A system approach for modelling key environmental and socio-economic Sustainable Development Goals (SDGs)

Abstract

The Sustainable Development Goals (SDGs) of the 2030 Agenda present a comprehensive set of environmental, social, and economic objectives for achieving sustainable development, but the complexity of analysing their interactions and spillover effects poses a challenge for their attainment. To address this, we employed a participatory model co-design process with local stakeholders to develop a system dynamics-based model, the Local Environmental and Socio-Economic Model (LESEM), for analysing and quantifying context-specific SDG interactions at the local level under a business-as-usual (BAU) scenario. Our focus was on quantifying the interactions among four high-priority SDGs in a case study in the north of Victoria, Australia, namely clean water and sanitation (SDG 6), agricultural activities (SDG 2), economic growth (SDG 8), and life on land (SDG 15). Our results suggest that agricultural lands are likely to decrease due to declining water resources under the BAU scenario, but agricultural production may still expand through agricultural intensification. However, agricultural intensification could help meet future food demand and lead to increased agri-food production, which could benefit the local economy. In other hand, this could lead to increased environmental threats due to the intensification process and reduced water availability. The LESEM enables policymakers to make holistic decisions and identify potential trade-offs and synergies that benefit other SDGs, ultimately promoting sustainability in local communities.

1 Methodology

1.1 Overview

The methods included four steps (Figure 1). In Step 1 we identified the socio-economic and environmental issues of high priority to local stakeholders in terms of the SDGs using a comprehensive contextual analysis involving interviews with local stakeholders, scientific papers and reports, and policy documents which has been fully described in Bandari et al. (2022). Also part of Step 1 we conducted a participatory process of problem identification to articulate the local challenges and construct theories of how the problems arose (i.e., dynamic hypotheses) via a workshop with a subcommittee of Goulburn Murray Resilience Taskforce. After delineating the system boundaries through problem identification and constructing dynamic hypotheses, we developed the LESEM system dynamics model of the GMID (Step 2). A second workshop was also run in Step 2 incorporating a participatory model development process to confirm model structure and identify and quantify important interactions with local stakeholders. In Step 3 we ran the model, identified those parameters which most strongly influence model behaviour, and validated its performance. Finally, in Step 4 we parameterised the model based on Business-As-Usual (BAU) and ran the model under these assumptions.

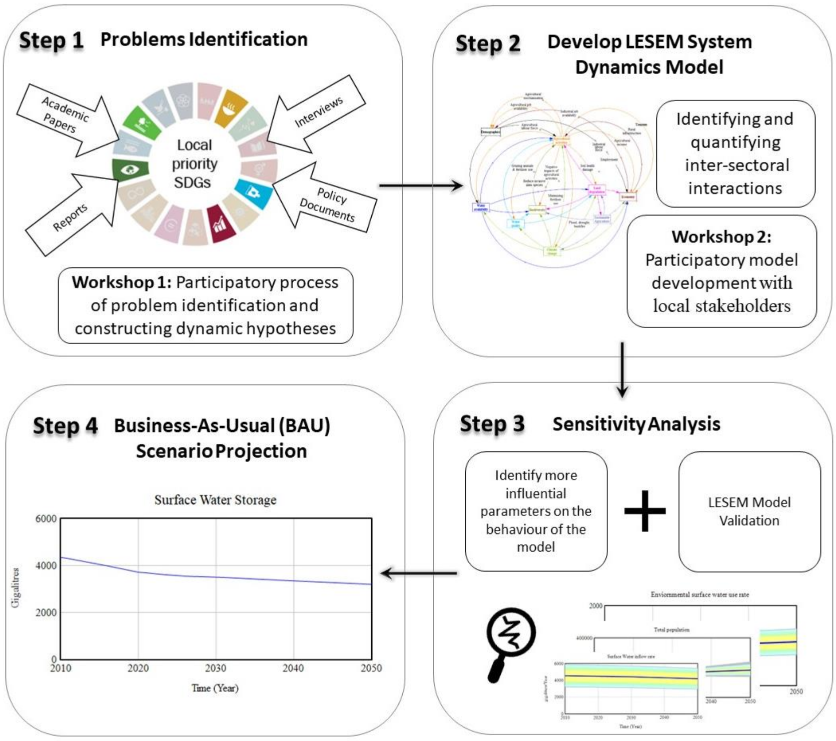

Figure 1. Conceptual schema of the LESEM participatory systems dynamics model-building process presented in this paper.

1.2 Study area

The Goulburn Murray Irrigation District (GMID) stretches from Cohuna in the west to Cobram in the east (Figure 2), with an area of 27,000 square kilometres in northern Victoria, and supports a population of 170,000 people (RMCG 2019). It includes six local government areas of Moira, Greater Shepparton, Loddon, Campaspe, Gannawarra, and Swan Hill (GMIDWL 2018). The GMID is a strategic agricultural area comprising 15,000 properties (RMCG 2019), with extensive areas of horticulture, dairy, mixed cropping and grazing, and agricultural activities are an essential part of the economy (Pearson et al. 2013). The GMID has faced of major drivers of change such as climate change, water availability, global market, technological change, water policy reforms, and market access (RPG 2020). Over the last twenty years, available water has declined by almost 50% (Bandari et al. 2022) due to the effects of climate change, water recovery plan, and competition for water from outside the GMID (RPG 2020).

Declining in water resources could be a threat to the agricultural activities and economy of the region (Bandari et al. 2022). While the region is dominated by the agricultural activities, the ageing and declining populations are other factors that affected agricultural activities of the GMID and could threaten future food production and wellbeing of the region (GBCMA 2013; RPG 2020). Furthermore, this region already has experienced environmental pressures like reduced water quality and salinity due to a combination of climate change and agricultural activities (Aither 2019). The region comprises a complex dynamic system with many interacting elements (e.g., climate, global markets, water availability, technology, agriculture, environmental issues, livelihoods) (RPG 2020). The GMID is changing faster and using the system dynamics modelling approach well suited to these uncertain conditions. The SD approach helps the policymakers to respond to these changes, plan for possible futures, and create opportunities for the region.

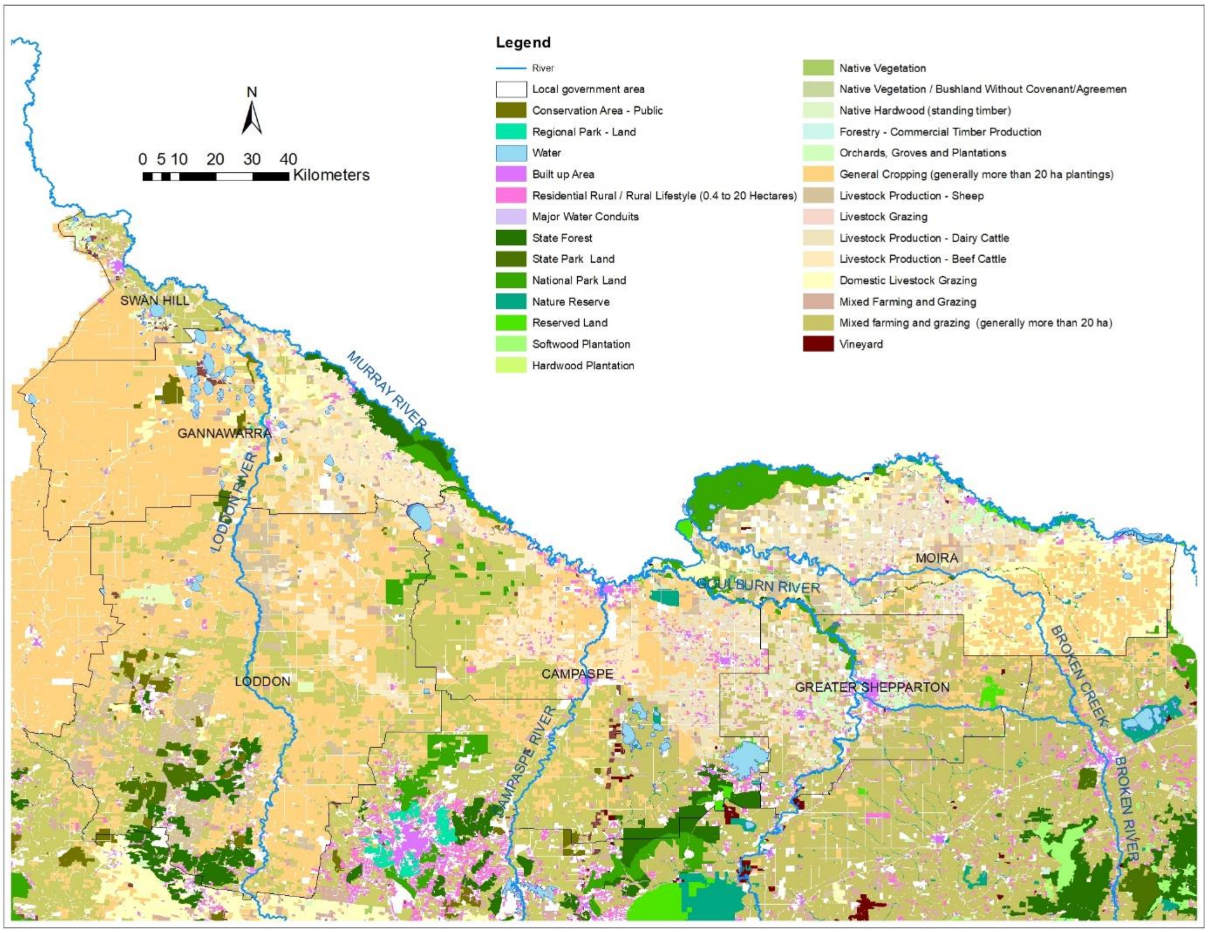

Figure 2. A map of the case study area. The Goulburn Murray Irrigation District (GMID) is specified with a black boundary. The inset map indicates the case study location in the context of the state of Victoria, Australia.

1.3 Participatory model development

System dynamics modelling is well suited for capturing multisectoral dynamics such as the complex interactions among SDGs within social-ecological systems (Chiu et al. 2019; Moallemi et al. 2021; Pedercini et al. 2020). Here, we build a system dynamics model to evaluate the main sustainability issues framed by the SDGs and their interactions, which can be a useful analytical tool throughout the policy evaluation process. The primary sources of information for defining system boundaries, including problem articulations and dynamic hypotheses included policy documents, academic papers, local sector reports, and interviews with local stakeholders which has been fully described in Bandari et al. (2022). Developing the model in consultation with local expert stakeholders has been demonstrated to be a beneficial way of elucidating complex processes in social-ecological systems (Pedercini et al. 2020). Hence, we conducted two additional face-to-face workshops with local expert stakeholders as participatory model development steps to complement the initial contextual framing.

In the first workshop, we implemented a face-to-face and hybrid participatory model-building process with a subcommittee of Goulburn Murray Resilience Taskforce, including 18 key local stakeholders from the Goulburn Broken Catchment Management Authority (GBCMA), the Victorian state government Department of Environment, Land, Water and Planning (DELWP), Agriculture Victoria, Goulburn Murray Water, Goulburn Valley Water, Regional Development Victoria, and Murray Dairy (Figure 3). We presented and shared the identified priority SDGs and local challenges to the subcommittee of Goulburn Murray Resilience Taskforce for verification, enrichment, and enhancement. To facilitate the participatory process, we displayed large posters to demonstrate the priority SDGs and their interactions. The participants were asked to edit the interactions between the identified priority SDGs by adding or deleting the interlinkages between the identified priority SDGs and write a short explanation of how they felt those SDGs were connected (Figure 33). The first workshop confirmed and determined the system boundaries, that is, the sectors within the GMID which were of most concern to the local stakeholders, how the different sectors of the GMID interact with each other, defining the main local problems, and articulate how those problems arose, and determining the contributing factors. On the basis of the first workshop, we understood causal relationships between the different sectors of model and thus developed related variables to represent those sectors align with related local problems.

We sketched out the causal relationships between the variables of each sub-model together and also with other sub-models in the form of causal loop diagrams and positive and negative feedbacks (Sterman 2002). We constructed the LESEM system dynamics model using Vensim DSS version 8.2.1 (Ventana Systems 2021). The agricultural activities, local economy, and water quality sub-models were constructed from scratch according to the local issues with the concepts and formulations extracted from different studies (GMW 2002; Navarro & Marcos Martinez 2021). In accordance with the dynamic hypotheses of the water sector and inspiration from the FeliX3 Model (Rydzak et al. 2010), the water availability sub-model was designed and adapted to the condition of the GMID and Goulburn Murray Water (Baker et al. 2018; Cummins 2016; GMW 2018a, 2018b, 2018c; Gupta & Hughes 2018; Naderi et al. 2021; Rydzak et al. 2013; Wang et al. 2021). The fertiliser use sub-model was inspired by the FeliX3 Model and changed according to the local issues and source of nutrients in the GMID (GBWQWG 1995b; Rydzak et al. 2013). The demographic sub-model was repurposed from the RUSEM Model (Navarro and Tapiador 2019), and other components like labour force and education were added to this sub-model according to the opinion of stakeholders.

On 15 July 2022, we hosted the second workshop through a face-to-face and hybrid participatory model-building process with nine attendees from the Goulburn Murray Resilience Taskforce. We presented the draft model, explained how the model works, and how components and key variables of the LESEM are connected. We then asked the participants to confirm or improve the LESEM causal relationships, using the groups' collective knowledge (Figure 3). To facilitate this process, we printed each sub-model as a separate poster and the workshop participants gave feedback on the model using posters in the room, and posters in an online Mural Board for those who were online. The participants were asked to write along those causal relationships with an explanation of how they felt those components were connected. Following that, we had a group discussion (Figure 3). Some parts of the model were improved in consultation with stakeholders to be more compatible with local problems.

Following the second workshop, causal loop diagrams were integrated and converted into a quantitative stock-and-flow systems dynamics model, and parameterised to perform simulations. The stock-and-flow systems dynamics model capture accumulations and depletions of stocks over time in response to flows throughout the system in a quantitative way based on differential equations (Gohari et al. 2017; Naderi et al. 2021). We iterated the model development process many times to improve each sub-model and their interactions to best align with the system understandings offered by local expert stakeholders.

Figure 3: Five images from the first workshop 1 (image credit: Jamie Rooney) and the second workshop (image credit: Reihaneh Bandari). Two bottom images refer to the Workshop 1 and three top images relate to the Workshop 2.

1.4 Model validation

Validation of model outputs is crucial to achieving the ultimate objectives of system dynamics modelling, which is to make better decisions and improve socio-economic and environmental outcomes by evaluating various policies and scenarios (Saysel et al. 2002). Direct structural tests and structurally-oriented behaviour tests were used assess the validity of the model structure (Naderi et al. 2021). This involves evaluating mathematical equations, dimensional consistency of equations, sub-models components, and all logical relationships in the model by comparing them with actual data and real-world knowledge and understanding of the local socio-ecological system. Direct structural tests can be classified as theoretical or empirical (Barlas 1996). We undertook theoretical structure tests by comparing the model structure with locally available literature like reports, academic papers, policy documents, and interviews with local stakeholders (Bandari et al. 2022). We conducted empirical direct structural tests in comparing the model structure with qualitative and quantitative information available describing the real-world system. The participatory modelling process of this research formed the main part of direct empirical structural tests through running two workshops with local expert stakeholders.

Structurally-oriented model behaviour tests were also used to indirectly evaluate the model structure's validity by via the use of simulation to detect potential model structural flaws. Validation of the model, including structural and structurally-oriented behaviour tests, was performed at all stages of the model development process. Because of the long-term nature of the system dynamics model, the emphasis of this test was more on pattern forecasting rather than point forecasting (Barlas 1996). Once the validity of the model structure was verified, the system behaviour patterns under the Business-As-Usual (BAU) scenario were compared with historical data from 2010 to 2022 to assess model applicability, reliability, and accuracy. We selected 15 target variables from the perspective of local sustainability: agricultural land-use, dairy land-use, cropping land use, dairy production, environmental water allocation, agricultural water allocation, salinity, annual dairy revenue, annual agricultural revenue, stream flow, agricultural surface water use, urban water use, population, labour force, and skilled workforce. The complete historical data records were unavailable for these target variables, so we used different historical data for each variable depending on their availability.

Furthermore, we calculated the maximum relative error (M) to quantitatively evaluate model performance as the degree of divergence between the historical and simulated data (Eq.1) (Liu et al. 2015; Naderi et al. 2021).

$$M = \frac{\Sigma(Ysim - Yobs)}{\Sigma Yobs} \qquad (1)$$

1.5 Model sensitivity analysis

Sensitivity analysis is used to quantify the influence of model parameters on model outputs, to identify the most influential parameters, and to determine the uncertainty in model outputs to variation in model inputs (Gao et al. 2016; Song et al. 2012). Thereby, model performance can be improved by targeting influential parameters for parameter refinement and enhanced accuracy. Sensitivity analysis can be beneficial for understanding the behavioural boundaries of the model and testing the robustness of scenario analysis and model-based policies (Chiu et al. 2019; Keyhanpour et al. 2021). We used Monte Carlo based sensitivity analysis for analysing the sensitivity and uncertainty of the system dynamics model, also known as multivariate sensitivity simulation (Jeon & Shin 2014). Monte Carlo simulation involves performing many hundreds or even thousands of simulations, and was implemented in the Vensim DSS (Keyhanpour et al. 2021; Ventana Systems 2021). In this multivariate method, all parameters are changed together.

We conducted the sensitivity analysis to identify which constant parameters can cause shifts in the sustainability target variables and behaviour of the system, and to demonstrate which parameter values form leverage points of the local social-ecological system. A list of 44 constant parameters across different model components was prepared for sensitivity analysis, the maximum and minimum values of each constant parameter was defined (**Error! Reference source not found.**), and simulation results were produced to analyse the behaviour of the nine sustainability target variables. As there is no information about the prior probability distributions for each model parameter, we assumed an independent uniform distribution for each parameter with a symmetrical ±30% variation around the reference value of selected constant components as the uncertainty bounds (Gao et al. 2016; Oijen et al. 2005; Song et al. 2012). We assumed We set the number of Monte Carlo simulations to 20000 and the random uniform was employed as the probability distribution of values. Both the validation and sensitivity analysis identified flaws in the LESEM, which required many changes in the structure of the model, which is an integral part of the iterative model-building process.

Table 1: Model parameter value ranges used for sensitivity analysis.

Variable	Units	Reference value	Lower Bound	Upper Bound
Demographic				
Avg migration rate	1/Year	0.00352	0.002	0.005
Fertility rate	1/Year	0.043	0.030	0.056
Mortality rate (Age group 0-14)	1/Year	0.00031	0.00022	0.00040
Mortality rate (Age group 15-64)	1/Year	0.00156	0.0011	0.0020
Mortality rate (Age group +65)	1/Year	0.03694	0.026	0.048
Water				
Fraction of environmental water allocation	Dmnl	0.13	0.091	0.169
Reference domestic water use per capita	Dmnl	0.058	0.041	0.075
Fraction of agricultural water allocation	Dmnl	0.27	0.189	0.351
Fraction of net water trade-in	Dmnl	0.102	0.072	0.134
Fraction of net water trade out	Dmnl	0.05	0.035	0.065
Average used surface water recovery rate	1/Year	0.12	0.084	0.156
Fraction of outflow from catchment	1/Year	0.55	0.385	0.715
Infiltration coefficient	Dmnl	0.17	0.119	0.221
Reference Yarrawonga water yield	Gigalitres/Year	4726	3308	6144
Conveyance water fraction	1/Year	0.1	0.070	0.130
Land use				
Fraction of urban land area change	Dmnl	0.014	0.010	0.018
Modified land to agricultural land allocation time	Year	1.9	1.330	2.470
Natural land to agricultural land allocation time	Year	4	2.800	5.200
Fertiliser use				
N and P runoff fraction in irrigated area	Dmnl	0.2	0.140	0.260
N and P runoff fraction in dryland area	Dmnl	0.075	0.053	0.098
Fraction of dairy sheds waste discharge	Dmnl	0.05	0.035	0.065
Fraction of lactation period	Dmnl	0.01	0.007	0.013
Lactation period	Day	300	210	390
TN concentration	Milligram/Litre	3	2.1	3.9
TP concentration	Milligram/Litre	0.025	0.018	0.033
Total nitrogen production per beef	Kg/Head	70	49	91
Total nitrogen and phosphorus production per sheep	Kg/Head	10	7	13
Total phosphorus production per beef	Kg/Head	3.939	2.757	5.121
The environmental water allocation policy	Dmnl	1.3	0.910	1.690
Water quality				
Reference water storage height	Meter/Year	185	130	241
Reference salt loads at Yarrawonga	Tonnes/Year	173423	121396	225450
Reference salt loads at Swan Hill	Tonnes/Year	233754	163628	303880
Economy				
Price elasticity of demand for beef meat	Dmnl	0.89	0.623	1.157
Price elasticity of demand for sheep meat	Dmnl	0.89	0.623	1.157
Price elasticity of demand for sheep wool	Dmnl	0.89	0.623	1.157
Price elasticity of demand for dairy	Dmnl	0.95	0.665	1.235
Price elasticity of demand for crops	Dmnl	0.38	0.266	0.494
Agriculture				
Productivity of sheep live exports	Tonnes/Head	0.048	0.034	0.063
Productivity of sheep wool	Tonnes/Head	0.007	0.005	0.009
Productivity of cattle live exports- Irrigated	Tonnes/Head	0.33	0.236	0.438
Productivity of beef meat-Dryland	Tonnes/Head	0.20	0.142	0.264
Productivity of cattle live exports- Dryland	Tonnes/Head	0.33	0.236	0.438
Productivity of dairy- Dryland	Litres/Head	5853.4	4097	7609
Productivity of dairy - Irrigated	Litres/Head	5854.4	4098	7611

1.6 BAU scenario

The BAU scenario examines the consequences of continuing recent historical trends in key system components (Guo et al. 2018; Rydzak et al. 2013). We specified ten parameters and set them under the BAU scenario, and the assumptions in each sub-model are presented in Table . All parameters throughout the LESEM model were set to historical data values for the model calibration period. Some parameters affected just one sub-model, and others involved more than one sub-model. For example, the water yield parameter affected water availability and water quality sub-models, but the migration rate parameter directly affected the demographic sub-model. However, the migration rate parameter may affect other sub-models indirectly, such as water availability through changing the population and increasing domestic water demand. Time boundaries for the model simulation were set from the year 2010 to the year 2050 to obtain a medium-long term projection of the results.

Table 2: The list of parameters under the BAU scenario setting in each sub-model.

Sub-model (s)	Parameter	Description
Demographic	Migration rate	The average migration rate from 2010 to 2020 is 0.00352 of the total population in each age cohort based on primary data obtained from Australian Bureau of Statistics census data (ABS 2022).
	Agricultural education rate	The agricultural education rate is 0.0316 of the total population in the age cohort 15-64. It was calculated according to historical data obtained from the Australian Bureau of Statistics census data for 2011 (ABS 2022).
	Agriculture sector employment rate	The employment rate in the agriculture sector is 0.0825 of the total population in the age cohort 15-64. It was calculated according to historical data obtained from the Australian Bureau of Statistics census data for 2011 (ABS 2022).
Agriculture, fertiliser use, land use, and local economy	Diet, waste, and feed efficiency (Food system)	This food system is a combination of the diet parameter (Willett et al. 2019), waste parameter (FAO 2011), and livestock feed efficiency parameter (Ridoutt & Navarro Garcia 2020) time series under SSP 245 scenario.
	Livestock productivity	Livestock productivity time series, including beef, sheep meat, wool (unit: tonnes/head), and dairy (unit: litres/head) under the RCP45 scenario was generated using the Australian national land use map data and the Australian ABS agriculture database from 2010 to 2050 (Navarro & Marcos Martinez 2021).
	Agricultural commodity yield	Agricultural yield time series (unit: heads/ha or tonnes/ha) under the RCP45 scenario was taken from (Navarro & Marcos Martinez 2021).
	Urban land-use change	Average urban land use change was set at 0.014 percents per year from 2010 to 2050. This scenario was generated using historical land-cover maps at 30 m resolution from 1985 - 2015 (Calderón-Loor et al. 2021).
Water availability & water quality	Water yield	The average water yield time series under SSP 245 scenario from 2010 to 2050 was generated using InVEST model. This model was applied different data sources, such as the Australian soil and land use grid, solar radiation data, WorldClim climate data, Priestley-Taylor evapotranspiration, and reference plant evapotranspiration coefficient (Sharp et al. 2018). The BAU average water yield scenario (i.e., SSP 245) was predicted to decrease gradually by 2050.
	Environmental water allocation	The current trend of environmental water allocation was derived from DELWP (2019) and DELWP (2021) from 2010 to 2019. We assumed this trend continues to rise and reach 1100 GL/Year of environmental water allocation.
	Surface water recovery rate	The average surface water recovery rate of 0.12 of total surface water use by all users was used which was calculated based on historic data from 2015 to 2019. Data was obtained from DELWP Water Accounts Online.

2 Results

2.1 Model structure

The LESEM (Figure) is based on the four highest priority SDGs as agricultural activities (SDG 2), water availability (SDG 6), economic growth (SDG 8), and life on land (SDG 15) which focus on socio-economic development outcomes and environmental impacts throughout the GMID. We split these four priority SDGs into the seven main sub-models: (1) demographic, (2) agriculture, (3) water availability, (4) land use, (5) local economy, (6) fertiliser use, and (7) water quality. The LESEM captures the main characteristics and issues of the study area. The model captures the effects of climate change (SGD 13) on water yield, agricultural productivity, agricultural yield, and food demand; as well as the effects of other ley parameters such as migration rate, employment rate, education, surface water recovery rate, urban land-use change rate, and environmental water allocation within and between these seven sub-models (Figure).

The water availability sub-model as an example of these seven main sub-models of LESEM is presented in Figure 5. This sub-model shows interactions between surface water storage, water allocation for different consumptive uses, water use by different users, surface water recovery, net surface water trade in GMID, infiltration to the ground water, evaporation losses through the system, agricultural water demand, and domestic water demand in the form of *stocks* and *flow* diagrams or other *auxiliary* variables. The water availability sub-model also connected with other sub-models of LESEM like demographic (by total population), agriculture (by reference yield of beef, sheep, dairy, and crops), local economy (by water requirement of beef, sheep, dairy, and crops-Irrigated), and land use (by projected beef, sheep, dairy, and crops land under agricultural land and water limitation-Irrigated). The detailed model documentation, including all seven sub-models, problems definition, equations, and used data, is available in the Supplementary Information.

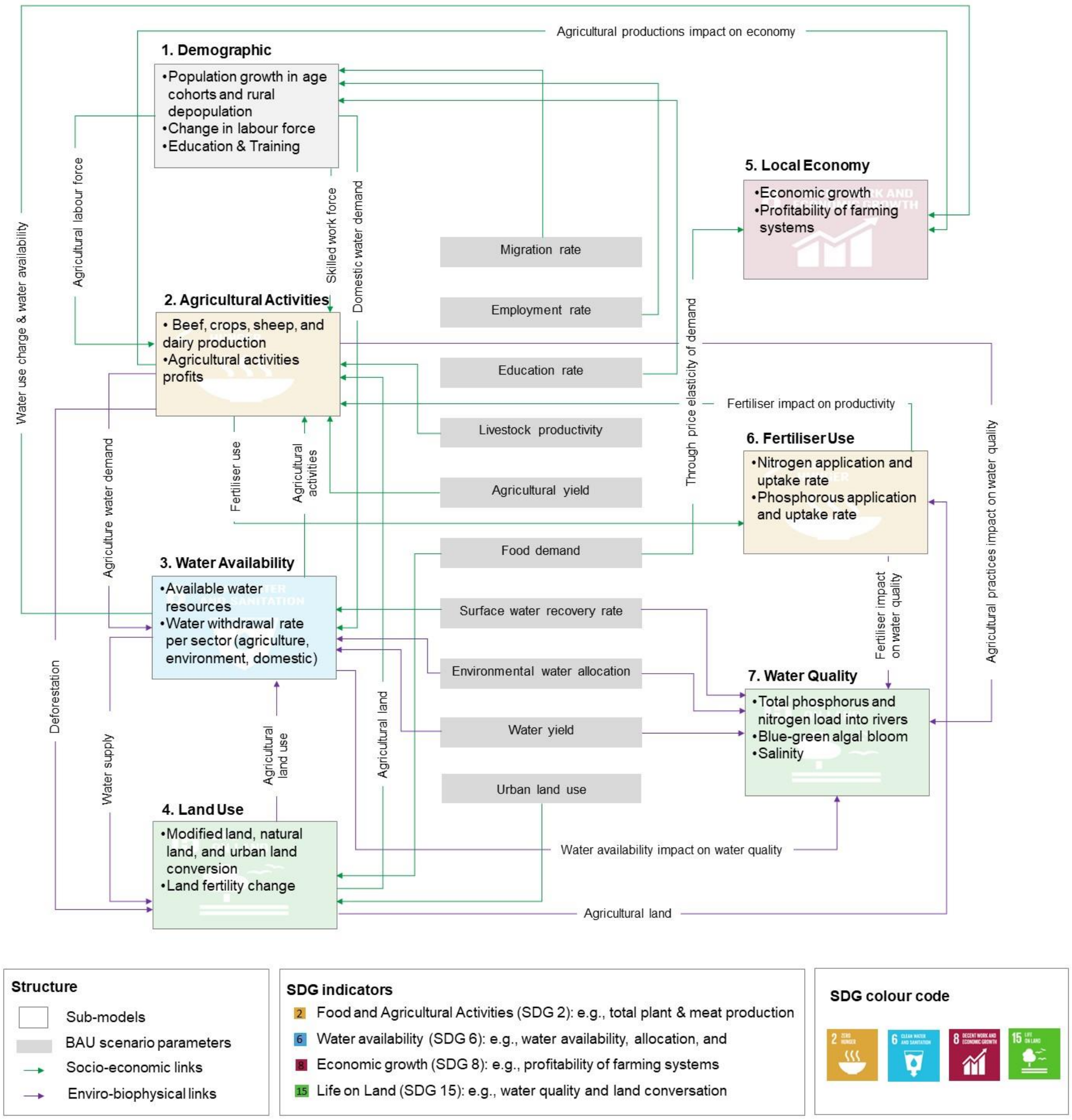

Figure 4. Structure and main sub-models of the LESEM. This model is composed of seven sub-models: demographic, economy, agricultural activities, food demand change, land use, fertiliser use, water availability, water quality, and ten BAU scenarios.

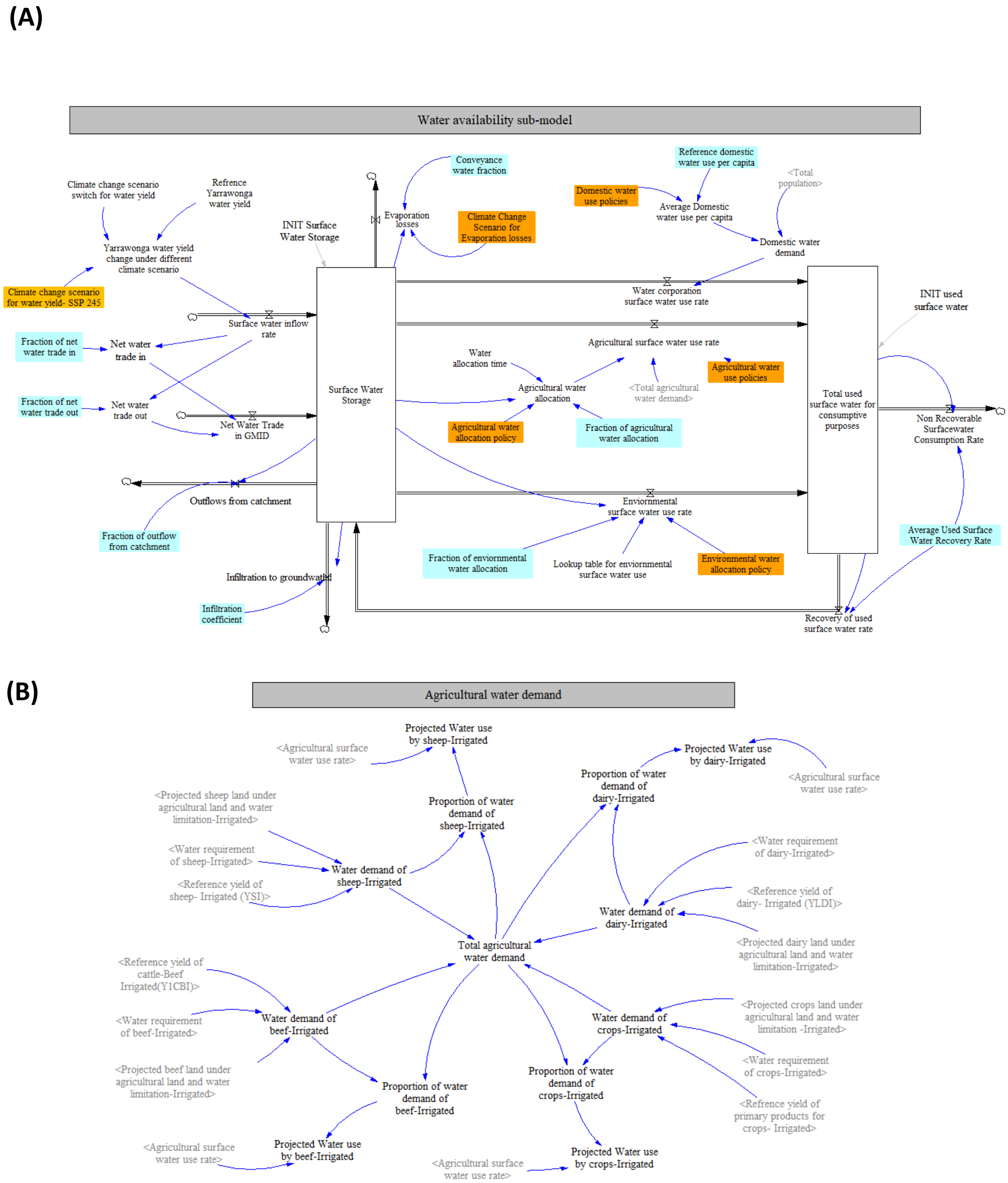

Figure 5. Schematic of system dynamics for the water availability sub-model. The water availability sub-model separated into structures for water availability (A) and agricultural water demand (B). The water availability sub-model includes causal loop diagrams, stock variables, flow variables, and other auxiliary variables. All these variables contain an equation which described in Supporting Information in details.

2.2 Model validation

The LESEM simulation results from 2010 to 2050 are shown in Figure , plotted alongside historical data. The validation results for the 15 target variables demonstrated that the behaviour of the LESEM model was acceptable, and the deviations observed in the simulated data were consistent with the behaviours and average trends of the target variables. It is evident from the simulation results that the projected trends of agricultural land, dairy land-use, stream flow, agricultural surface water use, and agricultural water allocation are decreasing over time. In contrast, based on the simulation results, the outcome variables of cropping land use, dairy production, environmental water allocation, salinity, annual dairy revenue, annual agricultural revenue, urban water use, population, labour force, and skilled workforce exhibit an increasing trend in their projections. The maximum relative error (M) values range from -0.06 for the area of dairy land-use to 0.18 for annual agricultural income (Figure). The validation results of the labour force, urban water use, annual dairy revenue, and cropping land use depict better performance with the lowest maximum relative error (M) among the other outcome variables.

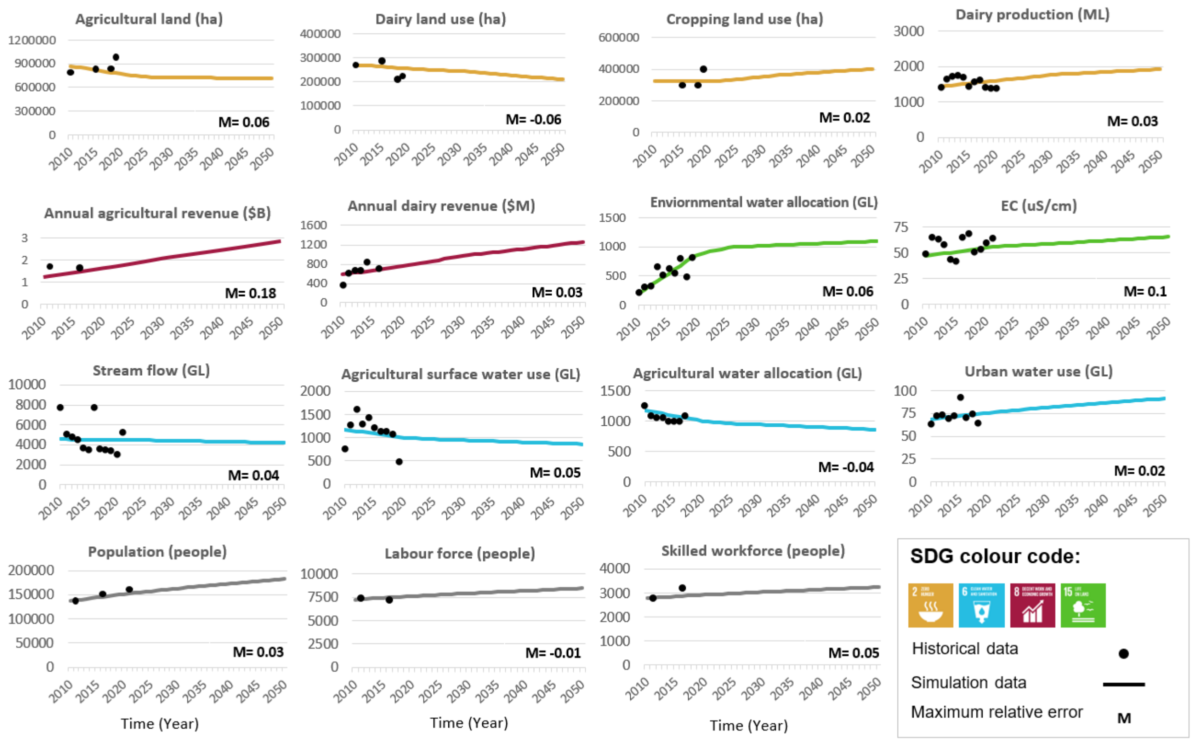

Figure 6. The comparison of the LESEM simulations with historical data. These plots demonstrate the BAU scenario projections for 15 outcome variables from 2010 to 2022 as well as future projections to the year 2050.

2.3 Sensitivity analysis results

Regarding the results obtained from the Monte Carlo sensitivity analysis of all constant parameters, some target variables were sensitive to the constant parameters. For example, the target variables of agricultural surface water use and environmental surface water use showed a high sensitivity to variation in constant parameters such as agricultural water allocation fraction and environmental water allocation fraction. These constant parameters were mainly affected by local policies and program priorities like environmental water and agricultural development policies. Furthermore, the blue-green algal bloom variable displayed sensitivity to the variables such as water storage height, total nitrogen, and total phosphorus. Both total nitrogen and total phosphorus mainly depend on various parameters such as agricultural land use, amount of fertiliser used, nitrogen and phosphorus concentration, and the number of cattle and sheep.

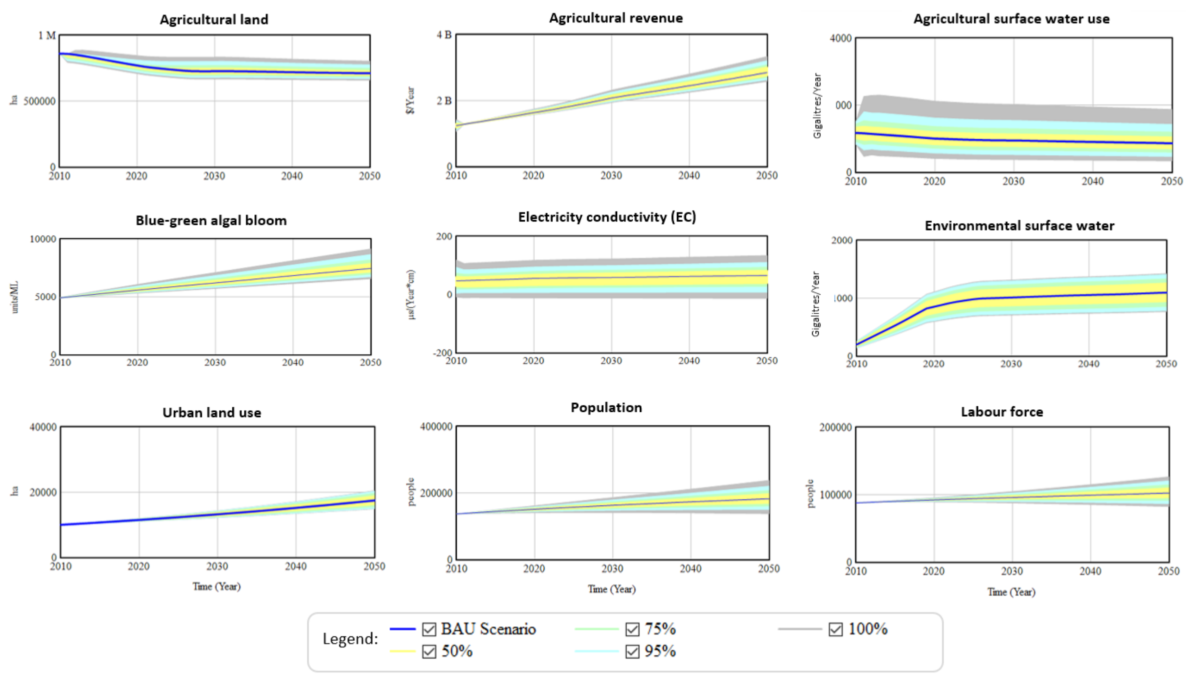

Figure 7. The sensitivity analysis results of nine sustainability target variables.

2.4 BAU projection

Business-as-usual (BAU) scenario was run for the period of 2022 to 2050, with the assumptions mentioned in Table . Examples of the sustainability variables projections under the BAU scenario are shown in Figure and Figure . BAU scenario analysis projected agricultural land use and agricultural surface water use in this region will gradually decrease until 2050. Specifically, the projections indicate that agricultural land use will decrease by 17%, and agricultural surface water use will decrease by 26%. However, the skilled and labour workforce are projected to show a 17% increase, and urban land use is expected to increase by 74% by 2050. Additionally, by 2050, blue-green algal bloom and electricity conductivity (EC) are projected to increase by 118% and 39%, respectively. In the other hand, agricultural revenue and environmental surface water allocation are projected to increase by 129% and 444%, respectively.

2.5 Interactions analysis

Analysing the SDGs in a silo and ignoring potential interactions between them can lead to adverse impacts on the overall fulfilment of the goals (Nilsson et al. 2016) and result in incoherent policies and adverse effects of development policies in specific sectors on the other sectors (Le Blanc 2015). The integrative nature of system dynamics allows for assessing the complex socio-economic and environmental system and analysing cross-sectoral interactions (Pedercini et al. 2020). We illustrated selected balancing (B) and reinforcing (R) causal loops as a sample of the LESEM's causal loop structure centred on food production (i.e., SDG 2) to demonstrate change across other sectors (i.e., four priority SDGs) under different scenarios (**Error! Reference source not found.**).

In **Error! Reference source not found.**, the integrated nature of the priority SDGs is illustrated with causal loops and the impacts of various scenarios within one SDG and related sub-model(s) propagates throughout the whole system. For example, increasing food production and agricultural activities (SDG 2) with limited ecological protection measures can create trade-offs and led to consequences in several other sectors, such as exacerbating water quality (SDGs 15) through using fertiliser (i.e., increasing total nitrogen or phosphorus) and reducing water availability (SDG 6). Reduced or increased available water affected food production, and consequently, food production impacted water availability in feedback loop B1. Concerning the balancing feedback loop B2, the increasing food demand scenario causes expanding agricultural land use, but water availability limits food production (SDG 2). Increased food production also impacts water availability by using more water in agriculture, while declining water availability decreases agricultural land use.

Reduced available water due to the water yield scenario affects the water-dependent ecosystems' environmental health by exacerbating water quality and limiting environmental water allocation (SDG 15). Increasing food production also directly influences economic growth (SDG 8) and consequently increases the local population. Feedback loops R1 and R2 capture the synergies effects of increasing the local population on the number of the labour forces and skilled workforces and their synergies impacts on food production in the GMID. Overall, the causal loop diagrams in **Error! Reference source not found.** depict how this system dynamics model integrates the priority SDGs interactions throughout all sub-models in the LESEM and how important it is to understand those SDG interactions to make coherent policy interventions and perform a sustainability assessment.

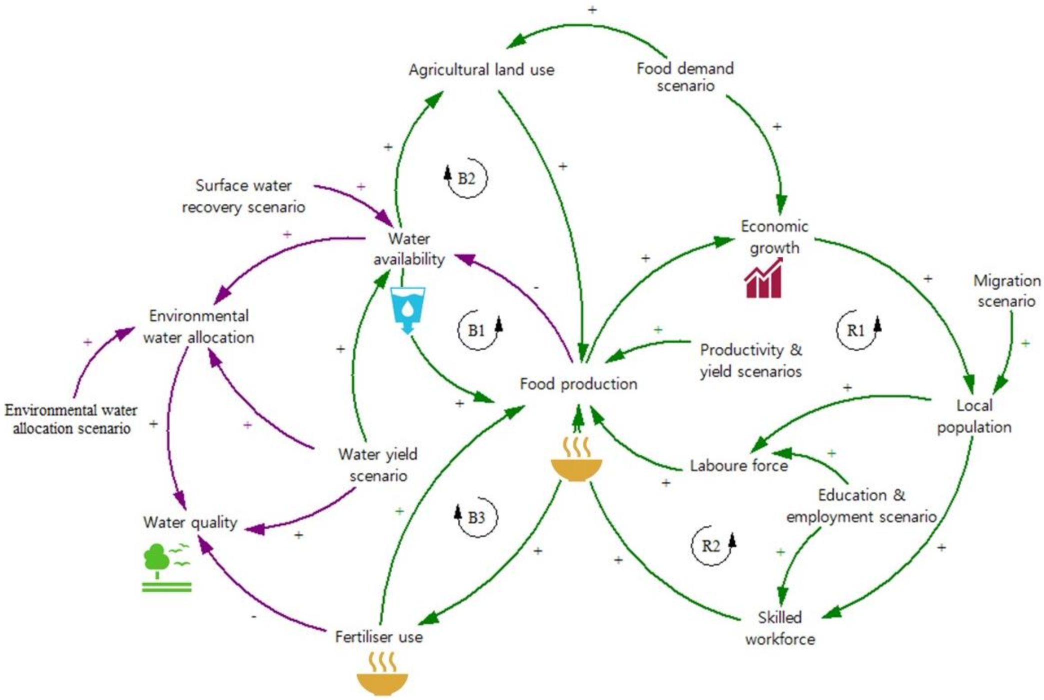

Figure 4: Selected balancing and reinforcing causal loops representing trade-offs or synergies interactions between agricultural activities (SDG 2), water availability (SDG 6), economic growth (SDG 8), and life on land (SDG 15). Positive feedback linkages are shown as a positive sign (+), whereas negative feedback linkages are shown with a negative sign (-). The purple arrows indicate the enviro-biophysical linkages. The green arrows indicate the socio-economic linkages. Reinforcing causal loops are depicted with the positive sign. Balancing causal loops are displayed with the negative sign. The SDGs icons are the courtesy of the UN SDGs communications material. Colours should be used for this figure in print.

3 References

RMCG 2016, Basin Plan - GMID socio-economic impact assessment, Final Report for the GMID Water Leadership Forum, RM Consulting Group, October 2016.

ABS 2022, *Search Census data*, Australian Bureau of Statistics, <https://www.abs.gov.au/census/find-census-data>.

Aither 2019, *Goulburn Regional Profile: An analysis of regional strengths and challenges*, Infrastructure Victoria, A Report prepared for Infrastructure Victoria, www.infrastructurevictoria.com.au/wp-content/uploads/2019/04/Aither-Goulburn-Regional-Profile-March-2019.pdf.

Alston, M, Clarke, J & Whittenbury, K 2018, 'Limits to adaptation: Reducing irrigation water in the Murray-Darling Basin dairy communities', *Journal of Rural Studies*, vol. 58, pp. 93-102, DOI https://doi.org/10.1016/j.jrurstud.2017.12.026.

Baker, D, Dunn, A & Olszak, C 2018, *Water markets report*, Aither,Melbourne, VIC, https://www.aither.com.au/wp-content/uploads/2019/03/Aither-Water-markets-report-2017-18-3.pdf.

Bandari, R, Enayat, AM, Rebecca, EL, David, D & Brett, AB 2022, 'Prioritising Sustainable Development Goals, characterising interactions, and identifying solutions for local sustainability', *Environmental Science & Policy*, vol. 127, pp. 325-36, DOI https://doi.org/10.1016/j.envsci.2021.09.016.

Barlas, Y 1996, 'Formal aspects of model validity and validation in system dynamics', *System Dynamics Review 12, 183–210*, https://www.researchgate.net/profile/Mahdi_Bastan/post/How_to_validate_a_System_Dynamics_Model/attachment/59d6257c79197b8077983cc6/AS:317830619172868@1452788133199/download/1996+Barlas+Yaman+Formal+aspects+of+model+validity+and+validation+in+system+dynamics+1.pdf

Calderón-Loor, M, Hadjikakou, M & Bryan, BA 2021, 'High-resolution wall-to-wall land-cover mapping and land change assessment for Australia from 1985 to 2015', *Remote Sensing of Environment*, vol. 252, DOI 10.1016/j.rse.2020.112148.

Chiu, C-C, Château, P-A, Lin, H-J & Chang, Y-C 2019, 'Modeling the impacts of coastal land use changes on regional carbon balance in the Chiku coastal zone, Taiwan', *Land Use Policy*, vol. 87, DOI 10.1016/j.landusepol.2019.104079.

Collste, D, Pedercini, M & Cornell, SE 2017, 'Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies', *Sustainability Science*, no. 6, p. 921, DOI 10.1007/s11625-017-0457-x.

Cummins, T 2016, *Water Market Trends, Trends in Northern Victorian Water Trade 2001-2015*, The State of Victoria Department of Environment, Land, Water and Planning 2015, www.waterregister.vic.gov.au.

Davis, JP & Eisenhardt, KM 2007, 'Developing theory through simulation methods', *Academy of Management Review*, no. 32(2): 480–499., DELWP 2019, *Water Market Trends*, The State of Victoria Department of Environment, Land, Water and Planning,

DELWP 2021, *Victorian Water Accounts-2019-2020, a statement of Victorian water resources*, the Department of Environment, Land, Water and Planning (DELWP),

Di Lucia, L, Slade, R & Khan, J 2021, 'Decision-making fitness of methods to understand Sustainable Development Goal interactions', *Nature Sustainability*, vol. 5, no. 2, pp. 131-8, DOI 10.1038/s41893-021-00819-y.

Eker, S, Zimmermann, N, Carnohan, S & Davies, M 2018, 'Participatory system dynamics modelling for housing, energy and wellbeing interactions', *Building Research & Information*, vol. 46, no. 7, pp. 738-54, DOI 10.1080/09613218.2017.1362919.

FAO 2011, *Global food losses and food waste – Extent*, causes and prevention. Rome,

Gao, L, Bryan, BA, Nolan, M, Connor, JD, Song, X & Zhao, G 2016, *Robust global sensitivity analysis under deep uncertainty via scenario analysis*, Elsevier, http://ezproxy.deakin.edu.au/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=ir00031a&AN=dul.30102069&authtype=sso&custid=deakin&site=eds-live&scope=site

GBCMA 2013, *Goulburn Broken Regional Catchment Strategy 2013-2019*, Goulburn Broken Catchment Management Authority, https://www.gbcma.vic.gov.au/downloads/RegionalCatchmentStrategy/GBCMA_RCS_2013-19.pdf.

GBCMA 2016, *Shepparton Irrigation Region (Agricultural Floodplains) Land and Water Management Plan 2016-2020*, Goulburn Broken Catchment Management Authority, https://www.gbcma.vic.gov.au/downloads/Publications/Agricultural%20Floodplains%20%20Land%20and%20Water%20Management%20Plan.pdf.

GBWQWG 1995a, *Dryland Diffuse source nutrients for Goulburn Broken Catchment*,

GBWQWG 1995b, *Nutrients in irrigation drainage water from the Goulburn and Broken catchments : summary*, Goulburn Broken Water Quality Working Group,

GMIDWL 2018, *An Inquiry into the effectiveness of the implementation of the Basin Plan and water resource plan*, Goulburn Murray Irrigation District (GMID) Water Leadership, Productivity Commission Murray-Darling Basin Plan: Five-year Assessment, https://www.pc.gov.au/__data/assets/pdf_file/0020/227540/sub062-basin-plan.pdf.

GMW 2002, *North-east salinity strategy surface water salinity monitoring*, Goulburn Murray Water,

GMW 2018a, *2017/18 Annual Report*, Goulburn-Murray Water, https://www.g-mwater.com.au/about/reports-and-publications/annualreports.

GMW 2018b, *Corporate Plan 2018/19 to 2022/23*, Goulburn-Murray Water, https://www.g-mwater.com.au/downloads/gmw/Corporate_Plans/2018-19_CorporatePlan.pdf.

GMW 2018c, *Goulburn-Murray Water*, Goulburn-Murray Water, retrieved retrieved 8 May 2019, <https://www.g-mwater.com.au/>.

Gohari, A, Mirchi, A & Madani, K 2017, 'System Dynamics Evaluation of Climate Change Adaptation Strategies for Water Resources Management in Central Iran', *Water Resources Management*, vol. 31, no. 5, pp. 1413-34, DOI 10.1007/s11269-017-1575-z.

Guo, L-l, Qu, Y, Wu, C-y & Wang, X-l 2018, 'Identifying a pathway towards green growth of Chinese industrial regions based on a system dynamics approach', *Resources, Conservation and Recycling*, vol. 128, pp. 143-54, DOI 10.1016/j.resconrec.2016.09.035.

Gupta, M & Hughes, N 2018, *Future scenarios for the southern Murray–Darling Basin water market*, Australian Bureau of Agricultural and Resource Economics and Sciences, https://www.agriculture.gov.au/sites/default/files/documents/abares-future-scenarios-for-southern-mdb.pdf.

Hart, BT 2016, 'The Australian Murray–Darling Basin Plan: challenges in its implementation (part 1)', *International Journal of Water Resources Development*, vol. 32, no. 6, pp. 819-34, DOI https://doi.org/10.1080/07900627.2015.1083847.

Hinz, R, Sulser, TB, Huefner, R, Mason-D'Croz, D, Dunston, S, Nautiyal, S, Ringler, C, Schuengel, J, Tikhile, P, Wimmer, F & Schaldach, R 2020, 'Agricultural Development and Land Use Change in India: A Scenario Analysis of Trade-Offs Between UN Sustainable Development Goals (SDGs)', *Earth's Future*, vol. 8, no. 2, DOI 10.1029/2019ef001287.

Jeon, C & Shin, J 2014, 'Long-term renewable energy technology valuation using system dynamics and Monte Carlo simulation: Photovoltaic technology case', *Energy*, vol. 66, pp. 447-57, DOI 10.1016/j.energy.2014.01.050.

Keyhanpour, MJ, Musavi Jahromi, SH & Ebrahimi, H 2021, 'System dynamics model of sustainable water resources management using the Nexus Water-Food-Energy approach', *Ain Shams Engineering Journal*, vol. 12, no. 2, pp. 1267-81, DOI 10.1016/j.asej.2020.07.029.

Kimmich, C, Gallagher, L, Kopainsky, B, Dubois, M, Sovann, C, Buth, C & Bréthaut, C 2019, 'Participatory Modeling Updates Expectations forIndividuals and Groups, Catalyzing BehaviorChange and Collective Action inWater-Energy-Food NexusGovernance', *Earth's Future*, vol. 7, no. 12, pp. 1337-52, DOI 10.1029/2019ef001311.

Le Blanc, D 2015, 'Towards Integration at Last? The Sustainable Development Goals as a Network of Targets', *Sustainable Development*, vol. 23, no. 3, pp. 176-87, DOI 10.1002/sd.1582.

Liu, H, Benoit, G, Liu, T, Liu, Y & Guo, H 2015, 'An integrated system dynamics model developed for managing lake water quality at the watershed scale', *J Environ Manage*, vol. 155, pp. 11-23, DOI 10.1016/j.jenvman.2015.02.046.

Lobell, DB & Gourdji, SM 2012, 'The influence of climate change on global crop productivity', *Plant Physiol*, vol. 160, no. 4, pp. 1686-97, DOI 10.1104/pp.112.208298.

Lukasiewicz, A, Finlayson, CM & Pittock, J 2012, *Identifying low risk climate change adaptation: A case study of the Goulburn Broken Catchment Management Authority*, Charles Sturt University, https://cdn.csu.edu.au/__data/assets/pdf_file/0012/884298/72_Gouburn-Broken-Case-Study.pdf.

Moallemi, EA, Bertone, E, Eker, S, Gao, L, Szetey, K, Taylor, N & Bryan, BA 2021, 'A review of systems modelling for local sustainability', *Environmental Research Letters*, vol. 16, no. 11, DOI 10.1088/1748-9326/ac2f62.

Moallemi, EA, Hosseini, SH, Eker, S, Gao, L, Bertone, E, Szetey, K & Bryan, BA 2022, 'Eight Archetypes of Sustainable Development Goal (SDG) Synergies and Trade-Offs', *Earth's Future*, vol. 10, no. 9, DOI 10.1029/2022ef002873.

Naderi, MM, Mirchi, A, Bavani, ARM, Goharian, E & Madani, K 2021, 'System dynamics simulation of regional water supply and demand using a food-energy-water nexus approach: Application to Qazvin Plain, Iran', *J Environ Manage*, vol. 280, p. 111843, DOI 10.1016/j.jenvman.2020.111843.

Navarro, J & Marcos Martinez, R 2021, *Estimating long-term profits, fertiliser and pesticide use baselines in Australian agricultural regions*, User Guide. CSIRO, Australia.,

NCCMA 2016, *North Central Victoria Regional Sustainable Agriculture Strategy*, North Central Catchment Management Authority, http://www.nccma.vic.gov.au/sites/default/files/publications/nccma_sustainable_agriculture_strategy_2016_final_web.pdf.

Neumann, K, Anderson, C & Denich, M 2018, 'Participatory, explorative, qualitative modeling: application of the iMODELER software to assess trade-offs among the SDGs', *Economics-the Open Access Open-Assessment E-Journal*, vol. 12, no. 1, DOI 10.5018/economics-ejournal.ja.2018-25.

Nilsson, M, Chisholm, E, Griggs, D, Howden-Chapman, P, McCollum, D, Messerli, P, Neumann, B, Stevance, AS, Visbeck, M & Stafford-Smith, M 2018, 'Mapping interactions between the sustainable development goals: lessons learned and ways forward', *Sustain Sci*, vol. 13, no. 6, pp. 1489-503, DOI 10.1007/s11625-018-0604-z.

Nilsson, M, Griggs, D & Visbeck, M 2016, 'Map the interactions between Sustainable Development Goals', *Comment in Nature*, vol. 53, no. 7607, DOI https://doi.org/10.1787/agr_outlook-2015-en.

Norström, AV, Cvitanovic, C, Löf, MF, West, S, Wyborn, C, Balvanera, P, Bednarek, AT, Bennett, EM, Biggs, R, de Bremond, A, Campbell, BM, Canadell, JG, Carpenter, SR, Folke, C, Fulton, EA, Gaffney, O, Gelcich, S, Jouffray, J-B, Leach, M, Le Tissier, M, Martín-López, B, Louder, E, Loutre, M-F, Meadow, AM, Nagendra, H, Payne, D, Peterson, GD, Reyers, B, Scholes, R, Speranza, CI, Spierenburg, M, Stafford-Smith, M, Tengö, M, van der Hel, S, van Putten, I & Österblom, H 2020, 'Principles for knowledge co-production in sustainability research', *Nature Sustainability*, vol. 3, no. 3, pp. 182-90, DOI 10.1038/s41893-019-0448-2.

Oijen, MV, Rougier, J & Smith, R 2005, 'Bayesian calibration of process-based forest models: bridging the gap between models and data', *Tree Physiology 25, 915–927*,

Pearson, LJ, Biggs, R, Harris, M & Walker, B 2013, 'Measuring sustainable development: The promise and difficulties of implementing inclusive wealth in the Goulburn-Broken catchment, Australia', *Sustainability: Science, Practice, and Policy*, vol. 9, no. 1, pp. 16-27, DOI https://doi.org/10.1080/15487733.2013.11908104.

Pedercini, M, Arquitt, S & Chan, D 2020, 'Integrated simulation for the 2030 agenda', *System Dynamics Review*, vol. 36, no. 3, pp. 333-57, DOI 10.1002/sdr.1665.

Pradhan, P, Costa, L, Rybski, D, Lucht, W & Kropp, JP 2017, 'A Systematic Study of Sustainable Development Goal (SDG) Interactions', *Earths Future*, vol. 5, no. 11, pp. 1169-79, DOI https://doi.org/10.1002/2017ef000632.

Ridoutt, B & Navarro Garcia, J 2020, 'Cropland footprints from the perspective of productive land scarcity, malnutrition-related health impacts and biodiversity loss', *Journal of Cleaner Production*, vol. 260, DOI 10.1016/j.jclepro.2020.121150.

RMCG 2019, 'GMID Strategic Plan: Regional Insights',

RPG 2020, *Goulburn Murray Resilience Strategy*, Regional Partnership Goulburn

Rydzak, F, Obersteiner, M & Kraxner, F 2010, 'Impact of Global Earth Observation - Systemic view across GEOSS societal benefit area', *International Journal of Spatial Data Infrastructures Research*, pp. 216–43, DOI 10.2902/1725-0463.2010.05.art9.

Rydzak, F, Obersteiner, M, Kraxner, F, Fritz, S & McCallum, I 2013, *FeliX3 – Impact Assessment Model Systemic view across Societal Benefit Areas beyond Global Earth Observation*, Austria: IIASA. Model Report and Technical Documentation, https://github.com/iiasa/Felix-Model/blob/master/Felix3_ModelReport.pdf.

Saysel, AK, Barlas, Y & Yenigun, O 2002, 'Environmental sustainability in an agricultural development project: a system dynamics approach', *J Environ Manage*, vol. 64, no. 3, pp. 247-60, DOI 10.1006/jema.2001.0488.

Sharp, R, Douglass, J, Wolny, S, Arkema, K, Bernhardt, J, Bierbower, W, Chaumont, N, Denu, D, Fisher, D, Glowinski, K, Griffin, R, Guannel, G, Guerry, A, Johnson, J, Hamel, P, Kennedy, C, Kim, CK, Lacayo, M, Lonsdorf, E, Mandle, L, Rogers, L, Silver, J, Toft, J, Verutes, G, Vogl, AL, Wood, S & Wyatt, K 2018, *InVEST User's Guide, Integrated Valuation of Ecosystem Services and Tradeoffs*, The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund,

Song, X, Bryan, BA, Paul, KI & Zhao, G 2012, 'Variance-based sensitivity analysis of a forest growth model', *Ecological Modelling*, vol. 247, pp. 135-43, DOI 10.1016/j.ecolmodel.2012.08.005.

Sterman, J 2002, 'Business Dynamics, System Thinking and Modeling for a Complex World', in Massachusetts Institute of Technology.

UN 2015, *Transforming our world: the 2030 Agenda for Sustainable Development*, A/RES/70/1. UN General Assembly, New York, https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf.

Van Soest, HL, Van Vuuren, DP, Hilaire, J, Minx, JC, Harmsen, MJHM, Krey, V, Popp, A, Riahi, K & Luderer, G 2019, 'Analysing interactions among Sustainable Development Goals with Integrated Assessment Models', *Global Transitions*, vol. 1, pp. 210-25, DOI https://doi.org/10.1016/j.glt.2019.10.004.

Vennix, J 1996, *Group Model Building : Facilitating Team Learning Using System Dynamics*, Wiley, https://www.wiley.com/en-ie/Group+Model+Building+:+Facilitating+Team+Learning+Using+System+Dynamics-p-9780471953555

Ventana Systems, I 2021, *Vensim DSS. Ventana Systems Inc*, Ventana Systems Inc <https://vensim.com/>.

Wang, G, Xiao, C, Qi, Z, Meng, F & Liang, X 2021, 'Development tendency analysis for the water resource carrying capacity based on system dynamics model and the improved fuzzy comprehensive evaluation method in the Changchun city, China', *Ecological Indicators*, vol. 122, DOI 10.1016/j.ecolind.2020.107232.

Willett, W, Rockstrom, J, Loken, B, Springmann, M, Lang, T, Vermeulen, S, Garnett, T, Tilman, D, DeClerck, F, Wood, A, Jonell, M, Clark, M, Gordon, LJ, Fanzo, J, Hawkes, C, Zurayk, R, Rivera, JA, De Vries, W, Majele Sibanda, L, Afshin, A, Chaudhary, A, Herrero, M, Agustina, R, Branca, F, Lartey, A, Fan, S, Crona, B, Fox, E, Bignet, V, Troell, M, Lindahl, T, Singh, S, Cornell, SE, Srinath Reddy, K, Narain, S, Nishtar, S & Murray, CJL 2019, 'Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems', *Lancet*, vol. 393, no. 10170, pp. 447-92, DOI 10.1016/S0140-6736(18)31788-4.

Zhang, Q, Prouty, C, Zimmerman, JB & Mihelcic, JR 2016, 'More than Target 6.3: A Systems Approach to Rethinking Sustainable Development Goals in a Resource-Scarce World', *Engineering*, vol. 2, no. 4, pp. 481-9, DOI 10.1016/j.Eng.2016.04.010.