A REVIEW OF AND SCOPING FOR WATER SCARCITY/SECURITY RESEARCH IN SOUTH AFRICA: TOWARDS A RESEARCH STRATEGY

Report to the
Water Research Commission

by

Jean-Marc MWENGE KAHINDA[1], Evison KAPANGAZIWIRI[1], Denis HUGHES[2] and Khodani KHAKHU[1]

[1] Council for Scientific and Industrial Research, Water Centre,

[2] Institute for Water Research, Rhodes University

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Obtainable from
Water Research Commission
Private Bag X03
Gezina
PRETORIA, 0031

orders@wrc.org.za or download from www.wrc.org.za

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EXECUTIVE SUMMARY

Panta Rhei, the current scientific decade 2013-2022 of the International Association of Hydrological Sciences, that focuses on hydrological change and its connection to society, will soon end. It is anticipated that the 23 Unsolved Problems in Hydrology (UPH) will be central to the upcoming scientific hydrological decade. The UPHs are articulated around 7 themes:

(1) Time variability and change,

(2) Space variability and scaling,

(3) Variability of extremes,

(4) Interfaces in hydrology,

(5) Measurements and data,

(6) Modelling methods, and

(7) Interfaces with society.

The relevance of the UHP to South African hydrology is explored and some national perspectives are emphasised. A systematic literature review (SLR) was utilised to objectively analyse available studies to determine the state of hydrology research in South Africa. Under the 7 themes, searches were performed on major databases such as Science Direct, Google Scholar, Scopus, and Web of Science between 2000 and 2021 using a variety of search terms. Several science questions are posed under each of the 7 themes, most of which comes from the 23 UPH, and several research questions are identified.

The upcoming organised society currently formed by the hydrology community of practice is the best body to develop and implement the South Africa Hydrology Research Strategy. This will however require close collaboration with the relevant government department and research entities at the level of the working groups addressing the 7 themes.

South Africa's domestic research development and innovation (RDI) expenditure is less than 1% of the gross domestic product. Data paucity precludes the quantification of hydrology research funding and its apportionment to different sources (government, corporations, international institutions/agencies and non-profit foundations). Nevertheless, the Water Research Commission remains the main funding body supporting water research, with roughly 20 to 30% (estimate) of its total RDI expenditure funding hydrology and water resources research. Hydrology is primarily funded nationally through the Water Research Commission and there is a potential to improve the funding mix by targeting stakeholders' needs, particularly corporations.

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ACRONYMS & ABBREVIATIONS

ACRU	Agricultural Catchments Research Unit
CSIR	Council for Scientific and Industrial Research
DEA	Department of Environmental Affairs
DHSWS	Department of Human Settlements, Water and Sanitation
DWAF	Department of Water Affairs
FRIEND	Flow Regimes from International Experimental and Network Data
GCM	General Circulation Model
HCOP	Hydrology Community of Practice
HELP	Hydrology for the Environment, Life and Policy
HRU	hydrologic response units (HRUs
IAHS	International Association of Hydrological Sciences
IPCC	Intergovernmental Panel on Climate Change (IPCC
IWR	Institute for Water Research
LULC	land use/land cover
PUB	Predictions in Ungauged Basins
QC	Quaternary catchment
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RDI	research development and innovation
SANCIAHS	South African National Committee for International Association of Hydrological Sciences
SANSA	South African National Space Agency
SLR	Systematic Literature Review
SPEI	Standardised Precipitation Evapotranspiration Index
SPI	standardised precipitation index
SWAT	Soil and Water Assessment Tool
UNESCO	The United Nations Educational, Scientific and Cultural Organization
VA	Voluntary Association
WRC	Water Research Commission

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

South Africa has a diverse climate and physiographic environment and is also faced with many problems related to the interactions between hydrology and society. Today, there is overwhelming global evidence that anthropogenic influences are greater, dominating the natural cycle of freshwater and causing environmental changes that are argued to have moved the planet into a new geologic period termed the “Anthropocene”. One signal of the Anthropocene that often goes unremarked is our drastic “re-plumbing” of the planet's freshwater. Thus, it is necessary to revisit the current hydrological research agenda to speak directly to the issue of water security for the country as, with a growing population, expanding urbanization, increased socio-economic development and a changing climate, water availability looks set to remain a limiting factor (Basson *et al.*, 1997). Fortunately, thanks to scientific advances over the recent past few decades of water research in the country, a lot of novel scientific developments have been undertaken to solve practical societal problems. However, the central question is whether there is a need for our scientific research to be redirected, especially to answer ‘new’ or emerging regional, national, and international challenges, such as water, food, and energy security to give the expected impetus to the national development agenda envisioned in the fourth industrial revolution.

Another relevant question is the appropriateness (including flexibility and robustness) of the tools and methods used to answer this question and the degree to which big data and data analytics can support the enhancement of hydrological research in South Africa. This new research agenda will need to conceptualise a portfolio that encompasses multiple scales (from the international to the national, sub-national and even individual basin), respond to current and immediate challenges, while at the same time continuing to scan the horizon to identify potential future risks and opportunities and be as much forward-thinking as it is retrospective (learning from the past to gain sufficient intelligence to avoid and correct previous missteps).

1.2 APPROACH

Hydrologists from all over the world have recently gathered and discussed the important hydrology questions that remain unsolved. Blöschl et al. (2019) spent more than a year surveying and soliciting opinions and concluded that there are 23 unsolved hydrology problems. These problems are articulated around 7 themes: (1) Time variability and change, (2) Space variability and scaling, (3) Variability of extremes, (4) Interfaces in hydrology, (5) Measurements and data, (6) Modelling methods, and (7) Interfaces with society. It is often difficult to frame a set of questions that relate to observed phenomena, are universal and specific (the three original requirements to formulate the problems). These questions have been developed and adopted for consideration by the hydrology community over the next few years. However, it is almost inevitable that most questions are related to a particular climate region or modelling rather than observed phenomena. While there are indeed a few unexpected questions that would trigger new thinking, it is true that most of the proposed questions clearly show that most colleagues simply proposed anything that, or places where hydrologists currently work, and the gaps they experience with nothing new offered to explore outside this narrow view. This gives us the latitude to think of questions that relate specifically to us, our conditions, or circumstances. The question of how to make hydrology more open and replicable is not reflected in the final set of questions, for example. The narrative below reflects what the relevance is of the 23 questions for South African hydrology, with a few additional questions that the team believes are of utmost importance (Table 1.1).

Table 1.1. Relevance of the 23 hydrological questions in South Africa

Theme	#	Questions	Relevance	Author's comments
Time variability and change	1	Is the hydrological cycle regionally accelerating/decelerating under climate and environmental change, and are there tipping points (irreversible changes)?	Yes	Might fall under the Climate Change KSA
	2	How will cold region runoff and groundwater change in a warmer climate (e.g. with glacier melt and permafrost thaw)?	No	We do not have glacier or permafrost
	3	What are the mechanisms by which climate change and water use alter ephemeral rivers and groundwater in (semi-) arid regions?	Yes	Important but can be estimated with existing modelling tools. Should explore two-way interactions with channels and groundwater. Consider local climate trajectories.
	4	What are the impacts of land cover change and soil disturbances on water and energy fluxes at the land surface, and on the resulting groundwater recharge?	Yes	We think a lot of work has been done on this already.
Space variability and scaling	5	What causes spatial heterogeneity and homogeneity in runoff, evaporation, subsurface water and material fluxes (carbon and other nutrients, sediments), and in their sensitivity to their controls (snow fall regime, aridity, reaction coefficients)?	Yes	We already know a lot about surface water, but probably less about Water Quality and sediments.
	6	What are the hydrologic laws at the catchment scale and how do they change with scale?	No	Too academic.
	7	Why is most flow preferential across multiple scales and how does such behaviour co-evolve with the critical zone?	No	Too academic.
	8	Why do streams respond so quickly to precipitation inputs when storm flow is so old, and what is the transit time distribution of water in the terrestrial water cycle?	No	Too academic.
Variability of extremes	9	How do flood-rich and drought-rich periods arise, are they changing, and if so, why?	Yes	Valid question, but probably difficult to get a better answer than we already have.
	10	Why are runoff extremes in some catchments more sensitive to land-use/ cover and geomorphic change than in others?	No	We generally know the answer to this question.
	11	Why, how and when do rain-on-snow events produce exceptional runoff?	No	Barely any snow.
Interfaces in hydrology	12	What are the processes that control hillslope-riparian-stream-groundwater interactions and when do the compartments connect?	Yes	Some previous work in different areas, but no real knowledge of regional variations. Probably need a combination of field and modelling studies.
	13	What are the processes controlling the fluxes of groundwater across boundaries (e.g. groundwater recharge, inter-catchment fluxes and discharge to oceans)?	Yes	The key issue is recharge, but more locally, information on inter-catchment fluxes is important (dolomites, TMS). There is previous work that needs to be synthesised.
	14	What factors contribute to the long-term persistence of sources responsible for the degradation of water quality?	No	This has to do with point and nonpoint sources of pollution.
	15	What are the extent, fate and impact of contaminants of emerging concern and how are microbial pathogens removed or inactivated in the subsurface?	Yes	While relevant, this falls under another KSA.
Measurements and data	16	How can we use innovative technologies to measure surface and subsurface properties, states and fluxes at a range of spatial and temporal scales?	Yes	We need to look beyond RS
	17	What is the relative value of traditional hydrological observations vs soft data (qualitative observations from lay persons, data mining, etc.), and under what conditions can we substitute space for time?	Yes	This could be very important given the lack of data coming from SAWS.
	18	How can we extract information from available data on human and water systems in order to inform the building process of socio-hydrological models and conceptualisations?	Yes	This is hard to frame and directly relates to water-related data.
Modelling methods	19	How can hydrological models be adapted to be able to extrapolate to changing conditions, including changing vegetation dynamics?	Yes	Lots of previous work, so we need to identify gaps.
	20	How can we disentangle and reduce model structural/parameter/input uncertainty in hydrological prediction?	Yes	Lots of previous work. Need better climate data. Recognition of uncertainty.
Interfaces with society	21	How can the (un)certainty in hydrological predictions be communicated to decision makers and the general public?	Yes	Many potential links between hydrological uncertainty and risk, decision making and others (e.g. insurance). Also links to future uncertainty and CC. There is some previous work (both locally and internationally).

Theme	#	Questions	Relevance	Author's comments
	22	What are the synergies and trade-offs between societal goals related to water management (e.g. water-environment-energy-food-health)?	Yes	Hydrology can contribute, but it is part of other sectors.
	23	What is the role of water in migration, urbanisation and the dynamics of human civilisations, and what are the implications for contemporary water management?	No	While environmental migration is a real issue, it is not tackled by hydrologists.
Additional questions relevant to South Africa	1	How can we improve the data on water use?	Yes	Quite a lot of possibilities to innovate (see 16).
	2	Model improvement for better process representation.	Yes	Wetlands, transmission losses and Karst. Riparian evaporation losses. Urban stormwater runoff. SW/GW interactions in different regions.
	3	A better structured hydrological society	Yes	The hydrology community of practice opted for an independent new society.
	4	National database of hydrological information	Yes	Very important but also many obstacles to achieving this.
	5	Land Type data & soils data.	Yes	How do we get and use the old land type data? Previous projects on hydrological characteristics of soils?

To identify relevant hydrological research that has taken place in South Africa, searches were conducted on major databases between 2000 and 2021, such as Science Direct, Google Scholar, Scopus, and Web of Science, using several search terms per theme. The recurring terms were "Hydrology" AND "South Africa" to focus the searches.

After the title screening, the abstracts of selected journal articles were then screened to confirm whether they focus on the objectives of this review. Journal articles dealing with different geographic regions were excluded from detailed review unless they were review papers or dealing with hydrological aspects not covered in South Africa. The remaining journal articles were reviewed, and the snowball technique was used to find other relevant journal articles, conference proceedings, reports, and thesis.

A systematic literature review (SLR) was used to objectively analyse available studies and gather information about the state of hydrology research in South Africa. An SLR follows a scientific and objective protocol to identify relevant studies; it limits the bias in producing a meaningful synthesis, and it identifies research or knowledge gaps and areas for future studies (Moher et al., 2015).

1.3 PROJECT AIMS

This study aims to review, consolidate and scope hydrological and water resources research considering the projected socio-economic trajectories, demand and need patterns and changes in weather patterns and climate. Such a revised research pathway would then be used to develop a hydrological and water resources science response strategy relevant and robust for such a future. The intention is, therefore, to also increase the confidence that can be expressed in the developed science to inform water stewardship, sharing (between basins and states), current and future socio-economic development and maintaining the ecological integrity of our water resources for sustainable development. This is necessary if the water, energy and food security in the nation, and mitigation of flood and drought disasters, are to be achieved.

The project targets to achieve the following three broad objectives:

1. To identify the main current and future potential hydrological and water science research questions that will inform national development plans.
2. To identify and assess a suitable governance framework detailing the stakeholder landscape and the institutional arrangements (strategic and operational levels) that are required to enable the implementation of a change of the hydrological research strategy.

3. To provide insights for the revision and re-direction of the scope and trajectory of hydrological and water resources science research in the country.

1.4 SCOPE AND LIMITATIONS

Unfortunately, the bulk of the important body of work funded and published by the Water Research Commission remains inaccessible online and at their offices. Subsequent attempts to get a list of past and ongoing hydrology-related research projects also remain unsuccessful. Consequently, this review excludes the findings of WRC research projects that are not published in scientific journals.

Relatively few comments were made to this document by the Hydrology Community of Practice (HCOP). The participants of the dialogue had not received and, therefore, perused the earlier version. Thus, mostly generic comments were provided. Those were incorporated in the subsequent version of the document that was circulated for wider and targeted comments. Unfortunately, only a handful of comments were received.

CHAPTER 2: THEME 1. TIME VARIABILITY AND CHANGE

In recent decades, a wide array of scientific research has been conducted to explore how water resources might respond to global change (Green, 2016). A small fraction of those studies has been conducted to explore how South Africa's water resources might respond to climate change. The thrust of most studies has been on surface water systems, due to their visibility, accessibility, and the more obvious recognition of the impacts of climate change on surface water. Furthermore, those studies have been confined to modelling the impact of climate change on streamflow. It is relatively more complicated to establish or demonstrate the impact of climate change on groundwater ("a hidden resource"; Moseki, 2017) than is the case of impacts on surface water.

South Africa has substantial expertise and technology in modelling hydrological processes linked to climate variability and climate change. The Agricultural Catchments Research Unit (ACRU) and the Pitman models are the main key approaches used to model the hydrological impacts of changes in rainfall and evaporation on the hydrological system in South Africa (DEA, 2013). The ACRU approach has strengths for understanding the impacts of extreme events at the daily timescale, and for fine-scale sector-specific understanding, while the Pitman model approach has strengths relating to broader time and spatial scales and for cross-sectoral integrated assessment (DEA, 2013).

There have been some site-specific assessments of the impacts of climate change on water resources, but only two national-scale assessments (Schulze, 2012; Cullis et al., 2015) whose results are currently publicly available. Schulze (2012) assessed the impact of climate change on water resources using the ACRU model and the outputs from the Intergovernmental Panel on Climate Change (IPCC, 2007) Fourth Assessment Report based on General Circulation Models (GCMs). Cullis et al. (2015) used the Pitman model and outputs from all existing GCMs in the form of hybrid frequency distributions developed by the Massachusetts Institute of Technology Global Change Group (Schlosser et al., 2012) to assess the impact of climate change on water resources.

Identified research/ Research question

When developing management plans to effectively address the future challenges that one expects to face because of climate change, the following questions should be posed:

- *What are the projected changes in climate in South Africa? This question is to a large part answered by meteorologists or climatologists.*
- *What are the estimated impacts of these changes on water resources (surface and groundwater) in South Africa?*
- *Are there areas (i.e. main water sources areas) that require a more detailed assessment of the impact of climate change on water resources and hydrology?*
- *Impact of climate change on water resources and water supply.*
- *Impact of climate change on water services.*
- *Impact of climate change on flooding.*

2.1 IRREVERSIBLE HYDROLOGICAL CHANGES UNDER CLIMATE CHANGE

Q: Is the hydrological cycle regionally accelerating/decelerating under climate and environmental change, and are there tipping points (irreversible changes)?

This fundamental question hinges upon the nature of the hydrologic cycle itself, and for which a geological perspective is needed (Sterling, 2020). To begin to solve this problem, long data records and accurate models are needed to identify regime changes in complex systems. In data-scarce South Africa, the hydrology fraternity might consider identifying regime changes for the period spanning from the last century to the next century.

From a system's perspective, a "tipping point" is the value of the critical threshold at which the future state of a system is qualitatively altered (Lenton et al., 2008), with important implications for humans, ecosystems, and resources. Regarding water, passing tipping points could lead to chronic water scarcity or excessive water in some regions of South Africa. It is thus a scientific priority to see if current and forthcoming changes in the water cycle have crossed or will cross in the future, tipping points.

Tipping points in complex dynamical systems like the hydrological cycle abound. They have been identified at various spatial scales and led to the collapse of fisheries, conversion of savannahs into forests, or desertification (Jaramillo, 2020). They have also been identified for the global scales for the climate system, biosphere, and ecosystems, among many others (Jaramillo, 2020). No such thresholds have been identified or quantified in South Africa.

Identified research/ Research question

What are the hydrological thresholds (maximum allowable floods that society can cope with and what are the minimum allowable flow levels that are required for ecological functioning, livelihoods, navigation, etc.) and how are these likely to respond to a changing and/or variable climate forcing?

2.2 CLIMATE CHANGE AND WATER USE IMPACTS ON EPHEMERAL RIVERS AND GROUNDWATER

Q: What are the mechanisms by which climate change and water use alter ephemeral rivers and groundwater in semi-arid regions?

Ephemeral rivers are primarily distinguished by their spatially and temporally variable hydrological regimes and by the loss of surface water connectivity when flow periodically fails – confining surface water to isolated pools (Avenant et al., 2010). Most of the country's rivers are ephemeral because of the highly variable and unpredictable climate experienced over much of the country but, also because of the number of dams along them. Only 4% of our river length is free-flowing and out of the 48 free-flowing rivers, only 25 are longer than 100 km (after Nel et al., 2011a).

According to the most recent assessment of water use, urban municipal areas account for 23% of the national water use, while rural settlements use only 4% (DWAF, 2009). Climate change affects both the water supply and the water use. Currently, the effort has been on assessing the impact of climate change on water resources and not on water services. Moreover, accurate data on water use per sector is hardly available, except at the regional and national scales and mainly for large users who are registered with DHSWS.

How the future climate will interact with land use changes, water use changes and affect hydrology and water resources availability requires more attention. Land use change and climate change form a complex and interactive system by linking human actions, viz. land use change, to environmental reactions which, in turn, impact again on human responses (Schulze, 2000). To further compound this nexus, both climate change and land use changes affect water use. The hydrological response of any catchment is greatly influenced by the climate (rainfall, evaporation) but also by all the anthropogenic activities (agriculture, settlements, water abstraction and return flow, etc.).

Nevertheless, as alluded to above, studies are confined to using hydrological models to quantify and qualify the impact of climate change on surface water, namely streamflow. In most instances, despite the use of hydrological models, the results are mostly inconclusive given the uncertainty that plague climate model projections. There are three main approaches to reduce the bias of climate models to improve the efficiency of climate change impact studies on hydrological regimes (Kour et al., 2016):

- Improving the GCMs and RCMs (it can be achieved by integration of state-of-the-art hydrological models in GCMs/RCMs and improved process descriptions). This approach is beyond the hydrological domain. The most detailed nationwide set of downscaled future climate change projections at an 8 x 8 km resolution were obtained by further downscaling of the CSIR's existing set of 50 km resolution Coordinated Regional Downscaling Experiment projections of future climate change.
- Including a multi-model ensemble approach: This may be achieved by using more than one GCM, RCM and/or hydrological model. Rather than using more than one hydrological model, hydrologists tend to use an ensemble of climate projections to force a single hydrological model (Cullis et al., 2015).
- Performing bias correction techniques. These are classified into the delta-change approach, linear scaling, local intensity scaling, variance scaling, power transformation and distribution transfer (Teutschbein and Seibert, 2012).

Groundwater is a buffer against climate variability, and our dependence on groundwater resources is likely to increase as water supplies are further stressed by population increase and projected increases in temperature and climatic variability over much of the country (Green, 2016). Unfortunately, quantifying the potential effects of climate variability and change on groundwater is more complex than with surface water. Consequently, very little research exists (Dennis and Dennis, 2012; Dennis and Dennis, 2013) on the potential effects of climate change on groundwater. Indeed, data paucity makes it difficult to determine the magnitude and direction of groundwater change due solely to climate change. As a result, the potential effects of climate change on groundwater and groundwater sustainability are poorly understood.

Identified research/ Research question

How will future climate interact with land use changes, land cover changes, water use changes and affect the country's hydrology and water resources?

What are the most suitable approaches to reduce the bias and uncertainty of climate models to improve the efficiency of climate change impact studies on hydrological regimes?

CHAPTER 3: THEME 2. SPACE VARIABILITY AND SCALING

3.1 SPATIAL HETEROGENEITY AND HOMOGENEITY IN RUNOFF, EVAPORATION, SUBSURFACE WATER AND MATERIAL FLUXES

Q: What causes spatial heterogeneity and homogeneity in runoff, evaporation, subsurface water, and material fluxes (carbon and other nutrients, sediments), and in their sensitivity to their controls (e.g. snow fall regime, aridity, reaction coefficients)?

Hydrological processes occur at a wide range of spatial and temporal scales (Figure 3.1) that span about eight orders of magnitude in space and time (Blöschl and Sivapalan, 1995). To compute spatial heterogeneity, catchments are subdivided into hydrologic response units (HRUs). An HRU is a homogeneous unit with similar climate, land use, soil and/or pedo-transfer properties, and hence a homogeneous hydrological response under equivalent meteorological forcing (Poblete et al., 2020).

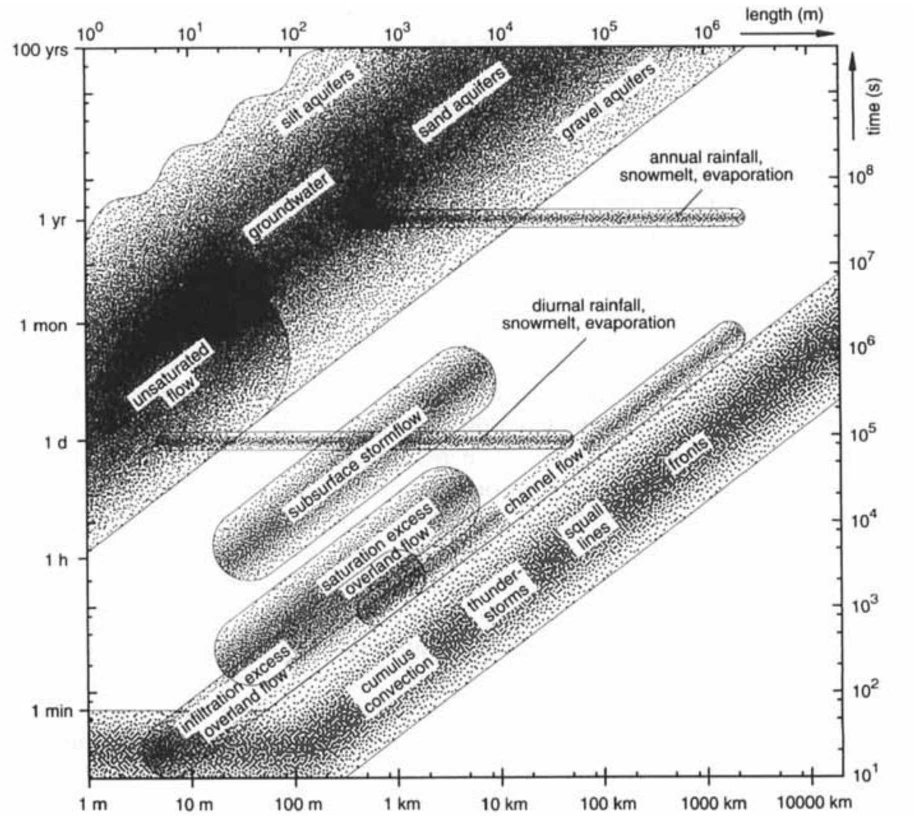

Figure 3.1. Spatial and temporal scales of hydrological processes (Blöschl and Sivapalan, 1995)

Quaternary catchments (QCs) are the standard management unit and hydrological response unit of the country. It is the scale at which we assess the national water resources. Because most QCs are too diverse physiographically and climatically to act as a basic and relatively homogeneous hydrological unit, they may require further discretisation into quinary level catchments (Schulze and Pike, 2004). The altitudinal quinary catchments (5838 upper, middle, and lower quinary catchments within South Africa, Lesotho, and Swaziland) represent hydrological and agricultural zones (Schulze et al., 2010). The freshwater quinary (9417 quinary catchments) represent planning units to manage the water resource and the surrounding land (Nel et al., 2011a). River network quinary catchments are nested hydrological catchments around the river reach of the 1:500 000 river network and major dams (Maherry et al., 2013). While the research question below, assumes that the objective is to address issues of catchment heterogeneity, it should also be recognised that all models (even fully distributed models) have limitations in their structures in terms of their ability to represent real hydrological processes. The model parameterisations are also limited by the amount of available data and understanding to define heterogeneity. Some models (including the Pitman model), attempt to overcome these problems by using distribution function type approaches that effectively represent process heterogeneity at quite large spatial scales.

Identified research/ Research question:

What is the optimum level of decomposition (hydrologic response unit) to sufficiently address the catchment heterogeneity? In the strictest sense of their definition, can quaternary or quinary catchments be used as HRUs, or they are simply convenient decompositions for national water resources management purposes? Or do we need to identify smaller decomposition?

Explore whether hillslope-based catchment decomposition approaches are superior to hydrologic response units (HRU) and explore if either of these offers real advantages over simpler spatially integrated approaches.

3.2 LAND TYPE DATA & SOILS DATA.

Surface runoff (as opposed to interflow contributions to streamflow) occurs only when the rate of rainfall on a surface exceeds the rate at which water can infiltrate the soil. Thus, soil physical and chemical properties greatly influence the runoff generation process. Because soil properties vary greatly over short distances, accurate soil data are difficult to obtain. The land type database is the only nationwide soil database, at a 1:250 000 scale, that covers the entire country. A land type is a polygon with a relatively uniform climate, geology, topography, and well-defined soil catena giving information on agriculture potential.

There have been attempts to produce thematic soil maps suited for delineation of hydrological response units (Malan, 2016) by combining various soil databases and using expert knowledge (Vischel et al., 2008, Mwenge Kahinda, 2013; Tetsoane et al., 2013) combined with some field observations (Malan, 2016). In addition, digital soil mapping is increasingly used to disaggregate land types into accurate soil association maps (Van Zijl et al., 2013; Flynn et al., 2019; Van Zijl, 2019; Van Zijl et al., 2019; Van Tol et al., 202)., with local area-specific research.

Although the land type database is currently the best, readily available soil information that covers the whole of South Africa, it was essentially compiled with agricultural potential in mind. Thus, there are limitations to using land type information for hydrological modelling. Van Tol and Van Zijl (2020) identified the key limitations as (a) The observation depth was limited to 1200 mm; (b) the documents describing most of the land types are out of print; (c) A land type is not a soil polygon but depicts soil distribution patterns and considerable variation can occur between soils on different terrain units, and (d) Significant variation within a specific terrain unit is also possible, therefore, merely identifying terrain positions to disaggregate land types is not sufficient

The need to characterise and quantify hydrological processes to manage scarce water resources led to significant progress in the field of hydropedology in South Africa during the past decade (Van Zijl, 2019). Hydropedology is the study of the hydrological interaction of water with soil and the fractured rock zone

Identified research/ Research question

Disaggregate the land types to provide the spatial distribution of various hillslope and hydrological soil types within a land type

Produce a high-resolution soil map of South Africa for hydrological purposes

CHAPTER 4: THEME 3. VARIABILITY OF EXTREMES

Floods and droughts are the most frequently recorded disasters associated with water occurrence, movement, and distribution in South Africa. The country experiences all the different types of floods (fluvial, pluvial, and coastal) and droughts (meteorological, agricultural hydrological, socio-economic, and ecological). Consequently, there has been several studies on these subjects.

4.1 CHANGES IN FLOOD AND DROUGHT RICH PERIODS

Q: How do flood-rich and drought-rich periods arise, are they changing, and if so, why?

4.1.1 Floods[1]

Flood assessment methods are divided into two broad categories – those based on analyses of observed or modelled floods and those based on observed or statistically predicted rainfall events (Smithers and Schulze, 2003; Smithers, 2012). Approaches have been developed using observed flood data which are then turned into regional estimates so they can be used in flood risk assessments (Smithers and Schulze, 2003; Van Bladeren et al., 2007). Flood estimation methods in South Africa are based on three general approaches: empirical (regional maximum flood, (Kovacs, 1988)), deterministic (rational formula) and probabilistic (Pegram and Parak, 2004). Although they are still widely used, those methods were developed in the late 1960s and early 1970s (Smithers, 2012). Research, directed at improving flood estimation techniques, include the estimation of extreme rainfall (Smithers and Schulze, 2004), the use of continuous simulation models (Chetty and Smithers, 2005; Smithers et al., 2013), the revisions of existing flood estimation methods (Smithers, 2012; Van Vuuren et al., 2013; Nathanael et al., 2018).

There have been several local refinements of the Kovacs' empirical method, some combined with models (Nortje, 2010; Pegram and Parak, 2004; Vischel et al., 2008a), and one that used sites from across the whole country (Görgens, 2007). There have been similar approaches that incorporated flood frequency but they have also only examined certain catchments (Smithers et al., 2015; Van Bladeren et al., 2007).

There are very few maps on flood hazard in South Africa, especially in rural areas. Moreover, available flood maps are seldom accessible. Data limitations dictate the flood modelling methodology to be used, as higher quality data allows for the application of more sophisticated modelling techniques (Els, 2011). Using the characteristics of the climate and the upstream water catchments and the areas of each settlement that are potentially exposed to floods, Le Maitre and Kotzee (2019) developed a flood risk assessment that identifies the municipalities (more than 1 600 settlements) that have a relatively high flood risk so that they can be highlighted for mitigation actions. It is currently the only countrywide study that analyses the current state of flooding in South Africa and the implications that climate change will have on floods in South Africa over the next three decades. It is, therefore, generally unclear how changing patterns of flood risk and how climate variations in the future might affect flood risks.

A three-water level (1, 3 and 5 metres) national potential flood map was developed from the Height Above Nearest Drainage product (SANSA, 2015). The product can be used to identify (1) areas vulnerable to flooding; (2) infrastructures located in flood risk zones; (3) flood lines.

[1] *Some sections are taken verbatim from Le Maitre and Kotzee (2019)*

Identified research/ Research question:

The questions come from Van Vuuren et al. (2013) and Els and Van Niekerk (2013)

Rainfall data – Patch and extend short duration rainfall

Rainfall data – Compile a register of Institutions/Contacts which owns and update short duration (intensity) rainfall data.

Catchment rainfall – Review of available spatial and temporal rainfall data to develop a strategy for rainfall data capturing.

Catchment rainfall – Relate spatial rainfall data to catchment rainfall

Rainfall modelling – Review the application of continuous rainfall data recording on runoff modelling. Asses the recorded data parameters to determine probability distributions and confidence levels.

Catchment parameter – Review different methods for the calculation of Tc and TL on catchment response in South Africa.

Catchment parameter – Redefine delineation of "Homogeneous" Flood Producing Regions

Flood data – Review and extend the stage-discharge curves (rating curves) for flow gauging stations and identify extreme storm events to obtain the volume flow rate relationships.

Flood data – Extend the application of (regional) Index Flood Methods.

Flood data – Extend the JPV method for different "homogeneous" regions.

Stochastic analysis Review the application of different frequency distributions and provide a guide for the selections of the most applicable distributions.

Flood calculation (T<100 years) – Review runoff coefficients (catchment response) for different catchment types.

Flood calculation (T<100 years) – Refine the application of the SDF method (Catchment basins, C2 and C100 coefficients).

Flood calculation (T<100 years) – Review the influence of other parameters which could be included in an improved SDF procedure.

Flood calculation (T<100 years) – Update SCS-SA method. Review the application for urban areas and compare and relate to SWMM.

Flood calculation (T<100 years) – Update SUH (Use available applicable data, review regions and storm losses).

Flood calculation (T<100 years) – Extend the empirical procedures for flood calculations and investigate new methods for smaller catchments (rural and urban).

Flood calculation (T>100 years) – Review the RMF procedure by including all the available data and refine the Kovács regions. Investigate the REFSSA procedure for other Kovács regions.

Flood calculation (T>100 years) – Investigate the probability of extreme flood events and develop a guide for design floods selection.

Flood calculation (T>100 years) – Include the available peak flood data to update the QT/QRMF ratios

Flood mapping – National and regional flood map for disaster management planning, 1:100 000-1 :1 000 000 (Extent)

Flood mapping – Local flood map for disaster management planning, 1:5000-1:50 000 (Extent, depth, and other parameters where appropriate)

Flood mapping – National and regional flood map for town planning, 1:100 000-1:500 000 (Extent, Extent for different probabilities, depth, velocity, and duration)

Flood mapping – National and regional flood map for emergency planning and management, 1:100 000-1:500 000 (Extent)

Flood mapping – Local flood map for emergency planning and management, 1:5000-1:25 000 (Extent and depth for different return periods, and other parameters where appropriate)

Flood mapping – Local flood map for public awareness, 1:10 000-1:25 000 (Extent for different probabilities and depth)

Flood mapping – Local flood map for public awareness, 1:10 000-1:25 000 (Extent for different probabilities, depth, and velocity if significant)

How is climate change likely to impact local floods (i.e. increases or decreases in the frequency and intensity of localised heavy rainfall), or on more widespread floods (i.e. increases or decreases in the occurrence of large area storms such as cut-off lows or tropical storms), or both types of flooding?

4.1.2 Drought

Drought is a creeping natural hazard that occurs everywhere in South Africa (both in high and low rainfall areas) and can develop over short periods (weeks or months) or longer periods (seasons, years or even decades). Over the past two decades, several drought events hit the country. Droughts differ from one another in four essential characteristics (severity, frequency, duration, and spatial coverage); and are generally divided into four types (meteorological drought, agricultural drought, hydrological drought and socio-economic drought). Hydrological drought refers to a lack of water in the hydrological system, manifesting itself in abnormally low streamflow in rivers and abnormally low levels in lakes, reservoirs, and groundwater (Loon, 2015). Due to their long duration and large spatial extent, hydrological drought events are severe natural disasters, and in terms of damage are comparable to large-scale floods and earthquakes (Wilhite, 2000).

Investigations of the description and classification of historical drought severity, using drought indices (mostly the Standardized Precipitation Index and the Standardized Precipitation Evapotranspiration Index) abound (Rouault and Richards, 2003; Moeletsi and Walker, 2012; Edossa et al., 2014; Naumann et al., 2014; Malherbe et al., 2015; Gebre and Getahun, 2016; Botai et al., 2017; Botai et al., 2019; Botai et al., 2020; Ndlovu and Demlie, 2020), as do attempts to forecast the occurrence of future droughts, using drought indices or models, (Trambauer et al., 2013; Winsemius et al., 2014; Wetterhall et al., 2015; Trambauer et al., 2015; Ikegwuoha and Dinka, 2020; Mathivha et al., 2020). The bulk of the work is about meteorological drought using the standardized precipitation index. Hydrologists must focus on and improve the seasonal forecasting of hydrological drought to inform operational water management (reservoir operation, irrigation abstractions, etc.) or management. So far, the investigations related to drought forecasting, focus on meteorological droughts.

Roualt and Richards (2003) use the standardised precipitation index (SPI) to monitor the intensity and spatial extent of droughts at different time scales (3, 6, 12 and 24 months). Moeletsi and Walker (2012) used the Water Requirement Satisfaction Index to determine the agricultural drought related to maize production over the Free State using a 120-day length maize cultivar for different planting dates. Edossa et al. (2014) characterised meteorological droughts in the Central Region of South Africa using the Standardised Precipitation Evapotranspiration Index (SPEI) and relationships with El Niño events. Malherbe et al. (2015) evaluated the occurrence of droughts in South Africa as a function of decadal-scale variability and determined significant hemispheric associations with decadal variability in South Africa for the period 1921-2014. Gebre and Getahun (2016) analysed the temporal climate variability and meteorological drought frequency in the Limpopo River Basin using the Standardised Precipitation Index at different monthly time scales (1, 3, 6, 9, 12 and 24) using the WATCH gridded data. Botai et al. (2017) assessed drought conditions over the Western Cape using the Standardized Precipitation Index (SPI) accumulated over 3-, 6- and 12-months and the four Drought Monitoring Indicators (Drought Duration, Severity, Intensity and Frequency). Botai et al. (2019) analysed drought characteristics and propagation patterns in the hydrological cycle over South Africa. Botai et al. (2020) used the multivariate copula-based functions to analyse characteristics of the joint distribution of drought duration (derived from the SPI time series) and severity in the Eastern Cape province of South Africa. Ndlovu and Demlie (2020) assessed meteorological drought across the KwaZulu-Natal Province using the per cent of normal precipitation index and the rainfall anomaly index. Naumann et al. (2014), assessed the ability of different global data sets and drought indicators (SPI, SPEI and Soil Moisture Anomalies) to represent the spatio-temporal features of droughts in different climate regimes across Africa. They also identify the main sources of uncertainty in the computation of the drought indicators.

Trambauer et al. (2013) identified models best suited to forecast hydrological drought at different spatial and temporal scales. Winsemius et al. (2014) assessed the ability of the European Centre for Medium-Range Weather Forecasts in predicting dry spells and heat stress, indicators relevant to farmer needs for the Limpopo basin. Trambauer et al. (2015) presented forecasting results for the Limpopo Basin achieved by a chain of process-based models with input from the seasonal forecasting system S4 and reanalysis data ERA-Interim by the European Centre for Medium-Range Weather Forecasts. Wetterhall et al. (2015) evaluate the skill of the ECMWF seasonal probabilistic forecasting system over the Limpopo basin in Southern Africa in predicting drought indicators. Seibert et al. (2017) compare the ability of three methods (multiple linear models, artificial neural networks, random forest regression trees) to forecast hydrological drought with up to 12 months lead time. Ikegwuoha and Dinka (2020) evaluate changes in the frequency and severity of historical droughts (1980-2018) and then model future drought occurrences (2019-2099) in the Lepelle catchment, using the Intergovernmental Panel on Climate Change (IPCC) General Circulation Model (GCM) simulations for two representative concentration pathways (RCP8.5 and RCP4.5). Mathivha et al. (2020) forecast short- and medium-term drought conditions in the Luvuvhu River Catchment using the Standardized Precipitation Evaporation Index (SPEI) at 1-, 6-, and 12-month timescales.

Identified research/ Research question:

Further our understanding of hydrological drought. Identify and address uncertainties and gaps in our knowledge about hydrological drought (Loon, 2015). Studies on drought evolution in the hydrological cycle in South Africa are expected to elicit further research on more complex topics such as drought termination typology (Botai et al., 2019).

Better quantification of hydrological drought; there is no single 'best' hydrological drought indicator and the most used indices (SPI and SPEI) fall short in many regards. The question of how to use a combination of drought indices, or even a composite index in hydrological drought monitoring is still to be investigated.

Moving to include the human aspects of hydrological drought (Loon, 2015). One of the questions is exploring the impacts of human intervention in drought propagation.

Application of drought research in water management and policy (Loon, 2015).

Changes in the drought signal due to propagation through the hydrological cycle, especially groundwater

4.2 LAND USE LAND COVER CHANGES

Q: Why are runoff extremes in some catchments more sensitive to land-use/cover and geomorphic change than in others?

Changing land use is a phenomenon that is growing in magnitude and significance in South Africa. It includes the conversion to agriculture, deforestation, afforestation, dams, changes to natural vegetation through bush encroachment and overgrazing, soil erosion, invasion by alien plant species, urbanisation, etc. Anthropogenic influences on the landscape and the resulting collective land use/land cover (LULC) changes impact the hydrology of any given area at different spatial scales.

Between 1961 and 2006, grazing land, land not classified as being used for forestry, for cultivation, for settlement, as well as land not identified as being unused/unproductive made up 72 to 76% of the country's total land area. The low rates of change resulted in relatively stable land-cover conditions throughout the period. Cultivated land was the second most important land use category, followed by forest land. Cropland expansion and decline, the spread of settlement areas and the spread of forest plantations had the strongest effects on land-use/land-cover change in South Africa in the observed period (Niedertscheider et al., 2012). Between 1994 and 2005, there was a total increase of 1.2% in transformed land specifically associated with urban, cultivation, plantation forestry and mining (Schoeman et al., 2013). Between 2014 and 2018, there was a marginal decrease in the areal extent of natural wooded land, shrubland, waterbodies and planted forests while grassland, wetlands, barren land, cultivated, built-up, mines and quarries experienced a marginal increase (Ngcofe et al., 2019). The spatial patterns do, however, vary geographically across provinces in South Africa.

The impact of LULC changes on streamflow is assessed using hydrological models (Warburton et al., 2012; Rebelo et al., 2015; Mathivha et al., 2016; Gyamfi et al., 2018) or by analysing historical LULC changes and the associated stream flows (Gwate et al., 2015; Rebelo et al., 2015).

Warburton et al. (2012) used the ACRU model to assess the hydrological responses (streamflow) to land use change of three selected South African catchments. Rebelo et al. (2015) used the ACRU model to improve the assessment of how LULC changes alter streamflow and flood attenuation capacity. Gyamfi et al. (2016) used the Soil and Water Assessment Tool (SWAT) model to assess the impacts of land use changes on surface runoff, water yields, lateral flow, groundwater, and evapotranspiration in the Olifants Basin. Mathivha et al. (2016) used the Hydrologic Engineering Center's Geospatial Hydrologic Modelling Extension to evaluate the effects of land cover changes on flood volumes and peak discharges.

Gwate et al. (2015) analysed changes in annual historical stream flow and rainfall patterns based on the dynamics of a catchment's land cover. Rebelo et al. (2015) used historical LULC scenarios to track key LULC changes over time and investigate their associated hydrological impacts.

Identified research/ Research question

Incorporate non-stationary LULC in hydrological modelling

Apportion the impact of LULC changes on hydrological processes

Consider both anthropogenically induced biophysical changes and natural long-term growth in LULC impact studies for large basins.

CHAPTER 5: THEME 4. INTERFACES IN HYDROLOGY

5.1 WHAT ARE THE PROCESSES THAT CONTROL HILLSLOPE-RIPARIAN-STREAM-GROUNDWATER INTERACTIONS AND WHEN DO THE COMPARTMENTS CONNECT?

This type of work has been done in a few different places based on relevant projects in operation at the time. Some catchment experimental catchments were used to examine some of these interactions.

To better understand hydrological processes and represent them in hydrological models, several research catchments have been set up in the country. South Africa has a few paired research catchments that were established to understand the hydrological impact of afforestation. The Jonkershoek Forest hydrological research station was established in 1935, followed by stations at Cathedral Peak in 1938 (Nänni, 1956) and Mokubulaan in 1955 (Van der Zel, 1987). Additional research stations were set up at Westfalia in 1975 and at the Witklip State Forest in 1980.

The Liebenbergsvlei research catchment (4 625 km^2) is a sub-catchment of the Vaal River catchment, situated near Bethlehem in the Free State Province (Pegram and Sinclair, 2002). Grassland and cropland cover the bulk of the catchment and farming is the main activity in the region (Vischel et al., 2008).

Intensively instrumented since 1998, the Weatherley catchment (1.57 km^2) is a sub-catchment of the Mooi River, Quaternary catchment (T35C), situated in the northern Eastern Cape Province (Uhlenbrook et al., 2005). The land use is mainly Highlands Sourveld grassland. The catchment has been central to the understanding of hillslope hydrological processes (Uhlenbrook et al., 2005; Wenninger et al., 2008; Van Tol et al., 2010).

Located in the foothills of the Drakensberg mountains in South Africa (29.3679°E, 28.8145°S) at an average altitude of 1310m, the Potshini catchment is a sub-catchment of the Emmaus catchment (V13D quaternary Catchment) in the Thukela River basin in South Africa (Kongo and Jewitt, 2006; Kongo et al., 2010). The Potshini research catchment was established to monitor hydrological processes at both field and catchment scales for water resources management research purposes. Smallholder farming is the main land use of the Potshini catchment.

In 2014, the University of the Western Cape established a research catchment in the Nuwejaars floodplain (64 km^2) to investigate wetland processes that are important for the characterisation and conceptualisation of surface-ground water interactions. The Heuningnes Catchment (1 401 km^2) is in the Cape Agulhas, within the Eastern Overberg region in the Western Cape Province.

The Potshini research catchment was established to:

(1) understand the hydrological impact of (clearing) invasive alien plants particularly on riparian zones and hillslopes.

(2) establish how different rural land uses affect water quality along the main tributaries.

(3) determine how hydrological responses, vary with topography and land uses.

(4) understand surface water groundwater interaction (wetlands and lakes).

The Two-Streams catchment, located in the Seven Oaks District in the KwaZulu-Natal Midlands of South Africa has been used as an experimental catchment over the past decade to investigate the impacts of *Acacia mearnsii* tree stands on hydrological processes (Bulcock and Jewitt, 2012).

While some of these research catchments have contributed to the improvement of hydrological models commonly used in South Africa, they do not cater for all key hydrological processes prevailing in the country. River transmission losses, surface-groundwater interaction in dolomitic areas, wetland hydrology, urban and peri-urban hydrology are key processes that are yet to be fully understood, to be incorporated in conceptual models. Hence, there is a need for experimental catchments to specifically address such shortcomings.

Identified research/ Research question:

Various sources of evolution and propagation of streamflow in the hydrological cycle in different physico-topographical settings (e.g. karst regions) in South Africa that may lead to improved processes understanding to develop methods to effectively protect the water source areas such as fragile headwater catchments

The complex interaction between human beings and the natural environment.

Better quantification of hydrological impacts of the invasion of alien vegetation in water source areas and along streamflow paths. The need to sustainably manage invasive alien vegetation to prevent drought conditions in fragile environments.

The need to monitor different types of (including alien) vegetation occurrences and their impacts on water resources availability. The question of how to use a set of multiple approaches to achieve this objective is still to be investigated.

Better quantify the interactions between surface and sub-surface systems.

Improve the representation of different runoff generation processes in hydrological models.

Few papers address the characteristics of groundwater flow to ephemeral streams from unconfined aquifers. Although initially considered an exclusive ephemeral arid and/or semi-arid stream feature, transmission loss from surface channels also occurs in streams in humid areas. Interestingly, we identify a significant omission in the literature, in that while it is common to observe nonlinear behaviour in streamflow recessions, the little explicit account has been given to the role of transmission loss which can be an important factor in identifying the structure of nonlinear recession models. (Tanner and Hughes, 2015; Mvandaba et al., 2018; Hughes, 2019)

Moving to include the human effects on the hydrological cycle. One of the questions is the exploration of the impacts of human intervention in irreversible change to streamflow generation processes in fragile headwater catchments.

5.2 GROUNDWATER FLUXES ACROSS BOUNDARIES

Q: What are the processes controlling the fluxes of groundwater across boundaries (e.g. groundwater recharge, inter-catchment fluxes and discharge to oceans)?

The key issue for this is groundwater recharge which replenishes the groundwater reservoir and determines availability and is thus a critical process in the provision of renewable freshwater resources to support local communities, especially in areas where surface resources are scarce, in arid and semi-arid regions globally. Groundwater recharge or deep drainage or deep percolation is a hydrologic process, where water moves downward from surface water to groundwater. Recharge is the primary method through which water enters an aquifer. This process usually occurs in the vadose zone below plant roots and is often expressed as a flux to the water table surface. Groundwater flow also encompasses water moving away from the water table farther into the saturated zone. Recharge occurs both naturally (through the water cycle) and through anthropogenic processes (i.e. “artificial groundwater recharge”), where rainwater and or reclaimed water is routed to the subsurface. Besides the physico-climate considerations such as the amount of rainfall, the underlying geology, soil surface conditions (impervious and soil impaction conditions)), slope, etc., other factors determining groundwater recharge include climate change and urbanisation (Scanlon and Goldsmith, 1997; Scanlon et al., 2003; Kim and Jackson, 2012).

The future of climate change has implications regarding the availability of groundwater recharge for the future drainage basin. Recent studies (e.g. Siebert et al., 2010; WWAP, 2012; Klove et al., 2013; Taylor et al., 2013; Famiglietti, 2014; FAO, 2015; Kidd, 2017; Rankoana, 2020) explore different results of future groundwater recharge rates based on theoretical moist, medium, and arid climates. From the results, it is predicted that a climate of equal humidity and dryness will have the smallest impact on groundwater recharge rates. Precipitation trends are predicted to relay minimal change quantitatively in the near future, while groundwater recharge rates are subject to increase because of global warming. This phenomenon is explained through the physical attributes of vegetation. With increasing temperature because of global warming affecting vegetation growth and densities, it is possible that leaf area index (LAI) would decrease in some places and during some periods in a year (Krishnaswamy et al., 2014; Hardwick et al., 2015; Kim et al., 2017; Lawal et al., 2019; Ramezani et al., 2020. This leads to higher rates of infiltration into the soil and less interception within the tree itself. A direct result of increasing infiltration into the soil is elevated rates of groundwater recharge. Therefore, with increasing temperatures and insignificant changes in precipitation patterns, groundwater recharge rates are expected to increase.

Other research initiatives (see Wu et al., 2020 for detailed discussion) also reveal that different mechanisms of groundwater recharge have different sensitivities to climate change. Increasing global temperatures can lead to excessive pumping of the water table, leading to a potential enhanced risk of over-drafting. Severe consequences of groundwater depletion include lowering of the water table and possible deterioration of water quality. If the potential groundwater recharge rate is less than extraction, access to groundwater is reduced. Consequently, this would lead to deeper drilling to access more water which leads to water being costly.

Research shows that the recharge rate can be up to ten times higher in urban areas compared to rural regions through leakages from the expansive water supply and sewage networks supported in urban regions in which rural areas are not likely to obtain (e.g. Wakode et al., 2018). At the same time, there is the potential for groundwater contamination from the same networks and it is also possible that most urban areas experience less due to rapid storm runoff and less infiltration. This needs further exploration to ascertain what exactly happens in different places.

From the South African perspective, the issues of importance include, at more local scales, collection, and collation of information on inter-catchment fluxes in such important localities as dolomites or the Table Mountain Group. These are important as primary sources of water for the support of local communities for domestic use. Xu and Beekman (2019) provide an update of an earlier review on groundwater recharge estimation (Bredenkamp et al., 1995 and Xu and Beekman, 2003) by incorporating emerging and grey literature from a wide range of research sectors in southern Africa, collected during the past decade. In southern Africa, most regional and local recharge studies (including groundwater exploration projects) have been carried out in semi-arid Botswana, South Africa, and Namibia, and in Zimbabwe and Zambia to a lesser extent, in the past. Isolated studies of recharge were conducted in Zimbabwe and Zambia through overseas aid agencies such as BGR, the German Geological Survey (Nyagwambo, 2006; Shamboko-Mbale et al., 2012).

Identified research/ Research question:

Further our understanding of processes controlling the fluxes of groundwater across boundaries. Studies on the role and importance of groundwater hydrology in the hydrological cycle in the South African landscape are expected to shed light and elicit further research on more complex topics such as karst hydrology.

Better quantification of groundwater hydrology to:

- *Bridge the gap between hydrology and hydrogeology.*
- *Improve modelling of the 'complete' hydrological cycle leading to*
- *Improve understanding of surface and groundwater interaction, and*
- *Lead to the development of more robust conjunctive uses of surface and groundwater sources to improve water security*

How are groundwater resources connected especially in the predominantly fractured rock aquifers of the country? What is their regional extent?

How would local over-abstraction affect other areas over a broader spatial scale?

What is the dependence of streamflows on groundwater? And therefore

- *How sensitive are streamflows to over-abstraction of groundwater, and*
- *How does this sensitivity vary in different regions of South Africa?*

CHAPTER 6: THEME 5. MEASUREMENTS AND DATA

6.1 INNOVATIVE TECHNOLOGIES TO MEASURE HYDROLOGICAL VARIABLES AT DIFFERENT SPATIAL AND TEMPORAL SCALES

Q: How can we use innovative technologies to measure surface and subsurface properties, states, and fluxes at a range of spatial and temporal scales?

The nation's *in-situ* rain gauge networks are diminishing, resulting in sparse networks whose records give a poor representation of rainfall occurrence, patterns, and magnitudes. Satellite remote sensing increasingly provides several observations of changes in hydrological states and variables over both time and space that can be used to monitor hydrological conditions and changes. Soil moisture, precipitation, runoff, evaporation (through air temperature and surface humidity), transpiration (like evaporation, plus added vegetation content), surface temperature, incoming short and longwave radiation (using the atmospheric temperature and humidity profile, cloud fraction), change in storage (surface and groundwater), dynamics of groundwater aquifers, can be observed/inferred directly or indirectly via remote sensing. Although so many components of the hydrological cycle are observable by remote sensing, attempts to close the surface water budget from remote sensing alone have generally been unsuccessful, suggesting that the current generation of sensors and platforms are not yet able to provide hydrologically consistent observations of the land surface water budget at any spatial scale (Tang et al., 2009). Remote sensing data collection platforms rarely measure the processes directly, they rather use surrogate observations (such as vegetation reflectivity to infer rates of evapotranspiration, or cloud top temperature to infer rainfall amounts). The observations need to be calibrated to generate data that are equivalent to ground-based observations. Therefore, the wealth of satellite data at various spatial scales, and different temporal resolutions are combined with traditional hydrological observations to piece together a complete picture of the land surface hydrological cycle.

A. Precipitation

Given its importance in the hydrological cycle, several studies explore the use of bias-corrected and/or downscaled satellite precipitation estimates to run models (Sawunyama and Hughes, 2008; De Coning, 2013; Suleman et al., 2020). Precipitation estimation using geostationary satellites, although less accurate, provides better spatial coverage, is updated frequently and is available in (near) real-time. Sawunyama and Hughes (2008) use a non-linear frequency of exceedance transformation technique to match the statistical properties of the satellite data to those of gauged rainfall, to drive the Pitman model. De Coning (2013) compares different ways to use and combine satellite precipitation estimates and numerical weather prediction model fields over the country to determine the optimal estimate of precipitation, which can also be applied in real-time to support flash flood predictions. Suleman et al. (2020) validated satellite rainfall products against available historical observed records and use them to force the ACRU agro-hydrological model in selected catchments in South Africa. Symeonakis et al. (2008) produced precipitation estimates for the entire sub-Saharan Africa region by interpolating rain gauge data, comparing them to satellite estimates and applying the two different datasets to model soil erosion over the continent.

B. Soil moisture

Over the last decade, efforts were made to support the calibration and validation of remote sensing products and hydrological models and to improve the understanding of temporal and spatial variations of soil moisture across the country. To this effect, several studies were undertaken to validate and improve methods of indirect estimation of soil moisture in Africa (Vischel et al., 2008a and b; Pegram et al., 2010; Sinclair and Pegram, 2010 and 2013; Sinclair et al., 2013; Sinclair et al., 2015; Mengistu et al., 2014; Everson et al., 2017; Gangat et al., 2020). Gangat et al. (2020) used Sentinel-1 and Sentinel-2 satellite data to estimate soil moisture content across a gradient of palustrine wetlands to terrestrial areas in the grassland biome of South Africa. Pegram et al. (2010), devised a multi-pronged approach to validate remote sensing products, which aimed to provide estimates of soil moisture at high spatial and temporal resolution in southern Africa. Vischel et al. (2008a and b) used the distributed TOPographic Kinematic Approximation and Integration catchment model to estimate the soil moisture from hydrological data and then to compare this estimate with remote-sensing estimates using two different types of satellite data.

C. Dam volume

Monitoring water levels and storage volumes of farm dams and dam reservoirs is essential to understand water resource availability amid climatic changes. Advancements in remote sensing data show great potential for studies about the monitoring of reservoir water volume variations. Over the past decade, the Department of Water and Sanitation has attempted to determine how much water is allocated for: (1) existing lawful use per specific requirements of the National Water Act, and (2) current water uses. The boundaries of farm reservoirs in KwaZulu-Natal (Kapangaziwiri et al., 2018) and the Western Cape were delineated from remotely sensed images (LandSat) and the full volumes were calculated using regression relationships based on the relief. A similar approach to calculate the full volume capacity of farm dam was first used at a regional scale (Hughes and Mantel, 2010) and a sub-basin scale (Oosthuizen et al., 2018). The same approach is now automated in the National Water Quantity Information Service to provide processed Sentinel-2 satellite data to calculate the volumes for all man-made dam levels across South Africa monthly (Thompson, 2018).

Identified research/ Research question

Evaluation and assimilation of various satellite-derived hydrological variable products over South Africa.

Investigate the accuracy of relevant satellite data from different sources against reliable ground station data

Bias correction of remotely sensed hydrological variables

D. Streamflow

River discharge is an integrated result of hydrological processes in a river system in transporting runoff from rainfall. Its accurate measurement is critical for applications such as water supply, navigation, recreation, management of in-stream habitat, and the prediction and monitoring of climate extremes (floods and droughts). Unfortunately, the already sparse in situ stream gauge network, of the Department of Human Settlements, Water and Sanitation, measuring river discharges is rapidly thinning in the country (Pitman, 2011).

Generally, river discharge measurements can be carried out using different techniques and instruments: hydraulic current meters, chemical tracers, dyes, acoustic Doppler instrumentation, or remote sensing observations (Dal Sasso et al., 2018). Establishing and maintaining in situ stream gauges is expensive, labour-intensive, and can place personnel at risk. Moreover, most of them provide spatially averaged features; the equipment is costly and needs long experimental campaigns and qualified personnel.

In the last decade, innovative methodologies have been developed to measure streamflow in real-time at high spatial resolution using terrestrial and unmanned aerial vehicle images. To this effect, four main algorithms (large-scale particle image velocimetry, space-time image velocimetry, optical flow algorithms and particle-tracking velocimetry) exist to monitor surface flow velocity from image-based observations deploying tracking tools (Eltner et al., 2020). All these approaches have their limitations outside the laboratory setting. The large-scale particle image velocimetry approach encounters issues in the field (camera lens distortion, poor free-surface illumination, scarce seeding, strong wind, etc.) that are not faced in a laboratory setting (Muste et al., 2008; Liu et al., 2021). Generated space-time image velocimetry contains a lot of noise and interference texture, which is inevitable in practical applications (Zao et al., 2021). While particle-tracking velocimetry approaches require highly defined round-shaped tracers, which are often difficult to observe outdoors (Tauro et al., 2018).

Today about 20 to 22 million people in South Africa use a smartphone, which accounts for about one-third of the country's population (Statista, 2020) and the number of users is increasing. This offers the opportunity to use citizen science using discharge measurement phone applications. DischargeApp is an example of an Android application, which optically measures open channels' water level and surface velocity and derives the discharge (Lüthi et al., 2014). In a laboratory flume under controlled conditions with flow rates of 20-120 Ls^{-1}, the DischargeApp provides an accuracy of ±15 Ls^{-1} (Carrel et al., 2019). For low to moderate discharge values (<35 $m s^{-3}$), the DischargeApp provide promising results; while, for extreme discharge events (>35 $m s^{-3}$), it failed to provide reliable measurements (Fehri et al., 2020).

Identified research/ Research question

Exploring innovative techniques and instruments to measure rainfall, river discharge, soil moisture, etc. in South Africa.

To what extent surface flow velocity measurement from image-based observations can be a viable alternative for the national database of streamflow information based on installed gauges.

6.2 TRADITIONAL HYDROLOGICAL OBSERVATIONS VS SOFT DATA

Q: What is the relative value of traditional hydrological observations vs soft data (qualitative observations from lay persons, data mining, etc.), and under what conditions can we substitute space for time?

South African hydrological data collection still relies on technologically complex and expensive measurements. Furthermore, the spatial and temporal variability of the water cycle, demands monitoring networks that measure time series of various hydrological states and fluxes (precipitation, discharge, reservoir levels, groundwater levels, *etc*.). The monitoring of the various components of the hydrological cycle is mostly confined to the professional environment and tailored to the specific needs of official monitoring networks and some private ones. Unfortunately, there is increasingly less data collected using traditional means, thus opening the door for less traditional collection methods like citizen-science, data mining and crowdsourcing.

Citizen science is a term for research that engages 'ordinary' people in the collection and generation of data. Citizen scientists enhance the breadth of the research through the collection of data over greater spatio-temporal scales (Hulbert *et al.*, 2019). The proliferation of smart cellular phones and their application, social media platforms, developments in sensing technology, data processing and visualisation create a wide range of new opportunities for public participation in scientific research. New technological developments provide different opportunities for citizen science hydrological based monitoring (Table 6.1). Thus, although citizen science has its origin at the start of the science practice, it is now possible for millions of South Africans to join big science projects and programmes.

Collecting environmental data is still the focus of citizen science in South Africa (Joubert, 2016). Volunteers monitor and record data on mangrove ecosystems, beach erosion, dying fynbos plants, endangered species and a variety of animals and insects. However, we could not identify a single hydrology citizen science project. One possible direct citizen science contribution to hydrology that could be effective is accessing private citizens' rainfall measurement networks. Also close to citizen science in hydrology is the miniSASS (Stream Assessment Scoring System), a simple tool that anyone can use to monitor the general health of a river by assessing the presence or absence of 13 aquatic invertebrate taxa in a water sample (Graham and Taylor, 2018).

Table 6.1. Commonly measured hydrological variables and identified challenges and opportunities emerging from citizen science applications (Buytaert *et al.*, 2014).

Variable	Opportunities	Challenges
Precipitation	Cheaper equipment (e.g. electronic tipping bucket rain gauges, disdrometers). Bulk analysis of environmental influences on rain captation. Merging with remotely sensed observations.	Proper installation, maintenance, and documentation of local environmental conditions. Long-term data collection.
Streamflow	Cheap and robust water level measurements; a collection of calibration data; emerging image analysis techniques for stage and flow measurements.	Proper installation and maintenance; quality control; technical support.
Water quality	Cheap analysis toolkits; automatic measurement of proxies; macroinvertebrate observation and identification.	Several parameters remain costly and difficult to analyse; need for adequate documentation of observation context; sampling strategy.
Soil moisture	Automatic measurements (e.g. Time-Domain Reflectometry) becoming increasingly affordable.	Relation with other soil properties; high spatial variability.
Vegetation dynamics	Very accessible technology (e.g. Global Positioning System, photography); remote identification.	Systematization; data processing; combination with remotely sensed data.
Water use	Availability of electronic sensors; convenient data communication via the internet in built environments.	Interpretation and extrapolation of generated data; potential human interference.

Although citizen science has limitations, it offers the novel prospects of achieving many of the aims of public engagement, such as creating linkages and dialogue between science and society; inspiring people to take an interest in science; enthusing young people about careers in science; and making science part of everyday life (Joubert, 2016).

To be sustainable, a hydrological citizen science programme should be operation-oriented, research-oriented, and education-oriented. Furthermore, it should be sustained across multiple projects (Hurbert et al., 2019) or be a funded programme.

Identified research/ Research question:

Citizen science-based network to record daily precipitation using low-cost tools across South Africa. Great potential to involve primary and secondary school learners.

Physical and virtual staff gauges for crowd-based stream level observations

6.3 WATER USE DATA

Q: How can we improve our water use data?

It is common practice that all the available hydro-meteorological data are used to establish a rainfall-runoff model to simulate representative time series of naturally available water resources. These estimates of natural streamflow are then used with the information on water use and other anthropogenic factors, such as land use change, within water resources systems models to estimate current levels of water availability. However, the reliability and accuracy of water use information, such as patterns of irrigation water use, changes in land use patterns and water utilisation practices are often questionable.

Water use data refers to the information on how the water is distributed and how much is used for various purposes. The information available for large schemes is generally adequate, but there are many additional users for which data are generally lacking. This water is mainly abstracted from either relatively small farm dams (on-, or off-channel) or run-of-river channels and groundwater for irrigation, domestic and industrial use. The main challenge with water uses in any basin is the fact that the abstractions or return flows impact the natural hydrology of the system. If they are poorly quantified, then the natural hydrology of the system will also be poorly quantified, even if the net outflows are gauged. Sawunyama (2009) investigated the contribution of water data uncertainty to total simulation uncertainty for selected basins in South Africa. In the same way, Oosthuizen (2016) investigated the impact of poorly quantified water use data on the estimation of the water resources of the Mogalakwena and Shashe sub-basins of the Limpopo River basin. Both studies emphasize the importance of accurate water data (i.e. abstractions, impoundments, return flows, etc.) on the estimation of water resources of the studied basins. So adequately reliable estimates of water use data are as vital to hydrological estimation as the other input data. One of the ways to solve this challenge would be the use of innovative approaches such as remote sensing. The challenge relates to both surface and groundwater. There would therefore be a need for links between remote sensing estimates and water balance modelling of the catchment.

Water use information, a fundamental component of any basin's water cycle, is of great importance for the estimation and management of water resources. Despite its importance, its role in the hydrological cycle has unfortunately received little attention relative to the surface and near-surface hydrologic processes, and there are no extensive networks currently in existence for monitoring this important component. Most water use measurements reflect use only in a few large-scale localised projects with the rest of the basins not covered. Even with water use licences that stipulate the installation of meters for the measurement of inflows and outflows, no reliable quantification exists. Remote sensing of potential water use quantities holds promise to overcome this difficulty, but contemporary techniques rely on indirect measures of various aspects of surface and groundwater hydrology (Becker, 2006).

As our understanding of interactive Earth system processes grows, and the need for more accurate assessment of world water resources increases, our capability to remotely quantify surface and groundwater storage and fluxes, including water uses must also necessarily be greatly expanded. Satellite observations of Earth's time-variable gravity field from the Gravity Recovery and Climate Experiment mission (Tapley et al., 2004) have the potential to present an opportunity to explore the feasibility of monitoring water use fluctuations variations from space (Rodell and Famiglietti, 2002).

The Water use Authorisation & Registration Management System (WARMS) is the national register of water use for South Africa (DHSWS, 2021). Unfortunately, the data are not very accurate in terms of actual, compared to registered, water uses. Fortunately, the DHSWS is undertaking the Verification and validation of existing lawful water use that will give a better understanding of how much water is allocated and used. Data generated through this exercise (users, farm boundaries, farm dam volumes, crop water use, stream flow reduction activities, etc.) will be used to update WARMS.

Additional databases that complement the WARMS data are the South African Register of Large Dams and the National Water Quantity Information Service (SANSA, 2021). 4 457 dams are registered in the South African Register of Large Dams (SANCOLD, 2021).

Identified research/ Research question:

How can we develop and implement a unified approach for collecting, collating, and disseminating water use information?

Update WARMS using the Verification & Validation of Water use data and other existing databases.

Identify and collate all relevant datasets and update WARMS. Work in cooperation with all entities collecting water-use information and compile these data to produce water-use information aggregated at relevant hydrological and administrative boundaries. Every five years, compile and disseminate the nation's water use data for the main water use categories.

6.4 NATIONAL DATABASE OF HYDROLOGICAL INFORMATION

We use hydrological data to better manage our water resources in ways that suit our economic and environmental needs by providing information on the availability and quality of water for all different uses. In addition, hydrological data help us prepare and plan for extreme events by identifying where the risks are highest.

There are several datasets/databases, however, most of them are fragmented, incomplete, dispersed, and heterogeneous. Data collected for different purposes have different attributes. These attributes impact how data are, or can be, used. General purpose categories include operational, broad decision-making, regulatory, and research.

- Operational data are used to inform day-to-day operations. Water and wastewater treatment plants data falls under this category.
- Broad temporal or spatial decision-making data are used to inform policy, investment, management, and other types of decision support systems. The data may be collected within an organisation or from outside organisations (such as government monitoring stations or citizen science data). Most data collected in South Africa falls under this category.
- Regulatory data are collected by mandate. Organisations are required to collect and store these data for a pre-defined amount of time. Most of these data are never used, aside from ensuring compliance and are unlikely to create additional value for the company collecting it. Nevertheless, pulled together, regulatory data can greatly complement existing national datasets.
- Research and Innovation data are collected to advance knowledge and innovate. The data are high risk (no new insights or information may be derived) but potentially high reward (data may provide great insights that radically improve current decision-making). Most of the *ad-hoc* data collected by research organisations fall under this category. It is time-consuming to access such data because most research institutions do not have a consistent data management protocol, whenever it exists.

Unfortunately, there is a real and concerning drop-off in the number of rain gauges (Pegram et al., 2016) and flow gauges (Pitman, 2011), which are by far the most monitored components of the hydrological cycle. While some datasets are free and relatively easy to access (streamflow, dam levels, dam volumes, etc.), other datasets are either very difficult to access and there is often a cost involved (rainfall, weather, etc.). All-time series have missing data that must be filled in before they are used. Consequently, the collection and collation of hydrological data take a lot of time.

The first infilled and extended daily rainfall database of South Africa became available towards the end of the 1980s (Dent et al., 1989) and was updated in the mid-2000s (Lynch, 2005). A similar exercise was repeated in the mid-2010s (Pegram et al., 2016) but monthly rainfall was infilled using a copula-based approach. The data derived from the later initiative were unfortunately not made publicly available.

A national data repository will leverage the potentially vast amounts of data in existing data surveys, ensure accurate, high-quality data collection going forward, and optimise utility to a broader end-user audience through proper documentation in the metadata and flexible querying abilities (Jaeger et al., 2021). The creation of the national hydrological data repository should therefore ensure and maximise usability and maintenance.

Identified research/ Research question:

How can we establish a national water data repository that is accessible for all purposes (research, operational and planning)?

Data Valuation – Calculate the value of water (related) data collected, stored, analysed and traded by organisations. Quantify, document, and communicate the value of open, shared, and integrated water data.

Explore means of integrating citizen science, remote sensing and ancillary data.

CHAPTER 7: THEME 6. MODELLING METHODS

7.1 ADAPT HYDROLOGICAL MODELS TO CHANGING CONDITIONS

Q: How can hydrological models be adapted to be able to extrapolate to changing conditions, including changing vegetation dynamics?

Quite a lot of work has been done on this aspect especially from the Weatherly Research catchments in KwaZulu-Natal by the University of KwaZulu-Natal, and smaller experiments by the Institute for Water Research (IWR) at Rhodes University to improve the ACRU and Pitman models respectively. These are generally the two models that enjoy the greatest use in the country.

Most hydrological models do not account for how an ecosystem evolves and adjusts its environment to maintain crucial hydrological functions (Savenije and Hrachowitz, 2017), while eco-hydrology explores the coevolution and self-organisation of vegetation in the landscape also with water availability (Sivapalan et al., 2012). The focus of ecohydrological studies in South Africa has generally been on the impact of invasive alien plants on water resources (Cullis et al., 2007; Dye and Jarmain, 2004; Görgens and Van Wilgen, 2004; Van Wilgen et al., 2006; Le Maitre et al., 2011; Dye, 2013, Dzikiti et al., 2007; Scott and Prinsloo, 2008; Dzikiti et al., 2013a; Dzikiti et al., 2013b; Le Maitre et al., 2015; Dzikiti et al., 2016; Le Maitre et al., 2016, Dzikiti et al., 2017; Ntshidi et al., 2018; Preston et al., 2018; Mkunyana et al., 2019; Le Maitre et al., 2020; Moncrieff et al., 2021), the costs and benefits of clearing alien trees (Le Maitre, 2002; De Lange and Van Wilgen, 2010; Crooks et al., 2020) and the impact of forestry on streamflow (Dye and Versfeld, 2007; Gush et al., 2002; Gush et al., 2005; Albaugh et al., 2013). The bulk of the research in recent years has been led by vegetation ecologists funded by the Working for Water Programme.

Identified research topic/ research question

How can models be flexible enough to be adaptable to changing environmental as well as human socio-economic conditions?

7.2 REDUCE HYDROLOGICAL MODEL UNCERTAINTY (STRUCTURE, PARAMETER, INPUT)

Q: How can we disentangle and reduce model structural/parameter/input uncertainty in hydrological prediction?

The 2003-2012 international hydrological decade, Predictions in Ungauged Basins (PUB), aimed to increase understanding and to reduce predictive uncertainty in data-sparse regions (Sivapalan et al., 2003). In South Africa, it greatly contributed to the recognition of uncertainty issues and specifically the need to quantify uncertainty and determine appropriate methods for reducing uncertainty under ungauged conditions (Hughes, 2013). There has been a shift towards the use of uncertainty principles and the further development of the widely used, monthly time step and semi-distributed, Pitman rainfall-runoff model. The key motivation for this research focus was the recognition that we always deal with data scarcity or data accuracy problems in the use of hydrological models in Africa and therefore all associated uncertainties should be explicitly included, wherever possible. These include uncertainties in the climate forcing data, the model structure, and the model parameters. The focus has been on developing a flexible uncertainty version of the Pitman model that can be used in many different situations. All the developments have been included in the freely available SPAtial and Time Series Information Modelling (Hughes and Forsyth, 2006) software framework (https://www.ru.ac.za/iwr/research/software/spatsim/). One of the key principles of one of the available versions of the model is that the simulated hydrological response of any incremental sub-basin can be constrained by a set of uncertain hydrological indices, that are derived for both gauged and ungauged areas using different regionalisation approaches (Kabuya et al., 2020; Ndzabandzaba and Hughes, 2017; Hughes, 2016; Hughes, 2019; Tambo and Hughes, 2015).

Identified research topic/ research question

How can we improve understanding of physical processes and thus improve how these processes can be adequately and accurately represented in models (linked to 7.3 below) and thus reduce model structural uncertainty?

- *Improve the data collection platforms to improve this.*

How can we identify, separate and quantify the impacts of different sources of prediction uncertainty?

Which estimated parameter (range) value would significantly change the decision(s) being made?

What is the acceptable uncertainty band of different applications?

To which extent additional field data can reduce the uncertainty and result in a different decision in the end?

7.3 MODEL IMPROVEMENT FOR BETTER PROCESS REPRESENTATION.

Q: How can we improve SA hydrological model to better represent processes?

In South Africa, the drive towards representing most of the processes of runoff generation within models (the conceptual approach) rather than opting for simpler transformation functions (the mathematical approach) with fewer parameters (Perrin et al., 2003) has led to the development of rather complex models. This approach is motivated by the need to use model parameters that are easier to evaluate for ungauged situations because they are more meaningful in terms of real hydrological processes and can be related to measurable catchment characteristics (Kapangaziwiri, 2011).

A basic premise of many experimental watershed programmes is that human activities on the landscape ultimately have some influence on the water resource. It is therefore universally possible to examine the use or misuse of land by measuring the properties (quantity and quality) of surface or subsurface waters. The use of research catchments is to either understand or demonstrate the integrated effects of specific management activities on water resources or to unpack specific hydrologic processes.

The idea of model improvement for better process representation is an ongoing undertaking that has no, and of necessity should not have, an end as measurement and, consequently, understanding of processes is evolutionary. This is premised on the understanding that process understanding, measurement techniques and computing power continue to improve. Various processes have been added to the initial model structures of the 1970s (i.e. the ACRU and the Pitman models) over the past few decades as necessity dictated that changes be made to the original structures for the models to be more relevant and be able to answer practical questions of the day.

For instance, the experiments in the Thukela catchment led to the improvements of the wetland process representation in the ACRU model (ref. Gray, 2011; Gray et al., 2012), while similar strides were also made in the Pitman model (ref. Hughes et al., 2013). Transmission losses and surface-groundwater interactions were introduced into the Pitman model through the work of Hughes and Sami (1992), Hughes (2004), Hughes and Parsons (2005), Tanner (2013), Tanner and Hughes (2015) and Mvandaba (2017). These were however based on rather few experiments of limited spatial coverage. The inclusion of riparian evaporation losses has been a part of the Pitman model since the work of Hughes (2004) that explicitly included groundwater routines into the Pitman model.

Be that as it may, explicit work on arid and semi-arid environmental processes seems to be missing in the model structures that are generally used in South Africa. Given that these model structures were created for the conditions that prevail in the southern Africa region, they therefore implicitly represent these arid and semi-arid conditions. The Namrom model, designed to work specifically in the basins of Namibia (De Bruine et al., 1993; Mostert et al., 1993), has not been tested in other basins of the region. Having identified aridity as an important climatic condition in the country the model was designed to simulate the hydrology of such areas including an allowance for varying, non-seasonal vegetation cover conditions and transmission losses to alluvial aquifers. The model is quite simple, being a four-parameter model based on a single equation of effective precipitation. With a sound conceptual basis, the model has potential for wider use in similar conditions and other models would benefit from its approach to the modelling of semi-arid and arid basins. Hughes and Meltzer (1998) added a dynamic vegetation cover to the Pitman model and achieved an improvement over the original model configuration in dry Namibian basins.

Identified research/ Research question

Which key hydrological processes are not properly represented in the Pitman and the ACRU models?

Update the Pitman model to better represent key identified hydrological processes. Update the ACRU model to better represent key identified hydrological

CHAPTER 8: THEME 7. INTERFACES WITH SOCIETY

8.1 COMMUNICATE UNCERTAINTY RESULTS

Q: How can the (un)certainty in hydrological predictions be communicated to decision makers and the general public?

Two projects on hydrological uncertainty (WRC projects K5/1838 and K5/2056) produced a wide range of scientific international publications that highlighted not only the scientific basis and importance of incorporating various sources of uncertainty in the estimation of water resources but also the need for dialogue between the scientific community, decision-makers and the public. It is not in dispute that there are many potential links between hydrological uncertainty and risk, decision making and others (e.g. insurance). There are also links to future uncertainty and climate change. The most critical issues seem to be how to communicate the issues of uncertainty to various stakeholders, and how to use uncertain information that is generated by all models in a way that increases confidence in decisions.

Identified research topic/ research question

What is the best and most effective way to communicate uncertainty in model-generated data and information?

What level of uncertainty is allowable for different decision-making contexts – this is already available with the different assurances of supply that are currently in use? Question is that would be explored is probably the efficiency and sufficiency of these metrics and how they should change in the future

8.2 SOCIETY AND WATER MANAGEMENT

Q: What are the synergies and trade-offs between societal goals related to water management (e.g. water-environment-energy-food-health)?

In most river basins humans substantially alter the hydrological cycle by constructing dams and through direct water withdrawals to irrigate crops, provide us with drinking water and carry out many of our industrial processes. As alluded to above, we generally have a poor understanding of human fluxes. Consequently, most studies focus on the naturalised hydrological cycle.

Hydrology and the science of managing water resources have both played key roles in human and economic development throughout history, yet these roles are often marginalised or obscured. The increased anthropogenic alterations of biogeochemical (the Anthropocene) prompted water experts to try to incorporate them through integrated water resources management, eco-hydrology and socio-hydrology (Savenije et al., 2014). The Anthropocene is an unofficial proposed new geological epoch based on the observation that humans significantly impact Earth's geology and ecosystems (Steffen et al., 2018).

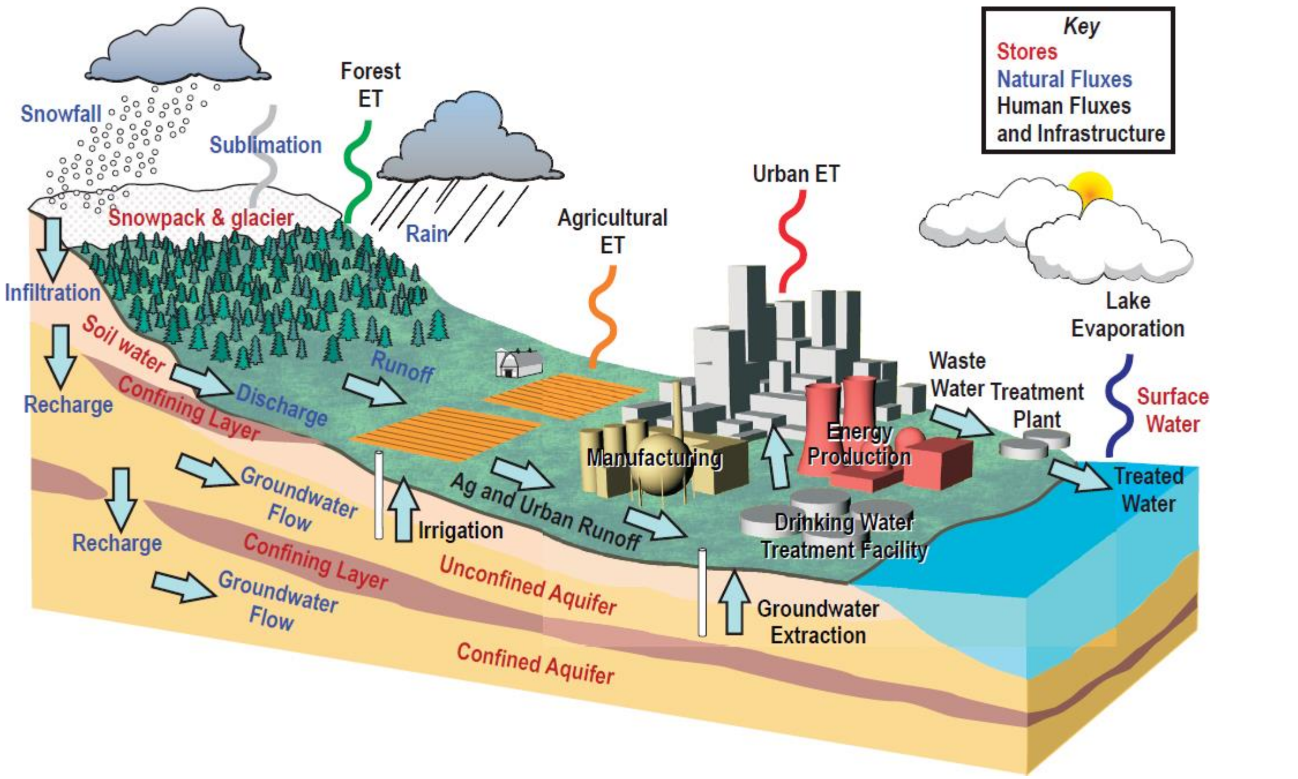

Figure 8.1. Influences of human activities on the hydrological cycle.

The Panta Rhei (Everything Flows) hydrological decade (Montanari et al., 2013) is a turning point for human-water systems that sees an increase in the interest of researchers in incorporating complexity and the human dimension into our water resources models (Madani and Shafiee-Jood, 2020). Socio-hydrology is an emerging hydrological science that recognises the co-evolution of social and hydrologic systems, and the complex feedbacks between the systems that govern it (Mount et al., 2016). Socio-hydrology must address several scientific challenges to strengthen basic knowledge and broaden the range of solvable problems (Di Baldassarre et al., 2019). Paramount of which is the engagement with social scientists to accommodate social heterogeneity, power relations, trust, cultural beliefs, and cognitive biases, which strongly influence how people alter, and adapt to, changing hydrological regimes (Di Baldassarre et al., 2019). What distinguishes socio-hydrology from problem-focused water resources research is the attempt to capture all human-nature interactions in a mathematical, holistic system model through mathematical expressions (Wesselink et al., 2017).

Identified research/ Research question:

Develop new methods to formulate and test alternative hypotheses for the explanation of emergent phenomena generated by feedback between water and society.

CHAPTER 9: COMMUNITY OF PRACTICE, EDUCATION AND RESEARCH FUNDING

9.1 THE HYDROLOGY COMMUNITY OF PRACTICE

The South African hydrology community of practice (HCOP) has been represented for many years by a relatively informal group known as the South African National Committee for International Association of Hydrological Sciences (SANCIAHS). The main task of this group has been to assist in the organisation of the biennial conference. The chairperson of SANCIAHS has also been the SA national representative to the International Association of Hydrological Sciences (IAHS) and can vote at IAHS conferences. For various reasons it has been suggested by several people that we need a more formal 'group' to represent our interests and explore the formation of an independent and new hydrological society. The process so far has included the solicitation of views from all known hydrologists in the country on the way forward and the shape of the new organization of the new formal group through a questionnaire survey. The results have been overwhelming majority support for an independent and new voluntary association (VA). A working committee of volunteers has been tasked with the temporary leadership of this body, starting with the development of a constitution. The idea is therefore that the SANCIAHS committee would be replaced by this committee and that the elected chair of the new committee could become the IAHS National Representative.

As was to be expected, the new committee of the VA is heavily laden by the necessary administration load. At the time of writing this report, the committee is finalising a constitution for the new VA which will be put to the scrutiny of the broader membership of the hydrological community.

Reports of the survey conducted indicate a preference for an independent formalised society. Priority interests ranged in order of preference from conference and symposia, publicising & discussing research, advocacy, searchable local network, … to provincial meetings. The draft vision is: *To be a strong, vibrant, diverse, and active network of hydrologists in South Africa*. The draft mission is: *To strengthen the hydrology community of practice and to promote and advance the science of hydrology in South Africa*.

The formalised society of the HCOP is the best suited.

The HCOP is made up of academics and scholars (including postgraduate students from honours to postdoctoral students), researchers, consultants, and government officials. Under the umbrella of the formalised society, the HCOP is the best entity to finalise and implement the hydrology research strategy. The society will need to form hydrology technical working groups aligned to the 7 UHP themes:

(1) Time variability and change,

(2) Space variability and scaling,

(3) Variability of extremes,

(4) Interfaces in hydrology,

(5) Measurements and data,

(6) Modelling methods, and

(7) Interfaces with society.

The working groups will refine the driving science questions or research areas listed under the themes, articulate the sub-themes or foci areas and define the time horizons for each science question or research area. The DHSWS must have at least one representative in each working group.

9.2 HYDROLOGY EDUCATION AND TRAINING

The perspective on the education and training needs related to hydrology and water resources science within the sub-Saharan Africa region, presented by Hughes (2012) is still relevant to South Africa. Thus, they will not be repeated in this section. Though hydrology is recognised as an earth science, it has been dominated in the past by contributions from hydrologists who have a background in civil engineering (Muzik, 1996) and has been largely driven by the need to solve engineering problems. Professor Desmond C. Midgley who is the "Father of Hydrological Modelling" in South Africa was a Civil Engineer.

9.2.1 Undergraduate and postgraduate offerings

Public universities in South Africa are divided into three types: traditional universities, which offer theoretically oriented university degrees; universities of technology ("technikons"), which offer vocational oriented diplomas and degrees; and comprehensive universities, which offer a combination of both types of qualification.

Most traditional universities (Table 9.1) award the Bachelor of Science Engineering (BSc.Eng.), Bachelor of Engineering (B.Eng.), Bachelor of Engineering Science (B.Eng.Sc.), Bachelor of Science in Engineering (B.S.E.) or Bachelor of Applied Science (B.A.Sc.) degree to undergraduate students of engineering study.

Table 9.1. Hydrology and civil engineering (water engineering) degrees currently offered by traditional universities of South Africa.

Institution	Founded	Location(s)	Degrees
University of Cape Town	1829	Cape Town	BSc Eng. in Civil Engineering. MSc Eng. in Civil Engineering
University of KwaZulu-Natal	2004	Durban, Pietermaritzburg, Pinetown, Westville	BSc. in Civil Engineering MSc Eng. in Civil Engineering BSc (Hons) Hydrology MSc Hydrology
University of Pretoria	1908	Pretoria, Johannesburg	B.Eng. Civil Engineering
Rhodes University	1904	Grahamstown	MSc and PhD in Hydrology and Water Resource Science
University of Stellenbosch	1866	Stellenbosch, Saldanha Bay, Bellville, Tygerberg	B.Eng, Civil Engineering (Stellenbosch)
University of the Western Cape	1959	Bellville (Cape Town)	BSc (Hons) Environmental & Water Science MSc and PhD in Environmental & Water Science
University of the Witwatersrand	1896	Johannesburg	BSc (Eng) in Civil Engineering MSc Civil Engineering

BSc Eng.: Bachelor of Science (*Baccalaureus Scientiae*); B. Tech: Bachelor of Technology (*Baccalaureus Technologiae*); B.Eng.: Bachelor of Engineering (Baccalaureus *in Arte Ingeniaria*); MTech: Master of Technology (*Magister Technologiae*); BEng Tech: Bachelor of Engineering Technology (*Baccalaureus Technologiae in Arte Ingenieria*)

The *Baccalaureus Technologiae* (B. Tech) degree is awarded by Universities of Technology (Table 9.1) and Comprehensive Universities (Table 9.3) and is generally, practice or career-oriented, as opposed to academically oriented. The degree is obtained after 4 years of study and is usually offered as a 1-year programme, following completion of a relevant three-year National Diploma.

Table 9.2. Hydrology and civil engineering (water engineering) degrees currently offered by comprehensive universities of South Africa.

Institution	Founded	Location(s)	Degrees
University of Johannesburg	2005 (1967)	Johannesburg, Soweto	B.Tech in Civil Engineering B.Eng. Tech Civil Engineering B.Eng. Civil Engineering M.Tech (Engineering: Civil) M.Eng. (Civil Engineering) M.Phil. (Civil Engineering) PhD (Civil Engineering)
Nelson Mandela University	2005 (1964)	Port Elizabeth, George	B.Eng. Tech in Civil Engineering M.Eng in Civil Engineering PhD in Engineering
University of South Africa	1873	Distance Learning	B. Tech in Civil Engineering
University of Venda	1982	Thohoyandou	Bachelor of Earth Sciences in Hydrology and Water Resources Honours of Hydrology and Water Resource Master of Earth Sciences in Hydrology and Water Resources Ph. D in Hydrology and Water Resources
Walter Sisulu University	1977	East London, Butterworth, Mthatha, Queenstown	BTech in Civil Engineering
University of Zululand	1960	Empangeni	B.Sc. (Hons) in Hydrology M.Sc. in Hydrology Ph. D in Hydrology

Table 9.3. Universities of Technologies and relevant degrees related to either hydrology or civil engineering

Institution	Founded	Location(s)	Degrees
Cape Peninsula University of Technology	2005	Bellville, Cape Town	BTech in Civil Engineering
Central University of Technology	1981	Bloemfontein, Welkom	BEng Tech in Civil Engineering
Durban University of Technology	2002	Durban, Pietermaritzburg	BTech in Civil Engineering
Mangosuthu University of Technology	1979	Umlazi	National Diploma: Civil Engineering
Tshwane University of Technology	2003	Pretoria, Mbombela, Polokwane, Ga-Rankuwa, Soshanguve, Witbank	BTech in Civil Engineering
Vaal University of Technology	1966	Vanderbijlpark, Secunda, Kempton Park, Klerksdorp, Upington	BTech in Civil Engineering MTech in Civil Engineering

Only three universities (the University of KwaZulu-Natal, the University of Zululand and the University of Venda) offer hydrology at the undergraduate level as a primary discipline.

9.2.2 Relevance of degrees offered

At the undergraduate level, students are mostly trained by lecturers and senior lecturers who only have masters' degrees and very limited to no field experience. Several professors of hydrology have either retired, joined the private sector or migrated overseas. As a result, most universities are understaffed. This also affects the postgraduate level, where there is a small number of qualified and experienced project supervisors.

It is perceived that formal undergraduate training in hydrology has not improved significantly, while practical and field experience has not improved at all. The South African hydrologic education community is not capitalising on the advances in research on science, technology, engineering, and mathematics education.

For decades, there has been simultaneously a concern, from the university hydrologic science perspective, over inadequate fundamental training in hydrologic theory, and from the engineering practitioner's perspective, over inadequate engineering, professional, and practical training (Rudell and Wagner, 2013). Thus, the current approach to hydrology education remains inadequate for current and future societal challenges.

Research in mainstream hydrology is mostly undertaken at a few university departments and by civil engineering consultancies (Hughes, 2007). The number of young hydrology scientists joining the established research community is decreasing. Most recent graduates join consultancies, which is a concern for the future sustainability of South African hydrology research (Hughes, 2007).

Given the specific complexity of the water problems the country is facing, the teaching of hydrology must adopt a more integrated view of the role of water in the natural and built environment around us. The expansion must include a better understanding of how hydrologic conditions impact human behaviour and how human behaviour impacts the water environment (Seibert et al., 2013).

9.3 FUNDING HYDROLOGY RESEARCH

Hydrology research suffers from a lack of funding data. It is challenging to get annual figures on water research data. Getting more granular hydrology research data is especially challenging. Thus, it is difficult to make a case for additional funding to be ring-fenced for hydrology research.

9.3.1 National funding

The Water Research Commission (WRC) is the main funding body supporting hydrological research in South Africa. The research development and innovation (RDI) expenditure of the WRC is a tiny fraction of the national RDI expenditure (Table 9.4). Moreover, the WRC water resources management budget which also encompasses hydrology research is only about 20 to 30% (estimate) of the total WRC RDI expenditure (Table 9.4).

It was not possible to ascertain the level of hydrology RDI funding from government departments like DHSWS.

9.3.2 International funding

Research programmes benefited from international and regional cooperation. South African hydrological scientists were actively engaged in various international research programmes including IAHS PUB (Prediction in Ungauged Basins), the UNESCO HELP (Hydrology for the Environment, Life and Policy) and FRIEND (Flow

Regimes from International Experimental and Network Data) initiatives. Predictions in Ungauged Basins (PUB) is an IAHS initiative that operated throughout the decade of 2003-2012, with the primary aim of reducing uncertainty in hydrological predictions. HELP is a joint UNESCO/WMO program designed to establish a global network of catchments to improve the links between hydrology and the needs of society. The FRIEND-Water initiative is a flagship programme of the UNESCO-International Hydrological Programme (IHP) that helps to set up regional networks for analysing hydrological data. It aims to develop a better understanding of hydrological variability and similarity across time and space, through the mutual exchange of data, knowledge and techniques at the regional level.

Over the last decade, there was barely any engagement in such international research programmes. South African hydrological scientists are not explicitly active in the current IAHS scientific decade of 2013-2022 of IAHS (*Panta Rhei*, Everything Flows), dedicated to research activities on change in hydrology and society. It is therefore important that the HCOP resume its involvement in regional and international research programmes.

Table 9.4. National and Water Research Commission Research Development and Innovation expenditures (2009/10 to 2018/19)

Year	Total National RDI Expenditure	WRC RDI Expenditure	WRC Water Resources management Expenditure
	R'000	R'000	R'000
2009/10	41 909 354	83 800	20 950
2010/11	40 507 610	104 474	26 119
2011/12	44 418 384	122 607	30 652
2012/13	47 742 438	116 726	29 182
2013/14	51 321 146	118 521	29 630
2014/15	58 689 954	176 457	44 114
2015/16	64 673 357	201 047	50 262
2016/17	71 385 946	213 306	53 327
2017/18	77 449 180	188 524	47 131
2018/19	73 567 935	164 702	41 176

9.3.3 Funding mix

Today, research is funded by a mix of grants from government (primarily carried out through universities, research councils, and consultants), corporations (through their research and development departments; and primarily carried out by consultants), international institutions/agencies and non-profit foundations. While all indications are that government is the main funder of hydrology research, it is not possible to either quantify or even apportion the hydrology research funding mix.

Nevertheless, all indications are that the HCOP needs to mobilise more funds and used such funds efficiently. While this document is a step towards focusing research using limited funds available for hydrology research by identifying critical hydrology and water security questions, there is still a need to diversify the funding mix.

Corporations seldom fund blue-sky research. Yet, without the continuous developments and insights derived from basic research, applied research wither away. It is, therefore, necessary to identify the hydrology research-related needs of different stakeholders and economic sectors. The South African National Trust and Assurance Company Limited (Santam) commissioned research into the impact of natural hazards (Nel et al., 2011b), especially fire on the insurance industry (Nel et al., 2011c and Forsyth, 2019). The 2019 report highlights potential fire hotspots in South Africa and includes recommendations to improve stakeholders' understanding of fire risk, as well as actions to mitigate the increasing risk of fires at the urban-wild interface.

Hydrological hazards include droughts and flooding and related events (e.g. landslides and river scour and deposition). Two-thirds of the country's natural disaster-related deaths occur in floods. The annual risk of flooding is 83.3% and the population vulnerability is high due to economic factors and geographical location (Zuma et al., 2012). Flood risk poses major problems for communities and insurance companies alike. Flood related losses directly or indirectly impact insurance levies and pay-outs. There is potential to raise research grants to provide insights into any of those hydrological hazards.

CHAPTER 10: THE NEXT STEP

Hydrology in South Africa faces an uncertain future as it grapples with challenges of declining capacity, dwindling hydrological data and unreliable funding. In March 2014, the Water Research Commission in collaboration with the new Department of Science and Innovation organised a high-level dialogue titled 'The State of Hydrology (Research) in South Africa: Towards a 10-year Science Plan' that included representatives from universities, governments departments and science councils. The meeting was timely as the International Association of Hydrological Sciences (IAHS) was launching its current scientific decade (2013-2022), entitled "Panta Rhei – Everything Flows", dedicated to research activities that target issues in hydrology and society.

At the scientific assembly of the International Association of Hydrological Sciences (IAHS) Port Elizabeth (Held 10-14 July 2017 in Port Elizabeth, South Africa), a new vision to harmonise hydrology research efforts that solve real societal problems, was outlined. Thus, the international hydrology community-identified twenty-three (23) major unsolved scientific problems in hydrology. As we work towards the South African hydrology research agenda, the document explores the relevance of these problems to South Africa's hydrology and water security. This document is also timely, as the hydrology community is about to embark on a new International Hydrological Decade.

Unfortunately, it was not possible to get comments from most members of the HCOP. Therefore, an online survey was developed (https://forms.gle/vuJmN1xeVosyHAmJ9), to enable the HCOP, to contribute to the strategy document that will shape hydrology research in the country. The survey enables respondents to contribute to the theme(s) where their expertise lies and, for each research question, they can indicate the time horizons. The survey distinguishes four basic time horizons: continuous, without cessation; short-term, less than 5 years; medium-term, 5 to 10 years; long-term, more than 10 years.

The purpose of the strategy is intended, in the short term, to help the WRC allocate funds to research proposals that will help answer critical questions. In the long-term, it will also help mobilise more hydrology research funds.

The hydrology discipline needs a community of practice to help decide on all critical aspects of hydrology in the country. This community will use this living document to guide some of the research that the WRC should prioritise. The draft hydrology research strategy is therefore a guiding or starting document.

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