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The impact of water resources management and resource optimisation during drought periods

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Abstract: Water scarcity affects approximately 40% of the global population, with drought events causing annual economic losses exceeding $5–8 bln. Traditional water management approaches are increasingly inadequate as climate variability intensifies. The current study aims to develop an integrated framework for water resource optimisation during drought periods that bridges theoretical models with practical implementation considerations. The research was conducted across three watersheds (Limpopo, Murray–Darling, and Colorado River basins) using comprehensive hydroclimatic, socioeconomic, and institutional data spanning 1992–2022. A system dynamics model with five interconnected subsystems was coupled with a Non-dominated Sorting Genetic Algorithm-III optimisation framework. The Institutional Analysis and Development framework assessed governance structures, while Sobol sensitivity analysis evaluated parameter influence. Optimised balanced strategies reduced economic losses by 19.4–24.8%, decreased social impacts by 25.8–28.7%, and increased environmental flow compliance to 49.2–61.7% compared to baseline management. The Murray–Darling basin demonstrated the highest implementation potential due to its comprehensive legal framework and established adaptive mechanisms. Under severe climate change scenarios, optimisation performance advantages declined by 21–29%. Effective drought management requires both technical optimisation and institutional adaptation. Basin-specific implementation pathways provide practical roadmaps for enhancing water security while balancing diverse stakeholder needs in increasingly water-stressed regions.

Keywords: drought management, institutional adaptation, multi-objective optimisation, system dynamics, water resources

INTRODUCTION

Water scarcity represents one of the most pressing global challenges of the 21st century, affecting an estimated 40% of the world's population and projected to intensify with climate change (Mishra, 2023; Shemer, Wald and Semiat, 2023). The increasing frequency and severity of drought events across various regions have highlighted the critical importance of effective water resources management and optimisation strategies (Minea *et al.*, 2018; Gusti *et al.*, 2023; Ibrahim *et al.*, 2024). Drought events cause significant socioeconomic and environmental impacts, with global annual economic losses exceeding $5–8 bln and affecting over 55 mln people worldwide each year (Wang *et al.*, 2022). Traditional water management approaches are increasingly inadequate to address these challenges, particularly as climate variability intensifies and water demand continues to rise with population growth and economic development (Kamyab *et al.*, 2023). This complex interplay of factors necessitates innovative approaches to water resource management that incorporate advanced optimisation techniques specifically tailored for drought conditions.

- **Evolving water management and persistent challenges**

The evolution of water resources management has progressed significantly from supply-oriented approaches toward more integrated and adaptive management frameworks. Historical water management prioritised infrastructure development such as dams and reservoirs to ensure stable supply (Bukhari, Khan and Noreen, 2024). However, contemporary approaches have shifted toward demand management, stakeholder participation, and recognition of the value of ecosystem services (Berg *et al.*, 2023). Integrated Water Resources Management (IWRM) emerged as a paradigm that balances economic efficiency, social equity, and environmental sustainability (Shukla *et al.*, 2024). Despite this evolution, implementing effective drought management remains challenging due to the complex, non-linear dynamics of hydrological systems and the difficulty in predicting drought onset, duration, and severity (Guemouria, Chehbouni and Bouchaou, 2024; Giacomello *et al.*, 2024). The uncertainty inherent in drought forecasting further complicates management efforts, particularly in regions experiencing both rapid development and changing precipitation patterns (Lisonbee *et al.*, 2025).

Resource optimisation techniques have become increasingly sophisticated in addressing water scarcity during drought periods. Mathematical programming approaches, including linear, non-linear, and dynamic programming, have been applied to optimise reservoir operations, water allocation among competing sectors, and infrastructure investment decisions (Yazdandoost, Razavi and Izadi, 2022; Zhexenbay *et al.*, 2020). Recent advances in artificial intelligence and machine learning have enhanced these optimisation frameworks by improving drought forecasting accuracy and enabling more robust decision-making under uncertainty (Kikon and Deka, 2022; Prodhan *et al.*, 2022; Danandeh Mehr *et al.*, 2023). Multi-objective optimisation models have proven particularly valuable for balancing trade-offs between competing water management objectives such as agricultural productivity, municipal supply reliability, ecological flow requirements, and hydropower generation (Hou *et al.*, 2025). Nevertheless, translating these technical optimisation solutions into practical management policies remains challenging due to institutional barriers, fragmented governance structures, and competing stakeholder interests.

Despite significant progress in water management and optimisation techniques, several critical gaps persist. First, while acknowledging uncertainty is common, many optimisation models still inadequately address the deep uncertainty of future climate impacts (Pérez-Blanco, 2022), often lacking mechanisms for truly adaptive responses. Second, existing frameworks frequently fail to integrate socioeconomic dynamics, particularly institutional factors, with biophysical processes in a truly coupled manner (Razavi *et al.*, 2025); governance structures are often treated as static constraints rather than dynamic components influencing adaptation potential, a limitation this study directly addresses by incorporating institutional adaptive capacity within the multi-objective optimisation itself. Third, the computational intensity of many advanced optimisation methods can restrict their operational use (Drogkoula, Kokkinos and Samaras, 2023), highlighting the need for efficient algorithms applicable in complex, real-world settings. Fourth, the transferability of optimisation methods remains limited, with models often calibrated for specific regions yielding static solutions (Santos, Carvalho and Martins, 2023), thus hindering the development of strategies that can adapt over time. In contrast to approaches focusing primarily on technical optimisation or static institutional settings, this study emphasises the development of flexible, context-specific, adaptive optimisation pathways designed to evolve in response to changing hydroclimatic conditions, institutional capacities, and stakeholder priorities. These persistent gaps underscore the need for the integrated and adaptive framework developed herein.

- **Rationale, problem statement, and study objectives**

The rationale for focusing on water resource optimisation during drought periods stems from the increasing recognition that drought represents not merely a natural hazard but rather a complex socio-environmental phenomenon requiring systemic interventions. As climate change intensifies the hydrological cycle, traditional infrastructure-based solutions alone prove insufficient to address emerging challenges (Santos, Carvalho and Martins, 2023). The potential applications of improved drought optimisation strategies extend across multiple sectors, including agricultural production systems, urban water supply reliability, ecosystem protection, and energy security (Alkhalidi *et al.*, 2023). Furthermore, enhanced optimisation approaches can support more equitable water allocation during periods of water scarcity, reducing potential conflicts between competing users and promoting social stability in water-stressed regions (Mahdi, 2024). The economic benefits of optimised drought management are substantial, with studies indicating that proactive drought preparedness can reduce economic losses by 30–60% compared to reactive approaches (Fernández *et al.*, 2023; Paez-Trujillo *et al.*, 2024).

A critical challenge hindering effective drought response and adaptation is the persistent disconnect between sophisticated theoretical optimisation models and their practical application by water managers and policymakers. Although sophisticated mathematical frameworks have been developed to optimise water resources during scarcity, their adoption by water management agencies and policymakers remains limited (Bouramdane, 2023). This implementation gap stems from multiple factors, including the complexity of optimisation algorithms, insufficient integration of stakeholder preferences, inadequate consideration of institutional constraints, and lack of user-friendly decision support systems (Chuenchum *et al.*, 2024). Additionally, most optimisation approaches remain predominantly technocratic, failing to incorporate local knowledge, cultural values, and equity considerations that significantly influence water management outcomes (Nugroho *et al.*, 2023). This implementation gap represents a substantive divide between technical potential and practical reality, significantly undermining efforts towards effective drought response and adaptation in increasingly water-stressed regions.

This study aims to develop an integrated framework for water resource optimisation during drought periods that bridges theoretical models with practical implementation considerations. The research seeks to advance drought management by introducing a novel hybrid optimisation approach that combines system dynamics modelling with multi-objective evolutionary algorithms to capture both the complex feedbacks within coupled human–water systems and the diverse objectives of stakeholders. Unlike previous frameworks, this approach explicitly incorporates institutional arrangements, governance structures, and implementation pathways alongside technical optimisation components (Kolahi, Davary and Omranian Khorasani, 2024). The novelty of this research lies in the development of adaptive optimisation pathways that can evolve as drought conditions change, institutional capacities develop, and stakeholder priorities shift. By embedding optimisation within a broader adaptive management framework, this study offers a pragmatic approach to enhancing drought resilience across diverse contexts while acknowledging the inherent complexity and uncertainty of water management in a changing climate.

MATERIALS AND METHODS

STUDY AREA

This research was conducted across three distinct watershed systems experiencing recurrent drought conditions: the Limpopo River basin in southern Africa, the Murray–Darling basin in Australia, and the Colorado River basin in the United States. These watersheds were selected based on their diverse hydroclimatic characteristics, varying levels of economic development, and different governance structures, providing a robust testing ground for the proposed optimisation framework. The Limpopo basin (414,800 km^2) represents a semi-arid region with highly variable precipitation (annual average of 530 mm) and significant agricultural dependency, serving five countries with competing water demands (Obwocha *et al.*, 2022). The Murray–Darling basin (1,061,000 km^2) exemplifies a complex water management system with extensive irrigation infrastructure, formalised water markets, and explicit environmental flow requirements (Wyborn *et al.*, 2023). The Colorado River basin (637,000 km^2) represents a heavily regulated river system operating under conditions of chronic water scarcity, with complex transboundary governance agreements and substantial urban water demands (Grigg, 2025).

DATA COLLECTION AND PROCESSING

A comprehensive dataset was compiled for each watershed, encompassing hydroclimatic, socioeconomic, and institutional variables spanning a 30-year period (1992–2022). This timeframe was selected to provide a robust long-term perspective encompassing several significant drought events crucial for analysing drought impacts and management responses, while also aligning with the availability of relatively consistent hydroclimatic, socioeconomic, and institutional data across the three distinct basins. Hydroclimatic data included daily precipitation, temperature, evapotranspiration, streamflow, reservoir levels, and groundwater measurements obtained from respective national meteorological services, U.S. Geological Survey, National Oceanic and Atmospheric Administration, Australian Bureau of Meteorology, and the South African Department of Water Affairs. These data were quality-controlled using standard procedures including gap-filling via multiple imputations (Melesse and Demissie, 2024). Socioeconomic data included sectoral water use (agricultural, municipal, industrial), economic output by sector, population dynamics, land use changes, and water pricing structures, collected from national statistical agencies, water utility reports, and previous research studies. Institutional data encompassed water rights allocations, governance structures, regulatory frameworks, and historical drought response measures, compiled through document analysis of legal frameworks, policy documents, and semi-structured interviews with 87 water managers across the three basins.

The standardised precipitation evapotranspiration index (*SPEI*) was calculated to identify and classify drought periods within each watershed (Vicente-Serrano *et al.*, 2022):

$$SPEI_i = \sum_{j=1}^{i} (P_j - PET_j) \tag{1}$$

where: P_j = monthly precipitation, PET_j = potential evapotranspiration calculated using the Penman-Monteith equation, i = timescale (3, 6, 12, and 24 months were analysed).

For the purpose of identifying and characterising the major drought events and informing subsequent analyses related to water resource system impacts, the *SPEI*-12 timescale was primarily utilised. This 12-month timescale was selected as it effectively reflects the cumulative precipitation deficits that lead to significant hydrological drought conditions (affecting streamflow and reservoir storage) and aligns with the annual cycle relevant for water allocation planning and assessing persistent socio-economic impacts, which are central to this study.

SYSTEM DYNAMICS MODELLING

A system dynamics modelling approach was employed to capture the complex feedback mechanisms between hydrological, socioeconomic, and institutional components of each watershed system. The model architecture followed a modular structure with five interconnected subsystems: (1) hydrological processes, (2) water infrastructure operations, (3) sectoral water demands, (4) economic impacts, and (5) institutional responses. Specifically, the hydrological processes subsystem simulates water availability considering rainfall-runoff dynamics and surface-groundwater interactions. The water infrastructure operations subsystem governs water storage and release decisions from major reservoirs based on operational rules and mass balance principles. Sectoral water demands are calculated for agricultural, municipal, industrial, and environmental needs, driven by factors like climate, cropping patterns, and population. The economic impacts subsystem translates water shortages into direct and indirect economic consequences for different sectors using production functions. Finally, the institutional responses subsystem simulates the activation and effect of drought management policies, allocation adjustments, and adaptive governance measures based on evolving system conditions and predefined triggers.

These subsystems are interconnected through various feedback loops critical for simulating system behaviour and decision-making responses. For instance, simulated low streamflow and reservoir levels (hydrological processes and infrastructure operations) can trigger pre-defined institutional responses (e.g., drought stage declarations and associated water restrictions). These responses, in turn, directly influence sectoral water demands and allocations, leading to subsequent changes in economic impacts. Furthermore, the cumulative economic and social impacts, along with environmental conditions, can feedback to influence the evolution of institutional adaptive capacity or future policy adjustments within the model's logic over longer simulation periods. The model was implemented using the Vensim DSS platform (ver. 9.2) with a monthly time step.

The hydrological module incorporated a semi-distributed rainfall-runoff model calibrated for each sub-basin using the Nash–Sutcliffe efficiency criterion. Surface water–groundwater interactions were modelled using a linear reservoir approach. Water infrastructure operations were represented through mass balance equations for each major reservoir system (Yimer *et al.*, 2023):

$$S_{t+1}^r = S_t^r + I_t^r - R_t^r - E_t^r - L_t^r \tag{2}$$

where: S_{t+1}^r and S_t^r = storage in reservoir r at times t+1 and t, respectively; I_t^r = inflow; R_t^r = releases; E_t^r = evaporation losses; L_t^r = seepage losses.

The water demand module calculated agricultural, municipal, industrial, and environmental water requirements. Agricultural water demand was estimated as:

$$D_{t,a}^{ag} = \sum_{c=1}^{C} A_{t,c,a} \cdot K_{c,t} \cdot ET_0 \cdot \left(1 - \alpha_{c,a} \cdot P_t\right) \tag{3}$$

where: $D_{t,a}^{ag}$ = agricultural water demand in area a at time t; $A_{t,c,a}$ = area under crop c; $K_{c,t}$ = crop coefficient; ET_0 = reference evapotranspiration; P_t = precipitation; $\alpha_{c,a}$ = effective rainfall coefficient.

The economic impact module quantified direct and indirect economic consequences of water shortages using a production function approach (Sapino, Pérez-Blanco and Saiz-Santiago, 2022):

$$E_{t,s} = \beta_s \left(\frac{W_{t,s}}{W_{t,s}^*}\right)^{\gamma_s} GDP_{t,s}^* \tag{4}$$

where: $E_{t,s}$ = economic output of sector s at time t; $W_{t,s}$ and $W_{t,s}^*$ = actual and optimal water allocations, respectively; $GDP_{t,s}^*$ = potential economic output under optimal water supply; β_s = sector-specific scaling parameter; and γ_s = elasticity of output with respect to water input.

MULTI-OBJECTIVE OPTIMISATION FRAMEWORK

A hybrid multi-objective optimisation framework was developed to identify optimal water allocation strategies during drought periods. The optimisation problem was formulated as:

$$\min_x F(x) = [f_1(x), f_2(x), \ldots, f_k(x)] \tag{5}$$

subject to:
$g_j(x) \leq 0, j = 1, 2, \ldots, m$
$h_l(x) = 0, l = 1, 2, \ldots, n$
$x^L \leq x \leq x^U$
where: x = decision variables (monthly water allocations by sector and location); $F(x)$ = vector of k objective functions; $g_j(x)$ and $h_l(x)$ = inequality and equality constraints, respectively; x^L and x^U = lower and upper bounds on decision variables.

The objective functions included minimising economic losses (f_1), minimising social impacts (f_2), measured through a composite index quantifying water supply reliability to vulnerable populations. This index considered factors such as the frequency, duration, and magnitude of water supply shortfalls affecting identified vulnerable groups (e.g., low-income domestic users, smallholder farms with insecure water rights) compared to predefined minimum requirements, maximising environmental flow compliance (f_3), and maximising institutional adaptive capacity (f_4). A novel aspect of this formulation was the inclusion of f_4, which was quantified through an institutional adaptation index developed through multi-criteria decision analysis with water management stakeholders. Conceptually, this index (f_4) aimed to capture the adaptive capacity of the basin's governance system, reflecting characteristics such as the flexibility of water allocation rules and legal frameworks during drought, the capacity for monitoring and learning from past events, the effectiveness of stakeholder engagement mechanisms in decision-making, and the ability to implement contingency plans and mobilise resources.

The optimisation algorithm employed was the Non-dominated Sorting Genetic Algorithm-III (NSGA-III) with reference points (Liu *et al.*, 2022), selected for its ability to handle many-objective optimisation problems efficiently. The algorithm parameters were set as follows: population size = 200, maximum generations = 500, crossover rate = 0.9, and mutation rate = 0.1. A Latin hypercube sampling approach was used to generate initial populations that adequately covered the decision space.

INSTITUTIONAL ANALYSIS AND STAKEHOLDER ENGAGEMENT

Institutional analysis was conducted using the Institutional Analysis and Development (IAD) framework (Jones-Crank, 2024; Rahman and Islam, 2024) to identify key governance variables influencing water allocation during drought. Semi-structured interviews were conducted with stakeholders representing water management agencies (n = 32), agricultural users (n = 28), municipal suppliers (n = 15), environmental organisations (n = 14), and industrial users (n = 12). These stakeholder categories were selected to ensure comprehensive representation of the key governmental bodies, major water-using sectors (agriculture, municipal, industry), and significant environmental interests directly involved in or affected by water allocation decisions and drought management within each basin. These interviews were transcribed and analysed using thematic content analysis to identify institutional barriers and enablers for implementing optimisation strategies. The specific elements influencing adaptive capacity, such as the presence of formal adaptive management structures, policy learning mechanisms, and the nature of stakeholder cooperation, were identified and evaluated through the synthesis of findings from this thematic analysis, the review of relevant policy and legal documents, and discussions within the participatory workshops.

A series of four participatory modelling workshops was conducted in each basin, involving a diverse set of stakeholders (25–30 participants per workshop). These workshops employed structured decision-making protocols to elicit stakeholder preferences regarding trade-offs between competing water uses during drought, institutional reform options, and implementation pathways. The Delphi method was used to develop consensus on the institutional adaptation index components, which were subsequently incorporated into the optimisation framework. This process involved three iterative rounds conducted with the stakeholder groups identified previously. In the first round, participants anonymously suggested potential components for the index based on their expertise and experience. Subsequent rounds involved rating the importance and relevance of the compiled components on a Likert scale and providing qualitative feedback on the aggregated, anonymised results from the previous round. Consensus for retaining a component in the final index was defined as achieving a minimum of 75% agreement (rated as important or very important) among participants, alongside demonstrated stability in the mean ratings between the second and third rounds.

MODEL VALIDATION AND SENSITIVITY ANALYSIS

The integrated modelling framework was validated using a three-stage process. First, the hydrological components were calibrated and validated using a split-sample approach, with data from 1992–2012 used for calibration and 2013–2022 for validation. Performance was assessed using multiple criteria including Nash–Sutcliffe efficiency (*NSE*), Percent Bias (*PBIAS*), and the Kling–Gupta efficiency (*KGE*). Second, the system dynamics model was validated through behaviour reproduction tests comparing simulated and observed system behaviour during historical drought periods. Third, the optimisation framework was validated by applying it to historical drought events and comparing model-recommended allocations with actual management decisions and their outcomes.

Sensitivity analysis was conducted using a variance-based global sensitivity approach (Sobol method) to identify the most influential parameters affecting optimisation outcomes. Specifically, both first-order and total-order Sobol indices were computed. First-order indices measure the direct contribution of an individual parameter's variance to the total variance of the model output, representing its main effect independent of interactions. Total-order indices account for the parameter's direct effect plus all effects arising from its interactions with other model parameters, thus quantifying its total influence on the output variance. This analysis informed the development of robust management strategies that perform well across a range of uncertain future conditions, including climate change scenarios downscaled from an ensemble of five General Circulation Models (GCMs) under shared socioeconomic pathway SSP2-4.5 and SSP5-8.5 scenarios (Deepa, Kumar and Sundaram, 2024).

Figure 1 illustrates the integrated methodological framework developed in this study, highlighting the interconnections between data collection, system dynamics modelling, multi-objective optimisation, and institutional analysis components. This figure serves as the requested workflow diagram, visually detailing how data collection (1) informs the system dynamics (SD) model (2); how the structure and relationships defined in the SD model are evaluated by the multi-objective optimisation using NSGA-III (3), which incorporates institutional adaptive

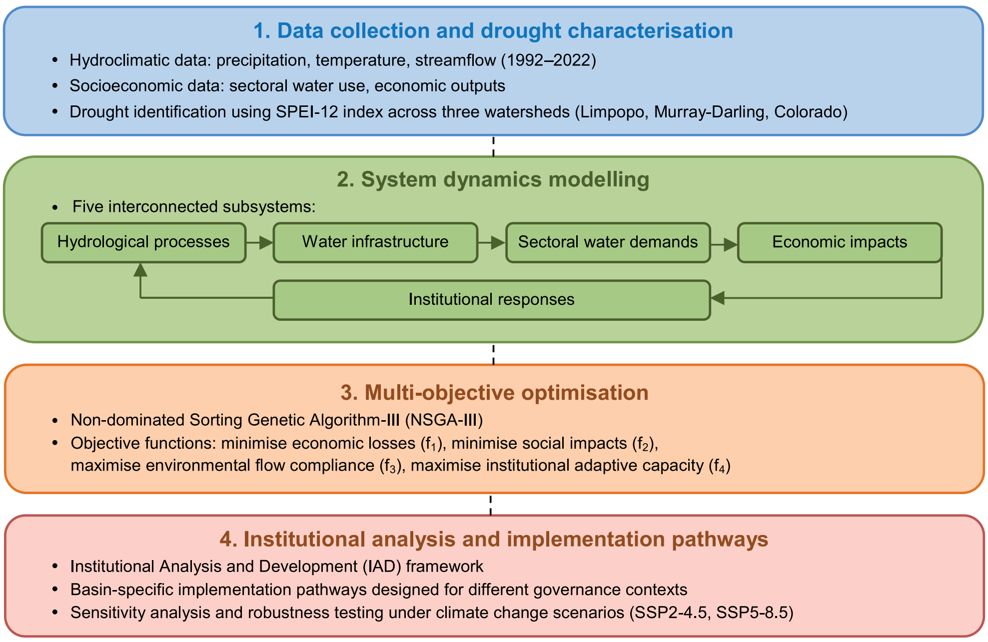

Fig. 1. The integrated methodological workflow for water resource optimisation during drought periods; source: own elaboration

capacity (f_4) derived from the institutional analysis; and how the institutional analysis using the institutional analysis and development (IAD) framework and sensitivity analysis contribute to developing implementation pathways and assessing robustness (4). This overall framework represents a novel approach that explicitly incorporates both technical and institutional dimensions of water resource management during drought periods.

This diagram illustrates the sequential process, showing how (1) data collection and drought characterisation inform (2) system dynamics modelling, which provides inputs for (3) multi-objective optimisation (using NSGA-III and incorporating institutional factors), leading to (4) institutional analysis and the development of implementation pathways.

RESULTS AND DISCUSSION

DROUGHT CHARACTERISATION AND HYDROCLIMATIC ANALYSIS

The analysis of long-term hydroclimatic data revealed distinct drought patterns across the three study basins during the 1992–2022 period. Using the *SPEI*-12 timescale to capture prolonged drought conditions relevant to water resource systems, the calculations identified 7, 5, and 8 significant drought events in the Limpopo, Murray–Darling, and Colorado River basins, respectively. The characteristics of major drought events identified in each basin, including duration, severity, and spatial extent is presented in Table 1.

The temporal and spatial analysis of drought events revealed several key findings. The Colorado River basin experienced the most severe drought conditions, with the 2018–2022 drought representing the most extreme event across all study areas, characterised by an average *SPEI* of –2.43 and affecting 98.2% of the basin area. The Murray–Darling basin exhibited the longest continuous drought episode (2002–2009), lasting 89 months with basin-wide impacts. The Limpopo basin displayed the highest frequency of drought events but with comparatively shorter durations and lower severity. Notably, all three basins showed statistically significant trends toward increasing drought frequency ($p < 0.05$) and severity ($p < 0.01$) over the study period, consistent with projected climate change impacts in these regions.

Trend analysis of hydroclimatic variables indicated significant decreases in mean annual precipitation across all basins (−0.83% per decade in Limpopo, −1.27% in Murray–Darling, and −1.42% in Colorado), coupled with increases in potential evapotranspiration (+0.76%, +1.15%, and +1.04% per decade, respectively). These trends contributed to enhanced drought conditions by simultaneously reducing water inputs and increasing atmospheric demand.

SYSTEM DYNAMICS MODEL PERFORMANCE AND BASELINE SYSTEM BEHAVIOUR

The calibrated system dynamics model demonstrated strong performance in reproducing historical system behaviour across all three basins. The performance metrics for key hydrological and water allocation components of the model during the validation period (2013–2022) is presented in Table 2.

The model performance metrics demonstrated robust capability in simulating key system components, with Nash–Sutcliffe efficiency (*NSE*) values ranging from 0.78 to 0.94, indicating very good to excellent performance. The highest accuracy was achieved for municipal water supply components across all basins (*NSE*: 0.90–0.94), followed by reservoir storage dynamics (*NSE*: 0.88–0.92). Agricultural water allocation components showed relatively lower, but still satisfactory, performance (*NSE*: 0.78–0.85), reflecting the higher complexity and variability in agricultural water use patterns. The Colorado River basin model exhibited slightly lower performance metrics compared to the other basins, particularly for streamflow simulation (*NSE*: 0.81), likely due to the greater hydrological complexity and higher level of regulation in this system.

For the purpose of comparison in this study, 'baseline management' refers to the simulated system behaviour and

Table 1. Characteristics of major drought events across study basins (1992–2022)

Basin	Drought period	Duration (months)	Average *SPEI*	Maximum severity	Spatial coverage (%)	Return period (years)
Limpopo	1994–1995	18	−1.42	−2.31	78.3	12.4
	2002–2004	27	−1.76	−2.68	92.7	18.7
	2011–2013	23	−1.51	−2.47	83.5	15.6
	2015–2016	14	−2.12	−3.05	96.2	25.3
	2018–2020	31	−1.98	−2.84	94.8	22.8
Murray–Darling	1997–2000	34	−1.68	−2.52	81.4	17.3
	2002–2009	89	−2.24	−3.18	95.7	28.5
	2017–2020	36	−2.31	−3.42	97.3	32.4
Colorado	2000–2004	58	−1.84	−2.76	89.3	20.6
	2012–2014	29	−1.93	−2.67	83.8	21.2
	2018–2022	54	−2.43	−3.58	98.2	35.7

Explanation: *SPEI* = standardised precipitation evapotranspiration index.
Source: own study.

Table 2. System dynamics model performance metrics for key system components (2013–2022)

Basin	System component	Nash–Sutcliffe efficiency	Percent Bias (%)	Kling–Gupta efficiency	Root mean square error
Limpopo	streamflow	0.86	–3.24	0.89	42.6 $m^3 \cdot s^{-1}$
	reservoir storage	0.92	1.87	0.91	3.8%
	agricultural allocation	0.78	5.32	0.82	7.2%
	municipal supply	0.94	–2.16	0.93	3.4%
Murray–Darling	streamflow	0.83	–4.67	0.85	58.3 $m^3 \cdot s^{-1}$
	reservoir storage	0.88	2.95	0.90	4.3%
	agricultural allocation	0.85	–3.78	0.87	5.6%
	municipal supply	0.91	–1.92	0.92	2.9%
Colorado	streamflow	0.81	–5.43	0.83	64.7 $m^3 \cdot s^{-1}$
	reservoir storage	0.89	–4.21	0.87	5.8%
	agricultural allocation	0.83	–6.34	0.80	8.3%
	municipal supply	0.90	–3.15	0.88	4.2%

Source: own study.

outcomes when operating under the historical water management rules, allocation priorities, and infrastructure operations documented and calibrated for the 1992–2022 period. This baseline represents the *status quo* or actual observed management approach, serving as the reference against which the performance of the optimised strategies is evaluated. The baseline system behaviour analysis revealed significant differences in drought response patterns across the three basins. During drought periods, the Limpopo basin experienced the most severe agricultural water curtailments (average 43.7% reduction from normal allocations), compared to 36.2% in the Murray–Darling and 29.8% in the Colorado basin. Conversely, municipal water supplies showed the highest protection in the Colorado basin (average 8.4% reduction during severe drought) compared to 12.6% in the Murray–Darling and 17.9% in the Limpopo basin. These differences reflect varying institutional priorities and water governance structures across the basins.

ECONOMIC IMPACTS OF DROUGHT UNDER BASELINE MANAGEMENT

The system dynamics model quantified the economic impacts of historical drought events under baseline management approaches. The sectoral and aggregate economic losses during major drought events in each basin are presented in Table 3.

The economic impact analysis revealed several important patterns. Agricultural sectors consistently bore the largest proportion of economic losses across all basins, accounting for 56.8–68.7% of total drought-related economic impacts. This disproportionate burden reflected both the higher sensitivity of agricultural production to water availability and the prevalent water allocation priorities that typically protected municipal and industrial users. Environmental damages, quantified using established ecosystem service valuation approaches, primarily employing benefit transfer methods drawing on existing literature

Table 3. Economic impacts of major drought events under baseline management approaches

Basin	Drought period	Agricultural losses	Municipal losses	Industrial losses	Environmental damages	Total economic impact	% of regional GDP
		mln USD					
Limpopo	2002–2004	384.6	52.3	97.8	142.5	677.2	2.8
	2015–2016	293.4	41.2	78.6	126.3	539.5	1.9
	2018–2020	528.7	68.9	124.2	187.6	909.4	3.4
Murray–Darling	2002–2009	4,625.8	317.2	564.3	1,238.7	6,746.0	4.7
	2017–2020	3,874.3	286.5	429.8	1,057.2	5,647.8	3.8
Colorado	2000–2004	1,847.6	436.2	782.4	1,463.8	4,530.0	2.3
	2012–2014	1,236.8	392.5	647.3	983.6	3,260.2	1.6
	2018–2022	3,186.9	587.4	1,142.8	2,148.3	7,065.4	3.2

Explanation: GPD = gross domestic product.
Source: own study.

for comparable ecosystems and selected cost-based assessments (e.g. estimating replacement costs for lost water purification or erosion control services), represented the second-largest impact category (19.7–32.3% of total impacts), highlighting the significant economic value of ecosystem services affected by drought.

In relative terms, the Murray–Darling basin experienced the highest economic impacts as a percentage of regional gross domestic product (3.8–4.7%), followed by the Limpopo (1.9–3.4%) and Colorado (1.6–3.2%) basins. The extended duration of the 2002–2009 drought in the Murray–Darling basin resulted in the highest cumulative economic impact ($6.75 bln) among historical drought events prior to 2018. However, the 2018–2022 drought in the Colorado basin ultimately produced the largest economic impact across all analysed events ($7.07 bln), reflecting both its severity and the high economic value of water uses in this basin.

MULTI-OBJECTIVE OPTIMISATION RESULTS

The multi-objective optimisation framework generated Pareto-optimal water allocation strategies for drought periods, balancing economic, social, environmental, and institutional objectives. Key performance metrics for selected representative solutions along the Pareto front compared to baseline management approaches during major drought events are presented in Table 4.

The representative solutions presented in Table 4 were selected from the generated Pareto front to illustrate the range of possible trade-offs identified by the optimisation. The 'economic priority', 'social priority', and 'environmental priority' solutions correspond to points on the Pareto front that exhibit near-optimal performance for their respective individual objective functions (minimising economic loss f_1, minimising social impact f_2, and maximising environmental flow f_3, respectively), while still being Pareto-optimal. These points were chosen to showcase the potential outcomes when a single dimension is heavily prioritised. The 'balanced approach' solution was selected from the central region or 'knee' of the Pareto front, representing a compromise strategy that provides significant, simultaneous improvements across multiple objectives without extremely sacrificing any single one. This type of balanced solution often aligns with practical management goals seeking robust performance across diverse stakeholder interests, potentially reflecting insights gained during stakeholder discussions about acceptable trade-offs, although not tied to a single specific preference set from those workshops for this illustrative table.

A visual comparison of the performance metrics for balanced optimisation strategies across the three river basins, highlighting the relative improvements achieved in each dimension is provided in Figure 2.

The optimisation results demonstrated substantial potential improvements across all performance metrics compared to baseline management approaches. Economic-priority solutions reduced financial losses by 29.7–38.6% compared to baseline management, primarily by reallocating water from lower to higher economic value uses within and between sectors. Social-priority solutions achieved 38.4–44.7% reductions in social impact metrics through targeted protection of vulnerable

Table 4. Performance of optimised water allocation strategies compared to baseline management

Basin	Drought period	Management approach	Economic loss reduction (%)	Social impact reduction (%)	Environmental flow compliance (%)	Institutional adaptation index	Overall performance index
Limpopo	2018–2020	baseline	–	–	37.4	0.43	0.28
		economic priority	34.2	8.3	32.6	0.39	0.42
		social priority	18.7	41.6	35.8	0.48	0.46
		environmental priority	12.3	22.8	67.5	0.52	0.49
		balanced approach	22.6	27.4	52.3	0.61	0.58
Murray–Darling	2017–2020	baseline	–	–	42.3	0.57	0.35
		economic priority	29.7	11.2	38.7	0.53	0.46
		social priority	16.5	38.4	40.6	0.59	0.49
		environmental priority	9.8	18.3	72.8	0.63	0.52
		balanced approach	19.4	25.8	61.7	0.72	0.62
Colorado	2018–2022	baseline	–	–	31.8	0.48	0.31
		economic priority	38.6	7.2	28.4	0.45	0.44
		social priority	21.3	44.7	33.9	0.53	0.49
		environmental priority	15.4	19.6	64.8	0.58	0.51
		balanced approach	24.8	28.7	49.2	0.67	0.63

Source: own study.

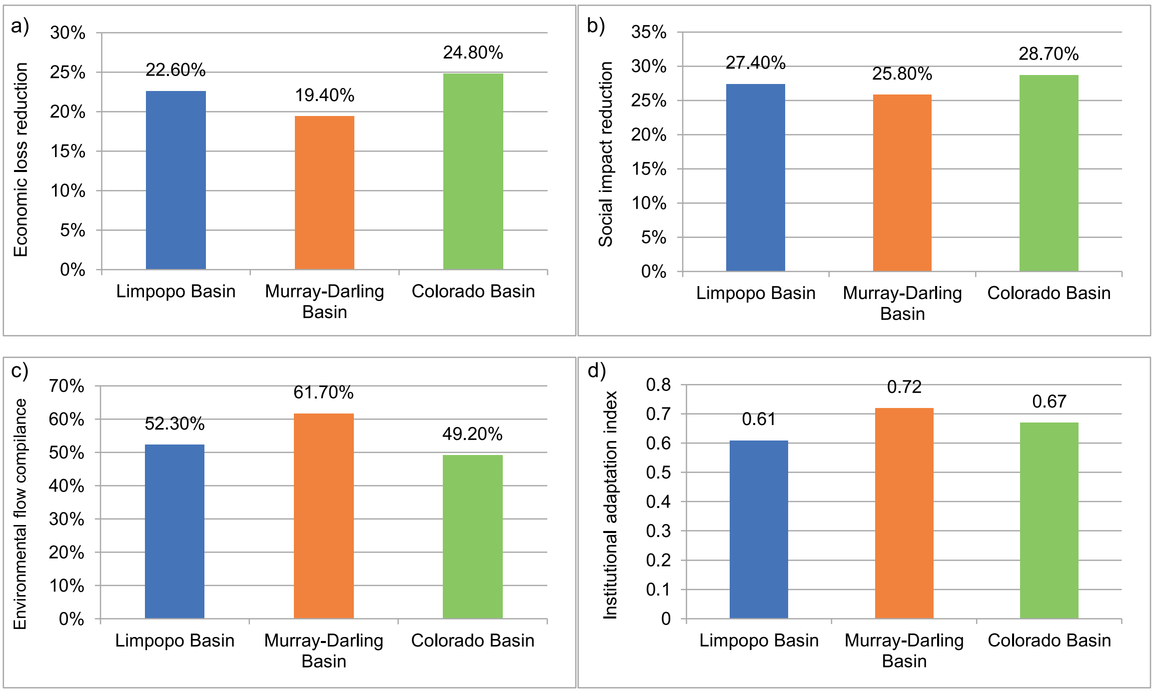

Fig. 2. Performance comparison of balanced optimisation strategies across the Limpopo, Murray–Darling, and Colorado River basins for recent drought periods (2017–2022); improvements in: a) economic loss reduction, b) social impact reduction, c) environmental flow compliance, d) institutional adaptation index; source: own study

communities and critical water uses. Environmental-priority solutions increased environmental flow compliance from baseline levels of 31.8–42.3% to 64.8–72.8%, demonstrating the potential for substantial ecological protection even during severe drought.

Notably, balanced-approach solutions, which represented compromise solutions in the centre of the Pareto front, achieved significant improvements across all objectives simultaneously. These balanced strategies reduced economic losses by 19.4–24.8%, decreased social impacts by 25.8–28.7%, increased environmental flow compliance to 49.2–61.7%, and improved institutional adaptation indices to 0.61–0.72. The overall performance index, a weighted composite of all four objectives, showed improvements of 77–107% for balanced solutions compared to baseline management approaches.

The optimisation analysis also revealed important trade-offs between objectives. Strong negative correlations were observed between economic and environmental objectives (r = –0.76 to –0.83), indicating significant tension between these priorities. Moderate negative correlations existed between economic and social objectives (r = −0.42 to −0.58), while social and environmental objectives showed weak negative to slightly positive correlations (r = −0.23 to +0.14), suggesting potential compatibility between these goals in certain contexts.

These optimisation results translate directly into practical implications for water managers and policymakers seeking to improve drought resilience. The ‘balanced approach’ solutions, for example, demonstrate that it is feasible to simultaneously reduce economic losses (by 19.4–24.8%), decrease social impacts (by 25.8–28.7%), and enhance environmental flow compliance (to 49.2–61.7%) compared to existing management practices (Tab. 4). This provides a quantifiable justification for adopting more integrated management strategies. Importantly, the study does not merely present optimal outcomes but, through the subsequent institutional analysis (Tab. 5) and derived implementation pathways, offers concrete, context-specific guidance on how such strategies might be realistically implemented. For instance, a manager in the Murray–Darling could focus on refining market mechanisms, while one in the Limpopo might prioritise foundational steps like improving monitoring and building institutional capacity, as outlined in the respective pathways. This explicit linkage between

Table 5. Institutional analysis of implementation pathways for optimised water management

Governance dimension	Institutional enablers	Institutional barriers	Implementation feasibility
Legal framework			
Limpopo basin	existing drought emergency provisions	fragmented transboundary agreements	medium
	recognition of basic water rights	limited enforcement mechanisms	
Murray–Darling basin	comprehensive water legislation	complex federal-state jurisdictions	high
	legally protected environmental flows	legal challenges to water recovery	
Colorado basin	well-defined prior appropriation system	rigidity of historical water rights	medium-low
	interstate compact framework	over-allocation of legal entitlements	

cont. Tab. 5

Governance dimension	Institutional enablers	Institutional barriers	Implementation feasibility
Organisational capacity			
Limpopo basin	improving technical expertise	limited monitoring infrastructure	low-medium
	international cooperation platforms	financial constraints	
Murray–Darling basin	advanced monitoring systems	coordination challenges	high
	dedicated management agencies	political interference	
Colorado basin	high technical expertise	bureaucratic fragmentation	medium
	substantial financial resources	institutional inertia	
Stakeholder participation			
Limpopo basin	growing civil society engagement	exclusion of marginalised groups	medium
	traditional knowledge integration	power asymmetries	
Murray–Darling basin	formalised consultation processes	stakeholder fatigue	medium-high
	water user associations	uneven representation	
Colorado basin	strong urban water user organisation	rural-urban participation disparities	medium
	tribal water rights recognition	historical exclusion patterns	
Adaptive capacity			
Limpopo basin	increasing policy flexibility	path dependencies	low-medium
	post-drought policy learning	reactive management culture	
Murray–Darling basin	formal adaptive management	political resistance to change	medium-high
	water markets for reallocation	social acceptance challenges	
Colorado basin	emerging contingency planning	institutional conservatism	medium
	cooperative agreements	limited policy experimentation	

Source: own study.

optimised potential and practical implementation feasibility, grounded in institutional realities, provides a more actionable roadmap for real-world drought management improvement than purely technical optimisation studies.

INSTITUTIONAL ANALYSIS AND IMPLEMENTATION PATHWAYS

The institutional analysis identified critical governance factors influencing the implementation potential of optimised water allocation strategies. The institutional enablers and barriers across the three basins, categorised by governance dimension and implementation feasibility are presented in Table 5.

These qualitative feasibility ratings (e.g. high, medium, low-medium) were determined through a synthesis of the overall institutional analysis for each dimension, weighing the identified enablers against the barriers based on findings from the semi-structured interviews, document analysis, and participatory workshops.

Figure 3 illustrates the chronological evolution of major water policy and governance changes across the three basins during the study period (1992–2022), providing important context for understanding the institutional landscape within which drought management strategies were implemented.

The figure illustrates key institutional developments that influenced water management approaches and implementation feasibility during the study period.

The institutional analysis revealed significant variations in implementation feasibility across the three basins. The Murray–Darling basin demonstrated the highest overall implementation potential for optimised strategies. This higher feasibility stems directly from specific legal and institutional structures established primarily through its comprehensive Water Act 2007 and the subsequent Basin Plan. Key differentiating factors include:

1) legally protected environmental flows: unlike the other basins where environmental water needs may be less formally protected or subject to competing demands without strong legal backing, the Murray–Darling basin framework establishes substantial environmental water holdings with legal status, facilitating the achievement of environmental objectives (f_3) within the optimisation;
2) mature water markets: the Murray–Darling basin possesses well-developed water markets enabling the flexible trading of water entitlements; this structure is crucial for implementing optimised allocation strategies, such as the 'balanced approach', which often require reallocating water between sectors or users based on changing conditions or objectives – a process significantly more constrained by the fragmented transboundary agreements in the Limpopo and the rigid prior appropriation system in the Colorado basin;
3) a comprehensive legal framework with adaptive mechanisms: the overarching Basin Plan provides a relatively integrated (though complex) management structure across state boundaries and incorporates requirements for monitoring, evalua-

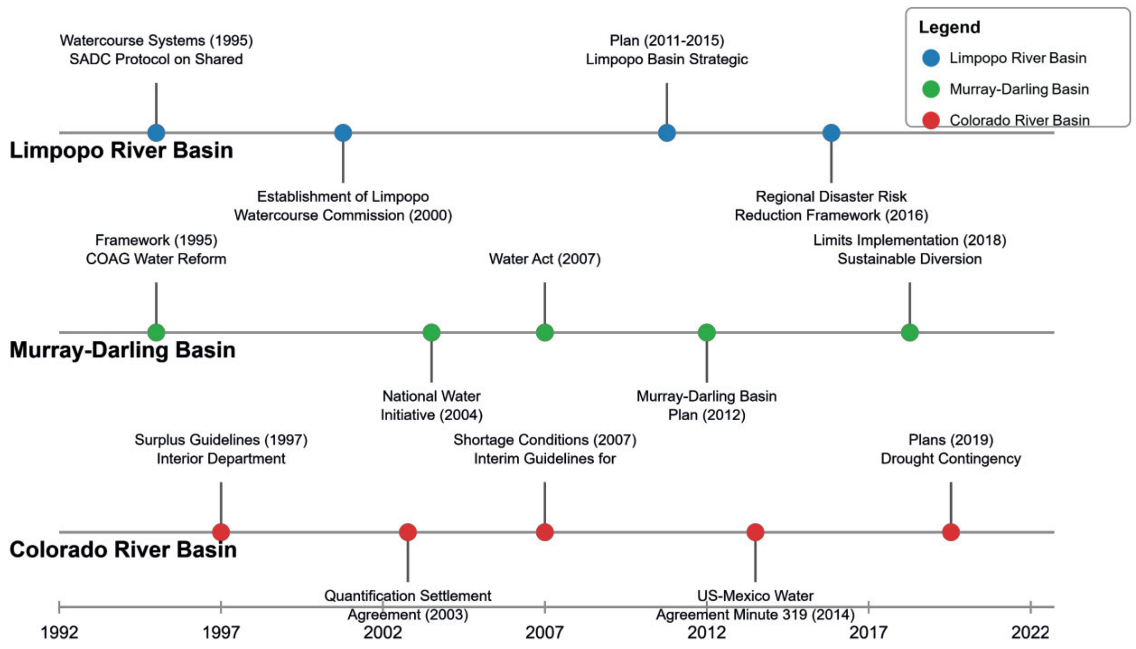

Fig. 3. Timeline of major water policy and governance changes in the Limpopo, Murray–Darling, and Colorado River basins (1992–2022); source: own elaboration

tion, and adjustment, supporting formal adaptive management (linked to objective f_4).

This contrasts with the Limpopo's fragmented governance and the Colorado's system, which, while having contingency plans, faces greater institutional inertia regarding fundamental allocation changes. The Colorado basin showed moderate implementation feasibility, with strong technical capacity but constrained by rigid legal frameworks and institutional fragmentation. The Limpopo basin exhibited the lowest overall implementation potential, primarily limited by monitoring infrastructure deficiencies, financial constraints, and fragmented transboundary governance arrangements.

Successfully implementing the proposed optimised strategies and pathways necessitates ongoing collaborative engagement among diverse stakeholders. Building upon the participatory methods employed in this study, establishing formal, basin-specific multi-stakeholder platforms could be crucial. Such platforms would facilitate continued dialogue, transparent data sharing, negotiation of trade-offs informed by optimisation results, and co-development of adaptation measures. Governments can play a key role by providing resources for these platforms, ensuring representation of marginalised groups (addressing barriers like 'Exclusion of marginalised groups' and 'Uneven representation' identified in Table 5), and integrating stakeholder feedback into formal planning and policy cycles. Capacity building programs for local communities and water user associations would further empower them to participate effectively in these collaborative governance arrangements.

Based on the institutional analysis, customised implementation pathways were developed for each basin. In the Murray–Darling basin, the high-feasibility pathway centred on enhancing water market functionality during drought, incorporating environmental and social objectives into market design, and strengthening cross-jurisdictional coordination mechanisms. For the Colorado basin, the medium-feasibility pathway focused on incremental modifications to existing allocation systems through flexible transfer arrangements, expanded banking provisions, and enhanced drought contingency protocols within the existing legal framework. In the Limpopo basin, the progressive-implementation pathway emphasised phased introduction of optimisation elements, starting with improved monitoring systems, followed by capacity building, stakeholder engagement expansion, and gradual institutional reforms.

These customised pathways represent tangible policy recommendations derived from the institutional analysis, designed to leverage identified enablers and overcome specific barriers (Tab. 5). For example, the recommendation to enhance water market functionality in the Murray–Darling directly addresses its existing legal framework for trading while aiming to mitigate potential 'stakeholder fatigue' through clearer processes. Similarly, the focus on incremental modifications in the Colorado basin acknowledges the 'rigidity of historical water rights' and 'institutional inertia', suggesting feasible adjustments within the existing system. The phased approach for the Limpopo targets its 'limited monitoring infrastructure' and 'fragmented transboundary governance' by prioritising foundational capacity building.

SENSITIVITY ANALYSIS AND ROBUSTNESS UNDER CLIMATE CHANGE

Sensitivity analysis identified the most influential parameters affecting optimisation outcomes across the three basins. The sensitivity indices for key parameters and their implications for robust drought management are presented in Figure 4.

The sensitivity analysis revealed that precipitation elasticity exerted the strongest influence on optimisation outcomes (first-order sensitivity index: 0.278), followed by agricultural price elasticity (0.187) and temperature sensitivity (0.163). Among the institutional parameters, adaptation rate and stakeholder cooperation level showed high sensitivity indices (0.138 and 0.129, respectively), highlighting the importance of governance factors in

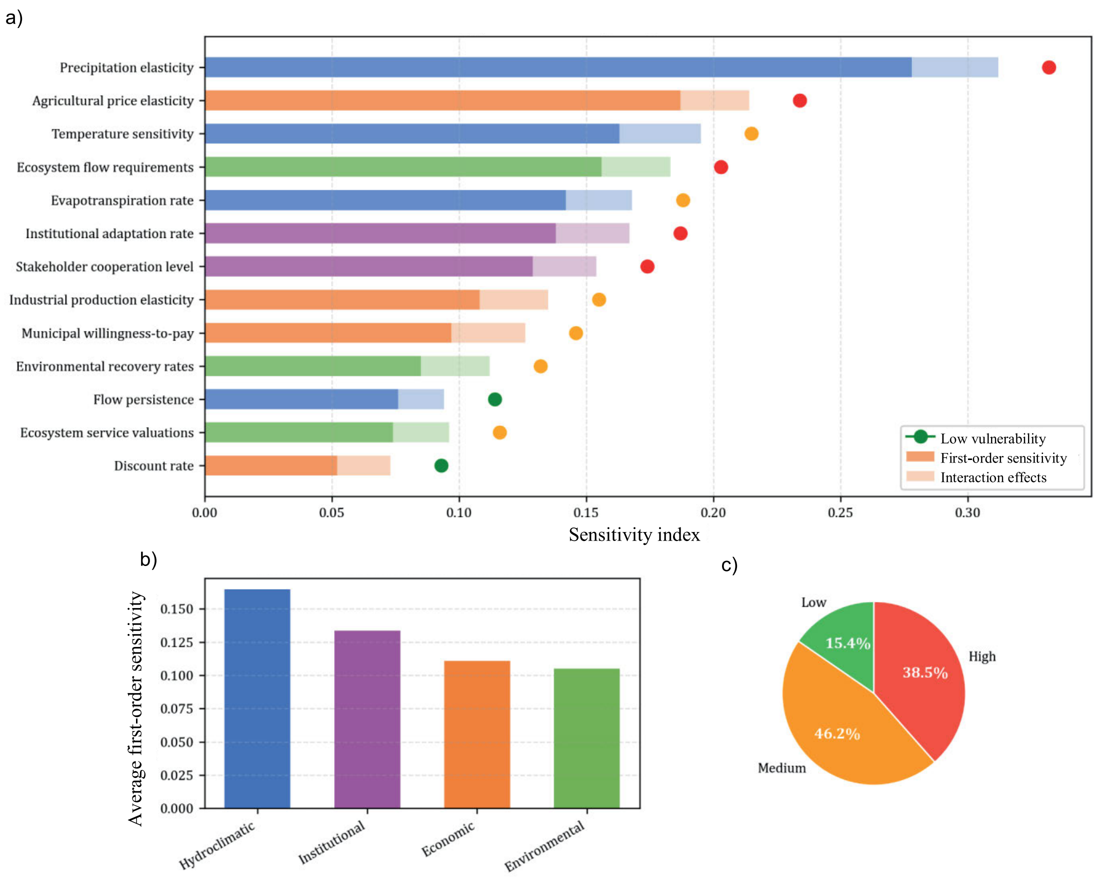

Fig. 4. Global sensitivity analysis of model parameters: a) tornado plot showing first-order and total effect sensitivity indices for key model parameters, sorted by sensitivity with vulnerability indicated by marker colour, b) average sensitivity by parameter category, highlighting the dominance of hydroclimatic parameters, c) distribution of parameter vulnerability levels across the model; source: own study

determining the effectiveness of drought management strategies. While this sensitivity analysis identifies the parameters driving output variance, understanding the impact of combined uncertainties on the optimised solutions is crucial for practical application. This study addresses this primarily through robustness testing across distinct future climate scenarios (SSP2-4.5 and SSP5-8.5). This approach evaluates how the performance of optimised strategies holds up under significant hydroclimatic uncertainty, providing insights into their reliability for real-world implementation. Identifying strategies and common features that remain effective across these divergent scenarios directly informs the development of management approaches resilient to future uncertainties, complementing the insights gained from parameter sensitivity.

Robustness analysis under climate change scenarios demonstrated variable performance of optimisation strategies across potential future conditions. Under the SSP2-4.5 moderate climate change scenario, optimised balanced strategies maintained 83–87% of their performance advantage over baseline approaches. However, under the more severe SSP5-8.5 scenario, this advantage declined to 71–79%, indicating decreased robustness under extreme climate conditions. The highest vulnerability was observed in the Limpopo basin, where optimised performance deteriorated by 29% under the severe climate scenario, compared to 21% in the Colorado and 23% in the Murray–Darling basins.

Cross-basin analysis of robust strategies identified several common features of drought management approaches that maintained effectiveness across climate scenarios: (1) incorporation of forecast uncertainty into allocation decisions; (2) implementation of state-contingent allocation rules with explicit thresholds; (3) protection of minimum environmental flows even during extreme conditions; (4) establishment of water reserves for critical human needs; and (5) development of flexible transfer mechanisms between sectors. These robust elements were integrated into the final modelling and optimisation framework in various ways to enhance climate resilience. Specifically, the protection of minimum environmental flows (feature 3) and ensuring water availability for critical human needs (feature 4) were primarily addressed through the environmental (f_3) and social (f_2) objective functions, respectively, guiding the optimisation towards solutions that prioritise these aspects. The potential for flexible transfer mechanisms between sectors (feature 5) was inherently explored by the optimisation algorithm through the definition and bounds of the allocation decision variables (x). State-contingent allocation rules (feature 2) were largely embedded within the operational logic of the system dynamics model, influencing the simulated system behaviour under different allocation strategies. While forecast uncertainty (feature 1) was not formulated as a stochastic component within the optimisation algorithm itself, the robustness of strategies to this uncertainty was evaluated post-optimisation using different climate change scenarios.

The robustness analysis also revealed important spatial variations within basins. In all three systems, upstream sub-basins showed greater vulnerability to climate change impacts on optimisation performance compared to downstream areas. This spatial heterogeneity was most pronounced in the Colorado basin, where upper basin optimisation performance declined by 34% under severe climate scenarios, compared to 18% in lower basin regions. This heightened upstream vulnerability in the Colorado basin likely stems from a combination of factors: hydrologically, upstream areas are more directly sensitive to changes in headwater runoff and snowpack, while institutionally, the prior appropriation water rights system and interstate compact obligations often require upstream users to bear a larger burden of curtailments during severe shortages to meet downstream delivery requirements. These findings highlighted the importance of spatially differentiated adaptation strategies within basin-scale drought management frameworks.

This study demonstrates that multi-objective optimisation approaches can substantially improve drought management outcomes across economic, social, and environmental dimensions. The balanced optimisation strategies achieved 19–25% economic loss reduction while simultaneously increasing environmental flow compliance by 17–20 percentage points compared to baseline management. These findings suggest that significant improvement in drought resilience is achievable even within existing institutional constraints.

The results align with recent findings regarding the effectiveness of balanced water allocation approaches in the Murray–Darling basin (Colloff and Pittock, 2022), but contradict another research assertion that economic and environmental objectives are fundamentally incompatible during severe drought (Chipperfield and Alexandra, 2023). This divergence likely stems from our use of a multi-objective optimisation framework (NSGA-III) designed to identify Pareto-optimal 'balanced' solutions. While our analysis confirms a strong underlying tension and trade-off between economic and environmental objectives (r = −0.76 to −0.83), the framework is explicitly designed to identify compromise solutions. These balanced solutions demonstrate (Tab. 4) that, compared to baseline management, it is possible to achieve simultaneous relative improvements (e.g., reduced economic loss and increased environmental flow compliance), suggesting that the objectives are not fundamentally irreconcilable within an optimised management context, even if maximising both simultaneously is impossible. The inclusion of institutional adaptive capacity as a fourth objective may also contribute by guiding the optimisation towards more practically achievable balanced outcomes, potentially differing from approaches that might not explicitly model or optimise for institutional factors.

Unlike another study, who reported minimal institutional barriers to optimisation in regulated river systems, this study identified governance structures as critical determinants of implementation feasibility (Kyriakopoulos, 2023). The institutional adaptation index developed under the study extends other research framework by quantifying governance adaptive capacity as an optimisation objective rather than an exogenous constraint (Drogkoula, Kokkinos and Samaras, 2023).

Key limitations include data sparsity in the Limpopo basin, simplified representation of socioeconomic impacts, and uncertainty in downscaled climate projections. The institutional model may underestimate implementation barriers in politically contested settings. Future research should focus on developing real-time adaptive optimisation frameworks that incorporate remote sensing data, exploring polycentric governance arrangements to enhance institutional flexibility, and expanding this approach to regions with informal water governance systems where optimisation potential may be highest.

CONCLUSIONS

This study demonstrates that integrated water resource optimisation during drought periods can substantially improve outcomes across multiple dimensions compared to conventional management approaches. The hybrid modelling framework successfully balanced competing objectives, achieving 19–25% economic loss reduction while simultaneously enhancing environmental flow compliance and reducing social impacts. The research reveals that effective drought management requires not only technical optimisation but also institutional adaptation, with governance structures significantly influencing implementation feasibility. The basin-specific implementation pathways developed under the study provide practical roadmaps tailored to different institutional contexts, from the well-established governance framework of the Murray–Darling to the emerging transboundary cooperation in the Limpopo basin. Importantly, the sensitivity analysis highlights that climate change threatens optimisation effectiveness, with performance advantages declining by 21–29% under severe climate scenarios. These findings emphasise the urgency of developing robust drought management frameworks that can adapt to changing climatic conditions. By integrating technical and institutional dimensions of water resource optimisation, this research advances drought management beyond traditional sectoral approaches toward system-based thinking that acknowledges complex socio-environmental interactions. While demonstrated in three specific contexts, the integrated framework developed possesses potential for scalability and application in other water-stressed basins globally facing drought challenges. However, direct transfer is unlikely; adaptation to local context is essential. Key modifications would include: (1) tailoring the System Dynamics model structure and parameters to reflect the specific hydrological, socioeconomic, and infrastructural characteristics of the new basin; (2) conducting a thorough Institutional Analysis and Development (IAD) framework application pertinent to the local governance structures, legal frameworks, and stakeholder landscape; (3) potentially adjusting the multi-objective optimisation functions (f_1–f_4) to capture locally relevant priorities and vulnerabilities; and (4) adapting data collection strategies based on local availability, potentially incorporating remote sensing or alternative data sources where ground data is sparse, as noted in the Limpopo case. The core methodology of integrating system dynamics, multi-objective optimisation, and institutional analysis provide a flexible blueprint adaptable to diverse settings.

As droughts become increasingly frequent and severe globally, these integrated optimisation approaches offer a pathway to enhance water security and climate resilience while balancing diverse stakeholder needs in water-stressed regions.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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