Chapter 1
A Review of Existing Knowledge on Water Use and Nutritional Water Productivity in South Africa

Vimbayi G. P. Chimonyo and Tafadzwanashe Mabhaudhi

Abstract In South Africa, while the nation is food secure at the national level, a substantial portion of the population lives in poverty and faces food insecurity, particularly in rural areas. The country's water scarcity, variable rainfall patterns, and unequal distribution of irrigation resources further complicate the issue. Agriculture, which relies heavily on irrigation, is a major water consumer and contributor to food production. Efforts to address these challenges include exploring strategies like rainwater harvesting and improving water productivity in agriculture. The Water Research Commission (WRC) has played a pivotal role in developing innovative solutions to enhance water productivity, focussing on environmentally sensitive approaches and the water–energy–food nexus. Achieving food security in water-scarce regions like South Africa necessitates dynamic institutions, improved water productivity, and sustainable agricultural practices. This chapter emphasises the urgency of addressing these issues to ensure a healthier and more productive life for rural communities while promoting sustainable development and water-based agriculture.

Keywords Resource use efficiency · Water scarcity · Sustainable development · Resource security · Irrigated agriculture

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1.1 Introduction

Although water is a renewable resource, its availability for human use is limited. Almost 70% of the globe is covered in water, 97.5% is seawater, and only 2.5% is available as freshwater (Shiklomanov 1991). Not all of the 2.5% fresh water is available for humans. Some of it is locked as frozen water or groundwater. Although water is a renewable resource, its accessibility is limited due to geographical distribution and human activities polluting it. Almost 60% of fresh water is available in only nine countries, representing 44% of the earth's surface, namely, Brazil, Canada, China, Columbia, the Democratic Republic of Congo, India, Indonesia, Russia, and the United States (Oki and Kanae 2006). The rest of the world's population faces physical or economic water stress/scarcity, with two-thirds experiencing water shortages for at least a month in a 12-month cycle (Mekonnen and Hoekstra 2016). Many developing countries face poverty, high unemployment rates, and, more importantly, food and nutrition insecurity within this two-thirds.

Water and food security is attained when there is an acceptable quantity and quality for health, livelihoods, ecosystems and production. However, today's grand challenges brought about climate change, technological development, rapid urbanisation and increasing population and incomes threaten the future availability of water for food. The demand for more water in agriculture has intensified competition for the resource within the agriculture value chain and across domestic and industrial sectors. Furthermore, existing challenges related to water insecurity are impacting the energy sector as it is used in its production (hydropower generation and biofuel production or for cooling in nuclear and geothermal power plants). There is, therefore, a need to produce more food to meet the growing demands of an increasing population using the same or even less water. Achieving optimal water productivity results in availing water resources to other equally important sectors including (i) enhancing the health of the environment, (ii) reducing pressure on other sectors of industry, and (iii) ensuring sustained economic development and growth.

Addressing the water and food insecurity challenges requires the strengthening of institutions and the promotion of transdisciplinary actions aimed at balancing water demand and supply. This is particularly relevant in the agriculture sector as over 60% of the available freshwater resources are used in the sector. There is a need for both the public and private sectors to work together in providing the relevant information that allows decision-makers to assess and respond effectively to the worsening water and flood risks (Masipa 2017). Agricultural production and livelihoods in water-scarce regions can be sustained only if priority improves water productivity and enhances water research and development (Cai et al. 2011). This book provides an overview of the role of agricultural water productivity in improving water-use efficiency in the whole food value chain under increasing water scarcity. The term water productivity is used in rainfed and irrigated agricultural sub-sectors. The book explores the implications of improved water productivity and then provides a systematic review to understand the limits and opportunities that are derived from improved water productivity. The discussion will focus on South Africa, a country whose status is water-stressed and has high food and nutrition insecurity at the household level.

1.1.1 An Overview of Water and Food Security in South Africa

South Africa is food secure at the national level, but over 50% of households are food insecure as evidenced by extreme poverty and economic inequality, particularly in densely populated, rural areas and informal settlements (Stats-Sa 2019). According to Statistics South Africa, almost 25.2% of the population in the country live below the poverty line (Stats-Sa 2019). Most households are faced with food insecurity (Chakona and Shackleton 2019), about 28.3% of the population are at risk of hunger, and 26% are food insecure (SADHS 2017). This has seen the government give monthly grants to many due to the prevalence of poverty. Besides these alarming statistics, rainfed agriculture is the third most important means of livelihood, yet it contributes only 10% to household income (Stats-Sa 2019). These challenges of resource insecurity are being exacerbated by the emergence of novel infectious diseases such as the COVID-19 pandemic. This requires an urgent need to provide smart technologies and practices that are cost-effective and support smallholder agriculture. The National Development Plan (NDP) acknowledges agriculture and rural development as key to job creation, economic growth, poverty reduction, and, more importantly, addressing household food and nutrition security (National Planning Commission 2012).

However, water security is one of many challenges affecting the implementation of many agricultural reform programmes. South Africa is water-scarce, the 30th driest country in the world. Rainfall in the country is highly variable and unevenly distributed in space and time across the country. The average annual rainfall received by over 60% of the country is less than 500 mm, which is the minimum needed for dryland farming, whilst 21% of the country's land area receives less than 200 mm (De Villiers et al. 2004). Seventy percent of crop production is rainfed, yet only 35% of the land area receives enough rainfall that is needed for rainfed crop production (CSIR 2010). The water deficit resulting from the low rainfall, which is compounded by climate change and exacerbated by the high evaporative rate, limits crop production under the rainfed agricultural system in the country (Van Averbeke et al. 2011). These challenges of water deficits are posing the greatest risk to national food production and security. The agriculture sector in South Africa is faced with complex challenges that need transitional pathways if the country is to continue to meet the growing food demands of an increasing population. These transformations include producing more nutritious food with less water per unit of output. This transition requires the adoption of novel and climate-smart technologies and practices. Provide. As the water challenge for agricultural production increases, the importance of irrigated agriculture in South Africa is expected to rise.

As already alluded to, over 60% of the available freshwater resources in South Africa are allocated to agriculture to irrigate about 1.3 million ha, which represents just under 10% of the arable land (Cousins 2007; Nhamo et al. 2016). Irrigated agriculture supports between 25% and 30% of South Africa's agricultural production and contributes about 90% of the high-value crops like potatoes, vegetables, and fruits, and between 25% and 40% of industrial crops that include sugarcane and cotton. The distribution of water for irrigation is determined along racial lines as most of the water is allocated to the white commercial farmers who own vast agricultural land (Lahiff and Cousins 2005). About 90% of the water supply is used in this commercial agriculture sector which is supported by massive state investment in infrastructure (Lahiff and Cousins 2005). Smallholder farmers, who are in the majority, are mostly found in resource-insecure former homelands or Bantustans (Van Averbeke and Khosa 2007), where they are only able to use about 7.7% of irrigated land, which is about 100,000 hectares (Hardy et al. 2011). The strategy of the National Development Plan (NDP) to increase the irrigated area under smallholder farming to about 200,000 ha has the risk of further straining the already scarce water and energy resources (Cai et al. 2017). This requires interventions through transformative and circular approaches that address synergies and trade-offs.

Some of the available options to increase water availability for irrigation include the construction of new dams to capture runoff and to increase the use of groundwater resources (Mabhaudhi et al. 2018). However, the country has limited options to construct more dams as it already has a high number of dam density. Therefore, the only option is to use groundwater resources; however, there is a lack of knowledge on the amount of groundwater stored in aquifers. Besides, the smallholder farmers lack water, energy, infrastructure and technical skills to irrigate, resulting in some of the land equipped for irrigation not being irrigated (Nhamo et al. 2024). Another alternative is for farmers to explore opportunities from rainwater harvesting and soil water conservation techniques. These challenges are being compounded by decreasing rainfall totals and the frequency of droughts and heatwaves that increase evapotranspiration (Fig. 1.1). Hence, the practicality of this approach under the increasing frequency of drought is quite limiting. Thus, smart technologies that enhance water productivity are envisaged to contribute immensely to water-use efficiency (Mabhaudhi et al. 2018). Therefore, system efficiencies can significantly improve water productivity and sustainable food production under water-limited conditions.

For over 50 years, the Water Research Commission (WRC) has developed effective, holistic, water-smart solutions and innovations to ensure water and food security. Interventions spearheaded by the WRC have included, but are not limited to, innovations in water quality and environmentally sensitive water development, a fundamental diversification of water-supply options, innovative water-sensitive designs, embracing the water–energy–food nexus and fully implementing a fourth industrial revolution (4IR) approach to agricultural water management. Enhanced WP has been central to these initiatives, spanning different temporal, spatial, and socio-economic scales. The mapping of research funded by the WRC can showcase the existing research networks on agricultural WP, emerging thematic areas and possible research and knowledge gaps in the global South. Such an exercise can aid

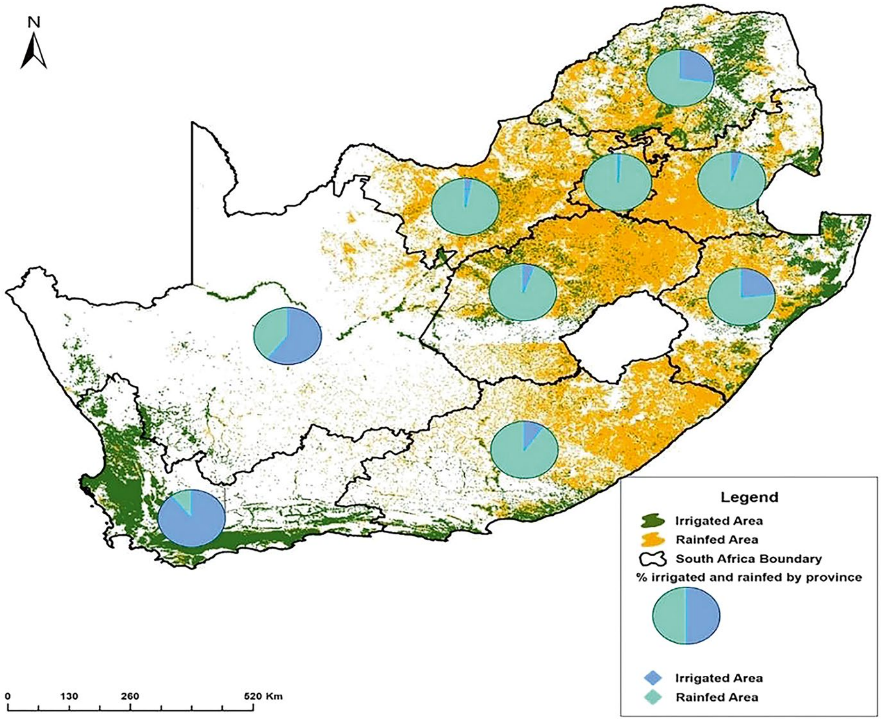

Fig. 1.1 The distribution of rainfed and irrigated areas in South Africa. The pie charts represent the percentage of irrigated and rainfed land by province (Mabhaudhi et al. 2019)

in aligning key global, national, and provincial plans, priorities and policy documents for ensuring food and water security, sustainable development and empowering rural communities, and other WRC's programmes for sustainable water-based agriculture in rural areas.

1.1.2 Aims and Objectives

This chapter aims to:

(i) To showcase the research (grey literature, journal publications, reports, popular articles, etc.) on water productivity emanating from South Africa
(ii) Identify gaps in the existing knowledge, clarify WP, and report on the types of evidence needed to address and inform the advancement of the WEF nexus

1.1.3 Methodology

The study conducted a state-of-the-art literature review on the current status of water productivity research within South Africa. The methodology is structured into four phases, namely, (i) a literature review of key terms and definitions used in the book, (ii) a mixed-methods approach to establish the status of water productivity research and the gaps, and (iii) a determination of the pathways to operationalise smart-technologies and practices that improve water productivity. These phases are detailed below.

Phase 1—Definition of Terms
Various definitions have been used to describe water productivity. Each of these has its meaning and context, which has caused incoherency at times. This book has identified the most relevant and contextualised definitions of key water productivity terms. The definitions of the terms provide a short formal definition, some additional characteristics and the available references. The terms to be defined include 'water productivity', 'water use efficiency', and 'water footprint'. Official guidelines, position papers, research and journal articles, and statements and reports from various sources were consulted.

Phase 2—Status of WP Research in South Africa
In this phase, an assessment of the thematic research areas emerged from the articles and scientific reports on WP within the WRC and globally. Firstly, scientific reports were downloaded from the WRC knowledge hub. The keywords used to search for these articles included 'water productivity', 'water use efficiency', and 'water footprint'. Three hundred forty-five reports and popular articles were retrieved and published between 1974 and 2021. To retrieve the global research trends, the same keywords were then inputted into SCOPUS. A total of 3540 articles were retrieved, and we extracted the top 200 cited articles to include in the study. It should be noted that the global research database on WP was not subjected to the same assessment since it only served to identify themes that show the advancements made in the subject area.

Phase 3
Identified literature and extracted data were subjected to qualitative analysis. To analyse the data obtained from the WRC knowledge hub, a word cloud was initially generated from the titles of research reports, articles and popular articles. A word cloud was used as a special visualisation of text whereby more frequently used words are boldly highlighted. The frequency at which a word appears within a document under review, the larger and bolder it appears in the image generated. This provides an overview of the main themes being addressed in the document. Word clouds are increasingly becoming popular in understanding the main theme of written material. However, word clouds have several limitations including their failure to group words with the same or similar meaning, such as 'water use' and 'water utilisation'. Further, the words were retrieved out of context as the technique omits

the semantics and phrases they comprise. To overcome these challenges, retrieved titles were subjected to bibliometric analysis.

Two separate bibliometric analyses were also conducted to reveal key terms in water productivity research within the global context and South Africa. Bibliometric analysis quantitatively assesses published articles and facilitates the evaluation of peer-reviewed studies in a specific subject of research (Rey-Martí et al. 2016; Small 1973). It examines secondary data obtained from digital databases from a quantitative and objective perspective (Albort-Morant and Ribeiro-Soriano 2016). Such an analysis facilitates the structuring of the evolution of a focal research area (Cobo et al. 2011; Klavans and Boyack 2006). The VOSviewer software was used for the analysis in this study and performed the key term analysis and network visualisation of relevant documents related to water productivity.

1.1.4 Results and Discussion

1.1.5 Terminology

1.1.5.1 Water Productivity Versus Water Use Efficiency

While the terms *water use efficiency* (WUE) and *water productivity* (WP) are aimed at addressing the term 'more crop per drop', they are being used interchangeably and, as a result, seemingly lack a clear definition. Experts from irrigation engineering, crop physiologists, and water managers tend to have opposing points of view on the correct terminology. Molden et al. (2003) came up with a detailed conceptual framework to communicate water productivity. Although water use efficiency and water productivity are used interchangeably, they are two distinct words.

Water use efficiency is the ratio of biomass or yield to water applied (Eq. 1.1), while WP is the ratio of biomass or yield to actual water used (Eq. 1.2).

$$\mathrm{WUE} = \frac{Y_a \text{ or } B_a}{\text{water applied}} \,\mathrm{kg\,m^{-3}} \tag{1.1}$$

$$\mathrm{WP} = \frac{Y_a \text{ or } B_a}{\mathrm{ET_a}} \,\mathrm{kg\,m^{-3}} \text{ or } \mathrm{kg\,ha^{-1}mm^{-1}} \tag{1.2}$$

Y_a and B_a are the actual yield and biomass (kg), respectively, and ET_a is the actual evapotranspiration (mm ha^{-1} or m^{-3} ha^{-1}) or water consumed. For the calculation of WUE, water applied suggests water entering the systems. It is silent on the unproductive water loss such as runoff, deep percolation, and capillary rise, and changes in subsurface flow, since it is challenging to quantify these.

1.1.5.2 Irrigation Efficiency

Irrigation efficiency is a water use efficiency that measures an irrigation system's effectiveness within specific limits. It determines the ratio of the amount of water consumed by the crop to the amount supplied through Irrigation (Irmak et al. 2011). It encompasses all types of irrigation, including surface, sprinkler, or drip irrigation. The term is important for characterising irrigation performance and evaluating irrigation water use (Howell 2003). Irrigation efficiency is measured according to irrigation system performance, homogeneity of water application, and crops' response to Irrigation (Irmak et al. 2011). The measurements are interconnected but differ with space or time. On a temporal scale, the measurements can be considered for a single application to a season or a year, while that on the spatial scale vary from a single field to as large as an irrigation district.

1.1.5.3 Water Footprint

According to Waterfootprint.org, *water footprint* (WF) measures the amount of water used to produce each of our goods and services. It can be measured for a single process, such as growing maize, or an entire value chain related to food production. The water footprint indicates the amount of water consumed by a country, or globally at any spatial scale (river basin or an aquifer). Water footprint, therefore, represents 'blue' water (sourced from surface or groundwater), 'green' water (precipitation and runoff used directly by plants), and 'grey' (water needed to assimilate pollutants) to provide information on volumetric water use and pollution from the perspectives of consumers, supply chains and products, or even specific geographies (Hoekstra 2017). Researchers agree that reducing the water footprint of crop production, that is, increasing water productivity can aid in increasing future food demands in the context of global water scarcity (Nyathi et al. 2019).

$$\mathrm{WF} = \frac{\mathrm{ET_a}}{Y_a \text{ or } B_a}\left(\mathrm{m^3 kg^{-1}}\right) \quad (1.3)$$

1.1.6 Status of Research on Water Productivity in South Africa

The current section highlights the work funded by the WRC to address water productivity challenges. Water and food are among some of the most important resources that sustain human life; therefore, their security is vital for achieving Sustainable Development Goals (SDGs) (Mensah and Ricart Casadevall 2019). This is highlighted in the collection of words identified by the word cloud and is consistent with one of the main goals of WRC. However, the security of water and food is threaded by increasing population and climate change which contribute to their depletion and degradation. Both water and agriculture are culprits and victims of climate change and changing how they are managed has the potential to alleviate the current challenges and contribute towards achieving the SDGs. Continued agricultural developments, intensification, and extensification have the risk of aggravating existing challenges related to land and water insecurity (Allen and Prosperi 2016). Furthermore, existing and future socio-ecological changes that are being driven by climate change require novel adaptation strategies that do not compromise livelihoods (UNGA 2015). The WRC has supported various frameworks, methods, practices and indicators aimed to support water use efficiency. Most of the financial resources from the WRC has achieved in establishing a criterion for water security based on four themes: the state of the water environment; human health and well-being; the sustainability of livelihoods; and the stability, functions, and responsibility of society (Figs. 1.2 and 1.3). These novel climate-smart technologies are enhancing the adaptation and resilience strategies and reducing the impacts of the prevailing socio-ecological changes including in the water and agriculture sectors. These interventions have seen an improvement in understanding the linkages and connections between agronomic practices and agricultural water management. All this is emanating from the knowledge that water and food continue to deteriorate as several countries face the double burden of hunger and undernutrition with overweight and obesity (IFPRI 2016). Research within the WRC has been proactive in addressing these challenges.

The analysis produced three thematic clusters of keywords that co-occur in literature, namely, the response of crops to water stresses (green), interactions between the environment and water use (blue), and water management in the production of agronomic crops (red).

(a) *Green Cluster*: Response of crops to water stress, particularly droughts (Green). Countries that contributed to research were mostly conducted in Southern

Fig. 1.2 Key terms identified in scientific report titles on Water Productivity submitted to the WRC

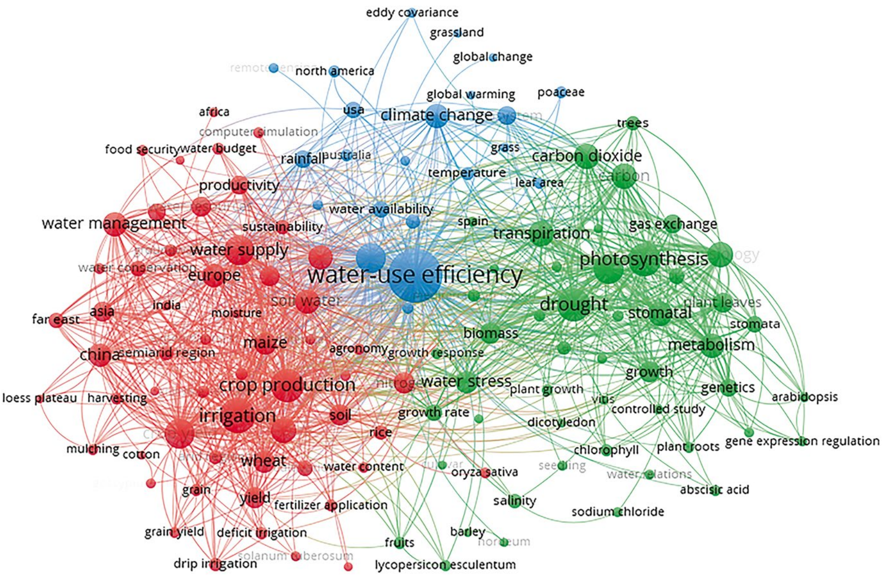

Fig. 1.3 Visualisation of thematic areas assessed across 200 relevant scientific reports on water productivity. The network map identified 30 terms to be the most relevant across identified scientific report titles. These key terms were designated into three thematic areas, namely, crop water use (green), water and climate change (blue), and agricultural water management (red)

Europe and Mediterranean regions. Central to the cluster are droughts and water, which together were closely linked. The keywords drought and water were linked to physiological responses such as photosynthesis, transpiration, and gaseous exchange. Most physiological response studies were conducted on roots, seedlings, and leaves, particularly stomata. This finding is not surprising since the leaf is the site for photosynthesis, and the stoma is the site for transpiration and gaseous exchange.

The strength of the connection between droughts and trees is weak, as denoted by the distance between both nodes. This may show that most researchers are concerned about crops' responses since they directly impact food security.

Although it is positioned in the upper extremity of the cluster, the keyword 'carbon dioxide' has been cited in many papers, as illustrated by the large size of the node. This may indicate that researchers acknowledge the significance of carbon dioxide concentration in water use and drought mitigation studies.

In research on response to water stress, plants included dicotyledons, Arabidopsis, *Vitis*, barley *(Hordeum)*, fruits, and *Lycopersicon* (tomato). All the plants in the network map were situated in the lower proximity of the green cluster. Studies that cited fruits as a keyword were connected to keywords in other clusters, except for the key terms 'water stress' and 'lycopersicon', which belong to the green cluster. The importance of fruits in food security cannot be underestimated; hence, this map features research on the effects of water stress on fruits.

Located on the outskirts of the map is the key term ‘gene expression regulation’. Keywords cited together with ‘gene expression regulation’ are drought, water, physiology, metabolism, and genetics. The key term and its linkages suggest regulation of gene expression as another angle of tackling the plant’s response to drought. The approach was associated with Arabidopsis, an important model plant in genetic experiments for its small genome that has already been sequenced. The plant is small and does not occupy much space in growth facilities. Arabidopsis also has high proliferation, which makes it an ideal plant for genetic studies.

(b) *Blue Cluster*: The blue cluster in the middle of the map consisted of key terms from research that focussed on the interactions between environmental elements and water use. The cluster contains key terms such as water use efficiency, climate change, ecosystem, temperature, rainfall, global warming, and evapotranspiration. The water use efficiency node represents the nucleus of the map, showing its central relationship with all terms from the three clusters in the map. The node’s size also denotes the large number of articles that have cited it (1017 occurrences).

The studies in the blue cluster were conducted in the United States and Australia. North America, in particular, was linked to studies on water use efficiency and evapotranspiration.

Climate change, the second largest node (205 occurrences), was linked to terms inside and outside the cluster. Inside the blue cluster, climate change had strong linkages with terms such as water use efficiency, ecosystems, evapotranspiration, and rainfall. Externally, climate change studies were associated with studies on physiological responses such as carbon dioxide enrichment, transpiration and photosynthesis (green cluster) and water use, agricultural management, productivity and food security in the red cluster.

Grasses (Poaceae) and trees are particularly dominant in this cluster. The only linkage of grasses that existed was with the term ‘water use efficiency’. Trees (forestry) were used collaboratively with water use efficiency and evapotranspiration and externally with transpiration, biomass, and drought in the green cluster, while soil water and water supply in the red cluster.

The eddy covariance is the only measurement technique associated with water use efficiency and evapotranspiration in the blue cluster. Although there is a linkage among the eddy covariance, water use efficiency and evapotranspiration, the distance between these nodes shows that the linkage’s strength is weak; thus, the long distance indicates fewer co-occurrences between the terms.

(c) *Red Cluster*: The common thematic area created by keywords in the red cluster was water management in producing crops of agronomic value. The most cited keywords (denoted by the size of the nodes) were irrigation (436 occurrences), crop production (391 occurrences), crop yield (310 occurrences), water supply (305 occurrences), wheat (232 occurrences), water management (211 occurrences), and soil water (204 occurrences), among others. The regions that contributed to the studies were Europe, Asia (China and India), the Far East, and the semi-arid and arid regions. The crops identified in the cluster included *Gossypium hirsutum* (cotton), *Solanum tuberosum* (potato), *Triticum* (wheat), rice, and maize. From the most cited keywords, it is clear that the cluster's objective was to investigate water availability and management in areas prone to physical water scarcity to ensure high yields of food crops. Irrigation was essential to sustain agronomy in semi-arid and arid regions (denoted by linkages between these regions and the irrigation node). Deficit and drip irrigation were researched to determine their applicability in arid and semi-arid regions. Drip irrigation is located at the cluster's periphery, possibly for experimental purposes, indicating its low use in agronomy. Most of the nodes were linked with those in other clusters. For example, irrigation co-occurred with water stress and growth rate in the green cluster and water use efficiency, rainfall and evapotranspiration in the blue cluster. This indicates the interdependency of the themes to ensure global food security.

Within the context of global research on WP, the results of the analysed keywords showed three thematic research clusters that co-occur in literature, namely, crop water use (green), water and climate change (blue), and agricultural water management (red) (Supplementary information 1). On the contrary, keyword analysis from WRC-funded research on WP produced five clusters, which were water governance (red), water management (yellow), water and climate change (green), women and water (purple), and smallholder irrigation (blue cluster) (Fig. 1.4). While these thematic areas may be regarded as different from those depicted by results from the global search, they represent sub-themes of broader research areas under climate, water, and agriculture. The clearer articulation of more defined research themes within the WRC research portfolio shows that research has been

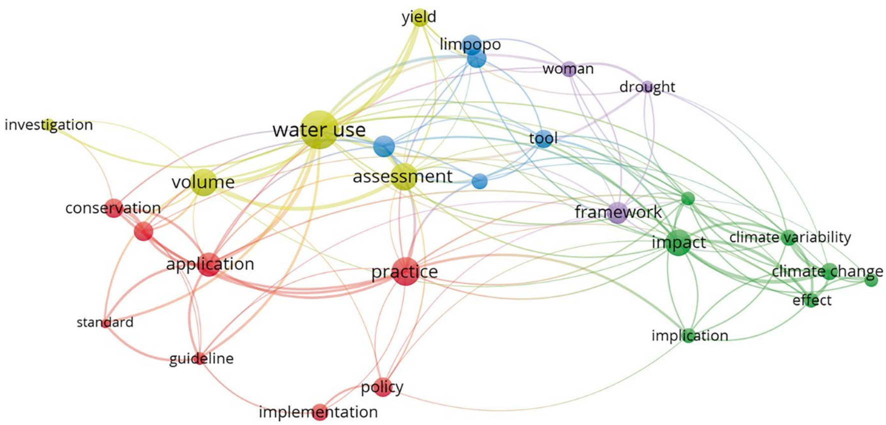

Fig. 1.4 Visualisation of the WRC-funded thematic areas assessed across 345 scientific reports on water productivity. The network map identified 30 terms to be the most relevant across identified scientific report titles. These key terms were designated into five thematic areas, namely, water governance (red), water management (yellow), water and climate change (green), women and water (purple), and smallholder irrigation (blue cluster)

contextualised around specific research areas. However, the research clusters are not all-inclusive, suggesting gaps in research focus.

1.1.6.1 Crop Water Use

Under the thematic area of crop water use (WU), the main keywords were in line with the definition of the term, which is the amount of water lost by the crop through evapotranspiration (transpiration, gas exchange, evaporation) in exchange for biomass accumulation (carbon dioxide, photosynthesis, gas exchange) (Dong et al. 2018; Kassam and Smith 2001). Crop water use (WU) is linked to the interconnectedness between plant roots and their ability to search for water in the soil, including the ability of the corresponding canopy to transpire (Morris and Garrity 1993). Plant water uptake is a function of the root density, soil–root system conductivities, and soil-available water, as determined by crop management and genotype (Ogindo and Walker 2005). An assessment of water use by crops is linked to biomass production and crop yield. Many of the keywords identified in this cluster suggested that research has been done from a physiological perspective by examining the interconnectedness between carbon uptake, growth, and water loss (Fig. 1.4). Agronomic and physiological understanding improvements have led to recent crop water productivity increases. The appearance of words relating to plants (genetics, gene expression regulation) shows that there is room for further improvements due to advances in understanding the physiological responses of plants to water supply, as well as the promise in the latest molecular genetic approaches.

Contrary to the observed global trends, only 23% (79 out of 345) of the WRC-funded projects focussed on crop water use of several fields, fodder, pasture, tree, and horticultural crops. Most of the showcased research used conventional methods of quantifying WU. On the contrary, global research has moved into the use of GIS and remote sensing (Haseeb et al. 2023).

1.1.6.2 Climate Change, Water, and Agriculture

Climate change has seen an increase in temperatures, deviations in rainfall patterns and variability, and increased intensity and frequency of droughts and floods. Furthermore, changing climate is compounding water stress and hydrologic variability, especially in semi-arid and arid regions. Under this cluster, several keywords related to climate change's impacts on water and water use efficiency (water availability, climate change, ecosystem, temperature, rainfall, global warming, and evapotranspiration). Climate change is risking water and food security, threatening to reverse the progress achieved in the past and the attainment of developmental outcomes like poverty reduction and sustainable development. It is generally understood that the water profiles of many water-stressed countries will worsen due to increasing temperature and temperature extremes. As such, most of the research articles under this cluster aimed at understanding the mechanisms of climate variability and climate change on water resources and crop yield. These articles showed the importance of multidisciplinary studies that involve agronomy, climatology, and hydrology.

Similarly, South Africa's research has focussed on climate change's impacts on water (green), emphasising climate-smart technologies to enhance WP. For instance, reports by Mabhaudhi and Modi (2016, 2019, 2020) suggest using underutilised crop species to increase crop water use in areas exposed to high climate risks. Crops that have been considered in water use efficiency projects included indigenous tree and crop species (Dye 2008; Oelofse 2008; Everson et al. 2015; Modi 2013, 2017; Modi and Mabhaudhi 2020), fruit trees such as apple, pomegranate, avocado, and macadamia (Dzikiti 2018; Taylor 2021), crops and trees for biofuels (Jewitt 2009), vegetables (Korsten 2015), and pastures (Truter et al. 2016). Many of these projects went on further to investigate the interaction between water use and biomass (Dye 2008; Gush 2014) and value chains (Grove 2012). Overall, water availability and subsequent use have highlighted the potential to alleviate poverty among disadvantaged groups through realising gender equity, capacity building, and entrepreneurial development.

Food and nutrient security have been at the forefront of most Agricultural studies funded by the WRC has been focussing on food, water, and nutrition security. A case study approach was applied on research focussing on improving food security (Chitja 2015; Denison 2015) and a scoping review approach (Wenhold et al. 2012). The topics aimed to empower vulnerable groups including women and children (Chitja 2015; Mudhara 2020) and smallholder farmers (Chitja 2015; Denison 2015). However the scoping study focussed on the whole country (Wenhold et al. 2012). Research on past and present 'food value chains' has also been key to improving water, food and nutritional security among the most vulnerable groups (de Lange 2014; Letty 2014). Studies on food security proposed future studies on developing pathways that promote the bottom-up approach starting from the grassroots level (Chitja 2020). Smallholder farming, particularly at the homestead food gardening level, has been critical for subsistence food security with no option of generating income. Titles with the phrase 'homestead food gardening' indicated the attempt of researchers to grow homestead food gardening to contribute to household food security.

1.1.6.3 Agricultural Water Management

The last cluster consisted of articles that focussed on agricultural water management. Overall, global research is stratified into research looking into (i) methods to increase crop yield for enhanced WP (agronomy, fertiliser), (ii) a decrease in water losses through soil evaporation (mulching, drip and deficit irrigation), and (iii) soil water storage (soil water, moisture). These thematic areas align with the research focus across many WRC-funded projects.

Irrigation Water Management

In South Africa, irrigation plays an important role in ensuring food security as it stabilises food production by covering up the water deficit due to unreliable rainfall. Irrigation supports 25–30% of South Africa's agricultural production as the sub-sector sustains about 90% of high-value crops (including potatoes, vegetables and fruit) and 25–40% of industrial crops (including sugarcane and cotton). Since its inception in 1971, the WRC has been supporting research that improves overall irrigation efficiency for sustained water, food, and nutrition security. Within the context of irrigation and irrigation efficiency, WRC-funded research has extensively covered the management, appropriateness, economics, and sustainability of irrigated agriculture (Figs. 1.3 and 1.4).

For instance, project TT465/10 suggested assessing irrigation efficiency from the source to the root zone (Reinders 2010). Reinders et al. (2012a, b) assessed the cost-effectiveness of large- and small-scale irrigation systems. Several irrigation technologies have also been evaluated (Reinders 2004). Other studies have applied models and measurement tools for evaluating water flow (Hlela-Mwanyama 2004) and the performance of filters (Volschenk et al. 2003). Decision support tools, such as OPERA (de Clercq 2019), SAPWAT (van Heerden 2008, 2020), PLANWAT (van Heerden 2008), and FARMS (Volschenk 2005) have been proposed, while (Singels 2008) offered a tool which offers real-time advice to farmers in issues on irrigation water management. The projects further developed and tested models that determined the economic effectiveness of water rationing in irrigation systems (Pott 2012).

Smallholder Irrigation Schemes

In South Africa, smallholder irrigation schemes cover about 3.3% of the total irrigated area (1.5 million ha). It is an important sector for job creation and poverty reduction. However, most smallholder irrigation schemes have collapsed while the rest suffer reduced efficiency for various reasons including incorrect water allocation, poor leadership among elected representatives, lack of understanding of governance issues, etc. Due to these schemes' importance, effective revitalisation is extremely important. According to van Verbeke (2012), the WRC first enquired into smallholder irrigation schemes in 1985, more than 10 years after their establishment. Legoupil (1985) concluded that smallholder Irrigation is struggling to produce high yields due to technical, management, training, agricultural policy, and financing issues. It was only in the late 1990s and early 2000s when research around smallholder irrigation schemes and the need to revitalise them took centre stage (see De Lange 1994; IPTRID 2000; Du Plessis et al. 2002; Shah et al. 2002; Backeberg 2006).

For more than 20 years, smallholder irrigation schemes have been the subject of research from the WRC. Most projects focussed on revitalising irrigation schemes indicate that the WRC is at the forefront of these efforts as shown by the theme's prominence (Fig. 1.3) and related key terms (Fig. 1.4). These studies have been done to address challenges related to rural poverty and unemployment and increased food and nutrition insecurity in former homelands (Zegeye and Chipfupa 2018). Denison (2007) studied 317 schemes showing the limitations of prior efforts to revitalise them including limited consultation, engagement with the intended beneficiary, and human and social capital. Some of the projects mapped the empowerment and development pathways associated with water productivity with the smallholder schemes to move towards commercial-based crop production (Jiyane 2019).

Aquaculture

Freshwater aquaculture is also key to economic development and food security in rural areas. It is important in sustainable agriculture as water is recirculated within the systems, partly addressing the challenge of water scarcity. According to Rouhani and Britz (2004), during the early 1980s, several fish hatcheries and production units were set up in the former homelands (Gazankulu, Ciskei, Transkei, and Venda) to contribute to food security. However, all these initiatives collapsed in the 1990s due to little or no backup in extension services, financial support, and a lack of political will. The WRC came in to support research that identified key research priority areas in the sector. An important area that was identified emphasised water quality in aquaculture (Salie 2008, 2013, 2017). These studies also singled out livestock production, and a risk-based approach for assessing livestock watering and aquaculture water quality guidelines was adopted (Moodley 2021). A smartphone application was also recently developed (Rouhani 2021) to convey a WRC manual on aquaculture to small-scale farmers.

Rainwater Harvesting

Several studies have focussed on rainwater harvesting (RWH) for agriculture and domestic water use in South Africa (Botha 2014; Mzezewa et al. 2011). However, its uptake in rural areas is very slow. Kahinda et al. (2011) highlighted the high labour requirements in constructing and maintaining RWH structures as a major constraint on the adoption of the technique. Some challenges with RWH include low human capacity and lack of economic aspects during the implementation of RWH technologies (Kahinda et al. 2007).

Water Security and Empowerment

Social protection, water insecurity, and gender are topical issues in South Africa, especially within social justice and equity. This is based on that water insecurity restricts women's participation in social protection (and related education and employment opportunities) and undermines efforts to promote health, nutrition, and food security (Mudhara 2020). The WRC has supported gender-sensitive improvements in water security by enhancing and empowering women's access to water (Denison 2015; Chitja et al. 2016; Oladele 2015, Figs. 1.2 and 1.3). WRC-funded research has focussed on increasing the capacity of marginalised communities and supporting initiatives to access markets (van Schalkwyk 2007; Korsten 2016). Overall, water security and empowerment studies focus on challenges related to water use, entrepreneurial development, and sustainable water use (Asiwe 2020; Zegeye and Chipfupa 2018).

1.1.7 Considerations for Improving Water Productivity

The key principles that have been identified to improve water productivity at any spatial scale include (i) improving the marketable yield of crops for each unit of water transpired by the same crop, (ii) reducing runoff, drainage, seepage, percolation, and evaporative), and (iii) increasing the effective use of rainfall, stored water, and water of marginal quality (Kijne 2003). These principles are applicable in both rainfed and irrigated sectors. However, options and practices associated with these principles require different approaches and technologies at different spatial scales.

1.1.7.1 Enhancing Water Productivity at the Plant Level

Plant-level options of crop-water productivity have been studied extensively and these studies relied mainly on germplasm improvements (Condon 2004; Morison et al. 2008; Richards et al. 2002, 2010; Richards 2006; Zoebl 2006). Improvements in crop-water productivity depend on early seedling establishment, improving seedling vigour, increasing rooting depth, increasing the harvest index, and enhancing photosynthetic efficiency (Table 1.1). For example, sorghum breeding has resulted in about a threefold increase in water productivity compared with traditional varieties (Xin et al. 2009). A range of crop varieties that match growth cycles with the expected water supply have been developed without any harm to both humans and the crop (Richards et al. 2010). Short- to medium-duration varieties are increasing water productivity as they escape late-season water stress (Kijne 2003). Breeding for and selecting crop species through enhanced architecture is also improving water productivity as deep root systems increase water uptake in deeper horizons while increasing adventitious roots will allow more water to be captured in the top layer before evaporative losses (Kell 2011; Richards et al. 2002). These advances are envisaged to be applied to many crop types with the aim of not only improving water productivity but also improving productivity and water and food security (Bennett 2003). This is based on the fact that drought tolerance and escape have been strategic in increasing water productivity and crop yield (Araus et al. 2002; Kulathunga 2013).

Table 1.1 Principles, strategies, options, and practices for enhancing crop water productivity at the plant, field, and basin scales

Principle	Strategy	Scale		
		Plant	Field	Basin
Enhancing the marketable yield of crops for each unit of crop transpiration	Increasing the yield or value of the product	Increasing harvest index, increasing photosynthesis, increasing sink strength	Crop and resource management for enhancing yield, synchronising water application with crop water demand, changing to high-value crops	Improving water management to synchronise system water supply and field-level water demand, reallocating water from value to higher-value uses, spatial analyses for maximum production and minimum transpiration
	Reducing transpiration	Reducing non-stomatal transpiration, reducing stomatal transpiration, shortening crop growth duration	Crop scheduling to match season with low evaporative demand; deficit irrigation	
Reducing non-beneficial atmospheric depletions and the outflows from the domain of interest	Reducing evaporation from soil and water	Early shading, seedling vigour	Crop scheduling to reduce evaporation during the fallow period, plant spacing and row orientation, tillage and soil management (e.g. minimum tillage, mulching) to reduce evaporation, Irrigation techniques (e.g. drip, subsurface irrigation), saturated culture with rice on a bed	Land use planning over the whole domain of interest reduces evaporation from fallow land and decreases free water surface
	Reducing transpiration from weeds	Increasing weed competitiveness	Weed management, levelling and precision irrigation, water-saving irrigation in rice	Land use planning to reduce weeds and other non-beneficial vegetation
	Reducing percolation	Seedling vigour, deep roots, aerobic rice	Levelling and precision irrigation, water-saving irrigation in rice	Reducing percolation and runoff into sinks, water reuse
	Reducing runoff		Water harvesting, tillage to increase infiltration	

Enhancing the effective use of rainfall, water with marginal quality and water stored in the domain of interest	Effective use of rainfall	Drought escape, drought tolerance, submergence tolerance	Risk management in rain-fed agriculture, synchronising crop demand and rainfall, nutrient management to reduce drought effects, drainage	Irrigation scheduling to account for rainfall variability, utilisation of medium and long-term weather forecasts for reducing risk
	Effective use of water storage	Deep rooting for drought avoidance	Water harvesting and supplementary irrigation	Conjunctive use of surface water and groundwater, increasing water storage within the domain to capture runoff
	Effective use of water with marginal water quality	Salinity stress tolerance	Mixing marginal water with water of good quality, crop management to reduce salinity effects	Land management to reduce salinisation hazard

Source: Kijne et al. (2003)

1.1.7.2 Improving Water Productivity at the Field Level

Improvements in crop, soil, and water management at the field level have been shown to enhance water productivity under irrigated and rainfed agriculture. These improvements include the selection of the right crops and cultivars, planting methods that reduce tillage, irrigation scheduling, nutrient management, and improved drainage for water table control (Table 1.1). In rainfed agriculture where farmers face the risk of intra-seasonal drought or rainfall variability, crop water productivity is improved by selecting adapted water-efficient crops that reduce unproductive water losses and ensuring optimum agronomic conditions for crop production, (Chimonyo et al. 2016a, b; Kijne 2003; Mabhaudhi et al. 2018; Rockström et al. 2003) Table 1.1.

Rainwater harvesting plays an important role in enhancing crop-water productivity (Kahinda et al. 2011). Coupled with soil conservation practices, RWH increases land productivity in terms of crop-water productivity (Mupangwa et al. 2006). The main RWH techniques are micro- and macro-catchment, which are indicated in Table 1.1. The promotion of RWH is based on the fact that irrigation currently uses more water than all other users, and agriculture faces competing demands for water from other sectors. About 1.3 million hectares, or under 10% of all arable land, are under Irrigation (Cousins 2007; Nhamo et al. 2016).

While the National Development Plan (NDP) projects to increase the area under irrigation to about 200,000 ha, there is a risk of straining other sectors like energy which is already failing to meet the national requirements (Cai et al. 2017). The construction of new dams may not be viable as the country is already over-dammed (Mabhaudhi et al. 2018). *Deficit irrigation* is an alternative but smallholder farmers lack the required knowledge yet it enhances water productivity (WHO 2003). Research has also shown that *drip irrigation* increases water use efficiency more than any other type of irrigation; its yield gains can be 100% and water savings about 40–80% (Rao et al. 2016; Ali and Talukder 2008; Zwart and Bastiaanssen 2004). *Supplementary Irrigation* is an option to reduce water stress in rainfed agriculture as it provides sufficient moisture for normal plant growth to improve and stabilise yields (ICID 2012). However, it depends on the precipitation of a basic source of water for the crop (Grafton et al. 2018; Guendouz et al. 2016; Li and Sun 2016; Zhang et al. 2017a, b; Steduto et al. 2012). Supplementary irrigation significantly increases crop-water productivity if water is applied at the moisture-sensitive stages of plant growth (Oweis and Hachum 2006; Ali and Talukder 2008).

1.1.7.3 System and Basin Level Water Productivity

Agricultural water management needs to advance and support ecological and human services under climate change (Rockström et al. 2010; Menéndez et al. 2016). Water users need to look beyond their farms and consider other users (Faurès et al. 2003; Kijne 2003). Upstream users need to also consider users downstream. The challenges require cross-sectoral interventions and move away from the current linear approaches (Blignaut et al. 2007; Griggs and Golet 2002; Molden et al. 2010).

Further, water management practitioners need to appreciate the scales at which water productivity interventions can be implemented.

There are four key strategies for improving water productivity at the basin level, including (i) increasing water productivity at plant and field levels, (ii) reducing non-productive loses of water flows by minimising water runoffs to sinks, (iii) improving the management of existing irrigation facilities and reusing return flows by controlling, diverting and storing drainage flows, and (iv) identifying water users and, relocate and allocate water among uses based on the value of use, e.g. relocating lower value to higher-value uses within and between sectors (Mabhaudhi et al. 2018; Mpandeli et al. 2018).

1.1.7.4 Policy and Water Productivity

Nhamo et al. (2018) explored opportunities for the WEF nexus to promote cross-sectoral policy linkages among the water, energy, and food sectors to achieve regional integration and sustainable development. The main recommendations were on transboundary water management for improved resource use efficiency. Mabhaudhi et al. (2018) assessed the status of irrigated agriculture in southern Africa from a water–energy–food (WEF) nexus perspective. They emphasised the need to increase water storage and human capacity and broaden the energy base to increase the area under irrigation. The WEF nexus approach addresses the multifaceted and interrelated nature of resource systems for any intended outcome or impact (Bizikova et al. 2013; Entholzner and Reeve 2016; Mpandeli et al. 2018).

The prevalent governance systems in an area determine access to water. Studies have focussed on climate change highlighting drought and its response in southern Africa (Davies 2000; Vogel et al. 2010; Vogel and Olivier 2019). The emphasis has been on assessing the administrative role of institutions and governance systems (Baudoin et al. 2017), interrogating past response mechanisms to reduce risk at different spatial governance scales. The most highlighted subject has been moving from reactive water management to a more proactive approach guided by working and strong water governance systems (Vogel et al. 2010). One example of a more proactive approach to water management is the National Water Act (NWA; Act 36 of 1998) and Water Services Act (WSA; Act 108 of 1997), administered by the Department of Water and Sanitation (DWS) at its core (RSA 1997, 1998; Vogel and van Zyl 2016). A significant gap, already noted by Hornby et al. (2016), appears to be the coordination of the widespread but localised efforts by the government, civil society, and private sector, particularly in identifying and responding to the areas and people most in need.

1.1.8 Water Management and the SDGs

The 2030 Agenda and Sustainable Development Goals (SDGs) are threaded together by a common denominator: water. Although SDG 6, the Water Goal, specifically addresses promoting sustainable water management, water is embedded in the rest of the SDGs, particularly those that focus on food, energy and the environment (Ait-Kadi 2016). Sadoff et al. (2015) established the symbiotic association between water and development. As such, achieving SDG 6 can be realised by fulfilling the other SDGs and vice versa. The WRC has also taken the same notion. The WRC research over the years speaks to the role of water in development. Improving water productivity for food security addresses SDG 2, which calls for zero hunger. The theme 'water security and empowerment' addresses gender disparity through women empowerment (SDG 5) by highlighting women's roles in water management. The thematic area' climate change water and agriculture' links with SDG 13, which mandates nations to work actively against climate change. SDG 14, which calls for sustainable marine resources, has been acknowledged in the WRC research theme, aquaculture. The agricultural water management research area has fulfilled SDGs 1 to 6 directly or indirectly.

1.1.9 Recommendations

Underwater scarcity, the success of agriculture lies in increasing water productivity. While food security is a priority, an integrated approach to addressing water productivity will ensure trade-offs with the environment and socio-economic constructs. The following recommendations are suggested:

- Policies and strategies must create an enabling environment for supporting investments in irrigation development and agricultural water management.
- Approaches should be transdisciplinary and involve stakeholders such as scientists, farmers, and public, private and civil partners.
- Capacity building at multiple levels is needed to support implementation and transformation at different scales.
- Promoting good agronomic practices, including climate-smart agriculture techniques that increase crop productivity and enhance efficient resource use under rainfed and irrigated conditions.

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