



# Developing a Conceptual Model for Sustainable water Resource Management and Agricultural Development: the Case of the Breede River Catchment Area, South Africa

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## Abstract

The complex relationship that exists between water resources and agricultural production has been increasing constantly globally. Several factors are interacting to influence the management of water resources making the system complex and dynamic. To increase the understanding of these complex and dynamic systems, relevant tools are needed to identify the causal relationships that exist between the drivers and their influences on the system. Participatory modelling based on the system dynamics approach provides a simplistic and visualisation tool that can improve the understanding of the functioning of a complex and dynamic system. A multi-stage participatory approach was used in this study involving relevant stakeholders in the development of an integrated conceptual system dynamic model using causal loop diagrams. This approach was used because it captures the thought process and mental model of relevant stakeholders in the development of the model, making it a valuable tool for policy and decision making at government and individual levels. The integrated model built in this study used causal loop diagrams to address problems of water management and agricultural sustainability in the Breede River Catchment. The model shows major causal-relationships and feedback loops that determine the functioning of the overall system. The model demonstrates the usefulness of the participatory approach in solving problems related to water management and agricultural development in the catchment.

**Keywords** Causal loop diagrams · Participatory modelling · Stakeholder participation · System dynamics modelling · Breede river catchment · Feedback loops

## Introduction

The issue of global water scarcity and food insecurity has become a major cause of concern to governments, international and local organisations, policy-makers, water-users, and water managers (Owusu-Sekyere et al. 2017). The

general objective of water resources management is to promote efficient freshwater use to maximise economic, social, and environmental welfares in an equitable, efficient, and sustainable manner (Zeng et al. 2012). Water management and agricultural development have received significant attention and transformation over recent decades (Basco-Carrera et al. 2017). Water resources are essential for agricultural production because they can limit food production, energy generation, and economic activities in other sectors in the economy (Schneider et al. 2011; Ringler et al. 2013; Chartres and Noble 2015).

Participation by all involved stakeholders in policy development and decision-making is very important and forms a crucial part of Integrated Water Resource Management (IWRM). IWRM is an approach used in water resource management, which allows water management issues to be solved holistically with active stakeholder involvement. IWRM ensures that the management of water, land, and related resources are properly coordinated in order

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to maximise the sustainability of economic and social welfare equitable without compromising vital ecosystems (Giupponi and Sgobbi 2008). The participatory approach is a common methodology within the IWRM as it allows “stakeholders at all levels of the social structure to have an impact on decisions at different levels of water management” (Global Water Partnership GWP 2000).

Environmental issues are quite dynamic and complex, therefore require flexible and strategic bottom-up policies which will pave the way for multi-stakeholder participation in planning and decision-making processes (Reed 2008). Water management and agricultural sustainability are some of the environmental challenges confronting natural resource managers and planners. Water and food systems are challenging to manage because of the complexities arising from the functioning of hydrological cycles and biological systems (Antunes et al. 2009; Kotir 2020). The system is made complex by the dynamic interaction of drivers such as rapid population growth, urbanisation, land-use change, climate change, land degradation, unsustainable water policies (Nyam et al. 2020). This complexity is further exacerbated when there multiple stakeholders with different perspectives, interests, values, and concerns regarding the use of water and land for human-related purposes (Kotir et al. 2017). Natural resource managers, researchers, and practitioners have often adopted a reductionist, linear cause-effect analytical approach to address problems related to water and food systems (Musavengane 2019; Moldavska and Welo 2019). However, linear-reductionist thinking analyses and explains parts of a complex system thereby making it an unsuitable framework for analysing complex systems with several interdependent and interconnected systems and drivers (Nayak and Waterson 2019; Turner and Baker 2019). A non-linear thinking approaches which offer a holistic framework to promote the sustainability of water and food systems are needed. Participatory modelling (PM) and stakeholder engagement based on the principle of systems thinking and system dynamics have become very important tools for facilitating strategic decision-making in complex natural systems (Reed et al. 2008; Voinov and Bousquet 2010; Voinov et al. 2014; Voinov and Gaddis 2017). Qualitative system dynamics based on PM is a useful technique for identifying and capturing feedback loops inherent in a complex system. Therefore, PM provides a suitable platform for planning and managing water and food systems (Mirchi et al. 2012).

Several studies have used PM to model water resource management around the world (e.g., Videira et al. 2009; Beall et al. 2011; Davies and Simonovic 2011; Carmona et al. 2013a, b; Butler and Adamowski 2015; Lopes and Videira 2015; Basco-Carrera et al. 2017; Kotir et al. 2017; Pluchinotta et al. 2018). Carmona et al. (2013a, b)

combined the Bayesian network with economic and crop models to develop an integrated modelling framework to support decision-making in water management under uncertainty in Spain. Pluchinotta et al. (2018) developed a model using system dynamics modelling to support decision-making in irrigation water management in agricultural systems in Southern Italy. Davies and Simonovic (2011) developed a system dynamics-based model to assess the nature and structure of connections between water resources and socio-economic and environmental change globally.

Furthermore, PM has been applied to water and food systems in Africa (e.g. Kotir et al. 2017; Simonovic et al. (1997); Daré et al. 2018). Kotir et al. (2017) developed an integrated conceptual model using causal loops diagrams to assist integrated water management and agricultural sustainability in Ghana. Simonovic et al. (1997) developed a system dynamics approach for long-term water planning and policy analysis in Egypt. Daré et al. (2018) used a Companion Modelling approach (ComMod) to develop role-playing games and a computerised agent-based model to support the identification of a problem shed areas Ghana.

In South Africa, PM has been applied to water management and as part of the IWRM (e.g. Sherwill et al. 2007; Farolfi et al. 2010; de Lange et al. 2010; Brown 2011; Du Toit et al. 2011; Claassen 2013). Farolfi et al. (2010) used companion modelling to develop multi-agent models to represent water supply and demand dynamics for the Kat River. However, the model developed did not consider the feedback processes operating between the system components. Studies by Brown (2011), Claassen (2013), Sherwill et al. (2007), and Du Toit et al. (2011) proposed frameworks for IWRM through the involvement of all relevant stakeholders in the decision-making process regarding water. Furthermore, Stone-Jovicich et al. (2011) used a consensus analysis to assess the mental models of water users and management in the Crocodile River Catchment. However, these studies did not examine the feedback processes operating within a dynamic system.

Here, we describe the development of a qualitative conceptual model for studying complex water problems in the Breede River Catchment to identify areas of convergence and divergence in understandings key issues. Specifically, we used causal loops diagrams (CLDs), also referred to as dynamic hypothesis (see Sterman 2000) to show the causal relationships that exist between drivers influencing sustainable water management and agricultural development in the catchment. This process involves the use of participatory modelling methods, which allows for the inclusion of relevant stakeholders in the model development process. Building on this approach, this paper further develops the method to elicit their mental models to explore how ecological scientists and farmers think about

agro-ecology and map areas of convergence and divergence in these understandings. Despite the importance of conceptual modelling, very few studies have attempted to use this modelling approach to understand the feedback processes that exist among the drivers influencing water management and agricultural development in South Africa. A knowledge gap exists and needs to be filled to understand the relationships and feedback processes that exist between the multiple drivers influencing water and food systems in the catchment in order to understand the systemic behaviour of the catchment.

## Study Area

This PM exercise was conducted in the Breed River Catchment, which is one of the largest catchments in the Western Cape Province. The catchment occupies an area of 12,384 km<sup>2</sup> and has a length of 337 km. According to the Breede catchment strategy, there are 15 dams within the Breede River Catchment. The biggest dam (Brandvlei dam) has a capacity of 475 million m<sup>3</sup> while the smallest dam (Pietersfontein dam) has a capacity of 2 million m<sup>3</sup> (see Fig. 1). Seven of the dams within the catchment are used for agricultural irrigation, and one is used for urban water usage and the rest are used for both urban and irrigation. The population of the catchment is estimated to be an estimated

300 000 people. According to Seeliger et al. 2018a, b, agriculture is the main economic driver and accounts for an estimated 87% of annual water demand, making the sector the largest water user in the catchment. The Breede-Overberg water management area (WMA) is made of seven local municipalities, consisting of Witzenberg, Breede Valley, and Langeberg in the north, Theewaterskloof and Overstrand in the south-west, and the Cape Agulhas and Swellendam in the southeast (Western Cape Government 2018).

Commercial agriculture is the major activity dominating land use in the catchment. Agriculture in the catchment is dominated by intensive irrigation for wine and table grapes, dairy and deciduous fruit production as well as extensive rain-fed (dry land) for cereal cultivation and livestock farming. Agricultural processing and packaging are also important economic activities in the catchment. The catchment is very crucial for agricultural development in South Africa because 70% of all table grapes, apples, and fynbos in South Africa are produced in the catchment (Western Cape Government 2018). The catchment is also strategic to agricultural development in South Africa because agricultural products produced in the catchment are consumed locally and internationally.

The water resources in the catchment are under pressure due to population growth, infrastructure development, and increases in water demand. Agricultural development

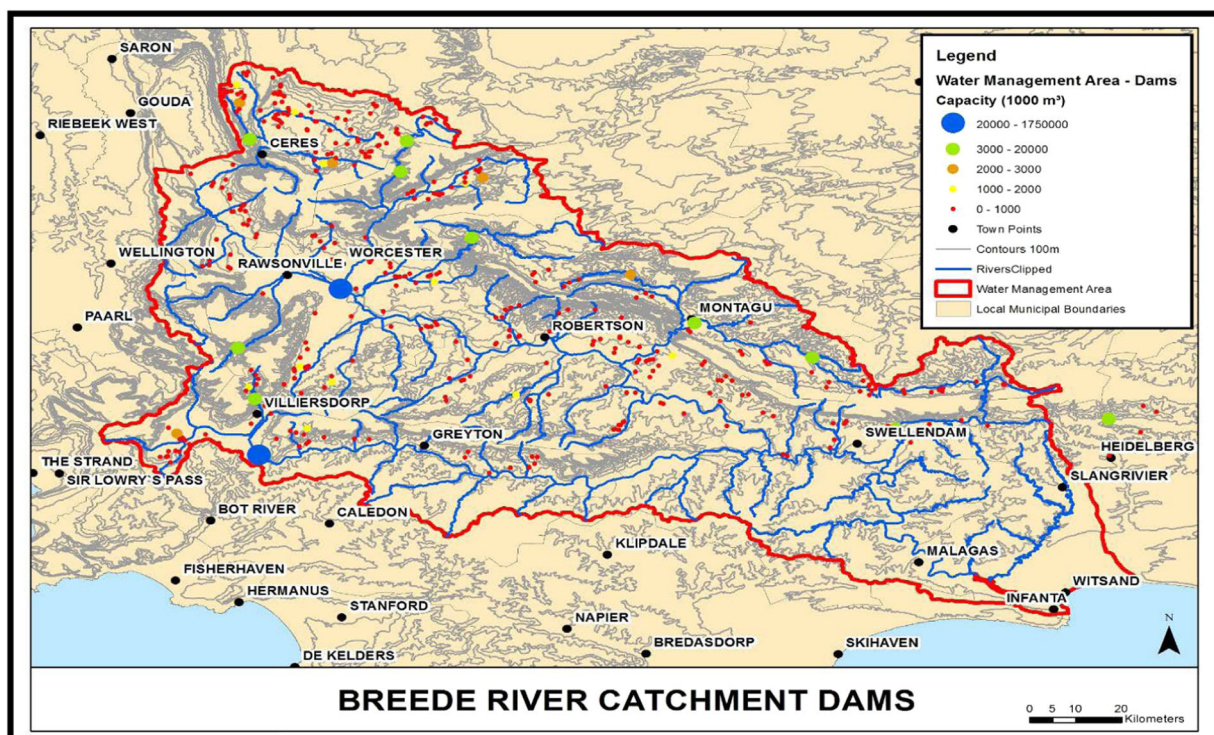


Fig. 1 Map of the Breede River Catchment Source: Seeliger et al. 2018a, b

combined with socio-economic development and ecological factors are interacting to influence water resources in the catchment. Therefore, as stated in the Breede catchment management strategy (2018:57), “policies are needed to balance the water-dependent requirements of economic development, social justice and ecological sustainability in this region”.

The catchment like most of the Western Cape province has a winter rainfall climate. The catchment experiences extensive rainfall during the winter months and very little or no rain during the other seasons. Rainfall can exceed 1 800 mm in the western mountainous areas of the catchment and as low as 300 mm/a rainfall lower eastern areas of the catchment. Additional surface water is recorded during winter months and shortages outside the winter months.

## Methodological Approach

### Participatory Modelling with System Dynamics

The PM used in this study is based on the system dynamics approach (Forrester 1961; Sterman 2000; Ford 2010). System dynamics is a methodology based on feedback systems borrowed from control theory and is mainly used to study the non-linear behaviour, time-delay and the multi-loop structures of the complex and dynamic systems (Forrester 1961; Bala et al. 2017). Models based on SD are generally designed as tools to improve system understanding of the decision-making process and foster system thinking skills and knowledge integration for modellers and end-users (Kelly et al. 2013). The involvement of diverse stakeholders is an important part of the system dynamics approach (Forrester 1961; Richardson and Anderson 1995; Vennix 1999). This has led to the upsurge in participatory system dynamics modelling (see Stave 2010; Beall and Ford 2010), which is the main approach implemented in this paper. Thus, participatory system dynamics modelling uses a system dynamics perspective in which stakeholders or clients participate to some degree in different stages of the model-building process (Stave 2010; Bala et al. 2017). It provides a mechanism for integrating scientific knowledge with local knowledge and building a shared representation of the problem (Stave 2010). It involves building shared ownership of the analysis, problem, system description, and solutions or a shared understanding of the tradeoffs among different decisions (Bala et al. 2017).

System dynamics models can be represented in an object-oriented form of casual loop diagrams or stock and flow diagrams (Sterman 2000; Amadei 2019). Stock and flow diagrams represent integral finite difference equations involving the variables of the feedback loop structure of the system and simulates the dynamic behaviour of the system

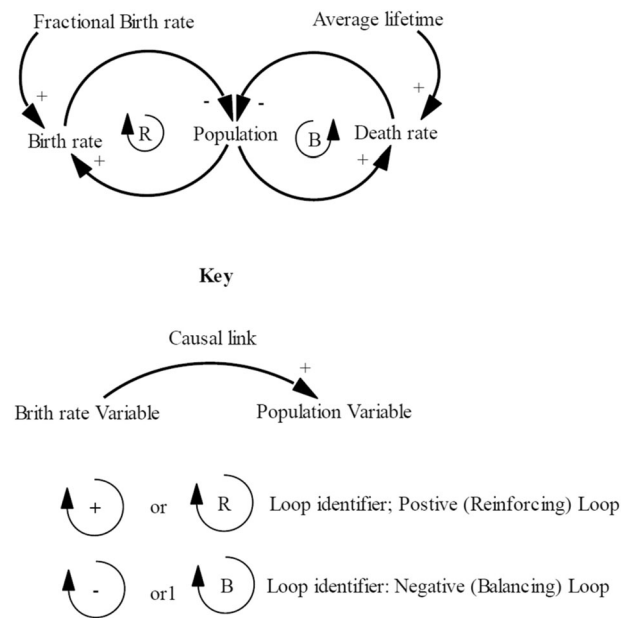


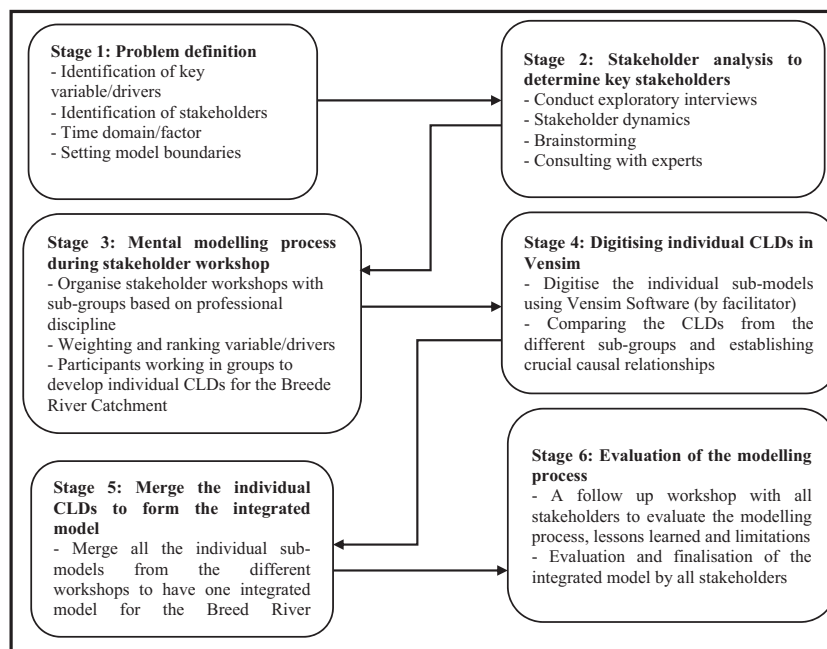
Fig. 2 Causal loop diagram notation (Adapted from Sterman 2000, pp 138). A positive (+) causal link indicates that an increase/decrease in one variable would lead to an increase/decrease in another variable. Similarly, a negative (−) causal relationship indicates a decrease/increase in one variable in the model will increase/decrease in another variable in the model

(Bala et al. 2017). On the other hand, CLDs comprised of words and arrows with appropriate polarity, depicting combinations of positive and/or negative causal relationships among key components or variables of a complex system from a cause to an effect (Sterman 2000; Mirchi et al. 2012). They help in laying out the different structural components of a system in a conceptual manner and show how they interact dynamically in a qualitative manner (Amadei 2019). This allows both reinforcing (R) feedback loop that can cause runaway behaviour in the system and balancing loops, which creates self-correcting processes that lead to stability, equilibrium, and reaching the desired outcome to be identified. Here, we used CLDs to explain the complex challenges in collaboration with key stakeholders in the catchment to represent how different sectors interact. An example of a CLD and its constituents elements is depicted in Fig. 2.

### The Modelling Approach

We approach participatory modelling from the perspective of the six broad steps of conceptual model building adapted from Inam et al. (2015) and Kotir et al. (2017) (see Fig. 3). Each step involved several key activities that guided the implementation of the overall process. A brief description of each step is described in the following sections. Note that the evaluation of the modelling process is self-explanatory, and so is not described (see Fig. 3).

**Fig. 3** Main stages of the proposed modelling approach in South Africa



### Problem definition

The first step in model building is to identify the problem, set its boundary, and state the specific objectives of the modelling exercise. While a clear articulation of the problem is particularly helpful in defining the purpose of the model, its boundaries, and the time domain, it also affects the selection of stakeholders in the modelling process (Inam et al. 2015). As part of the problem definition, drivers influencing water and food systems in the catchment have been identified and analysed (see Nyam et al. 2020).

### Stakeholder analysis to determine key stakeholders

Stakeholder analysis is the process of identifying, categorising, and selecting participants in the modelling process based on their role, interest, power, legitimacy, and urgency (Reed et al. 2009; Carr 2015). The aim is to evaluate and understand the stakeholders' relevance to a project or policy (Lienert et al. 2013). Generally, there are no standards or guidelines for identifying and selecting stakeholders for a PM process. However, it has been widely suggested that the process be all-inclusive—capturing a diverse group of stakeholders (Reed 2008; Voinov and Bousquet 2010; Voinov et al. 2016; Voinov et al. 2018). Since the problem to be addressed in this paper involved water management and its influence on agricultural development in the Breed River Catchment, it was important to ensure that stakeholders from both domains were represented.

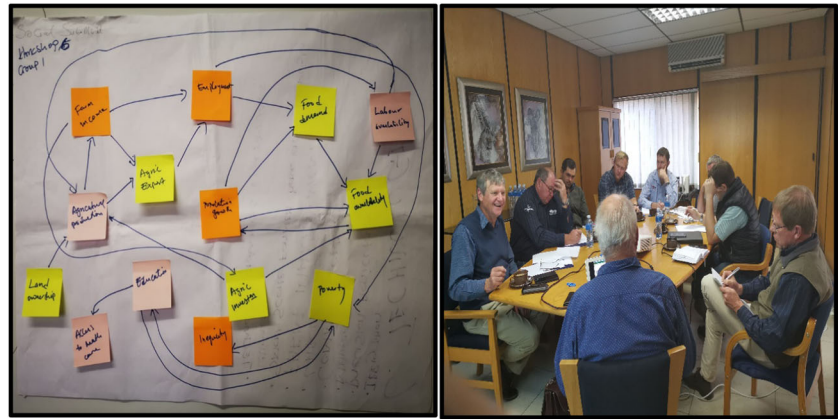
Thus, to begin the process of stakeholder identification, invitations were sent to the leaders of the main institutions involved in the water and agricultural sector in South

Africa. These included farmers' organisations, the Department of Agriculture (DoA), and other private organisations such as Greencape, and the Council for Scientific and Industrial Research (CSIR). Following Videira et al. (2009) and Kotir et al. (2017), a preliminary meeting was organised with the leaders of the farmers' organisations to explain the purpose of the project, system dynamics, the modelling process, and vensim software (primary software used in this study). Subsequently, these institutions were requested to nominate stakeholders within their organisations with multiple years of experience in research or practice and knowledge of water and agricultural related issues in the catchment and their likely availability to discuss problems of the catchment. Independent farmers (i.e. commercial and smallholder farmers) were also consulted through referrals to check their competencies and availability to be included in the modelling process.

### Mental modelling process during stakeholder workshop

According to Jones et al. (2011), a mental model is the internal representations of the external reality individuals have about how a system works, that forms a cognitive basis for their reasoning, decision making, and behaviour. Mental models are updated and maintained through direct observation, learning, and experience, and are continuously relied upon to reason, explain, design, communicate, act, predict, and explore (Anjum et al. 2019). As such, mental models are often of interest to those in the fields of natural resource management (Van Hulst et al. 2020). To capture the mental models of diverse stakeholders from different sectors, five workshops were organised with the identified stakeholders

**Fig. 4** A demonstration of stakeholders mental models during the workshops



described above. To manage group dynamics, each workshop participants were limited to a maximum of 22 participants (see appendix 1 for the profile of stakeholders). The first modelling workshop was organised at the Western Cape Department of Agriculture on the 2<sup>nd</sup> April 2019 in Cape Town with 22 specialists and experts from the Western Cape DoA, DWS, DEA, and Green Cape. The second workshop was organised with nine commercial (irrigation) farmers in Mpumalanga on the 24<sup>th</sup> of July 2019 and the third meeting was organised at the Stellenbosch agricultural society head office on the 29<sup>th</sup> of July 2019 with 11 experienced farmers and heads of the Stellenbosch agricultural society. The fourth workshop was organised with seven stakeholders in the Upington department of agriculture on 2 October 2019 and the fifth workshop took place with 13 smallholder farmers in Qwaqwa on 13 November 2019.

At each workshop, participants were introduced to the objectives of the project, the system dynamics modelling approach, and the modelling software (Vensim:<http://www.ventanasystems.com/>) and its functionalities. This was to allow participants with little or no modelling experience to grasp the objectives and procedures for conducting the modelling. Participants were then asked to brainstorm and identify the drivers that would influence water and food systems in the catchment and categorised under 5 clusters (namely; social, Biophysical/environmental, economic, infrastructural/technological, Political, institutional, and management clusters). After identifying and categorising the drivers under each cluster, participants were asked to rank the drivers under each cluster from the most influential to the least influential driver (see Nyam et al. 2020). This allowed the participants to understand the drivers of change influencing water resource management and agricultural development.

A3 type sheets and sticky notes were provided to each participant in the small workshops and each sub-group in the large workshop to develop their individual CLDs using the identified drivers, showing carefully the causal

relationships between the drivers of change (see Fig. 4). The drivers were written on the sticky notes and placed on the A3 type paper and arrows were used to show the cause-effect relationship between the drivers. In the end, individuals and group leaders were required to present and explain their mental models. Participants were allowed to comments, criticise, and suggest areas of improvement after each presentation. This made the process transparent and ensured that all the contributions of the participants were duly tracked and taken into consideration. According to Kotir et al. (2017), this method is highly effective because it allows stakeholders to continue amending their CLDs during the workshops until all participants are satisfied that they had built a simple model representing their mental model and have captured the most important causal-relationships. All workshops were facilitated by the lead author, specifically providing more explanation on the modelling process and tracking participants' responses.

#### Digitising individual (sub-models) CLDs in Vensim

After all the individual workshops, the lead author translated and digitised all the paper CLDs models using vensim modelling software, which is a widely accepted software for system dynamics modelling by previous studies. The sub-models focused on socio-political, economic, and ecological issues considered by the stakeholders to be vital in the sustainability of water and food systems in the catchment. The sub-models were digitised by the lead author capturing and comparing vital causal-relationships that exist within each cluster (biophysical, social, and economic). After this process, preliminary CLDs for all the sub-models were finalised and sent to the stakeholders for approval via email. The project team members after receiving comments and suggestions from stakeholders, checked the sub-models for simplicity and comprehensiveness, to ensure all important causal-relationships were captured, before finalising the sub-models.

## Merge the individual CLDs to an integrated model

These sub-models were merged to have the integrated model which aims to capture the different perspective and mental maps of all the stakeholders that participated in the workshops while taking into consideration the problems faced in the catchment, the causes, consequences, feedback loops, policies, and strategies (Mourhir et al. 2016; Elsayah et al. 2017), to address the problems related to the sustainability of water and food systems in the catchment. The integrated model allowed for all the views and opinions of all the stakeholders to be represented in a simple yet comprehensive model. The integrated model captures all the important causal-relationships, feedback loops, delays in the systems and allows for robust qualitative scenarios to be developed regarding the future of water management and agricultural development in the catchment (Zare et al. 2019).

## Results

### Thematic Sub-Models (Individual CLDs)

Individual CLDs were developed based on the clusters and drivers identified and ranked by the stakeholders as most important for water management and agricultural development in the catchment. Dividing the integrated model into thematic sub-models allows for the detailed evaluation of each sub-model and how the variables under the sub-models interact to influence water management and agricultural development in the catchment. The sub-models allowed stakeholders to visualise the interaction between the drivers identified and the causal relationships that exist between the drivers. Given that the next phase of this project is to develop a quantitative model, the sub-models allow for simplification of the model for easy quantification in the next phase.

Figure 5 represents the socio-political sub-model denoting 22 variables. The model is dominated by issues of land reform, land ownership, social conflicts, population growth, growth of informal settlements, food demand, food availability, and poverty (Fig. 5). The model hypothesised that land reform if done efficiently can produce positive results. The model shows that land reform can increase land ownership among the previously disadvantaged group in the economy. This will positively influence agricultural productivity, food export, farm income, reduce poverty and inequality among others. On the other hand, if land reform is not implemented effectively can increase farm attacks, reduce agricultural investment (due to uncertainty), social conflicts, and emigration from the catchment.

The economic sub-model is represented in Fig. 6. The model has 20 variables showing the causal relationships

between economic variables such government support, investments in water infrastructures, food exports, agricultural contribution to GDP, and how they interact with other related variables such as surface and groundwater availability, water demand, agricultural productivity, crop yield, labour availability, and food availability to influence water management and agricultural development in the catchment. The model hypothesised that government support especially to smallholder farmers will increase investment funds, investment in water infrastructures, surface water availability, total water supply, and agricultural production. This model places investment in the water and agricultural sectors as a top priority.

The biophysical sub-model is represented in Fig. 7, denoting 23 variables. This model is dominated by issues such as climate change, surface and groundwater availability, water demand and supply, agricultural production, crop yield, land availability, and food demand. Stakeholders identified this model as one whose interactions can severely influence water management and agricultural development in the catchment in the future.

### The Integrated Conceptual Model

The integrated conceptual model presented in Fig. 8 captures the major relationships in the different sub-models taking into account variables that can be quantified in the next phase. The integrated model has 36 variables representing several causal relationships. The model shows 21 major loops consisting of 13 reinforcing (positive) loops and 8 balancing (negative) loops. Loop R1 and R2 show the relationship between agricultural production, crop yield, food availability, food demand, crop prices, and farm income. As agricultural production increases, it leads to crop yield, food availability, food demand, crop price, and farm income being reinforced. This shows that agricultural productivity will increase crop yield and food availability, which will increase food demand, food prices, farm income, and eventually agricultural productivity. The recurring drought in the Western Cape Province has resulted in a significant decline in agricultural productivity, crop yield, and food availability in South Africa. The decline in agricultural productivity has resulted in rising food prices in South Africa. If water is not sustainably managed in the province, agricultural productivity will continue to decline resulting in low food availability and rising food prices (see loop R1 and R2). The drought conditions in the Western Cape reduced agricultural production significantly due to water scarcity and drove consumer prices for agricultural products higher (Ogundeji and Jordaan 2017). These loops are balanced by loop B5 and B7 which show that an increase in food availability will increase food demand and increases in food demand will reduce food availability.

Fig. 5 Socio-political sub-model

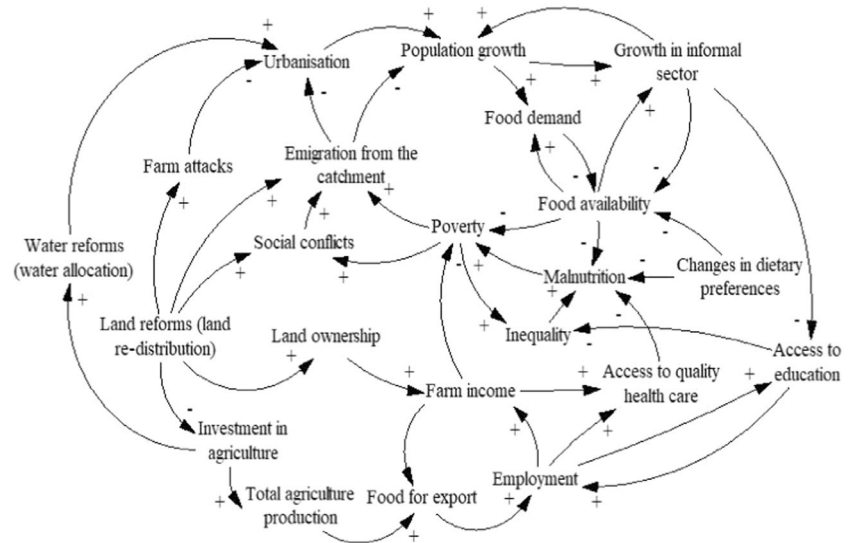


Fig. 6 Economic sub-model

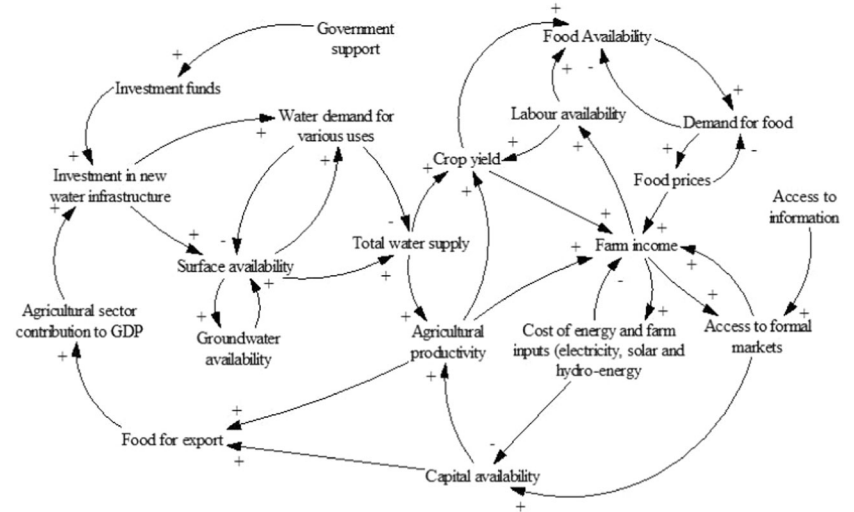
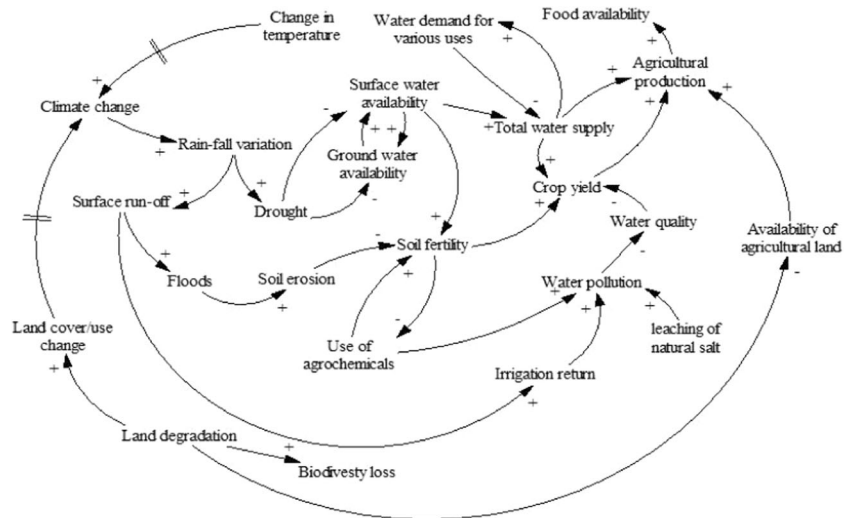
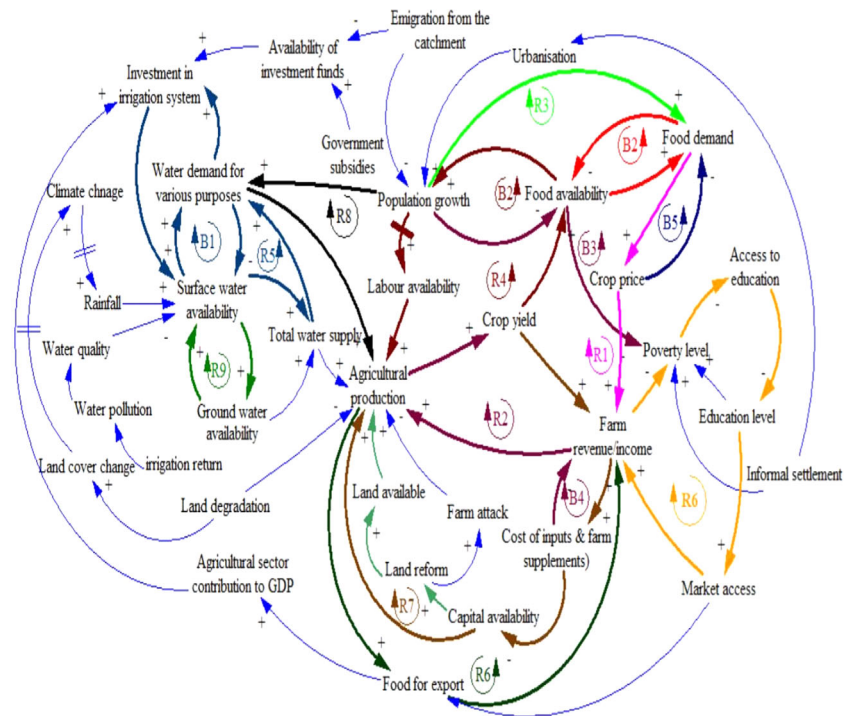


Fig. 7 Ecological sub-model





**Fig. 8** Integrated model for water management and agricultural development in the Breede River catchment



Furthermore, an increase in food demand will increase food prices all things being equal and increases in food prices will reduce food demand.

Loop R3 shows the population dynamics. This loop shows the causal-relationships between population growth, food demand, and food availability. Population growth will increase food demand, food demand will decrease food availability and food availability will reinforce population growth. Loop R3 is balanced by loop B4 which shows that population growth will eventually feedback to reduce the amount of food available to feed the population. Loop R4 shows a causal-relationship between population growth, labour availability, agricultural production, crop yield, and food availability. According to the model, population growth will lead to an increase in the labour force over time (after a delay), agricultural production, and consequently, crop yield. An increase in crop yield will lead to an increase in food availability and population growth. Other studies have found that population growth contributes to the reduction in agricultural land in most developing countries and poses a threat to food security and livelihoods (Premanandh 2011; Pham 2014). Population growth can also contribute to land and water-use conflicts with agriculture in urban areas (Chen 2007). Urban agriculture can benefit significantly from urbanisation through cheap and available labour which will allow farmers to sustainably manage resources and increase agricultural yield (Prokopy et al. 2008; Mkwambisi et al. 2011; Wästfelt and Zhang 2016). Loop R5 is very important because it demonstrates the

profit dynamics of the farmers. Farmers placed a lot of emphasis on this loop because it shows the causal-relationship between agricultural productivity, food export, and farm income. The loop indicates that an increase in food production will increase food for export, farm income, and reinforces agricultural production. According to stakeholders, policies should be geared towards enhancing agricultural production, which will increase agricultural export and farm income. As farm income increase, it reduces the poverty level of the farmers (especially smallholder farmers), which will increase access to education and education levels. Access to education and increases in educational levels will increase access to information, formal market channels, and access to markets will reinforce farm income (loop R6). Similar studies have found a positive correlation between farmer education and sustainable management of natural resources. An educated farmer has access to information, market, knowledge on water, and farm management and which positively influences agricultural productivity and income levels of farmers (Chen 2007; Food and Agricultural Organization FAO 2012; Danso-Abbeam et al. 2018). Educated farmers have the knowledge and skills to efficiently manage resources and adopt better production techniques to enhance productivity (Fan and Hazell 2001; Khapayi and Celliers 2016). Less-educated farmers are often slow to adopt efficient production techniques and adapt their farm activities to changing social and environmental conditions (Reimers and Klasen 2013; Li et al. 2016). Education and training have the

potential to equip farmers with efficient production and water conservation techniques according to the stakeholders. Loop B6 shows a balancing effect which indicates that food available will reduce poverty levels and an increase in poverty levels will reduce access to formal education, educational levels, access to information, and formal markets and eventually reduce farm income. Poverty reduces the capacity of farmers to manage and sustain resources (Hazell and Wood 2008; van Noordwijk 2019). According to Molden et al. (2010), poverty is a major driver of resource degradation and tools to manage water resources, agricultural lands, and agricultural sustainability, which support a majority of the population. Poverty reduces the ability of farmers to access formal education, access to formal markets, and standards of living (Kanianska 2016).

An increase in farm income will lead to agricultural expansion which will increase the cost of farm inputs and supplements. An increase in the cost of farm inputs and supplements will decrease capital available for agricultural investment. Capital availability will increase agricultural production, and crop yield and eventually reinforce farm income (Loop R7). Farmers expressed concerns over the increasing cost of production (due to increases in farm inputs and supplements) which is affecting capital availability and agricultural production. These concerns are expressed in Loop B8, which shows that farm income will increase the cost of farm inputs and supplements and an increase in the cost of farm inputs will reduce farm income. Loop R8 shows a very important causal-relationship in water management in the catchment. The loop shows that the availability of surface water will increase the availability of groundwater and an increase in groundwater availability will increase surface availability. This relationship is very important for the effective management of freshwater resources in the catchment. Loop R9 shows the dynamics between population growth, water demand, agricultural production, and food availability. This loop is very important and will play a vital role in the management of water and agriculture in the catchment according to the stakeholders. An increase in population growth will increase water demand for various purposes (especially for agricultural purposes), agricultural production, crop yield, food availability, and eventually reinforce population growth. Population growth will increase pressure on scarce water resources and food production in the catchment.

Loop 10 is equally an important loop in this model. The loop shows the water investment dynamics and establishes a very important causal-relationship between investment and water management in the catchment. Stakeholders were very concerned about loop 10 because according to them, the water problems faced in the catchment area due to the lack of or insufficient investment in the water sector in the catchment. The model shows that an increase in investment

in irrigation schemes and water infrastructures (such as dams, wastewater plants, salination plants, etc.) will increase surface water availability, total water supply, water demand for various purposes, and eventually reinforce investment in the water sector. Due to too much bureaucracy in the water sector, farmers (mostly commercial farmers) complained of being unable to invest in building dams on their farms to ease water issues. Some farmers also complained that they are not allowed to dig boreholes in their farms due to policies (such as non-compliance to AgriBEE). These frustrations were echoed by commercial farmers who felt their productivity is declining due to policies preventing them from investing in water infrastructures on their farms. Investment in appropriate technologies is the driving force behind improved water-use efficiency, soil health and fertility, and pest, weed, and disease management in most developed countries (Pham 2014). The use of appropriate technologies is the driver of water-use efficiency and improved agricultural productivity and agricultural sustainability in most developed countries worldwide (World Bank 2008). Technologies such as rainwater harvesting, efficient irrigation system, conservation tillage to reduce soil evaporation, and water-efficient crops have enhanced sustainable water management and agricultural sustainability in developing countries (Pretty 2008). Loop R10 is counteracted by the balancing loop B2, which shows that increases in water demand for various purposes will reduce surface water availability, total water supply and eventually reduce water demand for various purposes. In South Africa, investing in efficient and productive infrastructural services and technologies could be an important input to improve water-use efficiency vital component for economic growth and efficiency, productivity, and competitiveness (Ruiters 2013). Infrastructure productivity is crucial for managing rapid population growth in South Africa.

## Discussion

The results of this study show how stakeholders perceive the social, economic, and biophysical dimensions of water resources management and agricultural development in the Breede River Catchment. The stakeholder workshops were important in promoting an important dialogue between diverse participants from various backgrounds and helps in building a mutual understanding of water and food systems in the catchment. The participatory approach adopted in these workshops assisted in creating a collaborative partnership and helped participants understand the importance of collaboration in solving the issues of water management and fostering agricultural growth in the catchment. Similar to previous studies, the methodology proposed and tool

used here in this study can help bridge the communication gap between policymakers and local stakeholders. This situation highlights the importance of participatory modelling to incorporate the knowledge of key stakeholders for a holistic view of the complex system.

The integrated model shows an important causal-relationship between social, economic, and biophysical drivers influencing water and food systems in the catchment. The workshops conducted in this study have provided a framework for conducting future research on water management and agricultural systems in South Africa. The integrated model captured major relationships that exist in water and food systems consistent with related studies in the literature (see Inam et al. 2015; Kotir et al. 2017 for example). The model also shows leverage points that need policy intervention to ensure efficient water management and agricultural sustainability in the catchment.

### Leverage Points for Sustainable Water Management and Agricultural Development

The results presented in this study place decision-makers at public and private levels as the core agents tasked with the formulation and implementation of policies geared towards ensuring efficient water management and agricultural sustainability in South Africa. The study in general has contributed to enhancing our understanding of the dynamics of stakeholder analysis and stakeholder theories. Several empirical studies were also conducted to validate the theoretical claims relating to the stakeholder concepts. The sub-models and the integrated model have revealed some areas of major concern and leverage points for enhancing water and food systems. A leverage point in system thinking is a problem in a system structure that needs a solution to effect change in the system behaviour and it can either be a large or small change (Kotir et al. 2017). Few leverage points exist in the integrated model built by the stakeholder. For example, the stakeholders mentioned that population growth reduces water and food systems resilience by increasing demand for water (loop R9) and reducing land for agricultural production, increasing food demand (loop B4 and B5), and increasing food insecurity. Similar studies have already noted that a complete transformation in approach would be needed in South Africa to build resilient food systems that would require efficient water-use, reinforcing environmental, social, and economic pillars of sustainable development, and ensuring food security (World Wide Fund (WWF) 2018).

Increasing water scarcity and water demand due to population growth, economic growth, climate change, mismanagement of water resources, and deteriorating water quality are some of the challenges facing the water sector in the catchment. Water resources in the catchment are

threatened by the invasion of alien species, wastewater discharge, and return flow from agriculture and the household sector. According to Seeliger et al. 2018a; b, (pp 23), “The invasion of alien species is severely impacting the ecological sustainability of the Breede River catchment with about 70% of riparian areas in the catchment in a transformed state”. The collaborative approach proposed in this study is very important for solving the water problems in the catchment. Stakeholder investment is needed at the public and private levels to solve the water problems (both water quality and quantity) in the catchment. Furthermore, these challenges can be overcome by improving land and water productivity and reduce the non-beneficial use of land and water resources (Pereira et al. 2012). According to FAO (2012), increasing climate change events, rising input costs, ecosystem, resource degradation, shifting dietary preferences due to population and income growth, increasing social gap, and conflicts over resource use will continue to influence ecosystem management, water management, and agricultural sustainability in the catchment. Policymakers cannot fully understand food security in isolation because it has multiple economic, social, and environmental drivers influencing the system and must, therefore, be viewed within the framework of the intersecting resources of land, biodiversity, water, and energy (Godfray and Garnett 2014; Biggs et al. 2015; WWF 2018).

The issue of land reform is a topic of serious debate in South Africa at the moment (loop 13). The future of the agricultural sector in South Africa depends on policymakers ensuring secure land rights for all. The uncertainty regarding the land reform policy has reduced investment in the sector, especially by private sector investors. This has a serious impact on agricultural productivity in the catchment (Chamberlain and Anseeuw 2018). Land tenure is a driver that can affect the efficiency of land use (Pham 2014). Farmers will have less incentive to invest and use land sustainably if land rights are not properly secure (Toulmin 2009). According to Besley and Ghatak (2010), secure land tenure enables farmers to sustainably manage land, enhance productivity-enhancing investment, operate land markets that transfer land to its best and most productive use, and eventually access to capital by using land as collateral.

Loop R8 is a very important loop according to the stakeholders who consider investment in the water sector imperative to ensuring sustainable water management. Investment in water systems and water infrastructures will increase surface water availability. An increase in surface water availability will increase water supply and water demand for various purposes (B2). Decision-makers in South Africa should develop investment models required to close the water infrastructure funding gap, to extend access to water and efficiency in water-use especially by funding innovative techniques for managing water resources and

ensuring sufficient surface and groundwater availability (Ruiters 2013). Investments in agricultural water management, infrastructural development in rural areas, and related policies are the pathways to breaking the poverty trap in smallholder African agriculture (Hanjra et al. 2009; Valipour 2015).

The water and agriculture models developed in this study are very important in the South African context because it examines several drivers and includes diverse stakeholders. The method used to develop the model for this study is different from all other studies that have used system dynamics to model water and food systems in South Africa. The conceptual model developed in this study will be developed into a quantitative model that will enable the development of practical policy-based scenarios regarding water management and agricultural development in the catchment using real data. They are a plethora of biophysical, social, and economic drivers influencing water management and agricultural development in all the catchments in South Africa. Some of these drivers are unique to certain catchments and the stakeholders are different with varying needs and expectations. Developing a model like the one developed in this study for all the catchments could be beneficial for future research because developing policies targeted at the specific needs of different stakeholders could assist inefficient water management and sustainable agricultural development. The model developed in this study can easily be extended and adapted to other major catchments in South Africa and other transboundary river basins in Africa and beyond. The lessons from this study, described in the next section can help guide this future endeavour.

### Participatory Framework for the Sustainability of Natural Resources and Important Lessons

This study has identified important feedback loops and leverage points for sustainable management of water and food systems in the Breede River catchment using participatory modelling based on the principle of systems dynamics. This study has demonstrated that participatory frameworks are useful for including relevant stakeholders to constructively identify and capture important feedback loops inherent in complex systems and the dynamic interactions between important drivers thereby serving as an important framework for planning and management of water resources and agricultural sustainability. The approach equally shows policymakers can frame problems and design intervention strategies for solving them. Qualitative system dynamics tools offer a valuable platform for identifying and explaining system behavior over time (Mirchi et al. 2012). For instance, Kotir (2020), Kotir et al. (2017), and Inam et al. (2015) have applied qualitative tools based on system dynamics to explore and identify the key

system drivers influencing the mode of behavior and sustainability of coupled water-food systems. We have shown that qualitative system dynamics such as the ones developed here are capable of capturing the underlying feedback structures inherent in natural systems thereby making it valuable for sustainability planning, policy formulation, and research (Elsawah et al. 2017; Perrone et al. 2020).

Socioecological systems are complex and unpredictable due to the multiplicity of drivers and stakeholders with diverse opinions, values, and interests regarding water management and agricultural development (Reed et al. 2013). Participatory approaches are increasingly developed at different temporal and spatial to assist policymakers and stakeholders prepare for change (Pahl-Wostl 2002; Voinov et al. 2016). According to Gray et al. (2012) pp 94) “integrating stakeholder knowledge into natural resource governance is considered to add flexibility to socioecological systems because knowledge diversity reduces rigidity, represents multiple perspectives, and promotes adaptability in decision-making”. This study has demonstrated the value of including stakeholders in problem-framing, policy formulation, and decision-making processes because they are core agents with perfect knowledge of the system. According to Davila et al. (2018), the application of participatory approaches to natural resource management and policy formulation has increased considerably because they allow for important findings to be made and increases the knowledge of the stakeholders about the systems. Integrated water resource management is not a new concept in South Africa, but this study has provided a framework for involving stakeholders directly in the design of the models, which ensures that the models are aiming at the problems and stakeholders can use them. Conceptual modelling provides a suitable methodology for capturing the opinion of all relevant stakeholders and represent visually for easy understanding of complex system especially when there is uncertainty about the system or limitations of quantitative data.

Worthy of note is the fact that the participatory approach takes a great deal of time and effort to complete especially in a system where identifying and assembling the stakeholders with the necessary skills and competencies is quite difficult. It was also important to consider broad stakeholders with diverse knowledge and experience in the modelling process to develop a model that is inclusive, practical, and easy to use. It is also important to keep the number of participants small for easy management of the groups and to record all the important contributions of the stakeholders.

Many of the stakeholders were participating in this exercise for the first time and had no prior knowledge of modelling, thus making it difficult for them to fully understand the entire process. However, they found the entire process to be simple and transparent. The stakeholders stated that the CLD modelling process gave them a

visualisation map to see the interaction between the different drivers affecting water and food systems. Stakeholders expressed satisfaction in the way the process was conducted and the simplicity of the model building process. The stakeholders also appreciated the approach by stating that policymakers should adopt this approach for effective and practical policies that will target the needs and desires of water users in the catchment. This approach is recommended for future participatory research and policy design. It is important to note that the models presented in this study, are the ideas and thought processes of the stakeholders that participated in the workshops. As such, the categorisation of the sub-models, the integrated model, causal-relationships, and loops are the biases and assumptions of those stakeholders who were involved in the participatory exercises across South Africa.

## Conclusion

This paper used a multi-stage participatory modelling approach based on the principle of system dynamics to engage a diverse group of stakeholder in water and agriculture to develop an integrated qualitative, conceptual causal-loop model that would inform policymakers and all relevant stakeholders of the feedback structures and behaviour of the complex system in the Breede River Catchment. The 2014–2018 drought in South Africa in general and the catchment in particular, has given this model so much relevance because it will serve as a decision support tool to enhance sustainable management of water and food systems in the catchment. This is the first study that has attempted to develop an integrated model for coupled water-food systems including multiple drivers through active participation of a diverse group of stakeholders in the catchment. The CLDs were chosen for this study because it provides a simple visualisation tool that captures causal and non-linear relationships that exist between ecological, socio-political, and economic drivers interacting with each other to influence water management and agricultural development in the catchment. The CLDs identifies major causal-relationship, key feedback loops, and their polarities.

The results of this study show that the CLDs are very useful in participatory modelling that includes a diverse group of stakeholders some of whom might not have any modelling experience in the development of conceptual models involving several drivers of change in solving complex water management and agricultural development issues. The integrated model developed in this study indicates several feedback processes interacting to influence water management and agricultural development in the catchment. The model shows eight balancing (negative) feedback loops and 13 reinforcing (positive) loops, meaning

that the catchment has a complex system governed by multiple drivers. The model is dominated by positive feedback loops some of which are very important in determining the dynamic behavior of the catchment. All stakeholders agreed that water management was a real issue in the Western Cape. Stakeholders believed that radical actions are needed by all relevant stakeholders to ensure the equitable and sustainable management of water resources in the catchment. Stakeholders agreed that economic, social, and environmental policies were crucial in the management of water resources in the catchment. Investment in new water infrastructures, maintaining existing ones, population, land reform policy, water allocation (water re-distribution), accountability of relevant government structures, and cooperation between government structures were proposed as key strategies that can ensure sustainable management of water resources and food production in the catchment.

Most stakeholders had no prior experience in modelling and were happy with the model they had developed, the transparency of the workshops, and the general feedback from all stakeholders. Most of the stakeholders indicated that they were willing to participate in future participatory workshops for policy development and recommended that this approach be used to solve other socio-economic and environmental issues in South Africa in general. To develop realistic scenarios regarding water management and agricultural development in the catchment, a quantitative system dynamics model must be built so that proposed policy recommendations from the stakeholders can be tested using real data. This will enable practical scenarios to be developed. The next phase of this project will be to build a quantitative model capable of simulating alternative scenarios to support decision-making in water resource management and agricultural development in the catchment.

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## Compliance with Ethical Standards

**Conflict of Interest** The authors declare that they have no conflict of interest.

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