative and multi-level governance. Much empirical work

remains, however, before it is fully understood how stakeholder relations and local governance structures influence adaptation processes, such as the use, governance and management of groundwater resources. Nodal governance and social network analysis can help address this gap. As demonstrated by Ziervogel et al. (2017), the use of nodal governance and social network analysis enables the characterization and visualisation of nodes (points on a network, e.g. actors) and their connections, and explains their impact on governance outcomes including knowledge access, mobilisation of resources and critical relations to others. It also enables the analysis of how power is created and exercised within a governance system. As such, these theories and concepts can guide the design of interventions to respond to determined governance deficits. Thus, nodal and network conceptions of governance can be used to identify more innovative institutional arrangements to improve the delivery and distribution of social goods and common pool resources like groundwater.

A social network is a set of nodes (representing actors) and ties that show some relationship between the nodes or actors. The nodes in a social network may be individuals, groups or organisations, and the ties may be individual to individual ties (within a level of analysis) or individual to group ties between levels of analysis (Katz et al., 2004). Networks can be analysed on macro-, meso- and micro-levels, i.e. the entire network (macro-structures), subgroups (meso-structures), and the position of individual actors (micro-structures). A relationship or tie between nodes involves a flow of resources between actors (nodes) that can be material or non-material. Resources can include companionship, time, information, expertise, money, and shared activity. All social networks have hierarchy, in the sense that some nodes are at the centre of the network because they are highly connected, while others are peripheral and less connected. The position of an actor in the network reveals, and influences, their access to resources (Williams and Durrance, 2008). The structure of a network (i.e. the pattern of ties) and the strength of the ties influences the transmission of attitudes, norms and behaviour.

Network scholarship mostly focuses on examining social aspects of relationships, notably information sharing, trust, and regular communication between actors (Fischer and Ingold, 2020). Network analyses mostly leave out the rules and governance protocols, despite being recognized as critical drivers of collective action situations. This research aims to reveal and question the structure of the governance system and its suitability to address the challenges of enhancing the sustainability of groundwater sources and flows. By analysing the organisation of actors between sectors, across administrative units, and between levels of governance, it is possible to assess potential misfits between the social and biophysical aspects of the system that are likely to hamper the attainment of sustainability and equity goals.

Because the governance of groundwater entails a variety of actors operating in different sectors, at different scales and levels, interacting to exercise their groundwater usage- and protection-related interests, there is value in deploying network concepts and methods to analyse governance arrangements. Fischer and Ingold (2020, p.2) point out that “because formal political institutions have a hard time addressing issues that span political or sectoral borders, as is the case with water, (informal) networks of collaboration and information exchange among actors are even more important”. Networks are therefore both an empirical reality and a conceptually and methodologically useful way to analyse groundwater governance. In other words, networks of actors can be used to describe the reality of groundwater governance and network characteristics can be prescribed as a way of achieving or strengthening collaborative, adaptive governance aimed at achieving desired sustainability outcomes (Fischer and Ingold, 2020). A network governance analysis makes it possible to explore to what extent cross-sectoral and cross-scalar or multi-level coordination, collaboration and collective problem-solving is happening (Ziervogel et al., 2017). The

analysis can identify associated challenges and opportunities to strengthen such arrangements, needed to deal with the conflicts and trade-offs that exist, and that are likely to be aggravated under further climate change, population growth, urbanisation, and the accumulation of pollutants.

Cities provide a particular context in which to explore groundwater governance. Much of the work done to date – globally and in South Africa – has focussed on agricultural and mining contexts, where there has been a history of high groundwater dependency. Urban contexts have been much less explored and provide a particularly interesting governance context because of the density of co-located actors (including water users in the domestic, commercial, and industrial sectors, water polluters, and water-related managers and regulators). Urban contexts are also interesting because city governments are often larger and more capacitated than many of their rural municipal or local government counterparts, which changes the multi-level governance dynamics. Foster et al. (2020) highlight the critical role of groundwater in securing resilient water-supplies for rapidly expanding cities in sub-Saharan Africa. They stress the need for urban water utilities and water services authorities to pursue a proactive approach to managing and protecting aquifers and groundwater resources, including rationalising use, promoting enhanced recharge, and prioritising the installation of sewerage infrastructure to reduce pollution (Foster et al., 2020).

A review by Adams et al. (2015) highlights the challenges of groundwater management at the municipal level in South Africa. The intended devolution of water resource management to catchment management agencies (CMAs) and water user associations (WUAs) has been slow. Municipalities already struggling with their supply function (comprising mostly surface water) are tasked with management of their groundwater resources without comprehensive direction or support from the national government. These findings are supported by the work of Cobbing and Rose-Innes (2018) investigating the governance challenges associated with the Grootfontein Aquifer supplying the city of Mahikeng in South Africa's North West Province. They conclude that there is an urgent need to convene local groundwater users in a way that enables the negotiation and enforcement of usage and protection provisions suited to the local context. Cobbing and Rose-Innes (2018) point out that South African water legislation mandates the national Department of Water and Sanitation (DWS) to play this convening role, but DWS has yet to fulfil this role and as a result the levels and quality of groundwater in the Grootfontein Aquifer continues to decline.

Seward and Xu (2019) suggest there is value in increasing the use of Ostrom's design principles or best practices for governing common-pool resources as a way to improve groundwater governance research, policy and practice in South Africa. They explain that Ostrom's design principles are based on a recognition that governing common-pool resources, like groundwater, is too complex to determine an exact set of rules that will enable precise outcomes based on comprehensive analysis. Rules for how to manage the resource therefore have to be experimental and change as lessons emerge and conditions change. Ostrom's design principles provide a guide for creating governance systems that can learn, experiment, and adapt in an uncertain and changing environment. They argue that the Ostrom principles provide a common set of concepts and terminology for learning about the specific issues of a particular setting, learning from experiments in that setting, and learning from the experience of others. In line with Seward and Xu's (2019) assertion that determining a suitable compromise between the benefits of groundwater use and the problems caused by groundwater use is as much a socio-institutional and organisational governance challenge as it is a technical one.

3. South African cities context: the cases of Cape Town and Nelson Mandela Bay

While groundwater, especially natural springs, played a key role in the establishment and growth of many South African settlements, groundwater makes up a relatively small part of the supply mix in most contemporary South African cities. This mix is starting to change as cities increasingly turn to groundwater to deal with threats of water scarcity. The cities of Cape Town and Nelson Mandela Bay, shown in figure 2, are the focus of this research because of their recent and ongoing experiences of 'Day Zero' water crises that have turned much attention to the cities' water systems, including significant investment in increasing groundwater use, and to a lesser extent aquifer protection. Key differences in population size, local economy, rainfall patterns, as well as the size, resourcing and leadership of the municipal government all make for productive comparative learning between these two cities.

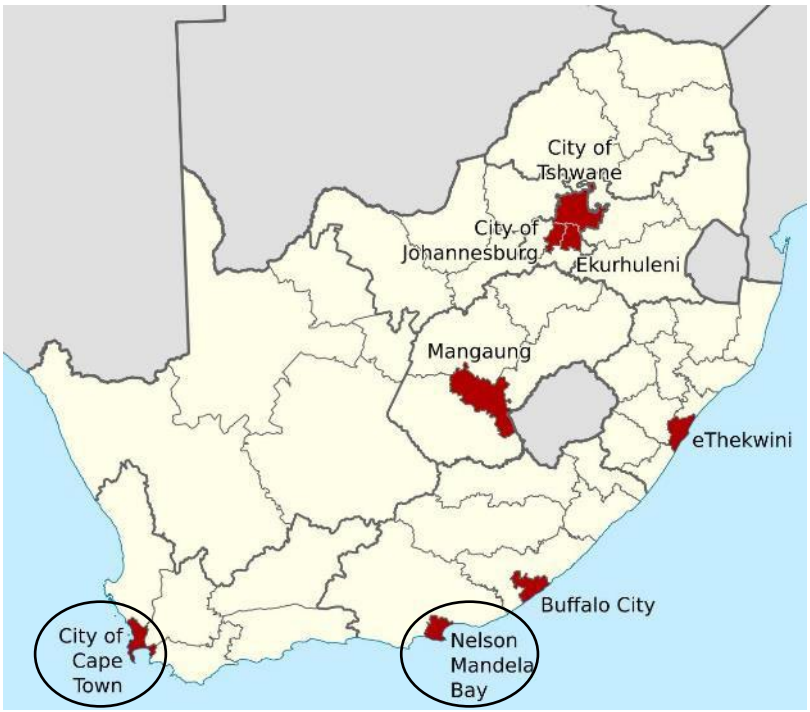

Figure 2. Map of South Africa with the metropolitan municipalities highlighted in red, showing with a black circle the two cases focused on in this project. Source: Htonl, 2016.

3.1. Cape Town case

The City of Cape Town (CCT) metropolitan municipality has a population of roughly 4,68 million people as of 2021 (CCT, 2022). The CCT local government has since 2006 been under the political leadership of the Democratic Alliance. As an indication of resourcing capacity, the municipal government, in the 2021/22 financial year, had a capital budget of R8,315 billion and an operating budget of R48,275 billion (CCT, 2021).

Metered municipal water in Cape Town is supplied via roughly 650,000 connections to approximately:

- 6 500 communal taps in 204 informal settlements throughout the city;
- 600 000 domestic consumers;
- 6 500 housing complexes and blocks of flats;

- 13 000 commercial consumers;
- 4 500 industrial consumers; and
- two other municipalities, Drakenstein (Paarl) and Winelands (Stellenbosch) municipalities (CCT, 2018).

In terms of volume of water supplied by the municipal reticulation system, before the drought in 2014/15, Cape Town used an average of 980 million litres of water per day (980 megalitres). During the drought, this was reduced to just over 500 million litres per day (CCT, 2019).

Prior to the 2015-2018 drought, groundwater use within the spatial extent of the City of Cape Town was very low, estimated at roughly 0.5% of the city's total bulk supply (CCT, 2020). This proportion has been expanding and according to the City of Cape Town's Water Strategy is set to increase to 7% of bulk supply by 2040, based on a planned total groundwater abstraction by the City of 105 Ml/day, and possibly up to 30% in the longer term. This does not include the volumes abstracted directly by private users for self-supply. The numbers around how much groundwater is abstracted privately for industrial, commercial and domestic self-supply is difficult to come by in a consolidated form, because many are below the threshold for requiring a water use licence and so do not appear on the WARMS database. Recent estimates range from 8158 to 26 000 private boreholes (Faragher, 2022). Local geohydrologist, Dr Roger Parsons, commented that "the drilling of boreholes at private homes, hotels, businesses, schools, shopping malls and critical service delivery facilities contributed to reducing the use of potable municipal water from around 1,200 ML/d down to 450 ML/d", and as such the development of groundwater self-supplies contributed considerably to avoiding the 'Day Zero' situation when municipal supplies would run out[1]. The Western Cape government alone, with a mandate to operate public hospitals, clinics, schools and social development facilities, investigated local groundwater supplies at 95 sites and implemented 61 groundwater supply systems, 38 of which are in Cape Town (Parsons, 2022).

Groundwater used in Cape Town is primarily sourced from the Atlantis-Silverstroom Aquifer, the Cape Flats Aquifer and the Table Mountain Group (TMG) Aquifers (including the Peninsula, Basement and Nardouw Aquifers), as shown in the figure 3. A managed aquifer recharge scheme has been in operation in Atlantis since the late 1970s. The production capacity of this scheme was expanded during the 2015-2018 drought by redrilling old boreholes, drilling new production boreholes, and refurbishing and expanding local Witzands and Silwerstoom water treatment works. Investigations into the feasibility of a managed aquifer recharge scheme are well underway for the Cape Flats Aquifer.

[1] https://www.dailymaverick.co.za/article/2022-04-19-making-the-invisible-visible-tapping-into-groundwater-must-form-part-of-cape-towns-future-water-supply/

Figure 3. Map showing main aquifers feeding the Cape Town water system. Source: CCT, 2018.

3.2. Nelson Mandela Bay case

The Nelson Mandela Bay Metropolitan (NMBM) municipality covers an area of 1959 km^2. It is the largest and most populated metropolitan area of the Eastern Cape Province, comprising the city of Gqeberha (formerly named Port Elizabeth), Uitenhage, Despatch, Colchester, Blue Horizon Bay and Seaview areas. NMBM is the economic hub of the Eastern Cape, contributing 35.5% to the GDP to the Eastern Cape and 2.76% to national GDP. The political leadership of the NMBM local government has been highly contested and volatile over the last decade, with a coalition of political parties led by the DA very recently having replaced ANC leadership of the City Council. As an indication of resourcing capacity, in the 2021/22 financial year, the NMBM had a Capital Budget of R1,37 billion and an Operating Budget of R13,33 billion (NMBM, 2021).

The 2016 census estimated the population of NMBM to be 1.26 million people, with a growth rate between 2006 and 2016 of 1.53% per annum, on par with the national population growth rate. In 2016, 93.15% of total households had access to flush toilets, with the remainder (6.85%) sharing access to Ventilation Improved Pit (VIP) toilets, pit toilets or no access at all. An estimated 77.8% of households had access to piped water inside the dwelling, 11.6% of households had piped water inside the yard and 2% had no formal piped water (Department of Water and Sanitation, 2018).

Water for NMBM is supplied by the Algoa Water Supply System (AWSS), which currently comprises three subsystems:

1. Western System providing water to NMBM and other small towns from Churchill, Impofu dams (Kromme Rivier), Kouga Dam (Kouga River) and Loerie Balancing Dam (Loerie Spruit);
2. Eastern System which receives water from the Nooitgedacht inter-basin transfer scheme from the Orange River (via the Fish and Sundays Rivers);
3. Central System supplies NMBM from Sand, Bulk, Van Stadens, Groendal Dams and Uitenhage Springs.

Overall, the current water mix for the AWSS is 48% surface water, 1% groundwater from natural springs and 51% comes via interbasin transfer from the Orange river (see table 2).

Table 2. Current water mix for NMBM, supplied from 3 main sources: surface water, groundwater and interbasin transfer (Sourced from Zutari in 2022).

NMBM current water mix	Ml/d	% total
Surface water	195.21	48%
Natural spring water (groundwater)	6	1%
Interbasin transfer – Nooitgedagt	410.73	51%
TOTAL	410.94	100%

The dams and rivers that comprise these three subsystems supply not only NMBM but several other surrounding municipalities such as Kouga Local Municipality, Gamtoos Irrigation boards, Lower Sundays River Water User Associations and other local irrigators. The details of how much water is supplied by the system can be found in Table 3. The combined total yield of the Algoa WSS is 167.4 Mm^3/a, equating to 458.6 Ml/d.

Table 3. Algoa Water Supply System. Sourced from Algoa Reconciliation Strategy (2016). Many of these figures are subject to change as and when certain interventions come into play. § refers to older dams.

Subsystem	Reservoir	Quantity (Mm^3/a)	Capacity (Mm^3/a)	Allocation (Mm^3/a)	Use	Total contribution to NMBM water supply (Mm^3/a)
Western System	Churchill	20.08	20.08	44	NMBM	65
	Impofu	18.00	18.00		NMBM	
	Impofu	2.00			EWR	
	Kouga/Loerie	26.92	23.00	75.5	NMBM	
	Kouga/Loerie	60			Gamtoos Irrigation Board	
Eastern System	Gariep	99.00		155	AWSS + other external users	26
	Darlington		187	unknown	Agricultural (some unknown volume sent to Scheepersvlakte)	
Central System	Uitenhage springs	2.40		2.4	NMBM	10

Subsystem	Reservoir	Quantity (Mm^3/a)	Capacity (Mm^3/a)	Allocation (Mm^3/a)	Use	Total contribution to NMBM water supply (Mm^3/a)
	Sand	6.00	1.83			
	Bulk §		0.91			
	Van Stadens §		1.10			
	Kwa Zunga §					
	Groendal	4.00	6.50		NMB	
	Groendal	2.40			Irrigation	
TOTAL		225.20	71.41	276.9		101

The Algoa Reconciliation Strategy, undertaken by the Department of Water Affairs in cooperation with NMBM, was originally written in 2010 in order to secure water supply for NMBM and the other towns served by AWSS. Its main purpose was to determine the water balance of the system and develop various possible future water balance scenarios for a 25-year planning horizon. In the 2011 Recon strategy, it was very clear that although the system was in balance at the time, any future increase in water demand would put the system at risk and that immediate action was required to reduce such risk. The strategy also detailed how much water might be needed and available under certain low and high growth scenarios, as well as climate change impacts on water availability (see figure 4). Growth scenarios included future requirements for irrigation, potable water use, industrial (non-potable water use) as well as ecological water requirements (EWR). In terms of climate change scenarios, lower mean annual rainfall had been predicted for the Kromme and Kouga river catchments (Stuart-Hill, Schulze and Methner, 2011), with the Orange River conversely reported to likely experience slightly higher mean annual rainfall, as well as slightly increased frequency of rainfall events, thereby increasing runoff into the catchment. Despite considerable uncertainty in these estimates, climate change scenarios were also included and were based on the assumption that runoff from all existing local water schemes serving the AWSS would reduce linearly by 10% over an 11 year period between 2011-2023. The Orange River was not accounted for in these climate scenarios. Based on these scenarios, several interventions were identified to either reduce water requirements or increase water availability:

- Water conservation and water demand management
- Increased operational efficiency of the current water supply system
- Trading of water use authorisations
- Re-use of water
- Groundwater schemes
- Interbasin transfer schemes
- Desalination of seawater and brackish water
- Surface water schemes

In the 10 years that have passed since Algoa Reconciliation Strategy (2011) came out, several interventions have been dropped either due to changing water policy or strategy decisions. In the

updated Algoa Reconciliation Strategy (2018), several other interventions had been identified such as rainwater harvesting, invasive alien plant removal from water source areas (particularly the Kromme, Kouga and Baviaanskloof rivers), reuse to both potable and non-potable (industrial standards).

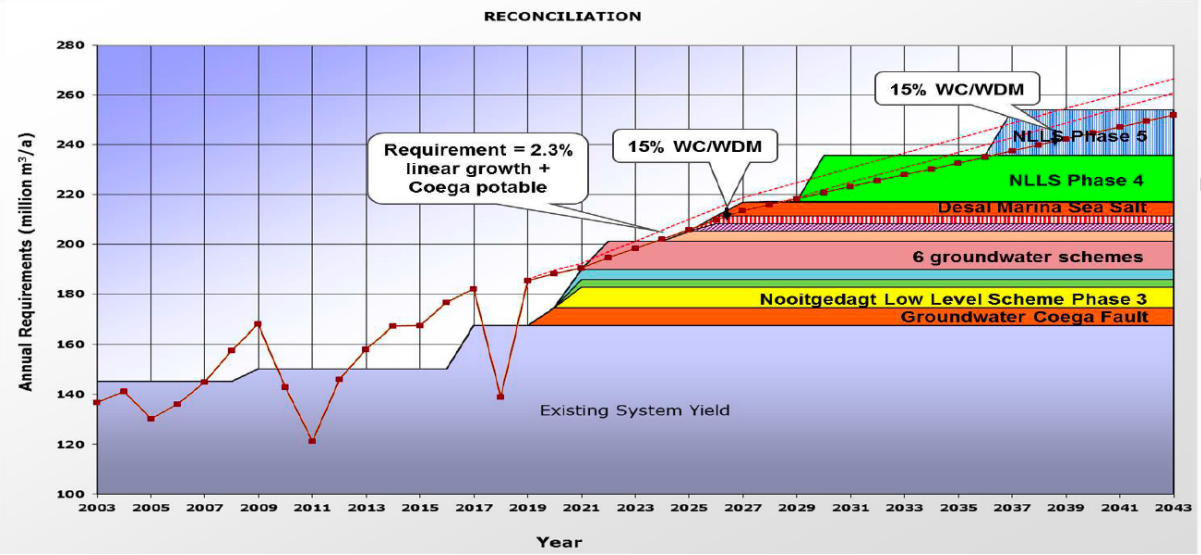

Figure 4. Continuation of historic water demand growth. Sourced from Zutari.

In terms of volume of water use supplied by the municipal reticulation system (measured as output of water treatment works), in 2014/15, NMB used an average of 310-320 million litres of water per day (~116 Mm^3/a – note that this is more than what is reported to be supplied to NMBM in Table 3). During the drought, this reduced to 280 million litres per day, but the City's drought mitigation plan aims to get it as low as 230 Ml/Day (Hills, 2022). The drought currently being experienced in the NMB region has been ongoing since 2015, leading to imposed water restrictions since 2016 and to the Executive Mayor declaring a Local State Disaster in May 2017 with devastatingly declining dam levels and water storage capacities. In September 2018, good rains occurred in the catchment areas that feed NMBM which managed to increase dam levels from 18% to 53%, but this was soon followed by the lowest monthly rainfall figures since the 1900s in August 2019 (Drought Mitigation Plan, June 2021 Review). Average dam levels have dropped to alarming levels. The municipality set a target of total water demand to be 230 million Litres per day (MLD), but current consumption remains 43 MLD over target (NMBM Drought Dashboard, September 2022). Strong messaging has been implemented by the municipality to drastically reduce personal consumption to 50 L a day, with little effect on total water demand.

Some of the interventions that were identified in the earlier Reconciliation Strategies have been fast-tracked to try to mitigate the imminent drought disaster, namely groundwater abstraction, recycling of water for both potable and non-potable uses (for industry) and desalination (see table 4). Several projects are either planned or currently in process in order to transition to a new water mix with project time frames ranging between immediate (fixing water leaks) and 5 years (construction of Return Effluent at Driftsands).

Table 4. Future water mix for NMBM including increased supply from groundwater, recycled water for both potable and non-potable uses (e.g. industry), and desalination. Sourced from Zutari.

NMBM future water mix	Ml.d	% total
Surface Water	195.21	32%
Interbasin transfer – Nooitgedagt	209.72	35%
Groundwater	53	9%
Recycled water – Coega	60	10%
Recycled water – NMU, etc.	3.5	1%
Recycled water – potable water	10	2%
Desalination	75	12%
TOTAL	606.44	100%

NMBM overlays one of South Africa's most important artesian groundwater basins, the Uitenhage Artesian Basin (UAB) which comprises the fractured Table Mountain Group (TMG) sandstones confined in the eastern part of the basin by overlying Cretaceous siltstones and mudstones (rendering artesian conditions) (Maclear, 2001). The aquifer is divided into separate hydrogeologically independent systems by the Coega Fault (see Figure 5). The southern Swartkops River Alluvial Aquifer (SA) is a minor shallow, semi to unconfined aquifer, and the northern Coega Ridge Aquifers (CRA) comprises quartz arenites of the TMG overlain by an aquiclude made up of impermeable mudstones and siltstones of the Uitenhage Group. The CRA is an important source of groundwater for large-scale abstractions such as irrigation, predominantly for citrus (for export) and lucerne and to a much smaller degree domestic use (Maclear, 2001).

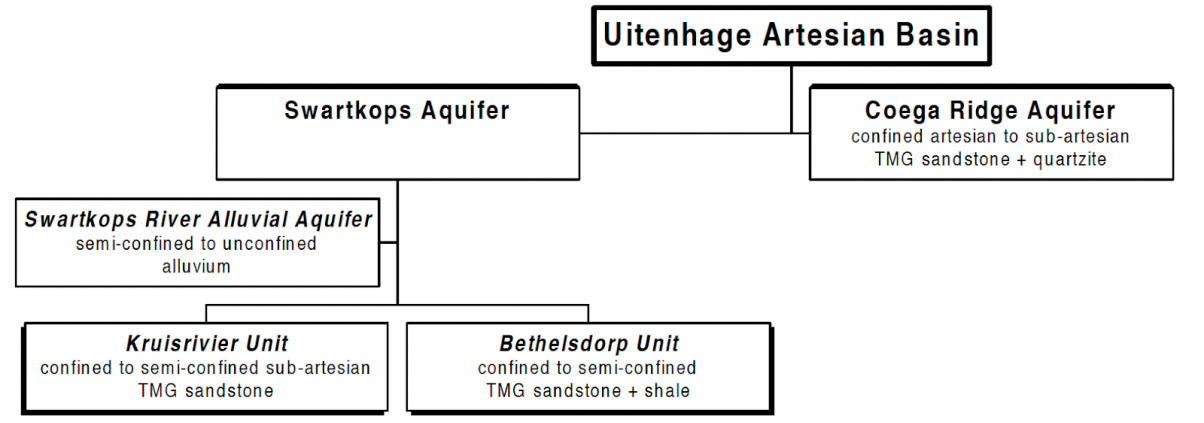

Figure 5. Subdivision of the Uitenhage Artesian Basin. Source: Maclear (2001).

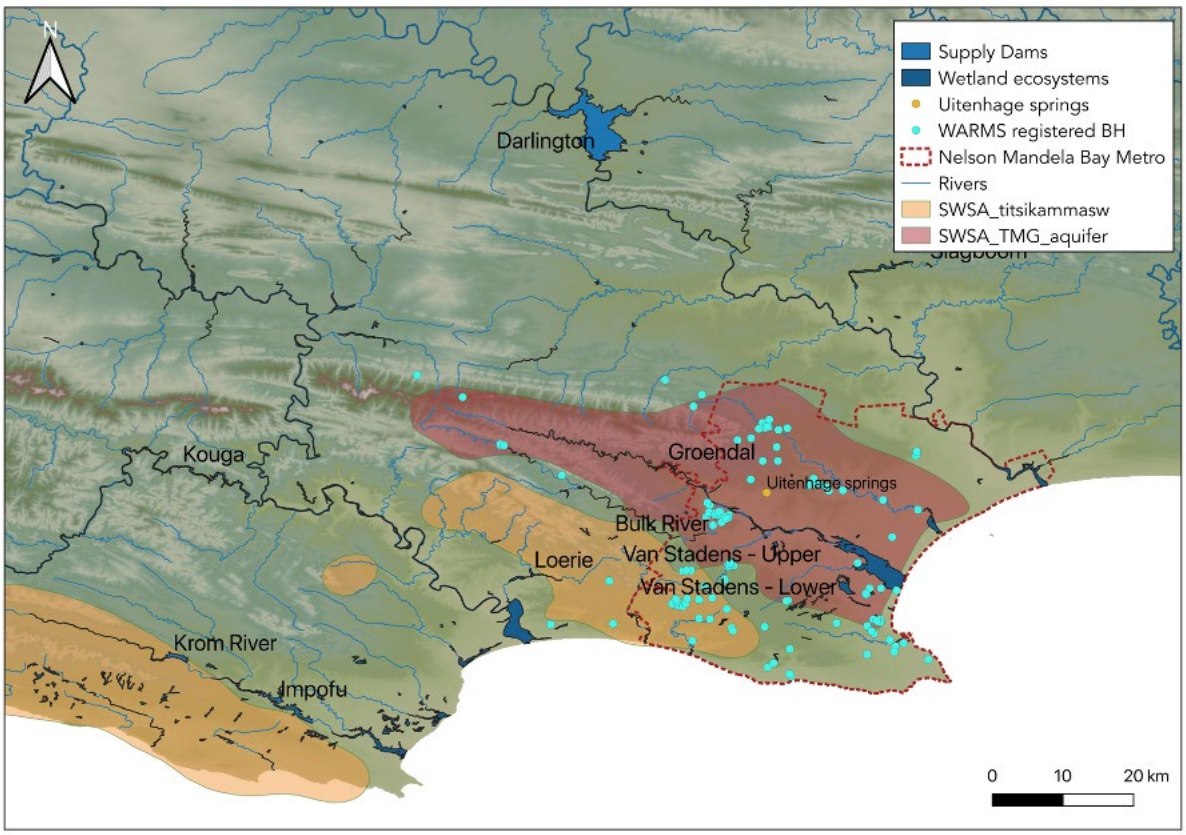

Figure 6. Nelson Mandela Bay Metropolitan Boundary (red dashed line) and the strategic water source areas (SWSAs) for groundwater (Coega TMG aquifer, shaded area in red) and surface water (Tsitsikamma, shaded yellow areas). Primary dams are indicated as supply dams. Blue points highlight the boreholes registered by WARMS.

The Uitenhage springs have historically been a source of groundwater, contributing roughly 1% of the municipal supply mix (as shown in table 2). Beyond that, groundwater had not been considered a traditional source of potable water for NMBM and is generally considered an underutilised resource for municipalities in South Africa. Within the TMG Aquifer and Tsitsikamma Strategic Water Source Areas (see figure 5), WARMS registered boreholes are allocated for a total of 6.4 Mm^3 $year^{-1}$, with most water being used for irrigation (70%), industry (15%), schedule 1 users (5%) and water supply services (5%) (see figure 7). The actual use by private users is considered to be almost 3 times higher than what has been allocated by DWS (Baron, 2000).

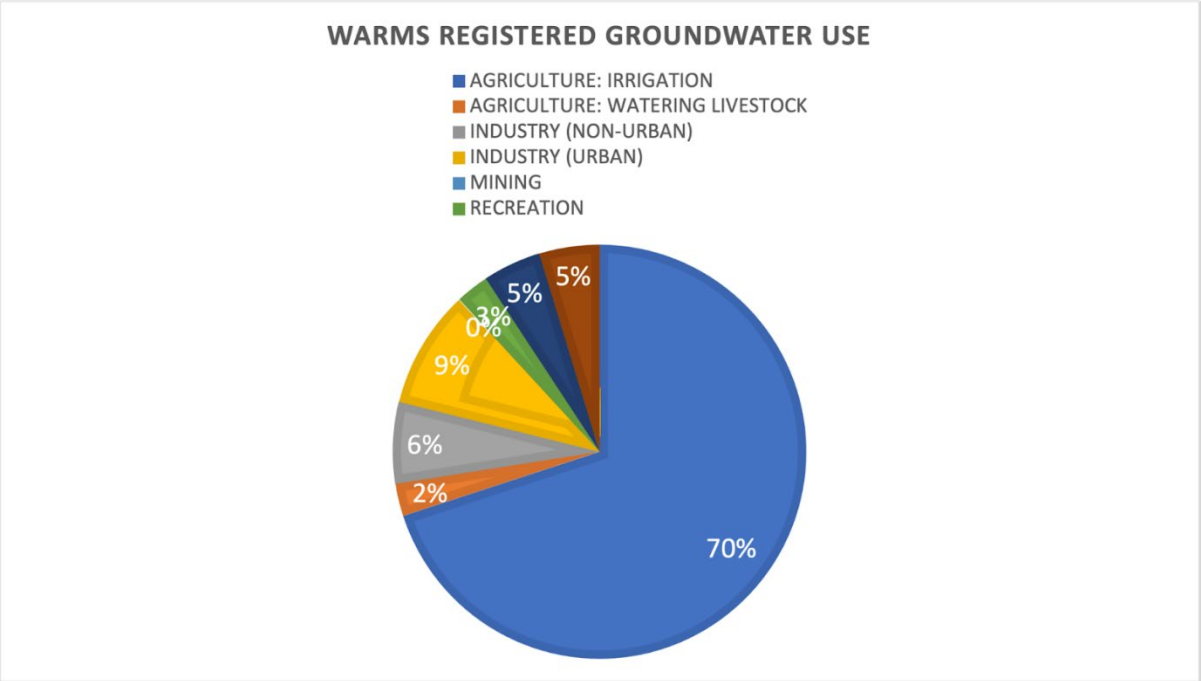

Figure 7. WARMS registered boreholes within the TMG Aquifer and Tsitsikamma Strategic Water Source Areas in and around NMB (Source: DWS).

Currently facing a water crisis, groundwater is being heavily invested in as an important source of potable water for the Nelson Mandela Bay municipality, with the intention of expanding groundwater abstraction to make up 9% of the future municipal supply mix (as shown in table 4). NMBM has fast-tracked its plan to integrate groundwater into its water mix and has subsequently drilled 200 boreholes in the region to locate suitable wellfield sites (see table 5 and figure 8) with the potential to bring between 21.4 and 41.31 MLD into the system. Numerous groundwater projects are underway, notably in Bushy Park, Coegakop, Glendinning, Fairview and Fort Nottingham, to add to the bulk water supply, highlighted by yellow boxes in figure 8.

Table 5. Potential groundwater abstraction wellfields in and around NMBM. Sourced from NMBM Water Outlook (February 2022).

Location	Low Yield (MLD)	Medium yield (MLD)	High Yield (MLD)
Coegakop	7.5	12.5	15
St Georges Park	2.1	2.85	3.6
Glendinning	1.5	1.6	2.2
Fort Nottingham	0.95	1.04	1.55
Fairview	0.35	0.68	0.96
Bushy Park	7.3	10.5	13.7
Churchill (future)	1.7	3	4.3
TOTAL	21.4	32.17	41.31

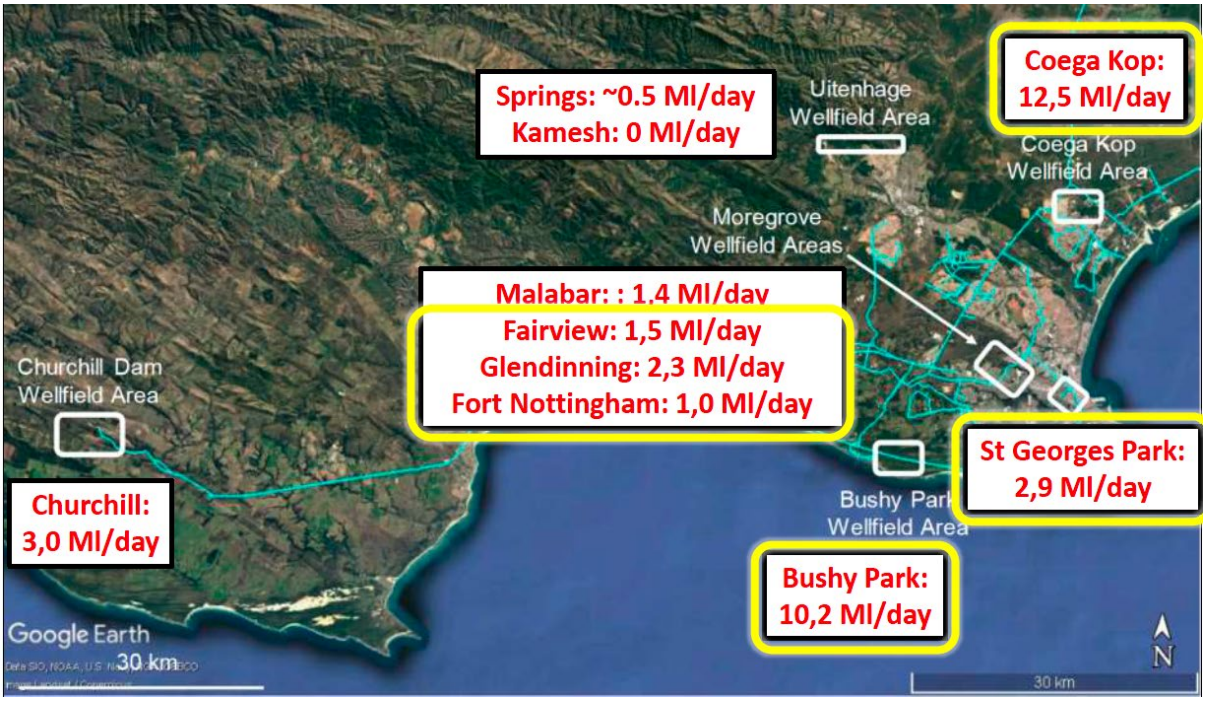

Figure 8. Map showing current and planned groundwater wellfield locations and potential yield. Source: NMBM, 2022.

The work underpinning the expansion of groundwater use in NMB dates back to the early 2000s when the WRC commissioned a study on high yielding groundwater areas around NMB (e.g. Jeffreys Arch, Gamtoos Basin, Algoa Basin). During the 2010-11 drought in the Eastern Cape, the NMB Municipality (NMBM) conducted further investigations to identify land owned by NMBM with high groundwater potential and drilled over 200 boreholes to locate suitable sites for bulk abstraction (with a total yield ranging between 21.4 and 41.31 Ml/day), notably at Coegakop, St Georges Park, Glendinning, Fort Nottingham, Fairview, Bushy Park and Churchill, as shown in figure 7 (Kelly, 2022). NMBM developed a plan for implementing groundwater projects that would ultimately yield an average of 35 Ml/day to be added to the municipal supply and used at municipal facilities like parks, sports fields and pools for non-potable uses. Many of these boreholes and wellfields are now in operation, while some are yet to be completed. The number of privately commissioned boreholes to abstract groundwater from the shallow unconfined aquifers within the NMBM boundary for industrial, commercial and domestic use is also rapidly expanding in response to the prolonged water crisis.

3.3. South African groundwater legislative and policy context

The National Water Act (NWA) of 1998 sets the legislative framework for managing water resources, including groundwater in South Africa. The NWA (RSA, 1998) vests the responsibility for managing all water resources with the Department of Water and Sanitation (DWS), with authority over the allocation, use and protection of water resources nationally. The NWA is given effect through the National Water Resources Strategy (NWRS) and the National Groundwater Strategy (NGS).

The NWRS, the third edition of which was published in 2022, lays out the institutional arrangements for managing water resources via regional water utilities, catchment management agencies (CMAs), catchment management forums, water services authorities (WSAs), and water user associations (WUAs). The logic of this institutional design centres on surface water catchments, which

undermines the suitability to managing aquifers and groundwater. On top of this, progress on establishing and operating CMAs and WUAs, with the associated delegation of functions, has been slow and remains incomplete in many parts of the country, further undermining the creation of aquifer management committees and groundwater users associations.

The NGS, developed in 2010 and updated in 2016, highlights the importance of utilising and protecting groundwater in securing the water supply of growing urban areas. It talks of the need for "coordination with the macro-policies of other sectors – such as agriculture, energy, health, *urban* and industrial development and the environment" (DWS, 2016, p.25, emphasis added). The NGS argues for a progressive shift towards a hybrid top-down and bottom-up management approach to adaptively manage aquifers and groundwater use in a context-sensitive way – what is termed a 'national facilitation of local actions' approach. However, the formal adoption and implementation of this strategy has been slow to materialise. And the strategy lays out twelve inter-connected themes, all broadly applicable to cities, but it contains very little with specific relevance to the complexity of managing groundwater allocations, uses and protection in densely populated metropolitan municipalities. The NGS notes the need to undertake localised institutional analyses covering: "What are the roles and functions of current institutions and their suitability/capacity for addressing different aspects of emerging [groundwater] problems?; Do existing institutions have the capacity to address [groundwater] management needs, including the involvement of critical stakeholders?; If not, how might they be restructured or what capacities need to be developed for them to address those needs" (DWS, 2016, p.36).

To operationalise groundwater management, DWS in Western Cape and Eastern Cape have a network of sites for monitoring water level fluctuations and water quality. However, the numbers and spatial distribution of these monitoring sites are acknowledged as being highly insufficient (DWS, 2010 and 2016). There is very limited abstraction monitoring occurring. The actual quantities of groundwater being used is highly uncertain due to a lack of sufficient data. Groundwater use reporting to DWS, as per licensing conditions, is often not fulfilled by municipalities and large-scale commercial and industrial abstractors. And the management of groundwater usage data that is reported to DWS is poorly captured and curated for use in decision-making through the Water Authorisation and Management System (WARMS).

Registered boreholes and boreholes identified through a hydrocensus are issued with a Regional Borehole Number by the DWS Regional Office and associated borehole data is obtained from the relevant consultants and entered into the National Groundwater Archive. However, any records missing data on required parameters are excluded from the database, which is a major limiting factor on the comprehensiveness of the archive and thereby its utility in actively and adaptively managing groundwater.

While municipalities have no legislative responsibility or authority to regulate and manage groundwater, as Water Services Authorities they do have a mandate to provide access to basic water supply services and ensure that no person uses water services from an alternative source without the approval of the water services authority. In both the City of Cape Town and Nelson Mandela Bay, rules regarding the use of alternative water sources, including the installation of boreholes and use of groundwater, are laid out in their bylaws. The NMBM Water and Sanitation Services By Law (NMBM, 2020) states that all borehole users must register with the NMBM, land owners must notify the Infrastructure and Engineering Directorate in writing of the intention to sink new boreholes, all boreholes usage must be restricted by 20%, and notice boards must be prominently displayed where water from sources other than the Municipality's water supply system is used. Similarly, the City of Cape Town's Water By Law and Amendments (CCT, 2018) states that every owner must ensure that

any borehole and well-point is registered on the City's database, a sign is prominently displayed on the property, and that any groundwater used is used sparingly and efficiently, in line with the City's usage rules and prevailing restrictions. Anyone intending to sink a well-point or borehole must provide written notice to the City at least 14 days prior to intended installation, stating the proposed location and purpose for which the water will be used. Both by laws also state that if any groundwater gets discharged into the sewerage system that a meter must be installed to monitor usage volumes.

4. Changing patterns of drought risk facing Cape Town and Nelson Mandela Bay

Drought is a climate hazard experienced in all regions of South Africa. Climatically, the country displays complex rainfall regimes, which can loosely be divided into regions where rainfall falls predominantly in winter (parts of Northern and Western Cape), or summer (Free State, KwaZulu Natal, Mpumalanga, Limpopo, Gauteng, Northwest), or all year round (parts of Eastern Cape). Drought is a natural feature in all rainfall regions of South Africa (Rouault and Richard, 2003) with often distinct and opposing signals of drought playing out across the country. Nationally, the IPCC Sixth Assessment Report (IPCC AR6) shows an observed decrease in precipitation; observed and projected increase in aridity, agricultural and ecological droughts in both the western and eastern parts of South Africa, as well observed and projected increases in heavy precipitation and pluvial flooding. The IPCC AR6 delineates South Africa into the larger regional West Southern Africa (WSA) and East Southern Africa (ESA), which do display some differences in observed and projected precipitation patterns.

At a local scale, that experienced by municipalities and local communities, the story is complex and highlights the need for a more nuanced and localised understanding of how drought plays out across the various urban areas of the country. Trends in rainfall and drought across the country are mixed and complex. Mackellar et al. (2014) identified some areas in the centre and north-east of the country that have experienced increasing dry spell durations. Kruger (2006) similarly identified some areas that have experienced increasing dry spells. In the Western Cape, the signal for drought varies across the province with several areas displaying some trend in drying, others displaying some degree of wetting, and some areas such as the succulent Karoo showing no trend at all (Wolski et al., 2021, Hoffman et al., 2009). What is key however is the combined effect of changes in rainfall and temperature which has driven increases in aridity across the region since the 1980s (Nicholson, 2018).

4.1. Climatic context of Cape Town and NMB

Cape Town is in the core winter rainfall region of the Western Cape and as such receives most rainfall during the austral winter period from April through September. Mid-latitude frontal systems and cut off low pressure systems, are responsible for the majority of the rainfall in the immediate city region, though summer convective systems play a role towards the north and further inland. Additionally, precipitation in the form of cloud droplet capture on vegetation in the mountains is thought to contribute significantly to high mountain catchment moisture budgets (Marloth, 1905). Rainfall across the city region varies significantly as a result of topographic influences and latitude with annual totals exceeding 3000 mm/annum in mountainous locations, but reducing rapidly away from the mountains and towards the north where annual totals of less 100 mm/annum are experienced (Wolski et al., 2021; Conradie, 2022).

NMBM is situated within the Algoa Bay region that lies in the transition zone between summer (most of subtropical southern Africa) and winter rainfall (western South Africa) regimes (Reason etr al., 2002) with Gqeberha and its surrounding coastline around 34^{o} considered to be relatively dry and an all-season region (Weldon and Reason, 2014). The Algoa region displays high interannual climate variability with many weather systems (from both tropical and mid-latitude origin) missing the region entirely (Mahlalela etr al., 2020). The Eastern Cape province receives on average between 100 mm and 520 mm of rainfall per year (Botai etr al., 2020). The region is also characterised by strong vegetation, soil and topographic gradients which contribute to complex

meteorology involving interactions with regional topography and the neighbouring Agulhas Current system.

4.2. Observed historical meteorological drought cycles

Over the century timescale, the Western Cape, in particular the region covering the catchments of the major surface water dams (the "big six") exhibits no significant decreasing trend in total annual rainfall (Wolski et al., 2021). However, shifts in seasonality and other characteristics such as dry spell duration and rainy day intensity can be observed in more recent decades. If the analysis includes the recent multi-year drought, then a clear drying trend is identified which is consistent with projected rainfall changes produced by an ensemble of climate model simulations (Otto et al., 2018).

Overall, the Eastern Cape province displays a significant decreasing trend in seasonal rainfall, however the picture is much less clear in the most western parts of the province. The spring season (September-November) which contributes ~25% of total annual rainfall shows the strongest and most consistent drought signal of all the seasons (Mahlalela et al., 2020). In the dam catchment areas for Gqeberha, a significant decreasing trend in spring rainfall is evident (Glenday, 2020).

4.3. Scenarios of future drought frequency and severity

Projected changes in rainfall over the winter rainfall region of the Western Cape, while uncertain in magnitude, are consistent in a drying trend. This drying is the result of a poleward shift in the westerly wind systems that produce the cold-fronts and cut-off low pressure systems responsible for the majority of rainfall in the region (Mahlalela et al., 2019; Sousa et al., 2018). Importantly, this drying is focused on the shoulder seasons suggesting a longer drier summer, while the core winter season remains wet. The complex and high topography of the region does introduce further uncertainties, especially with respect to localised orographic rainfall. Projected increases in temperature are consistent with the global average, having recently reached 1°C warming since pre-industrial temperatures. The increasing temperatures driving evaporation and transpiration are key to water resources, catchment dynamics (including vegetation), and storage.

Projecting the impacts of climate change on the regional rainfall patterns is a significant challenge for the Algoa region, not only because much less research has been carried out here compared to other regions, but also owing to the complex geography and meteorology of the region (Mahlalela et al., 2020). While future climate projections of the Eastern Cape region show a large spread in rainfall simulations across the region, the direction of change is consistent across the various model projections. Most models suggest a future decrease in winter rainfall on average, with increasing average temperatures and a likelihood of extreme events. While there is a large spread in the magnitude of predicted change, the direction of change displays much stronger agreement across the model outputs (Glenday, 2020).

5. Methodology for analysing urban water metabolism & groundwater governance networks

In order to understand and theorise urban groundwater governance it is necessary to analyse and compare the actor networks, arrangements and decision processes in numerous empirical cases. This requires the design and application of a case study methodology (Gerring, 2008; Yin, 2011) that can both do justice to characterising the governance arrangements in each city and can be replicable and scalable to cover many cities, thereby adding to the diversity and richness of the empirical foundation for theorising larger patterns. In line with developments in comparative urban research, learning and theorising across multiple cities, based on identifying common and different or unique processes operating in and across cities, is rooted in a relational comparative approach (Ward, 2010; Robinson, 2010). Rather than only comparing cities with a similar size, economy, and geopolitical standing, relational comparative research is designed to contrast and learn across a diversity of cities to develop new theories of urbanisation and urban governance, including of groundwater, that shed light on sustainability and equity outcomes and how to intervene to stimulate desirable change. This project focuses on developing and testing the methodology by applying it in the cases of Cape Town and Nelson Mandela Bay in South Africa, with the intention of then extending the application to cities beyond South Africa to further theorise urban groundwater governance from an African perspective.

The cases of Cape Town and Nelson Mandela Bay were selected based on:

- the recent and ongoing experiences the two cities have had with multi-year hydrological droughts and 'Day Zero' water crises resulting in extensive expansion in public and private groundwater abstraction;
- previous work analysing Cape Town's urban water metabolism (comparing before the 2015-2018 drought with the plans to become a water sensitive city);
- an interest in exploring the applicability and potential decision-support value of urban metabolism analysis in cities where data scarcity and fragmentation is a greater challenge (as is the case in Nelson Mandela Bay as compared with Cape Town);
- existing knowledge of and relationships with relevant units in the City of Cape Town, and the rich bodies of geohydrological and groundwater management work undertaken by the University of the Western Cape and Umvoto;
- exploring collaboration potential with academics at Nelson Mandela University working on groundwater issues.

5.1. Urban Water Mass Balance

The urban water cycles of City of Cape Town (CCT) and Nelson Mandela Bay Municipality (NMBM) were quantified as a steady-state mean annual average. The urban water cycle comprises anthropogenic and hydrological flows of water into, within and out of the city. Anthropogenic flows represent the volumes of water consumed and discharged by the urban areas serviced by CCT and NMBM with the point of entry as the water treatment plants and point of exit as the wastewater treatment works (WWTW). Hydrological flows represent precipitation, evapotranspiration, runoff, and groundwater recharge that occur within the defined system boundary, as well as surface and groundwater discharge out of the system into the ocean. Water that flows into the urban system via rivers and aquifers is not accounted for in this analysis due to uncertain flow rate data. For convenience, decentralised groundwater abstraction and non-potable reuse are assumed here to be

their own separate outputs, but as these rates may increase in the future, they could equally be considered to leave the system as evapotranspiration or groundwater discharge.

The water mass balance assumes a steady state and follows Equation 1:

$$Qi = Qo$$

$$(P+C)+Rp+MAR= (W+Rs+ET+Dg+Cufw+Gd+Rnp)-Rp-MAR$$

where Qi is the sum of all inputs and Qo is the sum of all outputs (including losses). Inputs consist of precipitation (P) and centralised bulk water supply (C); the latter comprising surface supply (Csw), springs (Cs), water transfer (Ct), desalination (Cd) and centralised and groundwater abstraction (Cg). Outputs consist of wastewater effluent (W), runoff (Rs), evapotranspiration (ET), decentralised groundwater abstraction (Dg), groundwater discharge (Gd), non-potable reuse (Rnp) and losses (Cufw). Water recycling terms (Rp and MAR) refer to potable reuse and managed aquifer recharge (MAR) and are included as both Qi and Qo, but are subtracted from outputs.

The steps taken were to:

1. Define the system boundary and quantify all parameters of the urban water cycle (Table 6), both anthropogenic and hydrological flows.

2. Conceptualise urban water cycle (Fig. 9), and conduct mass balance analyses (Equation 1 and Table 9) of the urban water cycle in 3 separate scenarios that relate to i) the current climate and water mix; ii) the future water mix; and iii) an idealised water sensitive city.

3. Assess the water sensitive performance of the urban water cycle under the 3 scenarios (Table 11) using performance indicators stipulated in (Renouf etr al., 2017).

The system boundary is defined as the Nelson Mandela Bay Metropole (see red dashed line in figure 6 above). The Algoa Water Supply System (AWSS) supplies the NMBM with potable water, which then in turn supplies several surrounding small towns that comprise the Kouga Municipality (Jeffreys Bay, Humansdorp, St Francis, Loerie, Thornill, Gamtoos Mouth, Mauritzkraal, Crossways, Rivierhoogte). Both the supply system and the water that is then sold to other towns extend far wider than the NMBM boundary. We have thus considered both the supply and external selling to smaller towns as external to the system boundary. Following (Renouf etr al., 2018), the targeted groundwater schemes for centralised supply is also considered an external resource as the targeted aquifers are from the TMG which extend beyond several 100 metres below ground.

Table 6. Type and sources of data and their time period, some parameters have more than one method as comparisons were made between various products (e.g. hydrological parameters).

	Parameter	Data Source	Data period/Version
	Landuse data	South African Landcover datasets (GeoTerraImage, 2018)	2018
	Soil type	(Schulze, 2012)	2012
	Digital Elevation Model (Slope)		

	National Vegetation Map	South African National Biodiversity Institute (SANBI)	2018
Anthropogenic flows			
Csw	Surface supply	NMBM	July 2015-July 2021
Cs	Springs	Algoa Reconciliation Strategy (DWS, 2018)	Annual average
Cd	Desalination	Zutari (*pers. comms*)	Annual average
Cg	Groundwater	NMBM and WARMS	Annual average
W	Wastewater effluent	NMBM	July 2013-July 2021
Rnp	Non-potable reuse	Algoa Reconciliation Strategy (DWS, 2018)	Annual average
Rp	Potable reuse	Zutari	Annual average
Cufw	Loss	NMBM	
	Other municipalities (water sold)	NMBM	Annual average
	Future Water Mix	Zutari	Annual average
Hydrological flows			
MAP	Precipitation	South African Water Resources Book of Maps 2012	Annual average
Et	Evapotranspiration	Schulze et al. (2007); Water Balance (ET = MAP - runoff - recharge)	Annual average
Rs	Runoff	Calculated as per Atkins et al. (2021) following SANRAL runoff coefficients; South African Water Resources Book of Maps 2012	Annual average
Re	Groundwater recharge	Water balance method; Groundwater Resource Assessment II - Task 3aE Recharge (DWAF, 2006)	Annual average
	Urban population	Stats SA	2016 Census

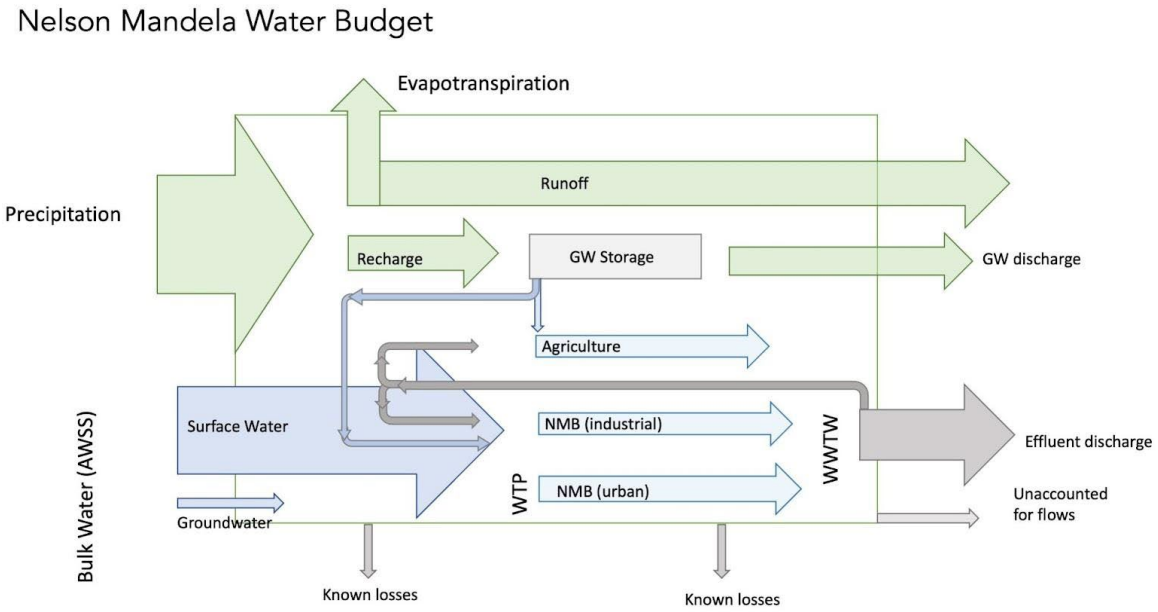

Figure 9. Conceptual diagram of the current water cycle for Nelson Mandela Bay Metropolitan.

5.1.1. Estimating hydrological flows

Following Atkins, Flügel and Hugman (2021) we used readily available spatial products. A mean annual precipitation map was obtained from the South African Water Resources Geographic Information System book of maps (Bailey, A. K. and Pitman, W.V., 2016). Two separate methods for evapotranspiration were assessed: 1) A mean annual evapotranspiration map was generated by (Schulze et al., 2007), using the FAO Penman-Monteith method (Allen et al., 1998), and was based on daily maximum and minimum temperatures, on a 1.7x1.7 km grid for 50 years, and empirically determined month-by-month gridded values of actual vapour pressure and daily gridded values of solar radiation, and 2) a water balance where ET = MAP - runoff - recharge. Two separate runoff products were compared, the WR2012 mean annual runoff (MAR) from South African Water Resources Geographic Information System book of maps (Bailey and Pitman, 2016), and an estimated mean annual runoff was calculated as per the rational method using runoff coefficients according to SANRAL (2013), taking into consideration soil type, slope and land use (See Supplementary tables 1-3 from Atkins, Flügel and Hugman (2021). For recharge, two separate products were also compared, the recharge maps generated by the Department of Water Affairs and Forestry (DWAF) 2006 Groundwater Resource Assessment II - Task 3aE Recharge (DWAF, 2006), and a mass balance (Recharge = MAP - ETo - Runoff). The values of all hydrological parameters presented in the analysis represent the sum of all pixels within the metropolitan boundary. A comparison of several spatial datasets was carried out and the products that made most hydrological sense, in relation to observed hydrological processes and published literature, were selected.

5.1.2. Estimating anthropogenic flows

Anthropogenic flows consist of water supply (as quantified by water treatment works output), recycled water, groundwater abstraction, desalination, wastewater effluent, demand by the NMBM, industry and agriculture. Monthly flow data of water supply and wastewater effluent were obtained from the Nelson Mandela Bay Municipality for the time period between July 2015-June 2021. Annual averages of both were calculated for that time period. Zutari also supplied a breakdown of the present and future water mix, detailing the various sources of water that are supplied to NMBM (see Tables 2 and 4).

Water recycling rates, industrial and agricultural use were found in the Algoa Reconciliation strategy (2010), but were recycling rates primarily taken from the current and future water mix as provided by Zutari. While the growth scenario provided some estimate of what increases in industrial use may be (for the Coega IDZ) the values presented are slightly outdated. Decentralised groundwater abstraction for the current day scenario represents data obtained from the Water Use Authorisation and Management Systems (WARMS) database. For future scenarios that represent the future water mix presented in 2022, centralised GW abstraction, desalination and water recycling rates have come from personal comms with Zutari personnel. Virtual water and other forms of imported and exported water (e.g. imported in food and bottles) have not been included in this analysis.

5.1.3. Performance Indicators

To be able to benchmark the performance of a city in relation to its water management objectives we have used several performance indicators (Table 1) proposed by Renouf etr al. (2017) and Paul etr al. (2018). Renouf etr al. (2017) proposed several indicators that relate to the water metabolic characteristics of urban water management: resource efficiency, supply diversification and internalisation, hydrological performance, and sustainable management of water resources. We have also incorporated several performance indicators derived for a developing country context by Renouf etr al. (2017) and Paul etr al. (2018) which include the replaceability of water supply by available water already within the system such as wastewater, stormwater, or a combination of both, and the recovery of water losses.

5.2. Social Network Analysis & Net-map

Social Network Analysis (SNA) is a set of methods to detect, analyse and interpret social relationships and flows between individuals, groups, and organisations (Fischer and Ingold, 2020). In the analysis, the relations, referred to as ties, can be binary (i.e. present or absent) or valued (i.e. a measure of intensity, frequency or strength of the ties). Ties can be non-directional or directional (i.e. if advice or funding only flows in one direction between two actors). The degree of reciprocity or mutuality (i.e. ratio of power) between nodes can differ. The basis of social network ties can include communication, familiarity, conflict, cooperation, issue involvement, shared beliefs, trust, joint protocols, and event co-participation (Fischer and Ingold, 2020). Gathering network data relies on information from practice, accessed through official documents and the expert judgments of those directly involved. Using various analytical methods (including participatory mapping and statistical modelling), networks can then be analysed using various SNA concepts and measures, notably: network segregation; modulatory; homophily and heterophily; centrality (degree centrality and betweenness centrality); polarisation; cohesion; clustering; network rules; and social capital (Fischer and Ingold, 2020b). This research focuses on the network of organisations involved in groundwater-related decisions in cities and takes a participatory mapping approach.

Analysing existing networks makes it possible to identify where important links between actors are missing, and thereby to make recommendations about where more effective means of collaboration and information sharing are required and should be invested in. A qualitative approach is used to address questions regarding who the actors collaborate with, what form that collaboration takes, and the perceived strength of the ties between them. Having done so, the second step of analysis is to then take a holistic view of the existing network of nodes to assess the limits, barriers and enablers to groundwater governance in the case study sites.

The focus of this research is on organisational and sub-organisational actor networks. Future research could focus on individual actors, the ties they hold, their position in the network, and the consequences of those individuals being lost from the network or moving organisations and

positions. The network approach also makes it possible to integrate other types of nodes and relationships or ties, beyond social actors and social ties, such as ecological actors, biophysical nodes, issues and institutions, and the relations between them, which potentially enables an integrated systems analysis by an interdisciplinary team. This would be an exciting direction for the research to take in future. Such analysis can combine qualitative methods and quantitative, statistical methods, which is proving increasingly valuable in furthering knowledge and building a shared understanding that fosters cooperation in tackling sustainability and equity challenges.

This research builds on the participatory network analysis methodology called Net-Map deployed by Hauck et al. (2016). Data is not readily available on the public and private actors involved, their capacities and the processes by which they exercise their political, economic and/or administrative authority to shape the decisions taken to allocate, utilise and protect groundwater resources. Some data is available through reports and websites, but it is highly fragmented and partial. Therefore, in addition to documentary analysis, methods are needed to collect this data directly from those involved, who hold experimental knowledge about the organisations they work in and with, and the means by which they and their colleagues carry out their work. In this project, data was gathered through in-depth interviews, focus group discussions, and by convening diverse groups of actors in a series of Learning Lab events. These are multi-stakeholder workshops convened over a few days and designed as a series of interactive exercises to harvest and collate data from various vantage points of people who are active in the groundwater space. As with all social science data collection methods, the quality of the data is contingent on how representative the study participants are of the full field of relevant actors and the quality of the engagements with the study participants.

5.3. Learning Labs

Learning Labs are facilitated events that bring together a broad range of stakeholders to constructively engage with complex urban sustainability issues, with the aim of building a shared understanding of the dynamics of the system, ways of adapting to changing conditions, and the various roles and responsibilities for enacting alternative approaches and implemented measures (Arrighi et al., 2016; Culwick et al., 2019). The Learning Labs in the GoFlow project were designed to be opportunities for co-producing knowledge. This involved designing the Labs to include information sharing from numerous positionalities, the deconstruction of information into data, the analysis and reconstruction of data into new knowledge. Four GoFlow Learning Labs were hosted in-person across the two cities in November 2021 (CPT LL1), March (NMB LL1), July (CPT LL2) and December 2022 (NMB LL2)[2]. A fifth, combined learning event will be hosted online to enable stakeholders from both cities to come together and engage with the findings of the project and deliberate possible ways forward emerging from this and other related work.

For the urban water metabolism aspect, the Learning Labs were considered an opportunity not only to present the analyses to participants for cross checking conceptual understanding of the urban water cycle in question (e.g. rates, direction and magnitudes of flows), but also to gauge how useful it is as a tool to bridge stakeholders from diverse disciplines, backgrounds and with different understandings of urban water cycles and how groundwater fits in. Urban water metabolism is a fairly new framework for conceptualising and quantifying urban water resource flows and is not yet a mainstream concept or term, even in water resource management communities (King, Kenway and Renouf, 2019). While urban water metabolism is viewed essentially as a water mass balance analysis, an exercise that many water engineers will be familiar with, UWM extends beyond

[2] Reports detailing each of these events are available at: http://www.acdi.uct.ac.za/goflow-governing-groundwater-flows-growing-cities-facing-drought-risks

engineered water flows to integrate the hydrological flows of the urban water cycle and also aims at providing some insight into how well the city is performing against its management vision or objectives. Work that has been done on urban water metabolism has mostly been of an academic nature, involving little communication or engagement with urban planners, civil servants, water resources practitioners or end users. This project has begun to address this need.

Exercising and transforming water governance (i.e. shaping decisions) and management (i.e. enacting decisions) in ways that enhance sustainability and equity is a complex, wicked problem requiring multi-stakeholder and multi-level participation (King, Kenway and Renouf, 2019). This involves increasing efforts to communicate, share and translate knowledge across disciplines, organisations, sectors and scales. Such efforts are crucial for integrating science and decision-making processes, and for science to be of better service to actualising and operationalising integrated and adaptive urban water management. Thus, the Learning Labs were designed and run to explore: how UWM may be better communicated; where participants see themselves in the larger urban water system; and what the information needs of participants are that the UWM can meet, or not. Approaching this through the use of scenario analyses was considered a useful, multi-dimensional knowledge sharing process (Davies, 2008). Scenarios are descriptions of possible futures that can support the decision-making process in circumstances of uncertainty by exploring and considering a variety of plausible storylines (Wollenberg, Edmunds and Buck, 2000). Scenario analyses were used in the GoFlow Learning Labs to promote discussion, questioning and dialogue amongst multi-stakeholder participants (for full list of participants see Appendix 1).

As UWM was new to almost all participants of the Learning Labs, adequate time was given to introduce UWM as a concept, its background, why it can be a useful tool, and to present the framework, discuss the methods used to amass the parameters that feed into the mass balance and the results of what the urban water cycle looks like. This was done as a basis for asking participants to ask questions of the framework and its application, both questions of clarification and questions that could inform further analysis and the communication of results. This enabled us to probe the perceived relevance and utility of information produced by applying the UWMF to various actors and the decisions they face.

The Learning Labs included presenting plausible climate change narratives for the Western Cape and Eastern Cape – with a focus on changes in evaporation as a key climate variable to consider, as most models project a drying trend – and discussing how these may be incorporated into UWMF scenario analyses, together with potential land use changes that impact water demand, runoff and infiltration. We discussed with Learning Lab participants the range of scenarios for Cape Town and Nelson Mandela Bay that could usefully be tested and explored using the application of the UWMF through a water mass balance model. We did this by looking at the sankey diagram (e.g. Figure 10) and introduced the metaphor of dials that increase or decrease various hydrological and anthropogenic parameters, representing key intervention points in the urban water cycle (see Figure 10). There are ‘dials’ for rainfall, evaporation, land cover, runoff, recharge, availability of surface supply, water demand, and circularising of water flows (i.e. water recycling, direct and indirect reuse). We explored with participants what dials do we want to turn within the hydrological cycle to see what the implications are? What do we want or need to consider, at what time scale and to what time horizon? Scenario options include: maximum reuse; weighted land cover change with change of porous aquifers weighted higher; spatially selective rewilding to maximise natural recharge; the conversion of all detention ponds into maximised infiltration ponds. The metaphor of turning dials on various flows is a useful one to think through how easily each dial turns, whether the dial can go in both directions or once opened it cannot be reversed (e.g. decentralised investments

in alternative water supplies that once installed cannot be removed or abandoned when there is surplus bulk water supply), and importantly, which actors are involved in turning which dials.

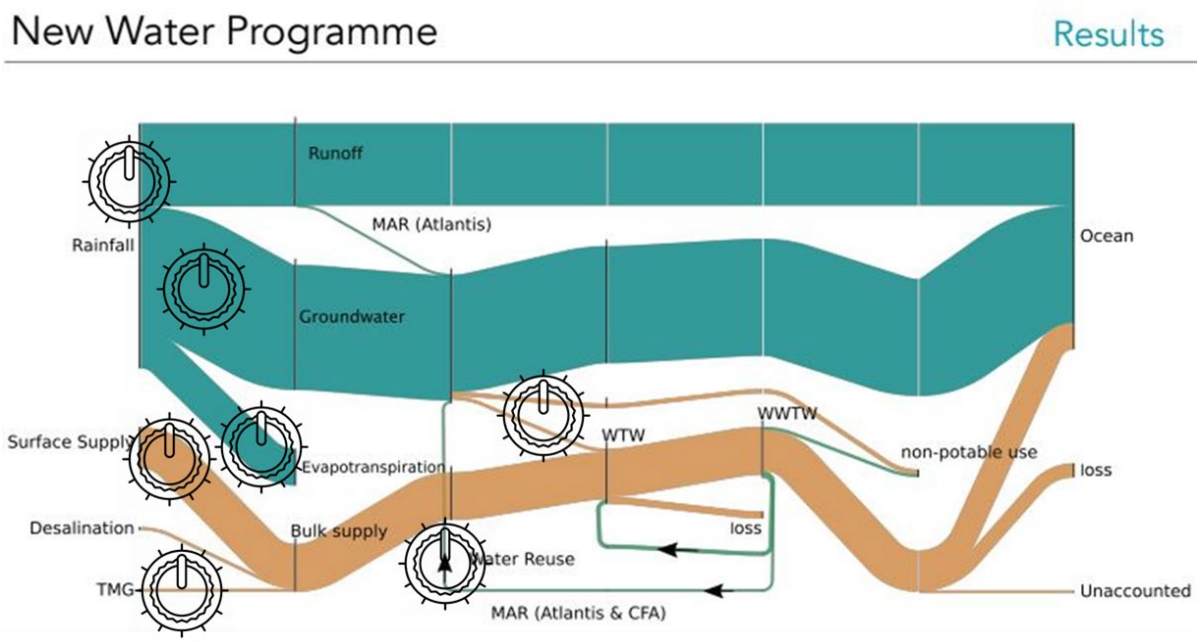

Figure 10. The sankey diagram viewed with a lens of dials to aid discussions surrounding scenario analyses and implications of certain decisions or future storylines.

For the groundwater governance aspect of the project, the Learning Labs were designed and facilitated in a way that various actors with an interest and stake in the cities' groundwater could connect, get to know each other better, share their knowledge of the system and how it works, share information about groundwater-related activities they are engaged in, and take a step back to think about the physical and social flows of the urban water system and how these could change. In so doing they were generating data on the characteristics of the governance network. The exercises run during each of the Learning Labs were set up to create a structured way in which people could share and document relevant information to collectively make sense of the joint knowledge held across the network. The focus was not only on which actors operate in the space, but also what capacities they have to exercise their agency in relation to groundwater, and the varying extents with which they interact. For example, in the first Learning Labs in each city, participants were asked to sort a set of cards, where each card displayed an actor, according to the influence each actor has over various water issues, identify if any key actors were missing, and indicate the flows of data, advice, finances, authorisations and partnering activities between them (see images 1, 2 and 3).

Image 1. Learning Lab participants discussing actors and linkages (left image); resulting map of actors and colour coded linkages depicting flows of data, advice, money, authorisations and partnerships (right image). Photo credit: Caron von Zeil (left) and Naadiya Hoosen (right).

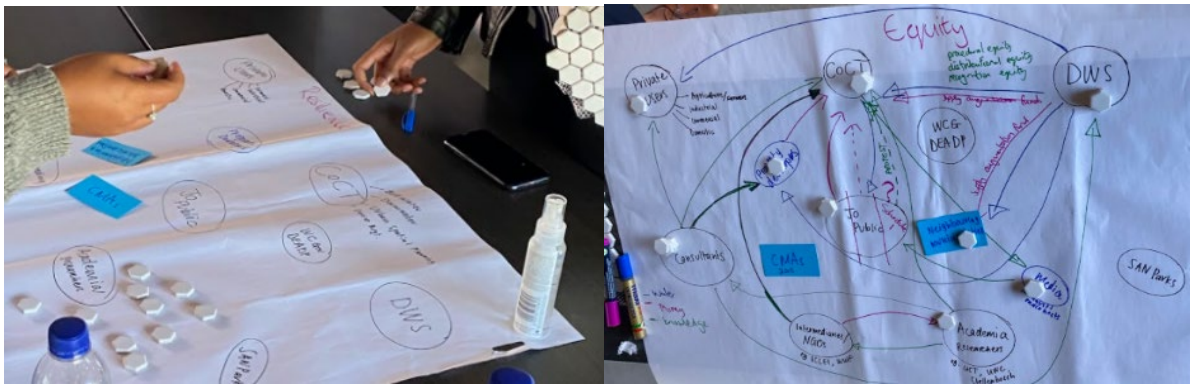

Image 2. Group in the first Cape Town Learning Lab working on adding influence towers and linkages between actors who have a bearing on the equity of water distribution, access and usage. Photo credit: Anna Taylor.

Image 3. Group in the first NMB Learning Lab deliberating the influence of various actors over protecting or conserving aquifers and/or recharge by positioning them in concentric rings of high, medium, low and no influence. Photo credit: Anna Taylor.

The identification of actors and their interactions was then further explored by focussing on the attributes of the actors and the strength of the ties between them. Participants in the Learning Labs were introduced to and worked in groups on exercises to explore five attributes of nodes in the

groundwater governance network, namely: actor type (state; interest group; science & research); governance level (local / sub-city / aquifer; city-wide; provincial; national; international); groundwater function (i.e. involving activities to understand, operate, regulate, and capacitate the system); capacities to implement their function; and strength of ties with other actors (see image 4).

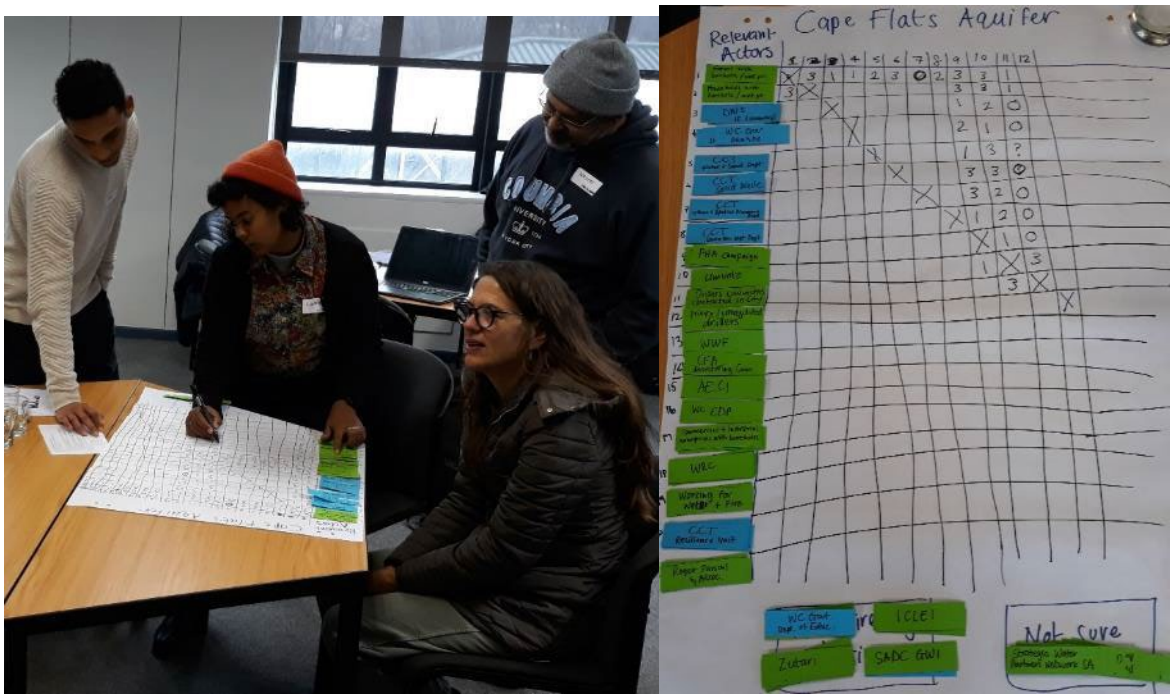

Image 4. Group at the second Cape Town Learning Lab deliberating strength of ties between actors using or managing groundwater in the Cape Flats aquifer on a scale of 0 to 3, from no interaction to frequent interaction, defined as more regularly than once a month. Photo credit: Anna Taylor.

The four types of functions were considered, namely:

1. *Understanding*, which includes delineating and characterising aquifers, estimating yields, delineating groundwater protection zones, monitoring groundwater levels and quality.
2. *Operating*, which includes installing boreholes and well points, operating and maintaining wellfields, and managing and maintaining aquifer recharge infrastructure.
3. *Regulating*, which covers processing water use licences, enforcing water use licences, preparing and revising (ground)water bylaws, enforcing bylaws, registering boreholes and well points, setting and enforcing usage restrictions, and designating and enforcing groundwater protection zones.
4. *Capacitating*, which covers training groundwater professionals, training groundwater users, public awareness raising and education, advocating for changes in groundwater use, rules, access, sanctions, and building and maintaining partnerships.

Image 5. Group at the second NMB Learning Lab coding the actors according to their functions, where each card shows the name of an organisational actor and colour dots are used to indicate which functions they fulfil (blue = understanding; purple = operating; red = regulating; green = capacitating). Photo credit: Naadiya Hoosen (left) and Anna Taylor (right).

Having identified the functions that each actor fulfils, participants were then asked to share their knowledge and deliberate the capacity levels of each actor to fulfil these functions. Participants deliberated within their groups and assigned a score for each of the dimensions or metrics of the capacity to implement, guided by table 7.

Table 7. Key provided to Learning Lab participants to deliberate and rate the capacity of each actor to fulfil their groundwater functions.

Metric	0	1	2	3
Formal / legitimised mandate	None	Contested / unclear	Limited	Clear & widely recognized
Number of staff working on groundwater programmes	No dedicated staff	Less than 5	5-10	Over 10
Level of technical expertise	None	Low	Medium	High
Efficient modalities to leverage capacity outside of org (procure or partner)	None	Low	Medium	High
Annual budget for groundwater programmes	No dedicated budget	Less than 1 million	1-10 million	Over 10 million

6. Findings on urban water metabolism

6.1. Nelson Mandela Bay

The findings from the NMBM analysis are presented below, first focussing on the quantification of the hydrological flows and then results from the mass balance analysis, including three scenarios.

6.1.1. Hydrological flows

Precipitation amounts to 536 mm per annum (Table 7). There is substantial discrepancy between the various products used to estimate the other hydrological parameters and these are summarised in Table 7. Using Schulze et al. (2007) evaporation is estimated at 140 mm/a or 26% of MAP, whereas using a water balance (and using the runoff and recharge products highlighted in green in Table 8), ET is estimated at 86% of MAP. For runoff, mean annual runoff map sourced from WR2012 book of maps (Bailey and Pitman, 2016) indicate runoff is 13% of MAP whereas using the rational method, runoff is estimated at 3% of MAP. In turn, if using the mass balance to estimate recharge, it amounts to 69% of MAP, whereas the DWAF (2006) GRAII products estimates recharge to be 5% of MAP.

Table 8. Summary of the spatial aggregate of all pixels from the various spatial products (as described in the text) with the various units for easy comparison. Green highlighted rows indicate the products used to construct the mass balance.

Hydrological parameters	Source/Method	Mm^3/a	ML/d	mm/a	% of P
MAP	WR2012	1050	2878	536	100%
ET	Schulze et al. (2007)	275	754	140	26%
ET	water balance	899	2463	459	*86%*
MAR rational	Atkins et al. (2021)	33	90	17	3%
MAR WR2012	WR2012	137	377	70	13%
Recharge (MAP-MAR-ETO)	water balance	721	1976	368	69%
Recharge (GRAII)	DWAF (2006)	53	146	27	5%

The large discrepancy between all products, which is an important finding of this work, makes it challenging to know which product for each hydrological parameter to use. Accessible research into bulk estimates of hydrological parameters is limited for the region, nevertheless several studies have been reported that allow us to make a reasonably broad approximation of the hydrological water balance. The neighbouring Kromme catchment is an important catchment that currently supplies NMBM with ~40% of its water supply via Mpofu and Churchill reservoirs. Mean annual precipitation (MAP) for the period between 1950-2000 was approximately 614 mm (Lynch, 2003) (a figure which is expected to be slightly higher than within the NMBM boundary owing to its slightly higher elevation), with pre-development/urbanised mean annual runoff estimated to be 75 mm, approximately 11% of rainfall (Middleton and Bailey, no date; Rebelo et al., 2015). WR2012 estimates used in this study give present day runoff to be 13% of MAP. Rebelo et al. (2015) carried out more in-depth modelling of runoff and evaporation in the Kromme catchment, using the ACRU Agrohydrological model, and found runoff to be around 26% of rainfall, and evaporation to be 70% of MAP. Another study that assessed the use of MODIS estimates of evapotranspiration found ET to be around 82% of measured rainfall in two Eastern Cape catchments (Q91C and P10A) comprising predominantly grassland (Finca, 2011). While it is acknowledged that these are very different

catchments to those found in the NMBM area, based on their findings and as a broad approximation we deemed the most reasonable estimates for the various hydrological parameters to be: WR2012 estimate of runoff (13% of MAP), the DWAF (2006) estimate for recharge (5% of MAP) and then a water balance for the evapotranspiration (86% of MAP). The uncertainty associated with these estimates merits substantial further research.

6.1.2. Mass balance

All data were collated into a mass balance analysis using Equation 1 and are summarised in Table 9. For the present day, total inputs equate to 1199 Mm^3/a comprising precipitation and bulk water supply; total outputs equate to 1146.7 Mm^3/a comprising wastewater effluent, runoff, evaporation, groundwater discharge, decentralised groundwater abstraction, recycled water and accounted for losses; and internal flows amount to 54 Mm^3/a as groundwater recharge and non-potable reuse.

Table 9. Water mass balance of the water cycle for Nelson Mandela Bay.

Type	Input		Mean (Mm^3/a)
nat	P	Precipitation (within NMB boundary)	1050.3
anthro	Csw	Surface water (dams)	71.2
anthro	Cs	Springs	2.2
anthro	Ct	Water Transfer (Nooitgedacht)	58.4
anthro	Dg	Decentralised GW Abstraction	6.5
anthro	Cg	Centralised GW Abstraction	
anthro	Cd	Centralised desalination (non-potable Coega)	11.0
nat-IN			1050.3
anthro-IN			149.3
sub-total			1199.6
	Internal flow		
anthro	Rnp	Recycled water (non-potable use)	1.7
anthro	Rp	Recycled water (potable)	
anthro	Rw(MAR)	Managed aquifer recharge	
nat	Re	Groundwater recharge	53.0
nat-internal			53.0
anthro-internal			1.7
sub-total			54.7

	Output		
anthro	Dr	Decentralised rainwater harvest	
anthro	W	Wastewater effluent	51.7
anthro	Cufw	Known losses (canal)	4.3
anthro	Rw	Recycled water (non-potable use)	1.7
nat	Rs(NMB)	Surface runoff (from within NMB boundary)	137.0
nat	Gd	Groundwater discharge	53.0
nat	ET	Evapotranspiration	899.0
nat-OUT			1089.0
anthro-OUT			57.7
sub-total			1146.7
Water Balance (total) (error)			4%
Water Balance (anthro) (error)			16%
Water Balance (nat) (error)			-4%

Assuming long-term averages are in equilibrium, inputs should equate to outputs, and thus we find a 4% error in the water cycle as a whole. As divided into anthropogenic and natural flows, 16% and -4% errors are found respectively. With regard to the 16% error in anthropogenic flows, we propose that it is a result of unaccounted for losses from the system as well as data discrepancies. Total centralised anthropogenic inputs into the system (as supplied by Zutari and comprising surface water, springs and water transfers via Nooitgedacht) amount to 131.3 Mm^3/a, far exceeding centralised anthropogenic outputs of 57.7 Mm^3/a, comprising wastewater effluent and reported known losses real losses of 29% (Table 9). It is worth noting at this point that water inputs reported via Zutari differ substantially to the data provided by NMBM for total water treatment works outputs (which on average amount to an average of 105.23 Mm^3/a between the years 2016-2020). When using the values provided in the 'Current Water Mix' (Table 2), 25% of water in the system remains unaccounted for. Using the data provided by NMBM for water treatment output, and assuming real losses remain at 29%, we get a more reasonable unaccounted for rate of 6%. The uncertainty associated with the true value of water being consumed by the NMBM as a whole (including industrial use) renders the water balance with a 16% error for anthropogenic flows.

Figure 11 and Table 10 provide an estimated breakdown of what happens to the water that enters NMBM via treatment works, indicating unauthorised consumption, metering inaccuracies, leakage in distribution/transmission, storage leaks and service connection leaks as the various potential fates of unaccounted for water. The -4% error in hydrological flows likely represents inaccuracies that exist in the spatial data and methods used to estimate natural flows. Further research into more reliable hydrological parameters is needed.

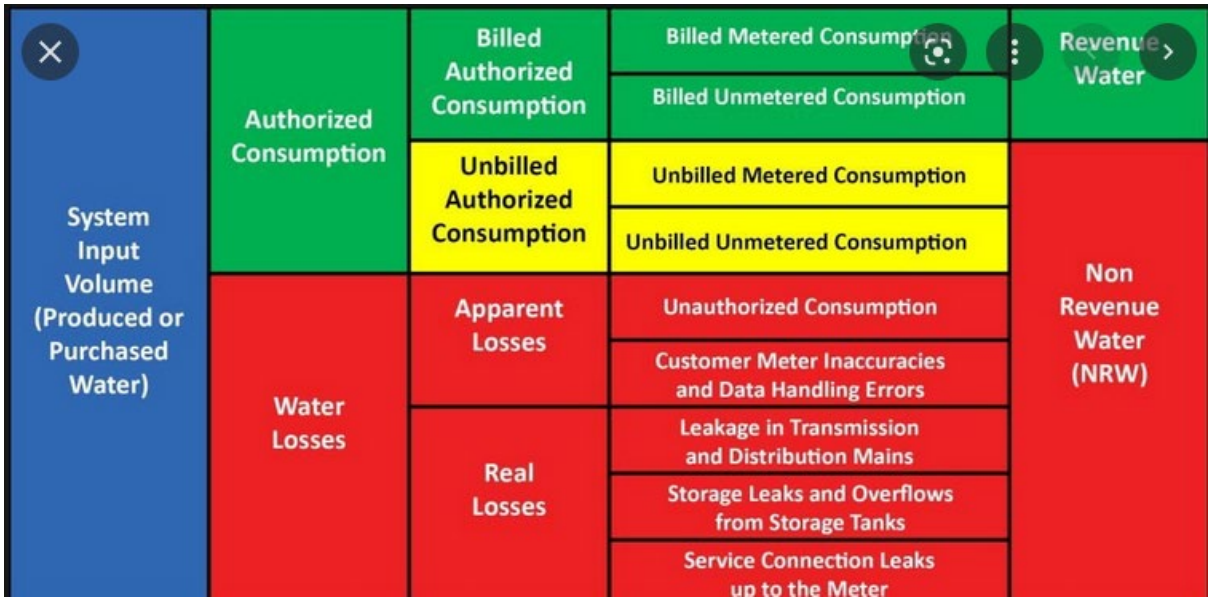

Figure 11. Breakdown of the various avenues of water flow that account for the large loss margins of anthropogenic water flowing into and out of the NMBM system. Relative values have not been provided. Source: NMBM.

Table 10. Measured annual loss rates between July 2021-June 2022. Source: NMBM.

	Mm^3/a
Volume treated	102.7
Revenue volume	56.9
Revenue water (%)	55
NRW volume	45.8
NRW (%)	44.6
Real losses	29.7
Real losses (%)	29
Water losses	40.8
Water losses (%)	40

6.1.3. Scenarios

Three separate water cycles were quantified in order to assess how each scenario fared in terms of being water sensitive: 1) Current scenario is the water mix as of 2022 before any major new drought-response interventions have come online 2) Future scenario is the future water mix as sourced from Zutari and 3) Idealised scenario is a hypothetical water mix according to the principles of a water sensitive city, which assumes that water supply is the same as the current water mix (Tables 11 and 12).

The water sensitive city principles in practice entail supply internalisation, wastewater and stormwater recovery and fit-for-purpose use where the strategic management of wastewater and stormwater is reflected in water sensitive urban design to promote aquifer recharge and ecosystem restoration. In the idealised scenario, Managed Aquifer Recharge (MAR) is an important tool in the

realisation of becoming a more resilient, water sensitive city. While it is hypothetical and has not been verified by any hydrogeological investigation, in theory there are areas that have been identified that could serve as potential recharge sites (DWA, 2009) which merit further investigation. The idealised scenario has been adjusted to reflect the same supply rates as the current scenario, assuming that groundwater abstraction replaces demand on surface water, as well as inter-basin transfer via Nooitgedacht, effectively creating supply redundancies which is another tenet of supply resilience.

Overall the idealised scenario reduces external inputs and increases internal flows by:

- Building in redundancy (capacity for desalination and increased transfer are there but not relied upon)
- Increasing water recycling (potable and non-potable uses)
- Wastewater and stormwater runoff are cleverly managed in the urban landscape for enhanced aquifer recharge.
- Losses are dramatically reduced.

Table 11. The three water mix scenarios for the Nelson Mandela Bay Metropolitan. 1) Current scenario is the water mix as of 2022 before any major interventions have come online 2) Future scenario is the future water mix as sourced from Zutari and 3) Idealised water mix according to the principles of a water sensitive city.

Source	Current (Mm^3/a)	Future (Mm^3/a)	Idealised (Mm^3/a)
Surface Water	71.3	71.3	50.8
Natural Spring	2.2	2.2	2.2
Water Transfer	58.4	76.7	58.4
Groundwater		20.4	20.4
Desalination	11.0	27.4	11
Recycled water (Coega)	1.7	21.9	27.50
Recycled water (NMU)		1.3	1.3
Recycled water (Drinking)		3.7	13.7
Managed Aquifer Recharge (MAR)			85.71
Loss recovery		7.3	20
Total External Inputs	142.8	197.9	142.9
Total Internal flows	1.7	34.1	148.21

Table 12. NMB water balance for the three scenarios.

			Current	Future Water Mix	Water Sensitive
Type	Input		Mean (Mm^3/a)	Mean (Mm^3/a)	Mean (Mm^3/a)
nat	P	Precipitation (within NMB boundary)	1050.3	1050.3	1050.3
anthro	Csw	surface water (dams)	71.3	71.3	50.8
anthro	Cs	springs	2.2	2.2	2.2
anthro	Ct	Water Transfer (Nooitgedacht)	58.4	76.7	58.4
anthro	Dg	Decentralised GW Abstraction			
anthro	Cg	Centralised GW Abstraction		20.4	20.4
anthro	Cd	Centralised desalination (non-potable Coega IDZ)	11.0	27.4	11
nat-IN			1050.3	1050.3	1050.3
anthro-IN			142.8	197.9	142.8
sub-total			1193.2	1248.2	1193.2
	Internal flow				
anthro	Cg	Centralised GW Abstraction	6.5		
anthro	Rnp	Recycled water (non-potable use)	1.7	23.2	23.18
anthro	Rp	Recycled water (potable)		3.7	36.7
anthro	Rw(MAR)	Managed aquifer recharge			123.83
nat	Re	Groundwater recharge	53.0	53.2	53.2
nat-internal			53.0	53.2	53.2
anthro-internal			8.2	26.8	183.7
sub-total			61.2	80.0	236.9
	Output				
anthro	Dr	Decentralised rainwater harvest			3
anthro	W	Wastewater effluent	51.7	110.2	83.0
anthro	Cufw	Known losses (canal)	39.6	52.1	1

anthro	Rw	Recycled water (non-potable use)	1.7		
nat	Rs(NMB)	Surface runoff (from within NMB boundary)	137.0	137.5	41.2
nat	Gd	Groundwater discharge	53.0	53.0	53.0
nat	ET	Evapotranspiration	899.0	899.0	899.0
nat-OUT			1089.0	1089.5	993.2
anthro-OUT			93.0	162.2	87.0
sub-total			1182.0	1251.7	1080.2
Water Balance (total) (error)			1%	0%	9%
Water Balance (anthro) (error)			-22%	41%	61%
Water Balance (nat) (error)			-4%	-4%	5%

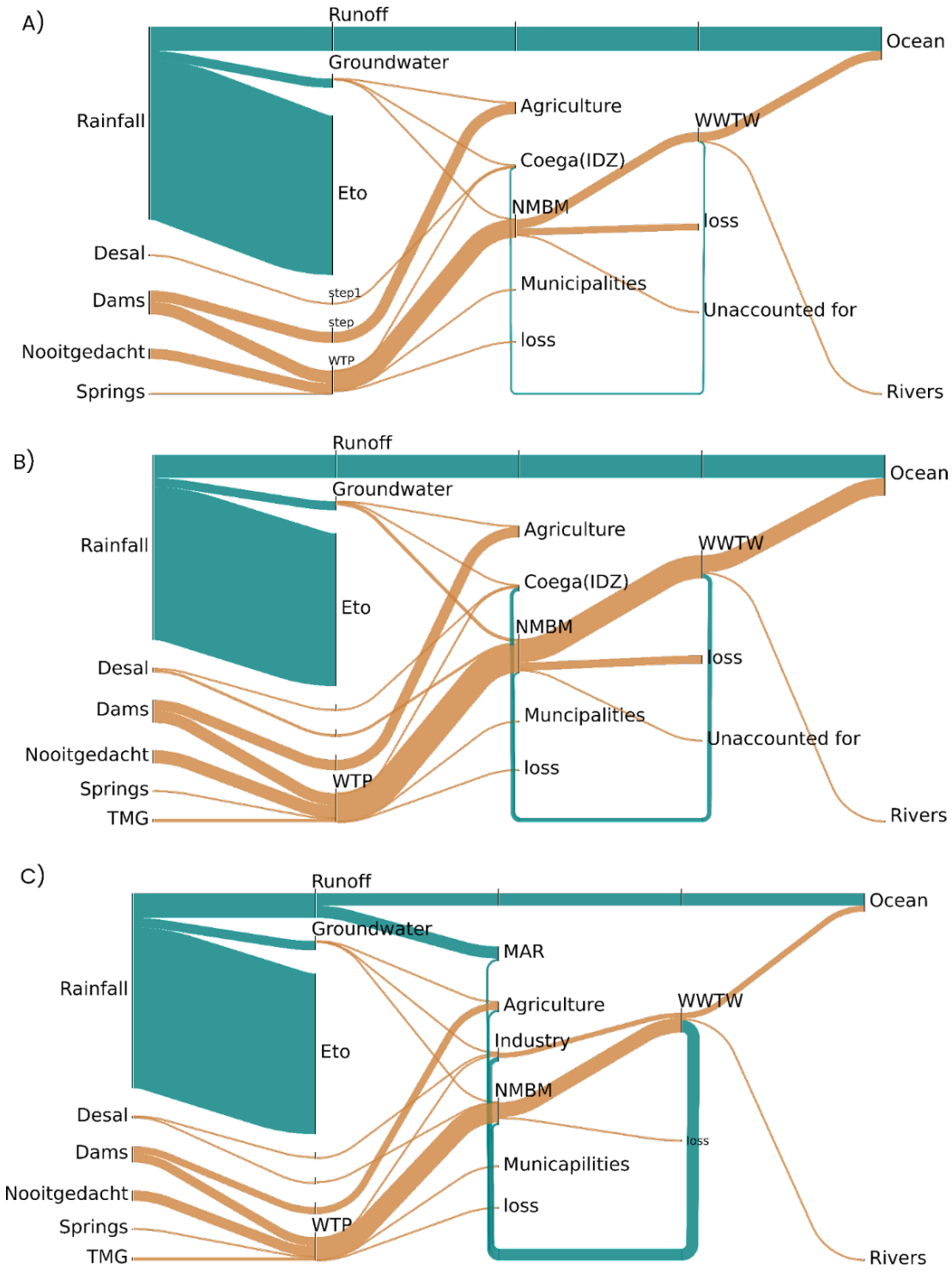

Figure 12. Comparison of sankey diagrams showing the urban water cycle for A) current water mix, B) future water mix and C) an idealised scenario.

6.2. Cape Town

The urban water metabolism for Cape Town has been published in the South African Journal of Science (Atkins, Flügel and Hugman, 2021) but is provided here for ease of reference. Details of all data sources for anthropogenic flows, and methods for calculating hydrological flows, and the discussion of results may be found in the publication.

6.2.1. Mass balance

Table 13: Urban water mass balance of the water cycle for Cape Town, under pre-drought conditions (published in Atkins, Flügel and Hugman, 2021).

			(Mm^3/year)
Type	Input		
Nat	P	Precipitation	1471.4
Anthro	Csw	Bulk water supply (surface water dams)	324.9
Anthro	Cg	Centralised groundwater abstraction (TMG)	0
Anthro	Cd	Centralised desalination	0
	Sub-total		1796.2
	Internal flow		
Anthro	Cg	Centralised groundwater abstraction (CFA+Atl)	3.3
Anthro	Rw	Recycled water (potable use)	0
Anthro	Rw(MAR)	Managed aquifer recharge	0
Nat	Re	Groundwater recharge	741.7
	Sub-total		745
	Output		
Anthro	Dr	Decentralised rainwater harvest	0
Anthro	Dg	Decentralised groundwater abstraction	26.9
Anthro	W	Wastewater effluent	234.8
Anthro	Cufw	Known losses	48.6
Anthro	Rw	Recycled water (non-potable use)	18.8
Nat	Rs	Surface runoff	492.3
Nat	Gd	Groundwater discharge	0
Nat	ET	Evapotranspiration	711.6
	Sub-total		1751.7
		Water balance (total) (error)	2%
		Water balance (anthropogenic flows) (error)	7%
		Water balance (hydrological flows) (error)	1%

6.2.2. Scenarios

A useful application of the urban water metabolism framework is to assess how urban water cycles may vary under varying climatic, land-use and management scenarios. This was done for Cape Town in Atkins, Flügel and Hugman (2021) where a comparison between the current water cycle was compared to how the water cycle would look under the New Water Programme, the interventions to bring in more water supply during and after the Day Zero water crisis. The use of performance indicators was helpful as a means to compare the performance of each water cycle under the various scenarios. The details of the performance indicators have been discussed in detail in Section 5.1.3 of this report and the original publication of them can be found in Renouf etr al. (2017).

For this project and for the purposes of the Learning Labs (as explained in section 5.3 above) we explored the implications of various scenarios on the overall urban water performance of Cape Town. The scenarios assessed (Table 14) are hypothetical and general but adhere to the projected climate change narratives for the Western Cape and the vision for Spatial Development Framework for Cape Town. Scenario 1 focuses on only climatic changes, with rainfall reducing by 10% and evapotranspiration increasing by 10%. Scenario 2 focuses on land cover and adopts an extreme approach to all cultivated land being transformed to residential. Scenario 3 is an extreme scenario which includes climatic changes (-10% for MAP, +10% for EVT) and all cultivated and residential areas become impervious hard urban spaces. While such a land-use scenario is highly unlikely in Cape Town, its effect on the urban water cycle is considered a useful point of learning and discussion for the Learning Labs. Scenario 4 is slightly less extreme and assesses the impact of reduced MAP (-10%) and increased EVT (+10%) and land-use scenario that follows the drive for residential densification with all existing residential areas becoming hard urban spaces, and all cultivated land becoming residential. These land-use scenarios (Fig. 13) are broad and are not intended to truly represent how the city may look in the future as we acknowledge that it is unlikely that some residential parts of Cape Town will ever become hard urban spaces (e.g. Constantia). The emphasis of this scenario analysis is placed rather on its heuristic value to participants of the Learning Lab as focal points of discussion, bringing diverse backgrounds onto the same page and for deeper learning on urban water cycles, climate and land-use change.

Table 14. Overview of the climatic and land-use various scenarios used to assess the changes, if any, to the urban water metabolism of Cape Town.

Scenario	Name	MAP	EVT	Landcover
Control	SC0	No change	No change	No change
Scenario 1 *Climatic changes*	SC1	-10%	+10%	No change
Scenario 2 *Land cover changes*	SC2	No change	No change	All cultivated = residential
Scenario 3 (extreme) *Climatic & land cover changes*	SC3	-10%	+10%	All cultivated and residential = hard urban space
Scenario 4 (less extreme) *Climatic & land cover changes*	SC4	-10%	+10%	All cultivated land = residential, Current residential becomes hard urban space

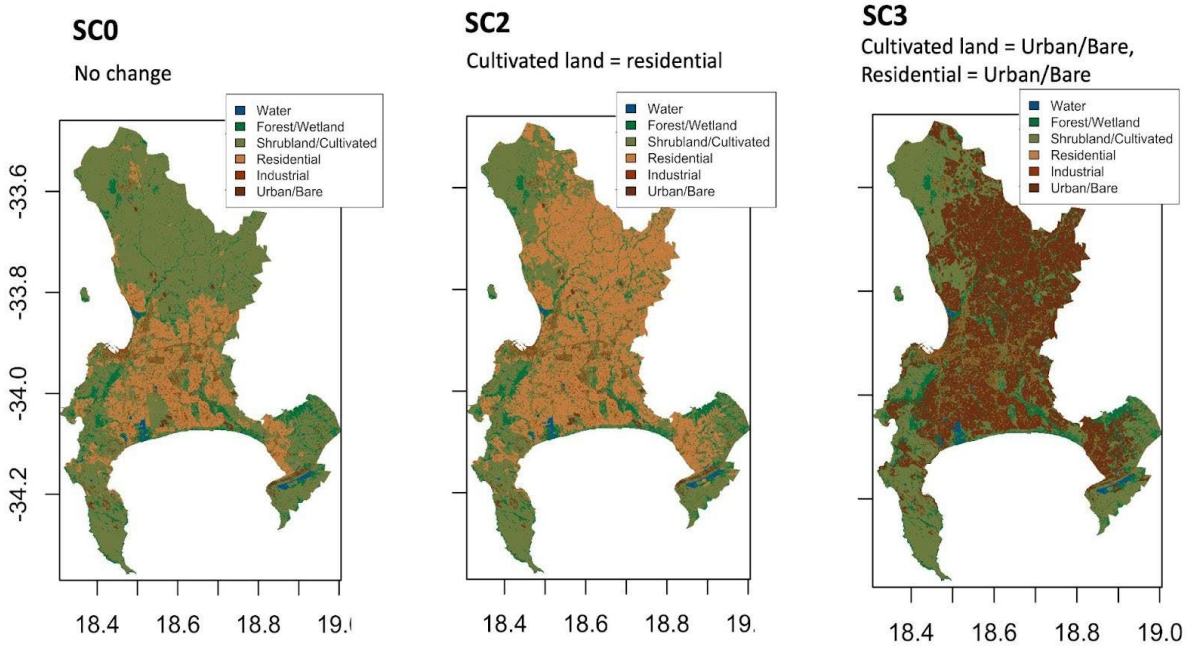

Figure 13. Spatial distribution of hypothetical land cover scenarios under the various scenarios, SC0 = no change in land cover, SC2 = all cultivated land to residential areas and SC3 = all cultivated and residential land to urban/bare under an extreme, high densification scenario.

6.2.3. Stormwater potential for water supply

Stormwater potential for water supply was chosen as an indicator to kick off discussions of UWMF scenario analysis at the Learning Lab. Runoff can change dramatically under varying climate and land use scenarios and the figures presented in Table 15 represent a theoretical upper limit of a closed-loop system and assumes that all stormwater is captured, which is not feasible nor even desirable (e.g. environmental flow requirements). Utilising stormwater is challenging as water quality is a real issue that would need to be addressed, requiring a significant shift in management practices and commitment to a holistic approach to integrated urban water management. Also, while the performance indicator is named 'Stormwater potential for water supply', it doesn't necessarily mean exclusively for potable water supply but rather to replace the supply of potable water for non-potable uses such as irrigation for peri-urban agriculture/parks/green spaces/schools and hospitals, enhanced aquifer recharge or wetland ecosystem restoration.

Table 15. Results of the scenario analysis in terms of the various hydrological parameters and their relation to mean annual precipitation (MAP). Here for the purposes of discussion in the Learning Labs, we focus on stormwater potential to replace water supply.

Scenario	SC0	SC1	SC2	SC3	SC4
ETO % MAP	14%	18%	14%	18%	18%
Runoff % MAP	39%	39%	47%	66%	47%
Recharge % MAP	46%	43%	38%	29%	47%
Stormwater potential to replace water supply	157%	142%	192%	240%	173%

The control (SC0) present day scenario indicates a particularly high stormwater potential already, 157% of water supply could theoretically be replaced by stormwater that falls on the ground within the CoCT metropolitan boundary. Under SC1, where only climatic changes occur and these are a reduction in rainfall (-10%) rainfall and an increase in evapotranspiration (+ 10%), stormwater potential to replace supply reduces to 142%. Under SC2, only land use changes occur with all cultivated farmland (e.g. Philippi Horticultural Area, and areas north of Bellville and Paarl) becoming residential, stormwater runoff increases substantially and the potential to replace water supply increases to 192%. The greatest impact on stormwater runoff is the extreme scenario of SC3, where climatic changes occur (-10% rainfall, +10% evapotranspiration) as well as extreme change in landuse (all cultivated and residential areas become impervious hard urban spaces) and stormwater potential increases to 240%. A less extreme scenario, SC4 (same climatic changes with cultivated land becoming residential and only current residential areas becoming hard surfaces), stormwater potential is 173% of supply.

The impacts of highly likely climatic changes of a reduction on rainfall by 10% and increase in evapotranspiration by 10% has very real consequences for the potential of stormwater to be a viable supply of non-potable water for the city. What the land use scenarios clearly indicate is the cumulative impacts of land use changes at the city scale and that even if reductions in available hydrological flows occur, careful management of landuse and land cover may still allow for effective capture and use of stormwater runoff in alignment with water sensitive principles. As Cape Town receives most of its rainfall during winter, storage is a key factor to consider in such projects. An estimated capacity of ~13 GL can be stored within the city-wide network of stormwater detention ponds (Okedi, 2019) and the potential to address the need for storage by using real-time control techniques is currently under investigation. Successfully making use of stormwater resources within the urban environment provides possibilities to restore wetland and vlei (shallow lake) ecosystems throughout the city to create blue and green spaces, in addition to mitigating against drought and flood in the form of storage. In order to fully explore the potential to store stormwater runoff in particular, the seasonal fluctuations in groundwater storage need to be included in this mass balance, as does better parameterisation of groundwater/surface water interaction in both wetland and river systems.

7. Findings on urban groundwater governance

This chapter presents the findings from undertaking the participatory Net-Map exercises and compiling various data sources to assess the networks that exist between actors that are groundwater governance nodes.

7.1. Actors and their functions

The Department of Water and Sanitation (DWS) – specifically the Western Cape and Eastern Cape DWS regional offices and associated Catchment Management Agencies (CMAs), i.e. the Breede-Gouritz-Olifants CMA and the Mzimvubu-Tsitsikamma CMA respectively – is an important yet remote actor when it comes to the current practices of managing groundwater use and protection in both the cities. While DWS holds the legal mandate to be the custodian of all water resources, their operational focus has traditionally been on groundwater use by commercial farmers for irrigation and mines, not on urban groundwater use. DWS coordinates the development and updating of Reconciliation Strategies for the Western Cape and Algoa Supply Systems, although much of the technical work is undertaken by consultants. The Reconciliation Strategies determine the current water balance and develop future scenarios to consider the sequencing of options to balance growing demand with variable supply. Representatives from the CCT and NMBM metros sit on the associated Strategy Steering Committees. In both cases, groundwater development has for some time been identified as a priority intervention for augmenting supplies. Resourcing the implementation of these measures have, however, been slow to materialise prior to times of water crisis. This highlights weak ties and powers of influence between DWS, municipal governments and National Treasury.

DWS reviews Water Use Licence applications and renewals, including those made by the CCT and NMBM municipal governments to abstract from boreholes and wellfields for bulk supply. However, many urban users are considered to fall under Schedule 1 usage rights, thereby not requiring a Water Use licence for their groundwater. This has in part been for the purposes of convenience and some within DWS are beginning to question the applicability of the Schedule 1 designation in urban contexts, where access to basic water services is provided by municipal supplies. Non Schedule 1 users, such as industry, commercial enterprises (like Coca Cola, Ardagh Glass Packaging, Aspen Pharmacare, Isuzu, Volkswagen SA) and public facilities (like government hospitals and sports grounds), have to be licensed and part of the licensing conditions are reporting their water levels, groundwater quality and usage volumes to DWS. However, the collecting and managing of this data remains weak. Intermediary organisations, such as GreenCape in Cape Town and the NMB Business Chamber, have played a key role during the water crisis in mediating between companies, municipal government and DWS, helping businesses navigate the technology choices and regulatory requirements around investing in groundwater as an alternative source.

DWS has been engaging with both the South African Local Government Association (SALGA) and the Department of Cooperative Governance and Traditional Affairs (COGTA) to encourage and support municipalities to put in place effective by-laws prescribing rules around accessing and using groundwater resources. While municipal governments have no legal authority to manage or regulate groundwater use, they do have a Constitutional responsibility to promote a safe and healthy environment, and as Water Services Authorities they have a responsibility to provide basic water supply services to communities in a sustainable manner and to regulate the use of alternative water sources for potable water supply (i.e. not if it is used for non-potable uses like irrigation). On this basis, municipalities can require property owners to declare alternative sources and their uses, which DWS is starting to promote.

The installation of boreholes and related infrastructure, and the associated discharge of water, in certain environmentally sensitive contexts (such as the wellfield around the Steenbras Dam outside Cape Town) trigger the requirement of an Environmental Impact Assessment. This brings the Department of Environmental Affairs and Development Planning in the respective Provincial Governments into play as groundwater actors, with particular relevance to protecting groundwater-dependent ecosystems.

The CCT and NMB metropolitan municipal governments are increasingly taking a role in groundwater use and groundwater protection, prompted by the experience of a water crisis. The City of Cape Town has recently added groundwater positions and expertise within their Bulk Water Branch of the Water and Sanitation Directorate, and recognised groundwater as a key component of the City's Resilience Strategy. As part of the New Water Programme, the City has installed a wellfield next to the Steenbras Dam to add groundwater from the Table Mountain Group Aquifer into the bulk supply system and is taking a phased approach to exploiting and artificially recharging groundwater from the Cape Flats aquifer. This in addition to the Atlantis Managed Aquifer Scheme that has been in operation since the 1970s. The Water and Sanitation Sub-Directorate in NMBM's Infrastructure and Engineering Directorate, as part of the Drought Mitigation Plan, is overseeing the installation of numerous groundwater projects, most notably at Coega Kop, Bushy Park, and around Churchill Dam. This in addition to the long history and continued use of groundwater from the Uitenhage Artesian Springs in the bulk supply system. In both cities, their water by-laws have been amended and updated. Both stipulate the need to register existing boreholes and notify the municipality of intent to drill a borehole or wellpoint. Also, signage indicating the use of borehole water is supposed to be clearly displayed on the property. However, the capacity to enforce these rules are very low in both metros, and public awareness of the rules remains low, despite increasing efforts at improved communication. The increasing number of domestic groundwater users in both cities are largely unregistered and reluctant to become visible to the authorities, partly out of a lack of trust in government and partly for fear of incurring additional costs. The metro police force exists to monitor and enforce compliance with bylaws. However, their capacity is extremely limited (even more so in NMBM than in Cape Town) and to-date has not been deployed in relation to infringements on water-related rules. In relation to the municipal governments' efforts to communicate water information and rules to residents, businesses and all water users, participants in both the NMB Learning Labs contested the role of traditional media outlets (newspapers and radio stations) and social media platforms in informing, sensitising and educating the public regarding water issues, including groundwater matters. While they do transmit information and messages put out by the city government, many felt the media companies also played a considerable role in spreading mis-information.

Consulting companies with geohydrology and engineering services play a key role in the urban groundwater space, holding much of the data, knowledge and expertise needed to do groundwater assessments, exploration, feasibility studies, designing and implementing groundwater schemes for both public and private clients, undertaking long-term monitoring, and demarcating groundwater protection zones. Umvoto, GEOSS, Zutari, SRK, Rodger Parson and Associates, Groundwater Africa, Kainos SA, Delta-H, Uhambiso Consult and alike all play an essential role in driving groundwater use and protection forward in Cape Town and NMB. Their operations are in turn underpinned by the universities in Cape Town and NMB that provide the research and training needed to equip groundwater professionals for their roles. The research commissioned and funded by the Water Research Commission, and the training opportunities these projects have provided, has played an integral part in expanding the knowledge of groundwater systems in and around Cape Town and NMB, and in developing urban groundwater management approaches.

The role and potential influence of drilling contractors and pump test contractors was highlighted as significant in that they enable prospective users to access the groundwater source. However, concerns over the lack of oversight and regulation of drilling and pump test contractors to ensure their clients are compliant was highlighted as a current weakness in the governance arrangements. Where previously there was a widespread practice of contractors logging their projects with the national database held by DWS, this is no longer the case. Stakeholders in both cities mentioned the increasing number of 'fly-by-night' contractors operating in the urban groundwater space, prompted by the water crisis. This surfaced the Borehole Water Association of Southern Africa as a potential important actor in promoting and providing the necessary training and skills for borehole contractors to collect and submit the appropriate data to the National Groundwater Archive (managed by DWS).

Groundwater has not traditionally been within the remit of most environmental, social development or disaster relief non-governmental organisations (NGOs) and civic organisations in Cape Town or NMB. The recent water crisis in both cities has, however, changed this picture slightly, as NGOs started moving into water advocacy, building public awareness around the urban water cycle, campaigning for behaviour change amongst consumers and policy change within municipal government, promoting various demand management and supply-side strategies, and working to cultivate relationships with water based on care and stewardship. WWF South Africa has been particularly active in Cape Town, working with faith-based organisations (notably the Green Anglicans) and schools to reach citizens with messages of groundwater stewardship, as well as partnering with DWS and CCT to build water partnerships and information sharing platforms. Local NGOs and civic organisations, such as the Philippi Horticultural Area (PHA) Campaign and EMG in Cape Town, working to protect aquifers from overexploitation and pollution, are operating without a formal mandate and with very few resources. Despite this, they are working within communities to build social awareness of and buy-in to the valuing and protection of groundwater, and holding the city government to account (sometimes through legal channels) for decisions over rezoning and development permissions that will impact negatively on the health of the aquifer. The PHA Campaign is actively lobbying for the establishment of a protection zone for the Cape Flats Aquifer.

There is less visible activity and engagement by non-governmental civic organisations active on groundwater issues in NMB, with the notable exception of the Gift of the Givers Foundation. In response to the worsening water crisis in NMB in 2022, the Gift of the Givers Foundation organised and paid to drill boreholes and install pumps, tanks, filtration systems and taps at schools in worst affected areas of Gqeberha. In the process of selecting sites, installing the infrastructure and handing the asset over to the communities, Gift of the Givers worked to establish community-based borehole committees, responsible for ensuring that the boreholes are functioning properly and are not vandalised. These committees present an interesting opportunity for follow up research on the local perceptions and practices within communities of boreholes as alternative water sources. Gift of the Givers has completed their work in Gqeberha and moved their attention elsewhere. In terms of promoting public awareness and education around groundwater use and protection in NMB over the longer-term, the Wildlife and Environment Society of South Africa (WESSA) Algoa Branch was mentioned as a potential actor. But they are not active on this front currently. Building links between local organisations in NMB and those in Cape Town, might foster such capacity.

Security companies were also revealed as important actors in the groundwater space, albeit not with a particular interest or influence over groundwater use or aquifer protection, but rather with a role in protecting groundwater-related infrastructure. Learning Lab participants in both Cape Town and NMB noted the increasing challenge many companies and public facilities are facing is the theft of

infrastructure and instrumentation, especially anything manufactured from steel. This is causing widespread losses, heavy costs associated with replacement and increasing security measures, and disruptions in functioning and data collection.

In the case of NBM, sand mining companies also emerged as actors having a negative impact on groundwater by stripping cover from underlying fractured rock. The sand acts as a buffer, enhancing infiltration, and the removal thereof thereby compromises the health of the aquifer. Sand mining is largely unregulated and is expanding around Gqeberha.

In Cape Town, three forums or aggregate actors exist in the groundwater space and play an important bridging role. The Table Mountain Group Aquifer Monitoring Committee and Cape Flats Aquifer Monitoring Committee, convened (but not chaired) by the City of Cape Town on a quarterly basis, both have extensive multi-stakeholder representation, although limited end user participation. The newly established Table Mountain Strategic Water Source Partnership, coordinated by WWF and chaired by DWS. All three are still in the relatively early stages of establishment and operation, so their impact on the governance network in terms of the strength of ties and the capacities to implement key functions largely remains to be seen. There is no equivalent in the case of NMB, highlighting an important gap and the potential for learning. The experiences of community-based borehole committees, where they have been established in NMB around boreholes installed by Gift of the Givers, could in turn provide useful insight for the Cape Town case in how to link aquifer scale collaborative management with localised borehole scale collaborative management.

An overview of the key actors – state and non-state, public, private, and civic – who execute authority (political, economic, technical or administrative) to shape the course of decisions and actions taken to allocate, utilise and protect groundwater in the cases of Cape Town and Nelson Mandela Bay are shown in the table 16.

Table 16. Overview of key actors involved in governing groundwater in Cape Town and Nelson Mandela Bay.

Categories of actors	Cape Town	Nelson Mandela Bay
State actors responsible for setting, implementing and enforcing binding rules	National Department of Water & Sanitation (DWS) Western Cape Office ● Water Resource Planning ● Institutional Establishment ● Water Resources Support Geohydrology National Department of Forestry, Fisheries and Environment (DFFE) Western Cape Government ● Department of Environmental Affairs & Development Planning ● Department of Public Works City of Cape Town	National Department of Water & Sanitation (DWS) Eastern Cape Office ● Water Information Management: Groundwater ● Water Use Technical Services: Groundwater National Department of Forestry, Fisheries and Environment (DFFE) Eastern Cape Government ● Department of Economic Development, Environmental Affairs and Tourism Algoa Supply System Steering Committee Nelson Mandela Bay Municipality

	• Department of Water and Sanitation • Urban Planning and Design Department • Resilience Department Overberg Water SAN Parks	• Infrastructure & Engineering Directorate • Joint Operations Centre / DRM
Interest groups, civic and non-governmental organisations that represent different public and private interests and work to influence policy making	CFA Monitoring Committee TMG Monitoring Committee WWF-SA Green Anglicans Umvoto Foundation ICLEI PHA Campaign Environmental Monitoring Group (EMG) Coca Cola AB-Inbev Ardagh Glass Packaging (previously Consol) Distell Growthpoint Old Mutual Mediclinic hospitals Provincial Govt hospitals / WC Dept of Health Drilling contractors (e.g. Boreholes for Africa, Top Boreholes, Countrywide Drilling, Steyn Drilling, etc.) Pump test contractors Working for Water Working for Fire	Coega Development Corporation NMB Business Chamber Drilling contractors Pump test contractors Coca Cola Aspen Pharmacare VW Isuzu Netcare hospitals Gift of the Givers [WESSA] Sand mining companies
Actors representing science and research, including academia and consultants, that provide data and analysis of the groundwater system(s)	Umvoto Zutari Geoss Delta-H Roger Parsons & Associates SRK Consulting University of the Western Cape University of Cape Town Stellenbosch University	Kainos SA Groundwater Africa SRK Zutari Uhambiso Consult Nelson Mandela University
Intermediaries	GreenCape Western Cape Economic Development Partnership WRI	NMB Business Chamber WRI South African Cities Network
Funders	WRC GIZ DANIDA Greater Cape Town Water Fund	WRC National Treasury Cities Support Programme (CSP) Gift of the Givers

Groundwater forums / aggregate actors	Table Mountain Group Aquifer Monitoring Committee Cape Flats Aquifer Monitoring Committee Table Mountain Strategic Water Source Partnership	Community-based borehole committees (linked to Gift of the Givers funded boreholes)

The difference in size of the two cities is reflected in the number of consultancies, universities, intermediary organisations and interest groups operating in Cape Town, with a much lower number operating in NMB.

7.2. Capacities and ties

The capacities held and mobilised by each actor to shape the decisions taken to allocate, utilise and protect groundwater resources emerge both from the formal mandates the actor holds and the resources at their disposal to exercise their mandate and take action toward achieving their intended outcomes. While resource constraints were often mentioned, problems of conflicting mandates and goals, for example between water, housing, environmental management, economic development and agriculture departments operating in municipal and provincial governments, surfaced as a strong theme throughout the Learning Lab deliberations.

Those with formal groundwater-specific mandates are DWS for groundwater reserve determination, licencing, monitoring and enforcement of licencing requirements, DFFE and provincial government for environmental authorisations, and metropolitan municipalities for registering boreholes, designating aquifer protection zones in spatial plans and zoning schemes, and enforcing by-laws. In addition to the role of regulating private groundwater users, the metropolitan municipalities are themselves bulk groundwater abstractors (requiring them to get the necessary licences and authorisations from national and provincial governments) and operators of managed aquifer recharge schemes (in the case of Cape Town). It is through the water use licences for bulk abstraction that local monitoring requirements are established, including setting up aquifer monitoring committees. The recently established Table Mountain Water Source Partnership looks to be an innovation in this space that may strengthen capacities of member organisations through forming alliances and coalitions, sharing data and information, and legitimating rules and regulations.

Consulting hydrogeologists and drilling contractors play a key role in the siting, design and installation of boreholes and wellfields. While the conduct of hydrogeologists is governed by professional bodies, such as the International Association of Hydrogeologists and the Groundwater Division of the Geological Society of South Africa, there is very little oversight and regulation of drilling contractors to ensure ethical conduct in line with the sustainable use of groundwater resources. DWS has recognised the need for and their role in regulating borehole drilling activities, however, not much progress has been made on this front as yet.

While efforts were made to collect more quantitative data on various dimensions of capacity held by each actor, as described in section 5.3 and summarised in table 7, the coverage and quality of this data proved insufficient to arrive at any robust and meaningful findings. Gathering data on the existence and strength of ties between actors that shape the decisions taken to allocate, utilise and protect groundwater resources has similarly proven challenging. This is because there are so many organisational actors involved in the urban groundwater space in these two cities, as laid out in the preceding section, not all of whom were represented in the Learning Labs and interviews. And also because the strength of the ties seems to be variable over time and between aquifers, partly due to

what projects are active. Table 17 below aggregates data gathered on actor ties from the three groups working on different aquifers in the case of Cape Town during Learning Lab 2. While participants worked to assess the ties between individual organisations, it became apparent that clustering them would be necessary and beneficial. Ties were assigned as being 0 if there was deemed to be no direct interaction, 1 if there was minimal or occasional interaction, less frequently than 6 months, 2 for semi-regular interaction with an average frequency of between 1 and 6 months, and 3 for frequent interaction, more than once a month on average. The findings suggest that generally ties are weak and the groundwater governance network is fairly fragmented, with geohydrology and engineering consultants, like Umvoto and Zutari, positioned as key bridging nodes, as the actors that hold relations and more frequent engagements with many other actors.

Table 17. Strength of ties based on frequency of interactions between types of actors.

Actors	DWS-WC	WC Gov	CCT	Consultants & contractors	Commercial g/w users	Domestic g/w users	NGOs
DWS-WC		1	2	2	1	0	0
WC Gov	1		2	2	0	0	0
CCT	2	2		3	1	1	2
Consultants	2	2	3		3	1	1
Commercial g/w users	1	0	1	3		0	2
Domestic g/w users	0	0	1	1	0		1
NGOs	0	0	2	1	2	1	

8. Discussion

This chapter discusses the findings presented above in relation to the use of these analyses in improving a shared understanding of groundwater as part of the larger urban water cycle, and strengthening participation in adaptively managing drought risks. Particular focus is placed on the usability of water metabolism-related information in city-scale and sub-city scale decision-making, and the value of the Learning Lab methodology for co-developing research in a way that makes it more readily applicable to operational contexts of decision-making.

8.1. The role of the Urban Water Metabolism Framework in groundwater governance

Urban Water Metabolism is an emerging field that still sits very much in academic literature, and its relevance to the governance of groundwater resources for growing cities facing increasing drought risk has not been explored. This research aimed to identify the key challenges and opportunities associated with groundwater governance in a South African setting by adopting the UWM, systems-oriented lens and framework to bring multiple diverse actors and the knowledge they hold together. Effective governance of groundwater requires the co-operation and coordination of multiple actors operating at various scales, with the ultimate aim of decision-making processes being transparent, participatory and inclusive, as well as adaptive to social, ecological and technological conditions (Kenway et al., 2022). We adopted the UWMF as an approach to share and integrate knowledge relating to the urban water system, including actors ranging from those who are involved in groundwater from the regulatory perspectives, through those who are domain experts and professionals operating in the field, to those who are beneficiaries of the resource. Through this work we identified numerous types of groundwater-related decisions faced in cities that would benefit from more transparent, inclusive and adaptive forms of evidence-based planning and decision making. These include decisions relating to:

- groundwater exploration and feasibility studies, assessing groundwater availability, exploitation potential, and associated costs (in relation to surface water supply options);
- where to cite boreholes and wellfields;
- borehole specifications (e.g. depth, diameter, type of casing);
- registering boreholes;
- groundwater uses and treatment requirements;
- granting or not Water Use Licences and what conditions to place on the licence;
- the design of monitoring programmes (e.g. sites, sampling frequency, variables tested);
- investing in developing, maintaining and integrating numerical groundwater models;
- instituting and repealing water use restrictions (at various levels of restriction);
- resting or decommissioning a borehole or wellpoint;
- environmental authorisations and conditions based on the expected or potential environmental impacts (including groundwater pollution and impacts on groundwater-dependent ecosystems);
- demarcate and establish aquifer / groundwater protection zone (to be reflected in Spatial Development Framework and trigger associated development and land use controls);
- selecting sanitation technologies and investing in sewerage infrastructure (to be reflected in the Integrated Development Plan and municipal budget);
- artificially enhancing the recharge of an aquifer;
- setting up multi-stakeholder aquifer monitoring committees and groundwater users forums;
- the use or discharge of groundwater from dewatering basements;
- and the collection and management of groundwater data and information (including on groundwater-dependent green infrastructure and ecosystems).

Kenway et al. (2022) argue that applying an urban water metabolism approach to water management is a helpful way to enhance institutional collaboration, and to facilitate and enhance cross-sectoral integration. According to the principles of water sensitive cities, the aspirational vision for whole-cycle urban water management, the sectors involved in governing and managing groundwater extend well beyond the traditional roles of water supply, to encompass the integration of entities responsible for urban planning, waste-water management, stormwater, parks and recreation, as well as public health. The challenges associated with integrating this multidimensional, cross-sectoral group of actors were apparent in the Learning Labs and mostly related to the wide and diverse understandings of, and roles associated with, groundwater as a distributed resource. These ranged from in-depth knowledge of the hydrogeology of a particular aquifer, to the groundwater-related policy environment, to using groundwater for farming practices, to activists for aquifer protection, to city-wide responses to drought and the implementation of new water interventions. We posit that the UWMF may be of value to the processes by which all such diverse actors are included into participatory decision-making by way of several key points:

- bridging knowledge sources (effective governance requires vertical knowledge integration – from aquifer dynamics through to policy);
- identifying where knowledge gaps are (knowledge gaps that help build the whole-of-system conceptual model, as well as knowledge gaps within the various sectors) ;
- identifying knowledge needs across the various sectors to promote a coherent, consistent governance approach for the appropriate groundwater unit;
- when used in a Learning Lab setting, UWMF can promote cohesion between actors across the various sectors through simply being in the same room.

We argue that while the data and methods used to build the urban water mass balance (from supply and sanitation, to rainfall and recharge) can always be improved upon, absolute accuracy of the mass balance is less important than the conceptual model it provides to understand the system and the general magnitudes of the stocks and flows involved. Information produced from applying an urban water metabolism framework can support integrated management efforts at the aquifer, catchment and city regional scales, as presented in table 18. Feedback from the Learning Lab participants indicated that such a framework was most useful in a more large-scale strategy, a point that was also highlighted by King, Kenway and Renouf (2019).

Table 18: An initial, high-level evaluation of the types of groundwater-related decisions that working with the UWMF can help inform. Red indicates limited value, yellow indicates modest value, and green indicates considerable value to support decision-making.

	Exploration and exploitation	Maintenance and Monitoring	Regulation and protection	Integration
Borehole/ wellfield	Where to cite boreholes and wellfields, borehole specifications (e.g. depth, diameter, type of casing); resting or decommissioning a borehole; Groundwater uses and treatment requirements	Collection and management of groundwater data and information; Design of monitoring programmes; Groundwater modelling	Register borehole, WULA	MAR; ASR
Aquifer	Feasibility studies, Groundwater modelling; Groundwater uses and treatment requirements	Collection and management of groundwater data and information; Design of monitoring programmes; Groundwater modelling; multi-stakeholder aquifer monitoring committees and groundwater users forums	Demarcate and establish aquifer / groundwater protection zone; multi-stakeholder aquifer monitoring committees and groundwater users forums; Water use restrictions;	Multi-stakeholder aquifer monitoring committees and groundwater users forums
Catchment			Environmental authorisations; multi-stakeholder aquifer monitoring committees and groundwater users forums	Demarcate and establish aquifer / groundwater protection zone
City-region		Multi-stakeholder aquifer monitoring committees and groundwater users forums	Water use restrictions;	Water sensitive city-regions

What the UWM approach provides more than other, often siloed, approaches to water management is a framework to explore the relationships between the various flows, such as the potential interaction between wastewater effluent and aquifer recharge, as an example. However, the interaction of these physical flows of water in an urban setting are most often the result of the social interactions that govern them. The Learning Labs touched on this in the scenario analysis discussions, by using the metaphor of dials on the various flows on the Sankey diagram: which dials affect which flows, in which direction (more or less flow) and who is involved in turning or shifting the dials (as shown in Figure 14).

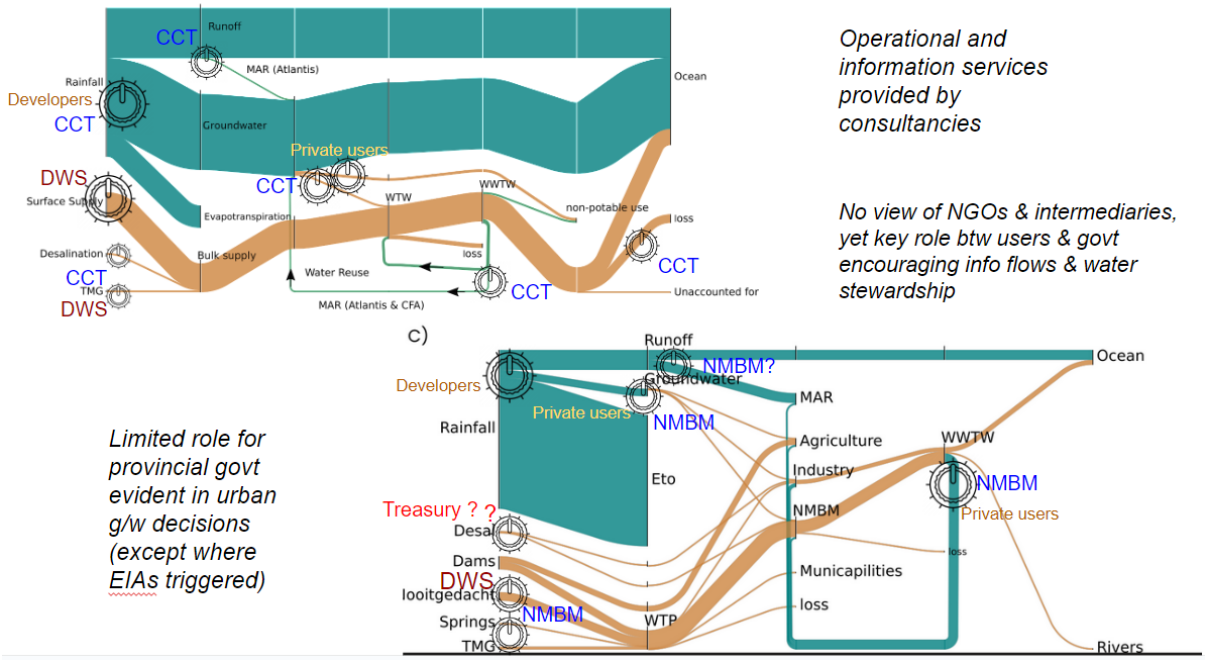

Figure 14: Graphic exploring metaphor of dials that change volume of flows as depicted in the sankey diagrams for each city.

It is clear that many actors have a stake in shaping the trajectory of groundwater quantities and qualities in cities. Traditional forms of governing by command and control are proving ineffective in sustainably utilising and protecting groundwater resources in densely populated and growing metropolitan municipalities. Therefore, more consultative and cooperative forms of governance are required. Currently, neither DWS nor the CCT and NMBM municipal governments have the necessary capacity or the cooperative governance mechanisms in place to implement what is laid out in the National Groundwater Strategy (DWS, 2016) and the Urban Groundwater Development and Management framework and tactical plan (Seyler et al., 2019) in either of these two cities.

South Africa hosts considerable hydrogeology and engineering expertise. Much of this expertise sits in consulting companies. While this is an asset, the problem is that this expertise is deployed in a project-based manner, resulting in piecemeal groundwater management. Consultants in both cities noted that the situation has worsened in recent years as public procurement processes have become more cumbersome and protracted, leading to discontinuities in programmes of work, as well as a 'gatekeeper' mentality that undermines data and knowledge sharing.

Limited data coverage and accessibility remain a critical hindrance to evidence-based decision-making around groundwater allocations and aquifer health. The work of WWF, GEOSS and partners

through the Table Mountain Strategic Water Source Area Partnership is leading the way – through citizen science and public education – in building the basis for collaborative groundwater management. Various phases of an urban hydrocensus are needed to build up an accurate picture of groundwater infrastructure, usage and quality across the cities. This ultimately needs to be coordinated by the municipal government and fed into the DWS database, with support from universities, NGOs, consultants and drilling contractors. This will require considerable investment in public communication, awareness raising and trust building. The lack of trust between citizens and government emerged as a recurrent theme throughout many of the engagements, particularly in relation to the reticence of urban groundwater users to register their boreholes or wellpoints, or report any usage data. The lack of trust is compounded by poor levels of understanding amongst many urban groundwater users as to the nature and functioning of the aquifer they are drawing from. Is there a way of building a cadre of urban water stewards in each of these cities to build relationships, provide learning opportunities and promote a collective care approach to dealing with groundwater? Drawing on experiences from elsewhere in the world, this might include the promotion of cultural practices that involve paying respect to water bodies and water sources, including springs, for example through the local co-creation of public art that is placed at strategic water sites. In the case of Nelson Mandela Bay, this could begin with the community-based borehole committees established around the boreholes installed by Gift of the Givers.

8.2. Learning Lab methodology

There were several aims for using Learning Labs as an approach for conducting this research:

- Bring together diverse stakeholders working or involved in groundwater in Cape Town or Gqeberha;
- Explore institutional and relational arrangements of groundwater governance through discussions/exercises that focus on drawing out knowledge held by the group of participants present;
- To introduce the Urban Water Metabolism Framework to a diverse group of participants, to cross check the teams conceptual understanding of the urban water cycle and to validate the data used to construct the mass balance;
- To explore the uptake and value of UWMF across diverse GW related sectors;
- Reflect on its value in improving groundwater governance in a South African context.

The Learning Labs were designed and facilitated in a way that various actors with an interest and stake in the cities' groundwater could connect, get to know each other better, share their knowledge of the system and how it works, share information about groundwater-related activities they are engaged in, and take a step back to think about the physical and social flows of the urban water system and how these could change.

To our knowledge, Learning Labs have not been used as a tool to build a shared understanding of the urban water cycle, nor as an approach in assessing the applicability/operationalisation of the framework in practice across the various sectors that have a role in groundwater governance and management. The urban water metabolism approach is still a new and emerging field, with many studies/projects adopting it (either implicitly or explicitly) often using different language or visuals to communicate it. The only study we found that assessed its uptake in various contexts (Australia, Europe and US) concluded that there is a need to find a common language in the field, and that 2-way communication within and outside of expert groups is crucial (King, Kenway and Renouf, 2019), which the Learning Lab methodology is well suited to. Their study indicated that the UWMF

was of more use to actors with more interest in the higher-level strategic picture of urban water management, which aligns to our own reflections on the UWMF in action.

In short, our use of Learning Labs as a tool in building the conceptual and analytical understanding of the urban water cycle has resulted in the following reflections:

- Most participants engaged with the framework and saw its value as a tool to engage with and discuss important urban water management issues;
- UWMF provides perspectives and context but is not always at the appropriate scale at which individual actors operate;
- Feedback from the Learning Labs regarding various flows and their magnitudes improved the accuracy of the water balance, the visual presentation via the sankey diagram was helpful in this regard;
- It was considered valuable as a heuristic tool in discussing and engaging with the urban water systems, and for larger, more strategic scenario planning.
- Not all stakeholders or actors working in the groundwater space see the value of such an analysis to their daily operational roles. The only real critique of the framework was that it was too academic for their purposes and did not include social aspects enough.

There was value in supplementing information shared during Learning Labs with data collected through in-depth interviews with those operating in key organisations. Especially those not represented by participants in the Learning Labs. In terms of designing the Learning Labs, one of the challenges participants noted in undertaking the exercise characterising the functions that various actors fulfil in the groundwater space, was differentiating between the functions that an actor should be doing and what they are effectively doing. The scoring of organisational capacities proved even more difficult as information about groundwater-specific budgets was not widely known and inaccessible. When rating the capacity of organisations to partner with others, participants wondered if it should reflect only existing partnering in real terms (i.e. actors are actively doing things with others), or whether the score should reflect that capacity exists but is not being exercised. These are all important insights to be used in designing future applications of such methods.

9. Conclusion

Drought and water scarcity will be an ongoing challenge for many growing cities in South Africa. The conjunctive use of groundwater as an alternative to surface supply is a viable proactive drought mitigation and urban resilience strategy, if abstractions and pollution risks are well managed. This requires new forms of and mechanisms for cooperative governance, not only between spheres of government, but involving business, industry and residents too. Intermediaries play a critical role in enabling this. Currently consultants (whether independent, in companies, or at research institutions) are partially playing a bridging function, but their ability to play the role effectively is hampered by commercial interests and the demands of their clients. NGOs are starting to move into the groundwater space in cities, but their role is still niche. Intermediary and networking organisations such as the Western Cape Economic Development Partnership, Green Cape and the NBM Business Chamber, need to be encouraged and supported to interface on groundwater issues and act as brokers between government entities, businesses and residents.

Analysing the metabolic flows of water through each of the cities provided an integrative framework through which to consider the conjunctive and increasingly circular uses of diverse water sources. The scenarios of potential changes in urban water metabolism highlighted various ways of enhancing the hydrological performance of the cities, notably through enhancing infiltration of run-off through increasing stormwater retention and surface permeability and thereby enhancing aquifer recharge, and through increasing reuse of treated wastewater for both non-potable and potable uses and for managed aquifer recharge. When using the metaphor of who has their hands on these dials (for increasing and decreasing various flows) it becomes apparent that municipal government (notably including spatial planners), large water users, private landowners and property developers are all central to making these shifts, with encouragement and oversight provided by DWS.

We argue that planning for resilience against drought should not be limited to water supply alone. Groundwater has much to offer cities by providing much needed evaporative free storage in aquifers and supporting the health of green spaces for urban cooling and recreational spaces for improved liveability and well-being. One of the questions emerging from this work, for which further research is recommended, is how to structure and convene groundwater user associations in urban contexts to facilitate localised data sharing and self-regulation of usage in line with changing conditions. The early experiences from Cape Town's two aquifer monitoring committees, as well as the community-based borehole committees in NMB may shed useful light on this. While the focus of this research is on organisational actor networks, future research could focus on individual actors, the ties they hold, their position in the network, and the consequences of those individuals being lost from the network or moving organisations and positions. The network approach also makes it possible to integrate other types of nodes and relationships, such as ecological actors, which enables a more integrated systems analysis to tackle sustainability and equity challenges.

The urban water mass balance analysis focuses on water quantity and is considered to be of value to groundwater governance by providing a tool, or framework, with which to integrate multiple diverse actors' understanding of the urban water cycle and consider the consequences of various changes in the system, both internal and external to the city. Through the use of Learning Labs, the systems-oriented lens of urban metabolism has the capacity to bridge across diverse groups of actors through knowledge sharing and exchange, both important requisites for participatory and inclusive decision-making, and cooperative governance. The UWM framework was viewed to be of most value at the

city-wide strategy and planning level of decision-making, where the absolute values of the stocks and flows of the mass balance were much less important than the overall conceptual model of the system, the relative magnitude of stocks and flows, and the engagement around the framework as a whole. Integrating the urban water metabolism analyses with the governance analyses makes it possible to better understand the system not just from a physical, material flows perspective, but also from the perspective of social flows in terms of which actors have greatest influence over the decision affecting water flows, and how this influence is exercised.

An important missing element in this research is the water quality of stocks and flows, which can undermine a system's capacity to operate effectively. The UWM needs to eventually be complemented with water quality considerations. Seepage from septic tanks, sewage infrastructure, solid waste and wastewater treatment facilities, as well as industrial effluents, pose a serious risk of contaminating groundwater. Quantifying, or at least estimating, these flows within and out of a city is an essential aspect to include in future metabolism analyses. The aspirational element of this would be to assess the nutrient recovery potential of particular flows, for example the recovery of wastewater for managed aquifer recharge or other fit-for-purposes uses such as irrigating sports fields/agriculture. Conducting city-wide Excreta-Flow diagrams (e.g. Peal et al., 2020) would also illuminate the fate of faecal flows and would be helpful in identifying the potential for resource recovery from a major flow of nutrient-rich water. Another means of bringing in water quality, with a whole-of-system lens, would be to conduct nitrogen and phosphorus budgets for the urban system, integrating both the natural processes that occur in the landscape (e.g. denitrification) with the anthropogenic inputs. Atkins et al. (2022) quantify the nitrogen budget of an urban watershed in Cape Town indicating that wastewater is by far the largest flow of nitrogen-rich water. The authors also found that wetlands play a crucial role in removing nitrogen from the landscape, providing an important ecosystem service to the City. Applying this to the city scale would complement the UWMF for water quantities, and highlight the importance of viewing waste-water as an important resource for the City.

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Appendix 1

List of participants involved in the Learning Labs

Cape Town Learning Labs	
Name	**Organisation**
Lauren Arendse	ICLEI Africa
Miriam Arinaitwe	UCT Future Water
Ffion Atkins	UCT ACDI
Dale Barrow	GEOSS
Dylan Blake	Umvoto
Kirsty Carden	UCT Future Water
Naledi Chere	UCT Future Water
Susanna Coleman	PHA Campaign
Julia Denny	University of California, Santa Barbara
Hallie Eakin	Arizona State University
Anya Eilers	Zutari
Tamsin Faragher	City of Cape Town
Tyrel Flugel	Umvoto
Nick Hamer	EMG
Naadiya Hoosen	UCT
Chris Jack	UCT CSAG
Candice Lasher Scheepers	City of Cape Town
Notiswa Libala	WC EDP
William Lilly	A.G.P.
Christo John Louw	DWS WC Office
Apiwe Mdunyelwa	EMG
Marlese Nel	WWF
Dean Palmer	Natural Justice
Kevin Pietersen	UWC

Klaudia Schachtschneider	WWF
Leanne Seeliger	Stellenbosch University
Helen Seyler	Delta-H / ERM
Jamy Silver	Bibliotec Design
Nazeer Sonday	PHA Campaign
Tasneem Steenkamp	One World
Anna Taylor	UCT ACDI
Caron von Zeil	Reclaim Camissa
Valli Yantolo	DWS WC Office

Nelson Mandela Bay Learning Labs	
Name	**Organisation**
Dan Abraham	Zutari
Ffion Atkins	UCT
Amanda Gcanga	WRI
Andre Hefer	NMU
Matthew Hills	NMBM
Naadiya Hoosen	UCT
Chris Jack	UCT CSAG
Vuyiseka Jack	DWS EC Office
Fhatuwani Aron Magonono	DWS EC Office
Amanda Magugwana	NMBM
Prince Matonsi	NMB Business Chamber
Sivuyisiwe Mbange	DWS EC Office
Lufuno Munzhelele	DWS EC Office
Tristin O'Connell	NMU
David Raymer	Umhabiso Consult
Anna Taylor	UCT

Graham Taylor	Coega Development Corp
Vhuthu Tshishonge	DWS EC Office
Leizel Williams-Bruinders	NMU
SanMari Woithe	Independent Geohydrologist