

**Tracking inclusive sustainable development at multiple
scales: South Africa's safe and just operating spaces**



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Abstract

Nations in the 21st century face a complex mix of environmental and social challenges. Population growth and natural resource use have led to ecosystem degradation and climate change and are pushing the planet towards and beyond its safe planetary boundaries. The global scale, speed of change and increasing complexity require international and regional cooperation. At the same time, human development has been uneven, with billions of people currently facing multiple forms of poverty and deprivation, and inequality within countries is increasing. These challenges are captured in the United Nations 'Agenda 2030 for Sustainable Development' and its 17 Sustainable Development Goals (SDGs), which represent the first globally agreed framework to address human development and environmental stewardship in an integrated way.

The 'planetary boundaries' concept and its extension through the addition of social well-being indicators to create a framework for 'safe and just' inclusive sustainable development, have received considerable attention in science and policy circles. As the chief aim of this framework is to influence public policy, and this happens largely at the national level, this thesis assesses whether it can be applied at the national scale, using South Africa as a test case. A decision-based methodology for downscaling the framework is developed and a national 'barometer' for South Africa is created, combining 20 indicators and boundaries for environmental stress and social deprivation. This barometer maintains the original design and concept of the framework whilst making it meaningful in the national context, raising new questions, exposing data gaps and identifying priority areas for national action. This

is the first case study for downscaling the planetary boundaries to the national level in a developing country, and the first national case study for the 'safe and just space' framework. The results show that South Africa has exceeded its safe environmental boundaries for biodiversity loss, marine harvesting, freshwater use and climate change, and that social deprivation is most severe in the areas of safety, income and employment. Trends since 1990 show improvement in nearly all social indicators, but progression towards or over boundaries for most environmental indicators.

As national indicators can hide significant heterogeneity, the thesis downscales the barometer further to define the 'safe and just space' for South Africa's nine provinces. The results show significant variation in environmental stress and social deprivation related to climate, population density, economic activities and historical disadvantage brought about by Apartheid. The provincial barometers and trend plots are novel in that they present comparable environmental and social data on key indicators over time for all South Africa's provinces, communicating key challenges and risks and supporting the prioritisation of actions to promote sustainable development.

Reducing inequality is a major focus of the SDGs and is reflected in the requirement to disaggregate national data by multiple aspects such as gender, race and geographical location. In this thesis, national piped water access, water use and water stress are mapped and reported at national, provincial, district, municipal, town and ward scales, and urban and rural areas in South Africa. The ward and town data are used to calculate national and provincial Gini indexes and Palma ratios for piped water access and per capita water use. The results show that although 45% of the population has water access in their dwelling this ranges from

0.07% to 100% at ward level, with a high level of inequality (Gini index of 0.36). National per capita water use (including losses) is 208 litres per person per day (l/c/d) but ranges from 8 l/c/d to 2,414 l/c/d at town level, with a Gini index of 0.27. The analysis shows that social factors such as water access and income, and not natural factors such as rainfall or runoff, have the greatest influence on per capita water use. The study provides the first in-depth analysis of per capita water use at the local level in South Africa, and suggests new water indicators that could be used in tracking progress towards the SDGs.

For progress towards the SDGs to be monitored, countries must develop their own set of national indicators for all 17 goals and 169 targets. Water is a fundamental enabler of development and SDG 6, 'Water and sanitation for all', is therefore an important goal to measure and achieve. Appropriate indicators can support decision-making and highlight key issues on inequality, unemployment and sustainability. In this thesis, a comprehensive suite of 26 indicators for SDG 6 is proposed for South Africa based on existing national indicators, and additional research on water inequality and water-dependent jobs and income. The Berg Water Management Area in the south-west corner of South Africa is used as a case study to illustrate the results. Figures for jobs and income per cubic metre of water use are calculated for agriculture, agriprocessing, aquaculture and mining, the most comprehensive figures to date for the area. Gaps in the data are identified and methodologies and standards that require development are highlighted. The approaches to measuring inequality and socio-economic benefits of water use are relevant for other countries seeking to measure the role water plays in achieving inclusive sustainable development.

Overall, this thesis provides a set of novel tools and datasets to track progress towards inclusive sustainable development at multiple scales in South Africa and around the world, contributing to the global goal to live within the safe and just operating space for humanity.

Acknowledgements

I embarked on this journey in 2012 with a conversation in Oxford about a doughnut. I had read Kate Raworth's Oxfam discussion paper on the 'safe and just space for humanity' and thought 'this captures the challenges of our generation in such a simple and compelling way'. I had spent the past 10 years working in South Africa, Oxford and Rwanda, expanding my interests from geology and geotechnical engineering in mining, to mine-to-mill and systems thinking, to climate change, water and energy research, and ultimately to how companies and countries contribute to sustainable development that benefits people's lives. I had always worked across departments and disciplines, and across hierarchies, collaborating with directors and senior managers through to technical and support staff. I found I could not work on one discipline without considering its connections to others. In this first D.Phil. meeting with my soon-to-be supervisor Mark New, he understood that and suggested creating a South African doughnut. A conversation with Kate Raworth followed, where she enthusiastically gave her support for what would be the first national doughnut – an advocacy tool for environmental protection and poverty alleviation. A third conversation with Sir David King, director at the Smith School of Enterprise and Environment at the time, led to the financial support I needed and a fourth conversation with Richard Bailey gave me a second supervisor who would guide and encourage me on my journey into academia. I am so grateful to these four people for being so supportive of this decision – it has been a wonderful learning experience.

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Acronyms and Abbreviations

BASIC	Brazil, South Africa, India, China
BAU	business as usual
BII	Biodiversity Intactness Index
BRICS	Brazil, Russia, India, China, South Africa
CBDR/RC	common but differentiated responsibilities and respective capabilities
CCT	City of Cape Town
CH ₄	methane
CMA	Catchment Management Agency
CO ₂	carbon dioxide
CR	critically endangered
CRR	Critical Risk Rating
CSIR	Council for Scientific and Industrial Research
CV	coefficient of variation
DAFF	Department of Agriculture, Forestry and Fisheries
DEA	Department of Environmental Affairs
DEA&DP	Department of Environmental Affairs and Development Planning
DEAT	Department of Environmental Affairs and Tourism
DM	district municipality
DPME	Department for Performance Monitoring and Evaluation
DPSIR	Driving forces-Pressures-States-Impact-Response
DSD	Department of Social Development
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
EN	endangered
EPI	Environmental Performance Index
ESI	Environmental Sustainability Indicators
FSSA	Fertiliser Society of South Africa
GDP	gross domestic product
GER	Gross Enrolment Rate
GHG	greenhouse gas

GHS	General Household Survey
GIS	Geographical Information Systems
GPI	Gender Parity Index
GWh	gigawatt hours
ha	hectares
HCFCs	hydro-chloro-fluoro-carbons
HDI	Human Development Index
HIV/AIDS	Human immunodeficiency virus / acquired immune deficiency syndrome
HSRC	Human Sciences Research Council
IDP	Integrated Development Plans
ILO	International Labour Organisation
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
kg	kilogram
l/c/d	litres per capita per day
LM	local municipality
LT	least threatened
LTMS	Long Term Mitigation Strategy
LUCF	Land use change and forestry
m	metre
m ³	cubic metre
m ³ /a	cubic metres per year
MAE	mean annual evaporation
MAP	mean annual precipitation
MAR	mean annual runoff
MCA	multi-criteria analysis
MDGs	Millennium Development Goals
mg/l	milligrams per litre
Mm ³ /a	million cubic metres per year
Mm ³ yr ⁻¹	million cubic metres per year
Mt	million tonnes
N	nitrogen

N ₂ O	nitrous oxide
NAQI	National Air Quality Indicator
NBA	National Biodiversity Assessment
NDP	National Development Plan
NEMP	National Eutrophication Monitoring Programme
NGO	non-governmental organisation
NUE	Nitrogen Use Efficiency
NPP	Net Primary Productivity
NWRS	National Water Resource Strategy
O ₃	ozone
OECD	Organisation for Economic Cooperation and Development
ODPt	ozone depleting tonnes
OWG	Open Working Group
P	phosphorus
PB	planetary boundaries
PM10	particulate matter of 10 microns
ppm	parts per million
pppm	per person per month
QLFS	Quarterly Labour Force Surveys
R	Rands
RDP	Reconstruction and Development Programme
SA	South Africa
SADC	Southern Africa Development Community
SAIMD	South African Index of Multiple Deprivation
SANBI	South African National Biodiversity Institute
SASAS	South African Social Attitudes Survey
SDGs	Sustainable Development Goals
SD	standard deviation
SDI	sustainable development indicator
SDSN	Sustainable Development Solutions Network
SES	social-ecological systems
SI	Supplementary Information
SJS	safe and just space
SOE	State of Environment

StatsSA	Statistics South Africa
TB	tuberculosis
TFCA	Transfrontier Conservation Area
TE	tipping element
UN	United Nations
UNCBD	United Nations Convention on Biological Diversity
UNCED	United Nations Conference on Environment and Development
UNCSD	United Nations Commission on Sustainable Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNSD	United Nations Statistical Division
US\$	United States dollars
VU	vulnerable
WARMS	Water Authorisation and Registration Management System
WCWSS	Western Cape Water Supply System
WHO	World Health Organisation
WMA	Water Management Area
WSS	Water Supply System
µg/l	micrograms per litre

Chapter 1 – Introduction

1.1 Context

The pathways to development in the past two centuries were built on abundant fossil fuels, mineral resources, arable land, water resources and stable functioning ecosystem services (Steffen et al., 2011). The accelerated growth since 1950 in population (2.5 billion to 7.3 billion in 2015 (UN DESA, 2015)), resource extraction (food, freshwater and fossil fuel use have more than tripled (Foley, 2010)) and greenhouse gas emissions (CO₂ emissions have increased 6-fold (Boden et al., 2013)) have put the planet under unprecedented pressure. Natural resource scarcity, ecosystem degradation, biodiversity loss and climate change are the environmental realities of the 21st century. After 10,000 years living under stable conditions, humanity is pushing the planet towards and beyond its safe planetary boundaries (Rockström et al., 2009a). The global scale, speed of change and increasing complexity require planetary stewardship of Earth's life support systems (Steffen et al., 2011).

Many people have benefited greatly from resource consumption, with global gross domestic product (GDP) growing exponentially from US\$ 1.3 trillion (current US\$) in 1950 to US\$ 74 trillion in 2015 (World Bank, 2017), and human well-being reaching very high levels in some countries (UNDP, 2016). However, human development has been uneven, with billions of people currently facing multiple forms of deprivation (UNDP, 2016) and 795 million people facing hunger (FAO et al., 2015). The rich OECD (Organisation for Economic Co-operation and Development) countries accounted for 18% of the global population in 2010 but

accounted for 74% of global GDP and 50% of carbon emissions, proxies for consumption and human impact on Earth systems (Boden et al., 2013; Steffen, Broadgate, et al., 2015). Wealth has become even more concentrated in the hands of the top 1% who own about 46% of global wealth (Milanovic, 2016). Ensuring the poorest obtain a socially-just standard of living will require far greater equity and efficiency in transforming natural resources to meet human needs (Raworth, 2012), which both require reformed global governance (UNDP, 2016). The central challenge of the 21st century therefore is to foster a transition to sustainability (Clark and Levin, 2009) by achieving equitable levels of human development whilst conserving the life-support systems of the planet.

This multidimensional challenge and goal has been captured in Raworth's visual framework – shaped like a doughnut (Figure 1.1) - that puts the 'safe and just space' for inclusive and sustainable development between an outer boundary, the environmental ceiling, and an inner boundary, the social foundation (Raworth, 2012). Above the ceiling lies unacceptable environmental degradation while below the social foundation (or social floor) lies unacceptable human deprivation. The 'safe and just space' is where both human and planetary well-being are assured. The framework builds on Rockström *et al.*'s (2009a, 2009b) planetary boundaries (PB) concept, which visually presented the state of nine Earth-system processes compared to their critical thresholds (Figure 1.2 and Table 1.1). Rockström *et al.* argued that when these PB are crossed, important subsystems could shift into a new state that could disrupt the planet's ability to support human life. They framed a goal of living within the 'safe operating space' where 'humanity has the freedom to pursue long-term social and economic development' (Rockström et al., 2009a).

Raworth's environmental ceiling is the boundary of the safe operating space and has the same nine dimensions (Figure 1.3a). Raworth's social foundation has 11 dimensions, derived from priorities in 80 government submissions to the UN Conference for Sustainable Development, or Rio+20 Earth Summit, in June 2012. Raworth selected 12 indicators, largely based on the Millennium Development Goals (MDGs), and plotted the current status using global data (Figure 1.3b and Table 1.2).

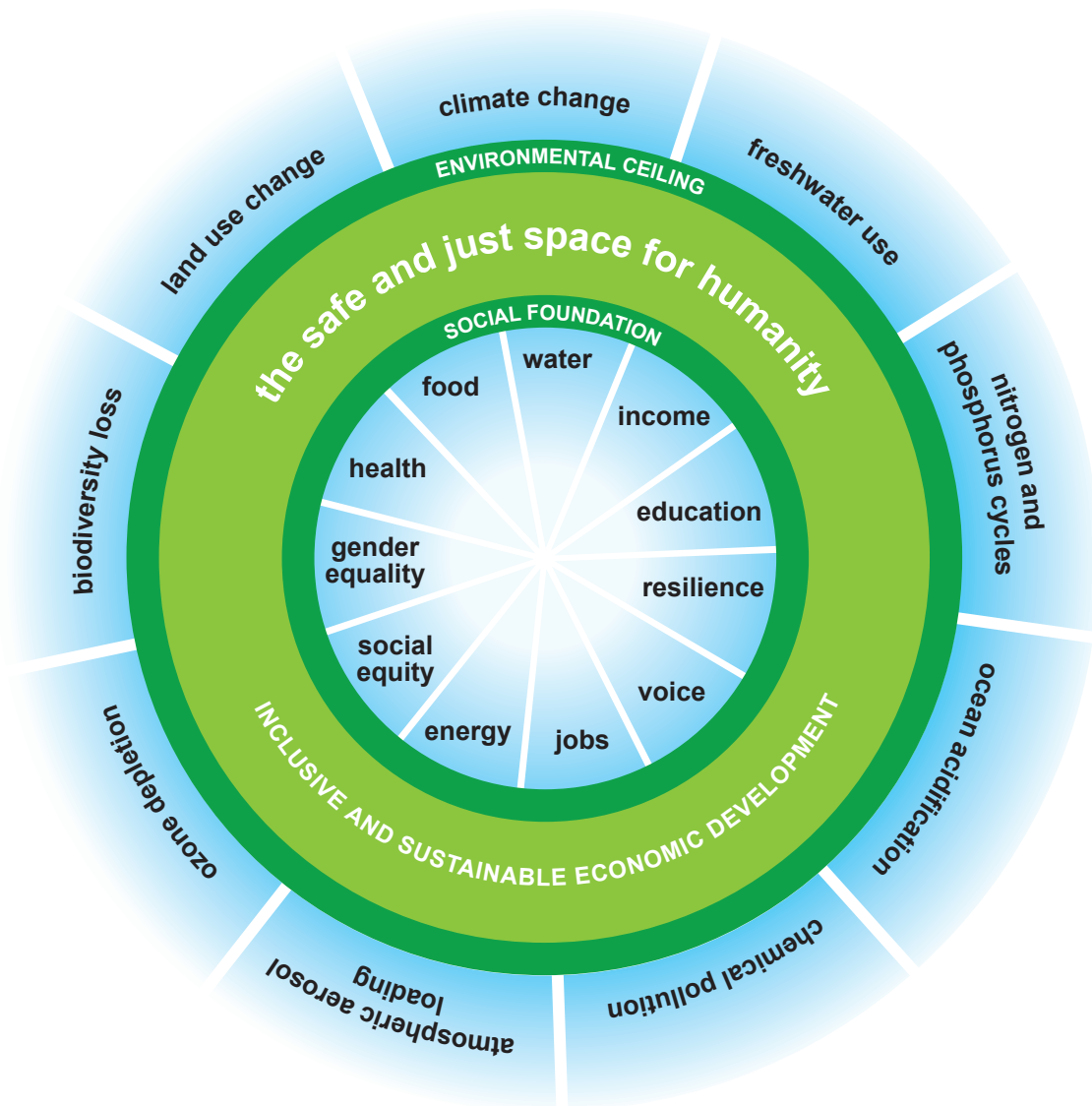


Figure 1.1 Raworth's 'safe and just space for humanity' (Raworth, 2012)

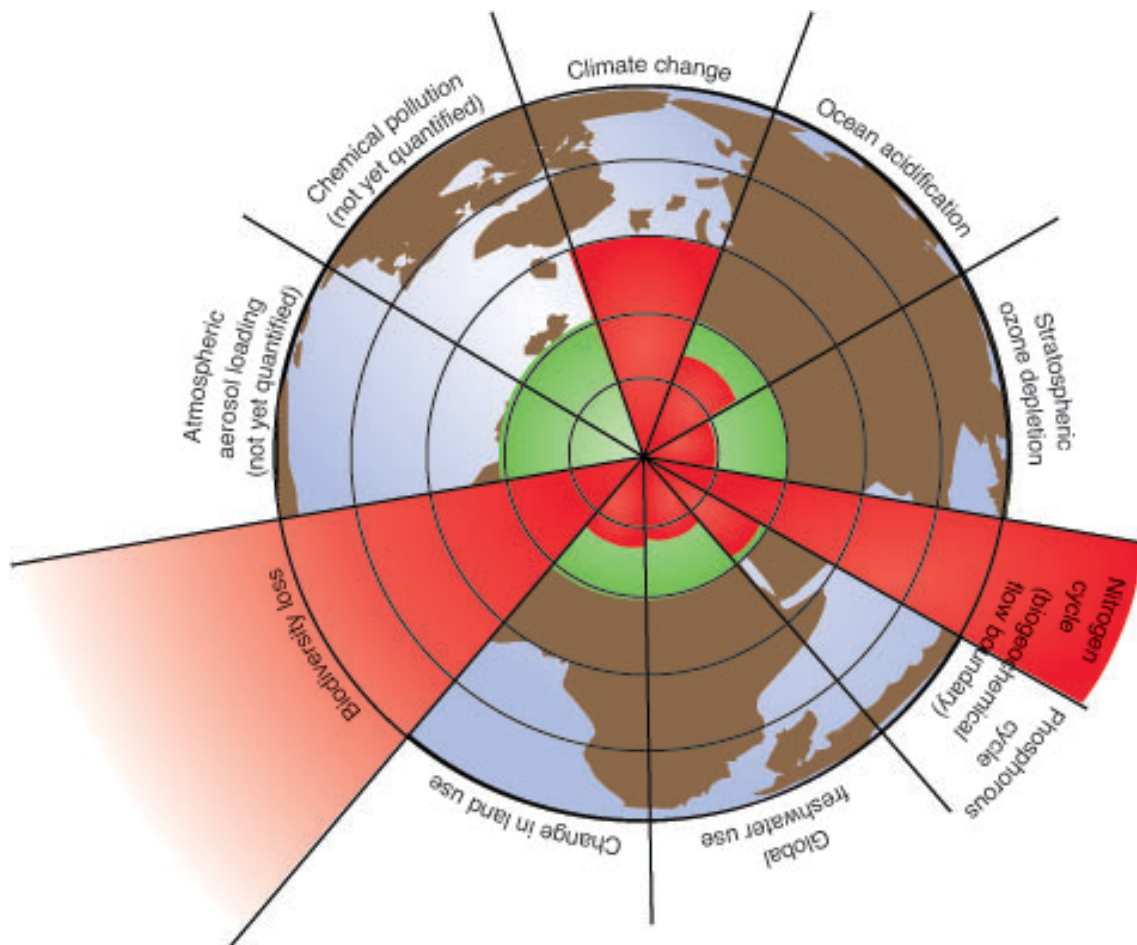


Figure 1.2 Rockström *et al.*'s planetary boundaries concept. The green shading represents the proposed 'safe operating space' (Azote images/ Stockholm Resilience Centre).



Figure 1.3 a) Environmental status and b) social status of the 'safe and just space' (Raworth 2012)

Table 1.1 Rockström *et al.* (2009a) planetary boundaries

Earth system process	Parameters	Baseline	Proposed boundary	Status
Climate change	CO ₂ concentration (ppmv)	280	350	387
	Change in radiative forcing (Wm ²)	0	1	0
Rate of biodiversity loss	Extinction rate (no. of species per million species per year)	0.1-1	10	>100
Nitrogen cycle	Amount N ₂ removed from atmosphere for human use (Mt/yr)	0	35	121
Phosphorus cycle	P flowing into oceans (Mt/yr)	~1	11	8.5-9.5
Stratospheric ozone depletion	Ozone concentration (Dobson units)	290	276	283
Ocean acidification	Global mean saturation state of aragonite in surface sea water	3.44	2.75	2.90
Global freshwater use	Consumption of freshwater by humans (km ³ /yr)	415	4,000	2,600
Land use change	Global land cover converted to cropland (%)	low	12	11.7
Aerosol loading	Overall particulate concentration in the atmosphere	To be determined		
Chemical pollution	<i>To be determined</i>	To be determined		

Table 1.2 Raworth's (2012) social foundation

Dimension	Indicator of deprivation	Percentage deprived
Food security	Population undernourished	13%
Income	Population living below US\$1.25 (PPP) per day	21%
Water and sanitation	Population without access to an improved drinking water source	13%
	Population without access to improved sanitation	39%
Health care	Population estimated to be without regular access to essential medicines	30%
Education	Children not enrolled in primary school	10%
	Children enrolled in tertiary education	11%
	Illiteracy among 15–24-year-olds	
Energy	Population lacking access to electricity	19%
	Population lacking access to clean cooking facilities	39%
Gender equality	Employment gap between women and men in waged work (excluding agriculture)	34%
	Representation gap between women and men in national parliaments	77%
Social equity	Population living on less than the median income in countries with a Gini coefficient exceeding 0.35	33%
Voice	<i>E.g. Population living in countries perceived (in surveys) not to permit political participation or freedom of expression</i> <i>Governance effectiveness (village councils, fishery board etc)</i>	To be determined
Jobs	<i>E.g. Labour force not employed in decent work</i>	
Resilience	<i>E.g. Population facing multiple dimensions of poverty</i> <i>Shocks (economic, natural, social)</i>	

The PB diagram is similar to the 'burning embers' diagram of the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) that identified five 'reasons for concern' regarding dangerous anthropogenic interference with the

climate system (Working Group II of the IPCC, 2001). The ‘reasons for concern’ framework visually communicates scientific understanding about risks in relation to varying levels of climate change. It has become a cornerstone of the IPCC assessments, being widely discussed and refined over time, and used to inform policy decisions (O’Neill et al., 2017; Smith et al., 2009). Similarly, the PB diagram and concept communicates scientific understanding about risks in relation to nine Earth system processes. It has been widely discussed in academic literature, with discussion on the conceptual framework (Biello, 2012; Brook et al., 2013; Cornell, 2012; Hughes et al., 2013; Lenton and Williams, 2013; Lewis, 2012; Robèrt et al., 2013; Saunders, 2015), defining individual boundaries (Carpenter and Bennett, 2011; de Vries et al., 2013; Rockström et al., 2012; Rockström and Karlberg, 2010; Running, 2012), governance (Galaz, Biermann, et al., 2012; Galaz, Crona, et al., 2012; Nilsson and Persson, 2012), equity (Steffen and Stafford Smith, 2013), economic growth (Heijungs et al., 2014; van den Bergh and Kallis, 2012), corporate sustainability (Whiteman et al., 2013) and the Sustainable Development Goals (SDGs) (Griggs et al., 2013; Hajer et al., 2015; Leach et al., 2012).

The PB were updated and refined in 2015 (Steffen, Richardson, et al., 2015) in two main ways. First, the area beyond the safe boundary was split into a ‘zone of uncertainty’ (increasing risk) and ‘beyond the zone of uncertainty’ (high risk), acknowledging there are no well-defined global thresholds. Second, regional (sub-global) boundaries for biosphere integrity (previously biodiversity loss), biogeochemical flows, land-system change and freshwater use, were added to complement the planetary boundaries. The authors also acknowledged that there are ‘strong arguments for planetary boundary thinking at levels where policy action

most commonly occurs'. The concept is being used to frame the policy agenda in the European Union (European Commission, 2014) and by the governments of Sweden, Switzerland, Finland, Germany and Belgium (Dao et al., 2015; European Commission, 2014; Hajer et al., 2015; Nykvist et al., 2013).

Raworth's 'safe and just space' (SJS) framework was developed as an advocacy tool aimed at influencing the discourse on the global development agenda. It has gained most interest in policy circles as a platform for integrated analysis and debate about global goals (IIED, 2012; Tearfund, 2013). It appears in the Worldwatch Institute's State of the World report (Stewart, 2013) and the International Social Science Council's World Social Science Report 2013 (Leach et al., 2013). An updated version was published in May 2017 with improved social indicators and data and incorporating the updated PB (Raworth 2017). Raworth's (2012) framework has some similarities to the 'environmental space' concept put forward by Spangenberg *et al.* (1994), which had a ceiling representing the 'maximum amount of non-renewable raw materials, land and water' that can be sustainably consumed, and a floor representing the 'minimum amount of resources necessary to overcome need and poverty'. Spangenberg *et al.*'s concept is limited to natural resource availability whereas Raworth maintains the idea of critical thresholds and acceptable limits.

Dearing *et al.* (2014) argued that downscaling Raworth's framework to sub-global scales can: (1) increase the policy impact of the boundaries concept as most governance takes place at the regional rather than planetary scale, (2) contribute to the understanding and dissemination of complexity thinking throughout

governance and policy-making, and (3) act as a powerful metaphor and communication tool for regional equity and sustainability. Adding to this, Fang *et al.* (2015) argued that measurable local and regional boundaries are needed as the quantification of boundaries is strongly scale-dependent and the non-transgression of a global boundary does not necessarily guarantee a sustainable society, because exceeding a regional or local boundary may still give rise to irreversible environmental degradation. This is particularly true for aggregated issues that are spatially heterogeneous and local-to-regional in scale. Dearing *et al.* provided the first case study of downscaling the SJS framework to the regional scale using two Chinese localities - Erhai lake-catchment, Yunnan Province and Shucheng County, Anhui Province.

The PB have also been downscaled to the national level at the request of some European governments. Nykvist *et al.* (2013) downscaled four of the PB for 61 countries in a study for the Swedish Environmental Protection Agency to test whether the PB concept could reflect the international dimension of Sweden's national environmental quality objectives. Dao *et al.* (2015) undertook a study for the Swiss Federal Office for the Environment to translate the PB to the Swiss context to develop recommendations for a set of 'footprint limits for a Green Economy'. Hoff *et al.* (2014) attempted to quantify the contribution of European consumption to total environmental pressures and associated transgressions of environmental boundaries, both within Europe and beyond its borders, for the European Union's Environment Action Programme. The European examples focus on determining a country's fair share of the global 'safe operating space', however from a developing country perspective, defining national boundaries has two main

goals: 1) to measure and manage a nation's contribution to the global problem to promote international cooperation and global ecological stability and 2) to measure and manage the biophysical capacity and state of a nation to achieve national sustainability.

There are numerous challenges related to determining safe environmental boundaries. It is notoriously difficult to predict where critical thresholds lie in natural systems (Schellnhuber, 2009). They can be driven by systemic global scale processes impacting sub-systems 'top-down' (e.g. climate change) or can arise at the local and regional scale which become a global concern if aggregated, impacting the global system 'bottom-up' (e.g. land use change) (Rockström et al., 2009b). Critical thresholds for global processes require downscaling to national and sub-national scales if they are to be avoided through international cooperation, which raises issues of equity and historical responsibility. Local critical thresholds can vary spatially and data do not easily aggregate to national and global scales as ecological and administrative borders seldom coincide. Also, defining what is 'safe' requires normative judgements of how societies choose to deal with risk and uncertainty (Rockström et al., 2009b).

There are also challenges to determining just social floors. 'Poverty is inherently a contested concept because it is not just a state of affairs, it is an unacceptable state of affairs' (Alcock, 2006). The definition of poverty in a society mirrors the ideals of that society (Noble et al., 2008). Absolute poverty refers to severe deprivation of basic human needs (World Summit for Social Development, 1995) while relative poverty refers to exclusion from ordinary living patterns, customs and activities

(Townsend, 1987). A socially acceptable minimum standard of living can be set higher or lower than the customary, or average, standard of living (Noble et al., 2008). The Millennium Development Goals (MDGs), an international poverty compact setting out indicators and time-bound targets for various dimensions of human well-being that received unprecedented support from around the world (Clarke and Feeny, 2011), challenged the focus on per capita economic growth and GDP and instead prioritised the poor and used the multidimensional concept of poverty (Hulme, 2010). They were focused on eradicating extreme poverty and thus the indicators set low social floors for income, health and education. Official government indicators in developing countries tend to follow this trend. While this highlights the plight of the most vulnerable in society, it does not define the average or aspirational living standards.

The PB and SJS were both used as advocacy and framing tools in the development of the Sustainable Development Goals (SDGs) (SDSN, 2013; UN General Assembly, 2012a; UNEP, 2013). The UN decision to develop SDGs was made at the Rio+20 Earth Summit in June 2012. The aim was to guide the international development agenda after 2015, when the MDGs were hoped to be met (UN General Assembly, 2012b). The Agenda 2030 for Sustainable Development and its 17 SDGs (Figure 1.4) and 169 targets (UN General Assembly, 2015) were developed through a three-year international process that engaged stakeholders from multilateral organisations, non-governmental organisations (NGOs), the private sector and 193 national governments, and were adopted by the UN General Assembly in September 2015 (UN General Assembly, 2015). The SDGs build upon the MDGs and on international treaties such as the UN Convention for the

Protection of the Ozone Layer, the UN Convention on Biological Diversity, and the UN Framework Convention on Climate Change. The vision of Agenda 2030 is ambitious, aiming to end poverty and hunger, protect the planet from degradation, ensure prosperity for all, and foster peaceful, just and inclusive societies by 2030 (UN General Assembly, 2015). The Agenda's 17 SDGs are wide-ranging and address environmental, social and economic challenges through 169 targets and 234 global indicators. Agenda 2030 will be implemented in all signatory countries by defining and monitoring national and sub-national indicators and targets. While the SDGs may not currently be the priority of national governments, lessons from the MDGs show that the SDGs are likely to influence donor-funding decisions, technology transfer, research and the approach to poverty alleviation. Although there has been criticism of the indicators used in the MDGs e.g. (Attaran, 2005; Easterly, 2009), they have galvanised political leaders, corporations, community groups, the media and NGOs across the world (Vandemoortele, 2011), supported national priority-setting (Sachs, 2012), clarified development policy objectives, justified additional funding from the international community during an era of aid fatigue, and made international donors and developing country governments more accountable to taxpayers and voters (Clarke and Feeny, 2011), and generated commitments and actions worldwide that would not otherwise have happened (Glaser, 2012).



Figure 1.4 The Sustainable Development Goals (UN, 2016)

Significant inequality can be hidden behind national sustainable development indicators. In the past two decades, there has been a major shift from inequality between countries to inequality within countries. In 2010, 72% of the world's poor, 960 million people, lived in middle-income countries whereas two decades before, 93% lived in low-income countries (Sumner, 2011). Economic growth has been favoured at the expense of the poorest and environmental constraints may further compound these inequalities (Gupta et al., 2015). One of the most notable advances of the SDGs over previous development goals and targets is the narrative of 'leaving no one behind' and the importance placed on measuring inequality in all its forms. Two of the 17 SDGs are dedicated to reducing inequality (SDG 5 and SDG 10) while most of the targets for the SDGs include the phrase 'for all' and data must be disaggregated by gender, race, age, geographical location and other context-specific factors (UN Economic and Social Council, 2015). This demands significant additional effort on data collection and reporting and has led to the call

for a 'data revolution for sustainable development' (Independent Expert Advisory Group on the Data Revolution for Sustainable Development, 2014).

1.2 Aim and research questions

This thesis seeks to contribute both theoretically and practically to discourses on defining and visualising the safe and just operating space for humanity, developing national and sub-national indicators for the SDGs, and measuring non-income inequality. These research topics cover multiple spatial scales and levels ranging from global to local, and South Africa is used as the case study. Thus, the thesis has two complementary themes: 1) tracking progress towards inclusive sustainable development in general, and 2) describing South Africa's progress towards its sustainable development goals.

South Africa is used as a case study for three main reasons. Firstly, it is a developing country with large, good quality environmental and social datasets, established national research institutes and regular indicator reporting at national and sub-national levels. It is therefore possible to define safe and just boundaries and assess existing indicators. Secondly, South Africa has diverse landscapes and climates and is ecologically megadiverse (Driver et al., 2012), and also has widespread poverty, extreme income inequality (Palma, 2011) and entrenched spatial inequality. As a result it has been termed a microcosm of the global challenges. This provides a stringent test for the SJS framework, highlights the challenges of scale and enables the development of new inequality measures. Finally, as the second largest economy in Africa (IMF, 2015), South Africa is influential both on the continent and globally as part of the BRICS group of

emerging economies, and the research is more likely to be shared through South-South cooperation.

The aim, research questions and objectives of the thesis are shown in Box 1. These research questions and objectives are addressed in four papers that develop and examine (1) the SJS for South Africa, (2) the SJS for South Africa's nine provinces, (3) inequality in water use and water access across all administrative levels in South Africa, and (4) SDG water indicators for South Africa, using the Berg Water Management Area as a case study. Figure 1.5 illustrates the relationship between the four papers, the research questions and the scale and nature of the analysis. Paper 1 describes the downscaling of the SJS from the global to the national scale to create a barometer for inclusive sustainable development. Paper 2 describes the downscaling of the national barometer to the provincial level and compares provinces, highlighting sub-national heterogeneity. Paper 3 maps and describes water access, water use and water stress from ward and town level to national level and compares towns, municipalities, districts and provinces. Paper 4 studies all aspects of water covered in the SDGs, using the Berg Water Management Area as a case study and comparing towns and municipalities in the South African context.

Box 1. Aim, research questions and objectives

Aim: to develop new approaches to monitoring sustainable development and inequality at national and sub-national scales, and to measure progress towards the SDGs in South Africa

Research questions and objectives

Q1. Can the visual framework, the 'safe and just space for inclusive sustainable development', be usefully applied at the national level?

- Determine nationally-relevant dimensions, indicators, status and boundaries for the 'safe and just space' in South Africa
- Visualise South Africa's 'safe and just space'
- Evaluate the utility of the 'safe and just space' with experts in South Africa

Q2. What heterogeneity and inequality do national sustainable development indicators hide?

- Determine provincial status and boundaries for South Africa's 'safe and just space' and compare provinces

Q3. How can the inequality hidden by national indicators be effectively reported to support policy-making?

- Map and describe water access, use and stress across South Africa
- Calculate and evaluate inequality measures for water use and water access (2 dimensions of the 'safe and just space') at multiple administrative levels in South Africa

Q4. How can the inequality in sustainable development outcomes related to water be measured and reported to aid decision-making?

- Populate a suite of SDG 6 water indicators for South Africa, the Berg Water Management Area and its municipalities and towns
- Calculate jobs and income per unit of water allocated for heavy water use sectors to assess inequality in benefits and efficiency of use

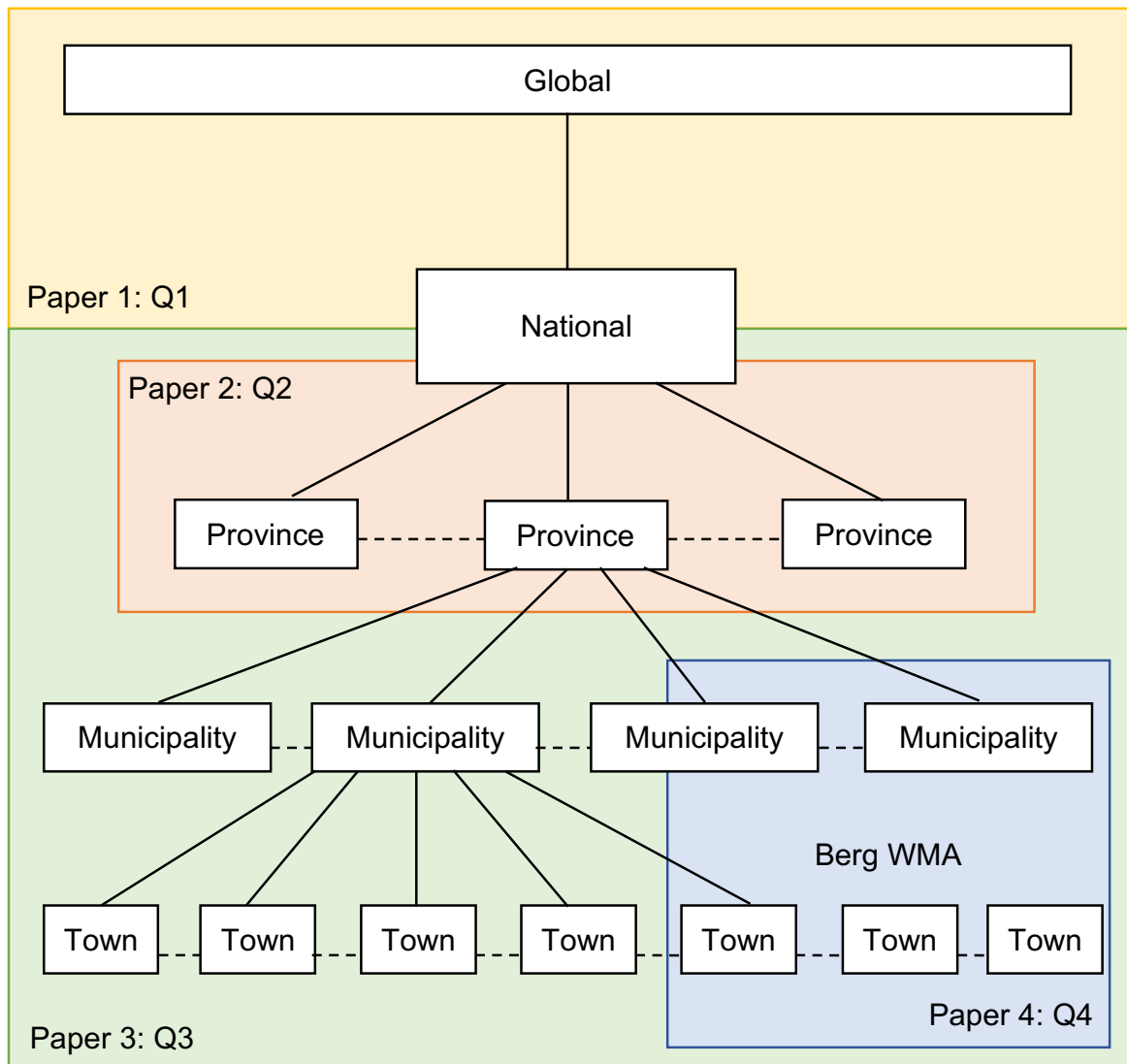


Figure 1.5 Overview of the scale and relationships within and between the four papers

1.3 Thesis structure and overview

This thesis follows the requirements for the University of Oxford's D.Phil. by submitted papers route; therefore, chapters 3 to 6 have been prepared and structured for submission to peer-reviewed journals. This introductory chapter provides the wider context for the research, discusses why this study is important, states the overall aims of the research and briefly summarises the four chapters. Chapter 3 was published in *PNAS Plus* in 2014, Chapter 4 was published in

Sustainability Science in 2017 and Chapter 5 and Chapter 6 were submitted to journals in 2017.

Chapter 2 provides the literature review of the key topics of the thesis, highlighting gaps in the research and setting a background for the subsequent chapters. The topics reviewed are:

1. Sustainable development and sustainability science
2. Sustainable development indicators
3. South Africa's sustainable development reporting
4. Environmental limits
5. Social floors
6. Data visualisation
7. Challenges of scale.

Chapter 3 (*Tracking sustainable development with a national barometer in South Africa using a downscaled 'safe and just space' framework*) addresses research question Q1. It describes how the PB concept and SJS framework were downscaled to the national level in South Africa. This was the first developing country case study of downscaling the PBs, and the first case study of downscaling the SJS to the national level. A decision-based methodology was developed for downscaling environmental and social dimensions, indicators and boundaries in a repeatable and consistent way. Data were taken from relevant national databases and reports, international databases and academic papers, and expert judgment was sought through semi-structured interviews with 43 South African experts from government, research institutes, universities and international NGOs. A national

'barometer' for South Africa was created, combining 10 environmental stress indicators and 10 social deprivation indicators into two radar plots. Trends were plotted on line graphs. The results showed that South Africa has exceeded four safe environmental boundaries and is furthest below its social floor for safety, income and employment. Experts agreed that downscaling the SJS to the national level could provide a useful tool in South Africa for removing inter-sectoral barriers and facilitating integrated debates, identifying gaps in the research, and raising new questions on social deprivation and environmental sustainability. The research addressed challenges of scale regarding indicator definition, data availability, mismatch of ecological and administrative borders, and international equity.

Chapter 4 (*Spatial variability in sustainable development trajectories in South Africa: provincial level safe and just operating spaces*) addresses research question Q2. It describes how the national barometer was downscaled to the provincial level to explore sub-national variability and define the 'safe and just operating space' for each of South Africa's nine provinces. Three methods of disaggregation of national data were used – sharing the national total amongst the provinces, aggregating local data to the provincial scale, and fitting data reported by ecological borders into administrative borders. The resulting provincial barometers and trend plots are novel as they present comparable environmental and social data on key indicators over time for all South Africa's provinces. The study showed that national reporting can hide significant heterogeneity in environmental status and social deprivation, caused by large natural variations in climate, terrain, soil and natural resources, the varying population density, varying economic activities and entrenched spatial inequalities. This highlighted that the

choice of national indicators should consider the application at sub-national scale, and that in some cases a national indicator is necessary for international reporting and governance but is actionable only in some sub-national settings.

Chapter 5 (*Spatial inequality in water access, use and stress in South Africa*) addresses research question Q3. It describes how data on national water indicators can be spatially disaggregated to expose and quantify the hidden inequalities. Piped water access, town per capita water use and town per capita water stress in South Africa were compiled, mapped and analysed at multiple levels using census data for 4,277 wards and 830 water reconciliation strategies. This created a new water dataset that could be used by other researchers. The results provide a suite of descriptive statistics and water inequality measures, including the Gini index and Palma ratio for piped water access and per capita water use. The paper provides the first in-depth analysis of per capita water use at multiple levels in South Africa. It shows that the scale of the dataset used has a significant impact on national reporting, and that the results change at different reporting scales, with local figures showing much larger heterogeneity than provincial figures. It also shows the utility of measuring non-income inequality.

Chapter 6 (*Developing a suite of SDG 6 water indicators: a case study of the Berg Water Management Area in South Africa*) addresses research question Q4. It describes how a comprehensive suite of 26 national indicators is proposed for SDG 6 'Water and sanitation for all', for South Africa. It incorporates research from Chapters 3 to Chapter 5 and develops new measures of water-use efficiency and inequality based on water-dependent jobs and income. The Berg Water

Management Area, in the south-western corner of South Africa, is used as a case study to test the indicators and methods, and enable local to national generalisation and comparison. Indicators on jobs and income per cubic metre of water for agriculture, agriprocessing, aquaculture and mining are developed, providing the most comprehensive analysis on water and jobs in the region to date. The results show variability and inequality in water access, water use, water quality and water benefits across local municipalities, and provide examples of disaggregation of national data by race, gender and geographic location. The study identifies gaps in the data and where methodologies and standards need to be developed for the full suite of indicators to be monitored in the SDGs.

Chapter 7, the concluding chapter, reviews the main findings, discusses the implications of these findings, outlines areas for additional and new research and provides concluding remarks. The main contributions of the research are:

1. a description of progress towards the SDGs in South Africa at national and provincial levels, and at finer scales for water;
2. downscaling the full PB to the national level for the first time in a developing country;
3. downscaling the SJS to the national level for the first time;
4. proposing a decision-based methodology for defining the SJS that can be used in other countries and contexts;
5. developing a novel method for comparing South Africa's provinces across both environmental and social dimensions;
6. providing early case studies of SDG data disaggregation of both environmental and social sustainable development indicators;

7. exploring the challenges and opportunities raised by sub-national indicator reporting relevant for the SDG implementation;
8. compiling a new database of local water use across South Africa;
9. creating new measures of non-income inequality for South Africa, namely Gini index and Palma ratios for water access and water use;
10. proposing a comprehensive SDG 6 indicator suite for South Africa;
11. calculating water-use efficiency in both jobs and income across heavily water-dependent sectors in the Berg WMA for the first time.

1.4 Study area: South Africa

South Africa lies at the southern tip of Africa, surrounded by the Atlantic and Indian Oceans, and has six neighbouring countries. The varied topography and ocean influence create a variety of climatic zones, ranging from desert in the north-west to lush sub-tropical in the east (GCIS, 2011). It is largely semi-arid with only 12% of land capable of supporting rain-fed crop production (DAFF, 2015) shown in Figure 1.5. South Africa is 30th driest countries in the world and more than 60% of rivers are fed by flow from only 20% of the land area (Strategic Water Source Areas), requiring large-scale inter-basin transfers (DWA, 2013). It primarily depends on its surface water resources, including imported water from Lesotho (DWA, 2013). South Africa is one of 17 megadiverse countries and has three of the world's 25 biodiversity hotspots, which are home to more than 20,000 plant species, half of which are endemic (Driver et al., 2012). South Africa's 3,000 km coastline is home to rich marine biodiversity; the country's commercial, subsistence and recreational fisheries catch more than 630 marine species (DAFF, 2012).

South Africa is one of the youngest democracies in the world, with elections in 1994 marking the end of white minority rule. The majority of the 55 million population are black African and roughly half are under the age of 25 (StatsSA, 2015). The population growth rate (including immigration) is 1.3%, significantly lower than the 2.7% for sub-Saharan Africa as a whole (World Bank, 2014). South Africa's population is projected to peak, plateau and then decline to between 60 and 70 million people in the second half of this century (UN DESA, 2012). People in South Africa live in more than 30,000 settlements, with 40% of the population in eight large metropolitan areas, 19% in medium-sized cities and towns, 6% in small towns in rural areas and 35% in small rural villages and scattered settlements (StatsSA, 2012). Figure 1.6 shows the location of metropolitan areas, Strategic Water Source Areas and good arable land.

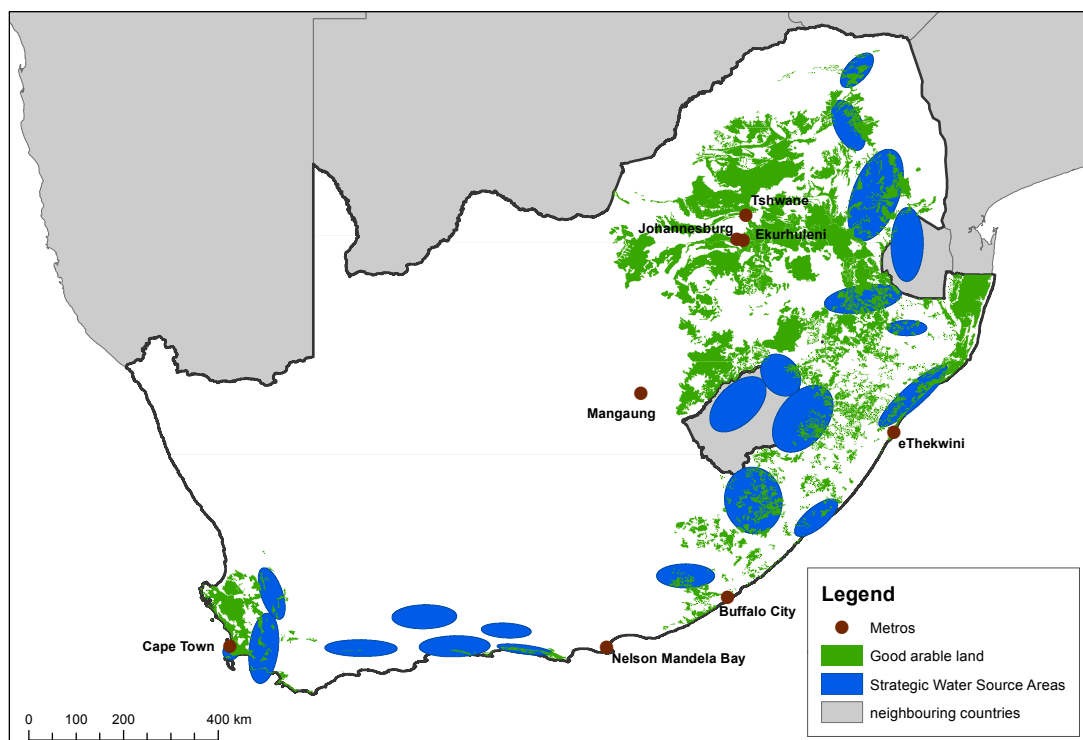


Figure 1.6 Map of metropolitan areas, good arable land and Strategic Water Source Areas in South Africa

South Africa has the second largest economy in Africa (IMF, 2015). The mining sector has played a key role in the economy for 140 years, making it the most industrialised country in Africa (Chamber of Mines of South Africa, 2013). In 2016, 70% of GDP was derived from services, while industry contributed 28% (14% manufacturing, 8% mining and quarrying, 4% construction, 2% utilities) and agriculture, forestry and fisheries contributed 2% (StatsSA, 2017a). Economic growth has slowed down in recent years from 3.1% in 2011 to 1.8% in 2015 (World Bank, 2016), lagging behind other emerging economies (IMF, 2015). The broad unemployment rate is 37% (StatsSA, 2017b), one of the highest in the world (DPME, 2015). Job creation has been led by the public sector rather than the private sector, which remains cautious of expansion due to economic and political challenges (Muthethwa, 2013).

South Africa is one of the most unequal countries in the world with a Gini index for income inequality of 0.65 (DPME, 2015) compared to 0.22 for Sweden, the least unequal country (Palma, 2011) (zero is pure equality). The wealthiest 4% of households receive 32% of total income, while 66% of households receive only 21% (Visagie, 2013). The top 1% have 41% of total wealth (Credit Suisse Research Institute, 2013). The 'middle class' (based on occupation, not median income) who make up 30% of the population only earned between R1,400 (US\$133) and R10,000 (US\$950) net per capita per month in 2008 money terms (Visagie, 2013), roughly a third of the earnings of the 'global middle class' (Kharas, 2010). Over 45% of South Africans live below the official poverty line (DPME, 2015) and 16% live in extreme poverty, on less than US\$1.90 per day (Sachs et al., 2016).

South Africa's 'triple challenge' of poverty, inequality and unemployment (The Presidency South Africa, 2014) is highlighted in the National Development Plan (NDP) Vision 2030 (National Planning Commission, 2012). The NDP is the most important policy document in the country and will guide development until 2030. The National Climate Change Response has been the catalyst for mainstreaming environmental issues in South Africa and is supported by the National Strategy for Sustainable Development and Action Plan (DEA, 2011), which promotes stewardship of limited natural resources, and the Green Economy Accord (EDD, 2011) which focuses on technology and job creation to meet development goals in a more sustainable way.

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Chapter 2 – Literature review

This chapter provides background literature for the following four chapters. It briefly describes the concepts of sustainable development and sustainability science as this is the field in which this thesis is placed. It discusses the history of sustainable development indicators (SDIs), their uses, some well-known indexes and the development and use of SDIs in South Africa. It then summarises the relevant literature on environmental limits and social floors, which are at the heart of the PB and SJS frameworks. As the success of the PB and SJS are largely due to the visualisation of the concepts, data visualisation is discussed. Finally, as the thesis is concerned with the effects of scale on SDIs, the concept and challenges of scale are briefly explored.

2.1 Sustainable development and sustainability science

‘The concept of sustainable development is the result of growing awareness of the global links between mounting environmental problems, socio-economic issues to do with poverty and inequality, and concerns about a healthy future for humanity’ (Hopwood et al. 2005). ‘Sustainable development is both a way of understanding the world and a way to help save it’ (Sachs 2013). The term ‘sustainable development’ was first used in 1980 in the World Conservation Strategy (IUCN 1980) but was defined in 1987 by the UN World Commission on Environment and Development, in its so-called Brundtland report (WCED 1987), as development that ‘meets the needs of the present without compromising the ability of future generations to meet their own needs’. Despite the global acceptance and use of this phrase, the term sustainable development has been open to interpretation

(Hopwood et al. 2005) with discourses on *what* is to be sustained ranging from the natural stock of resources, where critical natural capital is given priority, to present levels of production or consumption, where the population is given priority (Redclift 2005). The Brundtland definition highlights the principle of inter-generational equity but other principles that have been proposed include intra-generational equity, geographical equity, procedural equity and inter-species equity (Haughton 1999). Sustainability and sustainable development are often conceptualised as consisting of three dimensions - society, economy and environment – and the relationship between them shown graphically by a Venn diagram (Figure 2.1a) or three nested circles (Figure 2.1b) (Moir and Carter 2012).

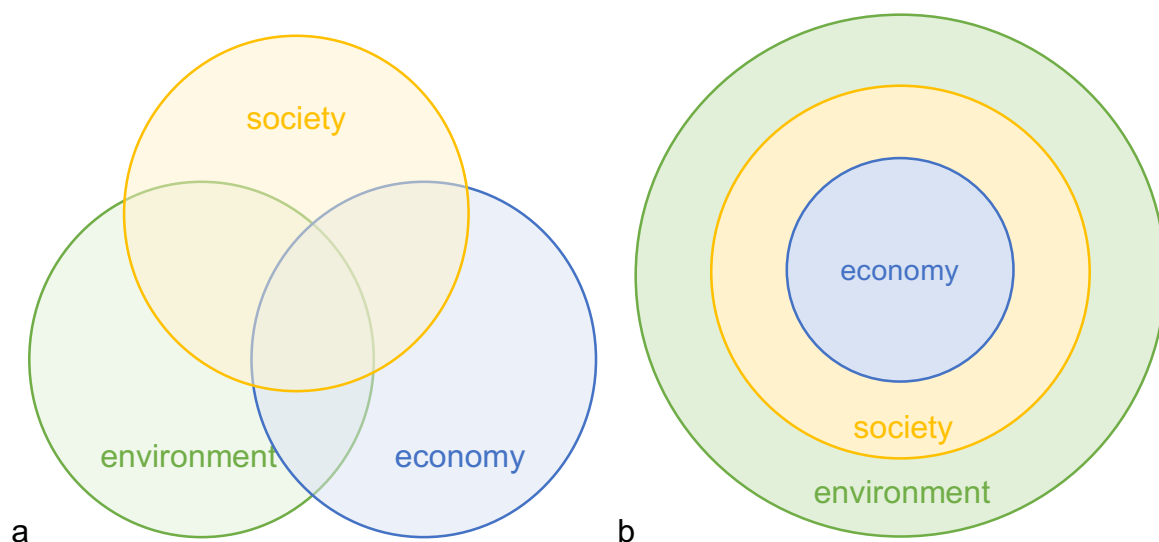


Figure 2.1 Pillars of sustainable development represented as a) a Venn diagram and b) nested circles (after Moir and Carter, 2012)

A major challenge in achieving sustainable development is its multidisciplinary nature. The linkages, possible synergies and trade-offs are not well understood and require the best available knowledge (Glaser 2012). Evidence-based policy has become the desired norm in many fields (Sutherland et al. 2012) and relationships of ‘coproduction’ have developed where researchers work together with ultimate

users, decision-makers and other actors. Unfortunately, the areas where scientific input is most needed by policy-makers are often the ones for which the science is most complex, multidisciplinary, and incomplete (Gluckman 2016).

Sustainability science has emerged in the last three decades as a ‘field defined by the problems it addresses rather than by the disciplines it employs’ (Clark 2007). It requires a multi-disciplinary approach that integrates practical experience with knowledge from some or all of the natural and social sciences, medicine and engineering, and mathematics and computation (Clark and Levin 2009). It often involves transdisciplinary research that arches over existing research (Kajikawa 2008). Key challenges facing sustainability science are decision-making under pervasive uncertainty associated with complex social–ecological processes (Anderies et al. 2007) and governance of the global commons (Ostrom 1999). Sustainability science has to span all spatial scales from global to local, account for temporal inertia and urgency, deal with functional complexity in social-ecological systems and recognise a wide range of views on what makes knowledge usable within science and society (Kates et al. 2001). Table 2.1 shows the three main research areas in sustainability science and their main methods and applications. This thesis focuses on the field of sustainable development indicators.

Table 2.1 Sustainability research – scale, methods and applications

Spatial level	Main research areas	Main methods	Main applications
Global	Global environmental change	Quantitative modelling	International agreements
National	Sustainable development indicators	DPSIR framework and multi-criteria analysis	National policy making
Regional and Local	Social-ecological systems	Case studies and physical models	Natural resource management

2.2 Sustainable development indicators

The first UN Conference on Environment and Development, called the 'Earth Summit' was held in Rio de Janeiro in 1992 to discuss global governance based on newly acknowledged sustainability principles (Redclift 2005). The outcome document, Agenda 21, was an action plan for the UN, multilateral organisations and national governments to reduce poverty and protect the environment (UN Sustainable Development 1992). Agenda 21 called for sustainable development indicators (SDIs) to be developed to support decision-making at all administrative levels. In the two decades since the Earth Summit, environmental indicators have become pervasive and influential in policy-making at multiple scales (Niemeijer and de Groot 2008). The great appeal of SDIs is that they have the potential to make the concept and aspirations of sustainable development a reality (Pintér et al. 2005).

Indicators are 'quantitative measures that are selected to assess progress toward or away from a stated goal' (Parris and Kates 2003). They provide a quantitative and rational basis for decision making (Senbel et al. 2003), simplify a complex reality to a manageable level (Galli et al. 2012), create a body of knowledge and comparable data for policy applications (Moran et al. 2008), measure trends over time, provide early warning signals, act as diagnostic tools (Cairns et al. 1993) and allow the public to evaluate society and its leaders (Fredericks 2013). Selecting sustainability indicators is usually done by a panel of experts using participatory multi-criteria analysis although there is a wide variety of selection criteria and methodological approaches that introduce subjectivity (Rowley et al. 2012). Ideally, multi-criteria analysis combines a normative approach where reference indicators

are defined by researchers and a participative approach where leaders select a subset of indicators from this list (Rey-Valette et al. 2007). The selection is influenced by the purpose but also by costs and feasibility of monitoring (Dale and Beyeler 2001). Most national environmental indicator sets use the Driving forces-Pressure-State-Impact-Response (DPSIR) framework to structure, integrate and analyse environmental information (Ness et al. 2010). The UN Environment Program (UNEP) recommends limiting the number of indicators, using existing data and proxies, being sensitive to scale and engaging stakeholders early on (UNEP-WCMC 2011).

The outcome document for the UN Conference on Sustainable Development in 2012 (known as Rio+20) stated that the Sustainable Development Goals (SDGs) indicators must be 'action-oriented, concise and easy to communicate, limited in number, aspirational, global in nature and universally applicable to all countries, while taking into account different national realities, capacities and levels of development and respecting national policies and priorities' (UN General Assembly 2012). The Inter-Agency Expert Group on SDGs, established by the UN in March 2015, conducted an open consultation to develop a global indicator framework that resulted in a final list of 234 global indicators in 2016 (IAEG-SDGs 2016). The framework includes a tier classification for indicators based on levels of available data, existing methods and standards. The next step is for national, sub-national and thematic indicators to be developed in order to turn the SDGs into a management tool and an annual 'report card' (SDSN 2015).

SDIs are often combined into an index or used as standalone indicators to communicate a single, clear message. They can be sub-divided into social, economic and ecological/environmental indicators and the most widely used indexes are described below.

2.2.1 Social indexes

The UN's Human Development Index (HDI) is probably the most well-known and widely used social index and is a composite of health, education and income indicators (UNDP 2011). The annual UN Human Development Report also reports a Gender-related Development Index and an inequality-adjusted HDI (UNDP 2016) (income and inequality are measures of social well-being not economic well-being). The Multidimensional Poverty Index, developed in 2010 by the Oxford Poverty & Human Development Initiative and the UNDP, uses 10 indicators to measure health, education and standard of living within and across countries (Alkire et al. 2011). The Gini coefficient or index, developed by Corrado Gini in 1912, is the most widely used measure of inequality, usually used to measure the distribution of income inequality across the whole of society (Wilkinson and Pickett 2010). Other social indexes include the International Energy Agency's Energy Development Index, which measures the progress in transitioning to reliable, clean and efficient fuels and energy services at the household and community levels for each of 80 countries (IEA 2010), and the International Telecommunications Union's Digital Access Index, which measures the overall ability of individuals in a country to access and use new ICTs (ITU 2003). Table 2.2 summarises the most widely used social indexes.

Table 2.2 Most commonly used social indexes

	Human Development Index	Multidimensional Poverty Index	Gini index
Sectors	Health, education, income	Education, health, water, energy	Income inequality
Number of indicators	3	10	1
Units	value between 0 and 1	value between 0 and 1	value between 0 and 1
Time range	1975-2016	2010-2016	1944-2015
Number of countries	185	109 developing countries	193
Data sources	Government statistics	Household surveys	Government statistics
Primary Application	Policy focus	Target local solutions	Economic policy
Reporting	Annually in UNDP's Human Development Report	Annually online by Oxford Poverty & Human Development Initiative	Annually by World Bank; national governments

2.2.2 Economic indexes

Economic indexes for sustainability generally seek to replace GDP as the dominant indicator of an economy's wellbeing, which is thought to be too simplistic and often records environmental degradation as a positive gain (van den Bergh and Kallis 2012). They frame the environment as 'natural capital' and take both the weak sustainability (human capital can replace natural capital) and strong sustainability (human capital and natural capital are complementary by not interchangeable) approaches. Indexes include the Genuine Savings Indicator (Pillariseti 2005), the Sustainability Gap (Ekins and Simon 2001), the Index of Sustainable Economic

Welfare (Daly and Cobb 1989; Lawn 2003), critical natural capital (Ekins 2003) and the Inclusive Wealth Index (UNU-IHDP and UNEP 2012).

2.2.3 Ecological indexes

Probably the most widely used ecological index is the Ecological Footprint developed by Rees and Wackernagel in 1996 in response to the then-current debates surrounding the Earth's carrying capacity - the maximum persistently supportable load that the environment can offer without impairing the functional integrity of ecosystems (Wackernagel et al. 2002; Kitzes et al. 2008; Ewing et al. 2010; Fang et al. 2015). The Ecological Footprint is a combination of six consumption-based indicators for 'bioproductive areas', namely cropland, grazing land, fisheries, forests, carbon and settlements. It has been used to compare the environmental impact of all countries (Moran et al. 2008) and as a resource accounting tool for governments, cities and companies to measure their impact and risk levels. A suite of footprint-style indicators have subsequently been developed to address specific sectors, namely the Water Footprint (Hoekstra and Mekonnen 2011), Carbon Footprint (Weidema et al. 2008), Nitrogen Footprint (Leach et al. 2012), Chemical Footprint (Zijp et al. 2014) and Material Footprint (Wiedmann et al. 2015), and Galli et al. (2012) have created the 'Footprint Family' of indicators. The material footprint is used as the first global indicator for SDG target 8.4 (IAEG-SDGs 2016).

The International Union for the Conservation of Nature's Red List of Threatened Species are used widely for classifying species by their risk of extinction. The Red List Index was developed to provide an indicator of the changing state of global

biodiversity, measuring four taxonomic groups: birds, mammals, amphibians, and corals (Butchart et al. 2005). It is used as the global indicator for SDG target 15.5 (IAEG-SDGs 2016). Similarly, the World Wildlife Fund's Living Planet Index measures the changing state of the world's biological diversity based on population trends of more than 3,600 vertebrate species (Collen et al. 2009). Each species trend is aggregated to produce an index for the terrestrial, marine and freshwater systems which is reported annually in the Living Planet Report (WWF 2012) and used as an advocacy tool. Other ecological indexes include the Falkenmark water stress indicator (Falkenmark 1997), which measures per capita water availability, the Biodiversity Intactness Index, which compares the biodiversity of a region relative to its 'pristine' state (Scholes and Biggs 2005) and the Human Appropriation of Net Primary Productivity, which measures human consumption of food, paper, wood and fibre (Erb et al. 2009). Table 2.3 summarises the main ecological indexes.

Table 2.3 Ecological indexes

	Ecological Footprint	Water Footprint	Carbon Footprint*	Living Planet Index
Ecosystem component	Biosphere	Hydrosphere	Atmosphere	Vertebrate species
Sectors	Agriculture, Forestry, Fisheries, Energy	Water	Energy	biodiversity
Indicators	6	1	1	14,152
Accounting approach	Demand vs supply	Consumption	Consumption	Gain/loss
Units	Global hectares (gha)	Million cubic metres per year (Mm ³ /yr)	Kilograms of carbon dioxide equivalent (kg CO ₂ e)	Value between 0 and 1
Time range	1961-2012	1996-2005	2001-2010	1970-2012
Number of countries	240	140	113	Regions only
Data sources	FAOSTAT, COMTRADE, FishSTAT, IEA, government statistics	FAO, PC-TAS, WTO, World Bank	UN, OECD, GTAP, IEA and others	Living Planet Database
Primary Application	Identify physical limits and support planning for government and sectors	Identify linkages; behaviour change of consumers and companies	Climate change mitigation in companies	Global awareness and behaviour change
Reporting	Annually by the Global Footprint Network	Annually by some organisations	Annually by some organisations	Every 2 years by WWF

*Methodology is not yet standardised and/or robust

2.2.4 Combined indexes

Some indexes combine ecological and social indicators. The Environmental Performance Index (EPI), developed at Yale University, has been used since 2006 to measure government performance on 19 indicators of 'environmental stresses on human health' and 'ecosystem vitality'; the 2016 report provided a ranking of 180 countries (Hsu et al. 2016). The Sustainable Society Index was developed by the Sustainable Society Foundation in 2006 to measure national sustainability using 21 indicators across three domains – human well-being, environmental well-being and economic well-being; the 2016 report ranked 154 countries (van de Kerk et al. 2014). It is also being used to measure regional and city sustainability. Unlike other indexes it does not use a single index but rather uses three. The Eco-sustainable Human Development Index, which combines the Ecological Footprint and the HDI (Türe 2013), although this is already being done by the Global Footprint Network to show the status of different countries and regions compared to a global sustainability goal.

Most recently, the Sustainable Development Solutions Network (SDSN), launched by the UN in 2012 to mobilise global scientific and technological expertise to promote practical problem solving for sustainable development, published an unofficial SDG Index and Dashboard as an analytical tool to assist countries with implementing the SDGs. In the 2016 report, 63 indicators were reported for 149 countries, using the official SDG indicators where possible and filling in gaps in data availability with variables published by reputable sources (Sachs et al. 2016). The SDG Index is an adjusted indicator score that ranks countries between the worst (0) and best (100) cases. The average score for all indicators for each SDG is

plotted on a radar chart, similar to the SJS social foundation (in Figure 1.3b) but with the upper boundary representing the best achieving country. The SDG Dashboard colour codes each goal, indicating whether the country has already achieved the goal (green), is in a “caution lane” (yellow), or is seriously far from achievement as of 2015 (red). The SDG Index radar plot and dashboard for South Africa in 2016 are shown in Figure 2.2 and Figure 2.3. South Africa’s performance on the other indexes is given in Table 2.4 (Solt 2009; Mekonnen and Hoekstra 2011; Alkire and Robles 2016; Hsu et al. 2016; UNDP 2016; Global Footprint Network 2017). A detailed description of the indicators and indexes that are actually used in South Africa is given in the next section.

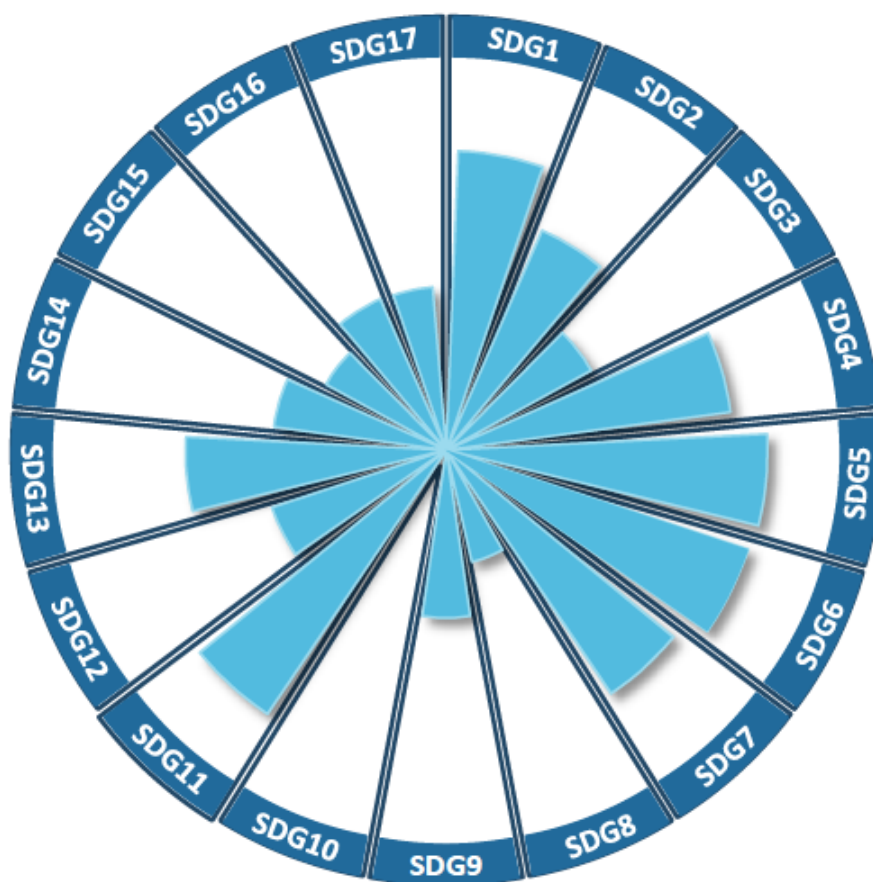


Figure 2.2 Unofficial SDG Index performance for South Africa in 2016 (Sachs et al. 2016)



Figure 2.3 Unofficial SDG Dashboard for South Africa (Sachs et al., 2016)

Table 2.4 South Africa's performance on commonly-used indexes

Index	Score or value	Ideal score	Ranking	Year
Human Development Index	0.67	1	123/193	2016
Gini index	0.63	0	97/100	2009
Multidimensional Poverty Index	0.044	0	42/103	2016
Energy Development Index	0.681	1	11/64	2009
Digital Access Index	0.45	1	78/181	2002
Ecological Footprint	3.31 gha/person	-	74 /188	2016
Water Footprint	1,255 m ³ /yr/capita	-	-	2011
Environmental Performance Index	70.5	100	81/180	2016
SDG Index	53.8	100	99/149	2016

2.3 South Africa's sustainable development reporting

South Africa journey towards sustainability reporting is shown in Box 2. The first attempt at compiling a coherent picture of the state of the environment was made

in 1992, in a national report to the UN Conference on Environment and Development (DEA 1992). While this reported a wide range of data on the environment, there were no indicators *per se*. The UN Commission on Sustainable Development only approved a 'Programme of Work on Indicators of Sustainable Development' in 1995 and the South African Department for Environmental Affairs and Tourism (DEAT) became involved in indicator testing in 1996. The first indicator report was published in 1998, presenting data for 134 indicators in the four categories economic, social, environmental and institutional (DEAT 1998). A year later the DEAT launched the first State of Environment reports and in 2009 the annual Environmental Sustainability Indicators (ESI) Technical Report were launched by the Department of Environmental Affairs (DEA). The ESI indicator selection was based on the DPSIR framework, Yale's EPI, and a national consultation process involving a wide range of stakeholders. It reports 45 indicators in five categories: state of environmental systems, environmental stresses, human vulnerability to environmental change, social and institutional capacity to cope, and capability to respond to global stewardship collectively. The categories of the ESI highlight the shift in thinking from listing indicators for the three or four pillars of sustainable development, to providing indicators to deal with the challenges of the 21st century. The most relevant ESI indicators for this thesis are given in Table 2.5. More detailed sector-specific indicators can be found in other national reports shown in Table 2.6.

Box 2. The development of sustainability indicators for South Africa

- 1972 Attended 1st UN Conference on Environment and Development (UNCED)
- 1992 Attended UNCED conference in Rio de Janeiro
- 1992 UN Commission on Sustainable Development (UNCSD) created
- 1995 UNCSD approved Programme of Work on Indicators of Sustainable Development
- 1996 UNCSD indicator testing process engagement – South African Department for Environmental Affairs and Tourism (DEAT) became involved
- 1997 UNCSD process started for 134 indicators
- 1998 DEAT report to UNCSD on indicator testing
- 1999 DEAT launched 1st National State of the Environment (SOE) report and 4 city SOE reports
- 2002 Hosted World Summit on Sustainable Development
- 2002 DEAT published 'Environmental Indicators for National State of the Environment Reporting'
- 2004 DEAT published 'Development of a Core Set of Environmental Performance Indicators'
- 2005 DEAT published UNCSD Country Report
- 2006 DEAT published 'Provisional Environmental Headline Indicators'
- 2006 DEAT published 2nd SOE report '2006 South Africa Environment Outlook'
- 2008 DEAT published National Framework for Sustainable Development
- 2008 DEAT published 1st Environmental Sustainability Indicators (ESI) report
- 2008 SADC published 1st 'Southern Africa Environment Outlook' report
- 2009 DEAT became Department for Environmental Affairs (DEA)
- 2010 DEA published 2009 ESI technical report
- 2012 DEA published 2010 ESI technical report
- 2011 DEA published National Strategy for Sustainable Development
- 2013 DEA published 2011 ESI technical report
- 2013 DEA drafted 'ESI Impact Assessment Report'
- 2014 DEA published 2012 ESI technical report
- 2016 DEA published 3rd SOE report '2012 South Africa Environment Outlook'

Table 2.5 Selected indicators in South Africa's annual Environmental Sustainability Indicators technical report

Dimension	Environmental Sustainability Indicators
Climate change	Annual CO ₂ direct emissions (total and per capita)
Ozone depletion	Annual production of CFCs, MBr and HCFCs Annual consumption of CFCs, MBr and HCFCs
Biodiversity loss	Threatened bird, mammal, amphibian and reptile species (%) Threat and protection status of vegetation types per biome (%)
Nitrogen and Phosphorus cycles	Fertiliser sales (kg)
	Freshwater quality – Total phosphate concentration in dams (P mg/l)
	Freshwater quality – Orthophosphate concentration in dams (PO ₄ mg/l)
Marine harvesting	West coast rock lobster landings (t) Catches of selected marine species (kg/nominal mass) Marine protected areas (status)
Freshwater use	Available water per capita (m ³) Capacity and levels of dams (m ³) Groundwater quantity (distance below ground level) Water stress per WMA in 2025 (yield v requirements)
Land use	Degraded and transformed land (%) Grazing capacity (ha/livestock) Protected land area (%)
Air pollution	Domestic fuel burning (Households by energy source for cooking & heating & lighting) Coal consumption (TJ) Vehicle use (vehicles/area) Death rate from respiratory diseases and TB

Table 2.6 Existing national reports on environmental indicators in South Africa

Title	Years reported	Department
Environment Outlook	1999, 2006, 2013	DEA
Environmental Sustainability Indicators	2008-2012	DEA
National Biodiversity Assessment	2004, 2011	South African National Biodiversity Institute
Greenhouse Gas Inventory	2009	DEA
State of the Climate	2008	DEA
State of Air	2011-2015	DEA
National Eutrophication Monitoring Programme	2002-2016	DEA
State of Rivers	1998-2011	Dept. of Water Affairs
State of the Coast	2006	DEA
State of Marine Fishery Resources	2010, 2012, 2014	Dept. of Agriculture, Forestry and Fisheries
State of the Oceans and Coasts	2014, 2015	DEA
Agricultural survey	2007, 2011, 2013, 2014	StatsSA
Land cover	1994, 2000, 2005, 2009	Agricultural Research Council
Land capability	2002, 2013	Dept. of Agriculture, Forestry and Fisheries

Since 1994, in parallel to the environmental sustainability reporting, there has been a large amount of reporting on social indicators, largely driven by the need to address the legacies of Apartheid. South Africa has a respected national statistics organisation, Statistics South Africa (StatsSA) which publishes numerous statistical reports on a monthly, quarterly, annual and ad hoc basis as well as a national census every ten years. The most relevant ones for this thesis are shown in Table 2.7. The Department of Planning, Monitoring and Evaluation (DPME) publishes an annual Development Indicators report on the state and change since 1994 of 86 indicators covering economic growth and transformation, employment, poverty and

inequality, household and community assets, health, education, social cohesion, safety and security, international relations and good governance (DPME 2015). It is used as a strategic document for medium-term planning purposes. The South African Index of Multiple Deprivation (SAIMD) was developed by the University of Oxford, South Africa's Human Sciences Research Council and Department of Social Development (DSD) to identify the most deprived areas to target social grants and initiatives at the small area level (Wright and Noble 2009). SAIMD has five deprivation domains - Income and Material, Employment, Health, Education, Living Environment – and 10 indicators shown in Table 2.8. It used data from the 2001 Census and the 2007 Community Survey.

Table 2.7 Selected national reports on social indicators in South Africa

Title	Years Reported	Department
Census	1996, 2001, 2011	StatsSA
General Household Survey	2002-2015	StatsSA
MDG Country Report	2005, 2007, 2010, 2013	StatsSA
Development Indicators	2008-2014	DPME
South African Index of Multiple Deprivation	2001, 2007	DSD
Multidimensional Poverty Index	2014	StatsSA
Quarterly Labour Force Survey	2000-2017	StatsSA
Living Conditions Survey	2007/8, 2014/15	StatsSA
Victims of Crime Survey	1997, 2011-2014	StatsSA
Community Survey	2007, 2016	StatsSA
Demographic and Health Survey	1998, 2003, 2016	StatsSA

Table 2.8 Indicators for the South African Index for Multiple Deprivation

Dimension	Indicators
Living environment	Number of people living in a household without use of electricity for lighting
	Number of people living in a household without piped water inside their dwelling or yard
	Number of people living in a household without a pit latrine with ventilation or flush toilet
	Number of people living in a shack, or in a household that is crowded
Education	Number of adults (18-65 years) with no secondary schooling
Health	Years of Potential Life Lost ^a (standardised mortality ratio)
Employment	Number of people who are unemployed (using official definition) plus Number of people who are not working because of illness or disability
Income and Material	Number of people living in a household that has a household income (need-adjusted using the modified OECD equivalence scale) that is below 40% of the mean equivalent household income (~ R1,003/month in February 2007 Rands) ^a
	Number of people living in a household without a refrigerator
	Number of people living in a household with neither a television nor a radio
Safety	<i>Not defined</i> ^c

^a In SAIMD 2001 but not in SAIMD 2007. ^b A national poverty line had not yet been defined.

^c The intention was to include crime but it was excluded due to lack of data.

2.4 Environmental limits

The concept of environmental limits has been in the literature since Meadows *et al.* (1972) published *The Limits to Growth* in 1972 which described their search for a 'model output that represents a world system that is sustainable without sudden and uncontrolled collapse and capable of satisfying the basic material requirements of all of its people'. Based on their modelling, they argued that economic growth could not be sustained indefinitely. An environmental limit is a critical level of damage to a natural resource system due to external pressures, that is no longer

tolerable or acceptable (Haines-Young et al. 2006). Therefore, while the limit is based on biophysical properties, it also depends on how people value the benefits of the natural resource system. When a natural system exhibits a 'regime shift' from a stable state to an alternative state, the environmental limit is called a critical threshold (Scheffer et al. 2001; Scheffer and Carpenter 2003). Regime shifts, or critical transitions, are often referred to as abrupt (in that the rate of response is considerably greater than the rate at which the driving factors change), but many unfold slowly in absolute terms after a threshold is transgressed (Hughes et al. 2013b). Evidence of critical transitions or tipping points in Earth systems exist at multiple scales and complex systems science is currently investigating the causes of these tipping points and uncovering indicators of the proximity to the thresholds (Scheffer et al. 2012). Evidence suggests that when thresholds are crossed, it may be difficult to return systems to their former state. Due to the natural variability and the uncertainties in understanding of the behaviour of natural resource systems, a 'precautionary approach' is often adopted to the definition of environmental limits and the setting of environmental targets.

While environmental limits and thresholds exist at multiple spatial scales, the global scale has received increasing attention. A new geological epoch in Earth's history, termed the Anthropocene has been proposed, where humanity is the main driving force of change in the Earth system (Steffen et al. 2007; Steffen et al. 2011). The iconic symbols of the Anthropocene are Steffen *et al.*'s 24 graphs plotting the trajectory from 1750 to 2000 of 12 key indicators of socio-economic development and 12 key indicators of Earth system functioning (Steffen et al. 2004). These graphs identified a dramatic change in the magnitude and rate of change of all the

indicators from about 1950 onwards which has since been termed the 'Great Acceleration' and used to illustrate the 'emergent, planetary-scale coupling, via globalisation, between the socio-economic system and the biophysical Earth System' (Steffen et al. 2015a). Over 40% of land has been converted to agricultural land or urban landscapes (Foley et al. 2011) and CO₂ concentrations are 35% higher than pre-industrial times (IPCC 2007). These planetary-scale state-shifts in the biosphere are due to population growth, resource consumption, land use change and climate change (Barnosky et al. 2012).

In 2009, the concept of global environmental limits and thresholds was framed as a set of 'planetary boundaries' (PBs) by a group of 28 global environmental change and resilience science experts (Rockström et al. 2009a; Rockström et al. 2009b). The PBs propose a safe distance from critical thresholds for nine Earth system processes; climate change, ozone depletion, freshwater use, land use change, phosphorus and nitrogen cycles, biodiversity loss, ocean acidification, aerosol loading and chemical pollution (Rockström et al. 2009a). The authors argued that when these PBs are crossed, the planet's ability to support human life could be disrupted. The PBs have fostered much academic debate about environmental limits. Concerns have been raised about the existence of global tipping points for some of the dimensions (Bass 2009; Molden 2009; Brook et al. 2013) and some of the specific metrics used (Samper 2009; Molina 2009; Schlesinger 2009; Biello 2012; Lewis 2012; Running 2012). A refined phosphorus boundary has been proposed (Carpenter and Bennett 2011) and a new boundary, Net Primary Productivity (NPP) was proposed (Running 2012), though Foley (2012) argues that NPP is a defined limit rather than a tipping point. There have been several attempts

to clarify the PB concept (Lenton et al. 2008; Foley 2010; Hughes et al. 2013a) and studies on the interactions between different Earth system processes used in the PB (Rockström and Karlberg 2010; Rockström et al. 2012). The large and varied response to the original PB paper shows that the field of environmental limits is complex and requires further research.

In 2015 an updated and improved version of the PBs was published (Steffen et al. 2015b) which adds regional (sub-global) boundaries to complement the planetary ones and acknowledges that there are 'strong arguments for planetary boundary thinking at levels where policy action most commonly occurs'. The case studies on downscaling the PB show that there are challenges to defining safe boundaries at national scales. Nykvist *et al.* (2013) and Hoff *et al.* use (2014) an equal share per capita approach while Dao *et al.* (2015) refine this approach by calculating budgets over time allocation so historical use can be accounted for and by considering countries as indirect allocation pathways for individuals to reduce the role of global demographics. The latter approach acknowledges Shue's (1999) Contraction and Convergence model and the Greenhouse Development Rights Framework (Baer et al. 2008). Although it takes one aspect of equity into account, it still does not fully address the principle of 'common but differentiated responsibilities and respective capabilities' that is fundamental to the UN conventions. None of these burden-sharing approaches would be accepted by developing countries in an international agreement. This thesis contributes to the PB scholarship by providing a developing country perspective on downscaling the planetary boundaries in Chapter 3.

2.5 Social floors

The concept of environmental limits can be extended to the social dimension of sustainable development. White (2004) defined a social minimum as ‘the bundle of resources that a person needs in order to lead a minimally decent life in their society’. The definition of what a person needs has been much debated. White (2004) identifies three main approaches: Bentham’s Welfarism which measures happiness (Baujard 2010), Sen’s Capability Approach which measures capabilities (Gasper 1997; Sen 2005), and Rawls’ and Dworkin’s Resourcism which measures income or wealth (Rawls 1971; Dworkin 1985). There are also legal approaches to social minimums based on the International Bill of Human Rights which consists of the 1948 Universal Declaration of Human Rights adopted (UN General Assembly 1948), the first global expression of rights to which all human beings are entitled, the International Covenant on Economic, Social and Cultural Rights (UN General Assembly 1966a) and the International Covenant on Civil and Political Rights (UN General Assembly 1966b). The human rights can be categorized as civil, political, economic, social and cultural and include the right to life, safety and security, adequate food, housing, health, work and education.

The Conventions do not define ‘adequate’ and two approaches to defining poverty can be used. Absolute poverty refers to severe deprivation of basic human needs, and poverty levels were agreed at the World Summit for Social Development in 1995 (World Summit for Social Development 1995). The most well-known example of an absolute poverty measure is ‘living on less than US\$1 per day’. Relative poverty, on the other hand, refers to exclusion from ordinary living patterns, customs and activities due to lack of resources (Townsend 1987). A socially

acceptable minimum standard of living can be set higher or lower than the customary, or average, standard of living, depending on the context (Noble et al. 2008).

Although the concepts of basic human rights and absolute or relative poverty are not new, the idea of national and global social floors only entered the global development policy agenda in the past decade (Voipio 2010). It builds on work by Townsend who pioneered the idea that poverty is a multi-dimensional challenge that requires multi-dimensional solutions (Townsend 1987). Townsend highlighted the importance of the local context when he defined deprivation as ‘a state of observable and demonstrable disadvantage relative to the local community or the wider society’ (Townsend 1987). This definition implies that poverty is not a binary state but rather that there are different levels of poverty within a society. In 2004, the World Commission on the Social Dimension of Globalization, established by the International Labour Organisation (ILO), concluded that a “minimum level of social protection needs to be accepted and undisputed as part of the socio-economic floor of the global economy” (ILO 2004). This informed the concept of a social protection floor and led to the One-UN Social Protection Floor Initiative which has a stated goal that “no one should live below a certain income level, and everyone should have access to essential public services such as water and sanitation, health and education” (ILO 2011). The aim of social protection is to reduce the impact of economic shocks among the vulnerable population, to serve as a macroeconomic stabiliser fuelling demand, and to enable people to better overcome poverty and social exclusion (ILO 2011). The ILO’s social protection floor approach involves a set of policies that seek to guarantee basic income security

and universal access to essential affordable social services, including health, water, sanitation, education, housing and food security. This idea has been included in the SDGs where SDG 1.3 calls for national measures of social floors (UN General Assembly 2015). South Africa's National Development Plan also aims to develop national social floors for the country and these are discussed for a set of 12 dimensions in Chapters 3 and 4, and specifically for water access in Chapter 5 of this thesis. The thesis chapters contribute to the scholarship on measuring multiple deprivation and defining relative deprivation.

2.6 Data visualisation

Sustainable development indicators are regularly made more visually appealing in maps, such as water poverty mapping e.g. (Cullis 2005), graphs, such as the Great Acceleration (Steffen et al. 2004), quantified metaphors, such as footprints (Moran et al. 2008) and dashboards, such as the Dashboard of Sustainability (IISD 2007) and the SDG Dashboard (Figure 2.3). The planetary boundaries concept gained traction partly due to its compelling visual image (Figure 1.2) that showed where global environmental limits have been transgressed. Raworth built on the visual image by showing graphically how far below the global social floor humanity is on different socio-economic dimensions, but more importantly, showing the concept of a 'safe and just space' as a doughnut-shaped global goal for humanity. The concept is commonly known as 'the doughnut' because of this powerful visual image (Figure 1.1). In downscaling the PBs or the SJS, the visual element therefore needs to be considered.

McInerny *et al.* (2014) believe that visualisations and graphics are fundamental to studying complex subject matter and should be among the main priorities for modern science and science policy and should support the whole information pipeline. There is currently an information gap between the wealth of data and information, and scientists' ability to study it and subsequently communicate it effectively to a range of users and stakeholders (Lubchenco 1998; Smith *et al.* 2013). The challenge is for scientists to move beyond communicating facts towards empowering understanding (Garnett and Lindenmayer 2011).

The objectives of data visualisations are to get the audience's attention (Spiegelhalter *et al.* 2011), to inform, to alter feelings, to change behaviour or to weigh possible benefits and consequences (Lipkus 2007). Some visualisations communicate detailed numerical information while others merely seek to convey a message (Nelson *et al.* 2009). It is important to be clear on the audience and desired outcome before designing the visualisation, as graphics can be tailored to the audience (Lipkus and Hollands 1999) and features that improve accuracy are different from features that induce behaviour change (Ancker *et al.* 2006). Effective graphics can summarise data concisely, highlight hidden patterns (Lipkus and Hollands 1999), gain and hold attention (Smerecnik *et al.* 2010), enliven information and arouse emotions ranging from inspiration to risk aversion (Visschers *et al.* 2009). They can create the impression of truth (Boggs 1949) while poor graphics are perceived to have a lower value or reputation (Thorndike 1920). Science-policy audiences are highly diverse and scientific outputs make numerous assumptions about their numeracy, vocabulary, expertise and level of interest (McInerny *et al.* 2014). A crucial issue in presenting information is the choice of perspective, known

as framing (Spiegelhalter et al. 2011). Data can be presented in a negative or positive light, for example, '30% of people live below the poverty line' compared to '70% of people live above the poverty line'. This can influence how the audience responds to the information.

Typically data is visualised using pie charts for simple proportions, bar charts for conveying magnitude and for comparisons, icon arrays for part-to-whole relationships and line graphs for trends (Spiegelhalter et al. 2011) while maps are used for comparing data across regions. Infographics – data visualisations aimed at a non-technical audience – have become common as the internet has made available online data and the public has shown more interest in quantitative information (Spiegelhalter et al. 2011). They have a strong creative element and many have interactive features which promote understanding and retention (Strecher et al. 1999; Bostrom et al. 2008).

This thesis uses data visualisation in all four case studies presented in Chapters 3 to 6 to support communication, advocacy and science-policy dialogue. It contributes to the scholarship on visualising sustainable development and on operationalising the PB.

2.7 The challenge of scale

Central to the challenge of sustainability is the challenge of scale. Agenda 2030 (UN General Assembly 2015) refers to scale (sub-national, national, regional and global) 32 times, particularly in the SDG goals and targets. There is widespread agreement that explanatory variables for a given phenomenon change as the scale of analysis changes (Gibson et al. 2000). The failure to account for scale and cross-

scale dynamics in human-environment systems in policy, management and assessment has led to numerous environmental problems, such as transboundary pollution problems, collapsing fisheries and vulnerability to repeated floods and droughts (Millennium Ecosystem Assessment 2005). The scale-based organisation of natural resources (such as water) that cross territorial boundaries proves to be one of the most intractable, yet most important tasks of environmental governance (Kaika 2003). The benefits of recognising scale challenges in policy integration have been well documented and cross-scale opportunities have led to improvements in public health and education, agricultural production, policy innovations, and business management strategies (Cash et al. 2006).

While the natural sciences have long understood the importance of scale, research in the social sciences has been less explicit, less precise, and more variable (Kok and Veldkamp 2011). Scaling issues were introduced by Allen and Starr's (1982) 'Hierarchy Theory' but the new research paradigm advocates cross-scale, integrated methods that include stakeholders, with the notion of the complex social-ecological system as a central concept (Kok and Veldkamp 2011). The concept of 'multilevel governance' has been in the literature since the 1990s, highlighting the multilevel or multiscale character of societal problems and the corresponding need to address these problems at multiple levels (Kok and Veldkamp 2011).

Different disciplines make different uses of the concept of scale – generally scale denotes a certain analytical dimension (e.g. hydrological), or a spatial level (e.g. local). Gibson *et al.* (2000) define 'scale' as the spatial, temporal, quantitative, or analytical dimensions used to measure and study any phenomenon. They define

'levels' as the units of analysis that are located at different positions on a scale and 'hierarchy' as a conceptually or causally linked system for grouping phenomena along an analytical scale. 'Cross-level' interactions occur among levels within a scale and 'cross-scale' interactions occur among different scales, leading to substantial complexity in system dynamics (Cash et al. 2006). The most studied scales are spatial scales (geographical space where phenomena occur over a continuous range of levels), temporal scales (can be divided into time frames related to rates, durations and frequencies) and jurisdictional scales (clearly bounded and organised political units, e.g. states or provinces, and nations), though institutional, management, network and knowledge scales have also been identified (Cash et al. 2006).

Cash *et al.* (2006) identified three common societal challenges related to scale: ignorance, mismatch and plurality. Ignorance is the failure to recognise important scale and level interactions due to their complexity. Examples are national policies that adversely constrain local policies, local actions that aggregate into large-scale problems, and short-term solutions that aggregate into long-term problems. Mismatch is the problem of fit involving human institutions that do not map coherently on to the biogeophysical scale of the resource, either in space or time (Gibson et al. 2000). Typical problems are transboundary pollution, migration of fisheries and aquifer management. Another example is the challenge of matching the scale of what is known about the world (scientific or indigenous knowledge) and the scale at which decisions are made and action taken (Kates et al. 2001). Plurality is the failure to recognise heterogeneity in the way that knowledge and scales are perceived and valued (as salient, credible, legitimate or important) by different

actors, even at the same level. Examples include global environmental issues that make effective institutional solutions invisible by defining the problem as “global only”.

Gibson *et al.* (2000) listed the most important science research issues related to scale as: (1) how scale affects the identification of patterns and problems – patterns that appear at one level may be lost at higher or lower levels; (2) how scale affects the explanation of observed patterns and social phenomena; (3) how propositions made at one level of a scale may be generalised and applied to another level of the same scale; and (4) how processes or functions can be optimised at points or regions on a scale. These four issues are addressed in the following four case studies described in Chapters 3 to 6.

This literature review has shown that the field of sustainability science is an evolving one with a focus on addressing the challenges of the day. The utility of SDIs has been widely recognised and they are an important tool for policy-makers and decision-makers across the world. The South African government has a 20-year history in developing SDIs and has incorporated international best practice in national reporting. South Africa’s National Development Plan calls for measuring of the state of natural resources and social floors, and the PB and SJS concepts have been used in the latest South Africa Environment Outlook to frame the sustainable development challenge. The literature on environmental limits highlights the biophysical and social components of defining safe limits, and describes the scientific debate around the planetary boundaries concept. The literature on social floors shows that while the term is relatively new it is based on decades of debate

on human rights, which encompass different conceptual approaches and numerous dimensions that could be measured. Data visualization is shown to be more useful and necessary than ever before, and different graphics and approaches are described. Finally, the importance of scale is discussed and challenges and research areas are described. The literature review has revealed that there is value in applying the PB and SJS frameworks to national and sub-national scales, to address the challenges of scale and provide visual SDI tools for policy and decision-makers.

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Linking statement – Chapter 2 to 3

The first step in achieving the overall aim of the thesis was to test whether the planetary boundaries concept and the 'safe and just space' could be usefully applied at the national scale. South Africa was chosen as a case study due to its large, good quality datasets, ecological megadiversity and high levels of poverty, and its influential role on the African continent and globally through its association with other BRICS countries. The study evaluated both whether it was possible to adapt the framework to suit the national scale, and whether South African experts believed that it would be a useful tool in the national context.

This chapter addresses the first research question of the thesis, 'Can the visual framework, the 'safe and just space for inclusive sustainable development', be usefully applied at the national level? It describes how the SJS framework was downscaled from the global level to the national level to create a visual 'barometer of inclusive sustainable development for South Africa'. This involved determining nationally-relevant dimensions, indicators, status and boundaries and adapting the PB and SJS diagrams. This provides a visual summary of the state of key national SDIs. In addition, a decision-based methodology was developed to ensure that the process was repeatable. Semi-structured interviews with 43 experts in South Africa contributed to the definition of indicators and boundaries, and evaluated the utility of the SJS in South Africa.

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Chapter 3 – Tracking sustainable development with a national barometer for South Africa using a downscaled ‘safe and just space’ framework

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Abstract

Nations in the 21st century face a complex mix of environmental and social challenges, as highlighted by the on-going Sustainable Development Goals process. The ‘planetary boundaries’ concept (1), and its extension through the addition of social well-being indicators to create a framework for ‘safe and just’ inclusive sustainable development (2, 3), have received considerable attention in science and policy circles. As the chief aim of this framework is to influence public policy, and this happens largely at the national level, we assess whether it can be used at the national scale, using South Africa as a test case. We have developed a decision-based methodology for downscaling the framework and created a national ‘barometer’ for South Africa, combining 20 indicators and boundaries for environmental stress and social deprivation. We find that it is possible to maintain the original design and concept of the framework whilst making it meaningful in the

national context, raising new questions and identifying priority areas for national action. Our results show that South Africa has exceeded its environmental boundaries for biodiversity loss, marine harvesting, freshwater use and climate change, and that social deprivation is most severe in the areas of safety, income and employment. Trends since 1994 show improvement in nearly all social indicators, but progression towards or over boundaries for most environmental indicators. The barometer shows that achieving inclusive sustainable development in South Africa requires both national and global action on multiple fronts, and careful consideration of the interplay between different environmental domains and development strategies.

Key words: sustainable development, South Africa, planetary boundaries, social deprivation, sustainable development goals

3.1 Introduction

Human impact on the Earth's biophysical processes and resources is a global concern. It is seen by many as a new geological era, the Anthropocene (4), with natural resource consumption accelerating in the past 50 years - food, freshwater and fossil fuel use have more than tripled (5) - and these trends are likely to continue as global population grows to 9.55 billion in 2050 (6). This concern has led to international treaties that seek to address global environmental challenges through negotiation and agreement amongst the nations of the world, such as the United Nations (UN) Convention for the Protection of the Ozone Layer, the UN Convention on Biological Diversity (UNCBD), and the UN Framework Convention on Climate Change (UNFCCC). It has also led to the proliferation of sustainable

development indicators (SDIs). The outcome of the 1992 UN Conference on Environment and Development, Agenda 21, calls for SDIs to 'provide solid bases for decision-making at all levels and to contribute to a self-regulating sustainability of integrated environment and development system' (7). Over 900 SDI initiatives have been undertaken to date (8) in recognition of the fact that indicators provide a quantitative and rational basis for decision making (9), simplify a complex reality to a manageable level (10), create a body of knowledge and comparable data for policy applications, measure progress (11), and allow the public to evaluate society and its leaders (12). Individual indexes, such as the Human Development Index and the Ecological Footprint, have been used to compare countries, and sustainability frameworks, such as Ostrom's framework for social-ecological systems (13) and the 'ecosystems approach' adopted by the UNCBD (14), have been developed to better understand the relationships between social and ecological systems.

In 2009 a new conceptual framework 'planetary boundaries' was proposed by Rockström *et al.* (1, 15) as 'a bid to reform environmental governance at multiple scales' (16). The planetary boundaries are an estimated 'safe distance' from thresholds associated with nine global environmental change processes which, when crossed, will take humanity into uncharted environmental territory (15). The nine processes (or dimensions) are climate change, ocean acidification, freshwater use, land use change, biodiversity loss, nutrient cycles (nitrogen and phosphorus), ozone depletion, atmospheric aerosol loading and chemical pollution. Three of these global boundaries (climate change, biodiversity loss and nitrogen fixation) have been transgressed and several others are in danger of being exceeded. The

authors proposed there should be a global goal to stay within the ‘safe operating space for humanity’, defined by these boundaries.

Despite a mixed reaction from the academic community, who have raised concerns about the existence of global tipping points for some of the dimensions (17–19) and the specific metrics used (20–25), the ‘planetary boundaries’ concept has been used in proposals for defining the UN Sustainable Development Goals (SDGs) (26–28). The SDGs will guide the international sustainable development agenda after 2015 and they represent an opportunity for science to inform policy making (29–31), for the UN to implement the lessons from the Millennium Development Goals (MDGs) and to expand them to include all countries, and for greater integration of environmental and social metrics in decision-making. In this context, the planetary boundaries concept was extended by Raworth (2) to include a set of 11 social dimensions, defining ‘a social foundation’ below which exists unacceptable human deprivation. This highlighted the notion that access to the benefits of natural resources is also of global concern and Raworth (2) argued that ending current global deprivation could be achieved with a minimal impact on the planetary boundaries. Raworth reframed Rockström *et al.*’s planetary boundaries concept as a ‘safe and just space for humanity’; this new framework brought together the dual objectives of poverty eradication and environmental sustainability as socio-economic priorities (2).

Raworth’s ‘safe and just space’ (SJS) framework has gained interest from the UN General Assembly (32), policy think tanks (e.g. (33)) and development agencies (e.g. (34)) as it provides a platform for integrated analysis and debate about global

goals. It appears in the Worldwatch Institute's latest State of the World report (35) and Griggs *et al.* (27) have since developed a similar framework to reframe the UN paradigm of three pillars of sustainable development as a nested concept.

However, social and environmental concerns are intrinsically scale-dependent and need to take local circumstances into account if they are to be acted upon by national governments, which are ultimately responsible for taking action. The downscaling of the SJS to sub-global spatial scales, with heterogeneity of biophysical and social conditions and the instruments of governance, is not straightforward. The particular challenges for the biophysical dimensions are highlighted by Nykvist *et al.* (36) who assessed national 'environmental performance' on four planetary boundaries (climate change, water, land and nitrogen) for 60 countries. As the chief aim of the SJS is to influence public policy, and this happens largely at the national level, our objective in this paper is to assess whether the SJS concept can be used at the national scale, using South Africa as a test case.

In this paper we first review the SJS concept and explore how it might be applied at the national scale. We then present a decision-based methodology and results for our case study on South Africa. Finally we discuss the applicability of the tool in South Africa, the local-regional-global links and the SDGs, and the data limitations, scientific challenges and further research needs.

3.2 A 'safe operating space'

The focus of the planetary boundaries concept is staying within the 'safe operating space' in which human civilisations have developed i.e. the relatively stable biophysical conditions of the Holocene (the past ca.10,000 years). The concept combines global environmental change and resilience science, which focuses on understanding the effects of and response to abrupt change in social-ecological systems (SES) in the context of sustainable development (37). Resilience can be defined as the 'capacity of a SES to continually change and adapt yet remain within critical thresholds' (38). Crossing a planetary boundary represents a risk of moving from the current known state to a new unknown, and possibly dangerous, state. These boundaries could be (but are not necessarily) critical thresholds or tipping points beyond which systemic planetary-scale regime shifts (the Earth system processes involved being referred to as 'tipping elements' (39)) may occur or dangerous levels of environmental change may be reached. Critical transitions are often referred to as abrupt (in that the rate of response is considerably greater than the rate at which the driving factors change), but many unfold slowly in absolute terms after a threshold is transgressed (40). An important potential property of such shifts is 'hysteresis', which describes the need to reduce forcing back beyond threshold-crossing levels in order to return the system to its previous state (41).

Barnosky *et al.* (42) identified global-scale critical transitions in the Earth's past and pointed out that the current global-scale forcing mechanisms, such as resource consumption, far exceed the rate and magnitude of the most recent global-scale state shift of the last glacial-interglacial transition. They also argued that local-scale

drivers have accumulated to the extent that global-scale drivers have emerged; 38% of Earth's terrestrial surface has been converted to agricultural land (43), CO₂ concentrations are 35% higher than pre-industrial times (44), rates of nitrogen fixation have more than doubled (45), and ocean acidity has increased by a pH of 0.05 (46).

For the planetary boundaries, Rockström *et al.* distinguish between thresholds driven by systemic global scale processes impacting sub-systems 'top-down', such as climate change, and thresholds that may arise at the local scale which become a global concern when aggregated, impacting the global system 'bottom-up', such as freshwater use. They defined ten indicators to measure the state of their nine dimensions, noting that determining a safe boundary involves 'normative judgements of how societies choose to deal with risk and uncertainty'. As Cornell (47) pointed out, these indicators actually comprise a mix of system properties, which results in conceptual tensions. Nykvist *et al.* (36) used the Driving forces-Pressures-States-Impact-Response (DPSIR) framework to categorise the indicators as one driver (nitrogen), two pressures (phosphorus loading, freshwater use), six states (ozone depletion, climate change, ocean acidification, aerosol loading, land use change) and one impact (biodiversity loss). Each indicator has an associated (safe) boundary, defined using the precautionary principle given the notorious difficulty in predicting where critical thresholds lie in natural systems. Hughes *et al.* (48) have subsequently defined the boundaries as safe levels of drivers of environmental change. As all drivers of environmental change are essentially driven locally, boundaries could be determined at scales other than global, including the national scale, which is the focus of the present work.

3.3 A 'just space'

In Raworth's SJS framework, the term 'just' describes the avoidance of unacceptable human deprivation and extreme global inequality in the context of human rights. It focuses on the opportunities component of justice and supports Rawl's 'Difference Principle' (which promotes pro-poor distribution of social and economic benefits) as described by Sen (49). The SJS highlights the multidimensional nature of deprivation, thus it builds on work by Townsend (who pioneered the relative deprivation approach) and Sen's capabilities approach (50). Townsend defined deprivation as 'a state of observable and demonstrable disadvantage relative to the local community or the wider society' (51) and thus the local, national and global contexts are important when selecting deprivation indicators. International agreements for human needs are more clearly articulated and institutionalised than environmental needs (52) and date back to the 1948 Universal Declaration of Human Rights. The MDGs, which represent voluntary time-bound targets that developing countries are evaluated on until 2015 (53), have created global awareness for extreme poverty and mobilised funds and established new organisations to promote basic human rights (54).

Raworth's global 'social foundation' has 11 dimensions of wellbeing – food security, energy, water and sanitation, education, health care, income, jobs, voice, resilience, social equity and gender inequality. They were drawn from the national social development priorities in 80 government submissions to the UN Rio+20 Conference in 2012, and therefore are both global and national in nature. The dimensions are measured with deprivation indicators largely taken from the MDGs although Raworth specifically selected indicators that measure the percentage of

the total population who are deprived. The boundary for each indicator is argued to be zero deprivation, based on human rights, thus the selection of the indicator determines the just boundary of unacceptable deprivation. As the social foundation measures the wellbeing of a population, it can be scaled to any level, including the national scale, which we will show in this paper.

3.4 National case study: South Africa

We chose South Africa as our case study for testing the SJS framework at the national scale for three reasons. Firstly, it has large, good quality environmental and social datasets and established national research institutes, which enables rigorous analysis and debate. Secondly, as the largest economy in Africa (55), it is influential both on the continent and globally as part of the BRICS group of emerging economies, and research is more likely to be shared through South-South cooperation. Thirdly, it is ecologically megadiverse (56), has widespread poverty and extreme inequality (57) and this heterogeneity will provide a stringent test for the framework.

South Africa is one of the youngest democracies in the world, with elections in 1994 marking the end of white minority rule. Twenty years on, its planned development pathway is described in the 'National Development Plan' (58) which has two overarching goals - to eliminate income poverty and to reduce inequality by 2030. The National Climate Change Response Strategy has been a catalyst for mainstreaming environmental issues in South Africa and is supported by the National Strategy for Sustainable Development (59), which promotes stewardship of limited natural resources, and the Green Economy Accord (60) which focuses

on technology and job creation to meet development goals in a sustainable way. South Africa is a signatory to a number of international environmental treaties, including the Montreal Protocol, the UNCBD and the UNFCCC.

3.5 Summary of methodology

To apply the SJS framework at the national scale, we developed a decision-based methodology (Figure 3.1) to assess the environmental and social dimensions, indicators and boundaries in a repeatable and consistent way. Details are provided in the SI (S3.1 and S3.2) and are summarised here. Our criteria for selecting the dimensions were ‘Is this relevant at the national scale?’ and ‘Does the set of dimensions include the main environmental and social concerns in South Africa?’ Our criteria for indicator selection were: ‘Is the indicator the best available direct measure of that dimension?’, ‘Are there sufficient reliable data that are measured on a regular basis?’, and ‘Can a national boundary be determined?’ If the existing dimension or indicator did not meet the criteria then it was removed or replaced with a more appropriate national-scale choice. The data were taken from relevant national databases and reports, international databases and academic papers, and we sought expert judgment through semi-structured interviews with 43 South African experts from national, provincial and metropolitan government, national research institutes, universities and international NGOs (see SI, S3.3). The experts were identified based on their experience, academic and/or professional credibility and involvement in national policy-making, as well as through recommendations by other experts.

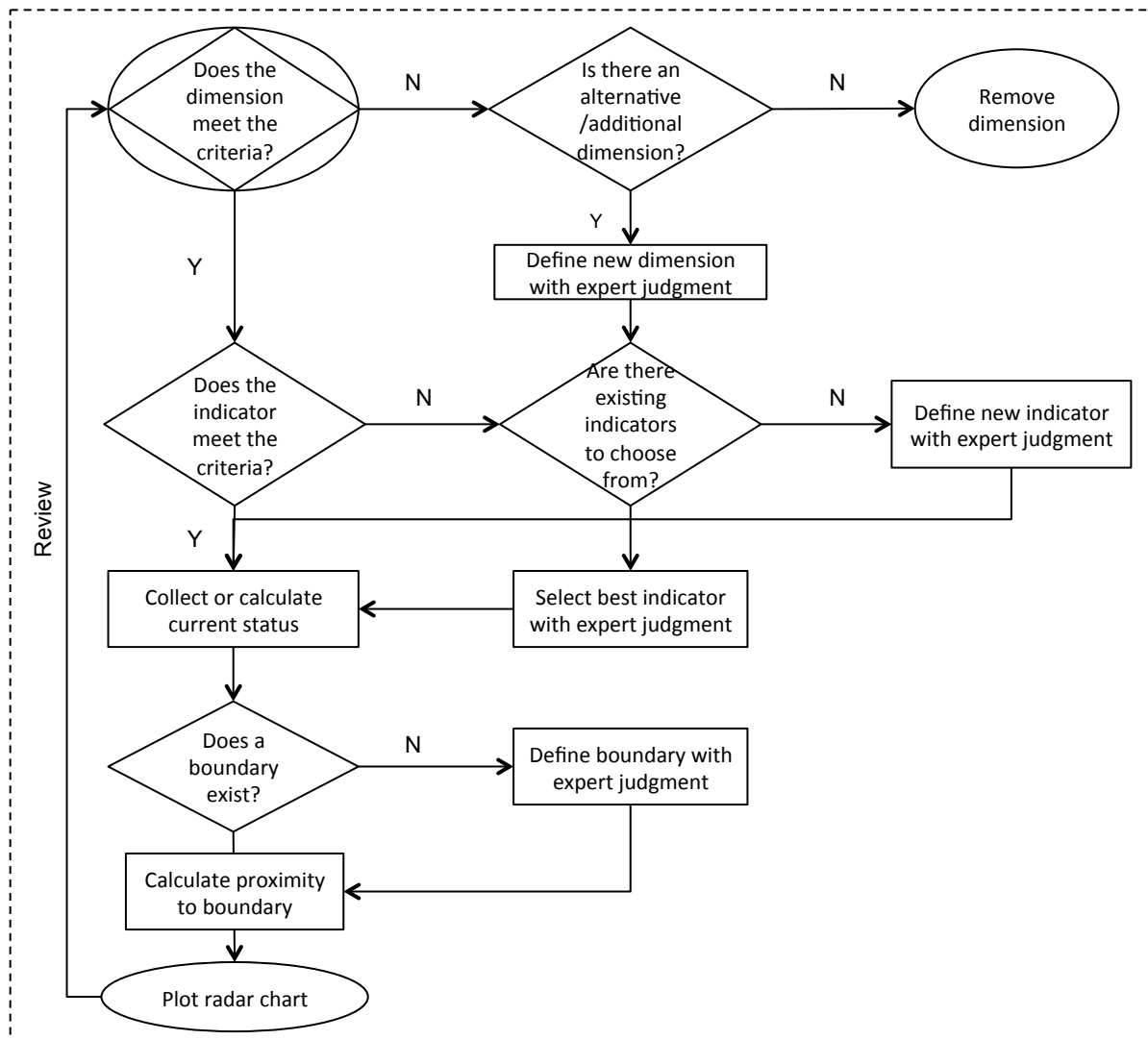


Figure 3.1 Decision-based methodology for selecting national dimensions, indicators and boundaries for the national barometer for inclusive sustainable development

3.5.1 Environmental stress

We used the Environmental Sustainability Indicators technical report (61) published by the Department of Environmental Affairs (DEA) as a starting point for our analysis as it was developed based on a comprehensive review of potential national indicators, Yale's Environmental Performance Index and the DPSIR framework. We then reviewed relevant national policies, reports and assessments, as well as academic literature to identify the most suitable dimensions, indicators and boundaries. While we changed only two of Rockström *et al.*'s global dimensions –

ocean acidification became marine harvesting and aerosol loading became air pollution – we adjusted all of the indicators and boundaries to suit national circumstances. The current status is a national average or aggregation of local data points and in most cases this calculation had already been done in the source documents. In three cases (phosphorus, biodiversity loss and marine harvesting) no pre-existing calculation was available and was performed by the authors (details in SI, S3.2). Environmental baselines were not used due to the very limited information on pre-industrial conditions.

Determining national environmental boundaries was challenging due to the novelty of defining local equivalents to planetary boundaries, the uncertainty in the data and because ideally safe boundaries should combine expert scientific opinion and societal acceptance. We identified three types of environmental boundaries, which arise from differences in the nature of the biophysical dimensions. The first type (Type A) is used for dimensions that are inherently global in nature – climate change and ozone depletion. Boundaries are based on global biophysical thresholds but necessarily incorporate some measure of multilateral political agreement to ensure that they take differences in national capability and responsibility into account. They can either be internationally agreed targets that set out national actions (Type A1), which is the case for ozone depletion, or national interpretations of a globally accepted threshold in the absence of agreed targets (Type A2), which is the case for climate change. The second type of boundary (Type B) represents national limits for land and freshwater resources. These can be purely natural limits (Type B1) or natural limits combined with human intervention such as infrastructure, technology and imports (Type B2). The third

type (Type C) combines local biophysical thresholds and a national safe boundary based on established research and expert judgment. These can be based on a single local biophysical threshold (Type C1), such as phosphorus concentrations in freshwater, or aggregations of biophysical thresholds of different components (Type C2), such as ecosystem types for biodiversity loss.

Type A: Global boundaries - climate change and ozone depletion

Global CO₂ and stratospheric ozone concentrations cannot be disaggregated to the national scale, however emissions are reported at the national scale. The Montreal Protocol contains internationally agreed phasing out schedules for the production and consumption of 96 ozone-depleting substances. South Africa has phased out all ozone-depleting (ODP) substances except hydro-chloro-fluoro-carbons (HCFCs) (62), producing 262 ODPt in 2013 (63). Our indicator 'Annual HCFC consumption' has a boundary based on the government's commitment to freeze HCFC consumption and limit it to the baseline of 370 ODPt by 2013 (64). South Africa is 29% below its ozone depletion boundary. Although no internationally agreed CO₂ emissions targets exist, South Africa has committed to reduce its emissions by 30-40% by 2050 from 2003 levels, after peaking at 650 MtCO₂ in 2020, based on the Long Term Mitigation Scenarios (LTMS) (65). Our indicator 'Annual direct CO₂ emissions' had a status of 461 MtCO₂ in 2010 (66) and we based our boundary on the emissions trajectory of the 'Required by Science' scenario in the LTMS, which sets the 2010 target at 451 MtCO₂. South Africa exceeds its climate change boundary by 2%.

Type B: National limits - freshwater use and arable land use

Freshwater and land are limited natural resources. We estimated that freshwater use in South Africa was $18,895 \text{ Mm}^3\text{yr}^{-1}$ in 2013 based on the Department of Water Affairs (DWA) Water Authorisation and Registration Management System database (67), and used this as our indicator. The DWA (68, 69) calculate that the country has $14,319 \text{ Mm}^3\text{yr}^{-1}$ total available yield for human use, which accounts for the 'ecological reserve', the minimum in stream flow needed to support ecological functioning (70), and assurance of supply. We used this as our safe boundary, which was exceeded by 34%, showing that human freshwater use is given priority over the ecological reserve. Although Rockström *et al.* focused on land use change, land cover in South Africa has been stable since 1961 (71). Instead we used 'rain-fed arable land converted to cropland' (11.9% in 2005 (72)) as our indicator as South Africa is a largely semi-arid country with limited land capable of supporting sustainable crop production. Only 12.1% is classified as rain-fed arable land (73) hence South Africa is 2% below its land use boundary.

Type C: Local thresholds

Nutrient cycles. While nitrogen (N) and phosphorus (P) cycles (essential for food production) are global in scale, the local negative impacts of N and P use pose the main challenge. Eutrophication of freshwater resources is widespread in South Africa and is a national concern (74), with P levels in major reservoirs used as a national indicator. We obtained the latest data from the National Eutrophication Monitoring Programme to calculate the current status of 0.098 mg/l in 2013 (75) and used Oberholster and Ashton's (76) critical threshold of 0.10 mg/l P in freshwater as the safe boundary. South Africa is 2% below its P loading boundary.

The negative impact on the N cycle in South Africa is largely through N removed from the soil by crop production, despite fertilisers being applied. Maize production uses nearly two thirds of N (77) and is the staple crop. On average, maize removes 27 kg N from the soil per tonne of marketable product (78), thus in 2011/12 an estimated 102 kg N/ha were removed from the soil. The average maize N application rate (our indicator) was 85 kg N/ha in 2012 (77), indicating that N is not being fully replaced. Rockström *et al.* identified the over-application of N as the main global concern and we therefore used Brentrup and Palliere's (79) N use efficiency threshold of 70%, which would translate to an N application rate of 144 kg N/ha for maize in South Africa, as our safe boundary. South Africa is 41% below its N boundary.

Biodiversity loss. Although Rockström *et al.* used rate of extinction to measure biodiversity loss, the more common indicator is threat of extinction e.g. (80). South Africa has undertaken biodiversity assessments since 1980 and in 2004 expanded from a species approach to an ecosystem approach. The 2011 National Biodiversity Assessment (56) reported the ecosystem threat status of 1,763 ecosystem types across six categories - Terrestrial, Rivers, Wetlands, Estuaries, Coastal and Inshore, and Offshore. It has four threat status classes; critically endangered (CR), endangered (EN), vulnerable (VU) and least threatened (LT) which incorporate biophysical thresholds. Our indicator, 'endangered and critically endangered ecosystems' (37% in 2011), is based on expert opinion and our safe boundary is set at zero i.e. no ecosystems should be endangered or critically endangered. South Africa exceeds its biodiversity loss boundary by 37%.

Marine harvesting. South Africa is at a very early stage in understanding ocean acidification (81) and the national priority for oceans is the sustainability of marine resources. Although the biodiversity loss dimension measures marine ecosystem stress, marine harvesting is better measured by the stock status of commercial fisheries. Seventeen fishery sectors and 45 species (or sub-species) are reported in the 'Status of South African Marine Fishery Resources 2012' (82) published by the Department of Agriculture, Forestry and Fisheries (DAFF). Stock status is based on the present biomass level (population size) and the biomass level at which maximum sustainable yield (the target for optimal utilisation) is obtained. Our indicator, the 'depleted marine fisheries stocks' (45% in 2011), is based on expert judgment and our safe boundary was set at zero i.e. no marine fisheries are depleted. South Africa exceeds its marine harvesting boundary by 45%.

Air pollution. Aerosol loading, a driver of regional climate change, is not a major concern in South Africa, hence we changed the dimension to address the national issue of air pollution that affects human health. The government (83) has identified particulate matter (PM10) and SO₂ as problem pollutants at a national scale, and uses the annual average concentration of each to calculate a National Air Quality Indicator. The latest 'State of Air' results for 2012 (83) show that PM10 is the 'greatest national cause for concern in terms of air quality'; hence we chose PM10 concentration as our indicator (46.9 µg/m³ in 2012) and the government's PM10 threshold of 50 µg/m³ as our safe boundary. South Africa is 6% below its air pollution boundary.

Chemical pollution. Similarly to Rockström *et al.*, we did not identify an indicator for this dimension due to the lack of detailed and accurate data. Although South Africa's National Waste Information Baseline Report (84) provides an estimated baseline of over 1.3 Mt of hazardous waste (most of which is landfilled) reporting is voluntary and measurement is incomplete.

3.5.2 Social deprivation

We used the South African Index of Multiple Deprivation (SAIMD) (85, 86) developed by the national Department of Social Development, the Human Sciences Research Council (HSRC) and Oxford University, and the annual Development Indicators report (87), published by the Presidency, as guidelines for selecting social dimensions and indicators. Both have been informed by international good practice and adapted to South African conditions, while the latter uses aggregate data from a range of sources covering the post-Apartheid period (1994-2013) and supplied most of the data for our barometer. Where it did not contain the required data, we used the latest General Household Survey (GHS) (88). We grouped the dimensions into four domains – basic services, public goods, livelihoods and living standards – to facilitate the analysis.

We made a number of changes to the original Raworth dimensions. Water and sanitation were separated into individual dimensions; housing, household goods and safety were added; and resilience, social equity and gender equality were removed. The experts we consulted saw resilience as a cumulative effect that is dependent on the other dimensions, and therefore an indirect measure. Experts also felt that both social equity and gender inequality should be incorporated into

the other dimensions, as they are cross-cutting. The Gini coefficient only measures income inequality and Palma (57) argues that it hides the homogeneity in the middle half of the population and the great heterogeneity between the top 10% and the bottom 40% of the population. As the five indicators of the UN's Gender Inequality Index (89) shows, gender equality could be addressed under the dimensions of health, education, voice and employment. Ideally, social equity and gender equality should be measured for all the dimensions of the barometer in future iterations.

We had to choose social boundaries from three types of indicator sets. The first type (Type 1) represents a range of levels of deprivation, which are commonly found in household surveys. For example, choosing 'access to piped water within 200m of the dwelling' rather than 'access to piped water in the dwelling' sets a lower boundary. The second type of indicator set (Type 2) is a range of definitions of the same indicator. For example, unemployment can be defined as narrow or broad, which includes discouraged jobseekers. The third type (Type 3) is a diverse set of indicators that represent different aspects of a dimension. For example, material deprivation can be measured by ownership of a range of household goods such as a refrigerator or television.

Basic services - Energy access, Water access, Sanitation and Housing

Household access to electricity, piped water, adequate sanitation and formal housing are all national priorities in South Africa. The GHS records seven levels of access to piped water (based on distance from the dwelling) and eight levels of sanitation. The official water target is '25l of potable water per person per day

without interruption for more than 7 days within 200m of the dwelling', known as the RDP standard, and the official sanitation indicator is 'access to at least a ventilated pit latrine on site'. In 2011/12, 23.5% of households were deprived of electricity access, 4.5% were deprived of piped water access (RDP standard), 16.6% were deprived of adequate sanitation and 22.3% were deprived of formal housing.

Public Goods – Education, Health care and Voice

There are numerous indicators to choose from when measuring education and health care. We did not use Raworth's MDG indicators as South Africa has achieved the MDG target of universal access to primary school, and there is no data for 'access to essential medicines'. We chose the SAIMD education indicator 'adults with no secondary schooling', the adult illiteracy rate in Development Indicators, which was 19.3% in 2011. The only health care (rather than health) indicator in Development Indicators is 'infant immunisation coverage' (90.8% in 2011), which we used. Raworth did not define an indicator for voice and experts recommended that voice should measure public participation in decision-making, which does not appear in Development Indicators. We chose to keep the dimension without a national indicator, with further research required.

Livelihoods – Jobs and Income

Poverty, unemployment and inequality make up South Africa's 'triple challenge' (90) and little progress has been seen since 1994. We chose the broad unemployment rate (36.3% in 2012) as our jobs indicator, with the potential for incorporating Raworth's indicator for gender equality, 'the employment gap in

waged work (excluding agriculture)', if the data becomes available. The official national poverty lines used in South Africa are a food poverty line of R305 per person per month (pppm), a lower-bound poverty line of R416 ppm and an upper-bound poverty line of R577 ppm in 2011 Rands (87). We used the latter as our income indicator, with a deprivation status of 52.3% in 2011.

Living Standards - Food security, Household goods and Safety

Food security, household goods and safety are important measures of living standards in South Africa. The only regularly reported national measure of hunger and food access is provided in the GHS, and we used the 'households without adequate food' as our food security indicator, with a deprivation status of 23.1% in 2013. The SAIMD uses the indicators 'ownership of a refrigerator' and 'ownership of a radio and/or landline telephone' to measure material deprivation. We selected the former as our household goods indicator (28.1% in 2013) as radio and landlines are being replaced by cell phones (88). Safety is a complex dimension to measure, as crime statistics do not compare well across jurisdictions, except murder. Our choice of indicator was limited as most indicators measure rates and not proportions of the population, hence we chose 'households that feel unsafe walking alone at night in their area', which was 63.5% in 2011.

3.6 Summary of national barometer results

The results of our case study are presented as two radar charts - environmental stress in Figure 3.2a and social deprivation in Figure 3.2b, which together form a barometer for inclusive sustainable development in South Africa. Four dimensions, climate change, freshwater use, marine harvesting and biodiversity loss have

exceeded their boundaries by 2%, 34%, 45% and 37% respectively; while arable land use, phosphorus loading and air pollution are within 10% of exceeding their boundaries. Deprivation was most widespread regarding safety (63.5%), income (52.5%), and jobs (36.3%) and least prevalent in basic services such as electricity and water access. Tables 3.1 and 3.2 summarise the details of the dimensions while Figure 3.3 shows trends in the indicators since 1990. Trends in environmental stress are difficult to analyse for five dimensions due to multi-year gaps between data points (land, water, biodiversity, nitrogen), a change in methodology (biodiversity), or a recent start to current data reporting (marine harvesting). Climate change, and freshwater use have been moving toward or beyond the safe boundary, while recent progress away from the boundary can be seen for ozone depletion and air pollution. Social deprivation has decreased in all dimensions (ranging from 33.8% in water access to 0.8% in food security) except safety and income, where deprivation has increased by 19.5% and 2.0% respectively. When the barometer's environmental dimensions are framed in terms of national policy applications (Table 3.3), it is clear that exceeding the environmental boundaries has implications for energy security, food security, water security, job security and human health; these in turn have potential to affect the national economy and bilateral trade agreements, highlighting that decisions on socio-economic development need to take environmental boundaries into account.

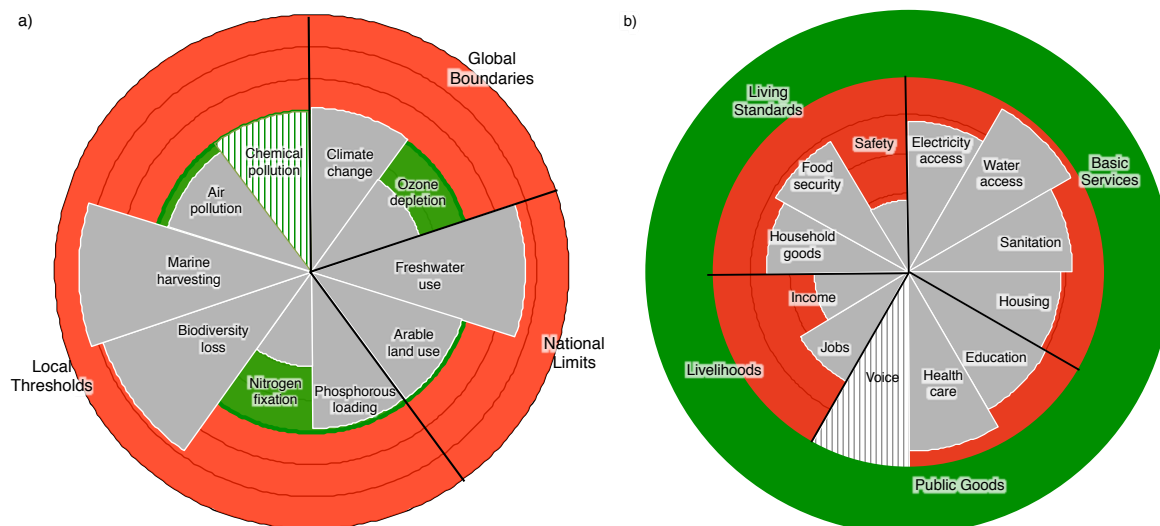


Figure 3.2 A national barometer for inclusive sustainable development in South Africa. The green areas represent the safe and just space, beyond which is excessive environmental stress (chart a) and social deprivation (chart b), shown in red. The grey wedges measure the national status for each dimension compared to its boundary as a percentage (0% at the centre, 100% at the boundary), the black dividing lines delineate the 3 types of environmental boundaries (chart a) or the 4 social domains (chart b). The striped wedges indicate no indicators were determined.

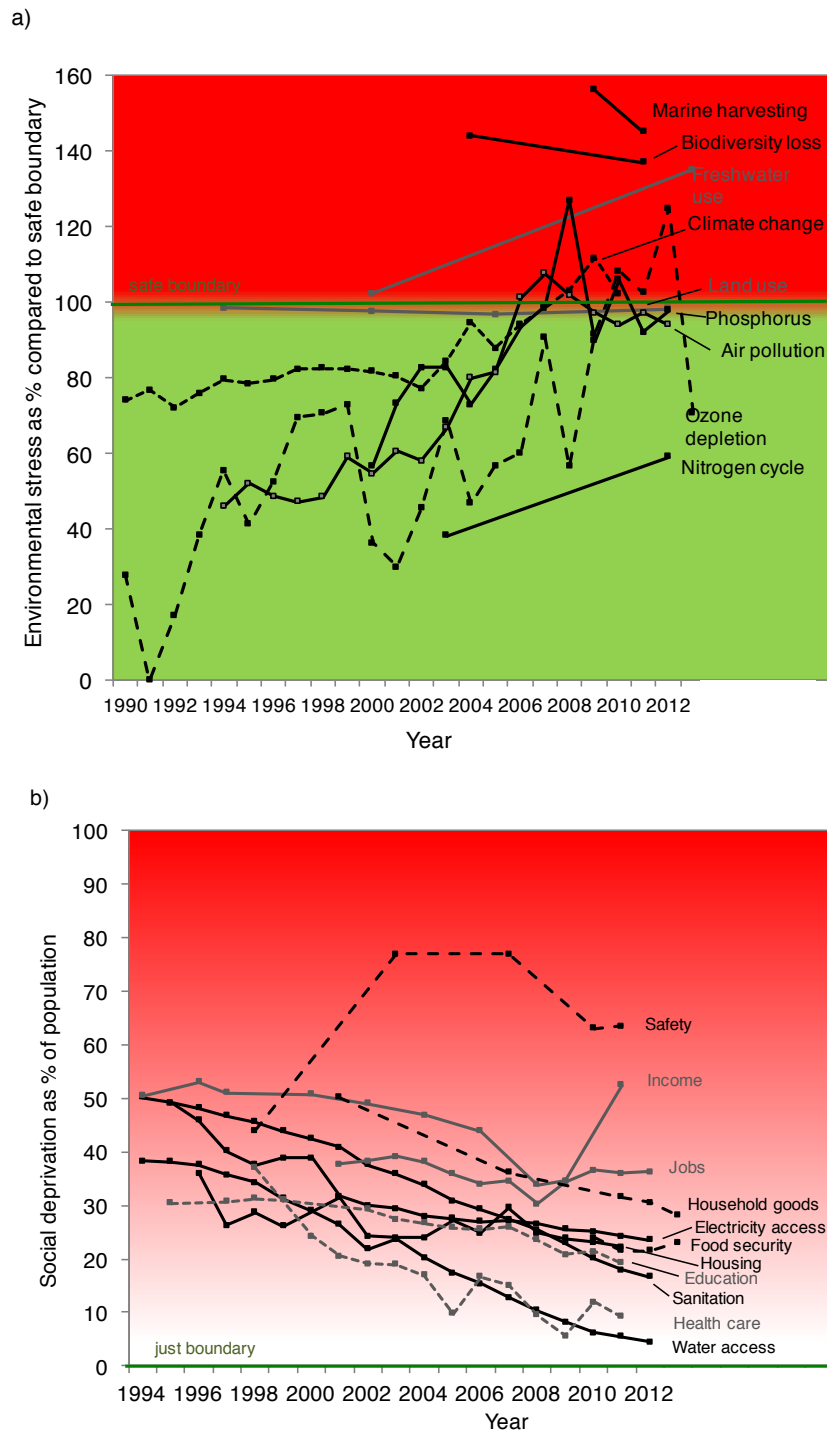


Figure 3.3 Change in a) environmental stress and b) social deprivation indicators in South Africa from 1990 to 2013.

Data sources in Table 3.1 and Table 3.2. a) Black dotted lines are Type A boundaries (climate change, ozone depletion), grey solid lines are Type B boundaries (freshwater use, land use), black solid lines are Type C boundaries (phosphorus, nitrogen, biodiversity loss, marine harvesting, air pollution).

b) Black solid lines are basic services (electricity, water, sanitation, housing) grey dotted lines are public goods (education, health care), grey solid lines are livelihoods (income, employment), black dotted lines are living standards (food security, household goods, safety).

Table 3.1 Dimensions and indicators of environmental stress for South Africa (using the most recent data available)

Dimension	Indicator	State				Boundary		Proximity to boundary	Type* of boundary
		Value	Year	Data source	Level of confidence	Value	Data source		
Climate Change	Annual direct CO ₂ emissions	460.1 MtCO ₂	2010	UN 2013 (66)	High	451 MtCO ₂	Scenario Building Team 2007 (65)	102%	Type A2
Ozone depletion	Annual HCFC consumption	262.0 ODPt	2013	UN 2014 (63)	High	369.7 ODPt	NEDLAC 2012 (64)	71%	Type A1
Freshwater Use	Consumption of available freshwater resources	18,895 Mm ³ /a	2013	DWA 2014 (67)	Low	14,196 Mm ³ /a	DWA 2004 (68), 2013 (69)	134%	Type B2
Arable land use	Rain-fed arable land converted to cropland	11.9%	2005	Schoeman et al 2013 (71)	Medium	12.1%	Collett 2013 (70)	98%	Type B1
Nutrient cycle	Total Phosphorus concentration in dams	0.098 mg/l	2012	DWA 2013 (75)	Medium	0.10 mg/l	Oberholster and Ashton 2008 (76)	98%	Type C1
	Nitrogen application rate for maize production	85 kg N/ha	2012	FSSA 2013 (78)	Low	144 kg N/ha	Brentrup and Poulter 2010 (79)	59%	Type C1
Biodiversity loss	Endangered and critically endangered ecosystems	37%	2011	Driver et al 2012 (56)	Medium	0%	Expert judgment	137%	Type C2
Marine harvesting	Depleted marine fisheries stocks	45%	2011	DAFF 2012 (82)	Medium	0%	Expert judgment	145%	Type C2
Air pollution	Annual average PM10 concentration	46.9 ug/m ³	2012	DEA 2013 (83)	High	50.0 ug/m ³	DEA 2013 (83)	94%	Type C1
Chemical pollution	To be determined								

* Type A1: global boundary with internationally agreed target, Type A2: global boundary with national target, Type B1: national resource limit without human intervention, Type B2: national resource limit with human intervention, Type C1: single local biophysical threshold, Type C2: aggregate local biophysical threshold

Table 3.2 Dimensions and indicators of social deprivation in South Africa

Dimension	Indicator of social deprivation	Current status of deprivation	Year	Change since 1994*	Data source	Type of indicator set^	Domain
Energy	Households without access to electricity	23.5%	2012	-25.6% (1995)	DPME 2013 (87)	Type 1	Basic services
Water	Households without access to piped water within 200m ($\geq$ RDP standard)	4.5%	2012	-33.8%	DPME 2013 (87)	Type 1	
Sanitation	Households without a toilet or ventilated pit latrines	16.6%	2012	-33.5%	DPME 2013 (87)	Type 1	
Housing	Households without formal dwellings	22.3%	2011	-13.7% (1996)	DPME 2013 (87)	Type 1	
Education	Adults (≥ 20 years old) without more than 7 years of schooling (adult illiteracy)	19.3%	2011	-11.1% (1995)	DPME 2013 (87)	Type 3	Public goods
Health care	Infant (< 1 year) immunisation coverage	9.2%	2011	-27.8% (1998)	DPME 2013 (87)	Type 3	
Voice	<i>To be determined</i>						
Jobs	Broad unofficial unemployment rate (adults aged 15-64 available to work)	36.3%	2012	-1.4% (2001)	DPME 2013 (87)	Type 2	Livelihoods
Income	Population living below the national poverty line (R577/month in 2011 Rands)	52.5%	2011	+2.0%	DPME 2013 (87)	Type 2	
Household goods	Household does not own a refrigerator	28.1%	2012	-20.9% (2001)	StatsSA 2014 (88)	Type 3	Living standards
Food security	Households without adequate food	23.1%	2013	-0.8% (2010)	StatsSA 2014 (88)	Type 3	
Safety	Households feel unsafe walking alone in their area at night	63.5%	2011	+19.5% (1998)	DPME 2013 (87)	Type 3	

*Or since start of measurements, year given in brackets. Negative value represents reduction in deprivation; positive value represents increase in deprivation. ^Type 1: range of levels of deprivation, Type 2: range of definitions of the same indicator, Type 3: diverse set of indicators that represent different aspects of a dimension

Table 3.3 Links between environmental stress and national policy applications

Environmental dimension	Energy security	Water security	Food security	Job security	Human health
Climate change	✓	✓	✓	✓	✓
Ozone depletion					✓
Freshwater use		✓	✓		
Land use change			✓	✓	
Nutrient loading		✓	✓		✓
Biodiversity loss		✓	✓		✓
Marine harvesting			✓	✓	
Air pollution					✓

3.7 Discussion

3.7.1 Utility of the barometer

The main aim of this case study was to evaluate the applicability of the SJS framework at the national level. The findings show that it is possible to maintain the original design and concept of the framework whilst making it meaningful in the national context. In interviews we conducted, there was consensus among experts that a ‘national barometer for inclusive sustainable development’ could be a very useful tool in South Africa, and this view is supported by the National Development Plan which recognises the need to measure and monitor progress on important social and environmental indicators (58). If the barometer were adopted nationally, the indicators would need to be further developed iteratively over time in a dialogue between scientists, civil society and government (as indicated in the flow chart shown in Figure 3.1).

Sustainable development indicators (SDIs) are not new and are regularly used in 'state of environment' or 'environment outlook' reports e.g. (91) and made more visually appealing in maps, such as the Dashboard of Sustainability (92), and quantified metaphors, such as footprints (11). The novelty of the barometer is twofold. First, it presents a visual snapshot of the state of a broad but manageable set of environmental and social indicators in relation to national priorities and realities that goes beyond colour-coding or single figures. Our trend charts provide additional information about progress (or lack thereof) over time that aid decision-making, and the combination of environmental and social dimensions highlights the dual nature of the sustainability challenge. Second, it goes beyond being merely a measure of the current status and highlights the country's proximity to its environmental boundaries and its acceptable level of social wellbeing. It is aimed at a national audience first and an international audience second, to encourage national action, and is science-based. Specific uses identified by the experts interviewed were that it removes inter-sectoral barriers, communicates a complex set of indicators in a relatively simple way, identifies gaps in the underlying knowledge base, and raises new questions in the discourse on social deprivation and environmental sustainability. Inclusion of the barometer in national reports, such as the State of Environment Report, was suggested as being highly beneficial.

It is recognised however that indicators are limited and can oversimplify complexities, making them better suited to conveying broad messages and encouraging discourse (93). Indeed, a criticism of the barometer from some experts was that it hides the complexity of the local scale i.e. the geography of social deprivation and environmental stress, which was also a critique of the planetary

boundaries. Biophysical thresholds vary spatially (e.g. from dry to wet regions) therefore the issue of scale is an important consideration in acting on national barometer results at sub-national scales. Specific sub-national analysis is needed to investigate if and/or how national thresholds could be determined that incorporate and do not mask this heterogeneity. Analysis at the sub-national level would also reveal inequalities in access to and use of resources, where both the ecological and political-economic borders are important, and this will be taken forward in future research. Nevertheless, broad sustainability indicators can provide substantial momentum to a more detailed debate, as the evidence from the MDGs shows, and can serve as first order proxies for inclusive development.

3.7.2 National-regional-global links

As a nation's political borders seldom match borders of biophysical systems, the national state of environmental stress has local, regional and global components. Similarly, perceived social and economic benefits lead to regional migration into South Africa which affects overall national social wellbeing. The fact that South Africa has exceeded or is close to exceeding almost all of its environmental boundaries highlights its own vulnerability as well as that of its neighbours, and raises the importance of international and regional cooperation. The proximity to Type A 'global boundaries' is likely to result in international pressure for South African to act, as seen in climate negotiations. The proximity to Type B 'national limits' indicates that neighbouring countries may be called on to provide water and arable land for regional food production, already evidenced by the DWA assessment of crop production potential in the region (94). The proximity to Type

C 'local biophysical thresholds' will probably result in pressure from local civil society.

International pressure will highlight the respective national contributions to the pressure on the planetary boundaries. South Africa has roughly 0.7% of the world's people (6) and 0.9% of its land area (95). It contributed 1.4% of global CO₂ emissions in 2010 (96), 4.4% of HCFC consumption in 2013 (63), 0.5% of global freshwater use (based on (15)) and 0.4% of global nitrogen fertiliser consumption in 2010 (97). It is therefore not a big contributor to the global pressure on the planetary boundaries. It is, however, the main contributor on the African continent, and as a member of the BRICS group, is closely associated with countries that do have a significant global impact. This provides impetus to act, but also raises the issue of how national environmental boundaries are determined.

Different boundaries could lead to different levels of international pressure and different national policy decisions. For example, Nykvist *et al.*'s (36) equal per capita share approach results in South Africa exceeding a global boundary for climate change by 335%, whereas our study (which uses nationally defined boundaries) puts the figure at 2%. The very large difference is due to the latter incorporating the UNFCCC principle of common but differentiated responsibilities and respective capabilities, which is arguably more realistic as no climate deal is likely to be agreed without it. Globally defined boundaries also fall short for other dimensions, where national resource limits and local thresholds are arguably more appropriate. For example, Rockström *et al.*'s 15% cropland boundary is inappropriate in South Africa, as only 12% of the land is capable of supporting rain-

fed crop production. Caution is also needed with comparing social deprivation across countries if different social boundaries, which need to be appropriate to the country's current level of development and able to adapt to changing circumstances, are used. For example, according to the MDG indicator for water access, 8.8% of South Africans are deprived; however, according to the more stringent SAIMD indicator (piped water inside the dwelling or yard), 26.6% of South Africans are deprived. South Africa's latest MDG Country Report (98) includes 69 'domesticated indicators' that were developed by 'adjusting the MDGS to reflect the local situation whilst ensuring that the globally designed targets and indicators are in line with local reality' through a stakeholder consultation process. Indicators that are inappropriate in the national context were identified and new targets and indicators required to fully reflect the local context were created. While the government supports the MDGs, viewing them as an integral part of the development agenda (98), the global indicators are used for international comparison and the domestic equivalents are used for monitoring national development. South Africa is likely to take the same approach to the SDGs. This adoption of multiple indicators for different purposes could be taken if we were to upscale a set of national barometers to the global scale. Each dimension could have a national and global indicator to meet the needs of both audiences.

The downscaling of the global SJS framework is not only complex for setting boundaries but also in calculating the current status. The social dimensions are relatively straightforward to calculate at different scales, as they are all aggregations of individual people or households, though care must be taken to ensure consistency when using either household or individual data and adjusting

for changes to political boundaries over time. The status of each environmental dimension is more difficult to calculate as they occur naturally at different scales. Despite the unavoidable complexity, each is based on local data sources and can therefore be scaled up to the national level, and possibly to the global level to recalculate Rockström *et al.*'s original planetary boundaries. The methodology for this would be similar to the one we have employed for turning local data into national values for South Africa. Some dimensions would be simpler than others, for example CO₂ emissions and ozone-depleting substances are already aggregated to regional and global levels in UN databases. While land and water use are also aggregated in global databases, the figures do not take into account national boundaries and need to be adjusted accordingly. The ecosystem level dimensions such as biodiversity loss and phosphorus loading could in principle be up-scaled through simple aggregation. One significant challenge is obtaining data for the same indicators across many countries, and additional indicators could be developed for each dimension to ensure there is some overlap. For example, marine harvesting could be changed to aquatic harvesting to incorporate a second indicator on freshwater fisheries to accommodate landlocked countries.

3.7.3 Gaps in the data and science

Our paper has provided a methodology for other countries to use to develop their own national barometers. We chose South Africa for this case study partly because it has a wealth of good data and research. Other countries may struggle to find the appropriate data to populate their own national barometer. Current research by MGN and co-authors on a barometer for Southern Africa has highlighted the challenges of finding and aggregating the same data for 12 different countries, as

the levels of research and monitoring are generally much lower than that of South Africa. This is likely to also be the case with the implementation of the SDGs. Perhaps instead of this being seen as a barrier, it should be used as an opportunity for data-poor countries to begin an efficient targeted collection of specific data needed to address these global and national challenges. This has been one of the positive outcomes of the MDGs – that new longitudinal data have been collected in developing countries, aiding national governments in making more informed policy decisions (99). For now, the ‘second best’ solution (100) – where existing constraints prevent the ‘first best’ solution from being obtained – is to use existing data and proxies and to refine the barometer over time as more data are gathered. We note that the approach we have taken is supported by UNEP recommendations in limiting the number of indicators, using existing data and proxies, being sensitive to scale and engaging stakeholders early on (101).

According to the Rio+20 outcome document, the SDGs must be ‘action-oriented, concise and easy to communicate, limited in number, aspirational, global in nature and universally applicable to all countries, while taking into account different national realities, capacities and levels of development and respecting national policies and priorities’ (102). Our barometer meets the first four of these five criteria and attempts to address the last and toughest criteria of global applicability and national relevance, which is a challenge given the significant socio-economic differences between the 193 countries in the UN. As we have shown, some of the MDG indicators do not suit the South African context and there is disagreement over the sharing of responsibilities for addressing environmental stress, especially climate change.

Based on the Zero Draft (103) from the Open Working Group on SDGs (established by the UN General Assembly in January 2013), all of the dimensions in the barometer are likely to appear in the SDGs. The proposal has 17 goals (see SI S3.4), which together have 148 targets. No indicators have been developed as yet, but there are likely to be more than 200 and therefore intrinsically difficult to communicate with ease. Our barometer seeks a balance between simplicity and complexity, and while countries will have to measure and report on all of the SDGs in time, it makes sense to highlight some of the more important indicators and ensure that the necessary data is gathered early-on in the process. It is likely that social indicators will be more readily available than environmental indicators, and multi-year research projects will be required to fill in the data gaps.

Apart from the data challenges, there are also gaps in the science on defining environmental boundaries, at both global and sub-global scales. Considerable effort is currently being put into investigating both the causes of tipping points in Earth systems and uncovering indicators of the proximity to critical thresholds (104). Schellnhuber (105) argues that the tipping elements (TE) issue ‘probably poses one of the toughest challenges for contemporary science’ and highlights ‘social TEs’ as an important research area. Similarly, Galaz (106) believes that ‘social connectors’, which can lead to tipping points that would not otherwise occur, need to be researched. While different scientific perspectives can lead to different national boundaries and indicators, so indeed could different political interests. Both scientific input and a robust process that involves all stakeholders are needed.

3.8 Conclusion

We have described a worked case study for applying Raworth's 'safe and just space' framework at the national scale, using South Africa as our test case. We developed a decision-based methodology for identifying and quantifying indicators and boundaries for both environmental and social dimensions, creating the first national barometer for inclusive sustainable development in South Africa. The barometer highlights environmental risks and unacceptable social deprivation intended to prompt public debate; indeed, similar barometers could be developed for other countries. Four dimensions, climate change, freshwater use, marine harvesting and biodiversity loss have exceeded their safe boundaries by 2%, 34%, 45% and 37% respectively, while arable land use, phosphorus loading and air pollution are within 10% of exceeding their boundaries. Social deprivation was most widespread regarding safety (63.5%), income (52.5%), and jobs (36.3%) and least prevalent for basic services such as water access. Trends show that environmental stress is still increasing for two dimensions (climate change and freshwater use), while social deprivation has reduced in all areas except safety and income. This case study provides insights into the challenges and complexities of developing relevant indicators and boundaries at national scales, and highlights areas where additional research is needed to refine and further develop the framework.

3.9 Acknowledgements

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Supplementary Information for Chapter 3

This Supplementary Information has four sections: Environmental parameters, Social parameters, Experts interviewed and Sustainable Development Goals.

S3.1 Environmental parameters

This section explains the choice of the indicator and determination of the boundary for the nine environmental dimensions in South Africa. Table S3.1 compares the original Rockström *et al.* (1) indicators to the relevant indicators in South Africa's annual Environmental Sustainability Indicators (ESI) Technical Report 2011 published by the Department of Environmental Affairs (DEA) (2) and the actual indicators used in our barometer. Each environmental dimension is described below, and is grouped by boundary type i.e. Type A Global Boundaries, Type B National Limits and Type C Local Thresholds.

Table S3.1. Comparison of the indicators for the planetary boundaries (1), the ESI 2011 (2) and our environmental barometer

Dimension	Planetary Boundary indicator	DEA's Environmental Sustainability Indicators 2011	Actual indicator used
Climate change	CO ₂ concentration (ppmv) Change in radiative forcing (Wm ²)	Annual CO ₂ direct emissions (total, per capita)	Annual total CO ₂ direct emissions
Ozone depletion	Ozone concentration (Dobson units)	Annual production of CFCs, MBr and HCFCs Annual consumption of CFCs, MBr and HCFCs	Annual consumption of HCFCs
Biodiversity loss	Extinction rate (number of species per million species per year)	Threatened bird, mammal, amphibian and reptile species (%) Threat and protection status of vegetation types per biome (%)	Endangered and critically endangered ecosystems
Nitrogen and Phosphorus cycles	Amount N ₂ removed from atmosphere for human use (Mt/yr)	Fertiliser sales (kg)	Nitrogen application rate for maize production
	Phosphorus flowing into oceans (P Mt/yr)	Freshwater quality – Total phosphate concentration in dams (P mg/l) Freshwater quality – Orthophosphate concentration in dams (PO ₄ mg/l)	Total mean annual P concentration in dams in mg/l
Ocean acidification / Marine harvesting	Global mean saturation state of aragonite in surface sea water	West coast rock lobster landings (t) Catches of selected marine species (kg/nominal mass) Marine protected areas (status)	Depleted marine fisheries stocks (% of known species)
Freshwater use	Consumption of freshwater by humans (km ³ /yr)	Available water per capita (m ³) Capacity and levels of dams (m ³) Groundwater quantity (distance below ground) Water stress per WMA in 2025 (yield v demand)	Consumption of freshwater by humans in Mm ³ /yr
Land use change / Land use	% global land cover converted to cropland	Degraded and transformed land (%) Grazing capacity Protected land area (%)	Rain-fed arable land converted to cropland
Aerosol loading / Air pollution	Overall particulate concentration in the atmosphere	Domestic fuel burning (Households by energy source for cooking & heating & lighting) Coal consumption (TJ) Vehicle use Death rate from respiratory diseases & TB	Annual mean PM10 concentration in ug/m ³
Chemical pollution	<i>Not defined</i>	<i>Not mentioned</i>	<i>Not defined</i>

S3.1.1 Type A. Global boundaries

Climate change

Climate change is inherently global and Rockström *et al.* use the global atmospheric concentration of CO₂ (in ppm) as their indicator and the Intergovernmental Panel on Climate Change (IPCC)'s estimated biophysical threshold of 350 ppm CO₂ as their safe global boundary. The global concentration of CO₂ cannot be disaggregated to the national scale, however direct CO₂ emissions (production-based) are reported in national inventories and are aggregated to the global scale to inform international negotiations. Work on consumption-based accounting of CO₂ emissions is growing (e.g. (3)) but the data is limited. There are other significant greenhouse gases such as methane (CH₄) and nitrous oxide (N₂O) however CO₂ is most commonly used as an indicator and has the least uncertainty in the data (4). Land use change and forestry (LUCF) is also included in calculations of GHG emissions, however due to the lack of data they are often not reported or used.

In South Africa, CO₂ contributes 85% of GHG emissions (measured in MtCO₂e) while CH₄ contributes 10% and N₂O only 3% (5). While there are a number of possible indicators, the ESI reports annual per capita and total direct CO₂ emissions (excluding LUCF) as they are Millennium Development Goal (MDG) indicators. We chose 'Total annual CO₂ emissions' as our indicator as it is a direct measure, is of national importance and is reported annually by the national Department of Environmental Affairs (DEA). The current status of 460.1 MtCO₂ was sourced from the UN MDG indicators database (6), which uses data from CDIAC (7), as this is used by DEA. It is an aggregation of multiple sources of CO₂

emissions in the country including domestic energy, industry and agriculture so sub-national analysis can also be done.

South Africa has ratified the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol, and has an influential role in international climate negotiations as a member of the BASIC group (Brazil, South Africa, India, China). As a developing country, it has been exempt from taking mandatory action to reduce GHG emissions however this is likely to change in 2020 when legally binding targets under the Durban Platform come into force. Although nations have agreed to limit global warming to 2°C, there are no internationally agreed boundaries for CO₂ emissions. In the Copenhagen Accord in 2009, SA pledged to reduce emissions to 34% below business as usual (BAU) by 2020 and 42% below BAU by 2030. These pledges were based on the Long Term Mitigation Scenarios (LTMS) and mitigation actions (8).

BAU in the LTMS is a scenario called 'Growth without constraints' and its emissions trajectory reaches 720 MtCO₂ in 2020, 1,000 MtCO₂ in 2030 and 1,640 MtCO₂ in 2050. The alternative is the 'Required by Science' scenario, which uses the IPCC biophysical threshold of 350 ppm CO₂ based on a 2°C maximum global warming target and the stated need to reduce GHG concentrations by 60% - 80% from 1990 levels by 2100. In the Required by Science scenario, 'climate security' is guaranteed through joint international action as developed countries reduce emissions by 80% from 1990 levels by 2050 while a developing country like SA reduces its emissions by 30% - 40% from 2003 levels (446 MtCO₂). This trajectory peaks in 2020 at 473 MtCO₂ and declines to 440 MtCO₂ in 2030 and 290 MtCO₂

(65% of baseline) in 2050. The 2010 'required by science' target is 451 MtCO₂ and we used this as our national safe boundary. This is a Type A2 environmental boundary, which South Africa has exceeded by 2%.

As this boundary has a large political component, alternative boundaries could be determined. For example, in order to compare countries Nykvist *et al.* (9) chose a boundary of 2 tCO₂ per capita per year based on the contraction and convergence approach, which translates to 106 MtCO₂ in 2010 for South Africa (using the 2013 mid-year population estimate (10) of 52.98 million). This is less than a quarter of the country's self-determined boundary of 451 MtCO₂ (and the current status of 460 MtCO₂ is 335% over this boundary), as it does not take equity and the principle of common but differentiated responsibilities and respective capabilities (CBDR/RC) into account. This is a controversial area of debate, which is still being negotiated under the UNFCCC.

Ozone depletion

Ozone depletion is a global phenomenon, which Rockström *et al.* measured using the stratospheric ozone (O₃) concentration. This cannot be disaggregated to a national scale hence a more appropriate indicator is the national production or consumption of ozone depleting substances. These are reported annually by the United Nations Environment Programme (UNEP) Ozone Secretariat (11) and also appear in MDG reports under Goal 7. Internationally agreed boundaries for ozone depletion exist in the Montreal Protocol, which sets out phasing out schedules (different for developed and developing countries) for the production and consumption of 96 ozone-depleting substances. Many of the phase-out periods

have passed and the focus now is on the consumption of methyl bromide (MBr) and hydro-chloro-fluoro-carbons (HCFCs). The developing country target is to phase out the use of MBr by 2015 and HCFCs by 2040.

Since signing the Montreal Protocol in 1990, South Africa has phased out all ozone-depleting substances except HCFCs, which are used for refrigeration and air-conditioning services and manufacturing of polystyrene and polyurethane (12). HCFCs have been declared national priority air pollutants in terms of Section 29(1) of the Air Quality Act (13) and are reported in ESI 2012 (14). HCFC consumption was therefore used for the ozone depletion indicator. The current status of 262 t for the year 2013 was taken from the UNEP database as it has the most recent data. In accordance with the Montreal Protocol commitments, the government aims to freeze HCFC consumption and limit it to a baseline of 369.7 ODpt (the officially reported average consumption of 2009 and 2010) by 2013, reduce it by 10% by 2015, 35% by 2020, 67.5% by 2025, 97.5% by 2030 and phase it out by 2040 (12). The safe boundary for 2013 is therefore 370 ODpt and the current status is 29% below the boundary, which represents a global international agreement, and therefore a Type A1 environmental boundary.

S3.1.2 Type B. National limits

Freshwater use

Rockström *et al.* argue that freshwater is a finite planetary resource and human pressure is driving change in the function and distribution of the global freshwater system (15). Their control variable, or indicator, is the consumption of freshwater by humans, a global aggregation of local use. The global consumptive use is 65%

of global withdrawals of runoff water, and is the cause of environmental degradation and water shortages. They propose a danger zone of consumptive freshwater use and set the safe boundary at the lower limit, which equates to 32% of available river runoff or 27% of total renewable water resources. This danger zone is based on research suggesting that withdrawals of runoff water in excess of 40% of available freshwater resources can lead to severe regional water scarcity, and DeFraiture *et al.*'s 2001 estimate that water withdrawals exceeding 60% of the utilisable resource is a threshold for physical water scarcity. They highlight that crossing a global threshold could have both environmental (e.g. collapse of ecosystems) and social impacts (e.g. famine) at multiple scales.

South Africa's mean annual runoff, MAR, (the average natural run-of-river flow per year over a long-term time period) is $49,210 \text{ Mm}^3\text{yr}^{-1}$ and its estimated utilisable groundwater exploitation potential (maximum allowable water level drawdown) is $7,500 \text{ Mm}^3\text{yr}^{-1}$ (16). Its total freshwater resources are therefore $56,710 \text{ Mm}^3\text{yr}^{-1}$ and Rockström *et al.*'s boundary would equate to $15,747 \text{ Mm}^3\text{yr}^{-1}$ (32% of MAR) or $15,312 \text{ Mm}^3\text{yr}^{-1}$ (27% of total). However, South Africa is the 30th driest country in the world with low and highly variable rainfall (both inter- and intra-annually), erratic runoff, high evaporation and shallow dam basins (17). More than 60% of its river flow arises from only 20% of the land area requiring large-scale inter-basin transfers (18). The South African economy primarily depends on its stored surface water resources, having $31,620 \text{ Mm}^3\text{yr}^{-1}$ of surface storage capacity (19), and imported water from Lesotho. A boundary based on a global rule of thumb is therefore unlikely to represent the local context.

The Department of Water Affairs' (DWA) first National Water Resource Strategy (NWRS), published in 2004, describes South Africa's water resources and requirements in the year 2000 (20), which are summarised in Table S2. The minimum amount of water needed for ecological functioning in rivers, the 'ecological reserve', was estimated at $9,545 \text{ Mm}^3\text{yr}^{-1}$ or 19% of MAR at the national level. This is an aggregation of the reserve calculated in each of the 19 Water Management Areas (WMA), which varied from 11% of MAR to 28% of MAR. These estimates do not take estuaries into account, which usually require a greater proportion of MAR. Hughes and Munster's (21) hydrological variability index based on desktop reserve estimates shows that for rivers which are strongly baseflow driven the reserve can vary from 17-80% of MAR for different ecological management classes, but that this range and %MAR reduces as variability increases.

The second edition of the NWRS published in 2013 (17) states that 25% of MAR is needed for the ecological reserve and that although the ecological reserve is mandated in the National Water Act of 2008, it is not met in at least four out of the nine new WMAs. The DWA is in the process of classifying all significant water resources to determine the ecological reserve for each catchment. The national Water Resource Classification System incorporates socio-economic considerations and aims to facilitate a balance between resource protection and resource development and utilisation at different scales, recognising that there must be trade-offs (22). Three Management Classes that reflect the future desired condition of an aquatic ecosystem have been defined and will be used to guide the quantity and quality of water to be reserved for that ecosystem (23), and therefore

the amount available for human use. To date only the Olifants-Doorn catchment (the old WMA 17, located in the Western Cape and Northern Cape Provinces) has been completed while six other catchment assessments are underway (24). This process is likely to result in an updated national figure for the ecological reserve, but until it is complete, we must rely on the NWRS2 estimate of 25% of MAR.

Using this estimate of the ecological reserve, we could calculate that $36,908 \text{ Mm}^3\text{yr}^{-1}$ of surface water remains for human consumption, although $3,000 \text{ Mm}^3\text{yr}^{-1}$ of this is lost as evaporation from dams (25), leaving $33,908 \text{ Mm}^3\text{yr}^{-1}$. This is not completely accurate though, as the impact of water use on the reserve varies depending on the season; for example, in the north and east of South Africa, the agricultural growing season is the rainy season hence there is minimal impact on the reserve, whereas in the south-west, the growing season is generally the dry season and it has a big impact on the reserve. Another flaw with this approach is that it does not take the availability of freshwater resources throughout the year into account – a prerequisite for domestic and industrial use.

The DWA calculates an annual total available surface water yield which is ‘the amount of water that can be supplied in a catchment using a set of human-built water supply schemes (such as dams and inter-basin transfers) as well as taking into account a specified reliability of supply, termed the “assurance of supply”’ (26). A 98% assurance of supply is used, which means that water will be available in 98 years out of 100 years. The DWA uses a hydrological systems model to simulate flows based on MAR, dam storage potential, water transfers and abstraction, and it incorporates the effects of land use change, including irrigation, afforestation,

alien vegetation, mining and urbanisation (25). The model calculates yields for large water supply systems and therefore excludes available water that is not being captured in storage dams, although there is very limited potential for new dams in South Africa (17). People living in rural areas continue to source water from rivers and streams where MAR is high but water services are limited. According to the 2011 Census (27), the main source of water for 17.5% of households in the Eastern Cape and 8.5% of households in KwaZulu Natal is a river or stream. Nationally, 651,244 million households, or roughly 2.6 million people, use rivers or streams as their main source of water. Using the DWA recommendations for low income housing of 60 litres per person per day, we can estimate this water demand to be $57 \text{ Mm}^3\text{yr}^{-1}$. This should partly be addressed by the building of two multi-purpose dams in the Eastern Cape which will provide hydropower and store 490 Mm^3 for domestic and agricultural use from 2018 (28), which should then increase DWA's total available yield.

The DWA estimated that the available surface water yield was $10,240 \text{ Mm}^3\text{yr}^{-1}$ in 2000, while the total available yield for human consumption was $13,227 \text{ Mm}^3\text{yr}^{-1}$, which included groundwater yield of $1,088 \text{ Mm}^3\text{yr}^{-1}$ and usable return flows of $1,899 \text{ Mm}^3\text{yr}^{-1}$. The NWRS 2013 estimate of groundwater yield was $2,000 \text{ Mm}^3\text{yr}^{-1}$, which would take the current total yield to $14,139 \text{ Mm}^3\text{yr}^{-1}$. If we add an estimated rural use direct from rivers, the total is $14,196 \text{ Mm}^3\text{yr}^{-1}$.

Give these complexities in the data and modelling, it is difficult to determine a safe boundary for freshwater resources in South Africa. We decided that the best option was to use our updated total available yield of $14,196 \text{ Mm}^3\text{yr}^{-1}$, as the indicator

being measured is consumptive freshwater use by humans i.e. water that is not supplied or allocated by the DWA cannot be used, except in rural areas where there is little or no water service provision. This is a Type B2 boundary as it is a national resource limit that has both an ecological component (the ecological reserve) and a physical component (infrastructure and imports), and crossing the boundary has both environmental and social impacts. The total available yield could increase in the future if additional water is imported from neighbouring countries, additional groundwater is accessed, return flows increase, and/or physical water losses in municipalities are reduced.

South Africa's total freshwater requirements for human use in 2000 were 12,871 $\text{Mm}^3\text{yr}^{-1}$, thus water supply and demand were roughly in balance. However these statistics are now 14 years old, a significant length of time in a rapidly changing policy environment and where population has increased by 18% (8.22 million people) since 2000 (10). Domestic consumption is likely to have increased by at least 18% as water access has increased and incomes have grown. Power generation increased by 3,616 GWh or 23% (29) and the economy has grown by an average of 3.5% each year (30) despite mine production falling by 12% (31). According to the DWA's WARMS database (as at 15 April 2014) (32), irrigation is currently allocated 11,005 $\text{Mm}^3\text{yr}^{-1}$, mining and bulk industrial are allocated 907 $\text{Mm}^3\text{yr}^{-1}$, urban use is allocated 3,325 $\text{Mm}^3\text{yr}^{-1}$ and trade and services are allocated 2,278 $\text{Mm}^3\text{yr}^{-1}$. Although these figures may not reflect actual water use, they are the best available estimate of current consumptive use. Taking all these changes into account, we estimate that overall water consumption in 2013 was 18,985 $\text{Mm}^3\text{yr}^{-1}$ (Table S3.2), 34% more than the total available yield of 14,196 $\text{Mm}^3\text{yr}^{-1}$.

This implies that either water is over-allocated by DWA or allocations are being exceeded.

Table S3.2 Water resources and use in South Africa based on the NWRS 2004 (20) and 2013 (17), the Enhanced WR2005 (16) and the WARMS database in 2014 (32)

Water Resources		Volume (Mm ³ yr ⁻¹)	Percentage of MAR	Data source	
A1	Mean Annual Runoff (MAR)	49,210		Enhanced WR2005	
A2	Ecological Reserve (in-stream flow requirements)	12,302	25%	NWRS 2013	
A3	Surface water storage capacity	31,620	64%	DWA 2014	
A4	Evaporation from dams	3,000	6%	Pitman 2011	
A5	Available surface water yield (assurance of supply)	10,240	21%	NWRS 2004	
A6	Surface water used in rural areas (direct from source)	57	0%	Census 2011	
B1	Utilisable groundwater exploitation potential	7,500		Enhanced WR2005	
B2	Available groundwater yield	2,000		NWRS 2013	
C1	Usable return flows/effluent yield	1,899		NWRS 2004	
	Total available yield (assurance of supply)	14,196			
Water Use		Requirements in 2000		Allocation in 2013	
		Mm ³ yr ⁻¹	% of total	Mm ³ yr ⁻¹	% of total
Irrigation		7,920	62%	11,005	58%
Forestry		428	3%	428	2%
Power generation		297	2%	365	2%
Mining and bulk industrial (non-urban)		755	3%	907	5%
Urban (industry and other)		2,897	23%	3,325	17%
Rural		574	4%	677	4%
Trade and Services*				2,278	12%
Total		12,871	100	18,895	100

*The WARMS category Water Supply Services includes construction, trade, services, tourism, transport, and communication

Land use

Land use change occurs at the local level and is largely driven by demand for food and fibre. Rockström *et al.* highlight the negative consequences on biodiversity, as well as climate and hydrological cycles, and use the indicator ‘ice-free land converted to cropland’ with a boundary of 15%. As biodiversity loss, climate change and freshwater use are already addressed in other dimensions, and because South Africa’s land cover has remained relatively stable since 1961 (33), we have chosen to focus on arable land use.

It is important to differentiate between land capability, land suitability and land use. South Africa is largely a semi-arid country with very limited land capable of supporting sustainable crop production. In 2002, the national Department for Agriculture published a National Land Capability Classification (34) and accompanying 1:250,000 map which adapted the international concept of land capability to the South African context using a national dataset developed over 30 years. The classification incorporates environmental risks and limits based on terrain (slope), soil quality and climate to classify land into eight main classes of agricultural potential as shown in Table S3 below. The crop production limitations include the choice of crop and the timing of planting, growing and harvesting but exclude low nutrient status since this can be rectified by liming and/or fertilisation (34). Classes I to IV constitute arable land (i.e. land that can be used for crop production), while classes V-VIII constitute non-arable land. Classes I-III represent rain-fed arable land of acceptable quality for crop production while Class IV represents marginal land for rain-fed crop production.

Since 2002, provincial studies of land capability have been undertaken for Gauteng and Limpopo and in 2012, the Department of Agriculture, Forestry and Fisheries (DAFF) updated the land capability information as part of the development of a new national policy on the “Preservation and Development of Agricultural Land” (35). The analysis excluded water bodies, protected areas and areas under forest plantations that are not available for agricultural production, which reduced the amount of agricultural land from the original 2002 definition. In addition, the analysis indicated that 3,139,290 ha of agricultural land were permanently converted for urban and mining developments, 63% of which was arable land (see Table S3.3). Thus in 2012, only 25% of land in South Africa is arable and only 12.1% of land is termed ‘acceptable arable land’. Arable land can also be degraded and South Africa is particularly susceptible to land degradation due to its semi-arid climate and unique land tenure situation of former homelands of the Apartheid regime (36). Land degradation within different land-cover types would be a useful indicator but this data is difficult to find.

While land *capability* is based on ecological sustainability, land *suitability* depends on economic and social factors in addition to environmental factors. Hence an area of land can be capable of crop production but deemed suitable for urban development or mining, resulting in the reduction in the total area of arable land available as indicated above. Land *use* in South Africa has been recorded in the 1:250,000 National Land Cover datasets of 1994/5 (37) and 2000 (38) which categorised land use as cultivated land, degraded land, forest plantations, urban built-up land, mines and quarries, and natural land. According to DEA, the accuracy of the land cover database ranges from 51% to 93% depending on the geographic

area (2). In 2009 SANBI (39) updated the national land cover map based on provincial studies (generated from satellite imagery), however actual values for the different categories at a national scale were not published. Most of South Africa's agricultural expansion took place before the 1960s although the threat of sanctions during the Apartheid era led the government to provide agricultural subsidies to promote food security, which in turn led to cultivation of marginal land (40). Schoeman *et al.* (38) developed a national land cover change map for the period 1994 and 2005, which showed a 1.2% change in land use. Urban, forestry and mining all increased their land cover however cultivated land decreased by 0.5%. Niedertscheider *et al.*'s (33) socio-ecological analysis in 2012 shows that land cover in South Africa was stable from 1961 to 2006, with cropland expansion and decline and the spread of settlements and forest plantations only causing minor changes in area extent for the whole period. Land degradation is difficult to measure, however, and is likely to be underestimated.

Based on the South African situation, we decided to measure how much of the limited national resource of arable land has been converted to cropland to provide a measure of land use and food production constraints, which contributes to food security. As there is no available direct comparison of arable land and cultivated land, we had to combine the indicator 'land used for crop production' (11.9% in 2005) and the boundary 'acceptable arable land for crop production (Class I-III)' (12.1% in 2012). Using this measure, South Africa is close to exceeding its boundary for cropland. The land use figures are eight years old and must be updated as soon as the data becomes available. The boundary for land is a Type B1 boundary as it represents a natural resource limit that has not been expanded

by human intervention. This would change to a Type B2 boundary if Class IV marginal cropland, which requires irrigation in dry seasons, were included in the boundary. Based on GIS maps of land cover and land capability, it is clear that cultivation is occurring on marginal land; hence we considered incorporating marginal land in the boundary. However we felt that excluding it represented a more ecologically sustainable approach, particularly considering the water resource constraints already identified, and as Biggs and Scholes (40) point out, marginal land is more prone to crop failures.

Table S3.3 South Africa's 2002 land capability classification and agricultural land in 2012
(Data source: Collett 2013 (35))

Land Capability Class			Land Capability Area in 2002 (ha)*	Agricultural Land in 2012			
				Area (ha)	Percentage of total land		
Arable	I	Very intensive crop production	2,733	2,634	0.0%	12.1%	25%
	II	Intensive crop production	1,878,597	1,720,506	1.4%		
	III	Moderate crop production	14,003,339	12,971,417	10.7%		
	IV	Limited crop production (marginal cropland)	16,447,446	15,658,941	12.9%	12.9%	
Non-arable	V	Pastures	13,609,335	13,354,526	11.0%	61.4%	71.4%
	VI	Veld reinforcement	18,114,793	17,576,101	14.4%		
	VII	Veld and Forestry	45,343,216	45,061,442	37.0%		
	VIII	Wildlife	12,279,370	12,193,972	10.0%	10.0%	
		Water bodies	246,052	-	-	-	
Total			121,924,881	118,539,538	97.4%	97.4%	

*Note. The 2002 land capability study covered all land in South Africa.

S3.1.3 Type C. Local thresholds

Biodiversity loss

Biodiversity loss occurs at the local scale and is aggregated by Rockström *et al.* to the global scale, using rate of extinction as the indicator. The more common way to measure biodiversity loss however is threat of extinction. The International Union for Conservation of Nature (IUCN)'s Red List Index documents species threat status and is used by the UN Convention on Biological Diversity as an indicator for the '2010 Biodiversity Target'. It is also a MDG 7 indicator (41). Threat of extinction, or threat status, is categorised as critically endangered (CR), endangered (EN), vulnerable (V), near threatened (NT) and least concern (LC) by the IUCN (42).

South Africa has undertaken biodiversity assessments since 1980 and has made a significant contribution to global conservation efforts (43). The 'Red Data Book of Mammals of South Africa' (44), published in 2004 assessed 295 terrestrial and marine mammals. The online 'Red List of South African Plants' was published in 2010, making SA the first mega-diverse country to fully assessed the status of its entire flora, some 20,456 plant taxa, 13,265 of which are endemic (43).

The South African National Biodiversity Institute (SANBI), established in 2004 through the National Environmental Management: Biodiversity Act, has expanded from a species approach to an ecosystem approach to biodiversity assessments and ecosystem threat status was assessed for the first time in 2004 (45). The assessment of ecosystem threat status is based partly on the species-area relationship within ecosystems, so species loss is to some extent implicit in this approach. National assessments are done every seven years and the 2011

National Biodiversity Assessment (46) reported the ecosystem threat status of 1,763 ecosystem types across six categories - Terrestrial, Rivers, Wetlands, Estuaries, Coastal and Inshore, and Offshore, as shown in Figure S3. It uses a threat status classification very similar to the IUCN Red List; ecosystems with less than 20% of their original extent in good ecological condition (as oppose to fair or poor condition) are classified as critically endangered (CR), ecosystems with less than 35% of their original extent in good condition are endangered (EN) and ecosystems with less than 60% of their original extent in good condition are vulnerable (VU). The classification therefore incorporates biophysical thresholds, and CR represents the so-called 'biodiversity target' – the minimum proportion of an ecosystem required to maintain a representative sample of that ecosystem type and its species.

To calculate a single national indicator and safe boundary for biodiversity loss, all six ecosystem categories have to be combined. Experts recommended combining the CR and EN classes to measure the total number or percentage of *endangered* ecosystems, rather than including VU to measure total *threatened* ecosystems. The current status can be calculated in two ways; either by using the absolute numbers of ecosystem types (Figure S1a), which gives a total of 42% of ecosystems endangered, or by using the percentages for each category (Figure S1b), which gives a total of 37% of ecosystems endangered. The former approach biases the total towards wetlands and terrestrial ecosystems as they have significantly more ecosystem types than the other categories; therefore we used the latter approach. The national safe boundary is zero ecosystems are endangered (CR and EN) and

was based on expert opinion. South Africa has therefore exceeded its safe boundary for biodiversity loss by 37%.

As CR is called the 'biodiversity target' it could be used for the indicator and boundary, however only 20% of the original extent of the ecosystems in good condition was not considered safe.

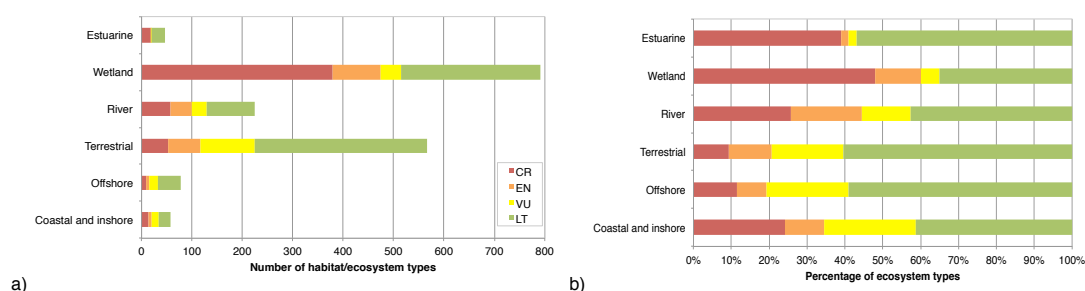


Figure S3.1 Threat status of ecosystem types by (a) number and (b) percentage (Data source: NBA 2011 (46))

Ocean acidification and marine harvesting

Ocean acidification is a climate change associated phenomenon, which will impact on the natural marine resources of South Africa within the 21st century (47). South Africa is at a very early stage in understanding ocean acidification and in March 2013 the Council for Scientific and Industrial Research (CSIR) held a workshop to start a national research response. They found that there is currently no long-term time series of in-situ data available to evaluate the current status and trends of the oceanic pH for the continental shelf ecosystems of South Africa, and therefore cannot confirm or reject the global biogeochemical climate model projections (47). The current national priority for oceans is rather the sustainability of marine resources. This is dependent on human drivers, which include acidification due to CO₂ emissions, but also includes fishing and other pressures. To better reflect this

reality, the “ocean” dimension was changed from ocean acidification to marine resources.

Commercial, subsistence and recreational fisheries in South Africa catch more than 630 marine species. The ‘Status of South African Marine Fishery Resources’ published by the Department for Agriculture Forestry and Fisheries (DAFF) in 2012 (48) provides information on 17 fishery sectors in 2011. These fisheries can contain a single species or multiple species. Two indicators are used – stock status, which is a result of a large variety of factors, and fishing pressure, the factor that can be managed most directly. Stock status is reported as Unknown, Abundant ($B > B_{MSY}$), Optimal ($B = B_{MSY}$), Depleted ($B < B_{MSY}$), and Heavily depleted ($B \ll B_{MSY}$), where B is the present biomass level (or population size) and B_{MSY} is that biomass level at which maximum sustainable yield (MSY) - the target for optimal utilisation - is obtained. For example, deep-water hakes (currently the most economically valuable fishery) have been depleted to 21% of the pre-fished biomass of 1,358,000 tonnes (B) and have a B_{MSY} of 24% of pre-fished biomass (325,920 tonnes), and are therefore classified as ‘depleted’. For some but not all multiple-species fisheries, the status is given per species. In some cases, the stock status and/or fishing pressure for a species may vary around South Africa’s coastline, in which case species are sub-divided into two or more categories e.g. Atlantic and Indian swordfish.

The 2012 stock status is reported for 45 species (or sub-species or multiple species), as shown in Figure S2 (species that are estimated between two status categories (e.g. abalone is depleted/heavily depleted) are counted as 0.5 in each

category). Of these, 5 are unknown, 5 are abundant, 17 are optimal, 12.5 are depleted and 5.5 are heavily depleted. The indicator for this case study was based on expert judgment and is the percentage of marine stocks that are depleted or heavily depleted. This could be either the percentage of all 45 species or of only the 40 whose status is known, and we chose the latter i.e. 45%. The safe boundary was set at zero per cent i.e. no marine fisheries are overexploited, therefore South Africa has exceeded its safe boundary for marine harvesting by 45%.

Further research could be done on weighting the fisheries by volume, economic value or employment.

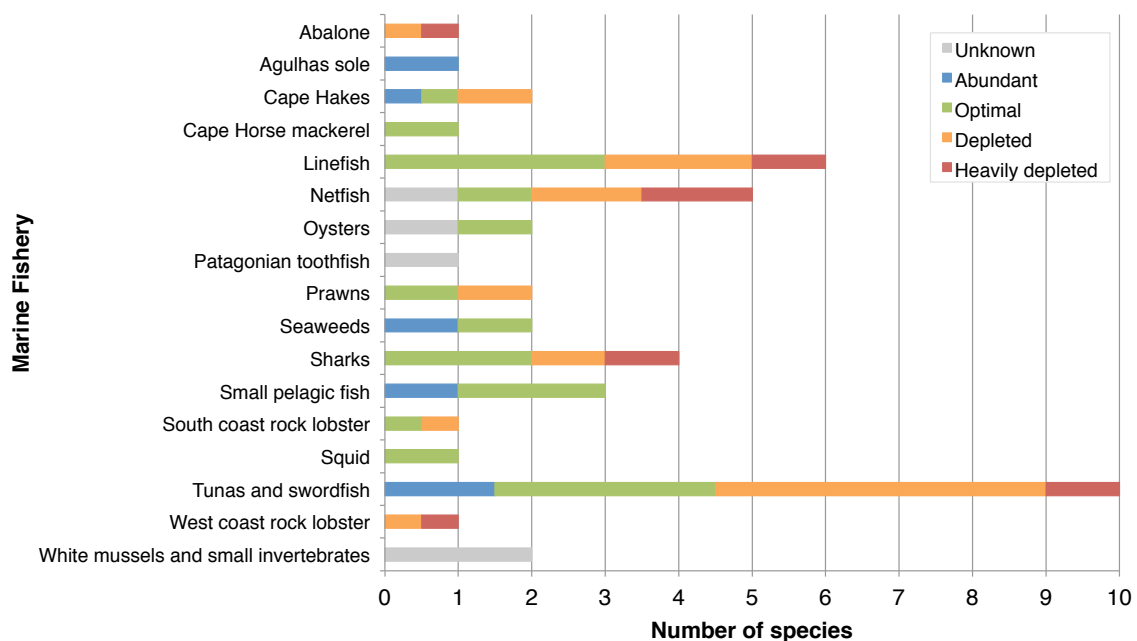


Figure S3.2 Status of South African Marine Fishery Resources 2012 (Data source: DAFF 2013 (48))

Nutrient cycles: Phosphorus loading

Phosphorus (P) is one of the building blocks of life and is essential for food production. Unlike other major elements such as nitrogen and carbon, it has no

gaseous phase and therefore the phosphorus cycle is more local and regional than global. Natural resources are concentrated in a few countries (Morocco has 85% of current known reserves) and the 'peak phosphorus' debate estimates that finite phosphate rock resources may be depleted in 30 to 300 years, posing a global food security concern (49). Phosphorus enters freshwater systems and oceans through natural weathering, through phosphate mining and its use in fertilisers, and through wastewater. Rockström *et al.*'s indicator for the phosphorus cycle is the annual inflow of phosphorus to the ocean, which could cause eutrophication at a regional scale.

Eutrophication of freshwater resources is widespread in South Africa and is a national concern (50). In 1980 the Department of Water Affairs and Forestry (DWAF) set an effluent discharge standard of 1 mg/l P and started its first monitoring programme in 1985. In 1988 the Phosphorus Management Objective of mean total phosphorus concentration in reservoirs was set at 130 µg/l P. In 2002, the National Eutrophication Monitoring Programme (NEMP) was implemented to measure mean annual levels of chlorophyll and phosphorus. NEMP currently has over 1,200 monitoring points in 16 drainage basins in its database, some of which date back to 1978. Single national values are reported in ESI 2011 for the period 2000 to 2011.

We therefore chose 'mean annual total P in dams' as our indicator of P loading, and obtained data for 11 drainage basins from DWA for 2012. We calculated a weighted average based on the gross volume of freshwater in each drainage basin to create a single national value of 0.098 mg/l. This obviously does not take the

seasonal variations into account and hides the variation in the drainage basins where individual values range from 0.02 to 0.26 mg/l, an order of magnitude difference.

The NEMP categorises the potential for algal and plant productivity based on mean annual total phosphorus as negligible ($P \leq 0.015$), moderate ($0.015 < P \leq 0.047$), significant ($0.047 < P \leq 0.13$) and serious ($P > 0.13$). Oberholster and Ashton (51) however specify 0.10 mg/l as the critical threshold for P in freshwater and this value is currently used as the effluent discharge limit for wastewater treatment plants in South Africa, the biggest point source of phosphorus in freshwater. We therefore chose this biophysical threshold as the safe boundary, and South Africa is therefore 2% below its boundary for phosphorus loading.

Nutrient cycles: Nitrogen fixation

Nitrogen (N), like phosphorus is essential for food production, however it is taken from the atmosphere in the form N_2 rather than from rock and is therefore a shared global resource. Nitrogen fixation has a range of local negative effects, described by De Vries *et al.* (52) as: (i) eutrophication of terrestrial and marine ecosystems, (ii) acidification of soils and fresh waters, (iii) formation of the greenhouse gas N_2O , (iv) air pollution due to ozone formation, (v) groundwater contamination by nitrate and (vi) stratospheric ozone depletion. Rockström *et al.*'s global indicator for the nitrogen cycle is the pressure 'nitrogen fixation during fertiliser production expressed in tonnes of N', rather than the impact. Their global nitrogen boundary is estimated as 25% of current nitrogen fixation which equates to 35 Tg N (or Mt N) per annum, which according to Schlesinger 'seems arbitrary and might just as

easily have been set at 10% or 50%' (53). De Vries *et al.* estimate that future global demand for nitrogen in fertilisers will range from 50 to 80 TgNyr⁻¹ (depending on use efficiency) and will therefore exceed this boundary. They calculate global nitrogen fixation boundaries for different N compounds (in air or surface water runoff) that vary from 20 to 120 TgNyr⁻¹, highlighting that the local impacts due to nitrogen fixation are critical for determining its boundary.

There are a number of approaches and indicators that could be taken to determine a national nitrogen indicator and boundary, focusing on the local impacts of nitrogen or on the use of nitrogen in fertiliser production. We reviewed various possible approaches and summarise them below.

Local impacts. De Vries *et al.* suggest four possible indicators for national nitrogen boundaries based on local impacts: atmospheric NH₃ concentrations that negatively affect biodiversity, radiative forcing from greenhouse gas NO₂, nitrate (NO₃) concentrations in groundwater that negatively affect human health, and dissolved organic N concentrations in surface water that cause eutrophication. Three out of these four indicators overlap with other planetary boundaries – biodiversity loss, climate change and surface water quality (through phosphorus loading, though nitrate is not necessarily correlated with phosphorus) – however groundwater quality has not been assessed in any other dimension. Nitrate occurs extensively in groundwater in southern Africa as a natural feature of the semi-arid to arid landscape and the nitrate concentration can vary greatly depending on the aquifer and its recharge characteristics (54). The main anthropogenic source of nitrate in groundwater is on-site sanitation (unlike high income countries where

agriculture is the main source of nitrate), while other sources are livestock feedlots, fertiliser application, land clearing and tilling of the soil (54). South Africa has official DWA specifications for potable water and stock watering similar to the World Health Organisation's guidelines. Potability classes measured with nitrate concentration are: Ideal ($<6 \text{ NO}_3\text{-N mg/L}$), Acceptable ($6\text{-}10 \text{ NO}_3\text{-N mg/L}$), Marginal ($10\text{-}20 \text{ NO}_3\text{-N mg/L}$), Poor ($20\text{-}40 \text{ NO}_3\text{-N mg/L}$) and Unacceptable ($>40 \text{ NO}_3\text{-N mg/L}$). For livestock watering the acceptable level is $<100 \text{ NO}_3\text{-N mg/L}$ (55). In 2009 Maherry *et al.* (56) created a national map of nitrate levels in groundwater which concludes that the Western Cape has seen elevated nitrate concentrations over the last decade; the Limpopo and Kalahari region have been and still are strongly affected by elevated nitrate concentration; and there is a scarcity of data points in certain urban centres and the central part of SA. While nitrates pose a human health risk in communities dependent on groundwater, it is not a national priority.

Similarly, nitrate concentrations (NO_3 as N in mg/L) in surface water are measured on a weekly or monthly basis under NEMP, but are not considered national indicators by the Government. A rapid analysis of the latest data obtained from DWA shows the median value of all 3,112 data points in 2012 was 0.125 mg/L, well below DWA's ideal potable water threshold of 6 mg/L. Nitrogen compounds (ammonia (NH_4) as nitrogen (N) and nitrate (NO_3)/nitrite (NO_2) as N) are also reported in the DWA's Green Drop regulation programme, which measures and compares the performance of 153 municipalities and 831 wastewater treatment systems to create a National Green Drop Performance Barometer (57). National data was not available and the local thresholds vary based on licence type and discharge locations, making a single national boundary impossible.

Fertiliser use. Nykvist *et al.* (9) calculated an equal share per capita nitrogen boundary of 5 kg N fertiliser consumption per year, based on Rockström *et al.*'s global boundary and used it to compare 60 nations. Using this method, South Africa would exceed the global boundary by 54% at 7.1 kg N per capita, however this absolute value does not take into account national conditions such as soil quality, rainfall and arable land area, and assumes that N fertiliser use has negative consequences, which may not be the case especially in developing countries. A better global comparison would be N fertiliser use per hectare of arable and permanent cropland, or per unit food produced, although the global boundary would ignore other national conditions. According to FAOStat (58), in 2010 South Africa used 31 kg N/ha compared to 53 kg N/ha for the Americas, 11 kg N/ha for Africa as a whole, 121 kg N/ha for Asia and 46 kg N/ha for Europe, and ranked 81 out of 159 countries.

The Fertiliser Society of South Africa (FSSA) publishes annual national data on fertiliser consumption and planted areas for different crops or crop types each year. In 2012, 6.873 Mha were planted with crops and 368,720 tonnes of N were applied at an average application rate of 53.6 kg N/ha, though rates varied from 12.9 kg N/ha for fibre crops to 170 kg N/ha for roots and tubers (59). Maize consumed almost two thirds of N (62.2% or 229,420 t N) on 39% of total cropland, while sugar crops consumed 8.9%, fruits consumed 7.4%, vegetables consumed 4.4% and wheat consumed 4.2% of total N. Crop production in South Africa contributes to food security, employment (on-farm and agro-processing), exports and GDP (60), therefore sustainable levels of N in the soil need to be maintained. A possible

indicator is therefore 'Sustainable N-application for crop production', however, determining a national boundary is more difficult.

Recommended fertiliser application rates are based on yield potential and soil status of N, P and K, as well as climate, soil depth and soil type, and therefore vary geographically as well as by crop and are affected by previous farming practices and irrigation. For example, the FSSA Fertiliser Handbook (61) recommends N-application rates for maize ranging from 20 kg/ha for a yield potential of 2 t/ha to 270 kg/ha for a yield potential of 12 t/ha and provides adjusted N-application rates for soils with clay content above 5%. In 2013, Adriaanse (62) reviewed 13 years of N-calibration studies for dry-land maize by the Agricultural Research Council, Grain Crops Institute (ARC-GCI) in SA to establish a single threshold value for inorganic N (in the top 600 mm soil) of 100 kg N/ha i.e. above this application rate the improvement in yield is less than 10%. He also established that inorganic N application rates should be between 70 and 133 kg N/ha (the range reflects different soil types and different levels of organic N) for biological and economic reasons with a maximum of 174 kg N/ha for maximum yield. Beyond this maximum, N application can have a negative impact on yield.

Brentrup and Poulter (63) describe two policy-relevant indicators for sustainable fertiliser use. The 'N balance', an established OECD indicator, is the difference between N inputs (fertilizer, manure etc.) and N outputs (arable, permanent and fodder crops) and is measured in kg N/ha. The Nitrogen Use Efficiency (NUE) has a number of definitions and methodologies, however, the one most suited to a policy context is the ratio between the amount of fertilizer N removed from the field

by the crop and the amount of fertilizer N applied i.e. N removed divided by N applied (63). The NUE considers productivity more than the balance and requires interpretation. Theoretically, a NUE of 100% would be ideal, however, in practice N losses such as leaching are partly unavoidable (63). A range of 80-90% is considered well balanced, while more than 90% poses a risk of soil mining (partly because the N requirements for roots and straw are not met by N input) and less than 70% poses a risk of high losses of N into the soil. The global average NUE was 55% in 2006. To explore these alternative measures we have used maize, the biggest user of N and the staple crop in South Africa, as an example but this would need to be done for all major crops types.

On average maize removes 27 kg N from the soil per tonne of marketable product (61). In 2011/12, SA produced 11.83 Mt of maize on 3.141 Mha (60), a yield of 3.8 t/ha, therefore 101.7 kg N/ha were removed from the soil. This is practically the same as Adriaanse's yield threshold of 100 kg N/ha. As mentioned, this was replaced by an estimated 229,420 t N on 2.699 Mha in 2012 or 85 kg N/ha. The N balance is therefore negative (-16 kg/ha) and the N removed is not being replaced. The NUE is 119% and would be classified as soil mining. Although in the long-term this could cause soil degradation it may not be a concern in the short-term. It is also almost 50% higher than the threshold for N losses into the soil from over-application of N, which affect water quality, so this is clearly not a concern.

This is a difficult safe boundary to define as too much or too little fertiliser is problematic, although Rockström *et al.* identified the over-application of N as the main global concern. We therefore used the NUE threshold of 70%, which would

translate to an N application rate of 144 kg N/ha for maize in South Africa. At 85 kg N/ha, South Africa would be 41% below this N-application boundary.

In summary, there are eight possible indicators and boundaries for the nitrogen cycle in South Africa. The four measures that have both the indicator and boundary give very different results ranging from 16% to 154%. As the 5kg/capita boundary does not take national circumstances into account, and surface water quality is already addressed, a sustainable crop application rates indicator is the most appropriate. We selected the N-application rate as it the easiest to understand and measure against the boundary. Due to lack of available data, we used maize production figures but all crops should be assessed in future. This analysis could contribute to the identification of the most suitable crops for South Africa.

Aerosol loading and Air pollution

Aerosol loading is a driver of regional climate change. Rockström *et al.*'s indicator for aerosol loading is overall particulate concentration in the atmosphere on a regional basis. As aerosol loading is not a major concern in South Africa, we decided to change this dimension to address the important national issue of air pollution that affects human health.

South Africans have a Constitutional right to clean and healthy air and Government Outcome 10 Output 2 Sub-output 2.2 is 'Atmospheric pollutants reduced' (64). The South African Air Quality Information System (SAAQIS) stores data from 90 ambient air quality monitoring stations across the country on CO₂, CH₄, carbon monoxide, nitrogen oxides (NO_x), sulphur dioxide (SO₂), ground-level ozone,

benzene, toluene, p-xylene, and particulate matter (fine particles found in the atmosphere, including soil dust, dirt, soot, smoke, pollen, ash, aerosols and liquid droplets) less than 10 microns (PM_{10}) and 2.5 microns ($PM_{2.5}$) (65). South Africa has three national priority air quality hotspots – the Vaal Triangle, the Highveld and the Waterberg – linked to coal and gold mining areas.

The government (66) has identified PM_{10} and SO_2 as problem pollutants at a national scale, and DEA uses the annual average concentration of each (from all monitoring stations) to calculate a National Air Quality Indicator (NAQI). Every year, the DEA presents the 'State of Air' in the country and the latest results for 2012 (66) show that PM_{10} is now the 'greatest national cause for concern in terms of air quality'. We therefore chose annual average PM_{10} concentration as our indicator for air pollution. The DEA has determined a safe boundary for PM_{10} of $50 \mu g/m^3$ and a policy target of '100% national compliance with National Ambient Air Quality Standards by 2020'. In 2012, the current status was $46.9 \mu g/m^3$, down from a peak concentration of $53.7 \mu g/m^3$ in 2009, showing that the policy intervention has had a positive effect.

While this single national value is useful for showing overall progress on improving air quality, it is an aggregation of multiple point sources across seven hotspots: the Vaal Triangle, the Highveld, Eskom, Johannesburg, Tshwane, eThekweni and Cape Town. In 2011, the PM_{10} values at the monitoring stations varied from 10 - $225 \mu g/m^3$ and 16 out of 42 stations (38%) crossed the safe boundary (67). The NAQI has replaced the indicator 'Number of metropolitan and district municipalities with air quality that does not conform to ambient air quality standards' defined in the

2007 National Framework. In 2009, 50 municipalities were considered to be non-compliant, although only 26 were known (>90% confidence) to be non-compliant (64). Together these municipalities are home to 36 million, 70% of the national population in 2011. Therefore although South Africa has not crossed the national safe boundary based on average PM_{10} , a large proportion of the population is living with poor air quality.

Chemical pollution

Chemical pollution, such as radioactive compounds, heavy metals and organic compounds, occurs at the local scale but has global impacts on human and ecological functioning, and affects other planetary boundaries (1). The international Basel Convention on trade in hazardous waste and the International Convention for Prevention of Pollution at Sea both seek to address it through global governance. Rockström *et al.* did not identify an indicator for this dimension due to the huge number of chemicals and the lack of aggregate global-level analysis. They did suggest indicators based on emissions, concentrations, or effects on ecosystem and Earth System functioning of persistent organic pollutants (POPs), plastics, endocrine disruptors, heavy metals, and nuclear wastes. They identified two approaches – to focus on persistent pollutants with global distribution (such as mercury), or to focus on their negative large-scale effects.

South Africa is a signatory to the international Basel Convention and has progressive national legislation in the National Environmental Waste Management Act 2008, however in practice there is a large gap between policy and practice (68). The National Waste Management Strategy sets targets for waste management and

the National Waste Information Baseline Report (69) published by DEA in November 2012 provides an estimated current status. Over 1.3 Mt of hazardous waste were generated in 2011 and were reported in 20 hazardous waste categories. Five categories dominated: 25% were 'miscellaneous', 22% were 'inorganic waste', 19% were 'tarry and bituminous waste' and 15% were 'Other organic waste without halogen or sulphur', all of which were landfilled. In addition, 49 Mt of unclassified waste were reported. The baseline is however limited by voluntary reporting; companies that generate hazardous waste are reluctant to report it. Also, as many large industries manage waste on-site, it does not enter the formal waste stream and is not measured. The South African Waste Information System (SAWIS) will provide updated information of enforced waste reporting in the future.

Due to the lack of detailed and accurate information on chemical pollution and its thresholds, we did not define an indicator or boundary for this dimension.

S3.2 Social deprivation parameters

This section explains our choice of social indicators and hence boundaries for social deprivation, and contrasts them with those used by Raworth (70) at the global scale. Table S4 compares Raworth's social indicators with the SAIMD indicators and the indicators used in this barometer. As explained in the main paper, there are three different types of indicator sets to choose from; Type 1: a set of indicators that represent a range of levels of deprivation (which are commonly found in household surveys); Type 2: a range of definitions of the same indicator or Type 3: a diverse set of indicators that represent different aspects of wellbeing. We grouped

the indicators into four domains – basic services, public goods, livelihoods and living standards – to make the results easier to analyse.

We chose social indicators based on the South African Index of Multiple Deprivation (SAIMD) as it is being used by the Department of Social Development to identify the most deprived areas to target their social grants and initiatives. SAIMD has five deprivation domains - Income and Material, Employment, Health (2000 version only), Education, Living Environment – the selection for these domains was based on the following criteria (71):

- It must be 'domain specific' and appropriate for the purpose (as direct as possible measures of that form of deprivation);
- It must measure major features of that deprivation (not conditions just experienced by a very small number of people or areas);
- It must be statistically robust.

The SAIMD reports national values for domains only, not for the individual indicators, and it would require significant statistical work to determine the national current status. Instead, the most similar indicators and their current status were taken from the 2012 Development Indicators Report (72) published by the Department for Performance Monitoring and Evaluation (DPME) in the Presidency and the statistical report by StatsSA on the 2012 General Household Survey (GHS), which surveyed a representative national sample of 31,144 Dwelling Units (73).

Table S3.4 Comparison of indicators in the SJS (70), SAIMD (71,75) and our barometer

Dimension	Raworth's SJS Indicator	SAIMD Indicators	Barometer
Energy	Population lacking access to electricity Population lacking access to clean cooking facilities	Number of people living in a household without use of electricity for lighting	Households without access to electricity
Water	Population without access to an improved drinking water source	Number of people living in a household without piped water inside their dwelling or yard	Households without access to piped water within 200m of household [^]
Sanitation	Population without access to improved sanitation	Number of people living in a household without a pit latrine with ventilation or flush toilet	Households without access to sanitation (ventilated improved pit latrines) [^]
Housing	-	Number of people living in a shack, or in a household that is crowded	Households not in formal dwellings
Education	Children not enrolled in primary school Children enrolled in tertiary education Illiteracy among 15–24-year-olds	Number of adults (18-65 years) with no secondary schooling	Adults without more than 7 years of schooling (adult illiteracy rate) [^]
Health care	Population estimated to be without regular access to essential medicines	Years of Potential Life Lost** (standardised mortality ratio)	Infant (<1 year) immunisation coverage
Jobs	E.g. Labour force not employed in decent work	Number of people who are unemployed (using official definition) plus Number of people who are not working because of illness or disability	Broad unofficial unemployment rate (adults aged 15-64 available to work)
Income	Population living below US\$1.25 (PPP) per day	Number of people living in a household that has a household income that is below 40% of the mean equivalent household income (~ R1,003/month in February 2007 Rands)*	Population living below the upper national poverty line (R577 a month in 2011 constant Rands)
Social equity	Population living on less than the median income in countries with a Gini coefficient exceeding 0.35	-	-
Gender inequality	Employment gap between women and men in waged work (excl. agriculture) Representation gap between women and men in national parliaments	-	-
Food	Population undernourished	-	Households without adequate food
Voice	<i>Not defined</i>	<i>Not mentioned</i>	<i>Not defined</i>
Household goods	-	Number of people living in a household without a fridge Number of people living in a household with neither a television nor a radio	Households without a refrigerator
Safety	-	- ***	Households who feel unsafe walking alone in their area during the night

*This was used in SAIMD because a national poverty line had not yet been defined. ** In SAIMD 2001, which was based on Census 2001, but not in SAIMD 2007, which was based on Community Survey 2007. *** The intention was to include crime in SAIMD but it was excluded due to lack of data in 2001 and 2007. [^]These indicators also appear in ESI 2011.

S3.2.1 Domain 1. Basic services

Energy access

Raworth used two indicators for energy access – ‘Population lacking access to electricity’ and ‘Population lacking access to clean cooking facilities’, neither of which appear in the Millennium Development Goals (MDGs). The SAIMD indicator is ‘Number of people living in a household with electricity access’ while the Development Indicators reports ‘Number of households with electricity access’ (76.5% in 2011/12). GHS 2012 reports the percentage of households that were connected to the mains electricity supply (85% in 2012) while the Census 2011 (27) reports the household electricity use (for cooking, lighting and heating) rather than access. Alternative forms of energy (gas, paraffin, wood, coal, candles, animal dung, solar, other) are recorded in Census 2011 and GHS 2012 however universal electricity access is the clear national priority. We chose the simplest deprivation indicator, ‘Number of households without electricity access’, and in 2012, 23.5% of households were deprived of electricity access, down from 49.1% in 1995 (72).

Water access

Raworth’s indicator for water access was ‘Population without access to an improved drinking water source’ which is MDG 7.8. The global MDG target is ‘20/ per person per day within 1km of household’ however the South African MDG target is higher at ‘25/ of potable water per person per day without interruption for more than 7 days within 200m of the household’, known as the RDP standard (74), and both are reported in Development Indicators 2012. Census 2011 and GHS 2012 record both access to piped water and the source of water. There are seven levels of access to piped water based on distance from the dwelling ranging from ‘tap

water in dwelling' to 'no access to tap water', shown in Table S3.5. The SAIMD indicator is 'Number of people living in a household without piped water in their dwelling or yard' which combines the best two levels. Census 2011 reports household access at this level as 73.4%. Therefore 26.6% of households were deprived of this level of water access, down from 39.3% in 1996. Table S6 also shows the possible range in the current status based on the level of access that is chosen as the indicator (i.e. the boundary of unacceptable deprivation). The difference between level 1 and level 2 is 29.1% and the difference between level 2 and level 3 is 11.7%. We used the RDP standard quoted in Development Indicators 2012 where 4.5% of households were deprived of this level of water access, down from 38.3% in 1994, as it is used as the official government indicator. This value of 4.5% is quite different to the Census 2011 value of 14.9% and should be reviewed in subsequent versions.

Table S3.5 Levels of water access in South Africa in October 2011 (Data source: (27))

Level of household water access	Indicator	Percentage access	Access deprivation
1 - Tap water in dwelling		46.3%	53.7%
2 - Tap water in dwelling or yard	SAIMD	73.4%	26.6%
3 - Tap water within 200m of dwelling	RDP standard	85.1%	14.9%
4 - Tap water within 500m of dwelling		88.7%	
5 - Tap water within 1km of dwelling	MDG 7.8	90.4%	
6 - Tap water >1km from dwelling		91.2%	
7 - No tap water access			8.8%

Sanitation

Raworth's indicator for sanitation was the MDG 7.9 indicator 'Proportion of population using an improved sanitation facility'. The South Africa MDG report 2010

(74) further specifies it as 'All households to have access to at least a ventilated pit latrine on site', which is reported in Development Indicators 2012. Similar to water access, Census 2011 and GHS 2012 define eight levels of sanitation for households that range from a 'flush toilet connected to a sewerage system' to 'chemical toilet' to 'bucket toilet' to 'none'. The indicator used for the SAIMD indicator is 'Number of people living in a household without a ventilated pit latrine or a flush toilet' which combines the first four levels and is reported in Development Indicators. We therefore used this indicator. In 2012, 16.6% of households were deprived of this level of sanitation, down from 49.1% in 1994.

In the South African Social Attitudes Survey (SASAS) 2005, 84% of respondents said that having a flush toilet in the house was essential (75). This could be used as the indicator (combining level 1 and 2) in the future, which would change the current status of deprivation from 16.6% to 60.1%.

Housing

Housing was added as a new dimension as it is included in SAIMD and is a Constitutional right in South Africa. Large informal settlements emerged during Apartheid and now hinder the provision of basic services. Over 3.38 million houses have been built since 1994 by the government to correct this historical imbalance and to support poverty alleviation (72). The SAIMD indicators are 'Number of people living in a shack (informal dwelling)' and 'Number of people living in a household that is crowded'. Development Indicators 2012 reports the number of 'households in formal dwelling' and we used this indicator as it reports national data. In 2011, 22.5% of households were deprived of formal housing, down from

36% in 1996. This deprivation figure includes households living in traditional dwellings and informal dwellings. Development Indicators excludes traditional dwellings from their measure of households without formal dwellings even though they distinguish between formal and traditional dwellings. If we chose this indicator, the deprivation value would drop from 22.5% to 12.3% in 2011.

Other indicators that can be taken from Census 2011 are average household size (3.4 in 2011, down from 4.5 in 1996) and tenure status (41.3% owned and fully paid off, 11.8% owned but not paid off, 25% rented, 18.6% occupied rent-free and 3.4% other).

S3.2.2 Domain 2. Public goods

Education

Raworth used two MDG indicators for education; 'Children not enrolled in primary school' (MDG 2.1) and 'Illiteracy among 15–24-year-olds' (MDG 2.3). South Africa has achieved universal access to primary school and therefore no longer reports this indicator. The SAIMD uses 'Number of adults (18-65 years) with no secondary schooling', which is a higher level of achievement and more suited to a middle-income country. Development Indicators reports an adult literacy rate, which is the percentage of adults 20 years and older who have achieved 7 years of education i.e. passed Grade 7, based on the GHS. We chose the deprivation indicator 'Adults without (≥ 20 years old) without more than 7 years of schooling (adult illiteracy)'. We used the current status given in Development Indicators 2012, which differs slightly from the GHS 2013 figures, as it has more historical data. In 2011, 19.3% of adults were deprived of this level of education, down from 30.4% in 1995. The

GHS has historically measured adult literacy rates based on an individual's functional literacy, i.e. whether they have completed Grade 7. As this may not correlate to an individual's ability to read and write, in GHS 2009, a separate question was introduced on the level of difficulty an individual has in reading and writing.

A number of other indicators are reported in Development Indicators 2012, including Early Childhood Development, learner-educator ratios, national senior certificate pass rates, and the Gender Parity Index (GPI) for basic and higher education. These provide an indicator of the quality of education and gender equality in education. A gender component could therefore be added to education by including the GPI, which is the ratio of GER (Gross Enrolment Rate) of female learners to the GER of male learners regardless of age, in public and independent ordinary schools for a given year. In 2011, the GPI was 0.98 for primary schools, 1.071 for secondary schools and 1.39 for higher education (72), showing a decrease in gender equality as children progress through the education system.

Health care

Raworth's indicator for health care was 'lack of regular access to essential medicines' (MDG 8.13) but there is no data available in national MDG reports. A number of health-related indicators are reported under MDG 4, MDG 5 and MDG 6, and many, such as child mortality, HIV and TB prevalence, malaria fatality rates and immunisation coverage, are reported in Development Indicators 2012.

The SAIMD identifies health deprivation as years of potential life lost (YPLL), where the level of unexpected mortality is weighted by the age of the individual who has died (76). This is a gender and age standardised measure of premature death and no national values exist. The closest indicator in Development Indicators 2012 is life expectancy (58.7 years in 2012) however this gives an average for the population hence it cannot measure what percentage of the population is deprived. The Department of Health's 'Health Data Advisory and Co-ordinating Committee' established a set of high-level indicators for Government Outcome 2 and identified the Rapid Mortality Surveillance (RMS) maintained by the South African Medical Research Council, as an important source of data (77). In addition to life expectancy and mortality rates, the RMS reports an 'adult mortality index ($_{45q15}$)', the probability of a 15-year-old person dying prematurely before the age of 60 years. In 2011, the adult mortality index in South Africa was 40%, down from 46% in 2009 (78). Again this indicator does not suit the barometer, as it does not measure what percentage of the population is deprived. The most suitable indicator for the barometer is immunisation coverage as it measures a proportion of the population rather than a rate or absolute number. In 2011 only 9.2% of infants were not immunised, down from 37% in 1998 (72). A gender component could be added to health by including 'maternal mortality ratio'.

Additional health-related data can be found in Census 2011, which reports on disabilities and assistive devices and medication. The four levels of disability reported are subjective i.e. dependent on how the respondent rated themselves (27). Very few people are totally disabled, up to 1.5% have a lot of difficulty with one or more disabilities, 1-10% of people have some difficulty and generally over

90% of the population has no difficulty. Results also showed that 12.3% of the population was on chronic medication, 14.0% used eye glasses, 2.8% used a hearing aid, 3.2% used a walking stick or frame, and 2.3% used a wheelchair. Disability is not a measure of deprivation, rather the lack of access to assistive devices represents deprivation. As this data is not readily available, it could not be used.

Voice

There is no agreed definition of 'voice' and Raworth did not define an indicator for voice, although her gender empowerment indicator 'gender gap in parliament' could be provide a gender component to this dimension. Development Indicators 2012 has a number of indicators under the heading 'Social cohesion: Voice and Accountability'. Social cohesion has become a common term in South African development debates where it refers to the ideal of a harmonious society, very different to the racially divided Apartheid society (79). Research by Struwig *et al.* (79) at the University of the Western Cape is on-going to develop a social cohesion barometer for South Africa. The Development Indicators that could measure voice are membership of voluntary organisations, voter turnout, female representation in parliament and the corruption perceptions index. None of these indicators were used, based on expert judgment or because the indicator is not a deprivation measure or is gender-specific.

Instead, experts recommended that voice should measure public participation in decision-making. South Africa has progressive legislation on local government where communities are consulted on their Integrated Development Plans (IDPs).

In the 2005 South African Social Attitudes Survey (SASAS), however, only 8% of respondents indicated that they participated in the IDP process, although this is thought to be over-reported (80). The majority (91%) of those who participated in the IDP process felt they had 'some' to 'much' influence on local government decision-making while only 28% of those who did not participate felt the same. The results from Round 5 of the Afrobarometer (citizen surveys of democracy and governance in Africa) in South Africa (81) show that 16% of respondents do not feel free to say what they think, 37% think that local councillors never take time to listen to people like them, 51% think local councillors are involved in corruption, 58% would never attend a protest march, 51% do not trust the police, 21% fear becoming a victim of political intimidation during election campaigns and 3% think that South Africa is not a democracy.

Due to the lack of wide support for any specific indicator, and the large range in values for different indicators, we decided to keep the dimension without a national indicator at this stage, with further research required.

Connectivity

Connectivity was considered as a new dimension in the Public Goods domain. Two aspects were reviewed – internet access and access to public transport – however neither met all the criteria for indicator selection hence we did not include it. The analysis does show potential for including connectivity in future versions of the barometer. Internet access is reported under 'global competitiveness' in Development Indicators 2012 as the percentage of the population who were internet subscribers (10.7%) and broadband subscribers (3.6%) in 2009. According

to GHS 2012, 40.6% of South African households have at least one member with access to the internet at home, work, place of study or internet cafés. This is a 5% increase from 2011 when the Census reported that 16% of households access the internet via cell phones, 8.6% accessed it from home and 4.7% access it from work and 5.6% access it from elsewhere. This provides a measure of deprivation that could fit into the barometer however it is not seen as a national priority at present.

Access to public transport is more complicated than internet access. It could be measured using GHS 2012 data on modes of transport for getting to school and work. Only 3.4% of scholars and only 9.2% of the workforce use the bus or train. This is partly due to affordability and proximity (69% of scholars walk to school) and partly due to private car ownership (36% of people use a private car to get to work). This does not directly measure deprivation as individual choice is involved.

S3.2.3 Domain 3. Livelihoods

Jobs

Raworth did not define an indicator for jobs but suggested 'Labour force not employed in decent work'. SAIMD calculates employment deprivation by adding the number of people who are unemployed (using the official definition) and the number of people who are not working because of illness or disability, which totalled 37.8% in 2007. Using data from StatsSA's labour force surveys, Development Indicators 2012 reported a broad unofficial unemployment rate (adults aged 15-64 without work and available to work) of 36.3% and a narrow official unemployment rate (adults aged 15-64 without work and available to work and have taken steps

to look for work or start a business) of 25.1% in 2012. As the broad definition is closest to SAIMD, it was chosen for this case study.

The narrow unemployment rate is further disaggregated by province, age and gender, and into long-term unemployed (68% of total) and short-term unemployed (32% of total). Youth unemployment (age 15-24) is 50.9% while female unemployment (27.9%) is 5.5% higher than male unemployment. Raworth's indicator for gender equality, 'the employment gap in waged work (excluding agriculture)', could be incorporated into this dimension, but as the broad official unemployment figures are not disaggregated we could not include it here.

Income

Raworth's indicator for income was the MDG indicator 'Population living on less than USD 1.25 (PPP) per person per day' though USD 2.5 (PPP) is also an MDG indicator. This can be measured by income or expenditure and for South Africa it equates to R191 or R382 per person per month in 2011 constant Rands (72). The SAIMD in 2007 used 'household income below 40% of the mean equivalent household income' (~R1,003 per person per month in 2007) in the absence of an official national poverty line. A number of different poverty lines have been used in South Africa since 1994, however Development Indicators 2012 reports a food poverty line (amount of money an individual will need to consume the minimum required energy intake) of R305 per person per month (in 2011 Rands), and an upper-bound and lower-bound poverty line (food poverty line plus average amount derived from non-food items of households whose total food expenditure is equal to the food poverty line) of R577 and R416 respectively. These are based on the Living Conditions Survey 2007/8 (82) which reported that 26% of the population

lived below the food poverty line, 39% lived below the lower-bound poverty line and 52% lived below the upper-bound poverty line.

There are therefore a range of different indicators that can be used for income deprivation, that give a very different picture of poverty in the country. We used the national upper-bound poverty line as it is an official level and is the closest to the SAIMD value, although it is still only roughly half of the SAIMD value.

S3.2.4 Domain 4. Living standards

Food security

Food security has three components – access, availability and utilisation (83). South Africa has been food-secure at a national scale for a number of decades and has produced enough maize for 47 out of the past 50 years, with drought causing the insufficiency in three years. Raworth's indicator was 'Population malnourished' which is based on MDG 1.9 'Proportion of population below minimum level of dietary energy consumption' but there is no recent national data for this in South Africa. The 2005 National Food Consumption Survey indicated that the proportion of underweight children under five years of age was about 10% while stunting in this age group was about 21% (72). The national MDG Report and Development Indicators have data for 'Severe malnutrition in children under five years old (MDG 1.8) but there are concerns over the accuracy of the data which is sourced from the District Health Information System. Food is not part of SAIMD as income was seen as a good proxy for food, and food was not recorded in the 2001 Census or 2007 Community Survey. The GHS 2013 did include questions about food access and it reports what percentage of households are vulnerable to hunger and percentage

of households with either adequate, inadequate or severely inadequate food (84). We used the indicator 'households without adequate food', which was 23.1% in 2013.

An alternative approach could be to use the food poverty line mentioned in the section of income. In 2008/9, 26.3% of the population lived under the food poverty line i.e. on less than R305 per person per month.

Household goods

We added 'Household goods' as a new dimension as it is included in SAIMD as part of material deprivation. The SAIMD has two indicators; 'ownership of a refrigerator' and 'ownership of a radio and/or landline telephone'. We chose the former indicator as radios and landlines are being replaced by cell phones (radio ownership fell from 72% in 2001 to 67.5% in 2011 and landline ownership fell from 23.9% in 2001 to 14.5% in 2011) (27). This data is collected in some household surveys and is reported in Census 2011 and GHS 2013, though it is not mentioned in the MDGs or the Development Indicators reports. In 2013, 28.1% of households did not own a refrigerator (84).

Other indicators for household goods reported in Census 2011 are household ownership of a cell phone (88.9%), television (74.5%), computer (21.4%), stove (77%), car (29.5%), satellite tv (25.8%), dvd player (59.3%) or washing machine (31.5%), which have all increased since 2001 i.e. deprivation has decreased.

In the South African Social Attitudes Survey (SASAS) 2005 (80), the household items that more than half of all respondents felt were essential were a refrigerator (89% said this was essential), a radio (77%), an electric cooker (74%), a television (72%), a landline phone (64%), a cell phone (63%) and a sofa/lounge suite (52%).

Safety

Safety was added as a new dimension as it is an important issue in South Africa and it was intended to be included in SAIMD but was left out due to lack of small area data. Safety is a complex dimension to measure; crime statistics do not compare well across jurisdictions (except for murder), perceptions of safety do not necessarily reflect potential for victimisation, and high risk does not necessarily equate to high crime rates. StatsSA has conducted four 'Victims of Crime Surveys' (1998, 2001, 2010, 2011), which measure household perceptions and experiences of crime. Development Indicators 2012 reports a range of indicators including perceptions of safety, serious crime rates, detection rates and prison inmates. Most of these indicators cannot be used as they measure rates and not proportions of the population. We chose the indicator 'households that feel unsafe walking alone at night', which was 63.5% in 2012, an increase of nearly 20% from 44% in 1998. As one of the few social indicators that are trending towards larger deprivation levels, this highlights a serious concern.

Raworth's dimensions that were removed

Resilience

Raworth did not define an indicator for resilience. Most South African experts thought that it did not fit in the barometer as it is a cumulative effect and is

dependent on the other dimensions, and therefore an indirect measure. For example, having a good health and education makes an individual more resilient to unemployment. As it does not meet the criteria, it was removed as a dimension for this case study.

Of interest is the National Income Dynamics Survey (NIDS) which includes questions on household shocks (85) and therefore provides a qualitative measure of resilience. It measures the types of shocks (health, economic etc), the severity of the shocks and households' coping mechanisms. Results show that most people respond to shocks by reducing spending and substituting with inferior goods e.g. using firewood instead of electricity. One of the biggest shocks is unforeseen shocks, such as food price spikes.

Social equity

Raworth's indicator for social equity is 'Population living on less than the median income in countries with a Gini coefficient exceeding 0.35' i.e. it measures income inequality. The Gini coefficient is a popular measure of income inequality, however, it is slow to change. The Palma index (ratio of top 10% income to bottom 40% income) for South Africa increased from 5.69 in 1993 to 7.05 in 2008 (86) and the Theil index for racial inequality dropped from 0.549 in 1993 to 0.240 in 2009 (87). Inequality is not confined to income but exists across the multiple dimensions of deprivation. In fact, the other dimensions of the barometer already discussed provide a set of inequality measures for South Africa, and we therefore removed it as a dimension. We would like to see future versions of the barometer incorporate inequality across race, gender, and geographical location.

Gender equality

Raworth had two indicators for gender equality; ‘Employment gap between women and men in waged work (excluding agriculture)’ and ‘Representation gap between women and men in national parliaments’. These have both been discussed in the earlier sections on jobs and voice. As with social inequality, gender equality is a cross-cutting issue that cannot be simplified into a single indicator. The UN’s Gender Inequality Index combines five indicators: maternal mortality, adolescent fertility, education, representation and labour force participation (88). As already mentioned, these could be addressed under the dimensions of health, education, voice and jobs. Ideally, gender equality should be measured for all the dimensions of the barometer. This was not done in this case study due to lack of available data, but data analysis of household survey results could provide the necessary information for future iterations.

S3.3 Experts interviewed in South Africa

Semi-structured interviews were held with 43 experts from government, national research institutes, universities and international NGOs in Johannesburg, Pretoria, Cape Town, Stellenbosch, Durban and Pietermaritzburg (see Table S3.6). A draft version of the barometer for inclusive sustainable development for South Africa was shown to the experts. Questions covered five aspects: perceptions of the barometer, environmental stress dimensions, social deprivation dimensions, the utility of the barometer, and suggested experts to contact. The interview questions were tailored to the expert’s sector/specialism so that experts were asked to recommend the most suitable indicator, boundary and data source for each

dimension of the barometer. Experts were also asked about data quality and availability and relevant current and future research.

Table S3.6 Organisation, location and number of experts interviewed

Organisation	City	Experts
Government		
National Government, Department of Environmental Affairs (DEA)	Pretoria	9
National Government, Department of Agriculture, Forestry and Fisheries (DAFF)	Pretoria	2
National Government, Department of Water Affairs (DWA)	Pretoria	1
National Government, Department of Social Development (DSD)	Pretoria	1
Western Cape Government, Department of Environmental Affairs and Development Planning	Cape Town	1
Ethekweni Municipal Government, Department of Climate and Environment Protection	Durban	1
	Sub-Total	15
National research institutes		
Council for Scientific and Industrial Research (CSIR)	Stellenbosch, Durban	8
Human Sciences Research Council (HSRC)	Cape Town, Durban	2
South African National Biodiversity Institute (SANBI)	Cape Town	2
	Sub-Total	12
Universities		
University of Stellenbosch (US)	Stellenbosch	1
University of Cape Town (UCT)	Cape Town	4
University of KwaZulu Natal (UKZN)	Pietermaritzburg	1
	Sub-Total	6
International NGOs		
World Wildlife Fund – South Africa (WWF-SA)	Cape Town	8
Oxfam GB	Johannesburg	2
	Sub-Total	10
	TOTAL	43

S3.4 Proposed Sustainable Development Goals

The Open Working Group (OWG), established in January 2013 by the UN General Assembly, was tasked with preparing a proposal for the SDGs. The OWG has developed 17 proposed goals to be attained by 2030, listed below, which together have 148 targets, defined as ‘global targets, with each government setting its own national targets guided by the global level of ambition but taking into account national circumstances’. No indicators have been developed as yet, but there are likely to be at least double the number of goals. Equity and gender equality are mentioned in most of the proposed goals and climate change is mentioned in nearly half of them. Table S3.7 compares the indicators used in our barometer with the most relevant goals in the OWG’s Zero Draft (89). All of the indicators in the barometer are covered except ‘household goods’ although this could be incorporated into proposed goal 1.

1. End poverty everywhere (7 targets)
2. End hunger, improve nutrition and promote sustainable agriculture (9 targets)
3. Attain healthy lives for all (10 targets)
4. Provide quality education and life-long learning opportunities for all (9 targets)
5. Attain gender equality, empower women and girls everywhere (9 targets)
6. Ensure availability and sustainable use of water and sanitation for all (7 targets)
7. Ensure sustainable energy for all (6 targets)
8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all (7 targets)

9. Promote sustainable infrastructure and industrialisation and foster innovation (8 targets)
10. Reduce inequality within and between countries (10 targets)
11. Make cities and human settlements inclusive, safe and sustainable (8 targets)
12. Promote sustainable consumption and production patterns (10 targets)
13. Tackle climate change and its impacts (4 targets)
14. Conserve and promote sustainable use of oceans and seas and marine resources (8 targets)
15. Protect and promote sustainable use of terrestrial ecosystems, halt desertification and biodiversity loss (9 targets)
16. Achieve peaceful and inclusive societies, access to justice for all, and effective and capable institutions (10- targets)
17. Strengthen the means of implementation and the global partnership for sustainable development (17 targets)

Table S3.7 Comparison of the barometer and the proposed SDGs from the OWG (89)

Dimension	Indicator used in barometer	Most Relevant Proposed SDG target	SDG Proposed Goal
Climate change	Annual direct CO ₂ emissions	Integrate climate change adaptation and mitigation into national strategies and plans (UNFCCC targets may be included)	13
Freshwater use	Consumption of freshwater (Mm ³ yr ⁻¹)	By 2030 bring freshwater extraction in line with sustainable supply, protect and restore ecosystems	6
Land use change	Use of arable land for cropland (ha)	By 2030, implement sustainable and resilient agricultural practices	2
Phosphorus cycle	Annual mean phosphorus concentration in reservoirs (mg/l)	By 2030 significantly improve water quality	6
Nitrogen cycle	Nitrogen application rate for maize production (kg/ha)	By 2030, implement sustainable and resilient agricultural practices	2
Biodiversity loss	Endangered ecosystems (%)	By 2020 take urgent and significant action to halt the loss of biodiversity, and protect and prevent the extinction of known threatened species	15
Marine harvesting	Depleted fish stocks (%)	By 2020 effectively regulate harvesting, end overfishing, illegal, unreported and	14

		unregulated (IUU) fishing and destructive fishing practices to restore by 2030 fish stocks at least to levels that can produce maximum sustainable yield	
Air pollution	Average PM10 concentration (ug)	By 2030, substantially reduce the number of deaths and illnesses from air (indoor and outdoor) pollution	3
Chemical pollution	To be determined	Promote the sound management of chemicals and hazardous wastes in accordance with agreed international frameworks and by 2030 significantly reduce their release to air, water and soil	12
Energy	Households without access to electricity	By 2030 ensure universal access to affordable, sustainable and reliable energy services	7
Water	Households without access to water infrastructure $\geq$ RDP standard	By 2030 achieve universal access to safe and affordable drinking water for all	6
Sanitation	Households without access to at least ventilated improved pit latrines	By 2030 achieve adequate sanitation and hygiene for all, paying special attention to the needs of women and girls	6
Housing	Households not in formal dwellings	By 2030 ensure universal access to adequate and affordable housing	10
Education	Adults without more than 7 years of schooling (adult illiteracy rate)	By 2030 ensure all girls and boys complete free, equitable and quality primary and secondary education leading to relevant and effective learning outcomes	4
		By 2030 increase adult literacy and basic numeracy by at least x%	4
Health care	Infant (<1 year) immunisation coverage	Achieve universal health coverage	3
Jobs	Broad unofficial unemployment rate (adults aged 15-64 available to work)	By 2030 achieve full and productive employment and decent work for all women and men, including young people and persons with disabilities, and equal pay for work of equal value	8
Income	Population living below the upper national poverty line (R577 a month in 2011 constant Rands)	By 2030, eradicate extreme poverty (less than \$1.25/day)	1
		By 2030, reduce by half the proportion of people living below national poverty lines	1
Food	Households without adequate food	By 2030, end hunger and ensure that all people have access to adequate, safe and nutritious food all year round	2
Voice	<i>Not defined</i>	By 2030 increase inclusive, participatory and representative decision-making at all levels	16
Household goods	Households without a refrigerator		
Safety	Households who feel unsafe walking alone in their area during the night	By 2030 reduce levels of violence and halve related death rates everywhere	16

S3.5 References

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Linking statement – Chapter 3 to 4

The previous chapter (3) described the downscaling of the 'safe and just space' to the national level, creating a barometer of inclusive sustainable development for South Africa. This downscaling from global to national leads naturally to the question of how the picture changes if the process of downscaling is continued to the next logical level. Many of the experts interviewed during field work for Chapter 3 pointed out that South Africa is an extremely unequal and diverse country and therefore national indicators did not give the full picture. In this chapter (4), the national barometer is downscaled to the provincial level to create nine provincial barometers to explore the heterogeneities that are hidden by national SDIs. Provincial governments have the mandate, and in theory the ability, to address many of the environmental and social challenges discussed in the previous chapter; monitoring at this scale is therefore useful for policy-making and tracking the implementation of sustainable development policies.

This chapter addresses the research question Q2, 'What heterogeneity and inequality do national indicators hide? It describes how environmental states and boundaries were defined for all South African provinces using different techniques for disaggregation from national to provincial level, and aggregation from local to provincial level. It provides a visual summary of the state of key provincial SDIs and compares the results across the provinces. The barometers show significant heterogeneity between provinces, highlighting the importance of monitoring and reporting at the provincial scale.

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The lead author co-designed the research with supervisors RMB and MGN, performed the research and wrote the paper. RMB and MGN reviewed and edited the paper.

Chapter 4 – Spatial variability in sustainable development trajectories in South Africa: provincial level safe and just operating spaces

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Abstract

The Sustainable Development Goals (SDGs) represent the first globally agreed framework to address human development and environmental stewardship in an integrated way. One approach to summarising national SDG status is our “barometer for inclusive sustainable development in South Africa”. The barometer downscales global social and planetary boundaries to provide status and trends for 20 critical indicators of environmental stress and social deprivation. In this paper we explore the sub-national heterogeneity in sustainable development indicators by creating barometers defining the ‘safe and just operating space’ for South Africa’s nine provinces. Our results show that environmental stress varies significantly and provinces need to focus on quite different issues. Although

generally environmental stress is increasing there are areas where it is decreasing, most notably marine harvesting. Social deprivation results show more of a pattern with high levels of deprivation in employment, income and safety across the provinces, and historically disadvantaged provinces showing the most deprivation overall. Although deprivation is generally decreasing, there are notable exceptions such as food security in six provinces. Our provincial barometers and trend plots are novel in that they present comparable environmental and social data on key indicators over time for all South Africa's provinces. They are visual tools that communicate the range of key challenges and risks that provincial governments face, and are non-specialist and accessible to a range of audiences. In addition, the paper provides a critical case study of spatial disaggregation of national data that is required for the SDGs implementation.

Key words: sustainable development, sustainable development goals, planetary boundaries, South Africa, disaggregation

4.1 Introduction

Environmental sustainability, poverty eradication and reducing inequality pose continuing challenges for African countries in the 21st century. Population growth and global environmental change are expected to strain natural resources even further creating an urgent need to solve sustainability challenges across the continent (Gasparatos et al. 2016). The adoption in late 2015 of the '2030 Agenda for Sustainable Development' and its 17 Sustainable Development Goals (SDGs) is the first time all nations have agreed to a 'broad and universal policy agenda' that addresses environmental, social and economic issues together (UN General

Assembly 2015). The SDGs build upon the Millennium Development Goals (MDGs), but importantly for Africa, many African governments and civil society organisations were closely involved in the process of defining the SDGs. In addition, the 169 targets include means of implementation i.e. finance, capacity building and technology transfer to developing countries. With over 230 global indicators (IAEG-SDG 2015) and many more national indicators to be developed, there is a need for tools to summarise and communicate progress on the SDGs and highlight national priorities. Some initial attempts have already been made with a SDG index for OECD countries (Kroll 2015), a regional SDG scorecard (Nicolai et al. 2015) and a SDG Index and Dashboard for all countries (Sachs et al. 2016).

In 2014 we developed and described a ‘national barometer for inclusive sustainable development for South Africa’ to propose a manageable set of national-level indicators and boundaries that are relevant in the South African context (Cole et al. 2014). Our barometer is based upon Rockström *et al.* (2009a, 2009b) ‘planetary boundaries’ and Raworth’s (2012) ‘safe and just space’ framework, colloquially known as the Oxfam doughnut. The planetary boundaries are a set of nine critical global environmental indicators plotted against their safe environmental boundaries (based on critical thresholds and unacceptable levels of environmental stress) to highlight where excessive stress is occurring at the global scale. The ‘safe and just space’ framework adds 11 social indicators plotted against their global social foundation/floor (zero extreme deprivation) to the planetary boundaries. Together they define a social floor and an ‘environmental ceiling’ and provide a visual aspirational goal for achieving inclusive sustainable development. Using the same approach as Rockström *et al.* (2009a, 2009b) and Raworth (2012), our barometer

is visually presented in two radar plots. It shows how close South Africa is to its safe environmental boundaries (for climate change, ozone depletion, freshwater use, arable land use, phosphorus loading, nitrogen cycle, biodiversity loss, marine harvesting and air pollution) and what proportion of the population lives below the national social floor (for electricity access, water access, sanitation, housing, education, health care, voice, jobs, income, household goods, food security and safety).

There are strong arguments for using planetary boundary thinking at sub-global levels where policy action and natural resource management most commonly occur (Dearing et al. 2014; Fang et al. 2015; Steffen et al. 2015). Our barometer brings critical thresholds and scientifically informed environmental limits into the national policy-making discourse in a simple and relevant way. Unlike the studies for European countries that use the planetary boundary concept to determine their negative global environmental impact (Nykivist et al. 2013; European Commission 2014; Dao et al. 2015; Hajer et al. 2015) our study uses it as a warning light that exposes the risks that could hinder South Africa's ability to meet its national development goals. This development focused approach, rather than the environmental limits thinking used in Europe, is relevant across Africa. As SI, Table S1 shows, all of the indicators in our barometer have direct relevance to the SDGs, and could be used as SDG indicators.

While national level reporting is both informative and necessary, knowledge of sub-national heterogeneity in environmental stresses and social deprivation is important for strategic planning to deliver sustainable development. Disaggregation to finer

scales would quantify sub-national states and boundaries, identify where the most pressing challenges are and where action is needed, and would better fit policy implementation scales. It would also contribute to SDG monitoring which requires data disaggregation to expose inequalities, encourage sub-national implementation and avoid perverse incentives and unequal progress (SDSN 2015a).

In this paper we disaggregate our South African national barometer to the provincial level to explore the heterogeneity in national indicators and to provide a case study of disaggregation for SDG implementation. In our methodology section, we provide details on three disaggregation approaches that we used for the environmental dimensions. In our results section, we present the data in radar plots similar to the original planetary boundaries and social foundation. We also provide trend plots for the change in status over the past 20 years. In our discussion section, we look at (a) sub-national variability in sustainable development indicators, (b) barometers as policy tools, (c) environmental governance and safe boundaries, (d) defining social floors, and (e) implementing the SDGs.

4.2 Methodology

4.2.1 South African context

South Africa has a diverse environment ranging from semi-desert to sub-tropical forest and exceptional biodiversity (Driver et al., 2012) making it one of 17 mega-diverse countries in the world (UNEP 2014). It is the 30th driest country in the world (DWA 2013) and only 12% of land is capable of supporting rain-fed crop production (Collett 2013). Climate change projections for South Africa show significant

warming, as high as 5 - 8 °C over the interior by 2100, and a risk of drier conditions in the west and south, and wetter conditions in the east (DEA 2013a). The country has rich mineral deposits, including gold, platinum, iron ore, diamonds and coal. The mining sector has played a key role in the economy for 140 years, making South Africa the most industrialised country in Africa (Chamber of Mines of South Africa 2013). South Africa is also the biggest greenhouse gases (GHG) emitter, and is responsible for 38% of Africa's carbon emissions (Boden et al. 2011).

Despite being the largest economy in Africa, roughly half of the population of 55 million live below the national upper-bound poverty line (DPME 2015a), and more than 10% of people live on less than \$1.25 per day (DPME 2013). Over 38% of the labour force (including discouraged jobseekers) is unemployed (StatsSA 2016a) and South Africa's labour force participation rate (58%) is among the lowest in Africa (World Bank 2016). South Africa has one of the world's highest levels of income inequality (Palma, 2011) with a Gini coefficient of 0.65 in 2010 (DPME 2015a). It has spatial inequality across multiple aspects of social deprivation (Wright and Noble, 2009), a legacy of the racial segregation of Apartheid.

South Africa has a unitary but decentralised state with cooperative governance between three spheres of government - national, provincial and local (Republic of South Africa 2012). The nine provinces - Eastern Cape, Free State, Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, Northern Cape, North West and Western Cape - were created as part of the transformation to democratic rule in 1994. They were based on a set of 'development regions' aimed at planning across previous racially-based administrative boundaries and were given considerable functions in

the Constitution (Wittenberg 2006). In 2015/16 the provinces received 43% of the national budget with significant autonomy to allocate resources to respond to provincial priorities and meet national objectives (National Treasury 2015). The provinces therefore have the mandate and in theory the ability to address many of the environmental and social challenges highlighted in our national barometer. The provinces are shown in Figure 4.1 and summarised in Table 4.1.

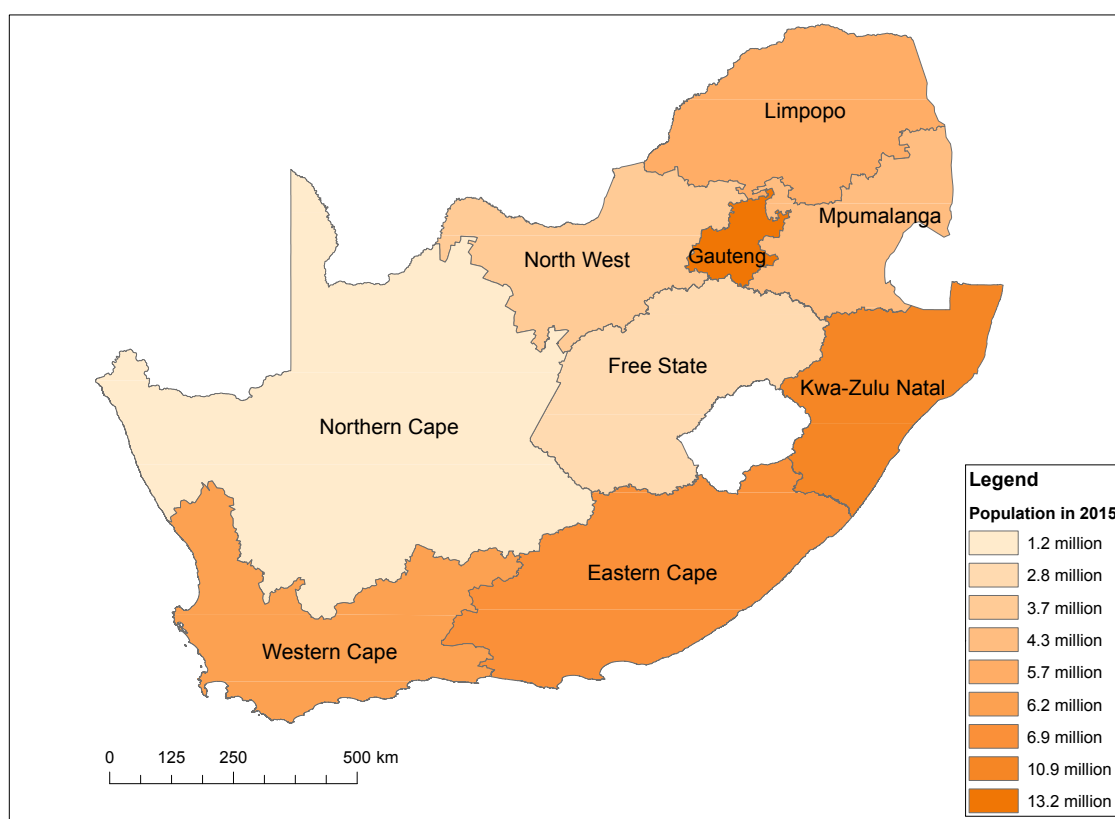


Figure 4.1 Map of the provinces of South Africa, shaded by population in 2015

Table 4.1 Population, area, population density and GDP of the provinces

Province	Population in 2015 ^a		Area (km ²) ^b	Population density (people / km ²)	% GDP in 2015 ^c	Metropolitan areas
	Number	%				
Eastern Cape	6,916,200	12.6	168,966	40.9	7.6	Nelson Mandela Bay, Buffalo City
Free State	2,817,900	5.1	129,825	21.7	5.0	Mangaung
Gauteng	13,200,300	24.0	18,178	726.2	34.4	Ekurhuleni, Johannesburg, Tshwane
KwaZulu-Natal	10,919,100	19.9	94,361	115.7	16.1	eThekweni
Limpopo	5,726,800	10.4	125,754	45.5	7.2	
Mpumalanga	4,283,900	7.8	76,495	56.0	7.5	
Northern Cape	1,185,600	2.2	372,889	3.2	2.1	
North West	3,707,000	6.7	104,882	35.3	6.6	
Western Cape	6,200,100	11.3	129,462	47.9	13.6	Cape Town
<i>South Africa</i>	54,956,900	100	1,220,813	45.0	100	

^aData source: Mid-year population estimates (StatsSA 2015b). ^bData source: Census 2011 (StatsSA 2012c). ^cData source: GDP Quarter 4 2015 (StatsSA 2016d)

4.2.2 National barometer

In creating our national barometer, we developed a decision flowchart to assess the environmental and social dimensions, indicators and boundaries that makeup the 'safe and just operating space' and adapt them to the national level. The aim was to ensure repeatability and consistency so that it could be used in other countries or at other scales (Cole *et al.* 2014).

The criteria used for selecting dimensions were ‘Is this relevant at the national scale?’ and ‘Does the set of dimensions include the main environmental and social concerns in South Africa?’. The criteria for indicator selection were (a) ‘Is the indicator the best available direct measure of that dimension?’, (b) ‘Are there sufficient reliable data that are measured on a regular basis?’, and (c) ‘Can a national boundary be determined?’ If the existing global dimension or indicator did not meet the criteria then it was removed or replaced with a more appropriate national-scale choice. These criteria are similar to the proposed criteria for SDG indicators, which should be relevant, methodologically sound, measurable, easy to communicate and access, limited in number and outcome-focused (UNSD 2015a). The data were taken from relevant national databases and reports, international databases and academic papers. We also sought expert judgment on indicators and boundaries through semi-structured interviews with 43 South African experts from national, provincial and metropolitan government, national research institutes, universities and international NGOs.

To create the provincial barometers, we did not use the decision flowchart to select new indicators, as we wanted to explore sub-national heterogeneity in those indicators we had already chosen. Instead we used three methods of disaggregation of national data for the dimensions in our national barometer: (a) share the national total amongst the provinces, (b) aggregate local data to the provincial scale, and (c) fit data reported by ecological units into administrative borders. These methods are described further below.

We updated the data sources where new data were available, or where sub-national data sources could be found. The data were used to produce nine provincial barometers for both environmental stress and social deprivation. We also plotted the average annual change since 1994 (or since data collection for each specific indicator began) for all the dimensions in two graphs. We did not plot the yearly status due to space constraints, as it would require 20 graphs.

4.2.3 Environmental stress

In our national barometer, we used the Environmental Sustainability Indicators (ESI) technical report (DEA 2013b) published annually by the Department of Environmental Affairs (DEA) as a starting point for our analysis. The ESI was developed based on a comprehensive review of potential national indicators, Yale's Environmental Performance Index (Hsu et al. 2016) and the DPSIR framework (e.g. Hammond et al. 1995; Gabrielsen and Bosch 2003). We then reviewed relevant national policies, reports and assessments, and academic literature to identify the most suitable dimensions, indicators and boundaries and tested these with experts. While we adapted three of Rockström *et al.*'s (2009a; 2009b) dimensions we adjusted all of the indicators and boundaries to suit national scale and circumstances. For the provincial barometers, we reviewed the most recent provincial State of Environment and State of Biodiversity reports.

Table 4.2 shows the environmental dimensions, indicators, data sources, level of confidence, and the method of disaggregation used in the provincial barometers. Table 4.2 also shows the type of safe environmental boundary for each dimension, as defined in our national barometer. Type A is an internationally agreed target

based on a global biophysical threshold, which varies by country based on differences in national capability and responsibility. Type B is a national biophysical limit for the sustainable use of land or freshwater resources, which can include or exclude human intervention such as infrastructure and technology, and uses local biophysical thresholds to define the boundary. Type C is a local biophysical threshold based on established research and expert judgment in the country being studied, and is unaffected by scale (i.e. national and provincial boundaries are the same). Each dimension is briefly explained below with further details given in the SI, S4.2.

Table 4.2 Dimensions for environmental stress for the provincial barometers

Dimension	Indicator (units in brackets)	State				Boundary		
		Data Source ^a	Year	Disaggregation method	Level of confidence	Data Source	Type	Disaggregation method
Climate Change	Annual direct CO ₂ emissions (MtCO ₂)	United Nations (DEA), StatsSA	2011	Share national total	Medium	Long Term Mitigation Scenarios	Type A	Share national total
Ozone depletion	Annual HCFC consumption (ODPt)	United Nations (DEA), HCFC Phase-out Plan	2015	Aggregate local data	High	HCFC Phase-out Plan		Aggregate local data
Freshwater Use	Annual consumption of available freshwater resources (Mm ³ /a)	Reconciliation Strategies (DWS)	2011	Aggregate local data	Medium	Reconciliation Strategies	Type B	Aggregate local data
Arable land use	Arable land converted to cropland (ha)	Preservation and Development of Agricultural Land Framework Bill (DAFF)	2013	Provincial data exists	High	Preservation and Development of Agricultural Land Framework Bill		Provincial data exists
Nutrient cycle	Total Phosphorus concentration in freshwater (mg/l)	National Eutrophication Monitoring Programme (DWS)	2012	Aggregate local data, Fit borders	Medium	Oberholster and Ashton 2008	Type C	Not affected by scale – same as national
	Nitrogen application rate (kgN/ha)	Not available				Brentrup and Palliere (2010)		
Biodiversity loss	Endangered and critically endangered ecosystems (%)	National Biodiversity Assessment (DEA)	2011	Fit borders, Aggregate local data	Medium	Expert judgment		
Marine harvesting	Depleted marine fisheries stocks (%)	Status of Marine Fishery Resources (DAFF)	2013	Fit borders	Low	Expert judgment		
Air pollution	Annual average PM10 concentration (ug/m ³)	State of Air Report (DEA)	2014	Aggregate local data	High	State of Air Report		
Chemical pollution	To be determined							

^aDEA = Department of Environmental Affairs, DWS = Department of Water and Sanitation, DAFF = Department of Agriculture, Forestry and Fisheries, StatsSA = Statistics South Africa

Climate change

Rockström *et al.* (2009a) based their climate change indicator and boundary on global atmospheric carbon dioxide (CO₂) concentrations. As this cannot be disaggregated to the national level, we used CO₂ emissions for our national indicator. Our safe boundary is based on the emissions trajectory of the 'Required by Science' scenario in the Long Term Mitigation Scenarios, LTMS (Scenario Building Team 2007), which South Africa uses for its national commitments to the United Nations Framework Convention on Climate Change. In 2011 South Africa emitted 477.7 MtCO₂ (UNSD 2015b) and the safe boundary is calculated as 453.7 MtCO₂. South Africa's national inventory (DEAT 2009) reports sub-national data by sector, not by region, with only four provinces having their own emissions inventories (but only for different years) (Gauteng 2007, Eastern Cape 2008, Western Cape 2009, Free State 2012).

For the provincial status we therefore had to share national CO₂ emissions for the status and boundary between provinces. As a province's share of the population can be quite different to its energy use, it would not be equitable to use population as the basis for disaggregation. Instead we used provincial electricity consumption (StatsSA 2012a) to allocate provincial emissions (see Table S4.2 in the SI) as it has the largest share (46%) of national CO₂ emissions. We used consumption (and not production) as it is reported at provincial level. Although this overestimates CO₂ emissions in provinces with low carbon energy sources such as wind and nuclear, we did not have the necessary data to adjust the figures. Our calculated figures correlate reasonably well with the four provincial inventories that are available (see SI). We shared the national boundary using the provincial contribution to GDP

(StatsSA 2012b) (see SI Table S4.3) to measure the energy intensity and thus mitigation responsibility of each provincial economy. To analyse the trends we used the year 2002 as this was the furthest back we could obtain electricity use by province (StatsSA 2002). As the LTMS baseline year is 2003 there is no 'required by science' target for the year 2002, hence we shared the actual national emissions of 347.7 MtCO₂ between the provinces (see SI Table S4.3).

Ozone depletion

Rockström *et al.* (2009b) based their ozone depletion indicator and boundary on the global ozone concentration. As this cannot be disaggregated to the national level we used consumption of hydro-chloro-fluoro-carbons (HCFCs) for our national barometer. In line with the Montreal Protocol, South Africa has phased out the production and consumption of all ozone-depleting (ODP) substances except HCFCs (DEA 2014a) and is a consumer rather than a producer of HCFCs. For the provincial status, we aggregated individual company HCFC-22 and HCFC-141b consumption data for 2010 (NEDLAC 2012). We then projected it to 2015 based on the latest national HCFC consumption figure of 238.6 ODPt reported by the UNEP Ozone Secretariat (UNEP 2016) (see SI Table S4.4).

This showed that distributors in Gauteng, Western Cape and KwaZulu-Natal consume all the HCFCs. The national boundary is based on the government commitment to reduce HCFC consumption to 332.7 ODP tonnes by 2015 and eliminate it by 2040 (NEDLAC 2012). We shared this between these three provinces based on their share of HCFC consumption. As historical sub-national data do not exist, for the trend analysis we used the 2010 provincial ratios of HCFC

consumption to share the 103.3 ODPT of HCFCs consumed in 1990 (UNEP 2016). We used the government target to freeze consumption at 370 ODPT in 2013 as no limits are defined before 2013.

Freshwater use

Rockström *et al.* (2009a) measure the consumption of freshwater by humans, the global aggregate of local use. In our national barometer we used South Africa's freshwater consumption reported in the National Water Resource Strategies (DWAF 2004; DWA 2013). Our safe boundary was the available water supply, which takes ecological requirements into account. For the provincial barometers, we could use the demand and supply of the 19 Water Management Areas and 87 sub-areas (see SI Table S4.5), however, these figures are only available for the year 2000. We considered using the government's current Water Allocation Registration Management System (WARMS) database, but this would only provide water allocation not demand and supply.

We decided to use demand and supply figures found in the Department of Water and Sanitation's (DWS) 840 reconciliation strategies for all towns in 2008 and Water Supply Systems that supply the metropolitan areas. The All Town Studies provide the first comprehensive water use information at the local level across South Africa and are aimed at informing water resource investment and management decisions (DWA 2013). As the reconciliation strategies do not account for ecological requirements, we reduced the supply using the ecological requirements for the year 2000 to provide a more accurate picture of the stress on freshwater supply (see SI Table S4.5). While this may overestimate the reserve as

total supply includes groundwater, the reserve figures in 2000 did not include estuaries, which usually have higher ecological requirements (DWAF 2004). As the reconciliation strategies focus on domestic water demand, agriculture and heavy industry are not included in our results. This is not ideal but it is the best available dataset. In addition, annual progress reports are published for the Water Supply Systems and the town strategies are being updated so more recent data will become available which will allow the calculation of long-term trends.

Arable land use

Rockström *et al.* (2009a) focused on land use change and its detrimental effects on biodiversity and climate change. However, South Africa's land cover has remained relatively stable since 1961 (Niedertscheider *et al.* 2012; Schoeman *et al.* 2013). The only national land degradation study was done by Hoffman *et al.* in 1999 and is qualitative not quantitative (DEAT 2006). South Africa is largely a semi-arid country with very limited land capable of supporting sustainable crop production (Collett, 2013). We therefore focused on land capability, i.e. the 'total suitability for use, in an ecologically sustainable way, for crops, for grazing, for woodland and for wildlife... exclusive of social and economic variables' (Schoeman *et al.* 2002). The national land capability classification defines eight classes based on a combination of climate, soil and terrain. Arable land (i.e. land that can be used for crop production) is termed 'arable land of acceptable quality for crop production' (Classes I-III) or 'marginal arable land' (Class IV).

Our indicator for land use is total arable land (Classes I – IV) converted to cropland and our safe boundary is acceptable arable land (Classes I - III). We excluded

marginal arable land from the boundary as it is more prone to crop failures in low rainfall years (Biggs and Scholes 2002) and requires irrigation to be sustainable in the long-term. Data at the provincial level is available in the draft Preservation and Development of Agricultural Land Framework Bill (DAFF 2015) which improves on previous datasets as it measures cultivated land for each land capability class. We aggregated cultivated land for the status (Class I – IV) and boundary (Class I-III) (see SI Table S4.6). Cropland in the non-arable classes (Classes V-VIII) is termed ‘unique farmland’, e.g. Cape Winelands in Class IV and VI which can be sustainably farmed despite shallow natural soil depth (Collett, 2013). As the specific figures for unique farmland are not provided we excluded it from the analysis, although this does mean that the Western Cape exceeds its boundary. We could not calculate the trend over time as the cultivated land per land capability class has not been reported before.

Phosphorus loading

Rockström *et al.* (2009a) argued that the additional phosphorus (P) and nitrogen (N) activated by humans is disturbing the global cycles. Eutrophication of freshwater resources is a global concern (Steffen *et al.* 2015) and is widespread in South Africa (van Ginkel 2011). South Africa’s National Eutrophication Monitoring Programme measures levels of chlorophyll and phosphorus at over 1,200 monitoring points in 16 drainage basins. In our national barometer we used mean annual total phosphorus (P) concentrations in freshwater as the indicator. We used South Africa’s critical threshold, and effluent discharge limit for wastewater treatment plants of 0.10 mg/l (Oberholster and Ashton 2008) for the safe boundary.

For the provincial barometers, we aggregated total P concentrations reported by drainage basin and calculated weighted averages using gross drainage basin volumes (DWA 2014). We then matched basins to provinces so that each province was an average of weighted total P values (see SI Table S4.7). Where basins were shared by provinces we included them in all the relevant provinces. We used the national boundary for all provinces as it is a local threshold. We calculated the trend from 2000 to 2012 using the same dataset and boundary.

Nitrogen cycle

Nitrogen is essential for food production. However, nitrogen fertiliser use can have a range of local negative effects (Rockström et al. 2009b; de Vries et al. 2013). Sustainable fertiliser use for crop production can be measured using the nitrogen balance or the nitrogen use efficiency (Brentrup and Palliere 2010). Both indicators are calculated using nitrogen (N) applied to the soil through fertilisers and nitrogen removed from the soil by crop production. In our national barometer we used the nitrogen use efficiency (N removed divided by N applied) in maize production, which uses 62% of all nitrogen in fertiliser in the country (FertASA 2013). Sub-national data on fertiliser consumption for maize or any other crop is not available. Sharing the national total between the provinces by crop area or yield (see SI Table S4.8) would not take variations in soil and climate into account. We therefore could not populate this indicator for the provinces.

Biodiversity loss

Rockström *et al.* (2009a) measured the extinction rate of species, which saw a massive acceleration in the 20th century. In 2004 the South African National

Biodiversity Institute (SANBI) started to assess biodiversity by ecosystem, rather than species, threat status. The methodology was improved in 2011 and we used the percentage of critically endangered (CR) and endangered (EN) ecosystems for our national biodiversity loss indicator. Our safe boundary was that no ecosystems should be endangered or critically endangered.

For the provincial status, each ecosystem type required a slightly different approach. Estuarine ecosystems were reported at district level (van Niekerk and Turple 2012) and had to be aggregated. Inshore marine and coastal ecosystems were reported by habitat type and geographic region (Sink et al. 2012) and had to be matched to the four coastal provinces. Terrestrial ecosystems were reported by province (DEA 2011). Interviews with experts at SANBI suggested we convert each total area to a percentage and average the three ecosystem types by area to obtain a single value for percentage CR and EN ecosystems per province (see SI Table S4.9). We kept the safe provincial boundary the same as the national boundary. We did not determine the threat status for freshwater ecosystems (rivers and wetlands) as they are reported by the old 19 Water Management Areas (Nel and Driver 2012), which do not match well to the provinces. We could not calculate trends as the methodology changed from 2004 to 2011.

Marine harvesting

In our national barometer we replaced Rockström *et al.*'s (2009a) ocean acidification with marine harvesting due to the lack of understanding of the process in South Africa's marine environment (CSIR 2012). Our national indicator was depleted marine fisheries (below the biomass level at which maximum sustainable

yield is obtained) and our safe boundary was zero depleted marine fisheries. Recently a new Ocean Acidification Indicator (ACID-I), defined as the aragonite saturation state, has been defined for the west coast of South Africa (DEA 2015a) but is not comprehensive enough to be used here. As marine harvesting is only relevant for the four coastal provinces (Eastern Cape, Western Cape, Northern Cape, KwaZulu-Natal) we considered changing the dimension to 'aquatic harvesting' to include inland fisheries. However, there are almost no data on inland harvesting rates or stock status (McCafferty et al. 2012). For marine harvesting at provincial level, we estimated the depleted status (percentage of total number of species with known status) per province based on the geographic location of the fisheries (DAFF 2014) (see SI Table S4.11). Our safe boundary is zero. We calculated the trend from 2009, when reporting started, to 2013, which is the most recent data.

Air pollution

In our national barometer we replaced Rockström *et al.*'s (2009a) atmospheric aerosol loading with the more relevant dimension air pollution. Particulate matter less than 10 microns (PM₁₀) is the 'greatest national cause for concern in terms of air quality' and is used for the National Air Quality Indicator, NAQI (DEA 2013c; DEA 2015b). Annual PM₁₀ concentrations for monitoring stations in mining or industry hubs, coal-fired power stations and very large urban centres are reported in 'State of the Air' reports. We used this data and indicator in our national barometer. We used the national PM₁₀ limit of 50 µg/m³ (DEA 2009) as our safe boundary.

For the provincial barometers, we aggregated the monitoring station data in the six provinces (Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, North West and Western Cape) used in the NAQI to determine provincial averages (see SI Table S4.12). The national PM₁₀ limit decreased to 40 µg/m³ in 2015 (DEA 2014b) and we used this for our provincial boundaries. Although monitoring began in 1994, it was not comprehensive and we calculated the trend from 2003 to 2014 to ensure all relevant provinces were covered.

Chemical pollution

Similarly to Rockström *et al.* (2009a) and Steffen *et al.* (2015), we did not identify a national indicator for chemical pollution due to the lack of detailed and accurate data. Although South Africa's National Waste Information Baseline Report (DEA 2012a) provides an estimated baseline, reporting is voluntary and measurement is incomplete.

4.2.4 Social dimensions

To determine the 12 dimensions and indicators in our national barometer we used the South African Index of Multiple Deprivation (SAIMD) (Noble *et al.* 2009; Wright and Noble 2009) and the annual Development Indicators report (DPME 2013), published by the South African Presidency. Both have been informed by international good practice and adapted to South African conditions and are used by the government on a regular basis. We made a number of changes to the original 11 Raworth (2012) dimensions. We separated water and sanitation into individual dimensions, we added housing, household goods and safety, and we removed resilience, social equity and gender equality. Expert interviews suggested that

resilience is a cumulative effect that is dependent on the other dimensions, and therefore an indirect measure. Experts also felt that both social equity and gender inequality should be incorporated into the other dimensions, as they are cross-cutting. Although social equality and gender equality have dedicated SDG goals (Goal 5 and Goal 10) they are mainstreamed throughout and will be covered by data disaggregation.

The social indicators in our barometer reflect national priorities and official indicators. The social floor (boundary) for each dimension is determined by the indicator selected and the goal that nobody (0% of the population) lives in deprivation. There is usually a set of indicators to choose from that reflects a range in social deprivation. The choice of indicator therefore partly determines the definition of the social floor.

There are three types of indicator sets that we identified. Type 1 indicators are typically reported as a range of levels of access, as are commonly found in household surveys. For example, choosing 'access to piped water within 200m of the dwelling' rather than 'access to piped water in the dwelling' sets a lower social floor. Type 2 indicators have a range of definitions of the same broad indicator. For example, unemployment can be defined as narrow or broad, where the latter includes discouraged jobseekers. Type 3 indicators offer diverse representations of different aspects of a dimension. For example, material deprivation can be measured by ownership of a refrigerator, washing machine, radio and/or television.

We did not define an indicator for voice in the national barometer. This is because there is a lack of a generally accepted definition of voice, a lack of consensus among experts on a single indicator, as well as a large range in values for different indicators. Without other countries to compare it to, it would not have added much value. However, for the provincial barometers, we felt that it would be worthwhile to select an indicator for voice as the comparison between provinces can circumnavigate the problem of the variation in values for different indicators. Development Indicators 2012 lists four indicators under the heading ‘Social cohesion: Voice and Accountability’ that could measure voice: membership of voluntary organisations, voter turnout, female representation in parliament and the corruption perceptions index. None of these were used, however, based on expert judgment or because the indicator is not a deprivation measure or is gender-specific. The most appropriate indicators were found in the Afrobarometer, a comparative series of independent public attitude surveys on democracy and governance run since 1990 in 35 African countries (Citizen Surveys 2013). We identified 14 possible indicators, shown in SI Table S4.13. There is quite good correlation between the different indicators in terms of comparing the provinces. We chose the indicator ‘people who feel they are not free to say what they think’ as it is easy to understand and shows meaningful variation between provinces.

As all social data could be found at the provincial level in existing reports or databases, no special disaggregation methods was performed. Table 4.3 shows the 12 social dimensions, indicators and data sources in our provincial barometers, grouped into four domains – basic services, public goods, livelihoods and living standards. We largely used the 2015 General Household Survey, GHS (StatsSA

2016b), a key data source for Development Indicators, as it had the most recent data. For the indicators not covered by the GHS, we used the Development Indicators 2014 report database (DPME 2015b), the 2014/15 Victims of Crime Survey (StatsSA 2015a), the Quarterly Labour Force Survey Fourth Quarter 2015 (StatsSA 2016c), and the South African Afrobarometer Round 5 (Citizen Surveys 2013).

To plot the trends in the social dimensions, we used the same data sources so that the figures are comparable, as sometimes other data sources used different calculation methodologies. We looked for data from 1994 or similar, as we had done in the national barometer. However, we found that the Development Indicators 2014 generally reported provincial data from 2001 onwards. In the case of water and sanitation, we used the 2001 Census data in StatsSA's SuperWeb database (StatsSA 2014) as it was not available in Development Indicators. We also used Census 2001 for household goods as it did not appear in the recent GHS's. StatsSA's historical revision of Labour Force Surveys (which preceded Quarterly Labour Force Surveys) (StatsSA 2009) was used for unemployment in 2001, as Development Indicators reported the narrow rather than the broad definition by province. For safety, we used the National Victims of Crime Survey 2003 (Burton et al. 2004). We could not find provincial data for three dimensions – housing, voice and income – as the indicators we used in the barometer were not reported.

Table 4.3 Dimensions of social deprivation for the provincial barometers

Domain	Dimension	Indicator of deprivation (units all %)	Year	Data source	Indicator type
Basic services	Energy access	Households not connected to mains electricity	2015	General Household Survey 2015	Type 1
	Water access	Households without access to piped water within 200m ($\geq$ RDP standard)	2013	Development Indicators 2014	
	Sanitation	Households without a toilet or ventilated pit latrine	2015	General Household Survey 2015	
	Housing	Households without a formal dwelling	2015	General Household Survey 2015	
Public goods	Education	Adult illiteracy rate (population aged 15 years or older with education level lower than Grade 7)	2015	General Household Survey 2015	Type 3
	Health care	Infant (<1 year) immunisation coverage	2014	Development Indicators 2014	
	Voice	People who feel they are not free to say what they think	2011	Afrobarometer 2011	
Livelihoods	Jobs	Broad unofficial unemployment rate (adults aged 15-64 available to work)	2015	Quarterly Labour Force Survey Quarter 4 2015	Type 2
	Income	Population living below the national poverty line (R577/month in 2011 Rands)	2011	Development Indicators 2014	
Living standards	Household goods	Households that do not own a refrigerator	2015	General Household Survey 2015	Type 3
	Food security	Households without adequate food	2015	General Household Survey 2015	
	Safety	Households that feel unsafe walking alone in their area at night	2015	Victims of Crime Survey 2014/15	

4.3 Results

4.3.1 Environmental stress

The results for environmental stress are shown in Table 4.4, Figure 4.2 and Figure 4.3. Table 4.4 provides the current status and boundary while the provincial barometers in Figure 4.2 show the normalised status of each dimension i.e. status as a percentage of the boundary. The barometers therefore show which provinces are exceeding their safe boundary and are contributing to the national boundary being exceeded. Figure 4.3 plots the trends, expressed as the annual change in the normalised status, for five of the environmental dimensions, as no comparable historical data was available for water use, arable land use or biodiversity loss due to a change in reporting methodologies. The trends in numbers are provided in SI Tables S4.3, S4.7, S4.11 and S4.12. The trends plot shows where the highest and lowest rate of change occurs among the provinces in the past 20 years.

The results show that there is significant sub-national variation in environmental status and stress. The biggest variation across provinces occurs for climate change (range 176% - max. 237% min. 61%), phosphorus loading (range 119% - max. 154%, min. 35%) and air pollution (range 84% - max. 140%, min. 56%). The smallest range occurs for marine harvesting (3%), largely due to the overlap in geographic location of fisheries. Marine harvesting and biodiversity loss exceed the boundary in all relevant provinces, whereas ozone depletion is below the boundary in all provinces. Every province has between two and four dimensions that exceed the safe environmental boundary and need urgent attention. We find that for freshwater use, arable land use and air pollution, some of the provincial environmental boundaries have been exceeded despite their national boundary not

being exceeded. KwaZulu-Natal has the highest risk of biodiversity loss (38% of ecosystems are endangered or critically endangered). Gauteng has the worst air pollution (PM10 concentration is 40% higher than the threshold). Mpumalanga has the highest carbon emissions intensity (137% over the GDP-based boundary) and water stress (demand is 27% higher than supply). The Free State has the most stressed arable land (39% of cultivated arable land is marginal). Phosphorus loading is highest in Limpopo (P levels are 54% above the acceptable threshold). Gauteng, KwaZulu-Natal and Western Cape contribute the most to total carbon emissions and ozone depletion.

Generally, there has been an increase in environmental stress across provinces over time, with the notable exception of marine harvesting. For the five dimensions that could be assessed, marine harvesting exhibits the most change nationally (17% decrease over a 4-year period) while CO₂ emissions shows the least change (5% increase over an 9-year period). Phosphorus loading has the highest variation between provinces (range 15% per year). Overall environmental stress has been increasing fastest in Mpumalanga. The Eastern Cape and Mpumalanga have seen the most change and North West and Western Cape have seen the least change in the measured dimensions.

Table 4.4 The current status (S), safe boundary (B) and normalised status (N) for dimensions of environmental stress for the provinces.

Province	Climate Change in 2011 (MtCO ₂)			Ozone Depletion in 2015 (ODPt)			Freshwater Use in 2011 (Mm ³ /a)			Arable Land Use in 2013 (ha)			Phosphorus Loading in 2012 (mg/l)			Biodiversity Loss in 2011 (%)			Marine Harvesting in 2013 (%)			Air Pollution in 2014 (ug/m ³)		
	S	B	N	S	B	N	S	B	N	S	B	N	S	B	N	S	B	N	S	B	N	S	B	N
Eastern Cape	21	34	61	-	-	-	395	325	121	828,507	1,122,937	74	0.064	0.1	64	15	0	115	41	0	141	-	-	-
Free State	19	24	78	-	-	-	239	209	99	3,070,570	2,204,698	139	0.119	0.1	119	11	0	111	-	-	-	-	-	-
Gauteng	131	157	84	106	170	68	1,325	1,092	116	306,597	772,377	40	0.099	0.1	99	31	0	131	-	-	-	55.9	40	140
KwaZulu-Natal	90	71	126	19	30	68	736	566	109	691,483	2,537,768	27	0.037	0.1	37	38	0	138	43	0	143	32.3	40	81
Limpopo	26	32	81	-	-	-	258	207	104	967,732	2,296,820	42	0.154	0.1	154	1	0	101	-	-	-	34.8	40	87
Mpumalanga	75	32	237	-	-	-	248	183	127	1,278,717	2,393,780	53	0.057	0.1	57	10	0	110	-	-	-	41.9	40	105
Northern Cape	11	10	107	-	-	-	139	119	78	0	0	-	0.147	0.1	147	16	0	116	44	0	144	-	-	-
North West	56	29	189	-	-	-	211	179	92	1,631,535	1,661,912	98	0.104	0.1	104	16	0	116	-	-	-	-	-	-
Western Cape	49	64	76	83	133	68	529	443	103	876,367	767,777	103	0.035	0.1	35	36	0	136	43	0	143	22.5	40	56
South Africa	477	454	105	208	333	68	4,066	3,285	111	9,651,508	13,758,068	111	0.101	0.1	101	34	0	134	43	0	143	39.2	40	98
Mean (N)	115 %			68 %			105 %			73 %			91 %			119 %			143 %			95 %		
Range (N)	176 %			0 %			49 %			112 %			119 %			37 %			3 %			84 %		
SD (N)	56 %			0 %			14 %			37 %			42 %			12 %			1 %			26 %		
CV (N)	0.54			0.00			0.13			0.54			0.42			0.09			0.01			0.26		

Notes: Units given in brackets. See Table 4.2 for indicator descriptions. Normalised mean, range, standard deviation (SD) and coefficient of variation (CV) refer to the status as a percentage of the boundary.

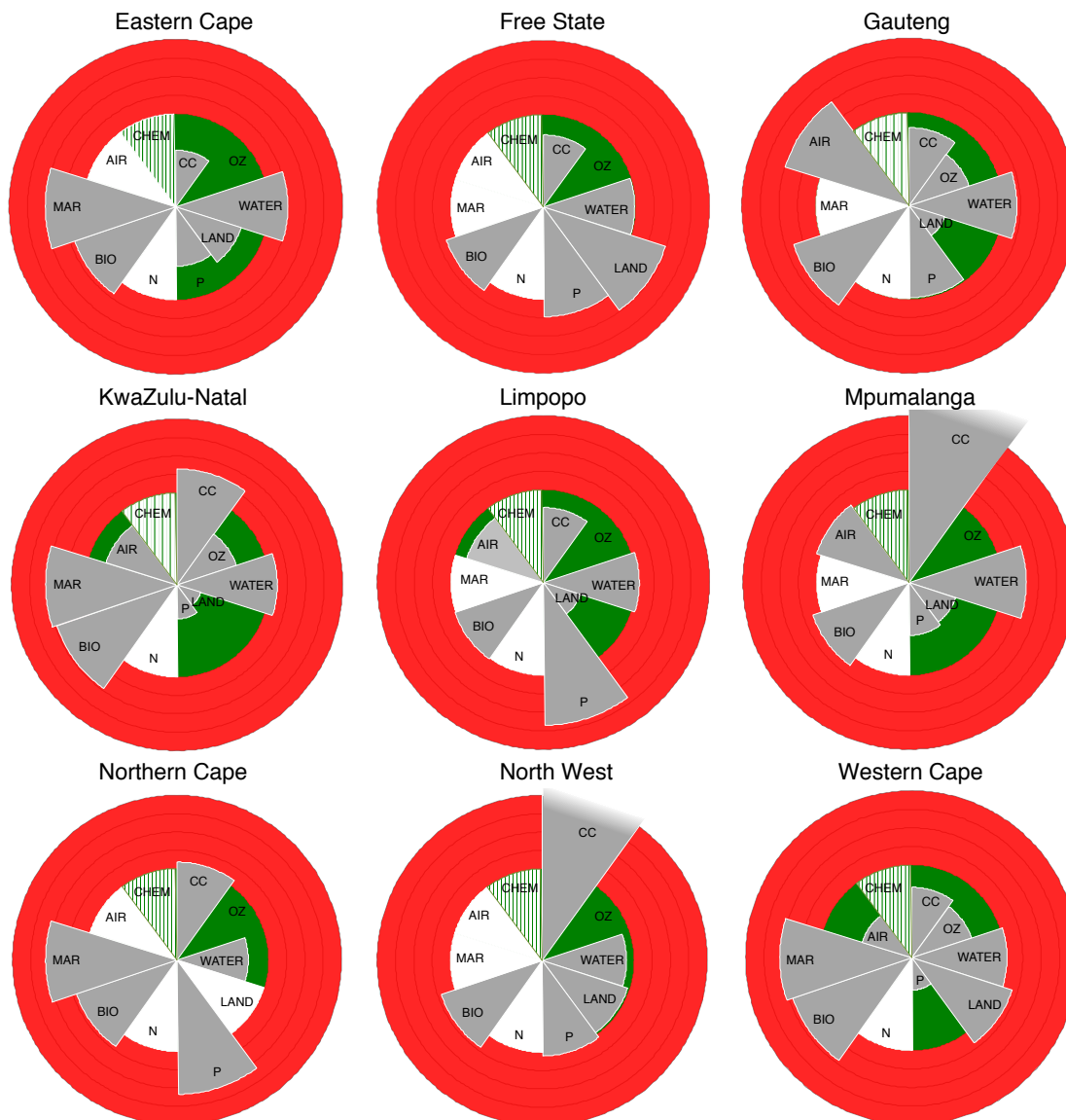


Figure 4.2 The nine provincial barometers for environmental stress in South Africa.

Note: Grey wedges plot the normalised status per dimension (see Table 4.4). Zero stress at the centre increasing to 100% at the boundary between the 'safe environmental operating space' (green area) and the unsafe environmental operating space (red area). White wedges indicate not relevant or no data available. Striped green/white wedges show the indicator was not defined. Dimensions are (clockwise from top right) climate change (CC), ozone depletion (OZ), freshwater use (WATER), arable land use (LAND), phosphorus loading (P), nitrogen cycle (N), biodiversity loss (BIO), marine harvesting (MAR), air pollution (AIR) and chemical pollution (CHEM).

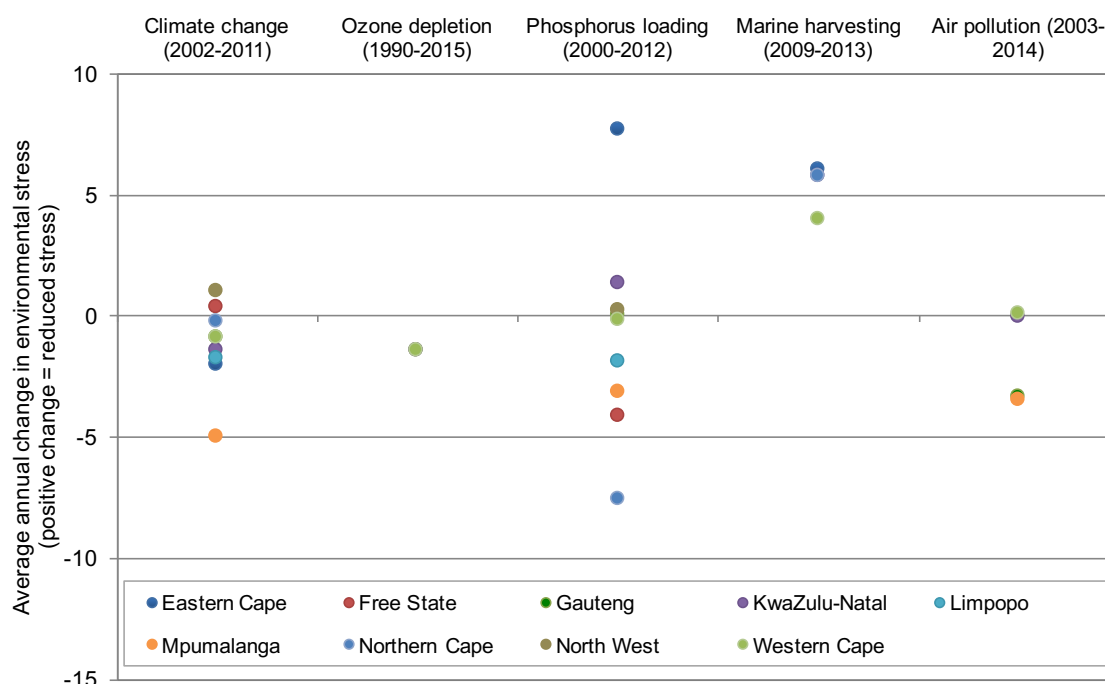


Figure 4.3 Average annual percentage change in environmental stress in the provinces. Note: Positive change indicates decreased stress while negative change indicates increased stress. The time period varies for each dimension based on available data and is shown on the x-axis.

4.3.2 Social deprivation

The results for social deprivation are shown in Table 4.5, Figure 4.4 and Figure 4.5. The status is expressed as a percentage for all dimensions and all boundaries (social floors) are zero, so no normalisation is necessary. Figure 4.5 shows the average annual change in percentage of the population who are deprived for eleven of the dimensions based on available data (no comparable historical data was available at provincial scale for voice). The actual numbers for the trends are provided in the SI, Table S4.14.

The provincial barometers show a similar pattern to the national barometer in that the most deprivation exists for safety, jobs and income while the least exists for

water access. Some marked differences are evident, across multiple indicators, between provinces. The largest range is 41% for income and 40% for sanitation while the range for health care, food security, water access and safety are all close to 30%. These represent large variations in the living conditions of millions of people. In Limpopo 64% of the population lives below the poverty line and 46% of households do not have access to ventilated pit latrines or toilets. At the other end of the spectrum, in Gauteng only 23% live below the poverty line and only 9% do not have the minimum level of sanitation. Limpopo is the most deprived in water access, sanitation, health care and income. The Eastern Cape is the most deprived in formal housing, jobs and household goods. North West has the worst food security. Western Cape scores lowest on voice. KwaZulu-Natal has the lowest access to electricity. The Free State has the lowest levels of safety.

Overall, across nearly all provinces and social dimensions, there is a clear trend towards decreasing deprivation since 1994. Notable exceptions are food security in six provinces and safety, jobs and housing in three provinces. Limpopo, KwaZulu-Natal and Eastern Cape have seen the greatest annual decrease in deprivation, while the Western Cape has seen the lowest annual change in deprivation in the measured dimensions.

Table 4.5 The current status for dimensions of social deprivation for the provinces.

Province	Basic services				Public goods			Livelihoods		Living standards		
	Electricity access (2015)	Water access (2013)	Sanitation (2015)	Formal housing (2015)	Education (2015)	Health care (2014)	Voice (2011)	Jobs (2015)	Income (2011)	Household goods (2015)	Food security (2015)	Safety (2015)
Eastern Cape	17.7	27.9	18.3	35.3	20.3	27.9	17.0	40.3	60.8	38.9	28.4	73.8
Free State	11.0	3.0	18.9	18.0	14.8	11.2	8.0	36.3	41.2	21.5	24.9	81.6
Gauteng	16.8	3.8	9.0	22.8	7.7	0.0	17.0	30.2	22.9	22.8	16.0	73.4
KwaZulu-Natal	178.3	24.5	24.3	25.6	17.0	13.9	17.0	36.8	56.6	32.4	25.3	61.6
Limpopo	7.1	31.7	46.2	9.5	18.8	31.2	14.0	38.6	63.8	38.3	8.2	51.9
Mpumalanga	12.2	15.8	34.2	14.6	16.8	29.1	15.0	39.4	52.1	28.2	31.7	74.5
Northern Cape	7.6	6.4	19.3	13.9	20.1	14.1	8.0	38.9	46.8	25.6	31.3	66.9
North West	16.0	18.3	33.6	22.5	19.8	26.9	5.0	38.9	50.5	32.3	39.0	68.8
Western Cape	9.8	2.3	6.7	19.0	8.8	13.9	24.0	22.0	24.7	15.0	24.0	68.0
<i>South Africa</i>	<i>14.5</i>	<i>14.8</i>	<i>20.1</i>	<i>21.9</i>	<i>14.3</i>	<i>15.9</i>	<i>16.0</i>	<i>33.8</i>	<i>45.5</i>	<i>27.9</i>	<i>22.8</i>	<i>68.9</i>
Range	11.2	29.4	39.5	25.8	13.0	31.2	19.0	18.3	40.9	23.9	30.8	29.7
SD	4.1	10.8	12.0	7.2	4.5	9.9	5.4	5.6	13.8	7.5	8.5	8.1
CV	0.28	0.73	0.60	0.33	0.32	0.63	0.45	0.17	0.30	0.27	0.37	0.12

Notes: Year of most recent data in brackets. All units are percentage population deprived. The social floor/boundary for all dimensions is 0%. See Table 4.3 for indicator descriptions.

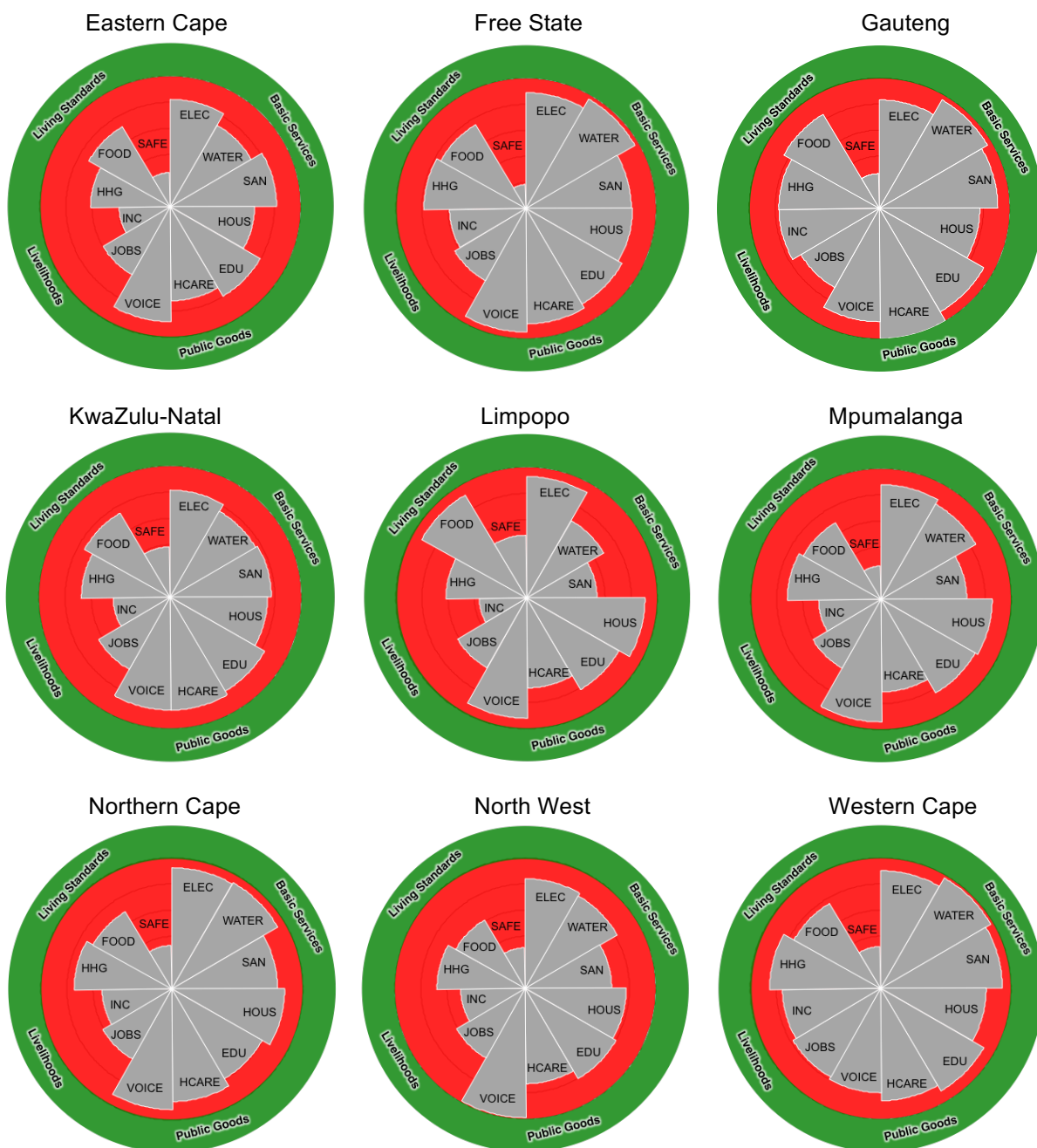


Figure 4.4 The nine provincial barometers for social deprivation in South Africa.

Notes: Grey wedges plot the status per dimension (see Table 4.5). 100% deprivation at the centre decreasing to zero deprivation at the boundary between the 'just social space' (green area) and 'unjust social space' (red area). Dimensions are (clockwise from top right) electricity access (ELEC), water access (WATER), sanitation (SAN), housing (HOUS), education (EDU), health care (HCARE), voice (VOICE), jobs (JOBS), income (INC), household goods (HHG), food security (FOOD) and safety (SAFE).

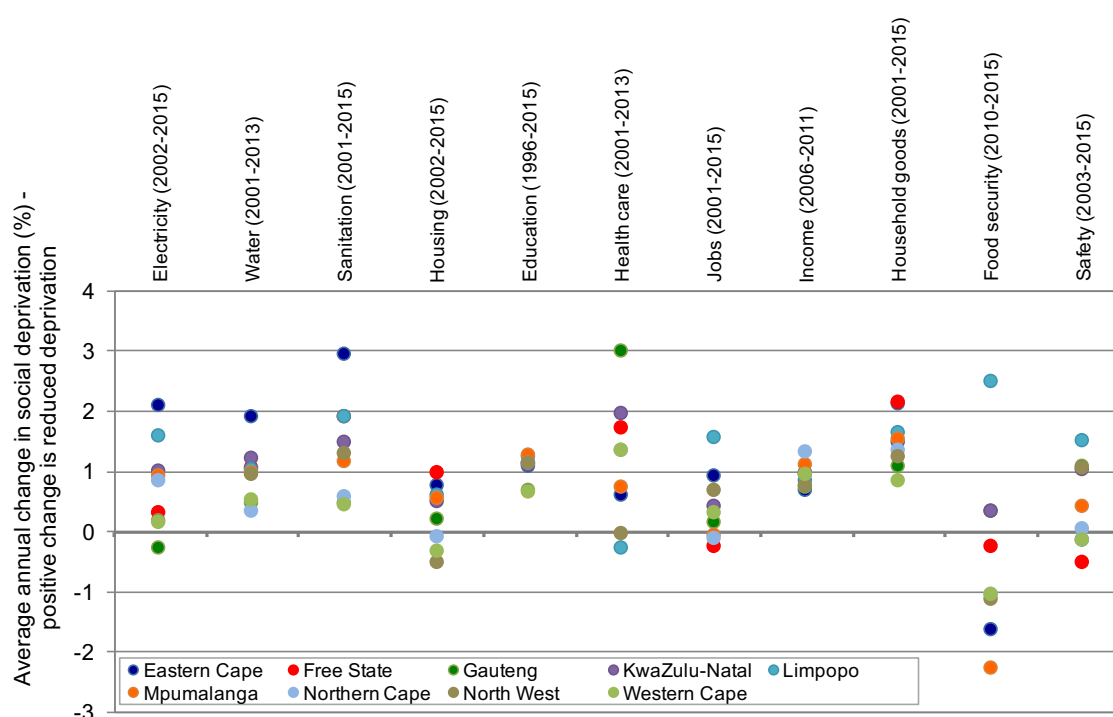


Figure 4.5 Average annual change in social deprivation in the provinces. Deprivation measured as percentage of population who are deprived.

Note: Positive change indicates reduced deprivation while negative change indicates increased deprivation. The time period varies for each dimension based on available data and is shown on the x-axis.

4.4 Discussion

4.4.1 Sub-national variation in sustainable development indicators

Our results show that South Africa is not on a sustainable development trajectory but there are promising signs that it could achieve this in the future. Social deprivation is decreasing across the country, and although environmental stress is increasing overall and in many provinces, there has been a reduction in stress from marine harvesting in all coastal provinces and CO₂ emissions, phosphorus loading and air pollution (PM₁₀) in some provinces. The province with fastest growing environmental stress, Mpumalanga, is experiencing a rapid increase in coal mining activity.

Social deprivation is decreasing faster in the historically disadvantaged provinces – particularly Limpopo, Eastern Cape and KwaZulu-Natal, which shows that government policy and programmes are working. However, this decrease is also partly due to migration to the cities and economic hubs, reducing the total population who need basic services and public goods in those provinces. StatsSA (2015d) estimate that for 2011-2016 over 100,000 people will have left the Eastern Cape and Limpopo provinces while net migration to Gauteng will be 543,109.

While our national barometer is a useful tool, the provincial barometers show that national reporting can hide significant heterogeneity in environmental status and social deprivation, including resource use, the means of obtaining income and a broader quality of life. The heterogeneity in the environmental status is a result of several factors such as, (a) the large natural variations in climate, terrain, soil and natural resources, (b) the varying population density and (c) varying economic activities (such as mining, manufacturing, farming and fishing) which have their own specific environmental impacts. The dimensions with the highest variation, namely climate change (CO₂ emissions), phosphorus loading (total P concentrations) and air pollution (PM₁₀ levels), all use indicators that measure pollutants and have strong social-ecological linkages. CO₂ emissions and PM₁₀ reflect different levels of industrialisation and/or electricity generation in different provinces while the main cause of phosphorus loading is the inadequate treatment of effluents discharged in river catchments (Oberholster and Ashton 2008). Ozone depletion has no provincial variation due to the calculation of the state and boundary both using an equal share approach.

The variation in social deprivation reflects the spatial inequality that was entrenched by the creation of 'homelands', partially self-governing territories set aside for black inhabitants of South Africa as part of the Apartheid agenda of racial segregation (see map in SI, Figure S4.1). These homelands had an extremely weak financial base and relied on transfer payments from the central South African government (Wittenberg 2006). Democracy in 1994 brought significant change to administrative boundaries in South Africa, with the nine provinces designed to combine homelands and parts of 'white' South Africa. Despite this, the Western Cape has no homeland areas while less than 3% of the area in Gauteng, Free State and Northern Cape were part of the homelands. These four provinces are the least socially deprived. In contrast, 34% of KwaZulu-Natal, 29% of the Eastern Cape, 27% of Limpopo and 25% of North West (DAFF, 2015) were part of the homelands and they are still the most deprived today.

The variation in deprivation also reflects economic activity. The least deprived provinces, Gauteng and the Western Cape, are the first and third largest provincial economies respectively. Gauteng's GDP per capita is US\$ 104,584, which is 16 times higher than the national average (StatsSA 2016d). There are also other factors that could affect the level of deprivation in the provinces, such as the quality of the provincial and municipal administration and the availability of skills. The provinces with the highest number of auditees with clean audit opinions in 2015-16 were the Western Cape (79%) and Gauteng (60%) (Auditor-General South Africa 2016).

4.4.2 Barometers as policy tools

Barometers are becoming useful tools to support policy making in Africa and South Africa in particular. Examples include the Afrobarometer (Citizen Surveys 2013), the Reconciliation Barometer (Hofmeyr 2016)), the Gauteng City-Region Observatory's barometer of development (GCRO 2014) and the University of Western Cape's social cohesion barometer (Struwig et al. 2011).

Our sustainable development barometer collates and summarises many of the key dimensions reported in the South African national reports on environmental and social indicators. Our provincial barometers are visual tools for decision-makers and communicate the range of key challenges that provincial governments face, including the current and past levels of risk. These data are seldom all presented at the provincial scale. Although social data are reported by province in household survey reports, they only appear in the online appendix of excel sheets in the annual Development Indicators reports (DPME 2015a). Environmental data are compiled at the national scale or by ecological unit (e.g. drainage basin or ecosystem type) by the national government (DEA 2012b; DEA 2014a; DEA 2016). While the provinces publish their own State of Environment reports, they have varying formats, indicators, frequency and data sources. Furthermore data availability varies considerably. For example, only four provinces have greenhouse gas inventories and each is calculated for a different year.

These differences make it difficult to compare provinces on an annual basis and track them over time. Our barometers and trend plots are novel in that they present comparable environmental and social data on key indicators over time for all

provinces of South Africa in simple diagrams. Like the national indicator reports, they are user-friendly and accessible to a range of audiences. This includes decision-makers who need to make decisions on a broad spectrum of issues without necessarily being experts on most of those issues.

4.4.3 Environmental governance and safe boundaries

There are two ways provincial data are used. The first is to monitor progress at the provincial level, and the second is to compare provinces at the national level. In this paper we have focused on the latter, and as a result some of the environmental indicators are not relevant for all provinces. This is because certain environmental stresses do not occur in that province (e.g. ozone depletion), are not relevant (e.g. marine harvesting in inland provinces), or do not meet the criteria of the national monitoring programme (e.g. air pollution). Only two provinces, KwaZulu-Natal and Western Cape, have data for all eight of the defined indicators. This clearly shows that the choice of national indicators should consider the application at sub-national scale if it is to be used to take action, and that in some cases (e.g. ozone depletion) a national indicator is necessary for international governance but is actionable only in some sub-national settings. It would be a useful exercise for each province to select their own set of dimensions and indicators using the decision flowchart developed in Cole et al (2014). In order to maintain comparability, both sets of indicators (national and provincial) would be required.

The variation in environmental stress revealed by the disaggregation requires quite different responses from different provincial governments. The type of safe environmental boundary plays an important role in this. For Type A boundaries

(based on international targets) the provinces must work together with the national government to determine their provincial boundary and action plans to meet international agreements. The methods we used for allocating responsibility would need to be debated and an acceptable approach agreed by all the relevant provinces to ensure that national targets are met. For ozone depletion, only three of the provinces (Gauteng, Western Cape and KwaZulu-Natal) would be involved, while all nine provinces would need to tackle climate change, although some provinces (particularly Mpumalanga, North West, KwaZulu-Natal and Gauteng) clearly have a larger role to play in reducing CO₂ emissions. Although electricity is a national issue, efficiency in use might need a provincial role. Transport is a provincial and local government issue, especially in the big cities where specific choices about transport are needed. Agriculture and land use change emissions can be treated provincially as well.

For Type B boundaries (based on finite natural resources) the barometers show where there are opportunities and risks. Some provinces have unfarmed arable land or unutilised freshwater resources that could be developed and used to support economic growth and job creation. Other provinces are farming large areas on marginal arable land (e.g. Free State) or using more water than is ecologically sustainable (six out of nine provinces) and might require a strategic change in agricultural policy to avoid environmental degradation. It is impossible to redistribute arable land, and it may well be technically or economically unfeasible to transfer additional freshwater between the provinces. Therefore the provincial barometers add a valuable insight into the nature of the water-food-energy nexus

in the country, and can inform resource-dependent development strategies and Spatial Development Plans to achieve 'spatial sustainability' (DRDLR 2013).

For Type C boundaries (based on local biophysical thresholds), provinces need to identify local areas where the stress is occurring in order to take action. Local data already exist for phosphorus loading, biodiversity loss and marine harvesting and air pollution and the safe boundary is the same regardless of scale. The thresholds have been set by the national government and should be maintained locally to protect human health and the sustainability of jobs dependent on these natural resources. In the case of fertiliser use affecting the nitrogen cycle, both local status and safe boundaries need to be determined for different crops and farming regions.

4.4.4 Defining social floors

The social indicators used in the barometer define national social floors i.e. what is considered an unacceptable standard of living. These are largely based on data availability and reporting by national government (e.g. the national poverty line). They should ideally also have input from citizens, particularly those experiencing deprivation. South Africa's National Development Plan (National Planning Commission 2012) aims to define the country's minimum social floor and ensure that no one lives below this social floor by 2030. In order to begin to define a 'democratic definition of poverty' for South Africa, a module was included in the South African Social Attitudes Survey to obtain a nationally representative list of items, activities and services that the majority of people defined as 'essential for everyone to have in order to enjoy an acceptable standard of living in South Africa today' (Noble et al. 2013). The results of this survey and other participatory

approaches could influence both national and sub-national indicators used in South African development reporting. It could also be used in the process of determining national SDG social indicators.

4.4.5 SDG implementation

One of the chief aims of the current South African government is to reduce inequality. The SDGs and Agenda 2030 have committed to 'leaving no-one behind' and targets will not be considered as met unless they are met for the whole population. The spatial disaggregation of social deprivation that we have shown for South Africa's nine provinces is an early case study of what is required for the national SDG implementation, and illustrates one approach to how that could be communicated. Our provincial barometers show that while the national statistics might show good progress overall there are some provinces that lag far behind.

While the SDGs call for disaggregation of social data it is also useful to disaggregate environmental data so that it can be better monitored and managed. Both the state and boundary of each environmental indicator need to be disaggregated. In this paper we have used three methods to disaggregate environmental data that could be used in any country across a range of indicators. The first method, "sharing a national total", is a similar approach to that often used to share global commons by countries, for example in debates on climate change mitigation. While this approach is necessary when local data are not available, it is not ideal as sharing based on population, GDP or another metric will never be as accurate as aggregating local data. As it has become obvious in the climate change negotiations, it also leads to discussions on equity and historical responsibility that

are hard to solve. The second method, “aggregating accessible local data”, is commonly used for national and global reporting. The challenge here is finding sufficient data that cover the whole country for annual or even for less frequent updates. We found that national reports often focus on the most stressed areas so not all local data are aggregated. While the ideal approach is to measure and collate large local data sets this is expensive. The SDSN estimates that a US\$1 billion per annum will be required to enable 77 lower-income countries (40 of which are in Africa) to implement statistical systems capable of supporting and measuring the SDGs (SDSN 2015b). The third method, “finding the best fit between ecological units and administrative borders”, requires either estimation or expert knowledge and can be quite time consuming to be accurate. As many of the administrative borders within African countries do not follow natural terrain, ecological units will probably not match administrative regions. In South Africa, the CSIR has taken steps to overcome this challenge by demarcating ‘mesozones’ – 50km² units based on municipal boundaries, rivers, mountains, roads, population density and socio-economic character (Naude et al. 2007).

One big advantage of the SDGs for African countries is that each country chooses its own national indicators. While the global SDG indicators and other sustainability indices are useful guides, they may choose indicators that are not relevant to the national context. For example, the Sustainable Society Index (van de Kerk et al. 2014) uses SO₂ emissions as a proxy for air pollution while the Environmental Performance Index (Hsu et al. 2016) uses PM_{2.5} and NO₂. However the South African government has identified PM₁₀ as the main national concern. As our national and provincial barometers are tailored for South Africa (and informed by

South African expert opinion) they could be used in the process of selecting the South African SDG indicators. However as they do not cover all of the SDG targets they could merely be one tool in a much larger indicator selection process.

4.5 Conclusion

As global environmental change and population growth strain natural resources in Africa, monitoring tools play an important part in helping countries solve their most pressing sustainability challenges. Our provincial barometers for inclusive sustainable development are visual tools for decision-makers that can communicate a range of key challenges that provincial governments face, including the current and past levels of risk. Our barometers and trend plots are novel in that they present comparable environmental and social data on key indicators over time for all South African provinces. They highlight the large variation in environmental stress and social deprivation across South Africa and emphasise the effect of geographical location on progress towards achieving sustainable development. In developing the barometers, we have highlighted three potential approaches to spatially disaggregate environmental data that could be used in other African countries for the SDG implementation. The study also provides insights into the ongoing debate on applying planetary boundaries at sub-global scales, particularly in developing countries.

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Supplementary Information for Chapter 4

S4.1 Comparison of indicators in the barometer with the SDGs

Table S4.1 Comparison of our barometer, the SDGs and global indicators (SDSN 2015)

Barometer		Most relevant SDG goal and target		Global indicator
Dimension	Indicator			
Climate change	Annual direct CO ₂ emissions	13.2	Integrate climate change measures into national policies, strategies and plans	62, 79
Ozone depletion	Annual consumption of HCFC (ODt)	12.4	By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle in accordance with agreed international frameworks...	74
Freshwater use	Annual consumption of freshwater (Mm ³ yr ⁻¹)	6.4	By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals of freshwater ...	49
Land use change	Use of arable land for cropland (ha)	2.4	By 2030, ensure sustainable food production systems and implement sustainable and resilient agricultural practices...	83
Phosphorus cycle	Annual mean phosphorus concentration in reservoirs (mg/l)	6.3	By 2030 improve water quality by reducing pollution, eliminating dumping...halving the proportion of untreated wastewater...	47
Nitrogen cycle	Nitrogen application rate for maize production (kg/ha)	2.4	By 2030, ensure sustainable food production systems and implement sustainable and resilient agricultural practices...	15
Biodiversity loss	Endangered ecosystems (%)	15.5	Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity, and by 2020 protect and prevent the extinction of threatened species	86
Marine harvesting	Depleted fish stocks (%)	14.4	By 2020 effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing practices and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield	82
Air pollution	Average PM10 concentration (ug)	3.9	By 2030, substantially reduce the number of deaths and illnesses from air (indoor and outdoor) pollution	69
Chemical pollution	To be determined	12.4	By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle in accordance with agreed international frameworks and significantly reduce their release to air, water and soil...	
Energy access	Households without access to electricity	7.1	By 2030 ensure universal access to affordable, reliable and modern energy services	51
Water access	Households without access to water infrastructure >= RDP standard	6.1	By 2030 achieve universal and equitable access to safe and affordable drinking water for all	45
Sanitation	Households without access to at least ventilated improved pit latrines	6.2	By 2030 achieve access to adequate and equitable sanitation and hygiene for all, paying special attention to the needs of women and girls	46
Housing	Households not in formal dwellings	11.1	By 2030 ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums	
Education	Adults without more than 7 years of schooling (adult illiteracy rate)	4.6	By 2030 ensure all youth and significant proportion of adults, men and women, achieve literacy and numeracy	33, 35
Health care	Infant (<1 year) immunisation coverage	3.8	Achieve universal health coverage, including...access to quality essential health-	19

			care services and access to safe, effective, quality and affordable essential medicines and vaccines for all	
Jobs	Broad unofficial unemployment rate (adults aged 15-64 available to work)	8.5	By 2030 achieve full and productive employment and decent work for all women and men, including young people and persons with disabilities, and equal pay for work of equal value	57
Income	Population living below the upper national poverty line	1.2	By 2030, reduce by half the proportion of people living below national poverty lines	1
Food	Households without adequate food	2.1	By 2030, end hunger and ensure that all people have access to adequate, safe and nutritious food all year round	8
Voice	Population who feel they can say what they think	16.7	Ensure responsive, inclusive, participatory and representative decision-making at all levels	
Household goods	Households without a refrigerator			
Safety	Households who feel unsafe walking alone in their area during the night	16.1 5.2	Significantly reduce all forms of violence and related death rates everywhere By 2030 eliminate all forms of violence against women and girls	94, 88

S4.2 Environmental dimensions of the barometer

S4.2.1 Climate change

The provincial inventories: the Western Cape reported 41.3 MtCO₂e energy emissions in 2009 (Western Cape Government 2013) – 13% of national energy consumption but 11% of national energy emissions, Gauteng reported 118.2 MtCO₂ in 2007 (Tomaschek et al. 2012), the Eastern Cape reported 23.4 MtCO₂ in 2008 (Government of the Eastern Cape 2011) and the Free State reported 22.6 MtCO₂ in 2012 (YM Mashalaba & Associates 2012).

Table S4.2 Disaggregating CO₂ emissions to the provincial level using share of population (StatsSA 2012a), GDP (StatsSA 2014) and electricity (StatsSA 2016a) in 2011 (year of most recent available CO₂ data)

Province	Population share (%)	GDP share (%)	Electricity use share (%)	Status based on electricity use (MtCO ₂)	Boundary based on GDP (MtCO ₂)	Normalised status (proximity to boundary)
Eastern Cape	12.7	7.5	4.4	20.8	34.0	61%
Free State	5.3	5.3	4.0	18.9	24.0	78%
Gauteng	23.7	34.5	27.5	131.3	156.5	84%
KwaZulu-Natal	19.8	15.7	18.8	89.8	71.2	126%
Limpopo	10.4	7.1	5.4	26.0	32.2	81%
Mpumalanga	7.8	7.0	15.8	75.3	31.8	237%
Northern Cape	2.2	2.2	2.2	10.7	10.0	107%
North West	6.8	6.5	11.7	55.7	29.5	189%
Western Cape	11.2	14.2	10.2	48.8	64.4	76%
South Africa	100	100	100	477.2	453.7	105%

Table S4.3 Downscaling climate change to the provincial level using share of GDP (StatsSA 2012b) and electricity (StatsSA 2016a) in 2002 (year of oldest available electricity use data)

Province	GDP (%)	Estimated boundary (MtCO ₂)	Electricity use share (%)	Estimated status (MtCO ₂)	Proximity to Boundary	Change from 2002 to 2011
Eastern Cape	7.8	27.1	3.4	11.8	44%	+17%
Free State	5.6	19.5	4.6	16.0	82%	-4%
Gauteng	33.5	116.5	25.6	89.0	76%	+8%
KwaZulu-Natal	16.3	56.7	18.5	64.3	113%	+13%
Limpopo	6.7	23.3	4.2	14.6	63%	+18%
Mpumalanga	7.1	24.7	12.5	43.5	176%	+61%
Northern Cape	2.2	7.6	2.1	7.3	95%	-12%
North West	6.6	22.9	13.1	45.5	198%	-9%
Western Cape	14.1	49.0	9.7	33.7	69%	+7%
South Africa	100	347.7	100	347.7	100%	+5%

S4.2.2 Ozone depletion

Table S4.4 Estimation of consumption of HCFCs by province

	Actual provincial consumption in 2010					Estimated provincial consumption in 2015	
Province	HCFC-141b in million tonnes*	% HCFC-141b	HCFC-22 in million tonnes**	% HCFC-22	% Total HCFC	Status in ODPt	Boundary in ODPt
Eastern Cape	0.6	0	0.0	0	0	-	-
Free State	0.0	0	0.0	0	0	-	-
Gauteng	1,391.7	77	958.0	26	51	106.2	169.7
KwaZulu-Natal	344.2	19	0.0	0	9	18.7	29.9
Limpopo	0.0	0	0.0	0	0	-	-
Mpumalanga	0.0	0	0.0	0	0	-	-
Northern Cape	0.0	0	0.0	0	0	-	-
North West	0.0	0	0.0	0	0	-	-
Western Cape	66.9	4	2,681.0	74	40	83.3	133.1
<i>South Africa</i>	<i>1,803.4</i>	<i>100</i>	<i>3,639.0</i>	<i>100</i>	<i>100</i>	<i>208.3[^]</i>	<i>332.7</i>

*Based on the foam sector baseline data in the HCFCs Phase Out Plan (NEDLAC 2012).

** Based on the largest importers in 2009/10 in the HCFCs Phase Out Plan. [^] Reported by the United Nations Environment Program Ozone Secretariat (UNEP 2016).

S4.2.3 Freshwater use

Table S5 shows the total supply, demand (including transfers) and ecological reserve (as percentage of mean annual runoff, MAR) for each province for the year 2000 using the sub-areas data in the first National Water Resource Strategy, NWRS (DWAF 2004). The only major overlap was in two sub-areas of the Lower Vaal WMA, shared between the North West and Northern Cape; here we split the supply and demand equally between the two provinces. This data was not updated in the 2013 NWRS. Although two of the provincial SOE reports quote supply and demand values we did not use them as we did not

know how they would affect the other provinces (Western Cape: supply 2522 Mm³/a, demand 2637 Mm³/a; Eastern Cape: supply 2181 Mm³/a, demand 1654 Mm³/a).

From 2004 to 2013 the Department of Water Affairs and Sanitation (DWS) undertook a large programme of work to develop water reconciliation strategies for the metropolitan areas (metros) as well as all towns and villages in South Africa to inform water resource investment and management decisions (DWA 2013). The eight metros are addressed in strategies for the major water supply systems (WSS): Western Cape WSS (DWA 2007), Algoa WSS (DWA 2011), Amatole WSS (DWA 2011), Greater Bloemfontein WSS (DWA 2012), Vaal WSS (DWA 2009) and KwaZulu-Natal coast and metros WSS (DWA 2009). We used 2011 data for all metros. In the DWS's 'All Town Studies' towns, villages and settlements were grouped into 838 logical clusters based on their water supply. The All Town Studies reported current (2007/8) and projected (2010 to 2035) water requirements (demand) and yields (supply). We aggregated the data in these studies to the provincial level shown in Table S6. The final column shows the supply minus the ecological reserve, calculated using the reserve as a percentage of MAR.

Table S4.5 Status and boundaries for freshwater use in 2000 and 2011 by province

	National Water Resource Strategy (DWAf 2004) 2000			Reconciliation Strategies (DWS) 2008-2011		
Province	Demand (Mm³/a)	Sustainable supply (Mm³/a)	Reserve as % MAR	Demand (Mm³/a)	Supply (Mm³/a)	Supply less Reserve (Mm³/a)
Eastern Cape	1,378	1,896	14.7	395	382	325
Free State	870	918	12.5	207	239	209
Gauteng	1,605	1,649	17.6	1,268	1,325	1,092
KwaZulu-Natal	1,779	1,735	23.1	617	736	566
Limpopo	1,382	1,166	19.7	214	258	207
Mpumalanga	1,472	1,214	26.1	233	248	183
Northern Cape	1,661	2,032	14.5	93	139	119
North West	571	570	15.0	165	211	179
Western Cape	2,025	1,936	16.2	456	529	443
<i>South Africa</i>	<i>12,743</i>	<i>13,116</i>	<i>19.2</i>	<i>3,648</i>	<i>4,066</i>	<i>3,285</i>

S4.2.4 Arable land use

The national land capability classification defines eight Classes. Classes I, II and III comprise rain-fed arable land of acceptable quality while Class IV is marginal arable land. The other four classes are non-arable.

Table S4.6 Land capability and cultivated land use by province (DAFF 2015)

Province	Total Land Area (ha)	Land Capability Class I-III Area (ha)	Status: Cultivated Class I-IV Land (ha)	Boundary: Available Land Capability Class I-III Area (ha)*	Cultivated Class I-IV Land as % of Available Class I-III Land
Eastern Cape	16,882,162	1,273,249	828,507	1,122,937	74%
Free State	12,980,148	2,254,177	3,070,570	2,204,698	139%
Gauteng	1,817,148	1,093,904	306,597	772,377	40%
KwaZulu-Natal	9,322,929	3,097,604	691,483	2,537,768	27%
Limpopo	12,573,636	2,534,914	967,732	2,296,820	42%
Mpumalanga	7,646,428	2,957,734	1,278,717	2,393,780	53%
Northern Cape	37,279,987	0	0	0	-
North West	10,486,312	1,777,280	1,631,535	1,661,912	98%
Western Cape	12,935,453	895,807	876,367	767,777	114%
<i>South Africa</i>	<i>121,924,881</i>	<i>15,884,669</i>	<i>9,651,508</i>	<i>13,758,068</i>	<i>70%</i>

* Original land capability area less land that has been permanently transformed, or is used for forestry plantations or is formally protected for biodiversity conservation

S4.2.5 Phosphorus loading

Table S4.7 Phosphorus loading by province

Province	Drainage basins	Status: Total Phosphorus in reservoirs (mg/l)		Boundary: Total Phosphorus in reservoirs (mg/l)	Annual change 2000 to 2012 (%)
		2012	2000		
Eastern Cape	P, R, S, T	0.064	0.156	0.1	-7.7
Free State	C, D	0.119	0.069	0.1	4.2
Gauteng	A, B, C	0.099	0.099	0.1	0.0
KwaZulu-Natal	U, V, W	0.037	0.053	0.1	-1.3
Limpopo	A, B	0.154	0.131	0.1	1.9
Mpumalanga	B, X	0.057	0.019	0.1	3.2
Northern Cape	D	0.147	0.056	0.1	7.6
North West	A, C	0.104	0.107	0.1	-0.3
Western Cape	E, F, H, K	0.035	0.033	0.1	0.2
<i>South Africa</i>	<i>ALL</i>	<i>0.101</i>	<i>0.074</i>	<i>0.1</i>	<i>2.3</i>

S4.2.6 Nitrogen cycle

Table S4.8 Total maize production and estimated fertiliser use by province in 1990/91 and 2012/13 (Source data: Grain SA 2013 and FSSA 2013)

Province	Status in 1990/91			Status in 2012/13			Boundary (kgN per ha)
	'000 ha planted	tN	kgN per ha	'000 ha planted	tN	kgN per ha	
Western Cape	2	137	69	3.3	272	82	144
Northern Cape	19	1302	69	53.2	4 388	82	144
Free State	929	63644	69	1 230.0	101 462	82	144
Eastern Cape	33	2261	69	18.7	1 543	82	144
Kwazulu-Natal	82	5618	69	95.0	7 837	82	144
Mpumalanga	591	40488	69	470.0	38 770	82	144
Limpopo	43	2946	69	53.5	4 413	82	144
Gauteng	134	9180	69	117.5	9 693	82	144
North West	1374	94129	69	740.0	61 042	82	144
<i>South Africa</i>	<i>3207</i>	<i>291 704</i>	<i>69</i>	<i>2 781.2</i>	<i>229 420</i>	<i>82</i>	<i>144</i>

S4.2.7 Biodiversity loss

In the NBA estuary technical report (van Niekerk and Turple 2012), (Table 10.5 on pages 119-120) threat status is reported by administrative district, hence we could calculate the area and number of EN and CR estuarine ecosystems for four provinces, shown in Table S4.8 and S4.9. In the marine and coastal technical report (Sink et al. 2012), threat status is reported for 58 coastal, 62 offshore benthic and 16 offshore pelagic habitat types (Table 14 pages 162-165). These can be grouped into 11 geographic regions – Agulhas, Delagoa, Namaqua, Natal, Natal-Delagoa, South Atlantic, Southeast Atlantic, Southern Benguela, Southwest Indian, Southwestern Cape and Pelagic. As the provinces do not have jurisdiction over the offshore regions, we focused on coastal and inshore habitat types only. We matched the regions to the four

coastal provinces to calculate the area and number of EN and CR coastal and inshore habitat types (see Table S10 and S11). There is some overlap between the provinces due to the large geographical spread of the regions so in some cases a region was assigned to two provinces.

We could not determine the threat status for freshwater ecosystems (rivers and wetlands) from the NBA 2011, as they are downscaled to the Water Management Area level (Nel and Driver 2012), which does not match well to the provinces.

The threat status of 567 terrestrial ecosystems was based on the National List of Ecosystems that are Threatened and Need Protection (DEA 2011) which reports the original area and remaining natural area for 53 CR ecosystems and 64 EN ecosystems, and records the province. The remaining area is reported as a percentage of the original area, which gives a measure of extinction or habitat loss only, rather than threat status. The remaining area is also reported as a percentage of the area of the province, however we wanted to use the original area to determine the total endangered (CR and EN) terrestrial ecosystems as this will then incorporate the habitat loss i.e. both the area at risk of crossing the safe boundary and the area that has already crossed the safe boundary. We used the original CR+EN areas as a percentage of total province area, calculated by SANBI for the NBA 2011, shown in Table S10. The total number of habitats is not reported so we could not calculate percentages per province.

There are two options for determining a single provincial value for biodiversity loss – we can either measure it based on habitat area (Table S10) or based on number of ecosystems, estuaries and habitat types (Table S11). Due to the lack of data for the latter, and advice from experts at SANBI, we averaged the ecosystems by area to obtain a single value (% CR+EN) per province. We kept the safe provincial boundary the same as the national boundary i.e. no ecosystems should be endangered or critically endangered.

For the trends analysis, we reviewed the 2004 National Spatial Biodiversity Assessment (NSBA) (Driver et al. 2005), which was the first time South Africa calculated ecosystem threat status rather than species threat status. Estuarine ecosystems were not assigned threat status and the marine and coastal ecosystems were not assessed by habitat area so neither could be determined per province. Although threat status per terrestrial vegetation type was reported, this was not done by province. In addition, the thresholds for EN and VU ecosystems were much higher in the NSBA 2004 than the NBA 2011; 60% of original extent rather than +15% for EN and 80% rather than 60% for VU. It was changed for NBA 2011 as it was unworkable as CR and EN ecosystems trigger Environmental Impact Assessments, and was not as defensible from a science point of view (Driver et al. 2005). This means that the two assessments are not comparable and we were not able to plot the change in biodiversity loss.

Table S4.9 Calculation of provincial critically endangered (CR) and endangered (EN) ecosystems using habitat area

Province	Terrestrial ecosystems		Estuarine ecosystems		Coastal and inshore ecosystems		Total
	Original area (ha) CR+EN	%Total Area CR+EN	Area (ha) CR+EN	%Total Area CR+EN	Area (km ²) CR+EN	%Total Area CR+EN	Average % CR+EN
Eastern Cape	106 312	0.6	3 525	41	110	2	14
Free State	1 466 064	11.3	-	-	-	-	11
Gauteng	557 695	30.7	-	-	-	-	31
KwaZulu-Natal	853 368	9.0	58 261	93	301	13	34
Limpopo	165 822	1.3	-	-	-	-	1
Mpumalanga	784 910	10.3	-	-	-	-	10
Northern Cape	75 147	0.2	243	19	2768	28	9
North West	1 672 581	15.9	-	-	-	-	16
Western Cape	2 181 136	16.8	14 817	80	1286	10	34
<i>South Africa</i>	<i>7 863 036</i>	<i>6.4</i>	<i>73 947</i>	<i>81</i>	<i>4464</i>	<i>15</i>	<i>29</i>

Table S4.10 Calculation of provincial critically endangered (CR) and endangered (EN) ecosystems using number of estuaries for estuarine ecosystems and habitat types for inshore and coastal ecosystems

Province	Estuarine ecosystems		Inshore and coastal ecosystems	
	Number of Estuaries CR+EN	% Estuaries CR+EN	Habitat Types CR+EN	% Habitat Types CR+EN
Eastern Cape	13	8	3	20
Free State	-	-	-	-
Gauteng	-	-	-	-
KwaZulu-Natal	21	28	3	9
Limpopo	-	-	-	-
Mpumalanga	-	-	-	-
Northern Cape	2	50	14	48
North West	-	-	-	-
Western Cape	27	51	10	33
<i>South Africa</i>	<i>63</i>	<i>22</i>	<i>30</i>	<i>38</i>

The updated planetary boundaries use the Biodiversity Intactness Index (BII), a measure of the 'average abundance of wild population relative to their reference populations' (Biggs et al. 2006), for regional boundaries for biodiversity integrity. Biggs *et al.* (2006) calculated the BII for South Africa in 1995 to be 81% i.e. terrestrial plants and vertebrates populations have declined by 19% from their presumed pre-colonial levels. At a provincial level, the BII ranged from 64% for Gauteng to 92% for the Northern Cape. As the BII is scale-independent and has already been used at national, provincial and local scale in South Africa makes it an attractive indicator for the barometer. It does not include marine and freshwater ecosystems, however, and has not been updated since 2006, thus the data are 20 years out of date. This means it does not meet our selection criteria.

S4.2.8 Marine harvesting

Table S11 shows the number of species and depleted species reported in the Status of the South African Marine Fishery Resources for the years 2009 (DAFF 2010) and 2013 (DAFF 2014). The fisheries are abalone, Agulhas sole, Cape hakes, Cape horse mackerel, linefish, netfish, oysters, Patagonian toothfish, prawns, seaweeds, sharks, small pelagic fish, South coast rock lobster, squid, tunas and swordfish, West coast rock lobster, and White mussels and small invertebrates.

Table S4.11 Marine harvesting in 2013, 2011 and 2009 by province

Province	Number of fisheries	2013		2009	
		Number of species	Depleted species	Number of species	Depleted species
Eastern Cape	15	39	14 (41%)	49	26 (65%)
KwaZulu-Natal	8	32	12 (43%)	44	25 (66%)
Northern Cape	12	34	14 (44%)	45	25 (66%)
Western Cape	16	45	17 (43%)	53	27 (60%)
<i>South Africa</i>	<i>17</i>	<i>49</i>	<i>18 (43%)</i>	<i>54</i>	<i>27 (60%)</i>

S4.2.9 Air pollution

For some air quality monitoring stations, monitoring started in 1994 while for others it only started in 2013. Other points have only one or two readings over that period. So it is difficult to identify a starting point to assess the provinces. To plot the trend, we decided to use the years 2003 and 2004 to ensure all relevant provinces were covered. This did mean that we only had 22 data points in total for 2000 whereas we had 50 data points in 2014. The North West province has only one monitoring station in Rustenburg and only has measurements reported for 2003 and 2004. We used the same boundary of 40 $\mu\text{g}/\text{m}^3$ for 2000 and 2014 in our trend analysis.

Table S4.12 Air quality (PM10 concentration in ug/m³) by province

Province	Monitoring point locations	2014		2003/04		Annual change 2004 to 2014
		Status	Boundary	Status	Boundary	
Gauteng	Tshwane (6), Vaal Triangle Priority Area (6), Eskom (1)	55.9	50	51.5	40	3.7
KwaZulu-Natal	eThekweni (4), Richards Bay (4)	32.3	50	40.2	40	0.0
Limpopo	Waterberg-Bonjanala Priority Area (3)	34.8	50	-	-	-
Mpumalanga	Eskom (9), Highveld Priority Area (5)	41.9	50	33.3	40	3.8
North West	Rustenburg (0)	-	-	62.9	40	-
Western Cape	Cape Town (7), towns (5)	22.5	50	28.6	40	-0.1
<i>South Africa</i>	<i>(41)</i>	39.2	50	39.8	40	1.8

S4.3 Social dimensions of the barometer

Table S4.13 National and provincial results for the South Africa Afrobarometer Round 5 Study in 2011

Question	Response	EC	FS	GAU	KZN	LIM	MP	NC	NW	WC	SA	Range
How free are you to say what you think?	Not free + Not very free	17	8	17	17	14	15	8	5	24	16	19
How free are you to join any political organisation?	Not free + Not very free	12	5	13	14	8	6	8	1	20	12	19
How free are you to choose who to vote for without feeling pressured?	Not free + Not very free	9	5	9	11	8	3	4	2	15	9	13
Have you attended a community meeting in the past year?	No, would never + No, would if had the chance	45	43	37	43	31	31	43	45	62	42	31
Have you got together with others to raise an issue in the past year?	No, would never + No, would if had the chance	59	54	47	65	45	47	57	72	70	57	27
Have you contacted a government department to raise an issue in the past year?	No, would never + No, would if had the chance	91	79	83	83	74	77	81	91	85	83	17
Have you contacted radio, TV or newspaper to complain about an issue in the past year?	No, would never + No, would if had the chance	98	95	90	90	86	90	97	94	93	92	12
Have you attended a demonstration or protest march in the past year?	No, would never + No, would if had the chance	93	83	87	89	75	89	86	89	90	87	18
Do you rate the 2009 national election as free and fair?	Not free and fair	4	3	2	3	4	2	5	1	5	3	4
How much of a democracy is SA today?	Not a democracy	4	3	1	3	4	0	4	1	6	3	6
During election campaigns, do you fear becoming a victim of political intimidation or violence?	A lot + Somewhat	19	11	17	33	18	19	11	26	20	21	22
How much do you trust your local councillor?	Not at all + Just a little	75	50	57	52	53	51	37	54	45	56	38
How many local councillors are involved in corruption?	All of them + Most of them	45	57	53	64	43	51	34	69	34	51	35
How much do local councillors listen to what people like you have to say?	Never	67	44	34	38	29	46	30	31	41	37	38

Table S4.14 Annual average change in social deprivation (%)

Province	Basic services				Public goods		Livelihoods		Living standards		
	Energy (2002- 2015)	Water (2001- 2013)	Sanitation (2001- 2015)	Housing (2002- 2015)	Education (1996- 2015)	Health Care (2001- 2013)	Jobs (2001- 2015)	Income (2006- 2011)	Household Goods (2001- 2015)	Food Security (2010- 2015)	Safety (2003- 2015)
Eastern Cape	2.1	-1.9	2.9	0.7	1.1	-0.6	0.9	-0.7	2.1	-1.6	-0.2
Free State	0.3	-1.0	1.9	1.0	1.1	-1.7	-0.3	-0.9	2.1	-0.3	-0.5
Gauteng	-0.3	-0.5	0.5	0.2	0.7	-3.0	0.1	-0.7	1.1	0.3	1.1
KwaZulu-Natal	1.0	-1.2	1.5	0.5	1.1	-2.0	0.4	-1.0	1.5	0.3	1.0
Limpopo	1.6	-1.0	1.9	0.6	1.2	0.3	1.5	-0.8	1.6	2.5	1.5
Mpumalanga	0.9	-1.0	1.2	0.5	1.3	-0.7	-0.1	-1.1	1.5	-2.3	0.4
Northern Cape	0.8	-0.4	0.6	-0.1	1.1	-1.3	-0.1	-1.3	1.3	-1.1	0.0
North West	0.2	-0.9	1.3	-0.5	1.1	0.0	0.7	-0.7	1.2	-1.1	1.0
Western Cape	0.1	-0.5	0.4	-0.3	0.6	-1.3	0.3	-0.9	0.8	-1.1	-0.2
<i>South Africa</i>	<i>0.6</i>	<i>-1.0</i>	<i>1.4</i>	<i>0.3</i>	<i>1.0</i>	<i>-0.4</i>	<i>0.4</i>	<i>-0.9</i>	<i>1.5</i>	<i>-0.2</i>	<i>0.6</i>
Range	2.4	1.6	2.5	1.5	0.6	3.3	1.8	0.6	1.3	4.8	2.0

S4.4 Map of former homelands

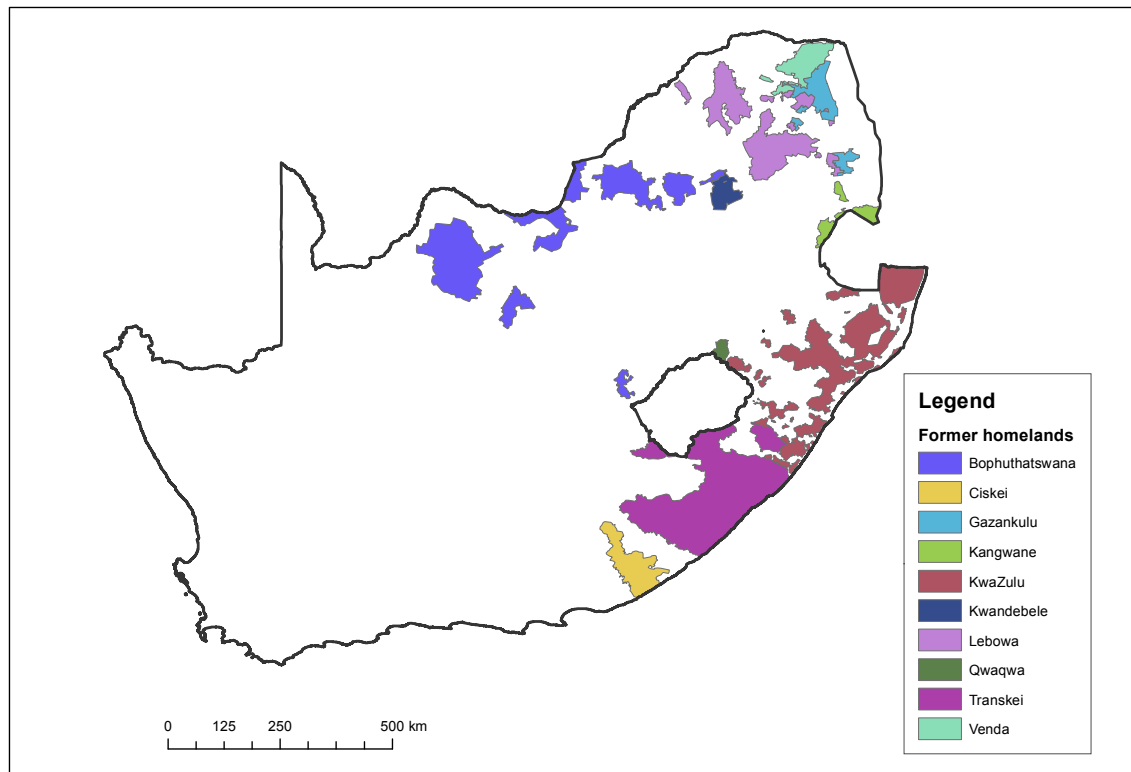


Figure S4.1 Map of former homelands in South Africa before 1994

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Linking statement – Chapter 4 to 5

In the previous chapter (4) the national barometer for inclusive sustainable development for South Africa was downscaled to the provincial level to create nine provincial barometers. This chapter (5) focuses on one aspect of sustainable development – water – to take the concept and analysis from the national to the local scale. Large datasets are created for the two water indicators in the barometer – piped water access and freshwater use – using national census data and water reconciliation strategies for all cities, towns and villages in South Africa. Three SDIs are defined – piped water access in dwellings, town per capita water use, and town per capita water stress – and data are compiled data at multiple governance scales. Several measures of inequality, including the Gini index and Palma index, are calculated for piped water access and town per capita water use, to compare how these differences change with scale.

This chapter addresses questions Q3, 'How can the inequality hidden by national indicators be measured and reported to support decision-making? Results at national, provincial, district municipal, local municipal and ward/town scale are visualised on maps, in bar charts and in Lorenz curves. The different scales are compared and the effect of scale on the results is assessed. Water inequality in piped water access and water use are reported at national, provincial and district levels. The results show that geographical targeting is important for effective policy implementation.

This paper was submitted to the journal *Water Policy* in 2017, with the full Excel datasets included as supplementary material:

Cole, M.J., Bailey, R.M, Cullis, J.D.S and New, M.G. (under review) Spatial inequality in water access, water use and water stress in South Africa.

The lead author co-designed the research with RMB, JDSC and MGN, performed the research and wrote the paper, and RMB, JDSC and MGN reviewed and edited the paper.

Since the submission of this thesis, the paper has been revised to address reviewer comments asking for additional policy recommendations.

Chapter 5 – Spatial inequality in water access, water use and water stress in South Africa

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Abstract

The importance of measuring inequalities in sustainable development is reflected in the requirement to disaggregate national data for the Sustainable Development Goals (SDGs). In this paper, piped water access, water use and water stress are mapped and reported at national, provincial, district, municipal, town and ward levels, and urban and rural areas in South Africa. The ward and town data are used to calculate national and provincial Gini indexes and Palma ratios for piped water access and per capita water use. The results show that although 45% of the population has water access in their dwelling this ranges from 0.07% to 100% at ward level, with a high level of inequality (Gini index of 0.36). National per capita

water use (including losses) is 208 litres per person per day (l/c/d) but ranges from 8 l/c/d to 2,414 l/c/d at town level, with a Gini index of 0.27. The analysis shows that social factors, such as water access and income, and not natural factors, such as rainfall or runoff, have the greatest influence on per capita water use. The paper provides the first in-depth analysis of per capita water use at the local level in South Africa, and suggests new water indicators that could support equitable allocation of water resources and SDG reporting.

Key words: SDGs, water access, per capita water use, water stress, inequality, data disaggregation, South Africa

5.1 Introduction

Since the term ‘sustainable development’ was coined in the Brundtland Report in 1987 there has been considerable debate on how to achieve development goals and reduce inequality whilst also avoiding detrimental environmental change. Population and economic growth have accelerated since the 1950s and been matched by an acceleration in environmental change on multiple fronts (Steffen et al. 2015). Although, global extreme poverty more than halved from 2000 to 2015, progress was uneven across countries and regions; millions are still trapped in poverty (UN 2015). Meanwhile income inequality within countries has been increasing since 1990 (Piketty 2014; Milanovic 2016).

The United Nations (UN) ‘2030 Agenda for Sustainable Development’ and its 17 Sustainable Development Goals (SDGs), adopted in September 2015 (UN General Assembly 2015) provide a global vision to end poverty and hunger, protect the

planet from degradation, ensure prosperity for all, and foster peaceful, just and inclusive societies by 2030. Although the focus of SDG monitoring will be the national level (SDSN 2015), member states are also encouraged to track progress at sub-national levels. In addition, national data must be disaggregated by income, gender, age, race, ethnicity, migratory status, disability, geographic location and other characteristics relevant in national contexts to measure inequality (UN General Assembly 2015).

Data disaggregation by geographic location is useful for social and environmental indicators as the data can support policy implementation at sub-national levels. Spatial disaggregation of social data, such as water access, is particularly useful in South Africa as spatial inequality was entrenched in the 1900s by the very limited service delivery to the ‘homelands’ (territories set aside for black inhabitants as part of the Apartheid agenda of racial segregation) and low-income urban and peri-urban areas. Spatial disaggregation of environmental data, such as water stress, is useful in South Africa as its limited water resources are very unevenly distributed across the country (Figure 5.1). Since democracy in 1994, water has been enshrined as a basic human right in the Constitution (Republic of South Africa 2012) and the focus of water resources management has shifted to equity and redistribution (DWA 2013).

In this paper, water access (SDG 6.1), water use and water stress (SDG 6.4) are mapped and reported at national, provincial, district, municipal, ward and town levels in South Africa (see details on administrative levels in the SI, S5.1). The Methods section describes how data were obtained from the national census and

843 water reconciliation strategies, and analysed using Geographical Information Systems (GIS), distribution plots, scatter plots, multiple linear regression, descriptive statistics and Lorenz curves. The Results and Discussion section provides maps, and measures of variability and inequality for water access, use and stress. Lorenz curves, Gini indexes and Palma ratios for piped water access and per capita water use are presented. Factors affecting the spatial distribution of per capita water use are identified, and new indicators for monitoring SDG 6 and measuring non-income inequality are suggested.

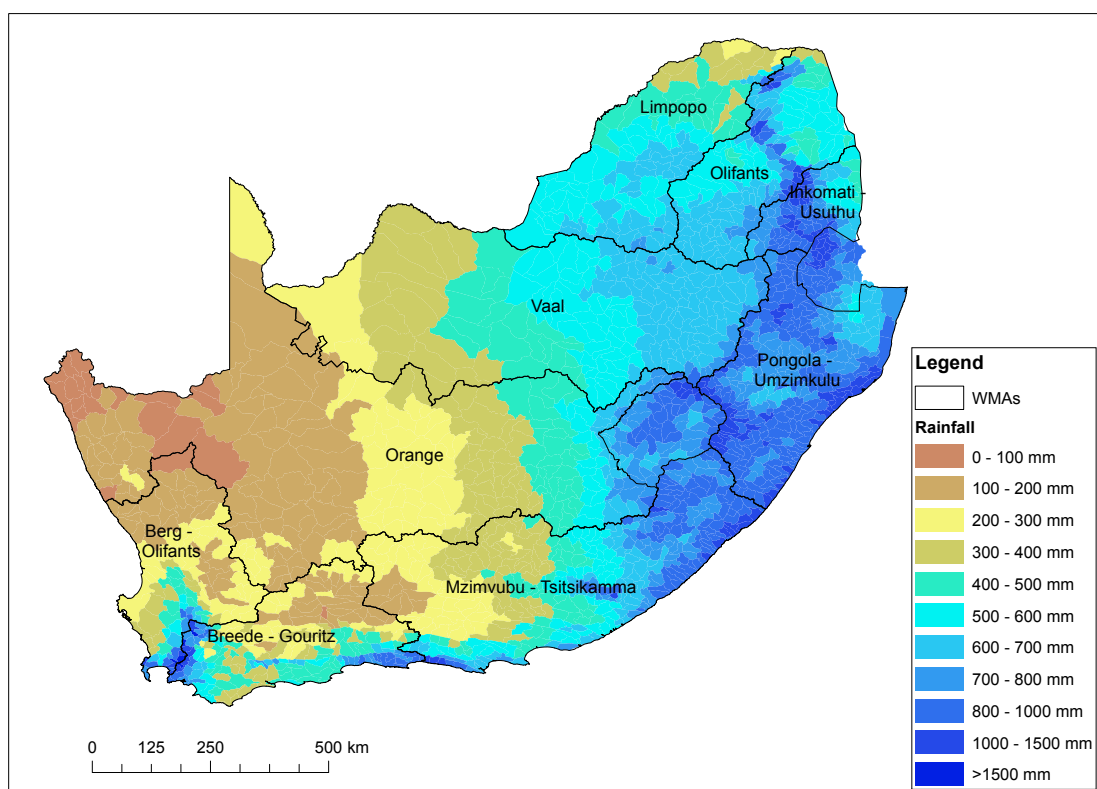


Figure 5.1 Map of South Africa's mean annual rainfall across Water Management Areas (WMAs).

5.2 Methodology

5.2.1 Selecting water indicators

South Africa's official development indicator for sufficient water access is 'households with at least 25 litres of potable water per person per day within 200m of a household, not interrupted for more than 7 days per year', termed the RDP¹ standard (DPME 2015). This level of access has steadily improved since the advent of democracy, increasing from 62% in 1994 to 86% in 2014 (DPME 2015). However, this indicator focuses on extreme poverty and does not tell us much about overall inequality. Less than half of South Africa's population has piped water access in their dwelling, only increasing slightly from 44% in 1996 to 46% in 2011 (StatsSA 2014). The UN Human Development Report 2006 and the World Health Organisation (WHO) recommend that 50-100 l/c/d of water should be piped into households for human development (Watkins et al. 2006) and to maintain adequate health (Howard and Bartram 2003). This is reflected in the government's unofficial target of 60 litres per capita per day (l/c/d). In this paper the indicators 'persons piped water access in the dwelling', 'per capita water use' and 'per capita water stress' are selected for analysis.

5.2.2 Sourcing the data

Data on piped water access are collected by Statistics South Africa (StatsSA) annually in the General Household Survey (GHS) and once a decade in the national census (StatsSA 2012a). The GHS results are reported at the provincial level while

¹ Reconstruction and Development Programme, the first democratic socio-economic policy framework

the census results are reported at municipal level, but sub-municipal census data can be found in the SuperCross and SuperWeb databases. The Department of Water and Sanitation (DWS) uses these figures to report households with water access 'at and above RDP standard' or 'below RDP standard' at the municipal level data. The most recent modelled and updated data are reported in the National Water Services Knowledge System (DWS 2016a). As the census is the only source that provides data on piped water access in dwellings at the lowest spatial levels, it was used as the source for piped water access data. Census data for all 4,277 wards were extracted from StatsSA's SuperWeb database (StatsSA 2014) and compiled by municipality, district and province (see SI datasheet) and by urban and rural area (classified as traditional/tribal area² or commercial farm 'geotype').

Per capita water use is not regularly reported in South Africa, and although it could be calculated from municipal water accounts, these are not publically available. Supply and demand in the eight metropolitan areas (metros), home to 40% of the population (StatsSA 2012a), were measured or estimated in DWS reconciliation strategies for the major water supply systems (WSS) (DWAf 2007; DWA 2009; DWAf 2009; DWA 2011a; DWAf 2011; DWA 2012). The different WSS studies were undertaken over an eight-year period so that the 'current' status varies from 2006 to 2011, but all except the most recent study (for Mangaung metro) has had regular status updates which are available on the DWS website. For this paper, the 2011 figures for demand and supply were extracted for the urban areas in the WSS reports to ensure that the per capita figures were as accurate as possible.

² Communally owned land under the jurisdiction of a traditional/tribal leader, and rural informal settlements (StatsSA 2012b).

In 2007/8, the DWS published water reconciliation strategies for all towns and rural villages in South Africa to inform water resource investment and management decisions (DWA 2013), providing the first comprehensive water use information at the local level across South Africa. The so-called 'All Town Studies' grouped towns and rural villages into 838 logical clusters based on their water supply. The studies reported 'current' (2007/8) and projected (2010 to 2035) water requirements including losses (demand) and yields (supply) based on population growth scenarios, reconciliation options (e.g. water conservation) and augmentation measures (e.g. groundwater). In many cases in the All Town Studies, insufficient data of actual water consumption and water supply were available, and estimates and assumptions had to be made. Demand estimates were based on water allocations reported in the Water Authorisation and Registration Management System (WARMS) database (DWA 2014) and/or population, type of housing/settlement and level of basic services (see details in SI, S5.2). Supply estimates were based on mean annual runoff (MAR), 98% assurance of supply, existing infrastructure, return flows, allocation in WARMS and the sustainability of groundwater resources. They did not make provision for the ecological reserve, the minimum requirement for ecological functioning in rivers, which varies significantly at the local scale and when aggregated is 19% of total MAR at the national scale (DWAF 2004).

Apart from two provincial summaries for the Western Cape (DWA 2011b) and Eastern Cape (DWA 2011c), there is no summary report of the All Town Studies. The 838 town reports are, however, available on the DWS website (DWS 2016b).

For this paper, the ‘current’ demand, supply and population data were extracted from each report and compiled at the town, municipal, district, province and national levels (see SI, S5.3 and spreadsheets). In addition, the residential per capita water use reported in 74 town studies in KwaZulu-Natal province was extracted to investigate the purely residential component of town use. Also, the end-user per capita use (which excludes bulk transmission losses and internal network losses) was reported in 278 town studies in the Eastern Cape and Western Cape, and this was also extracted for analysis.

5.2.3 Calculations

Using demand, supply and population in the WSS reports and All Town Studies, the per capita water use and per capita water stress (supply less demand divided by population) of each metro, town and village cluster was calculated. They were weighted by population so that small towns with high per capita figures did not skew the results.

The descriptive statistical properties (mean, range, standard deviation, coefficient of variation) of the three indicators (water access, water use, water stress) were calculated at municipal, district, provincial and national levels using the ward and towns data sets. The results were plotted on maps using the 2011 administrative boundaries provided online by the Municipal Demarcation Board (MDB 2015). It would have been preferable to plot the water use and water stress data at the town scale but no GIS data files were available for this.

Using the ward and town data sets, a Gini index and Palma ratio for piped water access in dwellings and per capita water use were calculated for South Africa, its nine provinces and 52 districts. Gini indexes and Palma ratios were not calculated for per capita water stress as many of the figures are negative. The detailed calculation method is provided in the SI, S5.4. The same properties were calculated at national level using aggregated municipal, district and provincial data to assess the effect that the scale of the data set used had on the result.

The Gini index, the most widely used inequality index, is a measure of the distribution of income inequality across the whole of society (plotted on a Lorenz curve) with a natural benchmark of pure equality of zero (Palma 2011; Cobham *et al.* 2015). The Gini index for net income varies from 0.22 in Sweden to 0.67 in Namibia (Solt 2009); South Africa's official Gini index was 0.65 in 2011 (DPME 2015). Although the Gini index is normally used for income inequality, it has been used to measure inequality in the distribution of land and water resources e.g. (Carter 2000; Erickson and Vollrath 2004; Cullis and van Koppen 2007; Wang *et al.* 2011), and by Bhorat *et al.* (2009) to measure changes in non-income inequality in South Africa. The Palma ratio is a new measure of inequality based on Palma's (2011) evidence that in most countries there is great heterogeneity between the top 10% (the tenth decile, D10) and the bottom 40% (the first decile, D1 to the fourth decile, D4) of the population. The Palma ratio measures the ratio of D10 to D1-D4; the ideal Palma ratio for income inequality is 0.25, though the global average is 1.8 and South Africa's is 11.6 (Cobham and Sumner 2013). The SDG target 10.1 on reducing income inequality uses language similar to the Palma ratio (IAEG-SDG 2015).

5.2.4 Analysis

To interrogate the variation in the town per capita water use results, 18 possible explanatory variables were identified and 14 (those with available data) were plotted in scatter plots (see SI, S5.5). Eight variables related to water supply were assessed: mean annual precipitation (MAP), mean annual evaporation (MAE) and MAR³, total supply, percentage groundwater in total supply, household main water source, overall water balance⁴ and piped water access in the dwelling⁵. Six variables related to water demand were assessed: household size, household access to flush toilets, household ownership of a washing machine, annual household income, formal housing and urban location. Factors that affect per capita water use but could not be included due to lack of available data were physical losses, water price, property size (identified by van Zyl *et al.* (2008) as the best parameter for municipal water-demand estimations in South Africa), and consumers' knowledge about their water use (identified by Smith and Visser (2013) as the most influential behavioural factor in water use in Cape Town). The six demand-related variables showed a correlation to per capita water use and were used in multiple linear regression to determine their effects on use. Full details are provided in the SI, S5.5. To interrogate per capita water stress, the results were compared with the water balances reported in the first National Water Resource Strategy (DWAF 2004).

³ for the quaternary catchment the town/village is located in

⁴ for the towns/villages

⁵ for the municipality the town/village is located in

5.3 Results and Discussion

Persons piped water access in dwellings, town per capita water use, and town per capita water stress, are mapped at municipal, district and provincial level in Figure 5.2. Piped water access in wards is mapped in the SI Figure S5.1. The maps are powerful communication tools, highlighting the spatial nature of poverty, inequality and access to resources, and supporting effective 'geographical targeting' - focusing efforts on key areas (Henninger 1998) - which has the potential to be a more efficient system of allocation of scarce resources than means testing⁶ (Bigman and Fofack 2000; Cullis and O'Regan 2004). The efficiency of geographical targeting improves as the resolution improves i.e. more of the poorer households are included at lower scales (Cullis and O'Regan 2004) and therefore the ward and municipal level maps are the most useful.

Table 5.1 summarises the results of the analysis of sub-national variability and inequality in water access, use and stress. Distribution plots for all three indicators are provided in the SI Figure S5.2. Figure 5.3 plots the Lorenz curves used to determine the national and provincial Gini indexes and Palma ratios for piped water access and per capita water use, using ward and town data respectively. The results for each indicator are discussed below.

⁶ usually based on income and savings

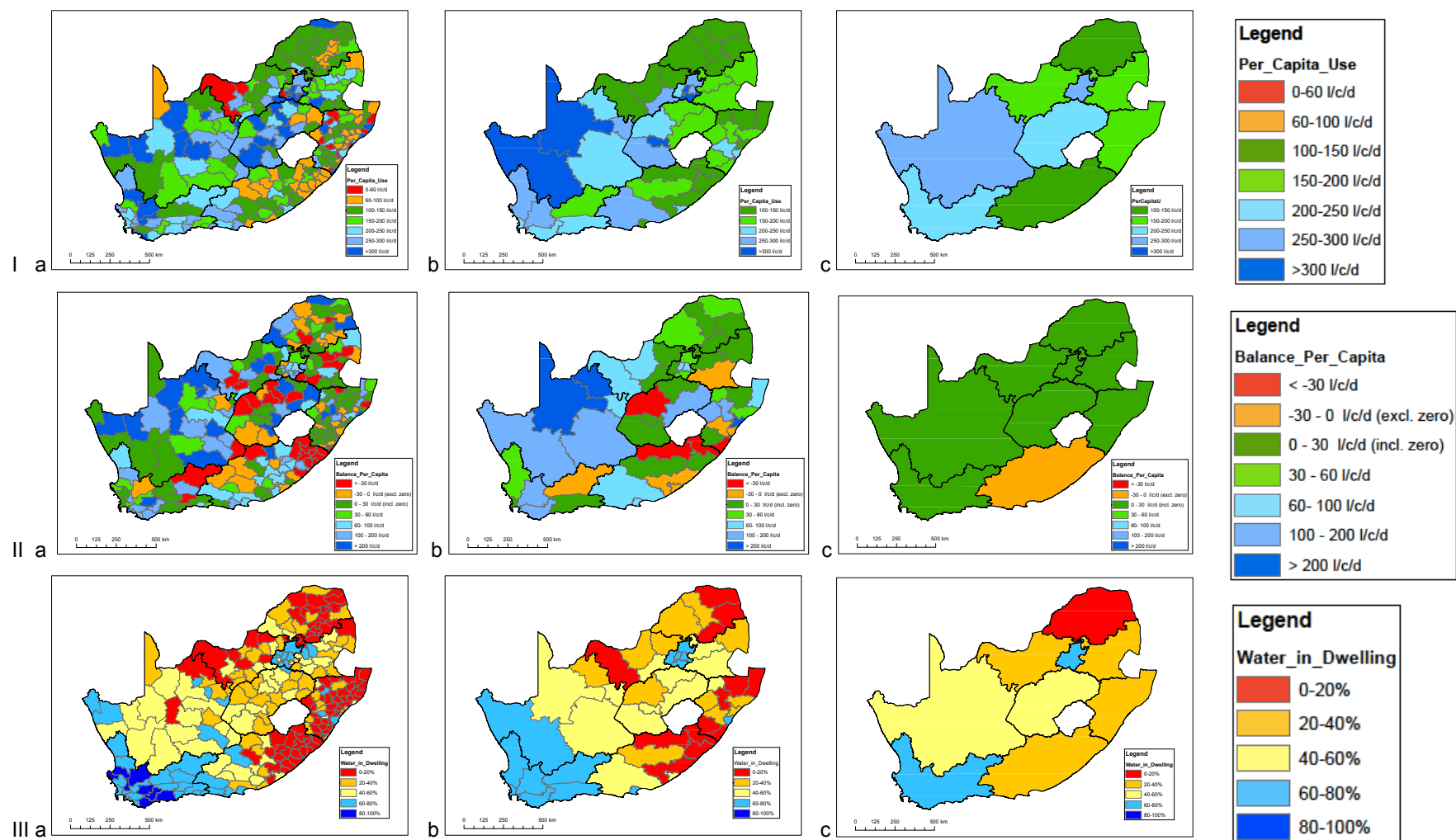


Figure 5.2 Municipal (a), district (b) and provincial (c) maps of I. per capita water use, II. town per capita water stress, and III. persons with piped water access in their dwelling.

Table 5.1 Summary of inequality in water access, use and stress in South Africa

	Access	Use	Stress
Indicator	People with piped water access in their dwelling (%)	Per capita water use (l/c/d)	Per capita water balance (l/c/d)
Weighted Mean	45	208	24
Minimum	0.07	8	-303
Maximum	100	2414	4949
Range	99.93	2406	5252
Standard deviation	33	182	402
Coefficient of variation	0.72	0.88	16.87
Gini index	0.36	0.27	
D1-D4 share (bottom 40%)	11.3%	20%	
D5-D8 share (middle 40%)	52.5%	46%	
D9-D10 share (top 20%)	36.2%	34%	
D10 share (top 10%)	19.3%	19%	
Palma ratio (D10/D1-D4)	1.71	0.95	

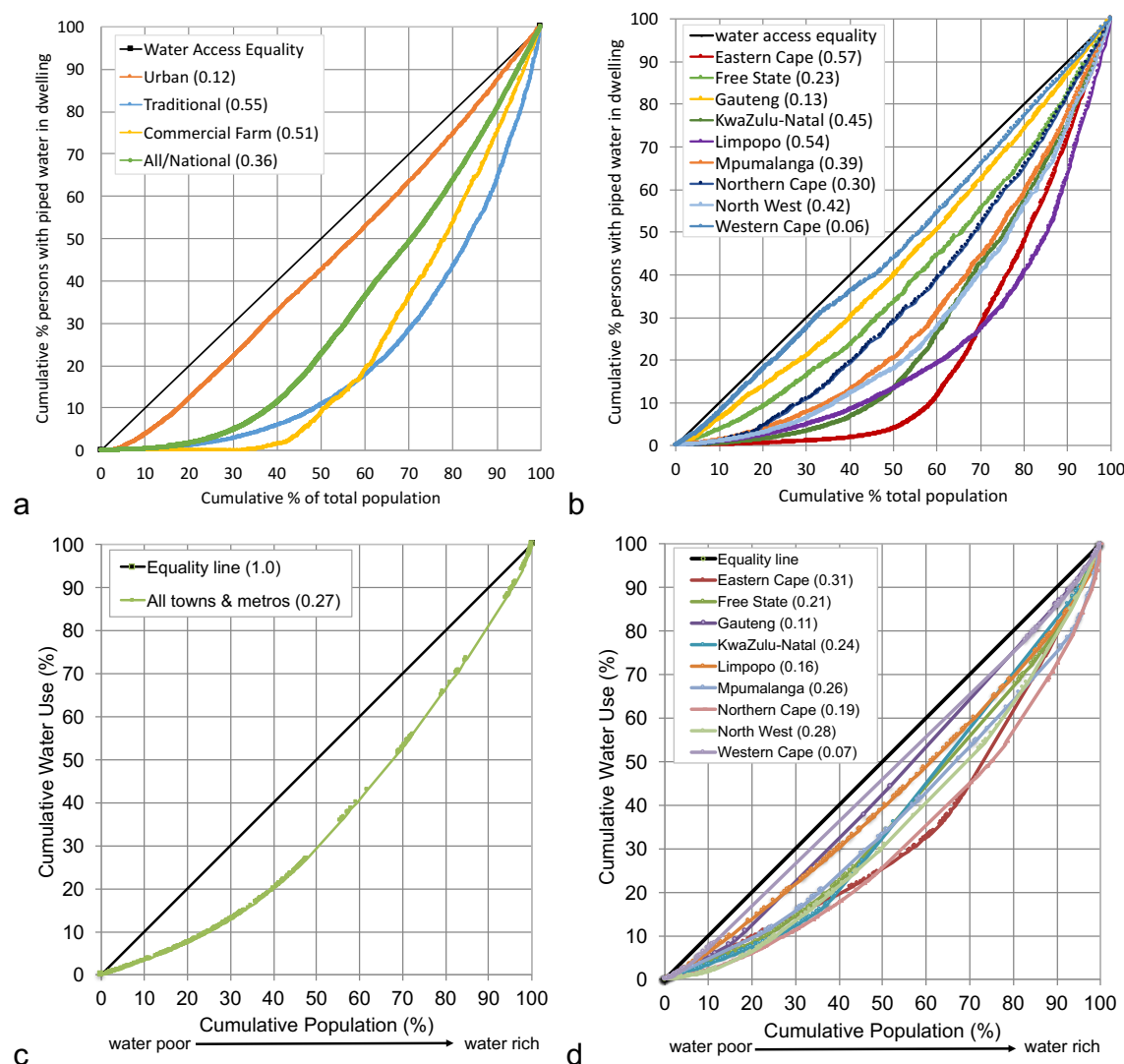


Figure 5.3 Lorenz curves for a) piped water access in dwellings in all, urban, traditional, and commercial farm areas, b) provincial piped water access in dwellings, c) per capita water use for all towns, villages and metros, and d) provincial per capita water use.

5.3.1 Piped water access

Although 45% of the national population has piped water access in their dwelling, this ranges from 0.07% in ward 19 in rural Umzimbuvu, Eastern Cape to 100% in the ward 9 in urban Midvaal and ward 19 in urban Merafong City, Gauteng. The wards with the lowest access (<2%) are almost all in traditional/tribal areas in the Eastern Cape and KwaZulu-Natal. There is a stark difference between urban, traditional/tribal and commercial farm areas, which make up 63%, 32% and 5% of

total population respectively. While 65% of urban dwellers have piped water in their dwelling, 34% of those living on farms and only 8% of those living in traditional/tribal areas have this level of access. Ninety per cent of people with piped water in their dwelling live in urban areas, indicating that the type of housing is not the main barrier to water access, but rather the geographic location. Across the provinces, piped water access in dwellings ranges from 18% in Limpopo to 78% in Gauteng (see SI Table S6). The national Gini index is 0.36 but varies across provinces, from 0.06 in the Western Cape (least unequal) to 0.57 in the Eastern Cape (most unequal), and across districts, from 0.05 in the Cape Winelands to 0.72 in O.R. Tambo.

Lack of service delivery in South Africa is largely due to logistics, cost and affordability, and national policy being to upgrade or replace informal settlements with formal settlements, which is a slow process. Major challenges to achieving universal service delivery are the growth in number of households (from 8.7 million in 1994 to 14.5 million in 2011) and internal migration between provinces and urban/rural areas (Nnadozie 2011). The government of South Africa aims to increase the percentage of households with access to 'a functional water service' to 90% by 2019. This is still a long way off from achieving piped water in all dwellings, the optimal type of water access for human development and health.

5.3.2 Per capita water use

Although the analysis shows that national per capita water use (including water losses) for towns is 208 l/c/d, this ranges from 8 l/c/d in rural Kokomeng, North West to 2,414 l/c/d in the mining town Aggeneys, Northern Cape. Across the

provinces, per capita water use ranges from 114 l/c/d in Limpopo to 295 l/c/d in the Northern Cape with a coefficient of variation of 0.29. The national Gini index is 0.27 but varies across provinces, from 0.07 in the Western Cape (least unequal) to 0.35 in the Northern Cape (most unequal).

Results showed that 75 towns and village clusters are at or below the government minimum threshold of 60 l/c/d. Of the 32 towns/clusters using less than 40 l/c/d, almost all of them rely solely on groundwater with relatively low borehole yields. At the opposite end of the spectrum, 28 towns use more than 500 l/c/d and seven towns use more than 1,000 l/c/d. Four of these are small mining towns in the Northern Cape - Aggeneys (2,414 l/c/d), Kleinsee (1,719 l/c/d), Hotazel (1,509 l/c/d), Kommagas (1,015 l/c/d) – and two are coastal holiday town clusters - Cape St Francis and St Francis (1,262 l/c/d) in the Eastern Cape and Betty's Bay, Rooi Els and Pringle Bay (1,196 l/c/d) in the Western Cape. The latter have high non-resident holiday populations that are not reflected in the per capita figures. There is greater variation in per capita use amongst the smaller populations (the smallest being 33 people in Cape Infanta) whereas there is an averaging effect for the larger towns and cities (the largest being 4,434,827 people in the City of Johannesburg) and therefore a smaller range. The metros and large towns should therefore be disaggregated to reveal a more accurate picture of the distribution within these areas. The range between municipalities is also significant, however, ranging from 29 l/c/d to 1,037 l/c/d.

The residential per capita use in 74 town reports in KwaZulu-Natal ranges from 50% to 100% of total demand, with an average of 80%. The town per capita end-

use (which excludes losses) for 278 town reports in the Western Cape and Eastern Cape ranges from 20% - 96% of total demand, with an average of 75%. The town per capita use figures are therefore overestimates of residential end-use, which would be the ideal inequality indicator. The large ranges in these figures mean that average residential percentages or losses cannot be applied to the other All Town Studies to assess residential end-use. This is an area for future research.

The scatter plots (SI Figures S5.5 and S5.6) show no correlation between water use and supply-related variables (e.g. rainfall) but some correlation (R-squared greater than 0.1) between water use and the demand-related variables (household size, piped water access, access to flush toilets, washing machine ownership, income and urban location). A stepwise regression (see SI, S5.5) shows that only three of these variables – income, access to flush toilets and ownership of a washing machine - should be included in the model. In this model, R-squared is 0.26 therefore it only explains 26% of the variation in per capita water use. Also, all three variables have imperfect collinearity i.e. they correlate with each other, so it is difficult to precisely estimate the individual effects of the variables. Although more than 20% correlation is considered good when predicting human behaviour (Van Zyl et al. 2008), the variables that could not be included due to lack of data (price, property size, physical losses, consumer knowledge) are clearly important ones. Comparing water use to income for only those households with piped water access in their dwellings produces a lower correlation therefore the level of access is more influential than the level of income.

These findings are supported by Howard and Bartram (2003) who showed that if off-site water (100-1,000 m away) was moved on-site, consumption would increase from 20 l/c/d to 50 l/c/d per day. The importance of income on water use has been recognised by the South African government through the introduction of a Free Basic Water allowance in 2001. It commits to supplying every household with 6,000 litres of water per month for free, which equates to 50 l/c/d for a household of four. It is not always easy to implement due to varying household sizes and means of access; in poor communities, the installation of pre-paid water meters for communal taps has in some cases forced people to drink from polluted rivers (Smith 2012). Another mechanism to address water poverty in South Africa is the Increasing Block Tariff structure for municipal water pricing, which charges below cost for low consumption and charges higher rates for higher consumption. However, Burger and Jansen (2014) found that the premium paid by the richest households is redistributed to middle income rather than poor households because of the lack of access, while the poor often purchase from water vendors or other households.

5.3.3 Town water stress

Although the analysis shows that national per capita water stress is 24 l/c/d per person, this ranges from a deficit of -303 l/c/d per person in Dullstroom, Mpumalanga to 4,949 l/c/d per person in Grootpan, North West. Over 16 million people living in 280 towns/village clusters had negative water balances in 2007/8. A further 18.5 million people in 148 towns/village clusters were within 10% of deficit and over 200 towns/village clusters were expected to experience a deficit by 2017/18. Of the metros, eThekweni and Nelson Mandela Bay, home to 4.6 million people, experienced water deficits. More than 70% of South Africa's population is

therefore in a vulnerable position with respect to water supply. Deficits do not necessarily mean the town experiences water shortages and water restrictions but can also mean that the town is using more water than it is allocated, which needs to be remedied. The per capita water stress highlights both first order water scarcity (physical water shortage) and second order water scarcity (lack of social adaptive capacity), common in rural towns and villages. For example, despite relatively high rainfall and runoff in the Eastern Cape, demand exceeds supply due to limited infrastructure because of low levels of economic activity or dysfunctional town water supply schemes (DWA 2011c).

Half of the settlements in deficit were located in sub-Water Management Areas with water deficits in 2000 (DWAF 2004), though it is not a direct comparison as the All Town Studies and WSS reports did not include non-town uses such as irrigation, or the ecological reserve. As the ecological reserve is implemented in the next decade, about a fifth of existing supply must be allocated to the environment and new supply sources must be developed to meet the growing demand required for socio-economic development. Sufficient water can be made available to meet future development needs, but at steeply increasing costs (Basson et al. 2010). The large number of towns with water stress is therefore likely to increase in the future.

5.3.4 Water indexes

The three indicators for water access, use and stress could be used in a water index. Several indexes have been developed in the past 20 years to assess water stress and water poverty, most notably Falkenmark's (1997) water stress index,

Gleick's (1996) water scarcity index, the Water Resources Vulnerability Index (Brown and Matlock 2011), Ohlsson's (2000) Social Water Stress/Scarcity Index, the Water Footprint (Hoekstra and Mekonnen 2011) and the Water Poverty Index (WPI) (Sullivan 2002). The WPI is a more holistic tool that measures progress in the water sector to identify those most in need at the community level. It has five components - water resources, water use, water access, human capacity and the environment – and multiple indicators. It has been adapted to create the Water Prosperity Index (Wilk and Jonsson 2013), the Water Needs Index (Moglia et al. 2012) and water poverty mapping (e.g. Cullis, 2005; van der Vyver and Jordaan, 2012). Using the three indicators in an existing or new water index is an area for further research.

5.3.5 Indicators for the SDGs

The three indicators could also be used as national indicators in the SDG 6 target 6.1 (achieve universal and equitable access to safe and affordable drinking water for all) and target 6.4 (substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity). It is likely that the South African government will use the official development indicator for piped water access (households with piped water within 200 m of the dwelling) for Target 6.1. However, using 'persons with piped water in the dwelling' better suits the ambition of the SDGs and is a better measure of inequality. We suggest that it is also used in SDG 6.1. Using persons rather than households produces a higher Gini index revealing greater, and more accurate inequality, and is therefore preferable. The target would not need to be 100% by

2030, as there are significant barriers to this in informal settlements and traditional/tribal areas. Perhaps 75% is reasonable as 34% of the population currently lives in traditional/tribal areas or informal settlements (StatsSA 2014). Plotting trends in this indicator would measure progress on service delivery to achieve sustainable development.

An ideal indicator for target 6.4 would be 'residential per capita water end use' (i.e. town use excluding water losses and other municipal uses). The national figure for South Africa would be roughly 113 l/c/d; the town average of 205 l/c/d minus 25% for physical water losses and 20% for non-residential use. To obtain an accurate figure, data would have to be obtained from local municipalities. The target could be a minimum of 60 l/c/d, the current government target or 100 l/c/d, recommended by the WHO. A maximum target could also be defined. The Rand Water Board, which manages the City of Johannesburg's water supply, put forward examples of 'inefficient' and 'efficient' residential end-user water use of 194 l/c/d and 71 l/c/d respectively as part of their Water Wise campaign (Rand Water 2016). Additional indicators for SDG 6.4 could include non-residential use to enable sectoral analysis, which is important for determining the socio-economic value of water which in turn guides water allocation decisions. This is an area for further research.

The range, standard deviation and coefficient of variation are useful figures for measuring variability in water access, use and stress. However, they are not generally used in the policy discourse. Most policy-makers are familiar with their Gini index for income inequality, making it a better choice. A Gini index of water access could be used in SDG 6.1 and a Gini index of water use could be used in

SDG 4. Adding the Lorenz curves and reporting by population decile provides further useful summary information and data visualisation, and both are easy to understand. The Palma ratio is still new and, although it is gaining traction, it remains to be seen whether it becomes a commonly used inequality measure and therefore whether it would be easy for decision-makers to relate to.

A Gini index could also be calculated for several other social dimensions in the SDGs such as electricity access, sanitation, housing etc. to ultimately provide a suite of Gini indices which would be more representative of a country's inequality than the income Gini alone. This would be similar to Borat *et al.*'s (2009) Gini for their non-income welfare index constructed using six public assets (dwelling, roof, wall material, electricity, water source, sanitation) and four private assets (telecommunications, radio, car, television). Reporting multiple measures of inequality (i.e. not only income) would help to gain a broader understanding of inequality in a country in the same way that multiple deprivation measures provide a better understanding of poverty.

The Gini indexes in this paper are quite low (0.36 for water access and 0.27 for water use) compared to the income Gini index of 0.65 for South Africa. This is because unlike income, which has no upper limit, piped water access cannot exceed access within a dwelling and water use also has practical limitations, although not as strict. This means that wealthy households can be recorded as the same as those who are much less well-off, and the inequality in their living conditions are not reflected in the Gini index for water access. In addition, for water use the metros and large towns are reported as single observations, and the

inequality remains hidden. For similar reasons, Bhorat *et al.*'s (2009) Gini index for non-income welfare in South Africa is 0.16. The Gini indexes may be most useful for comparing regions. In previous analyses of water use inequality in South Africa, Cullis and van Koppen (2008, 2007) calculated a Gini index of 0.96 in the Olifants WMA and values ranging from 0.78 to 0.92 for the nine provinces. Their figures were much higher because they included all agriculture and industry and equated them to a single household to compare them to rural households to highlight the inequality in water allocation. When measured a Gini index of water benefits by accounting for the jobs created by the water in industry and agriculture, the Gini dropped to 0.64 in the Olifants WMA. Extending the water use inequality analysis described here to measure the inequality in water allocation is an area for further research.

Geographic location is only one of many dimensions of data disaggregation that are part of the SDG global monitoring framework. The other dimensions (gender, age, race, ethnicity, migratory status, disability) have a geographical nature as the spatial distribution of, for example, gender equality, is important. The inequality measures tested in this paper could therefore be relevant across other dimensions of disaggregation.

Data collection is a significant challenge in tracking progress towards the SDGs. The results in this paper show that the scale of the data set used can have a large effect on the apparent levels of inequality (see Figure S5.4); using local level data to calculate inequality indexes is much better than provincial or district level data at exposing the inequalities. Local data supports local action to address water access,

use stress. The annual GHS, the main source of data between census years, only take a sample of the population and is therefore only representative at national and provincial level. These surveys are likely to form the basis for annual SDG reports in South Africa (and other countries) and if inequality measures are included, then it will be important to note the hidden inequalities. These are important points for data disaggregation and the SDGs. If national data are disaggregated to the first sub-national level (in this case provinces), only some of the finer scale inequality will be revealed.

The two data sets used in this study are not annually updated - the Census is undertaken once every 10 years and the All Town Studies are only being updated for the towns facing water shortages. However, these could be used as the baseline data while other sources could be used to create an up-to-date dynamic national database. Administrative data collected as piped water is provided to new households could be used to update the figure on access to piped water in dwellings, while satellite imagery could be used for more accurately determining households with communal taps or taps in their yard. Smart meters would improve water use reporting and crowd-sourced citizen reporting could identify areas of water stress. The 'data revolution for sustainable development' that has been prompted by the SDGs, is a vibrant new field of research and is likely to produce several innovative approaches for collecting local level data necessary for effective policy- and decision-making.

5.4 Conclusion

This paper has explored the variability in water access, water use and water stress at multiple spatial levels in South Africa. The results showed that while 45% of the

national population has piped water access in their dwellings, this ranges from 0.07% to 100% across wards. Nationally, the average town per capita water use is 208 l/c/d but it ranges from 8 l/c/d to 2,414 l/c/d across towns. Similarly, the average town per capita water stress is 24 l/c/d but ranges from -303 l/c/d to 4,949 l/c/d across towns. This makes it clear that measuring the sub-national inequality is as important, if not more so, than measuring the national average. This can be done with a Gini index of water access and a Gini index of water use, which are 0.36 and 0.27 for South Africa, respectively. The Gini index can be calculated for provinces and districts and used to compare sub-national inequalities in water access and use. The maps, indicators and inequality measures presented in this paper provide monitoring and communication tools that could be used for the SDGs and for geographical targeting for more effective decision-making.

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5.6 References

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Supplementary Information for Chapter 5

S5.1 Administrative levels and water management scales

Table S5.1 lists the administrative levels in South Africa together with their population in 2011 and area, and compares it to the water resource management levels and areas.

Table S5.1 Hierarchy of government and water management scales in South Africa

Water Services			Water Resources	
Administrative Levels	Population in 2011	Area (km ²)	Management Levels	Area (km ²)
National	51,770,560	1,220,813	National	1,220,813
Province (9)	1,145,861 to 12,272,263	18,178 to 372,889	Water Management Areas (9)	12,880 to 234,770
District (52)	71,011 to 4,434,827	1,645 to 126,836	Sub Water Management Areas (86)	1,500 to 104,000
Municipality (234)	7,003 to 4,434,827	252 to 36,128	Quaternary catchments (1,855)	48 to 18,128
Ward (4,277)	360 to 91,717	0.15 to 29,838		

Notes: The number of administrative or management units and are given in brackets. The ward boundaries used in the 2011 Census were defined in 2010. Eight metropolitan areas are classified as both districts and municipalities. Data sources: Census 2011 (StatsSA 2012b; StatsSA 2014) and GIS shapefiles (DWA 2012)

S5.2 Per capita water use requirements

The water requirements of communities and towns vary significantly throughout the study area, depending upon factors such as the climatic conditions, level of service, socio-economic situation, wet industries, institutional capacity and consumer

behaviour (DWA, 2011f, 2011g). Due to the lack of available municipal data on actual water use, the water requirements had to be estimated for many of the metro and town studies. In some cases, these estimates will be too low due to excessive per capita consumption and in other cases these estimates will be too high due to excessive water losses or lack of basic water infrastructure to supply the minimum requirements. There are guidelines on what constitutes an acceptable level of water consumption. The minimum domestic water requirement according to the World Health Organisation (WHO) is 25 litres per capita per day (l/c/d), which equals the accepted norm for free basic water of 6 kl/month for a household of eight. The Department of Water and Sanitation (DWS) recommendation and target for low-income housing is 60 l/c/d for planning purposes, while the water requirements in more affluent, developed towns can increase to 250 l/c/d and even further to above 400 l/c/d in holiday towns due to the seasonal influx of visitors. The data on actual water consumption needs to be improved with good metering programmes. Despite this, these are comprehensive studies and the best current estimates of water use in South Africa.

As different lead consultants undertook the work on the four planning regions, slightly different approaches were used for calculating the water requirements. For the Southern Planning region, which includes the Western Cape and Eastern Cape, the figures shown in Table S5.2 were used. WRP Consulting Engineers who prepared the reports for the Central Region, which includes the North West, Northern Cape and the Free State, based the water requirements calculation on the water use categories as developed by the DWA: Water Resource Planning Systems but updated them using the 2001 Census, 2007 Community Survey and

the Water Services National Information System (WSNIS) databases to make them more relevant, as shown in Table S5.3. Historical water use profiles were consulted and updated based on obtained actual water use and the revised water use categories.

Table S5.2 DWA per capita water requirements for residential land-use (DWA, 2011f, 2011g) based on the Red Book (CSIR, 2000) used by Umvoto for the Southern Planning Region (Western Cape and Eastern Cape)

Category of Settlement	Requirement in litres per capita per day
Medium size towns	150-200
Small towns (including animals and small gardens)	200-250
Coastal towns (permanent residents)	200-250
Coastal towns (seasonal visitors)	80-130
Rural villages	60-100
Farm villages (including animals and gardens)	100-150

Table S5.3 Per capita water use requirements based on DWA Water Resource Planning Systems and updated using 2001 Census, 2007 Community Survey and the Water Services National Information System, used by WRP for the Central Planning Region (North West, Northern Cape and Free State) e.g. (DWA, 2011c)

Category	Dwelling Type	Requirement in litres per capita per day
1	Flats	226
2	Clusters	255
3	Single residential: Low income	101
4	Single residential: Medium income	189
5	Single residential: High income	304
6	Single residential: Very high income	442
7	Informal: RDP level	40
8	Informal: No services	12

SRK Consulting prepared the reports for the Northern Region, which includes Limpopo, Gauteng and part of Mpumalanga, but do not explain their method in the reports. They say that ‘the current level of water consumption was used to calculate the future water requirements’ specifying per capita use for dwellings with house connections, dwellings with yard connections and for the dwellings supplied at or below RDP level.

Water for Africa prepared the reports for the Eastern Region, which includes KwaZulu-Natal and part of Mpumalanga. They estimated current water requirements based on historical consumption and on the information provided in the relevant Water Services Development Plans, which include a socio-economic assessment, water service infrastructure, water abstraction, water losses, wet industries and consumer units for sanitation.

The Amatole Water Supply System reconciliation strategy study (DWAF, 2011) prepared by SSI Engineers and Environmental Consultants uses slightly different consumption figures applicable to the socio-economic categories to calculate the domestic water requirements shown in Table S5.4 below, which correspond well with the consumption figures adopted by Buffalo City Municipality, albeit by means of a different characterisation. The figures include institutional, tourism and commercial water requirements. A minimum requirement of 120 l/c/d was adopted for waterborne sanitation for the upper water requirement scenario, rather than the current mix of wet and dry sanitation, which was used for the low water requirement scenario. As logistics, cost and affordability dictate against the traditional settlements being provided with waterborne sanitation, while national policy is to

upgrade or replace informal settlements with formal settlements during the planning horizon of this strategy, the intermediate scenario was taken as all households, other than traditional ones, having waterborne sanitation.

Table S5.4 Socio-economic categories used in Amatole WSS

Socio-economic categories		Water requirement in litres per capita per day
1	Upper income	320
2	Middle income	200
3	Lower income formal	120
4	Lower income informal	25
5	Traditional including allowance for limited gardening and livestock watering	60

For the Vaal and KwaZulu-Natal systems, the per capita requirements for the residential areas were based on seven housing categories defined in a report by DWAF in 2001, titled “The Distribution of South Africa’s Population, Economy and Water Usage into the Long Term Future”, shown in Table S5.5 (DWAF, 2007, 2008). Non-residential land-use includes business/commercial, industrial, hospitals, parks, education and sport stadiums and each different land-use has different water requirements, given in Table S5.6.

Table S5.5 Housing category definitions and default per capita water usage from the National Water Resource Strategy and used in the Vaal System, KZN, metro studies

Housing category	Description	Default per capita usage in litres/capita/day
Category 1	Fully serviced houses on large erven (>500m ²)	320
Category 2	Fully serviced flats, townhouse or cluster homes	320
Category 3	Fully serviced houses on small erven (<500m ²)	160
Category 4	Small houses, RDP type houses and shanties with water connection, but no or minimal sewage service	90
Category 5	Informal houses serviced only by communal taps and no waterborne sewage	10
Category 6	No service from any water distribution system	6
Category 7	Other/miscellaneous (includes hostels, military camps etc)	90

Table S5.6 Non-residential land-use water requirements in Vaal System

Land use category	Unit	Requirements per unit (litres per unit per day)
Business/commercial	m ²	4
Industrial	m ²	4.8
Hospitals	bed	260
Parks	m ²	2
Educational	pupil	20
Sport stadiums	seat	21

To understand the extremely high per capita use figures for some towns, we examined the seven towns/clusters with per capita uses exceeding 1,000 l/c/d. Our analysis shows that the top three - Aggeneys (2,414 l/c/d), Kleinsee (1,719 l/c/d), Hotazel (1,509 l/c/d) - are mining towns in semi-desert regions in the Northern Cape with water sourced from the Orange River or the Vaal River (DWA, 2011a, 2011b, 2011c). Their benchmark per capita figures (based on demographic profile) are

322, 309 and 260 l/c/d respectively and their populations are 4,299, 2,754 and 729 people respectively. None of them have supply constraints except through local infrastructure as they are such small users in very large water supply systems. The fourth town is Gariep (1,324 l/c/d) in the Free State. It also has a very small population (1,325 people) and is a negligible user in a larger supply system (Gariep Dam). The per capita figure includes water used by a fish hatchery (DWA, 2011e) which is probably the main reason it is so high. The fifth cluster is the two towns Cape St Francis and St Francis (1,262 l/c/d) which are coastal resorts in the Eastern Cape. Their population increases four times (from 2,800 to 11,200) during holiday seasons, which is probably the reason for the high average figure – if holiday makers were included it would drop to 316 l/c/d. The sixth town cluster is Betty's Bay, Rooi Els and Pringle Bay (1,196 l/c/d) which are coastal holiday towns in the Western Cape with a combined population of 2,786 (DWA, 2010). The seventh town cluster is Kommagas (1,015 l/c/d) located in a semi-arid copper mining area in the Northern Cape and receives its water from boreholes. It has a small population of 3,761 and a benchmark use of 188 l/c/d based on its demographic profile (DWA, 2011d).

S5.3 Datasets, ward map and distribution plots

Table S5.6 and S5.7 show the provincial data. Figure S1 shows piped water access in dwellings by ward. The data tables for districts, municipalities, towns and wards are available in an Excel spreadsheet.

Table S5.7 Piped water access in the provinces

Province	Number of wards	Piped water in dwelling (%)	Gini index	Palma ratio
Eastern Cape	715	30.1	0.57	15.91
Free State	317	45.1	0.23	0.76
Gauteng	508	65.5	0.13	0.44
KwaZulu-Natal	828	36.4	0.45	3.74
Limpopo	543	17.8	0.54	4.42
Mpumalanga	402	35.8	0.39	1.76
North West	383	29.1	0.42	2.08
Northern Cape	194	46.8	0.30	0.95
Western Cape	387	77.8	0.06	0.32

Table S8. Per capita water use and stress for all town/village clusters/metros in the provinces

Province	Number of towns*	Per capita water use (l/c/d)	Gini index	Palma ratio	Per capita water balance (l/c/d)
Eastern Cape	136	30.1	0.31	1.05	-5
Free State	71	45.1	0.21	0.85	36
Gauteng	16	65.5	0.11	0.42	13
KwaZulu-Natal	80	36.4	0.24	0.63	36
Limpopo	142	17.8	0.16	0.63	23
Mpumalanga	63	35.8	0.26	1.09	11
North West	97	29.1	0.28	1.08	45
Northern Cape	90	46.8	0.19	1.47	146
Western Cape	142	77.8	0.07	0.39	38

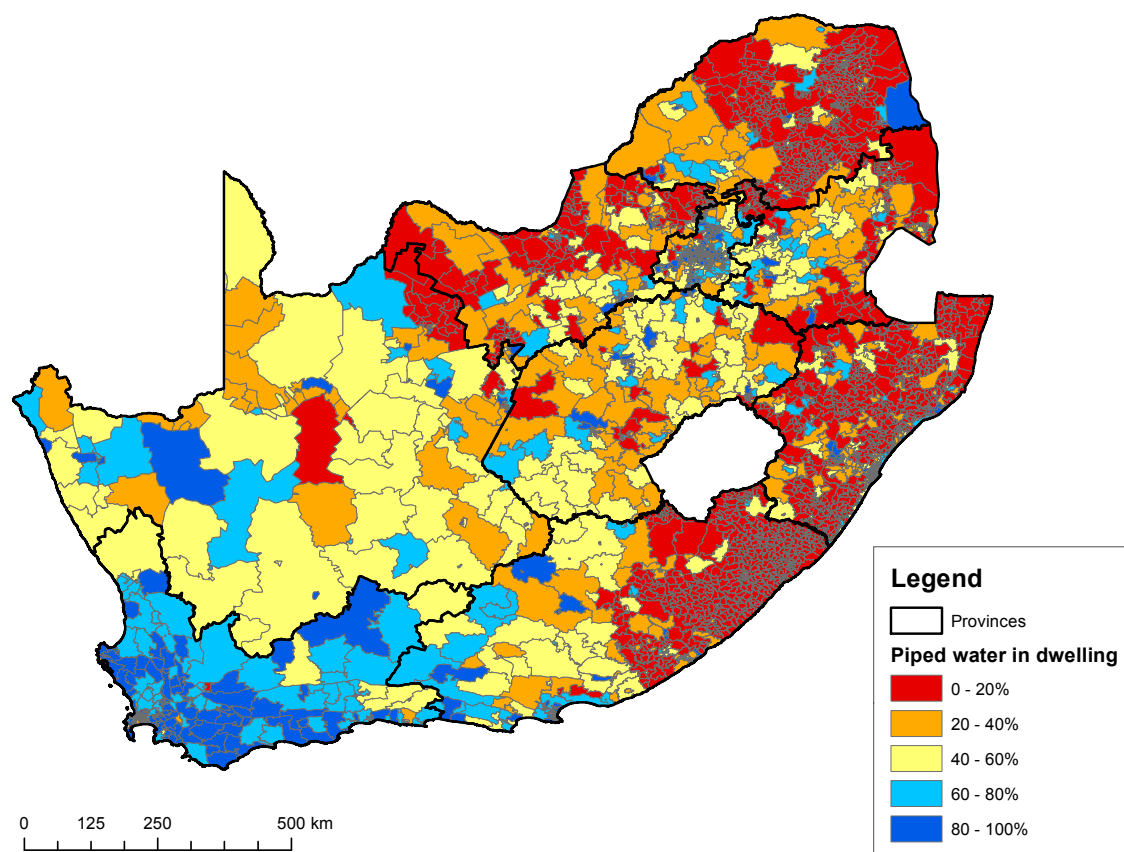


Figure S5.1 Ward map of persons with piped water in dwellings in 2011 in South Africa

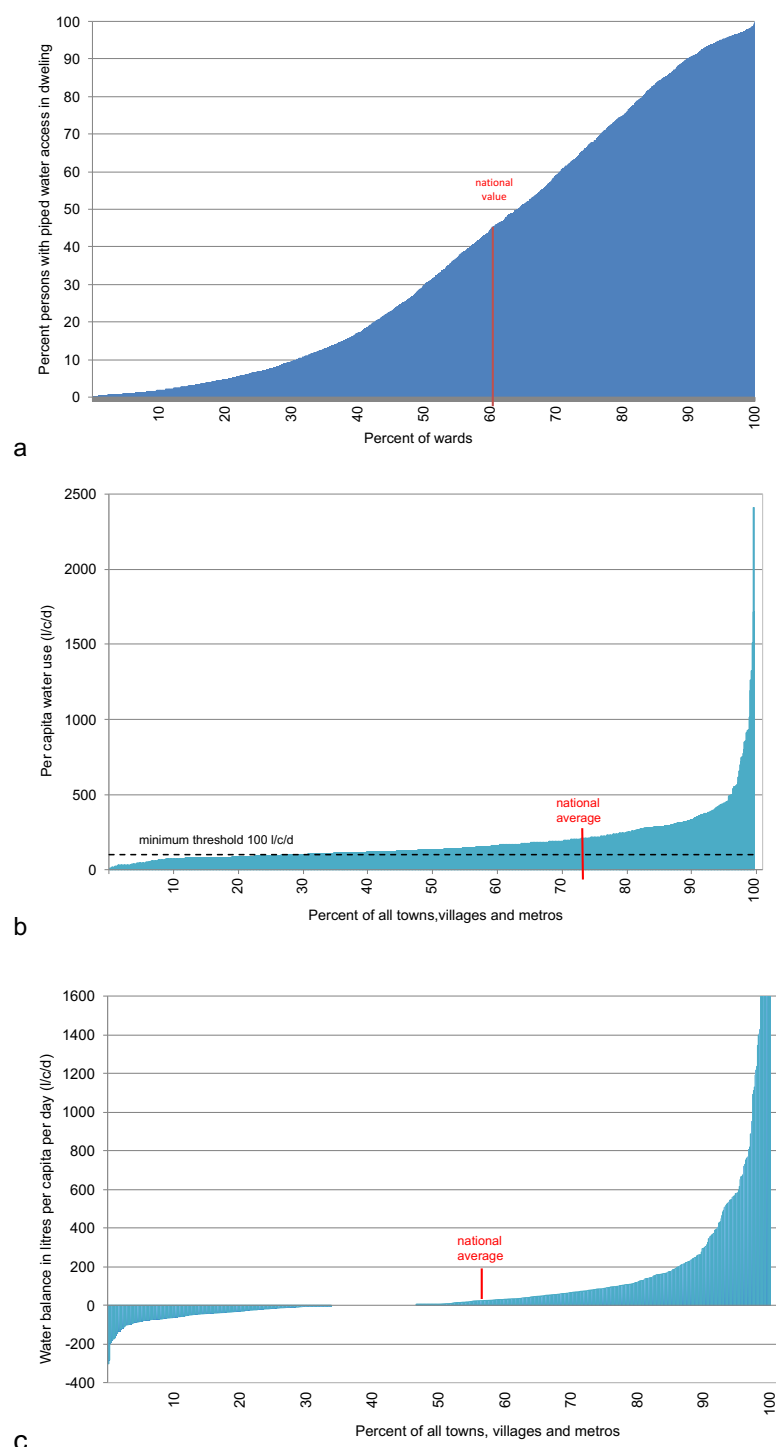


Figure S5.2 Distribution of a) persons piped water access in dwellings for all wards in 2011, b) per capita water use for all towns and villages in 2007/8 and metros, and c) per capita water balance for all towns and villages in 2007/8 and metros in 2011.

Note: 12 towns have per capita balance greater than 1600 l/c/d.

S5.4 Calculation of Gini index and Palma ratio

The Gini index normally measures the extent to which the distribution of income among individuals or households within an economy deviates from a perfectly equal distribution. A Lorenz curve plots the cumulative percentages of total income received against the cumulative number of recipients, ordered from the poorest individual or household to the richest. The Gini index is measured as the ratio of the area between the Lorenz curve and a hypothetical straight line of equality, and the total area under the line. Thus a Gini index of zero represents perfect equality, while an index of 100 implies perfect inequality (World Bank, 2016).

To calculate a Gini index for household piped water access, we listed all the wards with their number of persons with piped water access and population and calculated their respective proportions of the total persons with piped water access and total population. We then sorted the list by number of persons with piped water access (ordered from least to greatest) and plotted a Lorenz curve (Figure 5.4a). We calculated the area between the Lorenz curve and the equality line and divided it by the area under the equality line to determine the Gini index. We repeated this process using municipalities, districts and provinces (see Figure 5.4b).

To calculate a national Gini index for water use, we listed all the towns with their water use, population and per capita water use. We sorted the list by per capita water use, ordered from least to greatest. We calculated the respective proportions of the total water use and total population and calculated the cumulative distribution of water use and population plotted a Lorenz curve (Figure 5.4c). We calculated the area between the Lorenz curve and the equality line and divided it by the area

under the equality line to determine the Gini index. We repeated this process using municipalities, districts and provinces (see Figure 5.4d).

The Palma index is calculated using the data generated for the Gini index analysis shown in Table S5.8.

Table S5.8 Calculation of Palma ratio for water use and piped water access

Decile	Water use (%)	Cumulative use (%)	Piped Water Access (%)	Cumulative Access (%)
D1	3.3	19.9	0.3	11.3
D2	4.0		1.3	
D3	5.5		3.2	
D4	7.1		6.5	
D5	10.1	46.1	11.4	52.5
D6	11.0		13.6	
D7	11.0		12.8	
D8	14.0		14.7	
D9	15.0	34.0	16.9	36.2
D10	19.0		19.3	
Palma		0.95		1.71

Note: The deciles represent 10% of the population. Palma index = $D1/(D1+D2+D3+D4)$.

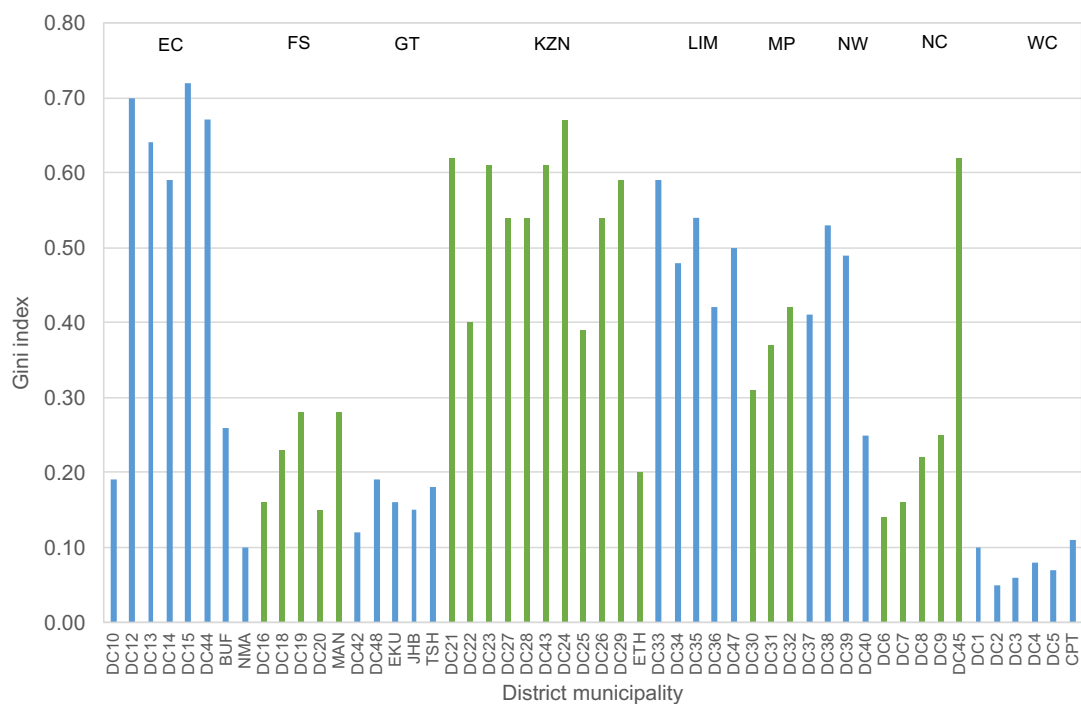


Figure S5.3 The Gini index of piped water in dwellings for all district municipalities using 2011 ward data

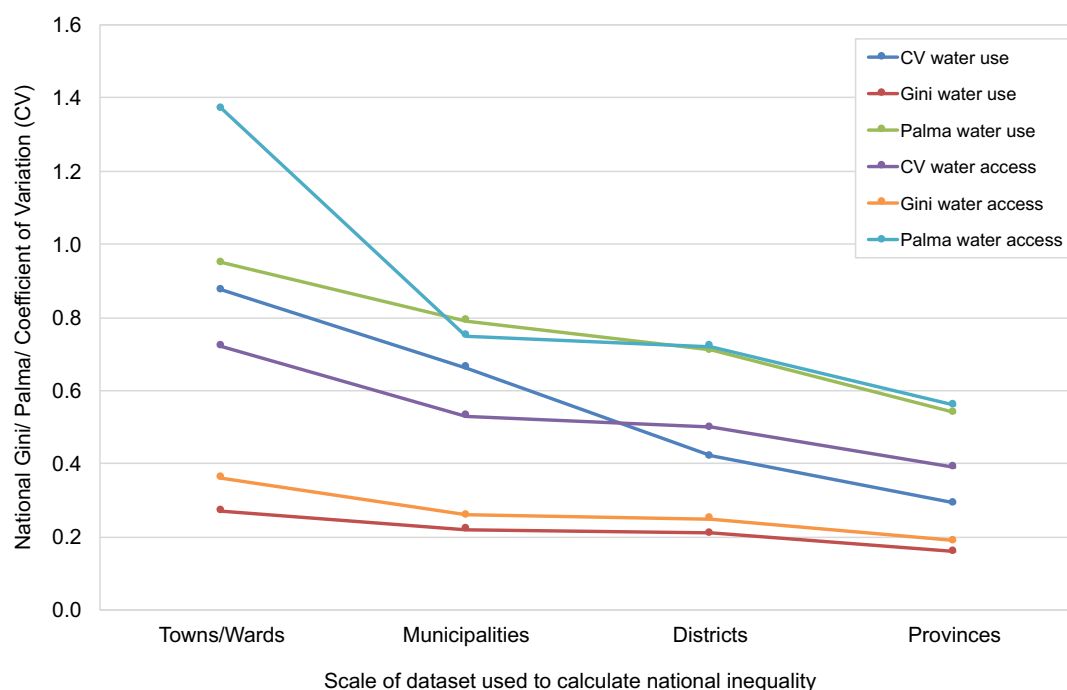


Figure S5.4 The effect of the scale of the dataset used to calculate four inequality measures (standard deviation, coefficient of variation, Gini index, Palma ratio) for persons piped water access in dwellings and per capita water use.

S5.5 Correlation and regression analysis

The analysis of the variation in town/municipal per capita water use across South Africa produced some surprising results and a range from 8 l/c/d to 2,414 l/c/d. The aim of this regression analysis is to identify the main underlying causes of this variation. An assessment of the extreme ends of the spectrum of town per capita use figures identified some important factors – the top seven have small populations and either have access to very large supply (despite being in semi-arid areas) or have a large holiday population (coastal towns), while the bottom 30 were entirely dependent on groundwater. The ‘typical’ household water end-use for South Africa is: drinking 3%, toilets 29% (4-15 litres per flush), bathing/ showering 20%, laundry 13% (50 litres per wash), gardening 35%.

The following independent variables were considered, with scatter plots shown in Figure S5.5 and Figure S5.6:

Factors with little (<10%) or no correlation

- mean annual precipitation (MAP) of quaternary catchment ($R^2=0.0065$)
- mean annual evaporation (MAE) of quaternary catchment ($R^2=0.001$)
- mean annual runoff (MAR) of quaternary catchment ($R^2=0.001$)
- water balance i.e. demand/supply ($R^2=0.016$)
- percentage of groundwater in total supply ($R^2=0.045$)
- natural household main water source river/stream/dam ($R^2=0.03$)
- formal housing ($R^2=0.07$)
- population ($R^2=0.0015$)
- total water requirement ($R^2=0.036$) – excluding metros
- total water yield ($R^2=0.036$) – excluding metros

- coastal vs inland location (binary)

Factors with correlation

- household size ($R^2=0.11$) - larger households use less due to poverty
- persons piped water access in dwelling ($R^2=0.22$)
- flush toilet as main type of toilet facility used by household ($R^2=0.24$)
- household owns a washing machine ($R^2=0.20$)
- percentage households in low income bracket (<R19,601 per year)
($R^2=0.22$)
- urban area ($R^2=0.18$)

Factors with not enough available data

- price of domestic water (varies across municipalities)
- property size (varies by household)
- consumer knowledge of consumption (salience in behavioural economics)
- physical losses (unaccounted for water is available but this combines
illegal connections and non-payment as well as leaks in bulk water supply)
- household agricultural activities (data collected in Census 2011 but not
available online)

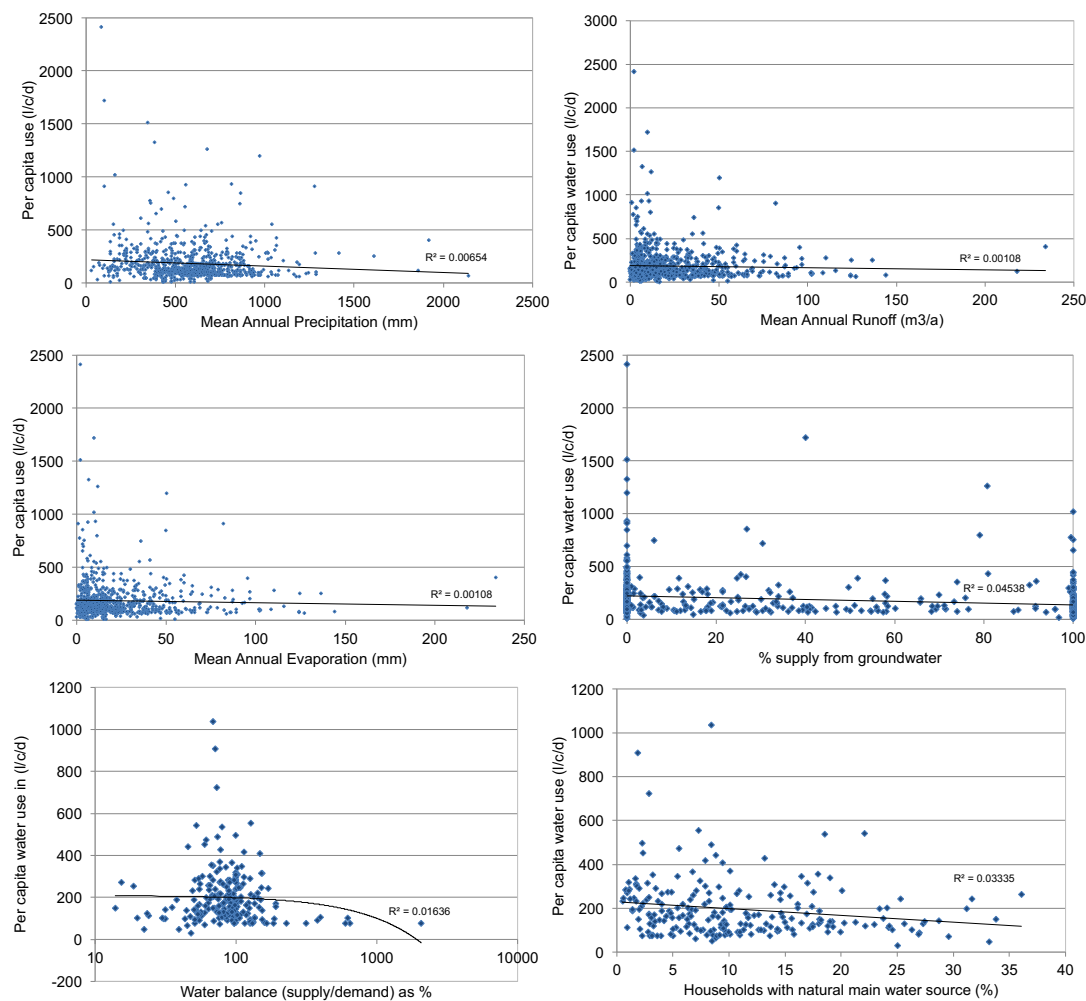


Figure S5.5 Supply-related variables and per capita water use

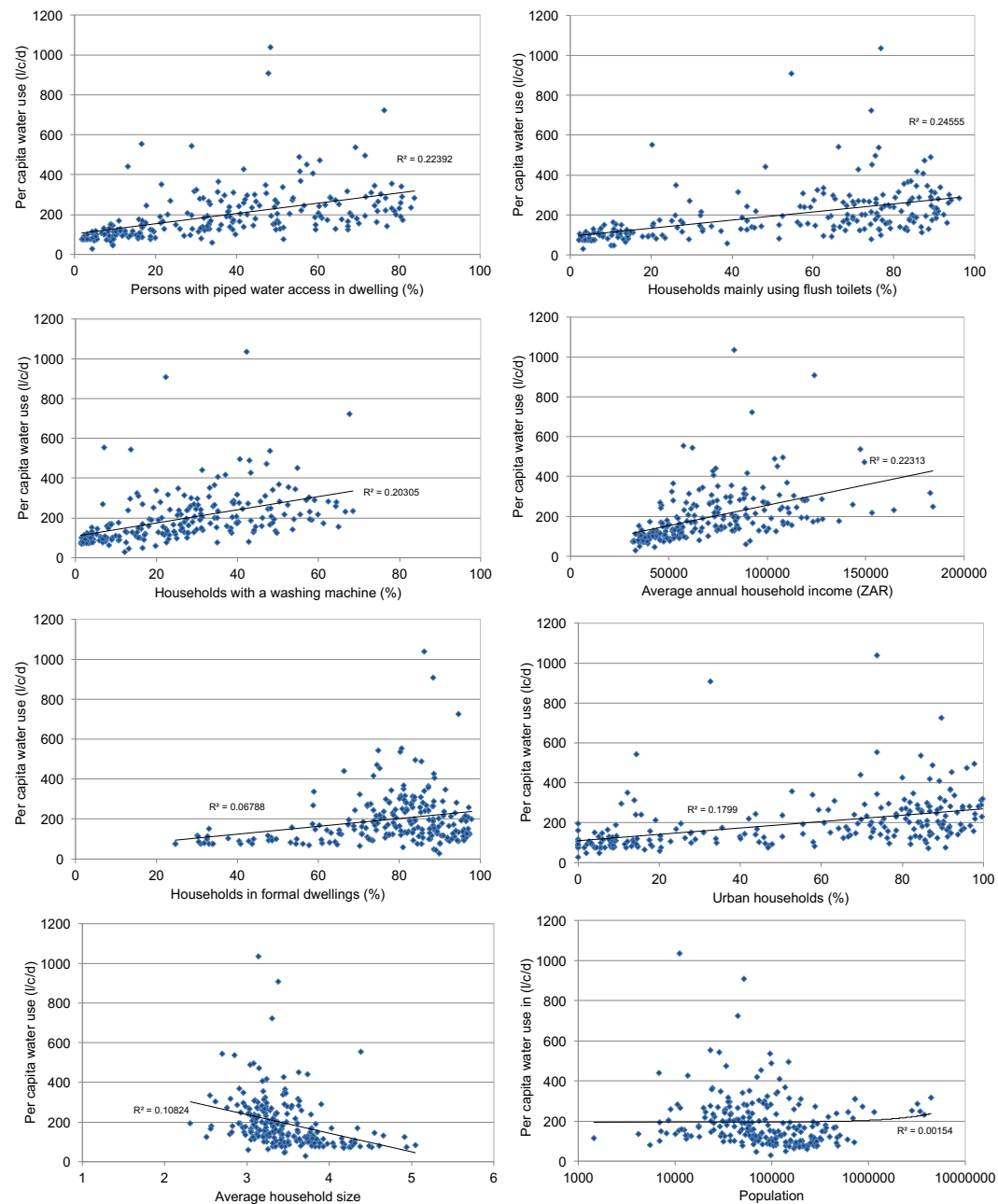


Figure S5.6 Demand-related variables and per capita water use

The six variables with correlation were used in the regression which was performed at the local municipality scale (225 observations – 9 municipalities have no per capita use data) with the dependent variable being municipal per capita water use (town data from 2007/8 All Town Studies and metro data from 2011 reconciliation strategies). It is important to note that the data set relies on estimates (rather than measurements) of per capita water use in most rural and informal settings. The

data set includes residential and non-residential water use and unaccounted for water, which includes physical water losses. Imperfect multicollinearity exists between the six independent variables ranging from a R^2 of 0.84 to 0.49.

We ran several single regressions with the six variables followed by a stepwise regression. To summarise, we show the results of the stepwise regression below.

Start: AIC=2135.29

PerCapUse ~ FlushToilet + LowIncome + PipedWater + WashingMachine + Urban + AvHHSIZE

	Df	Sum of Sq	RSS	AIC
- Urban	1	66	2797043	2133.3
- PipedWater	1	1330	2798307	2133.4
- AvHHSIZE	1	3423	2800400	2133.6
- WashingMachine	1	3825	2800802	2133.6
<none>			2796977	2135.3
- FlushToilet	1	38446	2835423	2136.4
- LowIncome	1	65226	2862203	2138.5

Step: AIC=2133.29

PerCapUse ~ FlushToilet + LowIncome + PipedWater + WashingMachine + AvHHSIZE

	Df	Sum of Sq	RSS	AIC
- PipedWater	1	1438	2798481	2131.4
- AvHHSIZE	1	3372	2800415	2131.6
- WashingMachine	1	3766	2800810	2131.6
<none>			2797043	2133.3
+ Urban	1	66	2796977	2135.3
- LowIncome	1	65182	2862225	2136.5
- FlushToilet	1	67897	2864940	2136.7

Step: AIC=2131.41

PerCapUse ~ FlushToilet + LowIncome + WashingMachine + AvHHSIZE

	Df	Sum of Sq	RSS	AIC
- AvHHSIZE	1	3348	2801829	2129.7
- WashingMachine	1	7480	2805961	2130.0
<none>			2798481	2131.4
+ PipedWater	1	1438	2797043	2133.3
+ Urban	1	174	2798307	2133.4
- LowIncome	1	66310	2864791	2134.7
- FlushToilet	1	79680	2878161	2135.7

Step: AIC=2129.68

PerCapUse ~ FlushToilet + LowIncome + WashingMachine

	Df	Sum of Sq	RSS	AIC
- WashingMachine	1	6862	2808691	2128.2
<none>			2801829	2129.7
+ AvHHSIZE	1	3348	2798481	2131.4
+ PipedWater	1	1414	2800415	2131.6
+ Urban	1	79	2801750	2131.7
- LowIncome	1	64830	2866659	2132.8
- FlushToilet	1	108500	2910329	2136.2

Step: AIC=2128.23

PerCapUse ~ FlushToilet + LowIncome

	Df	Sum of Sq	RSS	AIC
<none>			2808691	2128.2
+ WashingMachine	1	6862	2801829	2129.7
+ PipedWater	1	4895	2803795	2129.8
+ AvHHSize	1	2730	2805961	2130.0
+ Urban	1	45	2808646	2130.2
- LowIncome	1	73310	2882001	2132.0
- FlushToilet	1	104124	2912814	2134.4

The stepwise regression shows that of the six variables, only three – income, flush toilets and ownership of a washing machine should be included in the model. In this model, the R^2 is 0.26 therefore it only explains 26% of the variation on the data and most of the variation comes from factors that we do not have data for. Also, all three variables have imperfect collinearity i.e. they correlate with each other, so it is difficult to precisely estimate the individual effects of the variables.

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Linking statement – Chapter 5 to 6

In the previous chapter (5) the effects of scale and hidden inequalities in SDIs were explored through a case study on piped water access, per capita water use and water stress across South Africa. As these three indicators provide only a part of the picture on water and sustainable development, this chapter (6) broadens the water picture by assessing SDIs for all aspects of water included in SDG 6 'Water and sanitation for all', namely water access, sanitation, water quality, water-use efficiency and sustainability, water resource management, and water-related ecosystems. The Berg Water Management Area (WMA), in the south-western corner of South Africa, is used as a case study to test the indicators. As data on water-use efficiency is scarce, jobs and income per unit of water are analysed for heavily water-dependent sectors at the municipal level. The inequalities in the social benefits of water allocation are thus analysed and new water indicators are proposed. The study draws on research from all three previous chapters, using national indicators and boundaries and new measures of inequality to propose SDG 6 indicators and targets.

This chapter addresses question Q4, 'How can the inequality in sustainable development outcomes related to water allocation be reported? The suite of 26 proposed SDG 6 indicators is populated with existing town, municipal and WMA scale data for the Berg WMA, and with estimated jobs and income for the heavily water-dependent sectors of agriculture, agriprocessing, aquaculture and mining. The analysis exposes large gaps in the data on water-use efficiency and this,

together with establishing standardised methodologies for measuring water inequality, are proposed key research areas for SDG 6.

This paper was submitted to the journal *South African Journal of Science* in April 2017:

Cole, M.J., Bailey, R.M, Cullis, J.D.S and New, M.G. Developing a suite of SDG 6 water indicators: a case study of the Berg Water Management Area in South Africa

The lead author co-designed the research with RMB, JDSC and MGN, performed the research and wrote the paper. RMB, JDSC and MGN reviewed and edited the paper.

Since the submission of this thesis, the paper has been revised to address reviewer comments.

Chapter 6 – Developing a suite of SDG 6 water indicators for South Africa: a case study of the Berg Water Management Area

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Abstract

For progress towards the United Nations Sustainable Development Goals (SDGs) to be monitored, countries must develop their own set of national indicators for all 17 goals and 169 targets. Water is a fundamental enabler of development and SDG 6, ‘Water and sanitation for all’, is therefore an important goal to measure and achieve, especially in water scarce developing countries. Appropriate indicators can support decision-making and highlight key issues on inequality, unemployment and sustainability. In this paper, a comprehensive suite of 26 indicators for SDG 6 is proposed for South Africa based on existing national indicators, and additional research on water inequality and water-dependent jobs and income. The Berg

Water Management Area in the south-west corner of South Africa is used as a case study to illustrate the results. Figures for jobs and income per cubic metre of water use are calculated for agriculture, agriprocessing, aquaculture and mining, the most comprehensive figures to date for the area. Gaps in the data are identified and methodologies and standards that require development are highlighted. The approaches to measuring inequality and socio-economic benefits of water use are relevant for other countries seeking to measure the role of water plays in achieving inclusive sustainable development.

Key words: water, SDGs, indicators, water-dependent jobs, South Africa, Berg WMA

6.1 Introduction

Since the approval of 'Agenda 2030 for Sustainable Development' and its Sustainable Development Goals (SDGs) by the United Nations (UN) General Assembly in September 2015 (1), countries around the world have started work on their own national set of SDG indicators. The SDGs build upon the Millennium Development Goals (MDGs) but have a much broader vision, seeking to end poverty and hunger, protect the planet from degradation, ensure prosperity for all, and foster peaceful, just and inclusive societies (1). While the MDGs had an official set of 60 indicators across 21 targets and eight goals (2), the SDGs have 241 global indicators across 169 targets and 17 goals (3). In addition to this very large indicator list, the SDGs require data disaggregation by 'income, gender, age, race, ethnicity, migratory status, disability, geographic location and other characteristics relevant in national contexts' (target 18 of Goal 17, Partnerships for the goals). The task of

developing national indicators and monitoring them over time is therefore significantly greater and more complex.

Water is a fundamental enabler of sustainable development and economic growth, essential for food security, health and sanitation, and a basic human right (4). Water resources are under pressure due to population growth, water-intensive growth, pollution and a changing climate (5). According to the International Food Policy Research Institute (IFRPI), under a business-as-usual scenario, 45% of global Gross Domestic Product (GDP), 52% of the world's population and 40% of grain production could be at risk due to water stress by 2050 (6). The UN World Water Development Report 2016 (6), estimated that 1.35 billion jobs are heavily water-dependent while 1.15 billion jobs are moderately water-dependent; thus 78% of the global workforce depends on water for their livelihood. It is therefore essential that SDG 6, which seeks to achieve universal water access and sustainable water use, is met.

The six main targets of SDG 6 cover access to safe drinking water (6.1), access to sanitation (6.2), water quality (6.3), water-use efficiency and sustainability (6.4), integrated water resources management (6.5) and protecting and restoring water-related ecosystems (6.6). While nine global indicators have been defined, they need to be adapted to country contexts for monitoring purposes. In addition, target 6.4 requires several indicators if it is to properly measure water-use efficiency across all sectors and sustainability of supply as the target seeks to do, and there is very limited data on the socio-economic benefits of water allocation and use is available globally (6).

South Africa is one of the driest countries in the world with low and highly variable rainfall (both inter- and intra-annually), erratic runoff, high evaporation and shallow dam basins (7). The South African economy primarily depends on its stored surface water resources and imported water from neighbouring Lesotho, and is rapidly approaching full utilisation of surface water resources (7). More than 60% of its river flow arises from only 20% of the land area requiring large-scale inter-basin transfers (8). The water supply sector has become increasingly important for economic growth over the past three decades; it was ranked with the fifth highest simple GDP multiplier in 2010, up from 37th in 1985 (9). Poverty, unemployment and inequality are significant problems in South Africa. Almost 46% of the population are unable to meet their basic needs (10), the broad unemployment rate is 37% (11) and the Gini index of income inequality is 0.69, one of the highest in the world (10). The relationships between water allocation and/or use and jobs and income are therefore very important.

In this paper, a suite of 26 indicators for SDG 6 are proposed for South Africa based on existing official national indicators, a literature review of water governance in South Africa and water indicators, the authors' previously published research, and additional research on the social and economic benefits of water. To assess and refine the indicators, the Berg Water Management Area (WMA), situated in the south-western corner of the country, is used as a case study. The standard approaches used are contrasted with new approaches that respond to the requirements of the SDGs. The Berg WMA is described in a section on Context. In our Methods section, the rationale behind each proposed SDG 6 indicator is

described and a detailed description of the analysis of water, jobs and income is provided. Results are presented for municipalities in the Berg WMA across indicators, and where possible compare them to national figures and disaggregate data by gender, race and geographical location. Finally, the Discussion section covers the implications for South Africa, the relationship between water and jobs and income in the Berg WMA, SDG monitoring in South Africa and beyond, and how SDG 6 contributes to achieving the goal of living within a 'safe and just operating space for humanity' (12).

6.2 Context – the Berg Water Management Area

South Africa's national Department of Water and Sanitation (DWS) previously divided the country into 19 Water Management Areas (WMAs), each containing a large river system (13). The Berg WMA, in the south-western corner of the Western Cape province, is named after the 285 km long Berg River (14) and includes 29 fourth order sub-catchments. With the second National Water Resources Strategy of 2013 (7), 19 WMAs were reduced to nine, through amalgamating areas. As such the Berg no longer constitutes an individual WMA, but is still referred to as such in government assessments (15) and in this paper.

Rainfall occurs in winter and ranges from over 3,000 mm/a in the south-east mountains to less than 300 mm/a in the west and north-west coastal plain (see Figure 6.1a). The Berg WMA's natural mean annual runoff is 1,094 million cubic metres per year (Mm^3/a), 2.2% of the national total, and 65 Mm^3/a of groundwater resources are being utilised (15). It is home to the Cape Fynbos, a unique floral

kingdom with World Heritage status and the Berg River Estuary, which is of major conservation importance for birdlife (16).

Three district municipalities (DMs) fall within or partly within the Berg WMA, namely the City of Cape Town metropole, the southern part of the West Coast DM and the western part of the Cape Winelands DM. There are 45 towns within six local municipalities (LM) that fall within or partly in the Berg WMA - namely Saldanha Bay LM, Swartland LM, Drakenstein LM, Stellenbosch LM, the southern half of the Bergvliet LM and the western corner of Witzenberg LM (see Figure 6.1b). Over 4.5 million people live in the Berg WMA, with 85% in the City of Cape Town. The City of Cape Town contributes 71% of the Western Cape Province's GDP and is an important contributor to the economic growth in the area (17). Economic activity in the Berg WMA is quite diverse and includes tourism, irrigated and dryland agriculture, wine-making, food processing, manufacturing, fisheries, commercial forestry, financial services, ITC, nuclear power generation, hydropower generation and port operations (15). The Saldanha Bay Industrial Development Zone, designated as South Africa's fifth Special Economic Zone in 2013, aims to be a world-class marine engineering hub focused on the international Oil & Gas sector and its allied services and support industries (18).

The Berg River is a heavily utilised system with annual requirements of 690 Mm³/a, shared between domestic and industrial users (52%), irrigation (43%) and afforestation and alien vegetation (5%) (15). The Western Cape Water Supply System (WCWSS) serves 74% of the Berg WMA requirements (15). Two thirds of the WCWSS water is allocated to the City of Cape Town, 73% of which goes to

domestic water use. The WCWSS facilitates water transfers between rivers, including from the Breede-Gouritz WMA to the Berg River. The latest WCWSS report expects water demand to exceed current water supply in the year 2022, although plans are in place to increase supply through Berg River-Voëlvlei Dam augmentation, large-scale water re-use, large-scale Table Mountain Group Aquifer development and desalination of seawater (19). The increasing cost of water may constrain economic growth in the future (20).

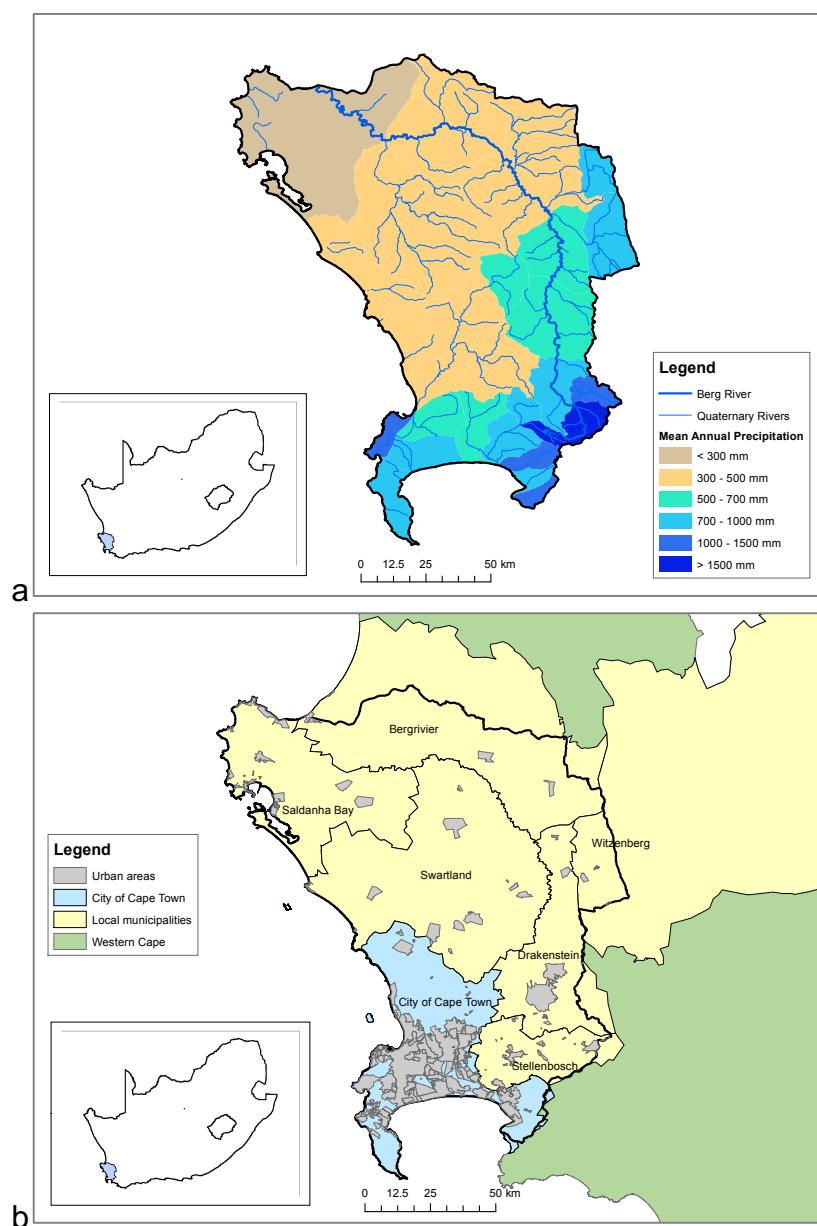


Figure 6.1 Berg WMA a) mean annual precipitation and quaternary rivers and b) urban areas, local municipalities and the City of Cape Town

6.3 Methods

This section describes the proposed selection of indicators for the six main SDG 6 targets, which are shown in Table 6.1 below, data sources for the Berg WMA results and our analysis of water, jobs and income in the Berg WMA. Table 6.1 includes the indicator tier which is a UN classification based on their level of methodological development and data availability (3). Tier 1 indicators are conceptually clear, have an established methodology and available standards and data are regularly produced. Tier 2 indicators are conceptually clear, have an established methodology and available standards but data are not regularly produced. Tier 3 indicators have no established methodology and standards or, at best, methodology/standards are being developed and/or tested.

Table 6.1 Proposed SDG 6 suite of indicators for South Africa

Target	Indicator	Data source	Tier
6.1 Water access	6.1.1 Persons with tap water within 200m of dwelling (%)	GHS, Census	1
	6.1.2a Persons with tap water in dwelling (%)	GHS, Census	1
	6.1.2b Gini index of tap water in dwelling	Census	3
	6.1.3 Implementation of Free Basic Water	Municipal accounts	3
6.2 Sanitation	6.2.1 Persons with access to ventilated pit latrine or better (%)	GHS, Census	1
	6.2.2a Persons with access to flush toilets (%)	GHS, Census	1
	6.2.2b Gini index of access to flush toilets	Census	3
6.3 Water quality	6.3.1 Total mean annual phosphorus concentration in freshwater (mg/l)	NEMP	2
	6.3.2 Drinking water quality: Blue Drop Score (%)	DWS Blue Drop System	1
	6.3.3 Wastewater quality: Green Drop Critical Risk Rating (%)	DWS Green Drop System	1
6.4	6.4.1a Domestic per capita water use (l/c/d)	Municipal accounts	2

Water-use efficiency and sustainability	6.4.1b Gini index of domestic per capita water use	Municipal accounts	3
	6.4.2 Physical water losses (%)	Municipal accounts	2
	6.4.3 Water stress: demand as proportion of available yield (%)	Reconciliation strategies, WARMS	2
	6.4.4 Jobs per million cubic metres (Mm ³) of water used in heavily water-dependent sectors	Census, QLFS, WARMS	3
	6.4.5 Total median income per cubic metre of water used in heavily water-dependent sectors (R/m ³)	Census, QLFS, WARMS	3
6.5 Water resources management	6.5.1 Implementation of Catchment Management Agencies	DWS	2
	6.5.2 Implementation of ecological reserve	DWS	3
	6.5.3 Implementation of Water Allocation Reform	DWS	3
	6.5.4 Proportion of international transboundary basin area with an operational arrangement for water cooperation (%)	DWS	3
6.6 Water-related ecosystems	6.6.1 Critically endangered river ecosystems (%)	NBA	2
	6.6.2 Critically endangered estuarine ecosystems (%)	NBA	2
	6.6.3 Critically endangered wetland ecosystems (%)	NBA	2
	6.6.4 River ecosystems well protected (%)	NBA	2
	6.6.5 Estuarine ecosystems well protected (%)	NBA	2
	6.6.6 Wetland ecosystems well protected (%)	NBA	2

Note: GHS = General Household Survey, NEMP = National Eutrophication Monitoring Programme, QLFS = Quarterly Labour Force Survey, WARMS = Water Authorisation Registration and management System, DWS = Department of Water and Sanitation, NBA = National Biodiversity Assessment

6.3.1 Access to safe affordable drinking water

The global indicator for target 6.1 (By 2030, achieve universal and equitable access to safe and affordable drinking water for all) is 'Proportion of population using safely managed drinking water services'. South Africa's 1996 Constitution enshrined 'access to sufficient water' as a basic human right (21) and the National Water Services Act of 1997 stated that 'everyone has the right of access to a basic water supply' (22). The official indicator for water access used in the government's Development Indicators reports (10) and in the South Africa MDG country reports (23) is '25l of potable water per person per day without interruption for more than 7 days within 200m of the household'. In Statistics South Africa's (StatsSA's) annual General Household Survey (GHS) and national Census, seven levels of access to piped water are defined based on distance from the dwelling. Although the data collected in the GHS and census are stored in the SuperCross database, reporting only refers to the proportion of the population living with or without piped water access within 200 m of dwelling. The official indicator and the indicator 'persons with access to piped water in their dwelling' should both be used in the SDGs as the UN Human Development Report 2006 argues that water piped into households is the optimal type of water access for human development (24) and Howard and Bartram (25) show that this level of water access makes it likely that people will meet the World Health Organisation's recommended 50-100 litres per person per day (l/c/d) to 'sustain life and health'. Reporting this higher social floor also provides a measure of inequality in addition to poverty, and fits better with the long-term aspirations of sustainable development. In this paper, both indicators are reported for the Berg WMA and its towns and municipalities

In previous work (26) the authors calculated Gini indexes of 'piped water access in dwellings' across wards for South Africa and all its provinces and districts. They argued that a Gini index is a useful tool for reporting inequality at the national scale and comparing levels of inequality across administrative regions. Although the Gini index is normally used for income inequality, it has been used to measure inequality in the distribution of water resources (27–29) and by Bhorat *et al.* (30) to measure changes in non-income inequality (including source of water and type of toilet) in South Africa. In this paper, a Gini index for access to piped water in dwellings is calculated for the Berg WMA using Census 2011 sub place data i.e. measuring the inequality between sub places of water access. This could be an indicator itself or form part of the disaggregation of this target.

Target 6.1 refers to safe, affordable drinking water. While safety is covered by water quality in target 6.3, affordability is difficult to measure. The Free Basic Water allowance was introduced in South Africa in 2001 to supply every household with 6,000 litres per month for free to ensure poor people are able to use the minimum amount of water (31). It is not always easy to implement due to varying household sizes and communal access, and is not currently publicly reported. As a start, the 'implementation of Free Basic Water' is proposed as an SDG indicator for South Africa.

6.3.2 Access to adequate sanitation

The global indicator for target 6.1 (By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations) is

‘Proportion of population using safely managed sanitation services’. The official indicator for sanitation used in the South Africa’s Development Indicators reports (10) and MDG country reports (23) is ‘households with access to at least a ventilated pit latrine’. In the GHS and national census, eight levels of sanitation for households are defined, ranging from a ‘access to a flush toilet connected to a sewerage system’ to ‘none’. Access may be within the dwelling or outside the dwelling. Although the data collected in the GHS and census are stored in a database, reporting only refers to the proportion of the population living with or without ventilated pit latrines or better. We propose that both the official indicator and the indicator ‘persons with access to flush toilets’ should be used for the SDGs as 84% of respondents in the South African Social Attitudes Survey said that having a flush toilet in the house was essential (32). Reporting this higher social floor also provides a measure of inequality in addition to poverty, and fits better with the long-term aspirations of sustainable development. In this paper, both indicators for the Berg WMA and its towns and municipalities are reported. A Gini index for access to flush toilets is calculated for the Berg WMA using Census 2011 sub place data. This could be an indicator itself or form part of the disaggregation of this target.

6.3.3 Water quality

Global indicators for target 6.3 (By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally) are ‘Proportion of wastewater safely treated’ and ‘Proportion of bodies of water with good ambient water quality’. Eutrophication of freshwater resources is widespread in South Africa and is a

national concern (33). Poor and insufficient wastewater treatment has often been referred to as one of South Africa's main water pollution problems (34). River water quality is assessed regularly by the DWS through the National Eutrophication Monitoring Programme (NEMP) while drinking water quality is measured in the incentive-based Blue Drop Certification Programme and wastewater quality is measured in the Green Drop Certification Programme. NEMP measures mean annual levels of chlorophyll and phosphorus (P) at over 1,200 monitoring points across the country. The indicator 'mean annual total P in dams' is used in the Department of Environmental Affairs annual Environmental Sustainability Indicators reports (35). Previously the authors obtained data for this indicator from the DWS, where individual values range from 0.02 to 0.26 mg/l P, and calculated a weighted average based on the gross volume of freshwater in each drainage basin to create a national value of 0.098 mg/l P (36) and provincial values (37). This is compared to the national critical threshold of 0.1 mg/l P in freshwater (38). There are 179 monitoring points in rivers, reservoirs and estuaries in the Berg WMA (15), which can be aggregated by catchment.

The Blue Drop and Green Drop programmes measure and compare performance of water service authorities and their providers via a standardised scorecard. Municipalities are then rewarded or penalised according to the legislated standards and international best practice (39). The Blue Drop Score and Green Drop Score are reported as a percentage with 100% being the target. The Green Drop programme also reports a Cumulative Risk Rating (CRR) and the ratio of CRR to CRR_{max} (the maximum value a wastewater treatment plan can obtain) which ranges from zero risk to 100% (40). A high CRR implies that poor quality water is released

into the environment, polluting rivers and oceans. The Blue Drop Score and the Green Drop $\%CRR/CRR_{max}$ are appropriate SDG indicators as they are already regularly reported by the national government. In this paper, these values are reported for the Berg WMA and its municipalities.

6.3.4 Water-use efficiency and sustainability

The global indicators for target 6.4 (By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity) are 'Change in water-use efficiency over time' and 'Level of water stress: freshwater withdrawal as a proportion of available freshwater resources'. Water-use efficiency implies maximising output per unit of water and is closely related to the concept of sustainable production and consumption (5). Sustainable freshwater withdrawals must take environmental water requirements into account for both surface water and groundwater, while freshwater supply must reduce the impact of water stress or scarcity on people. Five national indicators for South Africa are proposed described below.

Domestic per capita water use

Measuring domestic per capita water use addresses both water-use efficiency and equity. The National Water Act of 1998 (41) established the basic human needs Reserve which has been defined as 25 litres per capita per day (l/c/d) or 6,000 litres per household per month, which equates to 50 l/c/d for a household of four. Gleick (42) and the World Health Organisation (25) both recommended a minimum of 50 l/c/d for basic human needs. In a country with high TB and HIV/AIDS rates like

South Africa, the recommended usage is 100 l/c/d to maintain adequate health (25). In previous work the authors assessed town per capita water use across South Africa using the DWS reconciliation strategies in the 838 All Town Studies and five water supply systems (26). As these did not all differentiate between domestic and non-domestic use, in this paper, municipal water accounts for all towns in the Berg WMA (43–47) and the City of Cape Town was obtained. The municipal water use accounts report annual bulk water supply, treated water supply, water losses, and water use by sector. The residential per capita water use for all towns and the City of Cape Town was calculated using Census 2011 population data and water use data for the municipal water audit year July 2011 to June 2012 (as the Census was done in October 2011) to be as accurate as possible. In the case of Jamestown and Raithby, the DWS All Town Studies Version 1 (2007/8) (48,49) was used as they are included in Stellenbosch in the municipal accounts. Domestic use figures could not be obtained for the rural villages of Goedverwacht and Wittewater, which are privately owned by the Moravian church, and the mine village of De Hoek which is owned by PPC Ltd. The Riebeeck West mine village (also owned by PPC) residential per capita use figure was used for De Hoek. In previous work (26) the authors calculated Gini indexes for domestic per capita water use for South Africa and its provinces and districts. In this paper, a Gini index of domestic per capita water use is calculated for the Berg WMA. This could be an indicator itself or form part of the disaggregation of this target.

Water losses

Reducing water losses are a focus area for water-use efficiency strategies. Municipal water use accounts record the physical losses of raw water through bulk

distribution and water treatment (difference between raw water and treated water supply) and the losses of treated water through internal distribution (difference between treated water supply and billed metered consumption). Most towns in the Berg WMA receive treated water therefore the water losses quoted are for internal distribution only. In this paper, water losses for the Berg WMA and its municipalities and towns are reported.

Water stress

Water stress is a measure of demand compared to available supply. One of the most commonly used indicators is the Falkenmark water stress indicator, which is the total annual renewable water resources per capita (50). The Berg WMA present day mean annual runoff is 784 Mm³/a (15). Combined with 65 Mm³/a of groundwater resources, total renewable resources are 849 Mm³/a. With a total population of 4,387,811 in 2011, the Falkenmark indicator for the Berg WMA is 193 m³/capita/a, defining it as water scarce. The UN Food and Agriculture Organisation 'Aquastat' information system for water and agriculture differentiates between 'total renewable water resources' and 'total exploitable water resources' (51). Renewable resources combine surface runoff and groundwater (51,350 Mm³/a in South Africa) while exploitable resources are limited by existing water infrastructure and assurance of supply (11,972 Mm³/a in South Africa). The WCWSS yield with 98% assurance of supply is 596 Mm³/a (19), while the yield for towns not supplied by the WCWSS is 12.776 Mm³/a. The total supply to rural users outside the WCWSS is unknown although the total demand for the Berg WMA is 690 Mm³/a (15) so it must be at least 81 Mm³/a. If the figures for total supply were available, the 'total exploitable resources per capita' or demand as a percentage of available supply

could be calculated. The latter is more appropriate for the SDGs as it is easier to set a target. Water stress, or supply versus demand, can be measured at the town level, using the DWS All Town Studies mentioned above.

Water-dependent jobs and income

Water-use efficiency implies maximising output per unit of water. This output could be measured as gross value added, income or jobs. A few attempts have been made to determine water-use efficiency in the Western Cape and the Berg WMA (15,52,53). These have been limited to a single sector (agriculture or agriprocessing) or limited to general industry categories such as 'Agriculture, Hunting, Forestry and Fishing' and 'Manufacturing' which include jobs with a wide range of water-dependence. They do not specify between heavily-water dependent jobs, moderately water-dependent jobs, and jobs in other sectors. This challenge is addressed in this paper by using the microdata provided by StatsSA in the Census 2011 '10% sample'. Two SDG indicators are proposed: 'jobs per million cubic metres water used in heavily water-dependent sectors' and 'total annual income per cubic metre water used in heavily water-dependent sectors'.

The national census of 2011 was conducted from 9 to 31 October 2011 for the reference night of 9/10 October 2011 for all 51,770,560 South African residents (54). All persons aged 15 and older were asked about their employment status, employment industry and occupation. Unfortunately, the industry and occupation data is not included in the Census 2011 database provided by StatsSA. Instead, StatsSA has provided the Census 2011 '10% sample', which includes anonymised data for individuals in about 10% of all households and collective quarters. StatsSA

did not provide publicly available information on how the sampling was done but it is understood that they did systematic sampling on the households and then included individuals from the selected households. The '10% sample' includes (among many other variables) the employment industry, occupation, income and local municipality for individual people.

In the Berg WMA, the '10% sample' includes 132,564 employed people, 8.4% of the actual employed population. We grouped the 263 industry variables into sub-sectors related to their dependence on water as defined by the UN (6). Agriculture, forestry, inland fisheries, mining and resource extraction, energy and water supply, agriprocessing and manufacturing of textiles are defined as heavily-water dependent sectors. Manufacturing/transformation of wood products, rubber, plastics, metals and chemicals, and construction and transport are defined as moderately water-dependent sectors. All other sectors have low water-dependence. Using the 10% sample, we calculated the percentage of jobs that are heavily water-dependent and moderately water-dependent per municipality. Here, the ratio of sub-sector jobs to total jobs in the '10% sample', and the total number of jobs in Census 2011, are used to estimate the actual number of jobs per sub-sector and municipality. The income of each worker is aggregated to calculate a total annual income per sub-sector and municipality. As income is reported as an income bracket, not actual income, the median income of the bracket specified per person is used. The minimum and maximum total annual income are also calculated using the lower and upper ranges of the specified bracket. The results will be underestimates as they exclude 6% of jobs with 'unspecified' income.

Further analysis of water-dependent jobs is limited by water use data. The municipal accounts record water use for industrial/business/commercial, municipal, farm and 'other' sectors, but the exact industries and sub-sectors are unknown. The DWS database of all water use licences, Water Authorisation Registration and Management System (WARMS), specifies 11 water use sectors, namely, irrigation, livestock watering, aquaculture, industry urban, industry non-urban, other urban, mining, power generation, water supply service, recreation and schedule 1. It also records the customer name (person or organisation), water source and geographic location, which enabled us to identify which sector most of the 9,102 water use licences for the Berg WMA belong to. In this study, the WARMS water volumes for the heavily water-dependent sectors agriculture, freshwater aquaculture, mining and agriprocessing were aggregated. Power generation was excluded as the operations do not use freshwater. In addition, grey literature on heavy water users in the Berg WMA was reviewed to determine their water use and workforce. This identified steel processing in Saldanha (55) as a major water user.

The jobs and income analysis from the Census 2011 '10% sample' was combined with the water use analysis to calculate best estimates for the four heavily water-dependent sectors for the two indicators 'jobs per million cubic metres water used' and 'total annual income per cubic metre water used'. The detailed methodology for each sector is described below.

Agriculture. There are 2,540 active water use licences for irrigation and 89 for livestock watering in WARMS, with a total water allocation of 387,650,971 m³/a and 3,715,023 m³/a respectively. In addition, towns supply 1,304,352 m³/a to farms.

The total annual water use for agriculture is therefore 392,670,356 m³/a. Income for 4,314 jobs were analysed with the industry variables for crop farming, animal farming, mixed farming, agricultural and animal husbandry services and organic fertiliser production in the six LMs and the City of Cape Town in the Census 2011 '10% sample'.

Freshwater aquaculture. There are 16 active water use licences for freshwater aquaculture in WARMS with a total of 2,404,565 Mm³/a. They are located near Paarl, Franschhoek and Tulbagh and are likely to be for trout farming in mountain streams. The income for 119 jobs with the industry variable 132 were analysed in the Drakenstein and Witzenberg LMs in the Census 2011 '10% sample'.

Mining. There are only two mines in the Berg WMA, De Hoek in Bergrivier LM and Riebeeck West Mine in Swartland LM, both operated by PPC Ltd. Together they have a water use licence of 1,276,526 m³/a and a workforce of 400 employees in their limestone mines and cement factories (56). The PPC mines have associated mine villages, which are recorded as separate main places in Census 2011 with 324 employed people. One can assume that all these people work on the mine site. There are 61 quarries in the Berg WMA (57), but there is very limited information on their water use and jobs. The Census '10% sample' under-samples mining and quarrying with only two employed persons in Bergrivier LM and eight in Swartland LM. The income analysis is therefore limited to the employed people living in the PPC mine villages as there is confidence in the results.

Agriprocessing. Agriprocessing is a combination of different activities that transform agricultural products into useable items. The Western Cape Department of Agriculture provides the location and name of all agriprocessing facilities in the province in its online tool, CapeFarmMapper (58). The Berg WMA has 12 red meat abattoirs, eight white meat abattoirs, 129 agriprocessing plants, 137 dairies, five fruit packers, four cool chain facilities, 117 packhouses and 591 cellars – a total of 1,003 agriprocessing facilities. In 2015, the Western Cape Department of Environmental Affairs and Development Planning (DEA&DP) assessed the water use of eight priority agri-processing sectors: fruit juice, wine and brandy, olive oil, essential oils, dairies, poultry abattoirs and livestock abattoirs using CapeFarmMapper, a literature review and interviews (53). Based on a limited sample size, they estimated the water use of each sector in litres per unit. The WARMS database also provides information on water use and we extracted 57 active licences totalling 5,896,885 m³/a for one brewery, one tannery, seven food and beverage producers and 23 wine cellars. As neither sources cover all agriprocessing facilities, a literature survey was undertaken to fill in any gaps to estimate total annual water use per sub-sector per municipality.

For breweries, the Newlands brewery WARMS licence and an estimated average water use of 385 m³/a for 60 craft breweries (59) based on production figures (60) and SABMiller's figure of 8.55 litres of water required to produce one litre of beer (61) were used. For wine cellars, production figures (62) and DEA&DP's estimate of 3.9 litres of water use per litre of wine produced were used. For dairies, production figures (63) and DEA&DP's estimate of 3.6 litres of water per litre of dairy product were used. For food and beverage processing, the average water

volume for the six plants in WARMS was multiplied by the number of plants in CapeFarmMapper. For tanneries, the single WARMS licence of 55,000 m³/a was used. For white meat abattoirs, the number of abattoirs in CapeFarmMapper, an average number of birds per facility, and DEA&DP's estimate of 16.7 litres of water per bird were used. For red meat abattoirs, the number of abattoirs in CapeFarmMapper, an average number of animals per facility, and an estimate of 50 litres of water per animal were used. All these figures exclude the water required to farm or transport the required agricultural inputs – both food and pastures. All the figures have significant uncertainty due to the very limited data on actual water use in individual agriprocessing facilities and therefore extensive use of averages.

Overall, income for 3,594 agriprocessing jobs with the industry variables 301 to 306 in the six LMs and the City of Cape Town in the Census 2011 '10% sample' were analysed.

6.3.5 Water resources management

The global indicators for target 6.5 (By 2030, implement integrated water resources management (IWRM) at all levels, including through transboundary cooperation as appropriate) are 'Degree of IWRM implementation' and 'Proportion of transboundary basin area with an operational arrangement for water cooperation'. The concept of IWRM seeks to promote the coordinated development and management of water and land-related resources, to maximise economic and social welfare in an equitable way, without compromising the sustainability of ecosystems (5). IWRM implementation can be monitored by assessing policies, institutions, management tools and financing (5). The second indicator refers to

international cooperation on shared water resources. Roughly 60% of South Africa's streamflow is shared through transboundary water systems and South Africa is a signatory to the Revised Protocol on Shared Water Courses in the Southern African Development Community (7). In the second National Water Resources Strategy published in 2013, the DWS introduced the concept of 'developmental water management' which reflects and builds on the principles of IWRM but interprets them in the context of a developmental state (7). It differs from IWRM in three ways; water management is not an end in itself but rather subject to the goals of the democratic state, priority is given to getting the basics right (water infrastructure and service delivery), and equity is operationalised (64).

For this SDG target, four indicators are proposed: 1) implementation of the Catchment Management Agencies, CMAs, (responsible for managing water resources), 2) implementation of the 'ecological reserve' (minimum water required to protect aquatic ecosystems) both defined in the National Water Act of 2008 (41), 3) the implementation of the DWS Water Allocation Reform programme, which aims to operationalise equity by allocating 50% of water to historically disadvantaged individuals and the poor (65), and 4) proportion of transboundary basin area with an operational arrangement for water cooperation. Implementation of CMAs has been slow with only two CMAs (the Breede-Gouritz and the Inkomati-Usutu) established to date (66). The proposal for the establishment of the Berg-Olifants CMA (for the combined Berg WMA and Olifants-Doorn WMA) was published by the DWS in 2016 but is still in process. The ecological reserve in the Berg WMA is primarily implemented for the Berg River Estuary and releases from the Berg River Dam are intended to address the reserve requirements for the whole catchment.

The Water Allocation Reform programme's progress was assessed in 2013 where WARMS water allocation data was disaggregated by race, gender and geographical location (52). It showed that the current status was below the programme targets in all WMAs.

6.3.6 Water-related ecosystems

The global indicator for target 6.6. (By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes) is 'Change in the extent of water-related ecosystems over time'. Although the target mentions a range of ecosystems, these are the focus of SDG 14 (marine resources) and SDG 15 (terrestrial biodiversity). The focus here should probably be on freshwater ecosystems as all other SDG 6 targets relate to freshwater. South Africa's National Biodiversity Assessment (NBA) headline indicators are ecosystem threat status and ecosystem protection level (67). These two indicators are consistently assessed across terrestrial, river, wetland, estuarine, coastal and marine ecosystem types and will be updated every seven years. Ecosystem types are categorised as critically endangered, endangered, vulnerable or least threatened, based on the proportion of each ecosystem type that remains in good ecological condition relative to a series of thresholds. Ecosystem types are also categorised as not protected, poorly protected, moderately protected or well protected, based on the proportion of each ecosystem type that occurs within a protected area recognised in the Protected Areas Act. Six SDG indicators are proposed of the format 'percentage of freshwater ecosystems critically endangered' and 'percentage of freshwater ecosystems well protected', where freshwater

includes rivers, estuaries and wetlands. In this paper, both national and Berg WMA data for the six indicators are reported.

6.4 Results

Table 6.1 provides the proposed suite of 26 indicators for SDG 6 for South Africa, the original data source/s (and where data can be obtained in future) and the indicator tier. The suite has 17 more indicators than the set of nine global indicators which is partly to provide measures of inequality such as the Gini index, and partly to address the scope of the SDG targets. South Africa's 2013 MDG country report (23) had 69 domesticated indicators in addition to the 60 official global indicators, so this is not a surprising result. All the data sources are official government reports or databases that will be updated on a regular basis, though this varies from quarterly (QLFS, Quarterly Labour Force Surveys) to every seven years (NBA). Although the data can be sourced, only six indicators are classified as Tier 1. Eleven indicators are classified as Tier 2 as they require more regular updates and nine indicators as Tier 3 as their methodologies are not commonly used.

Table 6.2 shows Berg WMA municipal and overall data for indicators for SDG 6.1, 6.2 and 6.3. The Gini index for piped water access in dwellings in the Berg WMA is 0.16 compared to 0.36 nationally, while the Gini index for the Berg WMA for access to flush toilets is 0.06. Across these indicators, the Berg WMA does better than the national average. As the Berg WMA average is heavily influenced by the City of Cape Town, there are municipalities that do worse than the national average, but only on water quality. Water access measured by the lower social floors – piped water within 200m of dwelling - shows very little variation and all municipalities

score 95% or higher. Water access measured by the higher social floor - piped water in dwelling – is much more varied and drops as low as 71%. Sanitation measured by the lower and higher social floors - access to ventilated pit latrines and access to flush toilets – are very similar and there is very little variation across the Berg WMA with all municipalities scoring above 90%. Drinking water quality and wastewater quality both vary significantly across the WMA. Figure 6.2 disaggregates the Berg WMA water access and sanitation access data by race, gender and urban/rural location. This highlights the gap between black African people and other races in access to water services, though this is wider for piped water access in dwellings as flush toilets can be communal. It shows that women have greater access to water services than men and that urban areas have greater access than rural areas.

Table 6.2 Latest data for proposed SDG 6.1, 6.2 and 6.3 indicators for municipalities in the Berg WMA

Municipality	1. Water access		2. Sanitation		3. Water quality	
	Piped water within 200m of dwelling (%)	Piped water in dwelling (%)	Access to ventilated pit latrines or better (%)	Access to flush toilets (%)	Drinking water quality: Blue Drop Score (%)	Wastewater quality: CRR/ CRR _{max} (%)
Bergrivier	99	82	91	90	64	55
Saldanha Bay	99	85	96	96	69	58
Swartland	99	79	92	91	74	64
Drakenstein	99	81	95	94	72	56
Stellenbosch	98	77	91	91	80	80
Witzenberg	99	71	93	92	96	39
City of Cape Town	95	79	93	92	96	49
Berg WMA	97	79	93	92	93	57
South Africa	83	46	70	57	80	72

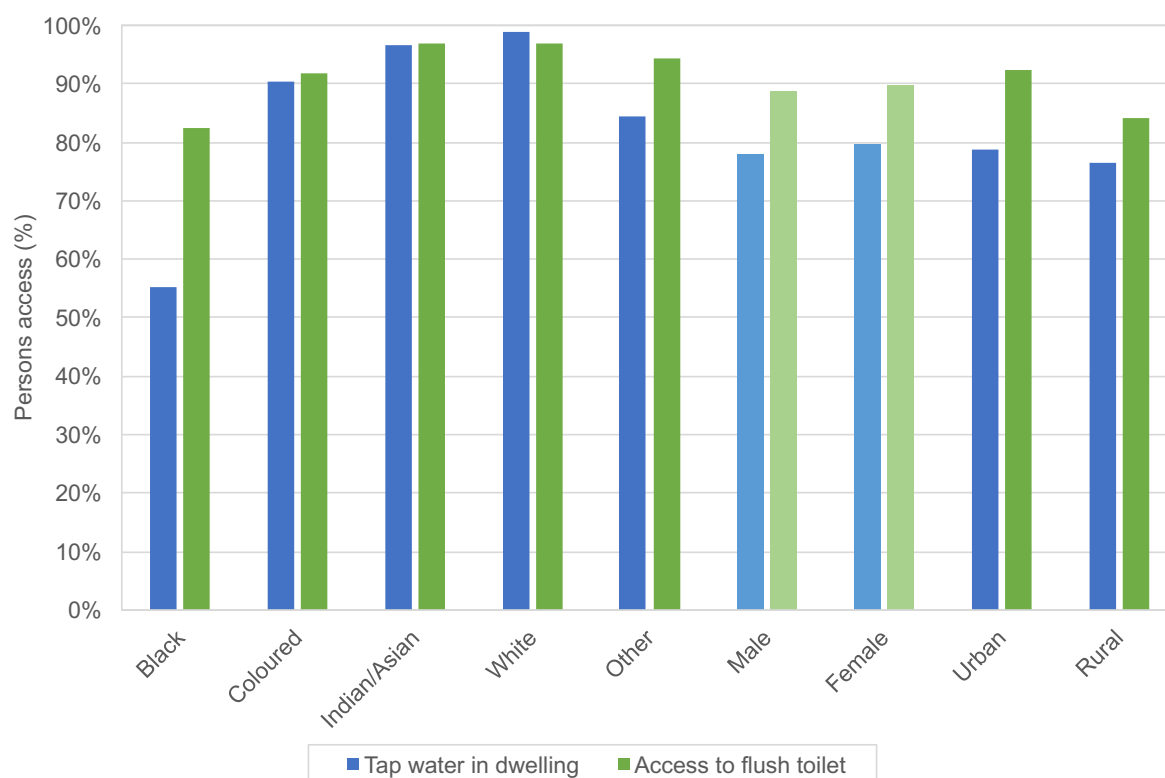


Figure 6.2 Disaggregation of Berg WMA data for piped water in dwellings and access to flush toilets by race, gender and urban/rural location

Table 6.3 shows data for the Berg WMA for the proposed SDG 6.4 indicators and Figure 6.3 spatially disaggregates domestic water use and water losses to the town level, highlighting local variability. The Gini index for domestic water use for the Berg WMA is 0.22 compared to the national figure of 0.27. These results show that although at the municipal level domestic water use is within the targeted range, 11 towns are below the recommended minimum target of 100 l/c/d and six are above the proposed maximum target of 300 l/c/d. Similarly, although municipal level water losses are all below 20%, they can reach over 50% at the town level. Figure 6.4 and Figure 6.5 compare the estimated jobs per million cubic metre and median income per cubic metre respectively for heavily water-dependent sectors across municipalities in the Berg WMA. Figure 6.5 has error bars showing that the income could range from the lower to upper end of the income bracket recorded in the

census. The data tables for Figure 6.4 and 6.5 are provided in the SI Tables S6.1, S6.2, S6.3 and S6.4. The jobs and income vary significantly for across municipalities and sectors but overall, agriprocessing produces the most jobs while mining produces the most income per unit of water used. Table 6.3 shows that the City of Cape Town and Saldanha Bay LM produce the most jobs and income per unit of water used.

Table 6.4 provides Berg WMA and national data for the proposed SDG 6.6 indicators which are all taken from the National Biodiversity Assessment (67). While national figures are readily available, only some of the data is reported by WMA.

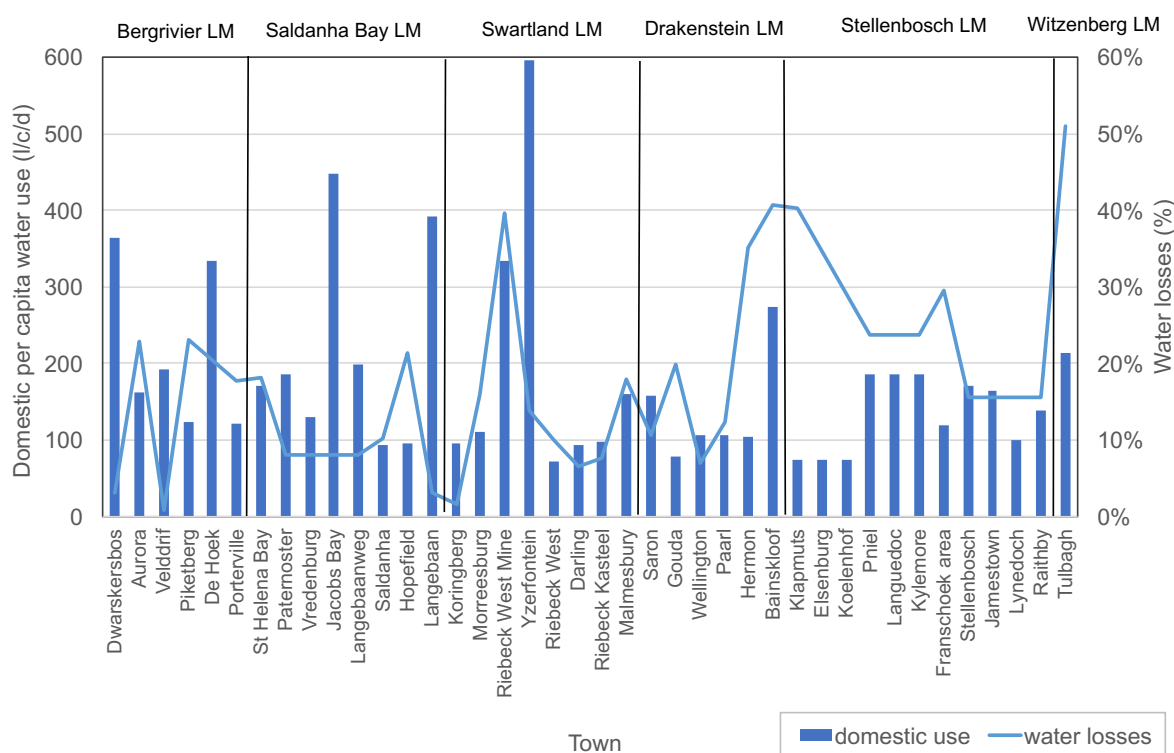
Table 6.3 Latest data for proposed SDG 6.4 indicators for municipalities in the Berg WMA

Municipality	Domestic per capita water use (l/c/d)	Water losses (%)^a	Water stress: town demand vs supply (%)	Jobs per million cubic metre in heavily water-dependent sectors^b (Mm³/a)	Total income per cubic metre in heavily water-dependent sectors^b (R/m³/a)
Bergrivier	138	13	86	114	79 ± 26
Saldanha Bay	112	18	93	786	239 ± 80
Swartland	107	15	111	234	102 ± 32
Drakenstein	106	11	62	41	18 ± 6
Stellenbosch	152	18	81	7	9 ± 3
Witzenberg	107	10	39	112	15 ± 5
City of Cape Town	125	14	85	932	187 ± 62
Berg WMA	124	16	-	177	184 ± 61

^a Internal distribution losses in municipal accounts. ^b Includes agriculture, freshwater aquaculture, mining, steel processing and agriprocessing.

Table 6.4 SDG 6.6 indicators and data for Berg WMA and South Africa

Indicator	Berg WMA	South Africa
6.6.1 Critically endangered river ecosystems (%)	81	25
6.6.2 Critically endangered estuarine ecosystems (%)	99	39
6.6.3 Critically endangered wetland ecosystems (%)		48
6.6.4 River ecosystems well protected (%)		14
6.6.5 Estuarine ecosystems well protected (%)		33
6.6.6 Wetland ecosystems well protected (%)		11

**Figure 6.3** Domestic water use and water losses (bulk water supply less end-use) in towns in the Berg WMA.

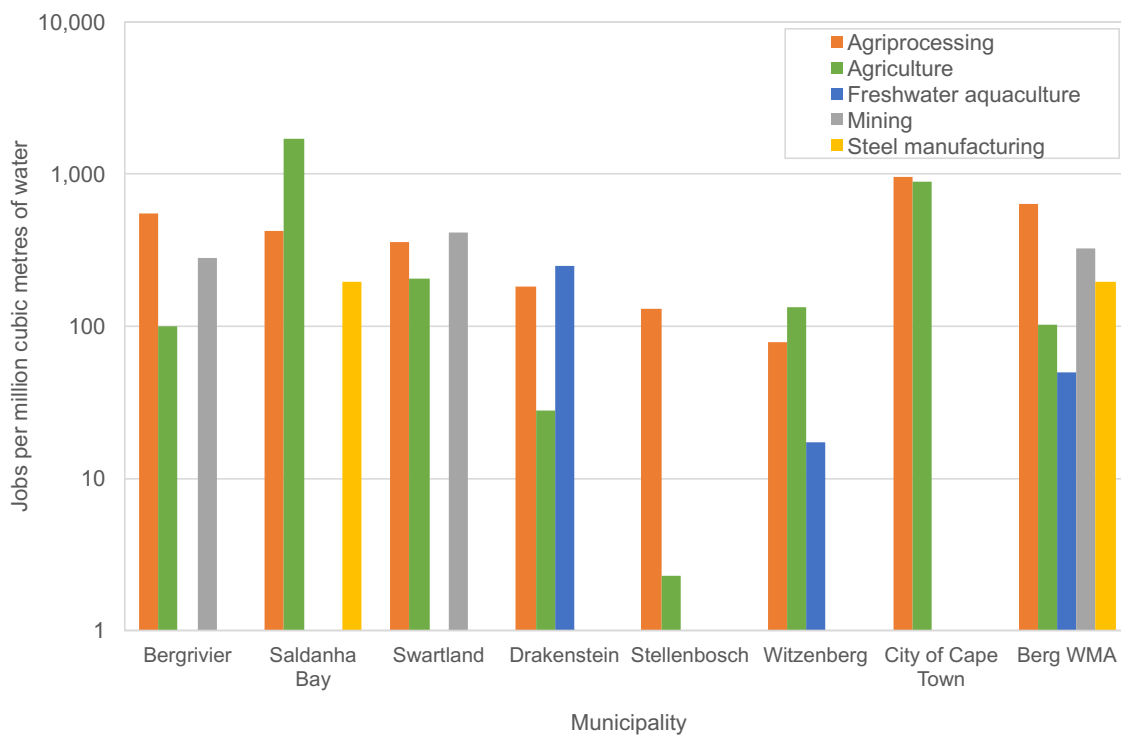


Figure 6.4 Total jobs per million cubic metres of water for heavily water-dependent sectors in the Berg WMA

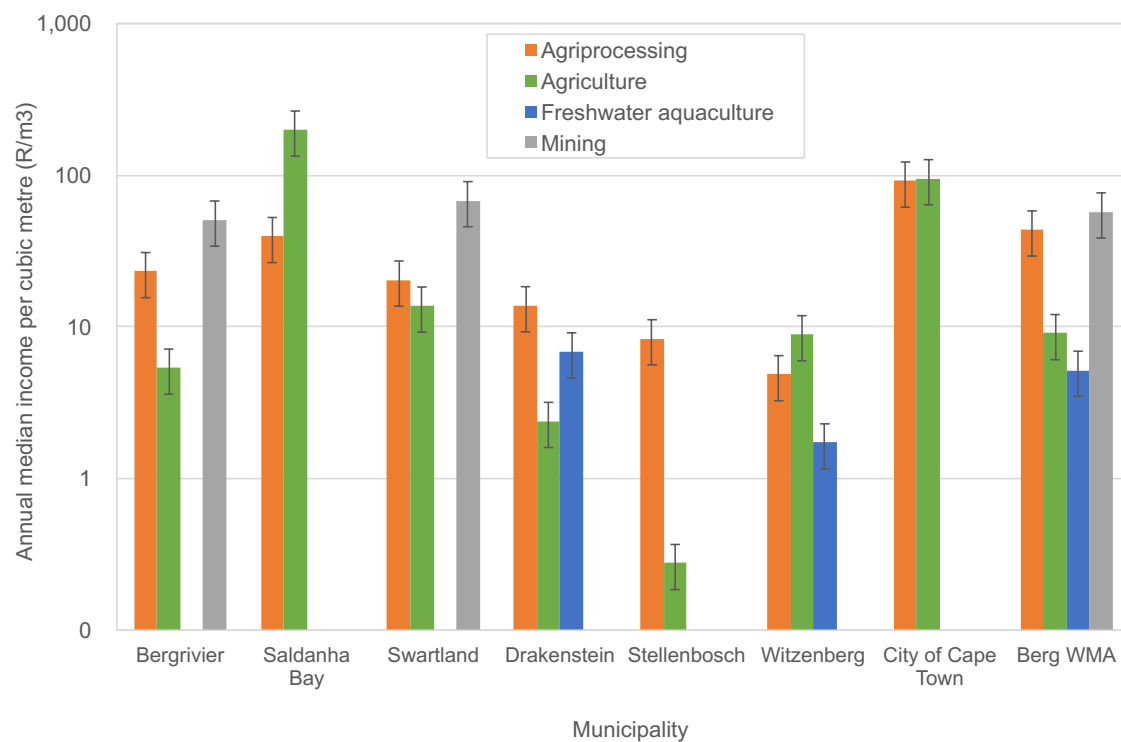


Figure 6.5 Total annual median income per cubic metre of water for heavily water-dependent sectors in the Berg WMA

6.5 Discussion

Where possible, water data have been reported for South Africa, the Berg WMA, its six local municipalities and 45 towns, and its metropole, the City of Cape Town. This has provided an insight into the variability that can be found at different spatial scales and levels. For example, while 70% of that national population have adequate sanitation, 93% of people in the Berg WMA do, though this ranges from 0% to 100% at the suburb level. Domestic per capita water use in the Berg WMA ranges from 73 l/c/d to 596 l/c/d and water losses range from 1% to 51% at town level. While only 25% of South African river ecosystems are critically endangered, 81% of Berg WMA river ecosystems are. A national average therefore hides significant heterogeneity and reporting indicators at multiple spatial levels will aid the prioritisation of activities in water action plans. This supports the SDG requirement to disaggregate data by geographical location and other factors. The disaggregation of access to water and sanitation data show significant racial inequality in the Berg WMA, that women have greater access than men, and that urban areas have greater access than rural areas. Data disaggregation thus provides a much more nuanced picture of the state of sustainable development and enables decision-makers to target specific areas for action.

The main challenge of data disaggregation is data availability. South Africa has good data available at national and sub-national scale for most of the proposed indicators in SDG 6, however, work is needed to regularly update some of the datasets to feed into annual SDG reports. The tier classification in Table 6.1 shows where there are data gaps and methodologies and standards that need to be developed. Only six indicators in targets 6.1, 6.2 and 6.3 can be classified as Tier

1. This shows that there is significant work to do to monitor this suite of water indicators in South Africa. Despite this, the proposed suite can provide a useful case study for other countries to consider.

6.5.1 Water-use efficiency through jobs and income

One of the main aims of this paper was to attempt to define and populate water-use efficiency indicators. Unfortunately, currently available water data are not sufficient to calculate accurate figures for jobs and income per unit of water, although the results provide the most comprehensive assessment to date and illustrate how these figures can be calculated in the future. The analysis would be greatly improved if StatsSA released the full industry Census 2011 dataset (rather than only the 10% sample) and if heavy water users were required to report their annual water use figures. Accurate water use data is most needed for agriculture and agriprocessing.

Water allocations to heavily water-dependent sectors create jobs and provide an income for the employees. The results show that 9% of jobs in the Berg WMA are heavily dependent on water and 16% are moderately dependent on water. This is largely influenced by the City of Cape Town, which has 87% of the population, and is much higher in the more rural Bergrivier LM (50% heavily dependent, 9% moderately dependent) and Swartland LM (31% heavily dependent, 11% moderately dependent). The biggest heavily water-dependent user by far is irrigated agriculture, followed by food processing, although there is significant uncertainty in the water use data for agriprocessing. The jobs analysis shows that agriprocessing produces the most jobs per million cubic metres of water used in

the Berg WMA at 634 jobs/Mm³, followed by mining (326 jobs/Mm³), steel processing (195 jobs/Mm³), agriculture (103 jobs/Mm³) and aquaculture (49 jobs/Mm³). The figures can vary significantly across municipalities within agriculture (from 2 to 1,712 jobs/Mm³) and agriprocessing (from 79 to 965 jobs/Mm³). This is due to the diversity in type of farming and crops farmed, and diversity in the type of agriprocessing facility. Water allocation decisions therefore should be made for specific sub-sectors and regions rather than for agriculture or agriprocessing as whole sectors. The two sectors are also directly linked so that the water allocated to agriculture supports jobs in both agriculture and agriprocessing.

The income analysis shows that mining produces the highest income per cubic metre of water used in the Berg WMA at R57,52/m³, followed by agriprocessing at R43.73/m³, agriculture at R9.07/m³ and aquaculture at R5.20/m³. Again, there is significant variation across the municipalities and significant uncertainty in the agriprocessing figures. Comparing the income analysis to the jobs analysis shows that some sectors like mining generate a few high paying jobs, while other sectors like agriculture generate many, lower paying jobs. The water allocated to each sector therefore has different benefits and outcomes to the socio-economic well-being of the area. While jobs and income measure the benefit of water allocation to individual people, it is important to also measure the gross value add of different sectors as this measures the benefit to the region and the country. This contributes to economic growth and indirectly to poverty reduction through social grants and service delivery.

The allocation of water resources to different areas and sectors will influence the potential for job creation and economic growth in the region. As the population grows and water resources come under increasing pressure, creating jobs with low dependence on water may become a priority or necessity. This may have a positive relative impact on the City of Cape Town, as it is dominated by the low water use service industry, but a negative relative impact on small towns that rely on heavy water users like agriculture and mining. Water allocation decisions therefore must consider the long-term future of all residents. This will require much better data collection on water use, employment and income in different sectors, GIS-based tools to facilitate spatial analysis, scenario development to analyse possible effects of different water allocation decisions, and stakeholder engagement with affected communities and businesses.

6.5.2 Safe and just operating space

The ultimate aim of the SDGs is to bring humanity into the 'safe and just operating space' where everyone lives above an acceptable social floor (minimum standard of living) and below a safe environmental ceiling (defined by critical thresholds) (12). Bringing the concept of just social floors and safe environmental boundaries thinking into the SDGs is helpful as it guides the selection of indicators and setting of targets. Ideally national SDG indicators and targets should define a country's social floor and its environmental ceilings. In SDG 6, social floors are relevant for target 6.1 on access to affordable drinking water, 6.2 on access to adequate sanitation and 6.4 on income from water-dependent jobs. Both official indicators and indicators with a higher social floor should be included in the SDGs to suit the ambition of Agenda 2030. Environmental ceilings are relevant for target 6.3 on

water quality, 6.4 on water stress, and 6.6 on water-related ecosystems. The targets for these indicators should take critical thresholds in freshwater systems into account together with stakeholder engagement and regular reviews to capture changing conditions over time. While achieving the SDGs may seem an ambitious task, the process of selecting indicators and targets will in itself address important issues facing governments and citizens today.

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Supplementary Information for Chapter 6

Table S6.1 Estimated water use (m³/a) in heavily water-dependent sectors per municipality in the Berg WMA

Municipality	Agriculture	Freshwater aquaculture	Agri-processing	Mining	Steel manufacturing
Bergrivier	49,753,965	0	1,283,949	786,202	0
Saldanha Bay	2,352,853	0	5,980,686	440,676	2,920,000
Swartland	27,422,600	0	5,976,213		0
Drakenstein	107,108,571	1,922,953	9,877,479	0	0
Stellenbosch	177,593,770	0	6,092,912	0	0
Witzenberg	3,694,358	500,000	988,873	0	0
City of Cape Town	24,744,229	0	33,517,406	0	0
Berg WMA	392,670,346	1,422,953	63,717,517	1,226,878	2,920,000

Table S6.2 Estimated water use (m³/a) per agriprocessing sub-sector in the Berg WMA

Municipality	Abattoirs	Dairies	Breweries	Food processing	Tanneries	Wine cellars
Bergrivier	500,000	48,543	385	735,021	0	0
Saldanha Bay	1,313,790	31,206	385	3,675,103	0	960,202
Swartland	2,063,790	235,781	1,539	3,675,103	0	0
Drakenstein	1,813,790	48,543	1,924	7,717,717	55,000	240,505
Stellenbosch	0	24,272	3,463	4,777,634	0	1,287,543
Witzenberg	250,000	3,467	385	735,021	0	0
City of Cape Town	5,568,950	83,217	1,772,005	26,093,234	0	0
Berg WMA	11,510,320	475,029	1,780,085	47,408,833	55,000	2,488,250

Table S6.3 Estimated numbers of heavily water-dependent jobs per sector per municipality in the Berg WMA in 2011 (based on Census 2011 10% sample)

Municipality	Agriculture	Fresh-water aqua-culture	Agripro-cessing	Mining & Oil/Gas	Energy & Water	Textile manufact-uring
Bergrivier	4,930	0	709	220	57	64
Saldanha Bay	2,999	0	1,864	42	110	737
Swartland	6,362	0	2,409	180	136	261
Drakenstein	2,353	40	1,073	127	326	437
Stellenbosch	340	46	710	85	162	517
Witzenberg	2,993	53	579	59	197	99
City of Cape Town	15,750	1,175	23,233	2,631	1,362	13,553
Berg WMA	35,727	1,329	30,578	3,344	2,350	15,668

Table S6.4 Estimated numbers of moderately water-dependent jobs per sector per municipality in 2011 (based on Census 2011 10% sample)

Municipality	Manufact./ transform-ation of wood products	Manufact./ transform-ation of metals and minerals	Manufact./ transform-ation of chemicals, rubber, plastics	Construc-tion	Transport
Bergrivier	21	11	8	64	48
Saldanha Bay	32	30	23	179	98
Swartland	21	14	11	184	97
Drakenstein	70	86	39	656	255
Stellenbosch	43	41	58	351	240
Witzenberg	31	35	12	354	107
City of Cape Town	1114	1412	1348	8370	5750
Berg WMA	1,332	1,629	1,499	10,158	6,595

Chapter 7 - Conclusion

The aim of this thesis was to assess and develop new approaches to monitoring sustainable development and inequality at national and sub-national scales, and to measure progress towards sustainable development in South Africa. The research questions were:

- Q1 - Can the visual framework, the 'safe and just space (SJS) for inclusive sustainable development', be usefully applied at the national level?,
- Q2 - What sub-national heterogeneity do national sustainable development indicators hide?,
- Q3 - How can the inequality hidden by national indicators be effectively reported to support policy-making?, and
- Q4 - How can the inequality in sustainable development outcomes related to water allocation be measured and reported to aid decision-making?

These questions were addressed in four case studies that were written up in papers and submitted to academic journals. Paper 1 (Chapter 3) addressed Q1 by downscaling the global SJS framework to the national level to create a 'barometer for inclusive sustainable development' in South Africa. It was published in PNAS Plus in 2014. Paper 2 (Chapter 4) addressed Q2 by downscaling the national barometer to the provincial scale in South Africa to explore the sub-national heterogeneity and inequality in national sustainable development indicators. It was published in Sustainability Science in 2017. Paper 3 (Chapter 5) addressed Q3 by downscaling the water dimensions in the barometer even further to the district, municipal, ward and town levels and calculating national inequality measures. Paper 4 (Chapter 6) addressed Q4 by proposing 26 national indicators for SDG 6

(Water and sanitation) for South Africa, using the Berg Water Management Area as a case study to test the indicators. This chapter reviews the main findings of the research, discusses the implications of these findings, outlines areas for additional and new research, and provides concluding remarks.

7.1 Main findings

7.1.1 South Africa's 'safe and just space'

Chapter 3 described the first worked case study for applying Rockström *et al.*'s (2009) planetary boundaries (PB) and Raworth's (2012) SJS framework at the national level, while Chapter 4 updated national figures and downscaled them further to the provincial level, creating barometers for inclusive sustainable development in South Africa. At the national level, six out of nine measured environmental dimensions - climate change, freshwater use, arable land use, phosphorus loading, marine harvesting and biodiversity loss - have exceeded their safe boundaries while air pollution is only 2% below the safe boundary. The provincial picture is more complex; the provincial barometers show that national reporting can hide significant heterogeneity in environmental status. The biggest variation across provinces occurs for climate change, phosphorus loading and air pollution. Every province has between two and four dimensions that exceed the safe environmental boundary and need urgent attention. For freshwater use, arable land use and air pollution, some of the provincial environmental boundaries have been exceeded despite their national boundary not being exceeded. This highlights the importance of downscaling the PB framework to national and sub-national levels.

National environmental trend plots showed that climate change and freshwater use are moving toward or beyond the safe boundary, while recent progress away from the boundary can be seen for marine harvesting, biodiversity loss, ozone depletion and air pollution. Provincial trend plots showed significant variation in five measured dimensions across provinces, particularly for climate change (CO₂ emissions), phosphorus loading (total P concentrations) and air pollution (PM10 levels). The spatial heterogeneity in the environmental status is a result of several factors such as, (a) the large natural variations in climate, terrain, soil and natural resources, (b) the varying population density and (c) varying economic activities (such as mining, manufacturing, farming and fishing) with their own specific environmental impacts.

The national barometer showed that deprivation exists across a wide range of basic services, public goods, livelihoods and living standards in South Africa. Social deprivation is most widespread regarding safety (68% of people feel unsafe at night), income (45.5% live below the national poverty line), and jobs (34% are unemployed) and least prevalent for education (14% of adults are illiterate), water access (15% of households do not have piped water within 200m of their home) and electricity access (15% of people do not have access to electricity). These figures are all based on a very low social floor and would change significantly if different indicators that represented higher social floors were chosen. The provincial barometers show a similar pattern to the national barometer but marked differences are evident across multiple indicators, demonstrating that national reporting can hide significant heterogeneity. The largest range in the proportion of the population that is deprived across provinces is 41% for income and 40% for

sanitation while the range for health care, food security, water access and safety are close to 30%. The deprivation patterns are closely linked to the location of former 'homelands', partially self-governing territories set aside for black inhabitants of South Africa as part of the Apartheid agenda of racial segregation. These homelands had an extremely weak financial base and relied on transfer payments from the central South African government. The provinces with the largest former homeland areas – KwaZulu-Natal, Eastern Cape, Limpopo and North West - are the most deprived today. The variation in spatial deprivation also reflects economic activities and the quality of the provincial and municipal administration and the availability of skills.

National barometer trend plots showed that since 1994 social deprivation has reduced in all areas except safety and income. Trend plots for the provinces show decreasing deprivation across nearly all provinces and social dimensions, with notable exceptions being food security in six provinces and safety, jobs and housing in three provinces. Social deprivation is decreasing faster in the historically disadvantaged provinces – particularly Limpopo, Eastern Cape and KwaZulu-Natal.

7.1.2 Downscaling the 'safe and just space'

In Chapter 3, a decision-based methodology for defining and quantifying environmental and social dimensions, indicators and boundaries was developed so that the process could be repeated in other countries and contexts. Dimensions, indicators and boundaries that were not appropriate in South Africa were replaced with ones that reflected the local context. If the barometer was adopted nationally,

the indicators would need to be further developed iteratively over time in a dialogue between scientists, civil society and government. In addition, a clear narrative would need to be developed to support the use of the barometer. A very similar decision-making flow chart was used by Teah *et al.* (2016) in their case study on downscaling the PB to the regional level in the Heihe River Basin in north-western China.

In Chapter 3, the environmental dimensions were categorised based on the nature of their safe boundary. Type A ‘global boundaries’ are based on global thresholds, international agreements, and national capability (climate change and ozone depletion); Type B ‘national limits’ are based on local thresholds and finite national resources (water and land); and Type C ‘local biophysical thresholds’ are based on local thresholds and national policy (phosphorus, nitrogen, air pollution, marine harvesting and biodiversity loss). The social dimensions were categorised into four domains to promote understanding and analysis: basic services, public goods, livelihoods and living standards.

In Chapter 4, three methods were used to disaggregate environmental data from national to provincial level for both current status and for safe boundaries, and these could be used in any country across a range of indicators. The first method, “sharing a national total”, is a similar approach to that often used to share global commons by countries, and raises questions of equity and responsibility. The second method, “aggregating accessible local data”, is commonly used for national and global reporting. The challenge here is finding sufficient data that cover the whole country for annual or even for less frequent updates. The third method,

“finding the best fit between ecological units and administrative borders”, deals with the problem of mismatch and requires either estimation or expert knowledge and can be quite time consuming to be accurate.

The findings show that it is possible to maintain the original design and concept of the SJS framework whilst making it meaningful in the national and provincial contexts. In interviews, there was consensus among experts that a national barometer could be a very useful tool in South Africa, and this view is supported by the National Development Plan, which recognises the need to measure and monitor progress on important social and environmental indicators (National Planning Commission, 2012). Specific uses identified by the experts were that:

- it removes inter-sectoral barriers and promotes integrated debate,
- communicates a complex set of indicators in a relatively simple way,
- communicates critical thresholds and environmental limits,
- prompts the question ‘what are we measuring and why?’
- identifies gaps in the underlying knowledge base, and
- raises new questions in the discourse on social deprivation and environmental sustainability.

Inclusion of the barometer in national reports, such as the State of Environment (SOE) Report, was suggested as being highly beneficial. In fact, the PB and SJS diagrams were used in the 2012 national SOE report (DEA, 2016) and the national barometer was used in the 2016 Limpopo Province SOE Report (EcoAfrica, 2016) to frame the sustainable development challenge. Additional views expressed by the experts that support the aims and objectives of this thesis are shown in Box 3.

Box 3. Quotes from expert interviews in South Africa

“The message for policy makers is that the boundaries are not arbitrary but could have significant effects on South Africa.”

“The Department of Environmental Affairs has not ventured into looking at thresholds so there is a gap for the PhD to fill.”

“Planetary boundaries will not get traction in South Africa without the social aspect.”

“The environmental debates have been very focused and very rarely do you see them come together. There is a need for a framework that gets people to think outside their area and to think holistically.”

“If the doughnut framework can be ultimately linked to a monitoring tool for current status that would help our evidence based and adaptive policy making.”

“Under Apartheid, no one discussed minimal levels of living.”

“The message of limits is important. We need to get people to the table to talk about planning decisions.”

“The national picture gives only a fraction of the picture – it’s not very reflective of the geography of social deprivation.”

“South Africa is so unequal that national level is not very useful. Spatial referencing is very important if you want it to be useful.”

“It’s critical to go to local level and look at the complexities.”

The novelty of the barometers is twofold. First, they present a visual snapshot of the state of a broad but manageable set of critical environmental and social indicators in relation to national priorities and realities that goes beyond colour-coding or single figures. The trend charts provide additional information about progress (or lack thereof) over time that aid decision-making, and the combination of environmental and social dimensions highlights the dual nature of the sustainability challenge. Second, they go beyond being merely a measure of the current status, but also highlight the country’s and provinces proximity to

environmental boundaries and acceptable minimum level of social wellbeing. This provides impetus to take action and supports prioritisation at the right administrative level. The barometers are aimed at a national audience first and an international audience second, to encourage national action, and are science-based.

Part of the reason that the PB could be downscaled to the national level in South Africa, is that the concept and definition of environmental limits already exists in many areas of policy and practice. Table 7.1 shows the 10 environmental dimensions of the barometer and the current proximity to the boundary for each one, based on the updated figures in Chapter 4. It indicates whether limits-thinking exists in national policy and whether the limits are being applied in practice. The table shows that the only two areas where limits thinking is not used are the nitrogen cycle and chemical pollution. The application of limits is more varied, and implementation appears to be much more difficult.

Table 7.1 Application of limits thinking in South Africa

Dimension	Proximity to national boundary^a	Limits thinking in national policy?	Applying limits in practice?
Climate change	Exceeded by 5%	Yes. Required by Science scenario in Long Term Mitigation Strategy	No
Ozone depletion	Below by 32%	Yes. HCFC Phase-Out Plan	Yes
Water use	Exceeded by 11%	Yes. Ecological reserve in National Water Act	In future plans – require additional supply first
Land use	Exceeded by 11%	Yes. Land capability in Preservation of Agricultural Land Act	In future plans – competing priorities for land use
Phosphorus loading	Exceeded by 1%	Yes. Treated wastewater effluent	Reporting but failing due to capacity issues
Nitrogen cycle	Below by 41%	No. Only in agricultural research	No
Biodiversity	Exceeded by 34%	Yes. Biodiversity targets for each ecosystem	Yes. Protected areas
Marine harvesting	Exceeded by 43%	Yes. Maximum sustainable yield for each species	Yes. Fishing licences based on total allowable catch
Air pollution	Below by 2%	Yes. National Air Quality Standards	Yes. Reporting and action in priority areas
Chemical pollution	?	No	No

^a data from Chapter 4, except for Nitrogen which has data from Chapter 3

In 2016, Hahya *et al.* (2016) reviewed all existing case studies dealing with operationalising the PB with the aim of providing a ‘consistently applicable approach for translating planetary boundaries into national-level fair shares of Earth’s safe operating space’. The case studies, location and downscaling

approach are shown in Table 7.2 below, along with information on additional case studies by Teah *et al.* (2016) and Fanning *et al.* (2016). While there are two case studies from China, the South African case study (described in Chapter 3) is the only national level study of a developing country. Hayha *et al.* identified the stakeholder engagement approach as the main strength of the national barometer for South Africa but criticised the fact that ‘no connection was made between global and regional sustainability criteria’ and that ‘the fairness in sharing the global safe operating space is not addressed’ This is not quite true as global sustainability criteria and fairness are accounted for in the national safe boundaries for climate change and ozone depletion, the only two dimensions with global thresholds. The climate change safe boundary is based on a national commitment to the UNFCCC to achieve the ‘required by science’ scenario for climate change mitigation by 2035, taking the principles of ‘common but differentiated respective capabilities and responsibilities’ and ‘right to development’ into account. International equity is essential to the UNFCCC agreements and the equal per capita share approach used in European national case studies would not be accepted by policy-makers in South Africa. Similarly, the ozone depletion safe boundary is based on South Africa’s commitment to phase out ozone-depleting substances in accordance with the Montreal Protocol and international treaty. That said, the link between global and national sustainability could be further explored in future work.

Table 7.2 Case studies of national and regional planetary boundary studies (after Hayha *et al.* (2016), with additional information from Teah *et al.* (2016) and Fanning *et al.* (2016).

Study	Country or region	Approach
Nykvist <i>et al.</i> (2013)	Sweden	National allocation based on equal per capita shares
Hoff <i>et al.</i> (2014)	European Union	National allocation based on equal per capita shares
Dao <i>et al.</i> (2015)	Switzerland	National allocation based on equal per capita shares considering past impact and future generations
Dearing <i>et al.</i> (2014)	Two Chinese regions	Regional boundaries derived from regional considerations
Cole <i>et al.</i> (2014)	South Africa	National boundaries based on national conditions
Teah <i>et al.</i> (2016)	Region in Gobi Desert, China	Regional boundaries based on regional data and local knowledge
Fanning <i>et al.</i> (2016)	Canada and Spain	National allocation by equal share and national footprints

The main contributions of this aspect of the research are:

- downscaling the ‘safe and just space’ to the national level for the first time;
- describing progress towards the SDGs in South Africa at national and provincial levels;
- proposing a decision-based methodology for defining the ‘safe and just space’;
- comparing South Africa’s provinces across both environmental and social dimensions in a novel way;
- providing an early case study of SDG data disaggregation of both environmental and social sustainable development indicators;

7.1.3 Measuring and understanding water inequality

Equality is at the heart of the Agenda 2030 for Sustainable Development and the SDGs. While Goal 10 is focused on inequality, equality is mainstreamed throughout the other goals through targets 'for all' and the requirement to disaggregate data by gender, race, geographical location and other context-specific factors. While reporting gender and race at national level may not require too many more indicators, reporting tens or hundreds of geographical locations such as local municipalities, is onerous. In Chapter 5, the aim was to identify how sub-national spatial inequality could be represented in national indicator reporting. Based on the research in Chapter 5, additional SDG indicators were suggested and were incorporated into the proposed national SDG 6 indicator suite in Chapter 6. In addition, 14 explanatory variables for per capita water use were assessed to improve understanding of the reasons behind water inequality.

The national barometer's indicators for water (freshwater use and piped water access) were spatially disaggregated to the provincial, district, municipal, ward and town level, mapped in GIS and a set of descriptive statistics (range, standard deviation, coefficient of variation) and inequality measures (Gini index and Palma ratio) were calculated. The indicators used were defined slightly differently to the national barometer to facilitate the inequality analysis. The indicator 'piped water within the dwelling' was used instead of 'piped water within 200m of dwelling' to give a holistic picture of water access inequality across South Africa, as 95% of people have the lower level of water access. In addition, the WHO recommend piped water in dwellings to ensure adequate health (Howard and Bartram, 2003). The indicator 'town per capita water use' was used instead of 'total freshwater use'

as only town data were available at the local level, and converting to a per capita measure enabled inequality analysis. The town use figures included water losses and therefore measured bulk supply rather than end-use. A social floor could be defined as 60 l/c/d (the current government target) or 100 l/c/d (the WHO recommendation). Defining the safe environmental boundary is much harder, as water supply at the local level is largely based on large-scale infrastructure and cross-basin water transfers. The analysis on per capita water use is the first study that compares and assesses per capita water use of all settlements in South Africa.

The results showed that although national per capita water use is 208 l/c/d, there is a large range between towns, from 8 l/c/d to 2,414 l/c/d, with a standard deviation of 182 l/c/d and a coefficient of variation of 0.87. The national Gini index for town water use is 0.27 (compared to 0.65 for income in South Africa, 0.22 for income in Sweden) and the Palma is 0.95 (compared to 11.6 for income in South Africa). Across the provinces, average per capita water use ranges from 114 l/c/d in Limpopo to 295 l/c/d in the Northern Cape and the Gini index ranges from 0.07 in Western Cape to 0.35 in the Northern Cape. Analysis showed that per capita water use is affected by socio-economic factors rather than natural factors, with the main influences being piped water access and income.

The results for the analysis on water access showed that 45% of the national population had piped water access in their dwelling in 2011. While 65% of urban dwellers had piped water in their dwelling, 34% of those living on farms and only 8% of those living in traditional/tribal areas have this level of access. Access ranged from 0.07% to 100% across the 4,277 wards, with a standard deviation of 33% and

a coefficient of variation of 0.72. The national Gini index (using ward data) was 0.36 while the Palma was 1.71. Across the provinces, piped water access in dwellings ranges from 18% in Limpopo to 78% in Gauteng while the Gini index varied from a low of 0.06 in Western Cape to a high of 0.57 in the Eastern Cape. The Gini index for districts ranged from 0.05 to 0.72. The results highlighted that the scale of the dataset used can have a large effect on the apparent levels of inequality.

The analysis showed that the Gini index could be a useful tool to measure and report non-income inequality in national SDG reporting. Both the numbers and the Lorenz curves summarise inequality in a simple way that is familiar to policy-makers. While the Gini indexes are low compared to South Africa's Gini for income inequality, this is because unlike income, which has no upper limit, piped water access cannot exceed access within a dwelling and water use also has practical limitations, although not as strict. This means that wealthy households can be recorded as the same as those who are much less well-off, and the inequality in their living conditions are not reflected in the Gini index for water access. In addition, for water use the metros and large towns are reported as single observations just like small towns and village clusters, therefore the inequality within metros and large towns remains hidden. As the lower-than-usual figures may give an impression of low inequality, the Gini is probably most useful for comparing provinces and districts.

The main contributions of this aspect of the research are:

- exploring the challenges and opportunities raised by sub-national indicator reporting relevant for the SDG implementation;

- compiling a new database of local water use across South Africa;
- creating new measures of water inequality, the Gini index and Palma ratio for water access and per capita water use;
- providing data and tools to support geographical targeting for effective policy implementation.

7.1.4 Water for sustainable development

In Chapter 6, the aim was to describe how water supports sustainable development outcomes, analysing water-dependent jobs and income in particular, and SDG 6 (water and sanitation) targets more broadly. A suite of 26 national indicators was proposed for SDG 6 covering water access (6.1), sanitation (6.2), water quality (6.3), water-use efficiency and sustainability (6.4), water resources management (6.5) and water-related ecosystems (6.6). Their data sources and SDG tier classification were listed to enable future use and to identify gaps in data and research. The indicators were populated with national data and data specific to the Berg Water Management Area (WMA), its towns, local municipalities and its metropole the City of Cape Town. The indicators for targets 6.1, 6.2, 6.3, 6.5 and 6.6 were based on research from Chapters 3, 4 and 5. Target 6.4 on water-use efficiency and sustainability required additional research. Domestic per capita water use, physical water losses, jobs per million cubic metres (Mm^3) of water used in heavily water-dependent sectors, and total median income per cubic metre of water used in heavily water-dependent sectors (R/m^3) were proposed as indicators for target 6.4. Five heavily water-dependent sectors in the Berg WMA were assessed: agriculture, agriprocessing, freshwater aquaculture, mining and steel processing.

The analysis provided additional insight into the variability that can be found at different spatial scales. For example, at the national level, 70% of people have adequate sanitation and 25% of South African river ecosystems are critically endangered. In the Berg WMA, 93% of people have adequate sanitation, though this ranges from 0% to 100% at the suburb level, and 81% of Berg WMA river ecosystems are critically endangered. Domestic per capita water use ranges from 73 l/c/d to 596 l/c/d and water losses range from 1% to 51% at town level in the Berg WMA. The disaggregation of water access and sanitation data showed significant racial inequality in the Berg WMA, that women have marginally more access than men, and that urban areas have greater access than rural areas. The national average therefore hides significant heterogeneity and reporting indicators at multiple spatial levels will aid the prioritisation of activities in water action plans. If made publically available, it could also help citizens hold government to account more effectively.

The analysis on water-use efficiency through jobs and income showed that 9% of jobs in the Berg WMA in 2011 were heavily-dependent on water and 16% were moderately-dependent on water. This is largely influenced by the City of Cape Town as it is home to 87% of the population in the Berg WMA. Jobs are more dependent on water in the more rural Bergrivier local municipality (50% heavily dependent, 9% moderately dependent) and Swartland local municipality (31% heavily dependent, 11% moderately dependent). While there is considerable uncertainty in the agriprocessing figures, results showed that this industry produces the most jobs per million cubic metres of water used in the Berg WMA at 634

jobs/Mm³, followed by mining (326 jobs/Mm³), steel processing (195 jobs/Mm³), agriculture (103 jobs/Mm³) and aquaculture (49 jobs/Mm³). The figures can vary significantly across municipalities within agriculture (from 2 to 1,712 jobs/Mm³) and agriprocessing (from 79 to 965 jobs/Mm³), due to the diversity in type of farming and crops farmed, and diversity in the type of agriprocessing facility. While not included in the analysis, 75% of jobs in the Berg WMA will be more efficient as they are not as dependent on water.

The income analysis showed that mining produced the highest median income per cubic metre of water used in the Berg WMA at R57,52/m³, followed by agriprocessing at R43.73/m³, agriculture at R9.07/m³ and aquaculture at R5.20/m³. Again, there was significant variation across the municipalities. Comparing the income analysis to the jobs analysis shows that some sectors like mining generate a few high paying jobs, while other sectors like agriculture generate many, but lower paying, jobs. The water allocated to each business and sector can therefore produce quite different socio-economic benefits and outcomes in an area.

This analysis on water-dependent jobs and income is the most comprehensive to date in South Africa and has highlighted significant gaps in water use data and research on water-use efficiency. It was used as an input to the South African Water Research Commission's work on setting the water research agenda for domesticating the SDGs and water-use efficiency will form part of the SDG research agenda going forward. This is significant given South Africa's water scarcity and high levels of unemployment and income poverty.

The main contributions of this aspect of the research are:

- proposing a comprehensive national SDG 6 indicator suite for South Africa;
- providing a case study on SDG data disaggregation by gender, race and geographic location;
- calculating new measures of water-use efficiency based on jobs, and income, per unit of water allocated.

7.1.5 Challenges and opportunities of scale

Scale is a cross-cutting theme in this thesis. In Chapter 3 and Chapter 4, the SJS framework was downscaled from the global to national level, and then to provincial level. In Chapter 5, water use and water access were assessed across six administrative levels and in Chapter 6 and 7, water indicators were assessed at national and local level, and at administrative and ecological scales. Together, these four case studies have addressed the three common societal challenges related to scale highlighted by Cash *et al.* (2006) – *ignorance* of cross-scale/level interactions, *mismatch* between ecological scale and human institutions, and *plurality* in the perception and value placed on knowledge and scales by different actors. The papers have contributed to the four most important scale-related science research issues identified by Gibson *et al.* (2000) - identifying patterns, explaining patterns, generalising propositions between levels of the same scale; and optimising processes or functions at points or regions on a scale.

The link between the four papers, the challenges of scale and the research areas related to scale are shown in Table 7.3. As all four papers sought to provide useful monitoring tools and information for policy-making, scale mismatch was a

challenge throughout. Paper 1 found a mismatch between the global and national 'safe and just space', and a diversity of views in South Africa on the importance of a global framework like the PB or SJS in the national context. It optimised the dimensions, indicators and boundaries of the SJS framework for the national level. For example, measuring the global CO₂ concentration is important for tracking the progress towards or away from a global tipping point for climate change, but CO₂ emissions must be measured at the national level if it is to be mitigated. Paper 2 addressed mismatch between ecological units and provincial borders by developing three approaches for disaggregating national data to the provincial level. It addressed ignorance of the effect of sub-national actions on South Africa's national safe boundaries by plotting provincial proximity to its safe boundary for eight environmental dimensions. Paper 2 identified patterns in provincial data across 20 SDIs and contributed to optimising action at the right spatial level by highlighting environmental and social provincial priorities. Paper 3 addressed plurality by mapping and reporting water use and access data and inequality at multiple administrative levels, and by assessing the correlation between per capita water use and 14 explanatory variables. This identified patterns in the data and provided explanations for the large variation in water use across South Africa. This could be used to optimise policy-making and implementation at the right scale. Paper 4 addressed mismatch and generalised the Berg WMA (one of 19 WMAs in the country) as a case study to propose a set of national indicators for SDG 6 (water and sanitation). The socio-economic benefits of water allocations were determined at the local scale to guide water allocation at the WMA and national level, though they highlighted the importance of the local context and optimising action at the right scale. Paper 4 highlighted the fact that safe environmental boundaries and

just social floors may need to change at the local level where conditions are quite different to the national picture. For example, sanitation levels in the Berg WMA are much higher than the national average, and the official indicator is not very useful.

The thesis has provided four case studies of data disaggregation by geographic location that are required in the SDG global monitoring framework. The other disaggregation dimensions - gender, age, race, ethnicity, migratory status and disability – will vary spatially and therefore also have a geographical nature. The lessons learned in these case studies are therefore relevant across all dimensions of disaggregation for national and sub-national SDG monitoring.

Table 7.3 The main challenges of scale and research contribution of each paper

Paper	Spatial scale/level	Main challenges	Main research contribution
1	Global - national	Mismatch Plurality	Optimising action at right spatial level
2	National - provincial	Ignorance Mismatch	Identifying patterns across 20 SDIs Optimising action at right spatial level
3	National – provincial – district - municipality – town - ward	Plurality	Identifying patterns in water use and water access Explaining patterns in water use
4	National – Water Management Area – municipality - town	Mismatch	Generalising from local to national Optimising action at right spatial level

7.2 Implications of findings

7.2.1 Global implications

South Africa is not a big contributor to the global pressure on the planetary boundaries. It is, however, the main contributor on the African continent, and is a member of the BRICS group that does have a significant global impact. It is also a member of the G-20⁷, the G-24⁸ and the UN Economic and Social Council. These relationships both put pressure on South Africa to contribute to meeting global environmental goals, and provide a platform for novel tools and strategies to be shared. South Africa is a leader in addressing ozone depletion, having already phased out all ozone-depleting substances except HCFCs, and in biodiversity assessments, pioneering the ecosystem approach. It has also played a leading role in the climate change negotiations through the BASIC negotiating group (Brazil, South Africa, India, China) and the African Group of Negotiators, and by pledging to voluntarily reduce CO₂ emissions to 42% below business as usual by 2030 in Copenhagen in 2009.

Given its strength of data and research, its experience with domesticating the MDGs, and its supportive business community (PWC, 2015), South Africa should be a global leader in developing national SDG indicators and monitoring progress towards the SDGs. Although it hosted the first UN World Data Forum in Cape Town in January 2017, it has not yet submitted a voluntary national review to the UN.

⁷ The G-20 (or group of Twenty) is an international forum for the governments and central bank governors from 20 major economies.

⁸ The G-24 coordinates the position of developing countries on monetary and development issues and promotes increased representation and participation of developing countries in negotiations on the reform of the international monetary system (G24, 2014)

Voluntary national reviews 'aim to facilitate the sharing of experiences, including successes, challenges and lessons learned, with a view to accelerating the implementation of the 2030 Agenda' and have been submitted by 73 countries to date (UN-DESA, 2017). While StatsSA held workshops on indicators for national, provincial and metro reporting in 2016, the reports have not yet been released (Naidoo, 2017). There is therefore an opportunity to bring the findings from this thesis into the SDG national review, which would then be shared with the global SDG community. If South Africa found the barometers and non-income inequality measures and water indicators to be useful monitoring, communication and advocacy tools at the national and sub-national levels, perhaps other emerging economies would follow suit.

7.2.2 Regional implications - Southern Africa

South Africa is one of 15 member countries (Figure 7.1) of the Southern Africa Development Community (SADC), which aims to achieve development, peace and economic growth through regional integration for its 277 million people (SADC, 2017). Although South Africa works most closely with its six immediate neighbours, it is committed to SADC policies, which include water, agriculture and energy. Environmental stress and social deprivation in South Africa impact on the region in several ways, particularly as South Africa is the economic hub and has attracted over a million migrants from SADC countries (StatsSA, 2015). Likewise, policies and actions in SADC countries will affect South Africa.



Figure 7.1 Location of SADC countries

Chapter 3 showed that South Africa has exceeded its climate change boundary, with CO₂ emissions above the 'Required by Science' target. Increasing electricity exports to SADC countries and hydropower imports from Mozambique, and in future the Democratic Republic of Congo (Mataboge, 2013), should reduce South Africa's emissions while contributing to development in other SADC countries. South Africa has exceeded its safe water boundary, but is already dependent on water imports from Lesotho. Further deterioration of river ecosystems in South Africa could affect water courses that are shared with Swaziland, Botswana and Namibia. Water stress and limited arable land in South Africa affects food security and the DWA has analysed the crop production potential in Zimbabwe, Zambia, Malawi and Mozambique as a way of reducing water demand (DWA, 2010). As demand for food rises in South Africa, it could either positively support agricultural development in SADC for mutual benefit, or it could become a drain on regional

resources as food (and the virtual water it incorporates) is exported from poorer countries to South Africa. South Africa has exceeded its biodiversity loss boundary, with 43% of ecosystems critically endangered. As biodiversity does not respect political boundaries, regional cooperation is necessary to prevent further loss of species and ecosystems. Terrestrial biodiversity conservation in Southern Africa is managed through Transfrontier Conservation Areas (TFCAs), which also support ecotourism in the region and South Africa shares six TFCAs with its neighbours⁹. There is also regional cooperation on marine species and ecosystems, such as the Benguela Current Large Marine Ecosystem programme, the Agulhas and Somali Current Large Marine Ecosystems Project, and regional partnerships between Namibia, Angola and South Africa focused on marine ecosystems off the south-west African coast (UNOPS, 2014). This regional cooperation should reduce biodiversity loss; however, it increases the complexity of managing South Africa's own ecosystems and failure to enforce conservation practices in neighbouring countries will impact on South Africa's performance on biodiversity loss.

7.2.3 National implications - South Africa

South Africa's development pathway must address the dual challenges of ending enduring deprivations faced by millions of residents while simultaneously ensuring resource use is nationally, regionally and globally sustainable. While Chapter 3 and 4 showed that deprivation has been decreasing in South Africa since 1994 across nine social dimensions, the environmental picture is much more mixed. The National Development Plan's ambitious target of 5.4% GDP growth and 11 million new jobs by 2030 requires a healthy, functioning natural environment if it is to be

⁹ Kgalagadi, Lubombo, Great Limpopo, Maloti-Drakensberg, Ai-Ais/Richtersveld

achieved. For example, a collapse in fish stocks would result in thousands of job losses. Further deterioration in water quality will reduce the available water supply and limit productive activities such as agriculture and manufacturing. A changing climate is already impacting on small and large-scale farmers, and flooding can halt mining operations, hinder transport of goods and leave commuters stranded. Climate change may also contribute to further environmental stress, such as freshwater availability, land use change and biodiversity loss, and the country's energy sources need to shift from coal-based to renewables. Table 3.3 in Chapter 3 indicated where environmental stress will impact directly on energy security, food security, water security, job security and human health, which in turn affect the national economy. If business-as-usual continues, the current nature of economic growth in South Africa is likely to cause further environmental stress and inequality, maintaining the status quo of social deprivation, or worsening deprivation if spend on services and grants decreases. These wide and far-reaching implications require a review of current national policies.

Table 7.4 and 7.5 suggest focus areas that are likely to have the most effect in achieving the safe and just space, and show the related existing laws and policies that should be reviewed in the light of the results in the barometers. Good governance, capacity building to ensure implementation, and spatial development planning need to underpin all of these policy focus areas. The 2013 Spatial Planning and Land Use Management Act promotes social and economic inclusion and sustainable and efficient use of land. It defines five principles, including 'spatial justice' aimed at redressing historical imbalances, and 'spatial sustainability' aimed at integrating economic, social and environmental considerations (Kidd, 2014).

Implementation requires adaptive management and this is a new opportunity to ensure development in South Africa moves into the 'safe and just space' across towns and cities.

Table 7.4 Policy focus areas related to environmental stress

Dimension	Potential Focus Areas	Existing Laws & Policies
Climate change	Expand renewable energy Support independent power producers Introduce carbon tax	Integrated Resource Plan for Electricity 2010-2030 Renewable Energy Independent Power Producer Programme Carbon Tax Policy Paper Draft Climate Change Bill
Ozone depletion	Eliminate HCFCs	HCFC Phase Out Plan
Freshwater use	Reduce physical losses Expand groundwater infrastructure Improve measurement of usage	National Water Policy Review National Water Resources Strategy 2
Land use	Review use of arable land Include land capability in mining licence approval process	Spatial Planning and Land Use Management Act Preservation and Development of Agricultural Land Act
Phosphorus loading	Skills development for waste water treatment plant maintenance and operation	Water Services Act Green Drop Programme
Nitrogen	Monitor fertiliser use by farmers	
Marine harvesting	Enforce Total Allowable Catches of commercial fisheries	Marine Living Resources Act Policy for the Small-scale Fisheries Sector
Biodiversity loss	Expand protected areas – land, aquatic and marine Rehabilitate critically endangered ecosystems	National Biodiversity Strategy and Action Plan
Air pollution	Reduce PM10 pollution	National Air Quality Act
Chemical pollution	Mandatory reporting of hazardous waste	National Waste Management Strategy

Table 7.5 Potential focus areas related to social deprivation

Dimension	Potential Focus Areas	Existing Laws & Policies
Electricity access	Off-grid electricity for remote areas	Integrated Resource Plan for Electricity 2010-2030 (IRP)
Water access	Free Basic Water for all	Water Services Act
Sanitation	Maintenance of community facilities	Water Services Act
Housing	Formal housing for shack dwellers	Housing Act
Education	Teacher training	National Education Policy Act, Employment of Educators Act
Health care	National Health Insurance	Green Paper on the National Health Insurance Policy
Voice	Community involvement in Integrated Development Plans	The Local Government: Municipal Systems Act
Jobs	Labour regulation Skills development Green jobs	Employment Tax Incentive Act, National Skills Development Act
Income	Reduce wage disparities	Basic Conditions of Employment Act
Household goods	Social grants	Social Assistance Act
Food security	Food banks	Social Assistance Act
Safety	Reduce violence against women	Protection from Harassment Bill Domestic Violence Act Sexual Offences Act

Probably the policy area that will go furthest in meeting the challenges described by the barometer are 'green jobs'. Creating employment will contribute to reducing poverty and inequality, raising living standards and improving basic services and public goods through tax revenues. If this employment is focused on reducing environmental stress across the dimensions discussed in this report, then South Africa will be taking significant steps towards achieving its 'safe and just space'. In 2011, the Development Bank of South Africa estimated that 816,000 jobs in the formal economy (excluding multiplier effects) could be created by 2025 (Maia et al.,

2011). Almost half of the jobs are associated with natural resource management, which involves biodiversity conservation, ecosystem rehabilitation and soil and land management, while energy generation would create 25% of green jobs, energy and resource efficiency would contribute 21% of green jobs, and the remainder would relate to emission and pollution mitigation (Figure 7.2). Jobs in these diverse sectors would contribute to addressing the challenges related to climate change, ozone depletion, air pollution, biodiversity loss, land use change, and freshwater use. Creating these 'green jobs' is different to 'greening' existing jobs. This involves decoupling economic growth from resource use which is important for achieving the 'safe operating space'.

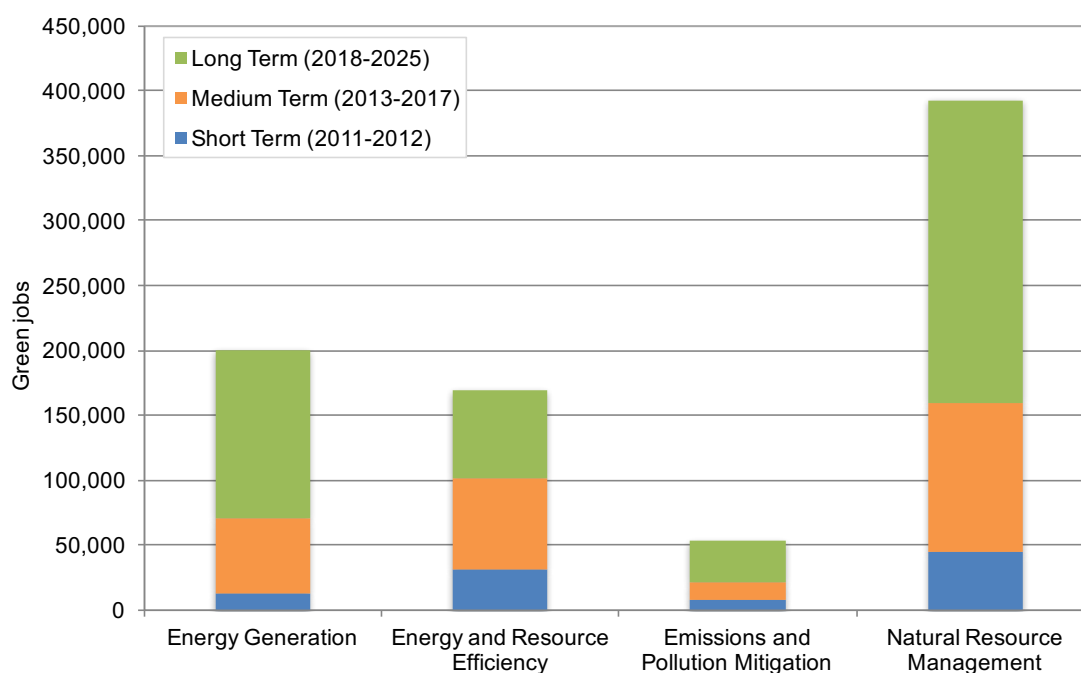


Figure 7.2 Green job creation potential in South Africa 2012 to 2025 (data taken from Maia et al., 2011)

Using the data from Chapters 3 and 4, it is possible to estimate when South Africa could achieve its social foundation, as defined in the national barometer. This is done in Table 7.6 for 11 of the 12 dimensions (voice has a single data point). While

this is a simplistic approach as it is only based on the latest status and rate of change, it does give an indication of how long it might take and the order of the dimensions. The shortest time is 14 years, for water access (in or within 200m of the dwelling), sanitation (ventilated pit latrine or better) and education (adult literacy). The longest is 102 years for safety (people feel safe walking in their area at night), though food security (households with adequate food) had a negative rate of change (over 5 years) so was not calculated. Combining the rate of change and status gives a more positive view on some dimensions, such as income which has the second worst status but the highest rate of change, and a more negative view on other dimensions, such as health care (infant immunisation) which has a relatively low deprivation status but low rate of change.

Table 7.6 Estimated time to achieve South Africa's social foundation

Dimension	Years with data	Latest status of deprivation	Annual rate of change	Years to achieve
Electricity access	2002-2015	14.5	0.6	22
Water access	2001-2014	14.0	1.0	14
Sanitation	2001-2015	20.1	1.4	14
Housing	2002-2015	21.9	0.3	66
Education	1996-2015	14.3	1.0	14
Health care	2001-2013	15.9	0.4	41
Jobs	2001-2015	33.8	0.4	32
Income	2006-2011	45.5	2.3	19
Household goods	2001-2015	27.9	1.5	30
Food security	2010-2015	22.8	-0.2	-
Safety	2003-2015	68.9	0.6	102

7.2.4 Sub-national implications

The variation in environmental stress and social deprivation revealed by the provincial barometers (Chapter 4) and water analysis (Chapter 5 and 6) require quite different responses from different provincial and municipal governments. The type of safe environmental boundary (defined in Chapter 3) plays an important role in this. For Type A boundaries (based on international targets) the municipalities and provinces would need to work together with the national government to determine their safe boundary and action plans to meet international agreements. The methods used for allocating responsibility would need to be debated and an acceptable approach agreed by all the relevant provinces and municipalities to ensure that national targets are met. For Type B boundaries (based on finite natural resources) the barometers show where there are opportunities and risks. Some provinces have unfarmed arable land or unutilised freshwater resources that could be developed and used to support economic growth and job creation. Other provinces are farming large areas on marginal arable land or using more water than is ecologically sustainable and might require a strategic change in agricultural policy to avoid environmental degradation. For Type C boundaries (based on local biophysical thresholds), provinces and municipalities need to identify local areas where the stress is occurring in order to take action. Local data already exist for phosphorus loading, biodiversity loss and marine harvesting and the safe boundary is the same regardless of scale. The thresholds have been set by the national government and should be maintained locally to protect human health and the sustainability of jobs dependent on these natural resources. The barometers could be used in the Integrated Development Plans, required for each local municipality, to identify and prioritise interventions.

Chapter 5 showed how the degree of natural resource use (water) was influenced by social rather than natural factors. To achieve a just social floor of 100 l/c/d will require piped water access in dwellings and increased income to the poor. To stay or move below a safe environmental boundary will generally require water conservation and water demand management of high water users. However, Chapter 5 also showed that the local safe boundary for water can vary significantly. High water users in some areas do not need to reduce their usage, while medium water users in other areas are under pressure to do so. This underscores the importance of disaggregating national data to ensure indicator and boundary definitions are fit for purpose.

7.3 Areas for additional and new research

7.3.1 Data collection and reporting in South Africa

The previous four chapters highlighted areas that require data collection in South Africa. Chapter 3 and 4 identified the areas of climate change, freshwater use, nitrogen cycle and chemical pollution. For climate change, not all provinces have their own GHG emissions inventories and the existing inventories use data from different years, so are not directly comparable. Reporting of provincial and local level data would support the implementation of the national long-term climate change mitigation strategy. For freshwater, supply and demand was last assessed at the national scale in South Africa using data from 2000. This needs to be updated and large water users, such as farmers and heavy industry, who have a water licence should be required to measure their annual water use. The ecological reserve (minimum ecological requirements in rivers) needs to be determined for several Water Management Areas to provide a more accurate measure of the

environmental limits and available supply, although this work is underway. For the nitrogen cycle, seasonal and annual reporting of the fertiliser application for different crops in different regions would enable the determination of the nitrogen use efficiency threshold and help analyse the impact of agricultural production on the nitrogen cycle. For chemical pollution, mandatory reporting of chemical waste for large businesses would help South Africa develop an accurate baseline and monitor the impact of chemical waste on the environment. This would contribute to the wider international research effort on understanding and measuring chemical pollution and novel entities.

An important aspect of data collection is the digital storage of data. Data need to be easily accessible and in a database format that allows for unique queries to be run if it is to be used by researchers and decision-makers. The analysis on town per capita water use in Chapter 5 highlighted the need for easier access to municipal water accounts if in-depth sectoral analysis on water use is to be done. This will be required for monitoring of SDG 6.4 on water-use efficiency. Chapter 6 identified the gap in digital employment industry data for Census 2011 that should be provided by StatsSA in its SuperCross database. Its omission from the database significantly limited the analysis on water-dependent jobs and income. Employment industry data are also collected in the quarterly labour force surveys but are only reported at the provincial level and by aggregated industry (e.g. 'Agriculture, Hunting, Forestry and Fishing' rather than crop farming, animal farming etc.) because the sample size is much smaller. It would be useful to find a method of updating the census employment industry data at the individual industry levels.

An important message that comes from the PB, is that the stable environment that we know could change rapidly to a new unfamiliar state if critical thresholds are crossed. To identify these thresholds and to manage the subsequent changes require more regular data collection. This is part of the 'data revolution for sustainable development' discussed in the SDG process. This will require using new data collection techniques, such as satellite monitoring, and new methodologies to standardise the data. For the social dimensions, big data and crowd sourcing could become standard sources for national SDG reporting.

7.3.2 Safe boundaries and SDGs

While the SDGs indirectly support the goal of living within safe environmental boundaries through the use of terms such as 'sustainably manage', the limits within which sustainability is possible are not explicitly mentioned or defined. Measuring and reporting on indicators will not prevent ecosystem collapse (SDG 6.6, 14.2, 15.1), or keep ocean acidification below the tipping point (SDG 14.3) or avoid eutrophication of water bodies that harm human health (SDG 6.3). The development of regional, national and sub-national indicators is an opportunity to bring critical thresholds and environmental limits into the SDGs more explicitly. This would require significant research for many developing and developed countries and international collaboration will play an important role. Chapter 3 and the other case studies mentioned in Chapter 1 could provide examples of how to go about defining safe national and sub-national boundaries.

7.3.3 Defining national just social floors

Chapter 3, 5 and 6 all mentioned how the selection of social indicators indirectly defines a country's social floors. The definition of national SDG indicators is therefore an opportunity for governments and citizens to engage in a national debate on what the social floors should be. Noble *et al.* (2008) made a start in South Africa by incorporating a set of questions into the 2005 South African Social Attitudes Survey on what items were 'essential to ensure an acceptable standard of living for people living in South Africa today'. The results showed that the government's official indicators, which imply a social floor, often do not correlate with the view of the public. For example, the official measure of adequate sanitation is access to a ventilated pit latrine, whereas the survey showed that 87% of people believe that access to a flush toilet is essential. In South Africa, the deprivation indicators in the government's Development Indicators should be compared to surveyed public opinion and used to feed into the SDG national indicators. This could then inform a revision of the national and provincial barometers described in Chapters 3 and 4. A similar process could be used in other countries around the world.

7.3.4 Data visualisation using barometers

Visual monitoring tools can be powerful and effective communicators of information and shared goals, and online tools support citizen engagement. The 194 countries in the UN General Assembly are likely to explore ways to visualise the results in their annual SDG reports to the UN. While the unofficial SDG Index and Dashboard provide a standardised visual tool, it is likely to be used for country comparisons. The national and provincial barometers presented in this thesis could be adapted

to provide useful tools in national and sub-national SDG monitoring. There are three areas of the barometers that would benefit from further work. Firstly, the environmental plots could incorporate a middle amber zone above the safe boundary but before a critical threshold that provides a warning to decision-makers to act, as shown in the updated PB diagram (Figure 7.3). Secondly, Gini indexes could be added to each dimension in the social plots to give an indication of the state of inequality. Thirdly, a clear narrative that is well-suited to different intended audiences and an implementation toolkit would need to be developed if it were to be used by government departments. This would need to be regularly reviewed to accommodate changing circumstances and priorities.

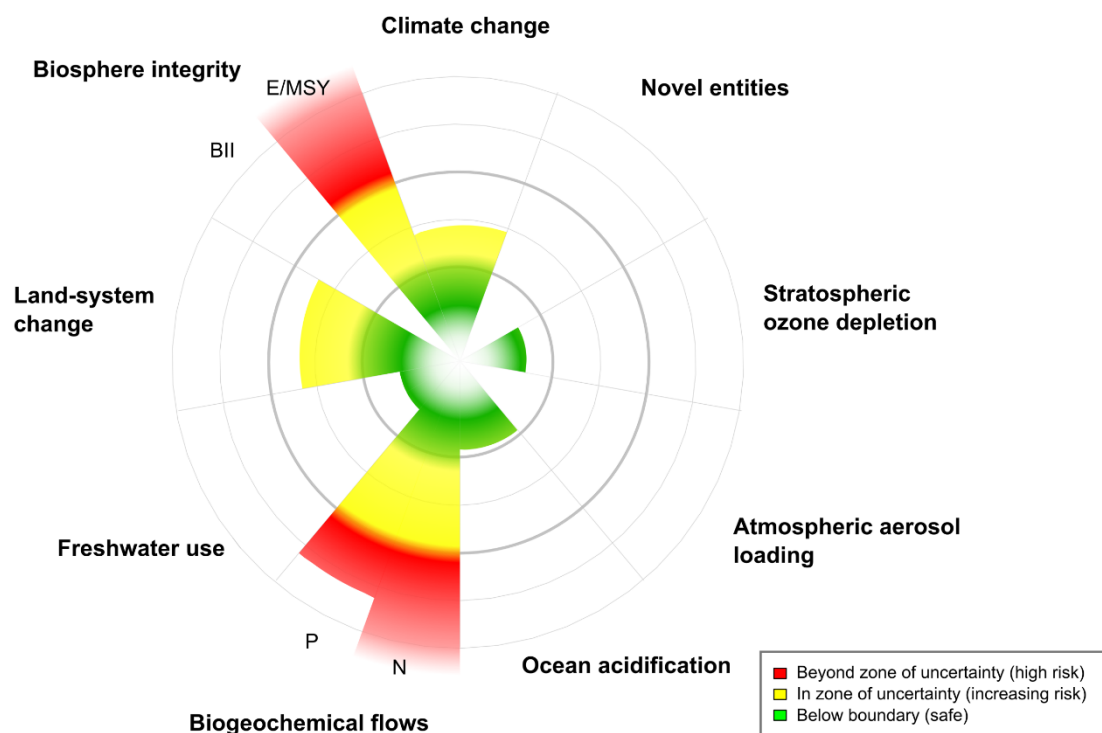


Figure 7.3 Updated planetary boundaries diagram (Steffen, Richardson et al. 2015). Reprinted with permission from AAAS.

7.3.5 Social-ecological trade-offs

Steffen, Broadgate *et al.* (2015a) illustrated an emergent planetary-scale coupling between the socio-economic system and the biophysical Earth system. The linkages between socio-economic and biophysical systems are even stronger at the local scale, and a large body of literature exists describing social-ecological systems. While Raworth (2012) argued that achieving the social foundation would not push the planet beyond its planetary boundaries, there is interesting research to be done to determine the ecological impact of achieving the just space for humanity. For example, one could estimate the additional water use that would result from universal access to piped water in dwellings at the national and sub-national levels. This could then be added to the current water demand and compared to the safe water use boundary. The defined social floor (i.e. piped water in dwellings vs piped water within 200m of the dwelling) would have a big impact on the results. It is important that this research is done using a framing of international equity so that the wrong message is not received. Rather, it would indicate how much additional effort is required by the state and the wealthier parts of the population to reduce environmental stress while significantly reducing inequality. This would be a powerful addition to the barometers and trajectories described in this thesis.

7.4 Concluding remarks

As global environmental change and population growth strain natural resources across the world, monitoring tools play an important part in helping countries solve their most pressing sustainability challenges. The national and provincial barometers for inclusive sustainable development presented in Chapter 3 and 4

communicate the scale of the challenge that South Africa faces in the 21st century, link national and global sustainability issues, and advocate action. The water maps and Gini indexes in Chapter 5 illustrate the extent of non-income inequality in the country, enable geographical targeting of water interventions, and will allow South Africa to track its progress on reducing water inequality over time. The SDGs, with an example of SDG 6 in Chapter 6, will be the focus of international development for the coming 13 years and research that improves the indicators, targets and data used could have a significant positive impact. This thesis has grappled with the challenges in applying the SDGs at the national and sub-national level, and has provided a set of novel tools and datasets to aid policy-makers in the 21st century. As South Africa's National Development Plan says: 'The future is ours, we must make it work'.

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