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Irrigation area, efficiency and water storage mediate the drought resilience of irrigated agriculture in a semi-arid catchment

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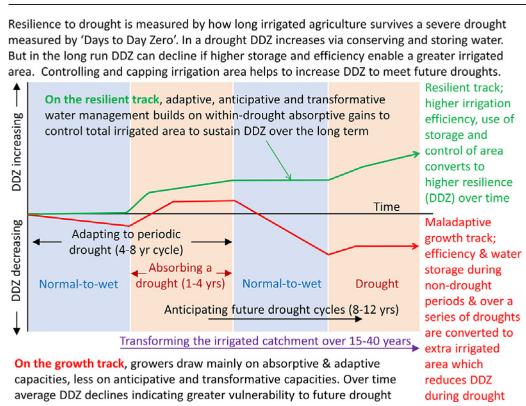
HIGHLIGHTS

- A 'Water, Efficiency, Resilience, Drought' framework and model was developed.
- Days to Day Zero (DDZ) measures the resilience of irrigated agriculture to drought.
- Absorptive, adaptive, anticipative and transformative capacities can change DDZ.
- Improved irrigation efficiency and water storage can increase resilience and DDZ.
- But resilience and DDZ decline if efficiency and storage expand irrigated areas.

GRAPHICAL ABSTRACT



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ABSTRACT

We examined the effects of hydrological variables such as irrigation area, irrigation efficiency and water storage on the resilience of (mostly commercial) irrigated agriculture to drought in a semi-arid catchment in South Africa. We formulated a conceptual framework termed 'Water, Efficiency, Resilience, Drought' (WERD) and an accompanying spreadsheet model. These allow the resilience of irrigated agriculture to drought to be analysed via water accounts and a key resilience indicator termed Days to Day Zero (DDZ). This represents the number of days that a pre- and within-drought supply of catchment water available to irrigation is withdrawn down to zero in the face of a prolonged drought. A higher DDZ (e.g. >300 days) indicates greater resilience whilst a lower DDZ (e.g. <150 days) signals lower resilience. Drought resilience arises through land and water management decisions underpinned by four types of resilience capacities; absorptive, adaptive, anticipative and transformative. For the case study, analyses showed that irrigators, with currently approximately 23,000 ha under irrigation, have historically absorbed and adapted to drought events through construction of water storage and adoption of more efficient irrigation practices resulting in a DDZ of 260 days. However, by not fully anticipating future climate and water-related risks, irrigators are arguably on a maladaptive pathway resulting in water supply gains, efficiency and other practices being used to increase irrigation command areas to 28,000 ha or more, decreasing their capacity to absorb future droughts. This areal growth increases water withdrawals and depletion, further stresses the catchment, and reduces future DDZs to approximately 130 days indicating much lower drought resilience. Our approach, supported by supplementary material, allows stakeholders to understand the resilience consequences of future drought in order to; reconcile competition between rising water demands, consider new water storage; improve agricultural and irrigation planning; and enhance catchment governance.

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1. Introduction

Although most agriculture in sub-Saharan Africa (SSA) is still subsistence and smallholder-based, high-value commercial farming, such as horticulture, for national consumption and export generates substantial, positive socio-economic impacts as well as contributing to the UN Sustainable Development Goals (UN, 2017). In South Africa, suitable soils and agro-climate conditions, coupled with historical water allocations favouring large scale commercial horticulture, have underpinned agricultural transformation for supporting valuable agro-export expansion (Cramer and Chisoro-Dube, 2021). However, a large proportion of export horticulture in South Africa is heavily dependent on irrigation (Baleta and Pegram, 2014). Expanding this kind of production in water-stressed areas both increases the volumes of water abstracted that would otherwise support growing water demands such as urban development (Bahadur et al., 2016). These trajectories of increasing water use and competition in the face of climate variability and shocks require different kinds of analyses (Sadoff et al., 2020). Supporting these analyses and recognising rising global food and water insecurities, our paper focusses on the resilience of irrigated agriculture to periodic drought (Falkenmark et al., 2019; Matthews et al., 2022).

Agriculture in Sub-Saharan Africa is widely regarded as the sector most influenced by climate, and in such circumstances, drought is the dominant hazard that causes the greatest agronomic impacts and socio-economic losses to production (Nhemachena et al., 2020; Wilhite et al., 2007). For example, the 2015–2017 drought in South Africa resulted in 30,000 job losses and c£320 M in economic losses in the Western Cape agricultural sector (WWF, 2018). Although smallholder farmers were impacted most by recent Southern African droughts due to their low levels of technology and adaptive capacity, commercial farmers were not exempt from impacts. These drought events significantly impacted their financial viability, with farming debt rising at an average annual rate of 14 % between 2005 and the end of June 2015 (Agri SA, 2016). However, the indirect impacts of drought on the broader South African economy remain unknown and there is limited understanding of how different response strategies such as shifts to irrigation, which consumes considerable volumes water, may impact the resilience of all water sectors (Schreiner et al., 2018). Collectively, more irrigation may reinforce societal inequalities and heighten the urgency to improve the resilience of irrigated agriculture to drought when irrigation dominates catchment water abstractions (Grafton et al., 2022; Ward, 2022).

To understand why we have focussed on the resilience of irrigated agriculture in South Africa to drought requires a concise explanation of our case study followed by a synthesis of three sets of relevant literature. Our semi-arid drought-prone catchment in the northeast of the country (the Groot Letaba) is dominated by the commercial irrigation of perennial fruit crops (i.e. citrus trees lasting 20–30 years) for export supplied by water drawn from a main large dam and other ancillary storage bodies including groundwater. Rather than aiming to survive a relatively short 100–120 days to grow a seasonal crop (e.g. maize), irrigators seek to successfully absorb long multi-year droughts that otherwise harm in-drought fruit production and the longer-term viability and recovery of orchard productivity. However, a future resilience optimum is also recognised; water conservation strategies to survive a drought enable more land to be irrigated over time which in turn undermines resilience in the long term by ratcheting up water demand. Furthermore, agricultural water use faces an upper limit due to the catchment's hydrology and rising demands for water to meet socio-economic development and protect downstream environmental flows. Our analysis is confined to understanding these effects of short- and long-term water management on resilience to drought. While this paper sits within a larger set of concerns regarding social-ecological water-related resilience and environmental stewardship (Adger et al., 2021; Beevers et al., 2021; Falkenmark et al., 2019; Walker et al., 2009), it does not discuss resilience in this wider sense or advise on the allocation of water to other sectors (Garrick et al., 2020). Furthermore, it does not instruct on optimising farm yields and income within a drought (Harou et al., 2010).

We interpret resilience via 'resilience to drought shocks' framed through the concept of capacities (Biggs et al., 2021). The concept of resilience has its roots in engineering and was initially and sometimes narrowly linked to the ability of a system to "bounce back" (Walker, 2020). Since then, multiple definitions have emerged ranging in interpretation from resilience as a 'system property', to resilience as a process or 'outcome' (Moser et al., 2019). More recently these interpretations have converged, with most definitions associating resilience with the 'ability' or 'capacity' of a system to respond to a disruption or change (Manyena et al., 2019). There are four main types of capacity (Bahadur et al., 2016; Béné et al., 2012; Béné et al., 2016; Manyena et al., 2019; Van Niekerk and Terblanché-Greeff, 2017; Walker, 2020; Walker et al., 2009) which our paper draws on:

(i) Absorptive – the capacity to moderate or buffer the impact of shocks in order to persist and recover from them. In our case of irrigated agriculture, we interpret absorptive capacity to include short-term responses that reduce exposure to a drought shock or reduce the impact of the shock (OECD, 2020). We consider this important because we observed fruit growers attempting to absorb 'within drought' impacts on their perennial orchard crops arising from a lack of water by deploying various water conservation practices such as switching to deficit irrigation (Saitta et al., 2021). Orchards that can successfully absorb a 2–3 year drought are more likely to recover from the drought afterwards (Skewes et al., 2016); an important economic goal for trees with a productive 20–30 year lifespan.

(ii) Adaptive – the capacity to learn, adjust and adapt in response to a shock or series of shocks. Adaptation is generally linked to on-going adjustments in farm operations including the use of different cultivars or investment in more efficient technologies (OECD, 2020). Managing available water supply and demand have been identified as drought adaptation in other studies (GWPEA, 2016; Smith and Edwards, 2021; Theron, 2022). We believe this to be important because we observed farmers adapting to drought both 'within a drought' and during its ensuing normal-to-wet period. Adaptation in this wetter period was being driven by the memory of the last drought combined with the fear of a returning drought.

(iii) Anticipative – the capacity to anticipate, prepare and plan for unexpected changes and disturbances. Anticipative capacity includes strategies that allow farmers to be prepared for future shocks, such as using scenario planning or early warning systems (Bahadur et al., 2016; Van Niekerk and Terblanché-Greeff, 2017). In our case study, we observed growers, in anticipation of future hotter drier conditions further down the catchment, developing new avocado orchards higher up in the cooler parts of the catchment.

(iv) Transformative – the capacity to fundamentally alter the social, ecological and economic processes that make a system untenable, which usually entails deep structural change. For example, transformation may be initiated by an inability to sustain the long-term viability of the system which necessitates actions such as the re-organisation of value chains to access alternative opportunities, or exiting agriculture all together (OECD, 2020). In our case study, we hypothesised that currently (early 2020s) transformative capacities, exhibited for example by exiting irrigation, were not being well articulated by catchment stakeholders.

Consideration of all four capacities and their inter-relationships is therefore necessary a) to understand resilience; b) to examine their definition and strength of expression during short term events (drought and inter-drought periods) and in the medium term (recurring drought-wet cycles over 6–8 years) (Boyd et al., 2015); and c) to explain long term change in the catchment up to 2020 and potential developmental pathways to 2040. In examining these relationships, we accept that these capacities overlap and coexist. For example, Manyena et al. (2019) highlight that adaptation can occur before, during or after a shock and incorporate components of both absorptive and transformative capacities. However, while some capacities can strongly and mutually reinforce each other (e.g. absorptive and adaptive capacity might correlate) others possibly undermine each other. For example, when strongly expressed, absorptive and adaptive capacities might hold back anticipative and transformative capacities.

Typically, strategies that increase resilience do so by fostering or drawing on one or more of these underlying capacities (Biggs et al., 2021). For example, installing drip irrigation is an adaptive strategy but it is product of an underlying adaptive capacity comprising financial capital, bank loans, land, knowledge, training and so on. In other words, drip irrigation as a strategy does not arrive out of nowhere. Given our paper is not about the underlying capacities, we use strategies to infer the respective capacities that growers are trying to draw on or enhance. This approach moves beyond the conventional capitals focus, to one that better reflects complex system dynamics and outcomes (Reyers et al., 2022).

Drawing on a second set of literature about the water accounting aspects of a drought-survival objective, we carefully considered the relationships between water conservation, irrigation efficiency and resilience. We view these relationships as time-, scale- and system-dependent, and influenced by water storage. These interdependences make simple generalisations about efficiency difficult. In the fields of engineering and infrastructure development, efficiency is usually aligned with resilience (Bhamra et al., 2011; Fiksel, 2003; Rogers et al., 2012). In this context, resilience strategies have largely focused on designing more resource efficient systems (Fiksel, 2003). Accordingly, the adoption of practices that promote resource use efficiency have been proposed as an important step towards climate-resilient development in agriculture (Lipper et al., 2014). However, engineering resilience has different interpretations to ecological resilience (Quinlan et al., 2016) which often positions efficiency in opposition to resilience. This interpretation is premised on an inverse relationship between efficiency, and redundancy and diversity (Elmqvist, 2017; Walker et al., 2009), with the latter features providing backups and increased buffering capacity (Biggs et al., 2015; Cabell and Oelofse, 2012). For example, Emlqvist (2017, p352) stated that “efficiency reduces diversity and redundancy, both of which are key features of resilience”. (Appendix C further discusses drought resilience and the wide diversity of water technologies found in the GLC). Ward (2022) and Matthews et al. (2022) warn that water conservation via increases in irrigation efficiency has the effect of amplifying water depletion which diminishes resilience. Others argue that the relationship between efficiency and resilience is dependent on a range of other variables. Illustrative of this, Scott et al. (2014) noted how increases in irrigation efficiency, not limited by caps on depletion, can increase total water depletion which reduces water availability for allocation to other sectors. Golgeci et al. (2020) also noted that the relationship between efficiency and resilience may vary over time. As we show in our paper, efficiency has the potential to increase resilience against drought, but if it is not holistically managed, it may undermine long-term catchment resilience. Appendix C in the Supplementary Material contains detailed discussions on irrigation efficiency and explains why our DDZ model works primarily with water withdrawals from water bodies rather than with water depletion, contrary to recommendations (Uhlenbrook et al., 2022).

Drawing on a third literature set on resilience indicators, we were interested in a focussed quantification of resilience to drought because we realised water accounting could be reformulated into a resilience indicator ‘Days to Day Zero’ (DDZ). This desire to work with a quantitative indicator responds to calls for better understanding of ‘resilience building’ which has been notoriously difficult to quantify (Angeler and Allen, 2016; Quinlan et al., 2016; Standish et al., 2014) or is often absent from water resilience discussions (Falkenmark et al., 2019). Our indicator helps to provide an objective assessment of how different resilience strategies affect resilience outcomes for irrigated agriculture facing both drought events and periodic drought over the longer term. The prosaic expression, ‘Days to Day Zero’ or ‘Day Zero’, is an expression that was used in the recent Cape Town drought (Burls et al., 2019). While we accept the contentious and political nature of ‘Day Zero’ as a socio-hydrological measure designed to nudge social behaviour (Warner and Meissner, 2021) we argue that DDZ functions well as a quantitative indicator of drought resilience.

2. Methodological approach and case study

We took an abductive approach to building and testing a conceptual framework and quantitative model (Franklin and Blyton, 2011) on the basis of a single case-study catchment: the Groot Letaba Catchment (GLC) in Limpopo province in South Africa. It was chosen as it grows significant amounts of fruit for export, nearly all of which is irrigated, and, characteristic of Southern Africa's climate (Conway et al., 2015) there have been recurring and severe droughts that have affected irrigated farming. Appendix A in the Supplementary Material provides the terms and abbreviations of the study, and Appendix B describes the case study and the agricultural, land and water data selected to build and populate the WERD model.

Over the period 2017–2020, we sought to comprehend the nature and composition of irrigated crop production and to interpret the key features of water-efficiency-resilience within the GLC. Information was gleaned from 41 meetings with individual stakeholders and three multi-stakeholder interactive workshops covering growers, and representatives of grower organisations, the Letaba Water User Association, Kruger National Park and government bodies. This purposive sampling was supported by the collection of land, water and crop data from stakeholders and GIS triangulation of production areas (Appendix B). Due to the sensitivity of water and land related issues in the catchment, the meetings were chronicled by written notes rather than filmed or recorded. In cases where further clarity was sought, follow-up telephone interviews were conducted.

By analysing the problematic of water efficiency for drought resilience of irrigated crops in the GLC and drawing on various literatures, we developed a conceptual framework of the relationship between efficiency and resilience called ‘Water, Efficiency, Resilience, Drought’ (WERD). An explanation of the framework is in Appendix C of the Supplementary Material. This Appendix also describes the various supply and demand management strategies that occur both between and within droughts.

We then represented the framework in a spreadsheet-based model termed WERD-M. The purpose of the WERD-model was to derive resilience metrics of catchment resilience based on the trends observed in the GLC from 1980 to 2020 and to explore the impact on resilience of three future alternative scenarios to 2040. The model used modified versions of calculations for water accounting (Goel, 2011; Molden and Sakthivadivel, 1999; Troch et al., 2009) to analyse the connections between water efficiency, water storage, irrigated area and resilience in fruit irrigation facing drought. In order to do this, WERD-M employed observed and estimated variables that describe different supply and demand technologies, activities and metrics that exist at different scales (e.g., areas under irrigation and volumes of water held in large dams), and applied water calculations to them. The inputs and outputs of WERD-M are therefore indicative of changes occurring in the GLC subject to predictive uncertainty typical of catchment-scale environmental deterministic models (Caminiti, 2004; Uusitalo et al., 2015). This proviso invites GLC stakeholders to accept WERD's analyses are simulations best employed to support catchment learning and dialogue (Beven, 2007). The model's key outputs are in Section 3.3 below and described in detail in Appendices D to G of the Supplementary Material.

3. Results

3.1. The WERD framework

The rationale that guided our WERD framework is that the irrigation sector in the GLC, attracted to profitable markets in South Africa and overseas, plus meeting social goods such as employment, aims to sufficiently ‘protect’ irrigated perennial crop transpiration in the face water shortages brought by periodic severe drought. Evidence of recent past droughts can be seen in Fig. 1 which shows four periods of declining rainfall and water levels of the main Tzaneen dam (used to supply irrigation water) during the time 1977 to 2016. Appendix B contains a brief analysis of historical crop production data showing that drought in the GLC has not significantly impacted fruit yields both during and after drought, and that GLC fruit production has continued an upward trajectory over time.

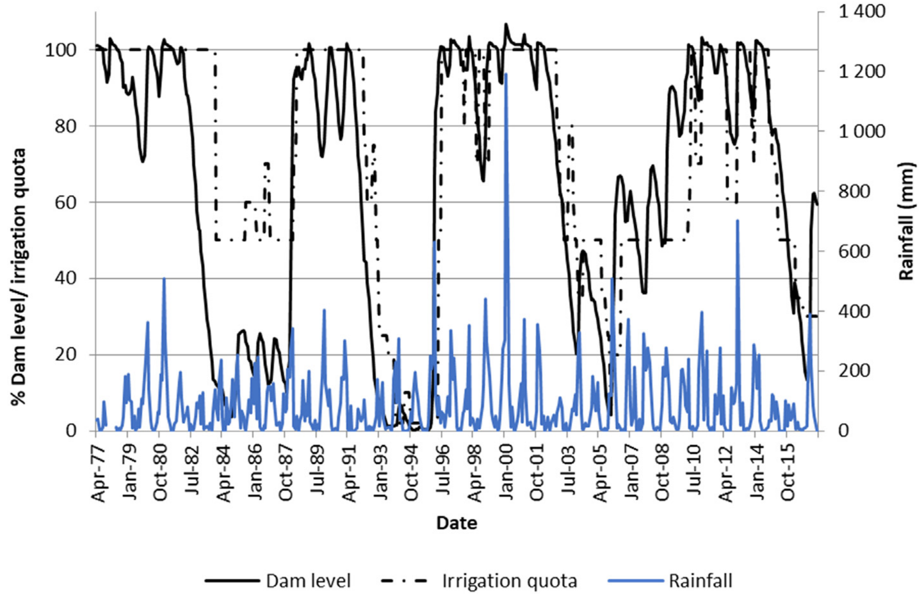

Fig. 1. Four droughts during 1977 to 2016 revealed by rainfall and Tzaneen Dam water levels.

The WERD conceptual framework is illustrated in Fig. 2. It shows in the upper left part of the diagram how water in a pre-drought wetter period refills the catchment's storage bodies in preparation for a drought. This stored water is withdrawn during a drought (shown by the red arrow) to meet irrigation water demands given by the concentric rings in the middle of the diagram. The inner black ring termed 'Drought Protective Irrigation' is the core crop transpiration that has to be protected during a drought to ensure viable yields and orchards. The text below contains a more detailed explanation of Fig. 2.

We define the protection of this core crop transpiration in the face of drought 'irrigation drought resilience' and argue it can be quantified by a

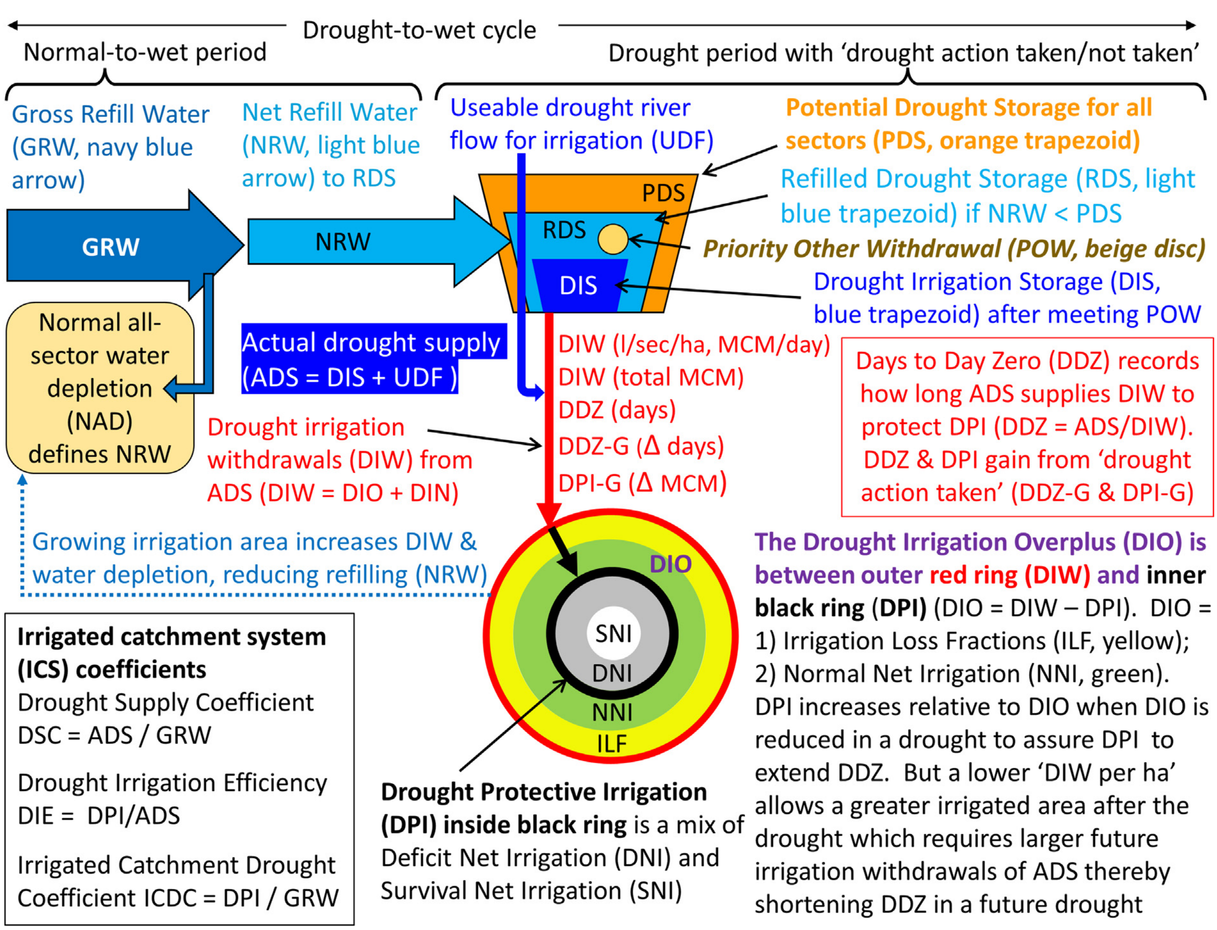

Fig. 2. The WERD framework for drought resilience of semi-arid irrigated catchments.

single metric called 'Days to Day Zero' (DDZ). DDZ indicates how long until a catchment's irrigation sector will theoretically run out of water during a drought in its attempt at keeping crops productive. DDZ is the water supply available to an irrigation in a catchment prior to and during a drought divided by daily withdrawals of water to supply irrigation during that drought which in turn 'protects' irrigated crop transpiration to hopefully see orchards survive until the drought breaks. A higher DDZ signals greater resilience to drought. As we show, DDZ can be employed to calculate, visually represent and discuss the merits and constraints of current and future agricultural pathways.

The irrigation sector achieves this 'transpiration protecting' (raising or at least sustaining DDZ) by managing two water efficiency conversions. The first conversion describes the efficacy with which catchment runoff prior to a drought is stored for use by irrigation during a drought. It is described by the Drought Supply Coefficient (DSC) and is the ratio of the 'Actual Drought Supply' (ADS) to the 'Gross Refill Water' (GRW), the volume of water the catchment receives preceding a drought. (GRW is the navy-blue arrow top-left in Fig. 2). The ADS is the sum of the Drought Irrigation Storage (DIS, the smallest blue trapezoid as a stock) and the Useable Drought Flow (UDF, the blue arrow) available to irrigation during a drought. DIS is the portion of the Potential Drought Storage in the catchment (large dams, groundwater and small farm dams) refilled in the normal-to-wet periods between droughts and used for irrigation withdrawals once Priority Other Withdrawals (POW) have been met. This refilling, termed the Net Refill Water (NRW), is the GRW minus the depletion of water by all sectors during the normal-to-wet period (NAD in Fig. 2). Depletion of water in non-agricultural sectors is calculated by deducting an assumed '10% return flow' and, in irrigation by adding five percentage points to the classical irrigation efficiency figures to derive the effective irrigation efficiency (Keller et al., 1996). Summarising; the more the catchment can potentially store water prior to a drought, refill that potential store, meet priority sector demands from that store, and access streamflows within a drought, the higher the DSC and the longer irrigation will survive a drought.

The second conversion called 'Drought Irrigation Efficiency' (DIE) converts the ADS to 'Drought Protective Irrigation' (DPI). The DPI is the minimum or 'core' volume of water that crops need to transpire to see through and productively survive a drought. The DPI is a mix of Deficit Net Irrigation (DNT, grey disc) derived from applying deficit irrigation to a portion of irrigated crops and Survival Net Irrigation (SNT, white disc) derived from withholding irrigation from crops. Concentrating on DPI means farmers; a) no longer use their 'normal' irrigation scheduling typical of non-drought periods; and b) cut down on irrigation losses (explained below, we assumed most losses occurring in GLC orchards were via non-beneficial evaporation/consumption). Summarising; when less water is lost or applied to unnecessary use in attempting protect crop transpiration, the longer the water supply (given by ADS) can be eked out. However, as shown below, other factors drive up water demand over the long-term. (Note, a third coefficient comes from merging these two conversions; the Irrigated Catchment Drought Coefficient (ICDC) is the ratio of DPI to GRW).

To achieve these two conversions and to increase DDZ, irrigators apply water supply and demand management strategies. 'Supply management' largely describes the first conversion; it seeks to push up DDZ by increasing the volumes of stocks and flows of surface and groundwater to capture rainfall and runoff prior to and within a drought for rationing out during a drought. 'Demand management' largely describes the second conversion as it aims to push up DDZ by reducing the withdrawals of water whilst still protecting crop transpiration during a drought. Reductions of withdrawals are achieved by reducing normal transpiration using full irrigation (the light green ring in Fig. 2) and reducing irrigation losses (the yellow ring). These supply and demand strategies exist in both short-term periods during a drought and long-term over a sequence of droughts, as now explained.

In the short-term, WERD focusses on a change in water practices responding to drought; between those occurring 'prior to a drought' to those occurring 'within a drought'. As explained in detail in Appendix C, the latter 'drought action taken' to conserve water can be compared to a situation where 'no drought action is taken' as if the drought has not yet been declared or recognised. For example, drought action taken means ceasing irrigation altogether in 20 % of the orchard area and applying deficit irrigation to the remaining 80 % of the area. 'No drought action' would assume that farmers continue with 'normal irrigation' across 100 % of their orchards. WERD therefore reflects how farmers manage water more carefully in response to a drought because this gains them additional days of irrigation during that drought. If they chose to undertake 'no action' in a drought they would experience a lower DDZ. In other words, irrigators 'within a drought' try to sustain the crop transpiration (DPI) that protects the productivity and long-term viability of the orchards by cutting down on less necessary water volumes. This focus on DPI simultaneously reduces the 'Drought Irrigation Overplus' (DIO), so that a reduced DIO leads to more core crop transpiration (DPI) met over a longer period. The volumetric gain in DPI achieved via 'drought action taken' is termed DPI-G. Thus, a greater DPI-G volume extends the number of days over which the crops survive, mirrored by a gain in 'Days to Day Zero' (DDZ-G) going from a lower DDZ if no action is taken, to a higher DDZ when drought action is taken.

As well as comparing short-term 'drought action taken' versus 'no drought action taken', WERD distinguishes practices changing over much longer time-periods comprising one or more drought-to-wet cycles. This reflects how farmers are aware they reside in a drought-prone catchment and face future droughts. As an example, the classical irrigation efficiency slowly increases over time as farmers replace older sprinkler or ageing drip irrigation technology with newer more precise equipment.

In examining long-term changes, WERD identifies that, paradoxically, improvements to water control, irrigation scheduling and efficiency can reduce DDZ in the long run. This occurs because over a longer period of drought-to-wet cycles, more efficient irrigation and other factors lead to increases in irrigated area. Let us first recap that water conservation actions cut out overpluses in a drought and reduce the amounts of irrigation water withdrawn and applied on a 'per hectare' and 'per day' basis, expressed as DIW in litres per second per hectare (l/s/ha) or DIW in million cubic metres per day (MCM/day). Note also this reduction in withdrawals extends DDZ because within a drought the farmed area remains more or less static. This fixed area within a drought means that as the per-farm water withdrawals decrease, the farmer can hold back their forestalled withdrawals in storage for later release to increase DPI and extend DDZ. However, between droughts, when rainfall and withdrawals from dams and streams return to 'normal', their new lower 'per hectare/orchard' water requirement allows the farmer to irrigate a larger area and boost production. Unless further new 'per hectare' reductions or additional storage can be found, this new larger farm area raises the daily amount of water withdrawn during a future drought. And this means that DDZ drops. In addition, the larger irrigation area increases the amount of water depleted during a normal-to-wet period which reduces the refilling of the potential drought storage (PDS). Thus conserving water, cutting out overpluses and raising irrigation efficiency has the effect of raising DDZ during a drought but potentially lowering DDZ in a future drought. A simple thought experiment reveals this; an irrigated farm cutting its 'per hectare' and 'per farm' water demand by 10 % during a drought has two options. First it can withhold that 10 % surplus in a dam to later use it to increase the period and volume of protective crop transpiration by 10 % (raising DDZ). Second, when the drought is over, the farm can use its lower 'per hectare' demand to irrigate another 10 % area which raises 'per farm' demand during a future drought which reduces DDZ. Imagined another way, the shrinking yellow and light green discs in Fig. 2 are converted in the future to ever-increasing core water needs shown by grey and white inner rings which then need to be serviced during a future drought.

For the purposes of our framework, we argue that in attempting to survive a drought, the irrigation sector is interested in these aims separate to meeting urban, domestic and ecological water priorities in the catchment. Mirroring current water policy in South Africa, priority other non-agricultural withdrawals are always met during drought, which why the small beige disc in Fig. 2 has to be first deducted before computing the amount of water available for irrigation. Therefore, in the model the irrigation sector does not 'gain' water by withdrawing and depleting water allocated to non-agricultural sectors (which would in effect constitute another conversion that favours the irrigation sector). However, in reality there are hydrological, commercial and political interests in the basin that reflect the dominant position commercial horticulture has in securing and using water, for example by sinking boreholes that have not been sanctioned (Knüppe, 2011; Pietersen et al., 2011; Seward and Xu, 2015), or by not pushing for meaningful water reforms that seek to address historical inequities and better manage drought events (Denby et al., 2016; Liebrand et al., 2012; Méndez-Barrientos et al., 2018).

To summarise, DDZ is our key metric of resilience which can be increased by; 1) increasing the volume of supply and storage made available prior to a drought; 2) reducing the depletion of water by all sectors prior to a drought so that more of the storage is filled in preparation for a drought and; 3) reducing the amount of water withdrawn during a drought so that the stored volume lasts longer in meeting core crop transpiration needs. Reducing withdrawals stems from irrigating less by using deficit and survival scheduling, as well as controlling non-beneficial evaporation, and recovered and non-recovered losses. WERD assumes that these water conservation practices raise irrigation efficiency by about 10 %–20 % within a drought. Appendices B and C further describes the various supply and demand management strategies that occur in the short and long-term.

3.2. The WERD-model

Appendices D to G describe the WERD-Model (WERD-M) in detail and provide more results generated by the model. The model considers six 'scenarios'; three historic (1980, 2000, 2020) that examine changes in the last 40 years, and three future (2040) trends representing 'growth track' (2040Gro), 'balanced track' (2040Bal) and 'resilient track' (2040Res). Over the past 40 years farmers have introduced technological innovations to the way they store and manage irrigation water with the aim of reducing water losses and improving irrigation efficiency. All farmers interviewed had implemented a variety of demand management strategies in response to periodic drought. As one interviewee put it, "drought is a good teacher". Examples include; deficit irrigation via reduced crop factors in irrigation scheduling; application of survival irrigation whereby watering of older orchards is ceased during severe drought; implementation of drip irrigation; covering orchards with shade cloth; use of tree planting schedules to diversify tree ages; restrictions on licences (both imposed and voluntary); fixing canal leaks; and cultivating at higher altitudes selecting avocado over citrus. In the three future scenarios, we projected forward these measures, for example adjusting irrigated area and raising irrigation efficiency to higher levels than found in the 2020 case. During 'normal' rainfall periods, some of these measures (e.g. drip irrigation and mild deficit irrigation) remained and were improved upon as day-to-day water management to meet growing market demand. Other strategies such as survival irrigation were suspended once rainfall returned.

In a related observation, the long-term expansion of areas under production has resulted in a mixture of young, mature and old trees, with the older trees usually replaced at a planned fixed rate. However, during recent protracted drought, farmers faced decisions about the productivity of their trees in the short- and long-term with the consequence that they removed, or heavily pruned and whitened the trunks and branches of older trees, or ceased to irrigate them as they are less productive convertors of water to fruit biomass and have the most developed root systems. As such, younger fruit-bearing trees were prioritized for irrigation during drought.

Reflecting the above observations, Table 1 provides the model's input variables and its intermediate results which show: a) an increasing area of total irrigation from 1980 to 2020; b) a reduction in future area under irrigation for the resilient scenario but an increase in the growth scenario; c) improving irrigation efficiency over time; d) a small step-up in efficiency during a drought when water conservation is undertaken; e) the application of normal, deficit and survival irrigation to percentage areas of crops; f) an increase in water sourced from groundwater and large and small dams over time (noting the resilient 2040 scenario assumes another 40 MCM of large dam storage); g) an increase in non-irrigation water demands to meet domestic, urban and environmental needs; and h) an increase in all-sector water depletion over time.

3.3. Outputs from WERD-M: Metrics of resilience

Only key results are given here, while the reader is referred a wider set of results in Appendix F. Table 2 and Fig. 3 present the modelling of the DDZ historically up to 2020 and the three projected futures to 2040. It is worth stating here that given the novelty of this method and its focus on one catchment, these results cannot be judged against national or international norms for how resilient an irrigated catchment is to prolonged drought measured by DDZ. Even translating these findings to similar semi-arid catchments is difficult given the characteristics unique to the GLC (e.g. volume stored, type and area of irrigation and hydrology). That said, it is possible to discern that between 1980 and 2020 resilience to drought has been declining despite investments made in irrigation efficiency and drawing on different water supplies such as groundwater. Referring to the results for 'drought action taken' DDZ has decreased from 982 to

Table 1
Input variables and intermediate results for the six scenarios in WERD-M.

Year/scenario	1980	2000	2020	2040Gro	2040Bal	2040Res
Smallholder irrigation area (ha)	5	50	400	1000	700	500
Vegetable and other fruit irrigation (area, ha)	7000	6000	5000	6000	5000	4000
Citrus area (ha)	2700	4800	10,700	11,000	10,000	9000
Avocado area (ha)	700	2500	6500	10,000	8000	7000
Total area (ha)	10,405	13,350	22,600	28,000	23,700	20,500
Smallholder irrigation, normal CIE%	40 %	45 %	50 %	55 %	60 %	65 %
Smallholder irrigation, deficit & survival CIE%	50 %	55 %	60 %	65 %	70 %	75 %
FFV, citrus and avocado, normal CIE%	50 %	55 %	60 %	70 %	75 %	80 %
FFV, citrus and avocado, deficit & survival CIE%	60 %	65 %	70 %	75 %	80 %	85 %
All crops, normal irrigation in a drought, % area	0 %	0 %	0 %	0 %	0 %	0 %
All crops, deficit irrigation in a drought, % area	80 %	80 %	80 %	80 %	80 %	80 %
All crops, survival irrigation in a drought % area	20 %	20 %	20 %	20 %	20 %	20 %
Large dams storage - for ALL sectors (MCM)	230	230	230	230	230	270
On-farm storage in small dams for drought (MCM)	9	18	32	38	38	38
On-farm aquifer STOCK for drought (MCM)	10	20	30	40	40	40
Potential Drought Supply (PDS) as stock (MCM)	249	268	292	308	308	348
Ecological reserve (MCM/yr)	19	19	19	19	19	19
Domestic and urban in GLC (MCM/yr)	5	12	15	20	20	20
Export to domestic in Polokwane (MCM/yr)	0	5	18	22	22	22
Gross refill water (GRW) normal-wet period (MCM/yr)	260	260	260	260	260	260
Normal all-sector depletion (NAD) (MCM/yr)	108	127	191	200	172	150

Table 2
WERD-M modelled DDZ.

Year/scenario	1980	2000	2020	2040Gro	2040Bal	2040Res
Total area (ha)	10,405	13,350	22,600	28,000	23,700	20,500
DDZ no drought action taken (days)	446	380	127	70	215	397
DDZ within-drought action taken (days)	982	813	259	131	403	752
DDZ gain by applying drought action (days)	536	432	132	61	189	355
Ratio of DDZ action to no action taken	55 %	53 %	51 %	47 %	47 %	47 %

259 days in the last 40 years. This declining trend can be attributed to a doubling of irrigated area (from approximately 10,000 ha to 22,600 ha) that has not been offset sufficiently by reductions in total depletion (which affects refilling of storage in between droughts) or by increases in water storage for use during a drought.

The period up to 2040 provides an opportunity to compare between three future scenarios. The growth track (2040Gro) selects a large irrigated area of 28,000 ha resulting in 'only' 131 DDZ of supply to meet irrigation withdrawals. For this reason, we also attach the descriptor 'maladaptive' to the growth track, suggesting that large increases in water withdrawals and depletion caused by increases in crop area undermines catchment resilience to drought. The balanced track offers approximately three times the drought resilience of 403 DDZ, while the 'resilient' track (with higher storage and lower irrigated area of 20,500 ha) generates the highest DDZ at 752 days, nearly six times that of the growth track.

Using the results of DDZ when 'drought action is taken', Fig. 3 depicts the changing DDZ over time for recent history and for three future diverging tracks; growth (red), balanced (blue) and resilient (green). It is worth noting that Fig. 3 (as well as Fig. 4 below) demonstrates how at a given threshold, DDZ begins to decline at a steeper rate. In the modelled GLC, this occurs in the Year 2000 when total command area reaches nearly 23,000 ha. At this point, irrigation demands are growing which both appreciably draws down existing water storage during a drought, but also impacts on the ability to refill storage bodies in the period between drought.

Table 3 provides further resilience outputs. For example, the potential, refilled and drought irrigation storage differ from each other and decline over time as a result of growing total all-sector depletion. Importantly, Table 3 contrasts the volume of water delivered via 'Drought Protective Irrigation' if no drought action taken versus when action is taken. In each scenario, the latter is larger than the former. For example, DPI in 2020 when no drought action is taken is 65 MCM but is 74 MCM when water conservation is applied. Thus water conservation taken during a drought boosts both DDZ and DPI as a function of reducing overpluses (DIO as normal crop transpiration and efficiency losses). This increase in DPI is picked up in discussions below.

Table 3 also presents the results of the three irrigated catchment coefficients (DSC, DIE and ICDC) from 1980 through to the three future scenarios. These results support the DDZ findings above in that the DSC effectively declines from >30 % in 1980 to <10 % in the maladaptive growth 2040 scenario but recovers to approximately 20 % and 30 % in the balanced and resilient 2040 scenarios respectively. What appears to be undermining the conversion of pre-drought water supplies to a useable and useful 'Drought Irrigation Storage' is the increasing all-sector water demand during the pre-drought period which means catchment sectors and stakeholders struggle to refill the various water storage bodies. One possible interpretation of these DSC figures and trends is that a threshold of 20 % DSC seems to be important; above this and DDZ is >400 days, but below this, the irrigation sector would be hit hard by a drought lasting more than a one and half years.

The Drought Irrigation Efficiency (DIE, Table 3) shows increases from 60 % in 1980 to 70 % in 2020 (using the 'drought action taken' results). The three future scenarios are 74 %, 79 % and 85 % for the growth, balanced and resilient tracks respectively. These show that efficiency is an important part in boosting resilience (higher DDZ) as long as area irrigated is controlled to between 20,000 to 23,700 ha seen in the resilient and balanced scenarios (Tables 1 and 3).

Table 3 shows a similar trend for the Irrigated Catchment Drought Coefficient (ICDC) which is the ratio of DPI to GRW. Referring to results from

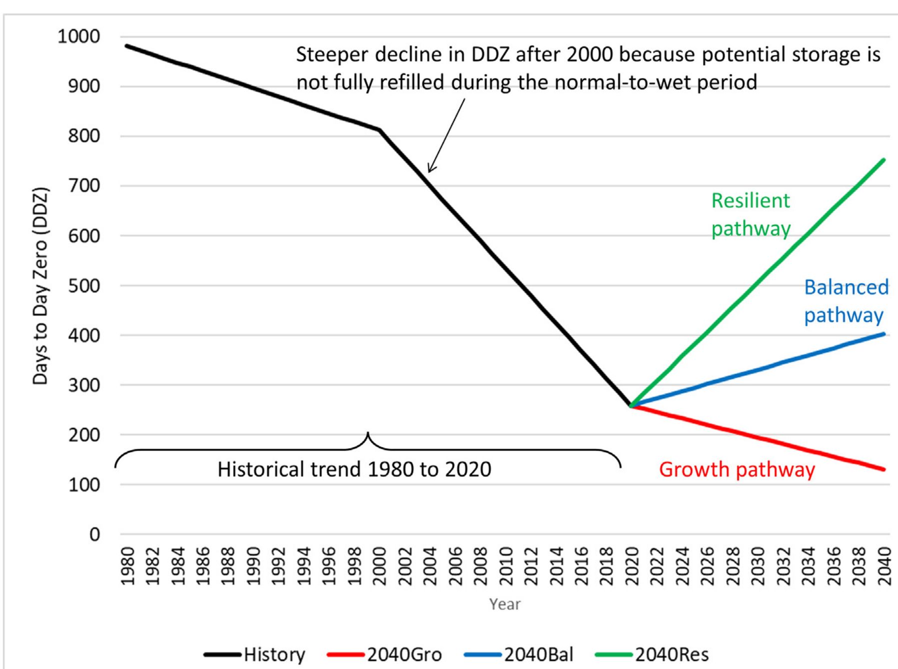

Fig. 3. Potential trends of DDZ over time and for three future scenarios.

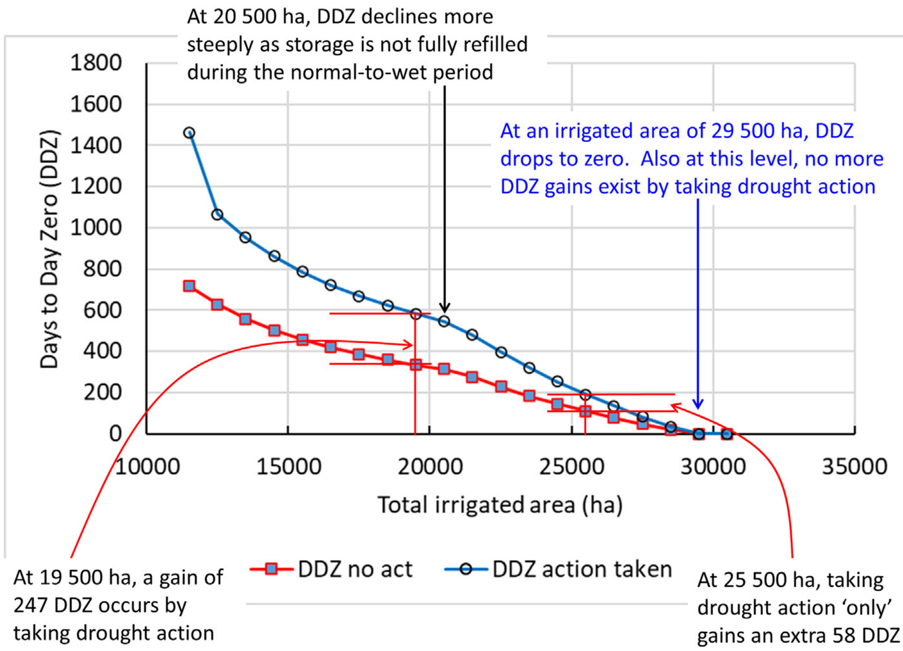

Fig. 4. DDZ responding to drought action taken and a growth in Citrus and total irrigated area.

'action during a drought is taken', the ICDC drops from 20 % to 10 % during 1980–2000 and declines down to 6 % in the 2040 growth track, returning to 16 % and 26 % for the balanced and resilient pathways respectively. If we accept 2020 to be a threshold of different future pathways towards 2040 then this points to a 10 % cut-off for the ICDC. In other words, when <10 % of GRW is converted to protective crop transpiration either through a failure to store enough water or to withdraw and apply it carefully, drought resilience is reduced.

In Fig. 4 we use results taken from Appendix G to show how WERD-M can track a declining DDZ over time as a result of increasing total irrigation area driven by an increase in the area under citrus. The analysis tests the response of DDZ to two variables; 1) whether or not drought action is taken; and 2) a growth in the irrigated area over time. In order to clearly demonstrate the expansion of irrigation on DDZ, this test utilises different starting variables to that employed above. For example, it uses increments of 1000 ha per year of citrus starting at 1000 ha and ending at 20,000 ha. The higher blue line shows an improved DDZ when 'drought action is taken' for any given total area as compared to the lower red line of 'no drought action taken'. For example, at a total of 19,500 ha, DDZ is 335 days for 'no action taken' but is 582 days if action is taken to conserve water, showing a gain of 247 DDZ. This extra resilience to absorb a drought 'within a drought' is then lost over time as irrigation area expands. When the total area grows from 19,500 ha to 29,500 ha, the 'drought action taken' DDZ has declined from 582 days to zero and, furthermore, a DDZ gain within a drought is now practically impossible. These trends show the risks to resilience of raising the irrigated area when not matched by additional water storage or efficiency gains. Also, similar to Fig. 3, Fig. 4 shows a 'tipping point' at 20,5000 ha when the declining rate of DDZ steepens. As explained above, this reflects both growing irrigation withdrawals during the drought and an impaired ability to refill storage between droughts.

4. Discussion

4.1. Absorptive, adaptive, anticipative and transformative capacities revealed by WERD

Figs. 5 and 6 explain our interpretation of drought resilience capacities emerging over time. Notwithstanding the legacy effects of actions taken in the past (e.g. the construction of the Tzaneen dam in the mid-1970s), Fig. 5

Table 3
Drought conversion coefficients.

Year/scenario	1980	2000	2020	2040Gro	2040Bal	2040Res
Gross refill water GRW as a volume pre drought (MCM)	780	780	780	780	780	780
Net refill water NRW as a volume pre drought (MCM)	457	398	207	181	264	331
Potential Drought Supply (PDS) as a stock (MCM/drought)	249	268	292	308	308	348
Refilled Drought Supply (RDS) as a stock (MCM/drought)	249	268	207	181	264	331
Drought irrigation storage (DIS) (MCM/drought)	201	196	103	59	142	209
Useable Drought Flow (UDF) during a drought (MCM/day)	0.041	0.041	0.041	0.041	0.041	0.041
UDF as a stock during a drought (MCM/DDZ drought)	40	33	11	5	17	31
Actual Drought Supply (ADS) as a stock (MCM/DDZ drought)	241	229	114	64	158	240
Drought Supply Coefficient (DSC)	31 %	29 %	15 %	8 %	20 %	31 %
Drought Protective Irrigation (DPI) if no action taken (MCM)	110	116	65	42	112	179
Drought Irrigation Efficiency (DIE) if no action taken	50 %	55 %	60 %	69 %	74 %	79 %
Irrigated Catchment Drought Coefficient (ICDC) No action	14 %	15 %	8 %	5 %	14 %	23 %
Drought Protective Irrigation drought action taken (DPI) (MCM)	145	149	79	48	126	203
Drought Irrigation Efficiency (DIE) action taken	60 %	65 %	70 %	74 %	79 %	85 %
Irrigated Catchment Drought Coefficient (ICDC) No action	14 %	15 %	8 %	5 %	14 %	23 %
Irrigated Catchment Drought Coefficient (ICDC) Action taken	19 %	19 %	10 %	6 %	16 %	26 %

recognises three types of time periods that shape on-going and future drought resilience. We consider four resilience capacities within each of these time periods as follows:

1) Current 'within drought' water management strategies that are relatively short-term (1–4 years) and are often temporary, for example a switch from normal to deficit irrigation scheduling. These responses reveal underlying 'absorptive capacities' intended to absorb the impact of the drought on crop production and orchard viability and longevity.
2) In the medium term, periods of normal rainfall (1–4 years) followed by drought (1–4 years) comprise water management activities that reflect 'adaptive capacity' in relation to the drought-prone character of the catchment. These learn from recent drought and anticipate the next drought. They require greater expenditure and risk-taking; examples include installing boreholes to augment water supplies and putting up shade cloth over orchards to reduce evapotranspiration.
3) Future drought-to-wet cycles (>10–15 years) encompass long-term agricultural strategies. During this time horizon, farmers focus on continuous improvements based on learnings from previous droughts, reflecting high adaptive capacity, plus they also continue to deploy absorptive strategies during droughts. Other strategies may require considerable planning and investments and are thus categorised as 'anticipative'. Examples of the latter include buying existing farms to merge their water rights or relocating high value cropping to wetter and cooler parts of the catchment. Furthermore, the future may be characterised by deep structural changes in land and water governance and can therefore be regarded as indicative of a 'transformative capacity'. Hypothetical examples might include a shift in collective stakeholder understanding that the area under irrigation should be reduced perhaps by as much as a third (i.e. capped at about 20,000 ha), whilst redeploying economic activity towards sectors that withdraw and deplete less water.

Importantly, some strategies may strongly reinforce and enhance one another. But this mutuality might also reduce other capacities and options available to farmers as they prepare for and respond to future droughts. This degree of mutuality is represented by the resilient and maladaptive pathways shown in Fig. 5. These pathways reflect different expressions of, and interactions between, absorptive, adaptive, anticipative and transformative capacities (or lack of) driven by a drought-prone catchment evolving over a long time. For example, on the maladaptive track B, absorptive and adaptive capacities strongly reinforce each other shaped by a series of droughts in order to extend DDZ within a drought. A similar strategy was employed by the City of Cape Town which, in response to two consecutive severe droughts, reduced water use by more than half in three years, thereby extending their DDZ (Wallace, 2021). However, this farm scale coupling of drought absorption and adaptation appears to undermine a more balanced and wider scale adoption of anticipative and transformative capacities. The risks of not balancing capacities and scale perspectives echoes observations by Pollard and du Toit (2011) that a focus on farm-scale actions and resilience can undermine catchment-scale resilience.

Fig. 6 shows a stylised graph of evolving drought resilience (expressed by DDZ), in a drought-prone irrigated catchment, for two pathways over a period of 20–40 years. The y-axis is DDZ, either increasing or decreasing from a central line representing no change. The x-axis is time reaching from 'today' to a future in 20–40 years. Placed on the x-axis are alternating and indicative 'drought' and 'normal-to-wet' periods of 2–4 years duration. Fig. 6 shows how irrigators respond 'within a drought' by increasing DDZ (both the red and green lines move up during a drought). Furthermore,

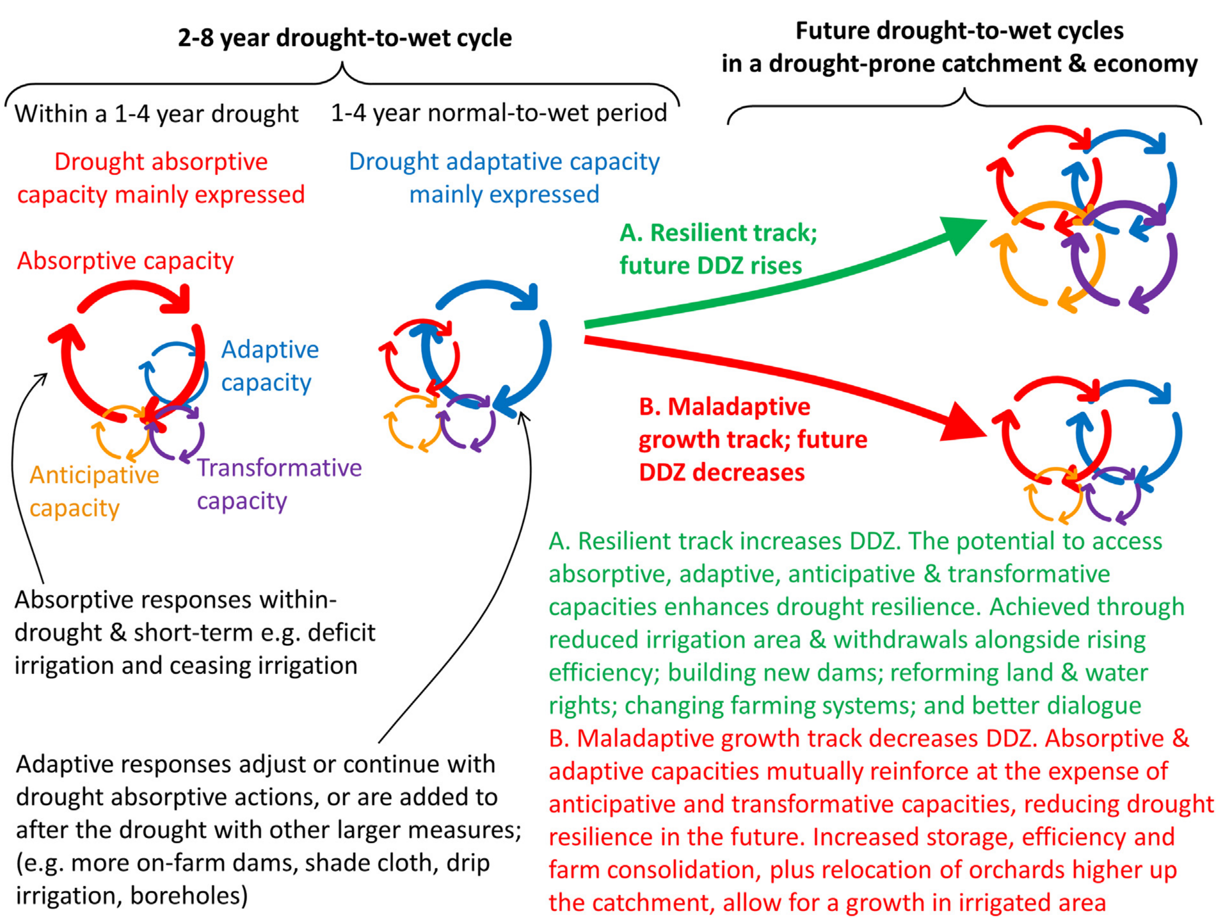

Fig. 5. Absorptive, adaptive, anticipative and transformative resilience capacities.

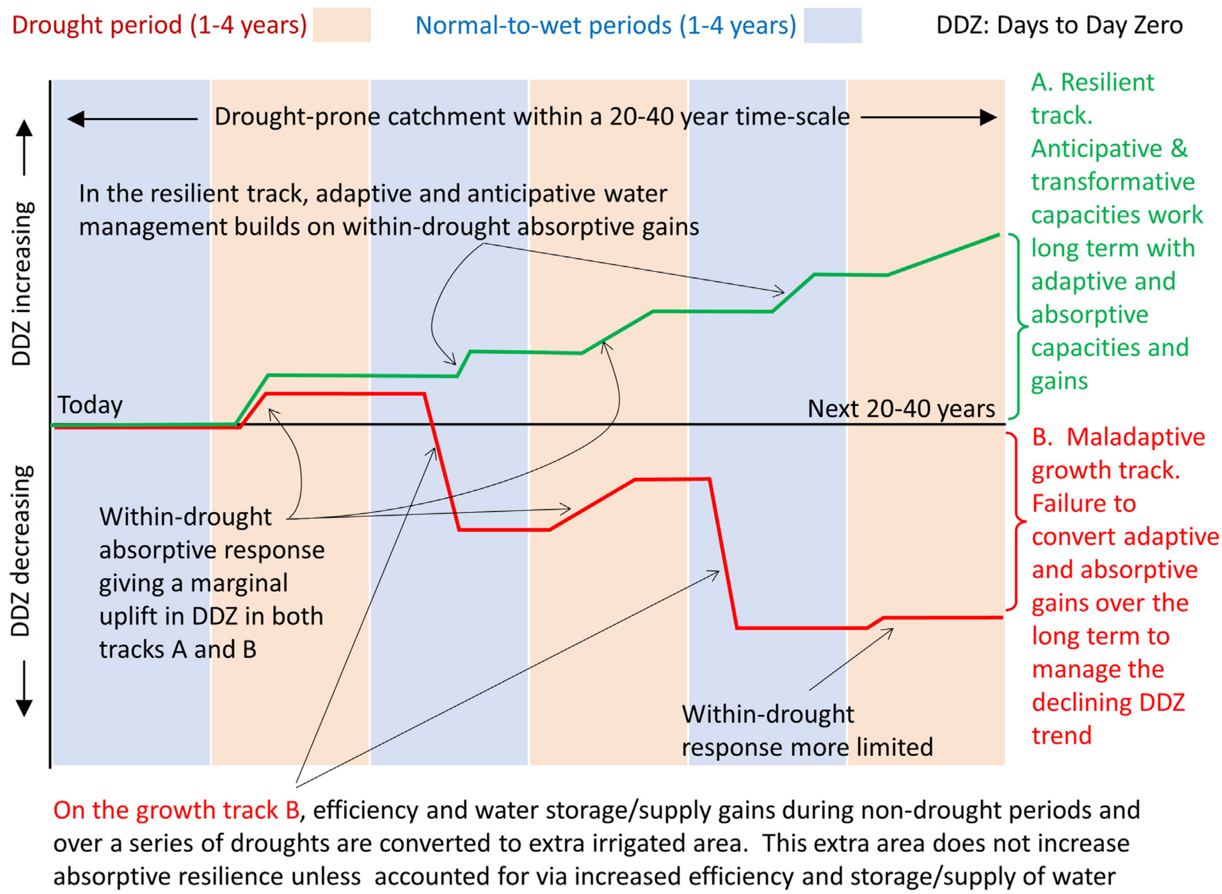

Fig. 6. Two alternate drought resilience pathways (resilient or maladaptive).

other options to raise DDZ might also occur both outside of drought and over a series of droughts. For instance, DDZ might be raised through the drilling of more boreholes and construction of on-farm dams in a normal-to-wet period. Both raise water volumes available during dry periods, which, for a fixed drawdown rate, extends the number of days until this new higher storage volume runs out.

The red line in Fig. 6 shows DDZ declining over time. This occurs via four mechanisms; first if storage is decommissioned or less efficient irrigation is installed. Both are unusual as purposive actions, but poor governance, maintenance and operation might unintentionally reduce water stored, accessed and delivered to meet crop needs. The second is that overall demand in the catchment increases between droughts which reduces the Net Refill Water (NRW) and the Drought Irrigation Storage (DIS) prior to a drought. The third is that, in the absence of any other water management actions, any extra water stored in large dams and on farms or 'saved' in orchard applications allows irrigated areas to be increased over time leading to higher water withdrawals in future droughts. This larger irrigation area poses a minor risk of 'running out of water' between droughts because with higher rainfall and river flows, its new more efficient water demand can be met from existing and/or newly augmented supplies. However, during a severe drought the larger area is much more exposed in terms of an imbalance between its additional irrigation demand and the lack of water to meet that demand. Fourthly, the second and third mechanisms combine to trigger very low DDZs in response to a growth in irrigation areas (in the model for example, a command area above 28,000 ha generates a DDZ of 'only' 131 days when drought action is taken). Beyond a threshold, a large irrigated area means that a) a smaller refill of storage between drought occurs and b) irrigation withdrawals during drought increase. This combined effect is indicated in Figs. 3 and 4, in the steeper decline in DDZ at approximately 20–22,000 ha.

Summarising, Figs. 5 and 6 capture two distinct resilience pathways arising out of how absorptive responses 'within a drought' connect to adaptive and anticipatory decisions taken 'over a series of droughts'. In the green coloured 'resilience track' (A), catchment irrigators and other stakeholders build on absorptive measures arising within a drought (increasing DDZs) by applying long-term water, agricultural and catchment governance strategies in anticipation of future droughts. Thus, over a series of droughts, the capacities of catchment stakeholders to negotiate, and then alter water supply, storage, efficiency, withdrawal and depletion enhances drought resilience of irrigated catchments. Central to this long-term governance are decisions to prioritise, or at least balance, drought resilience versus production maximisation, and central to that are decisions about capping total command area under irrigation that help determine withdrawals during drought.

In the red coloured 'maladaptive/growth track' (B), catchment irrigators and other stakeholders respond to periodic drought events (lifting DDZ via absorptive measures) but over time commute these supply and efficiency gains to higher command areas. Greater command area results in higher water withdrawals at the start of each subsequent drought. But without yet more additional storage or further efficiency improvements, this greater irrigated area results in higher water withdrawals from catchment storage, reducing the capacity to absorb future severe droughts. Track B portrays irrigators as not sufficiently anticipating risks of an expanded irrigation area to severe drought, meaning that the ability to absorb future droughts may be undermined. This might mean a future severe drought with significant orchard die-off leads to significant decisions about paring back the total command area under irrigation. Scott et al. (2014), in their study of the Limarí Basin in Chile, the Imperial Valley in the US, and the Guadiana Basin in Spain, observed a similar trend, noting that an expansion in irrigated area using "saved water", may aggravate water scarcity and undermine catchment resilience. Several other studies also note how some short-term adaptation strategies, including water supply management measures, may become maladaptive and unsustainable in the longer-term despite being beneficial for some individuals in the short-term (Erian et al., 2021; Stringer et al., 2020).

Finally, the above discussion illustrates how drought periodicity makes it difficult to define resilience capacities. Thus, while all four underlying capacities are available to growers across all time frames encompassing reoccurring droughts, some strategies are more clearly expressed within specific time spans. For example, implementing deficit irrigation or no watering of older trees in a drought is a clear example of an absorptive strategy. However, defining capacities outside of a drought is more complicated. To illustrate, one farmer may have learnt from the last drought and installed drip irrigation (which is adaptation), but their neighbour may install drip in readiness for the next drought (which is anticipation). This dilemma is also apparent when considering multiple shocks over longer time horizons as seen in our case study. Thus, an anticipative strategy to one farmer might mean a 6-month plan to install drip in part of their farm in preparation for the next drought, but to another grower, it may involve a longer-term and more protracted purchasing of farms to move up the catchment into avocado cultivation in readiness for droughts in 10–15 years' time. Or, echoing the discussion in Boyd et al. (2015), anticipation is best defined by implementing substantial changes that, for example, might cut out a third of irrigated area to significantly raise DDZ - a strategy that also arguably involves and defines the ‘transformation’ of the economy of the catchment away from irrigated horticulture.

4.2. On efficiency as a resilience factor

We argue that rather than undermining resilience (Elmqvist, 2017), irrigation efficiency mediates resilience in seven instructive ways. Key to understanding the significance of these ways is to recall they are operating within a drought or in a drought-prone catchment across a series of droughts. First, altering irrigation efficiency is a field and farm technical process effected by farmer decisions responding to drought. This means farmers rationally eke out (conserve) stored pre- and within-drought water supplies to last longer to avoid plant die-off and ensure economic production during the drought, and to allow perennial crops to recover after the drought. Responding to the last and anticipating the next drought, farmers also rationally continue to add or improve strategies to conserve and store water.

Also at the farm scale, irrigation efficiency positively influences crop productivity recognised as especially important in drought-prone areas (Nhemachena et al., 2020; Rockström, 2003). Drought productivity is central to, but implicit within, our framework because of the way that water control offered by high-tech (e.g. drip) irrigation systems help to schedule deficit irrigation, manage partial root wetting and coordinate crop inputs. In other words, precision water control manages water stress during critical periods (e.g. flowering and fruiting) to safeguard orchard production identified by WERD's ‘Drought Protective Irrigation’. In canal systems, not converted to drip, improved efficiency also enhances the control, progress and timing of irrigation scheduling to maintain readily available soil moisture thereby boosting crop production (Lankford, 2012; Lankford and Orr, 2022).

Third, undertaking water conservation ‘within a drought’ leads to more water being consumed as core protective crop evapotranspiration. WERD-M shows that when drought action is taken, the volume of Drought Protective Irrigation water goes up, mirroring the increase in DDZ. This DPI boost occurs because farmers can retain the difference between 1) smaller water withdrawals when drought action is taken and 2) larger water withdrawals to meet full irrigation when no action is taken. This difference can be held in storage bodies to re-ration it out more slowly and for longer during the drought. In other words, both the per-day and per-hectare water withdrawals and applications decrease when drought action is taken, but paradoxically the total water volume transpired by orchards goes up because; a) DPI is now a greater proportion of DIW; and b) the DDZ has been extended over more days.

Moving to longer time spans (>10–15 years), when combined with greater adoption of deficit irrigation, increases in irrigation efficiency help to catalyse increases in command area, which paradoxically can lead to higher water withdrawals and depletion, in keeping with concerns voiced by Scott et al. (2014) and Ward (2022). Efficiency-enabled growth depends on the legacy effects of generous irrigation licences drawn up in the 60s and 70s that assumed relatively low irrigation efficiencies (see Appendices B and F for further information). Without a parallel effort to store yet more water, larger irrigated areas and daily withdrawals lead to both a) lower DDZs during future droughts and b) smaller possible gains in DDZ when drought action to conserve water is attempted. But these adverse impacts are not necessarily given or direct consequences of water conservation. Instead, efficiency, storage and area can be controlled in various combinations to guard against excessive withdrawals and depletion in order to enhance drought resilience.

Fifth, building on the previous points we therefore argue that efficiency, water conservation and storage work together depending on circumstances. During a drought, farmers can conserve water in storage to re-ration it to meet core crop transpiration needs. Without storage, this holding back of water to release it more slowly cannot happen. This makes the capacity of water storage available to farmers central to DDZ gains achieved via ‘within-drought’ water conservation, a point returned to in Section 4.3.

Sixth, the GLC case counters and/or nuances the consensus that higher irrigation efficiency results in greater water depletion (Grafton et al., 2018; Matthews et al., 2022; Ward and Pulido-Velázquez, 2008). Instead, action taken within a drought (via water conservation and a marginally higher efficiency) results in less water withdrawn and depleted at any given period in the drought, as shown by the lower daily withdrawals in MCM/day given in Table F1 in the Supplementary Material (for example for the year 2020, DIW drops from 0.86 MCM/day to 0.44 MCM/day). Five conditions apply for efficiency-driven reductions in water withdrawals and depletion to function.

1. First, the hydrology of the GLC irrigation systems during drought means that the argument that ‘losses from one inefficient system are recovered by other irrigation systems’ (Grafton et al., 2018) does not apply. For most of the last 20–30 years, and especially during drought, commercial farmers operating sprinkler and drip systems under tight water, energy and financial budgets have not over-irrigated their orchards to the extent that large runoff and drainage flows occurred. From observations made, most ‘losses’ during drought arise from non-beneficial consumption/evaporation from wetted soil and grass between trees.
2. Related to the first point, the size and topography of the catchment and its hydrology during a drought mean that water releases from large dams and runoff are; a) highly apportioned to known uses and users and b) do not have an opportunity volume-wise or timing-wise (as they flow through the catchment in 3–5 days) to refill groundwater levels. This reinforces the first point that downstream irrigation does not grow during a drought by capturing groundwater movement from upstream over-watering. This is different during normal-to-wet periods when a combination of greater irrigation and rainfall will help refill groundwater bodies. Prosaically put, the GLC is a semi-arid catchment of relatively high relief, home to commercial drip and sprinkler horticulture. It is not a sub-humid flat floodplain home to state or parastatal large-scale gravity/canal irrigation of a lower efficiency.
3. The volume of water for withdrawal during a drought is largely fixed as it comes from limited storage and small in-stream flows (controlled in WERD by PDS, RDS, DIS and UDF). In the model, the fixed water storage is always drawn down to zero and furthermore it cannot be appreciably increased once a drought has started. However, in the medium to long-term, greater storage for use during drought does occur and this can raise irrigation areas, withdrawals and depletion (see Section 4.3). The qualifier ‘largely’ signals that while withdrawal volumes from surface and groundwater stores are fixed, withdrawals from Useable Drought Flows (UDF) can be marginally boosted when DDZ is extended. The slightly higher total withdrawal volumes (and therefore higher

depletion) in the 'with action taken' results of Table F1 in Appendix F compared with 'no action taken' (114 versus 108 MCM respectively for 2020) are because the higher DDZ provides a longer period over which UDF are accessed. If UDF is set to zero, WERD-M returns identical results for total DIW volumes. Summarising, water conservation within a drought lowers daily withdrawals but extends the days of withdrawal. This means withdrawals and by extension depletion are fixed unless surface streamflows are accessed for longer.
4. For the purpose of modelling DDZ, irrigated area is also fixed within a drought, a key factor that controls withdrawals and depletion. This is because, as a result of water shortages in a drought period, growers curtail areal expansion. However, when the irrigation area significantly grows over the long-term, enabled by rising efficiencies, more water is withdrawn and consumed.
5. A long-term growth in area, withdrawal and depletion is not only a function of higher efficiency; it is assisted by a growing storage of water accessed from new additional on-farm dams and boreholes. However, the refilling of this growing storage can be impaired by greater depletion between droughts from all sectors including irrigation.

Seventh, because of the above effects, irrigation efficiency and the three catchment coefficients act as a discursive goal to do better with limited water. This interpretation argues that efficiency is not an end in itself, but instead should feed into two resilience discussions; the management of crop water demand (controlling command area and stretching out scarce supplies to sustain production) and the management of catchment water via supply and storage management. Thus, efficiency becomes a boundary concept (Lankford et al., 2020) to inform the frugal (or otherwise) management of water across multiple scales from orchard to catchment and from short to long term. Thus, while we have considered the links between resilience and efficiency as they relate to water management within and outside a drought, these are nested within a broader context that includes legacy effects and future catchment governance.

4.3. On storage as a resilience factor

As a result of running various scenarios in WERD-M, we draw the following insights on how water storage mediates resilience:

- The presence of the large water storage bodies provides an important safeguard against drought impacts (McCartney and Smakhtin, 2010) and if governed well, helps build resilience (Matthews and McCartney, 2018). For example, in our modelled GLC, a refilled storage of 230 MCM can provide 402 days of protective watering for 28,000 ha of irrigated crops. Furthermore, dams and groundwater provide water security for supplying priority non-agricultural sectors.
- The presence of storage allows inter-drought water to be captured and stored which supports drought resilience. The larger the potential drought store (PDS) the greater the chance of this being refilled by high flow events leading to DDZ being sustained or increased (although this phenomenon was not fully modelled by WERD-M).
- The presence of storage underpins the ability of irrigators to conserve water and retain that conserved water in storage for release later in the drought to meet protective irrigation needs. Put another way, it is large volumes of water storage which enable the relative gains in DDZ and DPI to occur when water conservation is undertaken. Two corollaries follow - both of which can be demonstrated by adjusting variables in WERD-M. First, if access to storage is switched off so that farmers draw only on low UDF streamflows during a drought, their water conservation attempts would have a much smaller effect on boosting DDZ. Second, if farmers are given access to much larger UDF streamflows during a drought, their reliance on storage for retaining conserved water diminishes.
- In the long-term, the presence of high-capacity storage, combined with efficiency gains, allows irrigated area to increase by providing a buffer to drought. (A contrasting explanation is that with no or little storage, irrigation would be constrained by a lack of water during drought which would throttle long-term growth). This combined effect supports observations by Di Baldassarre et al. (2018) that higher water demand can offset the initial benefits of reservoirs.

Thus, similar to the previous section's discussion about efficiency, and as WERD-M demonstrates, the capacity of water storage and size of streamflows accessible by irrigation during a drought variously combine to mediate DDZ resilience. These interactions are further revealed and amplified when irrigated areas are controlled and capped in the longer-term.

5. Conclusions

We investigated the resilience of irrigated agriculture to drought in a semi-arid catchment using the indicator 'Days to Day Zero' (DDZ), with four important points emerging. Firstly, water storage and water conservation enable fruit growers to absorb drought impacts evidenced by how these strategies gain an increase in DDZ to sustain crop production during drought. Secondly, there are complex relationships between efficiency and resilience at both farm and catchment scales with trade-offs occurring across both time and space. Farmers can sensibly absorb a drought by implementing water savings at the orchard scale within 1–4 years, but over longer periods these water conservation practices can lead to larger irrigated areas with consequent increased water withdrawals and depletion. Because water supply in a drought is limited, larger areas and withdrawals reduce resilience seen in declining DDZs. These trade-offs demonstrate the paradoxical roles of improving irrigation efficiency in mediating resilience. Thirdly, our analyses revealed other water dynamics both prior to and during a drought. Three examples include; conserving water during a drought re-rations water leading to increased volumes of protective crop transpiration; water storage in dams and groundwater enables that conservation and re-rationing; and above a given area threshold, higher irrigation depletion undermines refilling of storage during inter-drought periods. Finally, our conceptual framework illustrates how absorptive, adaptive, anticipative and transformative capacities can facilitate discussions regarding catchment resilience and water governance in both the short and long term. In the short term, irrigators have every reason to absorb a drought event. In the medium term, growing perennial export crops in a drought-prone area incentivises technological and institutional changes, demonstrating absorptive and adaptive resilience. Over the longer term, trying to sustain production and business expansion across multiple droughts, irrigators and catchment stakeholders might poorly anticipate the extent to which future increases in irrigated area, insufficiently mitigated by fresh gains in efficiency and storage, diminishes their resilience to drought. Thus, by not controlling irrigated area, growers undermine the future basket of options available to them, implying that transformative change may be necessary to survive future droughts. The research informs water, land and agricultural policy aimed at enhancing rather than undermining resilience, including; reforming irrigation licences; farm area planning at the individual and catchment scales; involving multi-sector stakeholders in catchment decision-making; modelling additional storage; improving water and land monitoring to build water accounts; and advising on water management both during and between droughts.

CRediT authorship contribution statement

Lankford; conceptualisation, analysis, investigation, original draft writing and model. Pringle, McCosh and Shabalala; conceptualisation, field research investigations, methodology, review and editing. Hess; Funding acquisition, project administration, review and editing. Knox; review and editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare no competing interests.

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Appendices A–I. Supplementary material

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